Microcontroller-based Transient Signal Analysis and Distributed System for Intelligent Process Monitoring

Mohammad Manea Alyami

(BSc. MSc.)

A thesis submitted in candidature for the degree of Doctor of Philosophy of the Cardiff University

September 2008

Intelligent Process Monitoring and Management (IPMM) Centre, Cardiff School of Engineering, Cardiff University

ACKNOWLEDGEMENTS

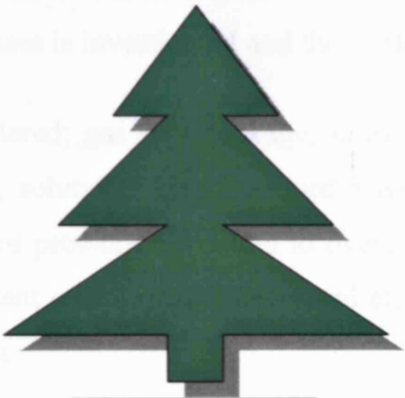
I would like to express my sincere gratitude to Dr Roger Grosvenor and Mr Paul Prickett for their supervision, expert guidance and patience during the course of this research. My thanks also go to the Engineering workshop at Cardiff School of Engineering for the assistance they provided to set up the test rig and for facilitating the "parts" required to make the activities of this research possible.

Warm thanks are extended to my friends; Ahmad Alqaoud, Bader Almutairi, Hassan Khayyat and Raees Siddiqui for their companionship and support throughout this research.

Special thanks to my dearest and lifelong friends; Saud Shayban and Abdullah Alguthami for being always there. The support and encouragement they provide are highly appreciated.

Thanks to the Royal Commission of Jubail, Saudi Arabia, for giving me the opportunity to further my education and providing the financial support required for the pursuit of this research.

Finally, thanks to my parents for their patience, support and for being a source of inspiration, without which engaging in this course would not be possible.



Dedication

This thesis is dedicated to Yara and Lamar; the essence of life.

SUMMARY

The research presented in this thesis considers the feasibility of utilising dsPICs (digital signal controllers) in the development of effective monitoring systems which have the capability to adapt to changes in operating conditions and can be quickly calibrated to suit a range of applications, thus helping to reduce the development time constraint. The capability of these monitoring solutions to detect and isolate faults occurring in pneumatic processes is investigated and their effectiveness verified.

Three applications are considered; gas pipe leakage, linear actuator operations and gripper action. In each case, solutions are developed based upon the dsPIC. The solutions utilise the analysis of pressure transients to overcome the limitation in the dsPIC memory. The deployment of minimal sensors and electronics was essential to optimise the cost of the system.

Leak detection techniques are developed with application to gas fitting pipes. The speed at which correct decisions are determined was the essence of this work. The solutions are tested, compared and their capability validated using pipes which had been rejected according to industrial standards. In this application a dsPIC digital signal controller and a pressure sensor were deployed, thus ensuring a low cost monitoring solution.

Linear actuator "end of stroke" monitoring has, previously, largely been possible using limit switches. A more challenging method based upon the deployment of a pressure sensor is outlined. Monitoring model surfaces were obtained and their capability to determine the health of the process was proved, at various supply pressures.

With regard to the gripper monitoring, a performance surface by which the gripper action can be monitored is generated and embedded within the dsPIC. Various faults are simulated and their effect on the gripper performance investigated. Leakage and blockage are also investigated at various places in the pneumatic circuit to allow for an algorithm to be devised. Faults may be detected and isolated, and their locations identified to allow for timely recovery treatment, thus supporting an enhanced process monitoring strategy.

CONTENTS

ACRONYMS

ADC	Analogue to Digital Converter
AGU	Address Generation Unit
ALU	Arithmetic Logic Unit
ANN	Artificial Neural Network
CAN	Controller Area Network
CCD	Charge Coupled Devise
CPU	Central Processing Unit
DCI	Digital Converter Interface
DSC	Digital Signal Controller
DSP	Digital Signal Processor
dsPIC	Digital Signal Peripheral Interface Controller
EEPROM	Electrically Erasable Programmable Read-Only-Memory
FDD	Fault Detection and Diagnosis
FDI	Fault Detection and Isolation
FEN	Front End Node
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FTP	File Transfer Protocol
GUI	Graphical User Interface
HTTP	Hyper Text Transfer Protocol
HVAC	Heat, Ventilation and Air Conditioning
ICD2	In-Circuit Debugger 2
ICSP	In-Circuit Serial Programming
IIR	Infinite Impulse Response
IP	Internet Protocol
IPMM	Intelligent Process Monitoring and Management
I/O	Input/Output
ISO	International Standards Organisation
IVT	Interrupt Vector Table
LAN	Local Area Network
MAB	Message Assembly Buffer

MCU	Microcontroller
MSLD	Mass Spectrometer Leak Detector
NCAP	Network Capable Application Processor
NIC	Network Interface Controller
NN	Neural Network
OSI	Open System Interconnection
PCB	Printed Circuit Board
PDA	Personal Digital Assistant
PIC	Peripheral Interface Controller
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PLL	Phase-Locked-Loop
PSVPAG	Program Space Visibility Page
RAM	Random Access Memory
RTSP	Run-Time Self Programming
SPI	Serial Peripheral Interface
SoC	System on Chip
STIM	Smart Transducer Interface Module
TCP	Transmission Control Protocol
TTL	Transistor-Transistor Logic
UART	Universal Asynchronous Receiver Transmitter
VDI	Visual Device Initializer

LIST OF FIGURES

LISTS OF TABLES

Chapter 1

INTRODUCTION

Pneumatically-driven robotic systems play a very important role in manufacturing especially in pick and place operations where no sophisticated control scheme is required. In particular, linear actuators and two-finger parallel grippers are widely used in "bang-bang" applications. Compressed air provides the required energy, thus yielding a clean and safe environment. They provide high power-to-weight and cost-to-benefits ratios which encourage their use in many industries including automobile, electronic, pharmaceutical, agriculture and material handling. They are used to perform tasks that require repetitive actions and high degree of accuracy. The deployment of such devices allows many production processes to become automated.

The design and control aspects of actuators and grippers have been the subject of a great deal of research. Many techniques have been proposed to achieve better control strategies of such devices so as to optimise their performance. In addition many researchers have identified problems with the design of grippers and developed alternative solutions. Grippers in particular are often task oriented and the design of generic grippers is still a requirement so that tool changing can be minimized and production efficiency increased. Research to identify problems related to their operation was found to be limited and hence motivated the research undertaken in this thesis.

The monitoring of such systems is vital so that faults arising in the process can be detected and real time remedial measures undertaken. Faults occurring in the process need to be detected and dealt with to support a successful production strategy. As a result, production efficiency can be improved and energy resources saved. Operational costs and shutdowns can also be reduced. The added emphasis being placed upon the quality of products necessitates the importance of continuous monitoring in order to cope with the changing market demands. Economical monitoring solutions are required. Such solutions have become possible to achieve with the current trends in technological advancements.

As will be seen, the literature review demonstrated that the currently reported, adopted approaches normally employ multi-sensing elements as well as personal computers to undertake the monitoring function. The cost associated with these approaches can be high. Their deployment in industrial environments could also be impeded due to, the environmental conditions, noise and lack of space. Thus, monitoring approaches require further development in order to make this important activity accessible in terms of cost and flexibility. The availability of embedded technology can help to facilitate the development of monitoring systems capable of fulfilling these essential requirements. The new generation of microcontrollers (the dsPIC for example) offer a high level of integrated devices and operate at low power. These devices can in fact make the deployment of compact and cost-optimised monitoring systems the ideal solution for industrial environments. A distributed monitoring system based upon embedded devices was recognised as an alternative solution. Under this architecture various devices collaborate with each other to enhance the overall monitoring power and system capabilities. In this way a balance can be struck between power and cost.

The need for a compact and generic monitoring system is thus considered in this research. To address the cost associated with the monitoring system, a single pressure sensor was used and hence the reduction in the overall system cost was emphasised. A new generation of microcontrollers, dsPIC controllers, emerged at the start of this research and were thus selected to overcome the limitations of 8-bit microcontrollers in terms of processing power and speed. A system based on such devices can be placed close to the signal source to ensure that signal integrity remains intact. The approach adopted in this research also supports the evolution of applying such systems within the IPMM research group at the Cardiff School of Engineering.

Although the dsPIC devices are superior to previous generations of microcontrollers, they are still limited in terms of on-chip memory. Robotic systems in pick and place operations are fast and should be monitored to assess their performance. Taking into consideration the limited memory, this research was aimed at assessing whether this can be undertaken by capturing and analysing air pressure transients during the motion of such devices. Pressure transient analysis was deemed to be of great potential as the basis by which faults arising in the process may be detected and isolated.

The monitoring of processes can lead to improvement in reliability and safety on the factory floor where robotic systems are assigned to undertake assembly tasks in a production line. A literature review is provided in Chapter 2, reporting work undertaken into various aspects of the monitoring of pneumatic systems. Many techniques have been developed and various approaches considered. The review also discuses different application areas. It summarises the various techniques developed to improve the design and control of pneumatic devices. Monitoring approaches were also summarised. Transient analysis as a tool used to identify faults occurring in the process was emphasised. The need for low-cost monitoring systems is considered and thus the deployment of microcontroller-based systems across many application areas is identified.

The requirements to optimise process performance were identified through the various monitoring approaches reported within the review. A low-cost distributed monitoring architecture is proposed in Chapter 3. The current technology in embedded devices forms the basis of this architecture. The dsPIC technology in particular was selected as a low-cost process monitoring solution. Its suitability and technical attributes are described. Various aspects of signal acquisition and analysis are also discussed. The ability of the system to provide real-time information about the process being monitored is a requirement for quality management. To achieve that, the required communication protocols are presented.

Three applications are presented in the next chapters to explore the capabilities of dsPIC based monitoring approaches. The integrity of commercial gas fitting pipes is crucial. It can be checked during production and/or before their assembly into consumer products. Chapter 4 proposed the development and validation of speedy methods to inspect the health of such pipes. The capability of the dsPIC in terms of acquisition and processing power is investigated. The applicability and advantages of the monitoring solution to replace existing operator-dependant methods is discussed.

The effectiveness of the developed techniques is verified through tests performed on pipes considered faulty by industrial standards.

Chapter 5 presents the development of surfaces (derived from determined mathematical models) relating end of stroke and supply pressure to the time taken for movement of a linear actuator. The extending/retracting motions are considered first with the deployment of limit switches. By comparing the expected time to the measured one, the health of the actuator is monitored. To explore the feasibility in the approach, a monitoring method is developed based upon the deployment of a pressure sensor in addition to a limit switch providing the home-position signal. A more challenging method was based on the use of only the pressure sensor. The analysis of the pressure transients led to the evolution of a surface capable of providing the correct position of the actuator during the extending motion. A detailed description of this approach is provided.

Two-finger parallel grippers are the most widely used tools for pick and place operations in many industries. Monitoring their operation is essential in order to detect faults which may arise in the process. Chapter 6 describes the development of a system based upon a dsPIC device and a pressure sensor for the third of the application areas. Again the cost of the monitoring system is an important consideration. A monitoring technique based on the development of a surface relating the part size to the gripping time over the operating pressures is proposed. The analysis of pressure signal was identified as a powerful tool through which many faults can be detected. Simulation of various common faults occurring during the gripper operation is provided.

Chapter 7 explains the implementation of the developed system to detect part size while performing pick and place tasks. The flexibility of the method developed to adapt with possible changing conditions due to the replacement of the gripper is assured. The capability of the dsPIC as a modelling tool is investigated. The proposed network architecture encompasses a server which facilitates further analysis and surface modelling whenever deemed necessary, thus eliminating the need for the dsPIC to carry out the modelling function. The hardware and software of a standalone monitoring system are described. Validation of the approach was conducted and results are provided indicating that the system is capable of making the correct decision about the manipulated parts.

A discussion is provided in Chapter 8 bringing together the methods developed towards the monitoring of a pick and place station commonly found in production lines. Monitoring nodes, the dsPIC devices, can communicate with each other to assess the health of the process and receive updated parameters information via the internet. This link also allows data to be sent to the server for analysis when required. Faults identified at this level can be added to fault library held in the monitoring scheme at the monitoring nodes. This allows the monitoring system capability to be continually enhanced.

Finally, Chapter 9 draws conclusions on the developed systems and paves the road so that further enhancement to the monitoring system can be carried out in the future.

Chapter 2

A REVIEW OF THE MONITORING OF PNEUMATIC SYSTEMS

2.1 Introduction

The improvement of reliability, efficiency and safety make monitoring an important consideration across a wide range of technical processes. Monitoring may be defined as "a continuous real-time task determining the conditions of a physical system by recording information, recognising and indicating abnormalities in the behaviour" [2.1]. Faults which may arise in the process are broad sources of high maintenance costs and undesired downtime. A fault is a deviation in the process variables from normal conditions. It can be an abrupt "hard" fault such as a sudden failure in the controlling valve of a pneumatic system or a broken tool in a milling machine. A "soft" fault which appears to develop over time is sometimes known as "incipient". Examples include the degradation of the seal inside a pneumatic cylinder. A fault that occurs occasionally in a process is referred to as an "intermittent fault" [2.2].

The application of an appropriately defined monitoring strategy must allow all such faults to be detected. Failure in process components can often be predicted before the event occurs thus saving energy resources and supporting reductions in operational costs. The role of e-Monitoring systems in the current industrial world is thus become increasingly important.

This chapter provides a review of monitoring techniques and their applications. This section introduces the subject with a review of general monitoring approaches. Section 2.2 provides a brief review of the Intelligent Process Monitoring and Management (IPMM) research at Cardiff School of Engineering. IPMM research has been based upon the evolution of a distributed microcontroller based monitoring approach. It is this approach that has been adopted within the research described in this thesis.

The focus of this work is pneumatic systems, which are widely used in many industries. They are employed in the field of automation to perform tasks such as pick and place operations. In modern manufacturing systems quality control and product integrity are essential, thus section 2.3 reviews publications describing various approaches for tackling problems specific to pneumatic processes. Within such "high speed" systems, transient analysis may represent a powerful tool using which important features can be extracted. This is the basis of identifying many faults occurring in the process and of supporting methods allowing such faults to be detected and identified. Section 2.4 examines transient analysis and considers its applicability in different fields as a diagnostic tool to determine the health of the process.

The most common approaches to condition monitoring are based upon personal computers. When deployed in an industrial environment although such systems are powerful they have certain disadvantages. For example, the set up of such a system can be complex; infrastructure is needed and often cables would have to be laid within the factory floor. The cost associated with integrating these systems can be very high. Signal integrity may also be compromised. A system which is compact and can be placed close to the data source thus offers an economical and effective solution. For these reasons, embedded systems such as those based upon a microcontroller are gaining momentum as monitoring tools. Section 2.5 provides a brief review of the deployment of microcontroller based systems in a range of applications. Finally, a summary of the present state of the art in related monitoring techniques is given in section 2.6.

The monitoring of process performance provides technical knowledge and economic solutions which may benefit all kind of industries. Many researchers are making efforts to encourage industry to invest in the monitoring of various processes. It is argued that process performance can be improved by applying developed techniques. Such approaches can also lead to the better management of assets and resources. This section considers a range of applications where monitoring techniques are employed. Much of this work has been developed based upon the analysis of vibration signatures that can lead to the detection of many faults in rotating machines. The occurrence of a fault may lead to known changes in key machine parameters. These exhibit signal patterns which can be used to characterise the state or condition of the machine [2.3].

Reviewing the research undertaken in this context is a difficult task. Isermann and Balle [2.1] for example undertook a review of more than 100 papers published between 1991 and 1995 to explore the suitability of variously developed methods as they were applied to technical processes for fault detection and diagnosis (FDD). They recognised that mechanical and electrical processes were investigated more than others. The DC motor in particular was found to receive most attention. Among the model-based methods, parameter-estimation and observer-based techniques are used in the largest number of applications. Their review reported that nearly 70% of applications used these two methods; with more than 50% of sensor faults detected using observer-based methods. For the detection of actuator faults which are of relevance to this research, both parameter-estimation and neural net (NN) methods were being used. Observer-based methods were found to be the most common in the applications considered. The detection of faults within processes was found to be mostly performed using parameter-estimation methods. Observer-based methods however were most commonly deployed for processes with nonlinear models. For processes with a linear or linearized model, both parameter-estimation and observer-based methods were frequently used. Concluding their extensive review, the authors observed that parameter-estimation and observer-based methods were also the most frequently used methods to detect faults but that fault isolation was most often carried out using classification approaches. The use of NN and fuzzy logic methods has been growing in this context and both are shown as the tools more suited for the isolation of faults.

The findings of papers such as this review tend to support the application of condition monitoring systems that are designed for specific applications on a bespoke basis. It is helpful to consider some such examples. In the following sections different approaches are therefore outlined, starting with research undertaken within the IPMM centre

2.2 A brief Review of the IPMM Research

The IPMM group have previously researched a wide range of applications related to the condition monitoring of machine tools and process plants. This short review considers the most relevant recent research. Current technological advancement and consumer demands have led to high levels of complexity in the machines and systems associated with manufacturing processes. The IPMM research group has evolved a distributed monitoring architecture of three layers as a practical approach for deployment within a range of applications. This architecture is represented in Figure 2.1.

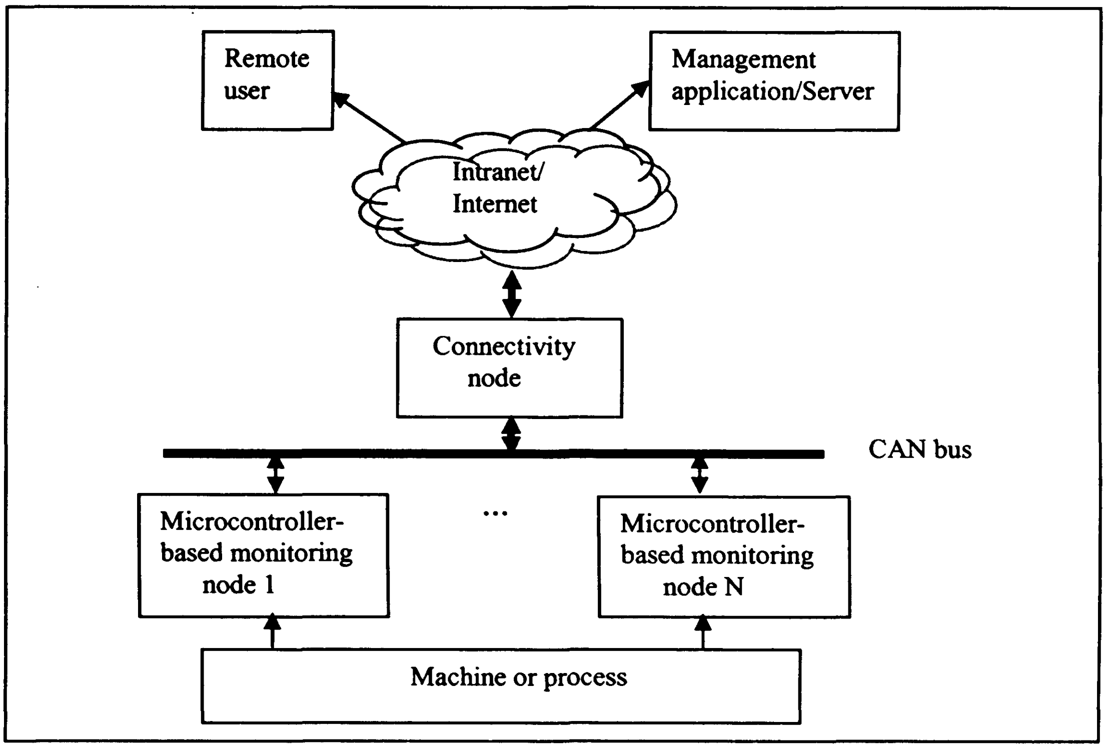


Figure 2.1: IPMM distributed system architecture.

The system was developed in part to allow different monitoring functions located within a process or system the capability of being able to communicate with each other if required, thus supporting flexible and more effective fault diagnostics. To enhance the effectiveness of any approach to fault diagnosis some practical issues need to be considered. The cost associated with the system needs to be low. The speed at which information about the health of the process is provided must be acceptable within the context of each application especially in the case where machines are in remote locations and data thus needs to be sent online and analysed in real time [2.4].

In an attempt to reduce the cost of deploying and operating a monitoring system Prickett and Grosvenor [2.5] advocated the use of existing machine controller signals. Process and machine condition monitoring approaches usually depend on information generated when sensors are deployed. The most appropriate sensors to undertake this function must be identified. However, the utilisation of existing (built-in) machine sensors is considered to be a potential alternative and seen as offering a cost-optimised option. This effectively eliminates the need to deploy additional sensors and avoids the associated logistical difficulties. The authors applied a Petri-net approach to describe a process as a set of machine states and events. Digital levels of the machine controller signals and embedded process sensors were monitored so that events can be detected and states updated accordingly. The idea was to monitor machine operation, extract performance information and identify the occurrence of events. On this basis actual process states and historical events could be used to indicate the cause of a fault.

To test this approach, the authors deployed a method which monitored tool condition during a milling cutting process. The axis feed drive signals of the milling machine were captured. The assumption then made is that once the process parameters are set the controller reacts to any disruptions and attempts to keep the process under control. Various cutting conditions were tested using this approach and the outcome indicated its effectiveness in determining whether a tooth is healthy or not.

Prickett [2.6] reported the potential of deploying Petri-net based monitoring to support machine tool maintenance and management. He argued that reference to the history of events can lead to the diagnosis of particular failures. In this approach fault isolation can then be based on the signals preventing the occurrence of an expected event. The approach also suggested that variations in the manufacturing cycle, which may result in production being stopped, can be detected at an early stage, thus leading to a significant reduction in machine downtime. This approach was tested in the diagnosis of a machine tool failure.

The early research showed the possibility that microcontroller devices could be embedded within manufacturing equipment. A microcontroller-based monitoring system was developed in which first layer devices or "nodes" were based upon 8-bit microcontrollers. These were designed to support data acquisition and processing tasks [4]. These microcontrollers are low cost devices that can be embedded within the process to undertake monitoring functions. Frankowiak et al [2.7] investigated the capability of such devices to support the monitoring of several process applications. They developed the use of a Petri-net approach whose performance was reported to be very satisfactory. The resulting monitoring devices communicate with each other by means of a fast and robust Controller Area Network (CAN) bus. The second layer formed by a connectivity module again consisted of microcontrollers from Microchip Technology Incorporation. These communicate via a serial port protocol (RS232C). This layer was equipped with an Ethernet controller to enable the transmission of information to a remote PC located at the third layer. The coding of the Petri-net structure for a given applications was, in effect, as a look-up table within the microcontroller program. With the remainder of the developed program remaining essentially unchanged, the Petri-net approach allowed rapid re-deployment of the system for new and different applications. Analog signals were also utilised in this generation of the Petri-net system. Detailed information about CAN and Ethernet controllers as used in this current research is presented in Chapter 3.

Further developments were considered by IPMM researchers, with the capabilities of the microcontroller devices being utilised as they evolved. Ahsan et al [2.8] developed a compact monitoring system based upon acquiring and analysing control signals in various process rigs. They indicated that variations in control loop signals can be used to provide clear indications of faulty conditions arising in process variables and that such signals could be the basis of fault diagnosis. Control loop signals were therefore analysed and appropriate methods devised to detect and identify different faults occurring in the process. The system was tested to assess its efficacy in fault detection and isolation and its performance was reported to show promising results. The small size of the system and low cost of the monitoring module meant they would be embedded within the process and hence support an effective maintenance and management network in production environment.

Amer et al [2.9] undertook research investigating machine tool monitoring. Various techniques were developed in both the time and frequency domain, and implemented on microcontrollers. Tests were carried out to investigate the capability of a sweeping filter technique to detect tool breakage. The technique proved to be effective in tool breakage detection. The limitations in the capabilities of this approach were a reflection of the available processing power of the microcontrollers. In order to improve fault detection methods and achieve reliable machine diagnosis, the need for more powerful devices was identified. Siddiqui et al [2.10] reported the limitations of 8-bit microcontrollers particularly in terms of speed, processing power and memory resources. Amer et al [2.11] stated that fast Fourier transform techniques may be effective but implementation on an 8-bit microcontroller was not possible. Although representing important developments in the application of microcontroller devices to process monitoring this body of work also indicated the limitations imposed. The introduction of more powerful devices such as the dsPIC digital signal controllers used in this current research offers much greater potential. The technical capabilities and potential attributes of monitoring modules based upon these devices are outlined in Chapter 3. The design and implementation of the approaches thus made possible form the basis of this research. In particular the capabilities of such approaches to the monitoring of pneumatically operated devices and systems are examined.

2.3 Monitoring of Pneumatic Systems

Pneumatic systems can be found today in many different environments. They are used extensively in the field of automation in particular to perform pick and place material handling operations. A large body of research has been undertaken into various aspects of the monitoring of pneumatic systems. The following sections consider this research as applied to the areas of interest developed later in this thesis. The overall aim of such monitoring devices is to support the diagnosis of faults in real time so as to identify problems in system operation before product quality is affected. In this context pneumatic systems often represent challenges in terms of the speed of operation needed. They also generally present requirements in terms of the need for low cost solutions. In both cases the applicability of the IPMM approaches offers good potential. There are however other possible methodologies which should be considered.

2.3.1 Leak Detection

Leaks can be a source of tremendous threat to humans and the environment. For example, it is essential to maintain air pressure in the cabin of passenger aircrafts for the safety and comfort of the crew and passengers. Juricic et al [2.12] described a fault detection and isolation (FDI) technique of the actuator system controlling a cabin's air supply. The actuator is driven by a brushless DC motor. The pressure controller determines the desired position based upon the required cabin pressure and communicates this information to a microcontroller attached to the motor. The model-based condition monitoring system applies a parameter estimation method which the authors claim to have deployed to produce high degree of accuracy and stability.

Financial losses associated with leaks can also be enormous. The most widely used methods to detect leakage are mainly operator-dependant and require strict supervision. They include visual inspection, chemical trace, gas sniffing and ultrasonic testing. These methods however can not quantify the degree of leakage. The commonly deployed techniques by which leaks can be quantified are measurement of pressure variations, flow and changes in concentration [2.13].

It is possible to understand the current achievements of research in this area by considering specific examples. One conventional method of leak detection is to deploy a trace gas. Calcatelli et al [2.14] reported a leak detection method based on the application of mass spectrometry to a trace gas. They considered mass spectrometer leak detectors (MSLD) to be the best for industrial applications due to their sensitivity and associated high testing speeds. This method depends upon the measurement of tracer gas flow coming out of a leak or entering through it. For quantitative evaluation, the object may be tested by the pressure-vacuum technique in which it is filled with tracer gas (usually helium) and located in a chamber connected to the MSLD. Alternatively it may be evacuated through the pumping system of the MSLD and placed in a chamber filled with tracer gas. In the event that an object is leaking, tracer gas flows from the object to the test chamber and the mass spectrometer of the leak detector gives a signal reading. If a preset threshold or the acceptable leak flow rate (determined by industrial standards) is exceeded the system generates an alarm and the object is rejected and removed. They estimated the testing cycle to take from 15 to 40 seconds. The time needed and costs of this approach limit its application in higher speed industrial applications.

Montague and Watton [2.15] developed an automated, computer-controlled test procedure by which leakage in a solenoid-operated pneumatic valve can be determined. The valve is used to control air pressure in patient pressure relieving mattresses found in hospitals and nursing homes all over the world. According to industrial standard, "the valve should seal a 200 litre volume of air so that an initial gauge pressure of 100 mmHg (preferred pressure unit in medical field) should not drop below 80% of this value within 12 hours". LabVIEW software was used to control the rig designed for this project and capture data from various sensors. PCI-1200 data acquisition card was also used. The valve dynamic leakage characteristic was the basis of the approach. Using the pneumatic flow theory in pressurised system, a model describing the pressure decay was obtained and can be used to estimate the volume of air that escapes through leakage.

Traditionally, the quality of seals in food packaging is determined using visual inspection. The increased use of plastic bottles created a need for more sophisticated and sensitive leak detection techniques. The integrity of these food containers must remain intact and no leak should occur prior to consumption. Consumer health safety cannot be compromised for financial gains. Sivaramakrishna et al [2.16] investigated the ability of an online pressure differential leak detector to assess the quality of seals in polyethylene terephthalate (PET) bottles. It is intended that this method achieves the 100% inspection of all packages produced during production run. In the approach outlined two load cells measure the resistance of the package to an applied force. The measurements are transmitted to a PC to calculate the difference between the two values. The method relies upon the fact that very little difference occurs when non-leaking bottles were tested. The conclusion was that this method will accurately detect leaks, however at least 2.8 seconds are required for their sealing.

Boehm [2.17] introduced state of the art flow sensors which allow self-monitoring in pneumatic systems. These flow sensors operate based on the anemometry measuring principle and can be placed in the appropriate locations within air distribution system to monitor air consumption. They can measure from 50 ml/min to 5000 lpm with ± 0.3% (full scale) accuracy and are suited for most industrial environments. The anemometer is placed in a bypass channel within the housing where a pressure differential is generated due to the shape of the main channel, thus forcing a well-defined proportion of flow through the bypass. This provides a means by which leaks occurring in the process may be detected. These sensors have, built-in, the necessary electronics to measure and record cumulative air consumption and provide data in real-time. They can also communicate with the process controller. When a threshold is exceeded, a flow sensor can generate an alarm to indicate a faulty situation. Additional methods of flow measurement (with their advantages and limitations highlighted) can be found in [2.18].

On a larger scale it is essential to monitor the integrity of commercial gas pipelines for defects that can cause potential problems in the future. The area of detecting leaks in gas pipes has attracted considerable attention. Although not relevant in terms of the magnitude of the pipes and leaks being considered, some of the approaches are worthy of consideration here. Varma et al [2.19] implemented a detection method based on acoustic sensors. These types of sensors can be deployed to detect ultrasound emitted from defects (holes or cracks) in pressurised gas systems. They suggested that a sensor can be tuned to the sound frequency generated by the gas escaping from flaws to give a positive indication of leaks. Such solutions are however of limited applicability with high speed industrial applications, which may often take place in very noisy and dirty environments.

To avoid the interruption of gas supply and the associated high cost Licciardi [2.20] described a prototype "pig" developed by BG Technology to detect and locate leakage. The "pig" is 1.2 m long with a diameter of 20 cm and consists of a valve module housing solenoid valves, differential pressure and absolute pressure transducers. The device contains a microcontroller to control the valves, read sensors and transmit data to a PC. Tests were conducted in which once the pressures of an outer and inner test volume of the "pig" are equal, the valve regulating supply to test volume is shut. The differential pressure transducer signal is monitored over a period of one second and if it is observed to decay a possible leak is located. Various seals with calibrated leaks were tested and models were produced; the gradients describing the rate at which pressures decay indicate their relationship to the size of leaks. The method thus identifies the potential of deploying a microcontroller based pressure transducer signal as a diagnostic tool.

Taghvaei et al [2.21] described a leak detection technique for pipelines using Cepstrum analysis. Cepstrum has the ability to detect periodic structures in the logarithm of the signal spectrum. The method uses pressure waves caused by the rapid opening and closing of a solenoid valve. A pressure transducer was used to obtain time domain signals of the pressure transients in the pipeline. Low and high frequency signals were analysed using the Cepstrum method which identified the time delay between initial wave and its reflection. Some features of the pipeline network were also revealed. To investigate the effect of leakage, calibrated holes were induced into the pipeline network. These led to the occurrence of new peaks, thus identifying the presence of leaks. Increasing the leak size led to the realisation that these peaks increased as the cubic root of the hole diameter.

Souza et al [2.22] presented a technique for leak detection in pipelines based on the spectral analysis of pressure signals. Experimental tests were carried out on a 1250 m long pipeline under various operational conditions (flow rate, leaks). Four transducers were deployed to obtain the pressure transients during start/stop conditions of the pumps. A PC was used for the acquisition and analysis of the signals. They proposed that by observing the pressure signal profiles, in the frequency domain, in pipeline sections between two reflection joints located close to each other, leaks may be identified. The reflection points are provided by valves and curves in the pipeline system where stationary signals are formed. In this context a stationary signal is a signal which preserves its statistical parameters over time. i.e. its amplitude distribution and standard deviation remain constant if measured at different times. Pressure was sampled at 550 Hz and the fundamental frequency was determined to be 14 Hz. To simulate the effect of leakage, side outlets fitted with solenoid valves were installed into the system at different locations. Depending on the size of leak and location, different frequency oscillations were generated and observed in the frequency spectrum of the pressure signal. Once these oscillations were detected an alarm was generated indicating the presence of leaks. Overall these pressure based systems seem to be of more potential in industrial environments when compared to trace gas options.

The final approach to detecting leaks is based upon sound. This method is generally used in association with a human to sense the leak. Other alternatives have been explored, including research by Zhang et al [2.23] who investigated the capability of neural networks as a tool for leak detection in a pneumatic pipe system. A high accuracy sound meter used to measure the environmental noise. An analogue to digital (ADC) converter was used to sample the signal at 8 kHz and a computer was used for processing and data analysis. The pneumatic system apparatus consists of an air pump, air reservoir electromagnetic valves and pipework and is used to provide power to a robot gripper. In this experiment the authors considered first a normal pipe (non-leaking) and acquired data to design the neural network filter. Then three pipes with calibrated leaks were installed to test the monitoring system while supply pressure changes from 1 to 5 bar. It was reported that the noise generated by the leaks at different pressures was accurately detected by the neural network filter thus isolating leaking and non-leaking conditions of the pneumatic system. The main challenge faced with such an approach lies in its deployment within a noisy environment such as often arises in industry.

During this review, a number of examples were found where neural networks were being used as a tool for fault detection and diagnosis. This may indicate that their use is rapidly growing. In pneumatic applications in particular Nakutis and Kaskonas [2.24] investigated the utilization of artificial neural networks to detect leakage. Different sizes and locations of leakage were introduced into the system. Load mass variation between 0 and 5 kg and supply pressure in the range 4-4.5 bar were also applied. Flow and pressure sensors were deployed to capture signals using a PC. Extracted features used as inputs to the neural net include air flow magnitudes for extend and retract pneumatic cylinder operation and air consumptions over a fixed period of time. Supply pressure was also used as input to the neural network. Several neural network-based models were obtained, tested and found to be capable of making the correct diagnosis.

2.3.2 Linear Actuators

Pneumatic linear actuators or cylinders are widely used in the automotive, manufacturing and food packaging industries. Due to the problems associated with accurate position/stroke control these devices tend to be limited to fixed end position tasks such as pick and place operations. Some research has attempted to identify control strategies that may offer enhanced operation. This work can be used to indicate potential parameters that may be of interest when approaching the monitoring of such systems. These parameters include the number and type of sensors deployed, the nature of the computational resources and the operating variables considered. Of particular interest here is research where microcontrollers have been deployed as part of an integrated process management system.

Bone and Ning [2.25] designed two control algorithms for the position tracking problem in pneumatic cylinders. Both algorithms are based on sliding-mode control regimes of linearized and nonlinear plant models. Different payloads, stroke lengths and orientation (vertical or horizontal movement) were adopted in their experiments. The pneumatic system consisted of a double acting cylinder, a linear encoder to provide the piston position, two pressure sensors measuring the chamber pressures and a proportional pressure valve. A PC was used to provide control, data acquisition and analysis of the system. The sampling frequency used was 500 Hz and supply pressure to the system was 6.5 bar. They found that position tracking performance for the sliding-mode control based on the nonlinear model was better than those previously reported. Csiszar and Andras [2.26] applied an alternative algorithm of sliding mode controller implemented on a DSP platform. Two pressure sensors were used to provide the pressure in each chamber. A linear encoder provides the position, while velocity and acceleration were obtained numerically. A PC allowed the code to be downloaded into the DSP board. Achieving a minimum positioning error of the servo pneumatic actuator used in the experiment was claimed.

Wang et al [2.27] proposed a position control strategy for servo pneumatic actuator systems. Servo pneumatic actuators differ from conventional pneumatic cylinders by the fact that they operate by flow regulators in combination with (ON/OFF) solenoid valves. Their experimental system included a PC for data acquisition and analysis, a

PID controller, a proportional flow control valve, a position transducer and a cylinder. The authors reported that this control strategy was applied to a pusher mechanism in the packaging of confectionery products and achieved the accuracy required by the production task. In their control strategy, two algorithms were involved: the first was a time-delay minimisation algorithm which took into account the effect valve displacement had on the time required to build up a pressure difference across the piston to overcome stiction. The second was a target position compensation algorithm which meant that the difference between the desired and measured positions (i.e. error) is used as a correction. The concept of stiction is an important one, and is of direct relevance to the monitoring research reported later in this thesis (section 5.3.1).

Guoliang and Xuanyin [2.28] considered the friction of cylinder based on the analysis of an inner pressure control system, an outer motion control system and static and kinetic friction of the cylinder. The deployed system employs position and pressure sensors, a proportional control valve and a controller. The pressure and position of the cylinder were the feedback signals to the computer. The proportional valve output was connected to the controller to give closed-loop control.

Richardson et al [2.29] introduced a self-tuning controller incorporating an external force balancing term for a low friction pneumatic actuator under the influence of gravity. The system employs force, position and pressure sensors in addition to two pressure control valves. The operation of this cylinder was compared to a conventional cylinder and improved performance was claimed.

Dunbar et al [2.30] developed an algorithm to detect and isolate friction changes in a high precision positioning mechanism with applications to a pneumatic actuator. This algorithm was based on dynamic modelling and parameter estimation techniques so that terms which represent a specific fault can be identified. To monitor the effect of friction on the performance of the system, the load was configured to allow sudden changes in the friction conditions. An acceleration sensor was added to the load to capture these changes. In addition the voltage to the control valve was monitored. Experiments were performed to acquire data using a PC. The dynamic behaviour of the actuator from the valve voltage to the mass acceleration was modelled experimentally and model parameters were then estimated. The authors stated that the approach was tested and verified.

Some attempts have been reported based upon taking advantage of advances in low cost computing resources. To exploit the recent advancements in fieldbus systems, microprocessors and computing technologies, Pu et al [2.31] advocated the concept of "smart" components-based servo pneumatic actuation systems. They identified design templates for smart sensors, smart valves and smart actuators. They addressed some of the issues required for the development of components-based pneumatic drive systems such as simulation tools, algorithms and controller development, sizing, tuning, installation and commissioning. In so doing, they suggested that intelligence can be embedded in such devices so that they can provide information rather than raw data. They showed that these smart devices may be integrated as a single unit to form a smart pneumatic servo system; with the capability to communicate with the external world when required. A case study based on the packaging of confectionery products in Mars Confectionery (UK) Plc. was carried out using a pneumatically-driven gantry pick and place handling system to demonstrate its capability in point-to-point positioning at high speed.

With the intention of preventing the failure of devices that can cause shutdowns, loss of production time and profits, and harm to the environment and personnel, Li and Kao [2.32] introduced an analytical fault detection and diagnosis (FDD) strategy for pneumatic systems. The approach was signal-based and employed wavelet decomposition using several sensor signals such as pressure and flow to determine leak configuration. Leakage was simulated using manual valves at the extending and retracting sides of a cylinder. A pattern recognition technique was developed to diagnose unknown leakages based on the established FDD information using mapping. The cylinder was controlled by two solenoid valves. Two proximity sensors were deployed to detect end and home positions. Pressure and flow sensors were also used at different locations. Data acquisition and control was accomplished using a graphic user interface implemented on a PC. Signal analysis was performed using Matlab. They claimed that experiments were carried out to test and verify the effectiveness of the proposed approach and leaks were successfully located.

A fault detection and diagnostic system was introduced by Lehrasab et al [2.33] for applications such as the simple mechanical systems operating pneumatic train doors commonly found in rapid transit systems. These doors are often controlled by solenoid valves and can be a significant source of delay in railway services. The health of the system can be determined using feature extraction methodologies. This includes throw and activation time characteristics, spectral features of the door displacement profile as well as abstract features such as velocity profiles and pressure drop during the throw. Once a fault is detected neural network models are utilized for diagnosis. The authors suggested the implementation of this approach in a distributed architecture and proposed that diagnostic results be integrated into the maintenance information system in order for a proactive maintenance regime to be produced.

The use of intelligent approaches to actuator monitoring was reported by Xuanyin et al [2.34] who designed an instrument for fault diagnosis of pneumatic systems in automatic production lines using neural networks. They designed a PC-based program to acquire pressure data and modelled it under various simulated faults. The main idea of the approach is to determine if the pneumatic system has a fault and then diagnose which component is faulty.

In addition, Karpenko et al [2.35] investigated a neural network based fault detection and identification system for actuator faults in a process control valve. A software package supplied with the valve was used to communicate with onboard sensors and obtain the position response of the valve under various operating conditions. Fault signatures of incorrect supply pressure, actuator vent blockage and diaphragm leakage were considered. Experimental data were collected and neural networks trained, and tested. The authors claimed to be successful in the detection and identification of various magnitudes of the faults of interest.

Puig et al [2.36] reported two methods for fault detection with application to the DAMADICS actuator benchmark problem. Both methods are model-based and they explicitly take the modelling uncertainties into account. The first one represents the dynamic behaviour with an interval model which bounds the normal behaviour at every sample time within a confidence interval. The residuals between actual and estimated behaviour of the process differ only if a fault had occurred. The second deals with the process as a quantised (continuous input and output signals are transformed into discrete sets or sequences) system which monitors the qualitative behaviour of the process. Two faults (clogging and diaphragm perforation) in a servo pneumatic valve were simulated to compare the performance of both techniques and a good outcome was reported. The importance of this work lies in the use of a model against which performance is compared. This is an area that will be explored later in this thesis.

The research outlined above is presented to identify the current level of actuator monitoring. It highlights the potential for developing low cost monitoring approaches that can be applied to industrial pick and place operations. Most of the reported systems are not suited to such applications, either due to cost considerations or due to the time needed for diagnosis.

2.4.3 Grippers

Considerable research has been undertaken into the design and control of grippers without which robots may become useless. Advances made in electronic devices and sensing elements have supported the deployment of robotic systems in almost every industry. Fault detection in the gripper operations is therefore of utmost importance. In addition to identifying hardware problems monitoring gripper performance can lead to the detection and identification of faults arising during assembly and pick and place tasks. It can ensure and verify the success of the gripper in performing the required operations. Health, safety, quality of the product, cost optimisation and reduction in shutdowns are issues being considered when deploying grippers in automated processes and are emphasised throughout the reviewed publications. The following research papers are considered to place the monitoring of the operation of a gripper into the context of this thesis. Specifically the aim of this research is to provide such monitoring using low cost microcontrollers without the need for the addition of any sensors.

Specialized grippers handle objects of similar physical properties such as shape, size, and weight. In applications where a robot is required to assemble parts of varying properties, grippers have to be changed to match the part being assembled [2.37]. In this context, Friedrich et al [2.38] developed an approach to variable product handling that adopts a modular sensor-oriented methodology. Automated handling of products in the food industry motivated this approach. The mechanical, sensing and control aspects of their gripping design were described. The system constitutes a two-finger parallel gripper, a drive and several sensors. Strain gauges, optical sensors and limit switches were employed to provide the gripping force control, finger position control and event control respectively. Strain gauges were also used for slip detection. The gripping procedure is performed using a 68HC11 microcontroller. The authors reported the use of the designed gripping system with an ABB 2000 industrial robot and trials were successful. The capability and limitations of the system were acknowledged. It was able to distinguish objects' firmness clearly. A successful identification of objects weight was limited to 20 gram levels while dimension was limited to 10 mm levels.

Terada et al [2.39] designed and developed a semi automatic pick and place work robot to handle silicon modules for assembly on a ATLAS SCT barrel tracker. Multiple cameras and sensors were deployed to support the operation. The module positioning accuracy was considered. The control system consists of a graphic touch panel, a PLC and a PC for motion control. The system was tested, its success was verified, but the need for further improvement was reported.

Ottaviano et al [2.40] designed a pneumatically actuated two-finger parallel gripper to handle items of variable physical properties. The main goal in the design was to control the force exerted by the gripper on the object (i.e. grasping force) which is often difficult to achieve due to the compressibility of air. The gripper system consists of a two-finger gripper controlled by a proportional pressure valve and two computers. One computer is equipped with an acquisition card while the other facilitates off-line programming. A force sensor was used to provide a closed-loop force control for the gripper. A PLC was also deployed to implement the control scheme of the gripping operation. An adjustable choke valve was used to regulate piston speed to avoid damage to the objects during the closing action of the gripper mechanism. They reported that a prototype model was manufactured and tested to show the feasibility of the grasping system.

Luo [2.41] described the design of a pair of microcomputer-based intelligent gripper fingers with the capability to sense information from multi-axis force/torque signals obtained using piezo-resistive strain gauges. These fingers were designed to operate with a servo-controlled gripper for small part assembly tasks. The output from the force/torque sensor is converted into a frequency form. He argued that this technique performs better in terms of signal conditioning and processing. The sensing and control program was based on Intel 8085 microprocessor, which reads the sensor outputs and sends them to a PC for analysis.

Hirzinger [2.42] highlighted issues faced in the past which prevent the realisation of multisensory integration and feedback in robot grippers. The sensing elements investigated include force/torque sensors, proximity and tactile sensors. The disadvantages of such sensors include the sensors being too expensive, too big and difficult to integrate into the robot controller. The sensor pre-processing element and cables that come with it were found to be not reliable. The current sensors however overcome these shortcomings, are viable and can be based on microcontrollers.

Alpek et al [2.43] proposed a multi-sensor system based on force/torque/pressure for the monitoring of grippers. They argued that the applications of these various sensors in robotized production can solve many monitoring tasks. For example, grasping force can be controlled using a pressure or a force sensor while trajectory can be tracked using a force/torque sensor. For the system to be realised, different techniques were tried so that sensors may be built into or mounted on the gripper. A pneumatically-driven two-finger parallel gripper system based on force/torque/pressure sensors was developed. They stated that the capability of the system is still to be tested.

Tlale et al [2.44] reported the design, control and implementation of a generic gripper for the assembly of electronic components on printed circuit boards (PCBs). The design of the gripper allowed for the variability in components' size, shape and weight and hence increased the efficiency and flexibility of automated assembly stations. Components were divided in five groups based on which the gripper was designed. Three sensor circuits were integrated into the design by which control logic circuits and decision algorithms receive information. A contact sensor (limit switch) provided the gripping information; three limit switches per finger monitored the orientation of the part. A switch was located at the foot of the gripper to manipulate horizontally the cylindrical resistors. A standard digital input/output card interfaced the digital signals to a PC for signal processing. The authors stated that system was tested and proved to work for small batches of electronic part manipulation.

Choi and Koc [2.45] developed a flexible gripper based on pneumatically inflated rubber pockets. The gripper had two parallel fingers with inflatable rubber pockets and may meant to handle objects of different shape, size, weight and type; with 0-6 bar operating pressures. Detailed specifications of the gripper were provided. Various strategies concerning flexible gripping were discussed. The design process to realise the flexible gripper was also explained. It was reported that a prototype was made and experimental tests were performed. The capability and limitations of the flexible gripper were disclosed. They reported that parts of different shapes, weights and sizes were handled successfully but rubber material type, and thickness and elasticity of the jaws can affect the accuracy of the gripper.

The gripper related research reviewed above considered aspects of gripper design and control. The following papers are reviewed with regard to the monitoring of the gripping act itself. The dynamic stability of the workpiece and a gripper during gripping is related to the nature of the contact made, the configuration and control of the gripper fingers and compliance.

Li et al [2.46] applied Liapunov stability theory to assess the dynamic grasping stability. As a case study, the dynamic response of a three-finger industrial gripper equipped with three force sensors and a position sensor was investigated. The system contained a digital signal controller (dSPACE) equipped with an ADC for signal acquisition. They concluded that the grasp must be controlled so that dynamic stability can be achieved and maintained.

Ceccarelli et al [2.47] investigated the operation of a robotic gripper for harvesting of horticulture products. The difficulties of the environment and the gripping mechanism were considered. A number of mechanical designs to achieve an optimum grasping mechanism were discussed and analysed. A pneumatic actuation with grasping force control was chosen for the gripper. A bi-directional choke valve was used to regulate piston speed. The gripper had two fingers with force sensors. A PC was also deployed for data acquisition and processing. A PLC executes the control scheme for the gripping operation. Two control strategies (open-loop and closed loop) were discussed and tested.

Costo et al [2.48] designed a pre-hensor with three articulated fingers driven by motors; vacuum cups are attached to the fingers for picking and handling of limp sheets. The pneumatic circuits of the conceived design consist of four valves to operate the suction cups and to control the pressure. It was reported that the pre-hensor has been tested and its effectiveness verified. Kolluru et al [2.49] presented another design of flat surfaced robotic gripper for limp material manipulation. It used electrostatic attraction functionality and proximity sensors. Partial pressure differential was used as the mechanism for pick up. The static and dynamic stability of the grasp were discussed. A prototype model was integrated with industrial robot arms and the stability of the grasp evaluated.

Kavoussanos and Pouliezos [2.50] introduced a prototype robotic system for depalletizing and emptying material sacks. A PC with the appropriate plug-in cards was used to carry out the tasks of control, vision, gripping and monitoring. A pneumatic gripper performs the task of lifting of the sacks. A CCD camera is used to provide the information of the position, the orientation of the pallet and the arrangement of the sacks while limit switches are used to confirm the grasping of the sacks. The PC monitors the error signals of all position control loops for fault detection. The prototype is said to be designed to cope with the harsh industrial environment.

Holweg et al [2.51] presented two algorithms for slip detection using rubber-based tactile sensors. The first employed the elasticity of the rubber while the other considered the fluctuation of the forces measured by the tactile sensor. Description of the algorithms and experimental set up were provided. The sensor used was a tactile matrix sensor designed and constructed at the Electronic Instrumentation Laboratory of the Delft University of Technology, Netherlands. The authors stated that experiments were carried out and the results confirmed the capability of the first method to detect the slip at the initial stage while the second method detected slippage during movement of the object.

The approaches to monitoring gripping actions outlined above are based upon the analysis of sensor information relating to force or pressure. A separate category of gripping monitoring research is the use of vision based monitoring. Vision based systems are not directly applicable to the current research and thus only a limited part of this review is dedicated to this field. Examples of such an approach include work by Ahmad [2.52] who described a laboratory experiment aiming to teach some concepts on sensor-based robot assembly systems. The experiment involved the assembly of a diesel engine oil pump using an IBM RS-1 robot. The gripper system was equipped with a force sensor and an optical position sensor for the detection of parts. A GE Optomation binary vision system was used to monitor the workspace via CCD cameras mounted on the robot arm. Information received from the sensing elements was processed to recognise components and verify the assembly operations in real time. Practical sensor-based motion strategies were discussed. In other applications CCD information can be integrated with other sensors to provide a more advanced solution.

Continuous changes occur in the environment within which a robot performs assembly operations. A monitoring system should have the ability to cope with such changes and allow for the task to be successful. Errors may be detected and their propagation eliminated. Abu-Hamdan and El-Gizawy [2.53] developed a computer-aided strategy for flexible assembly operations using knowledge-based expert systems for fault detection and diagnosis. One expert system provided a fault detection function that carried out the preconditions' verification and execution monitoring of a task as a fault could occur before and during execution. The second expert system provided fault diagnosis based on an AND/OR tree. This allows recovery from an error as the prime objective so that assembly line productivity can be resumed. The authors listed the possible fault causes inferred by the diagnosis expert system based on the special assembly work cell for which it was designed and these are shown in Table 2.1. Expert systems can be built to fit the needs of the assembly operations in a production line. The developed system was implemented on a prototype robotic assembly work cell and verified. They reported that it was capable of diagnosing a variety of faults which are commonly encountered in assembly activities.

Misalignment during insertion
Misalignment during picking
Misalignment after a pit k operation
Misalignment after insertion
Safety zone is not clear
Incorrect part dimensions
Missing insertion hole, or insertion hole has incorrect dimensions
Missing or incorrect part in the picking pallet
Attempting to pick up a part while gripper fingers are closed
Obstacle in the robot's pathway
Part is slipping from the gripper
Part was not picked up
Part was dropped
Part is positioned incorrectly in the picking pallet
Old tool is not in the tool changer
Old tool is not released from the tool changer
Tool changer is not aligned properly with the old tool position
Another tool is in the old tool position
Tool changer is not aligned properly with the new tool position
Missing requested tool or another tool is in the new tool position

Table 2.1: Fault causes in an assembly work cell.

Konukseven and Kaftanoglu [2.54] proposed a multi-sensor based system for automated pick and place operations. The system is claimed to be capable of identifying parts placed on a moving conveyer. The robot tracks the parts along a straight line path over the conveyer using CCD cameras, while the gripper (equipped with 6 infrared proximity sensors) performs the grasping operation under closed-loop fuzzy-logic control based on the knowledge of the process. The system used two computers for data acquisition and processing as well as the robot controller and optical encoder to measure the speed of the conveyer belt.

A common application of automated handling systems is to relieve humans from hazardous material handling and heavy lifting. When dealing with nuclear materials in particular, reducing human exposure to radiation and minimizing mishandling errors is a crucial consideration. To this end, Drotning et al [2.55] developed a sensor-based automated handling system at Mason & Hanger- Pantex Plant (a US department of energy facility). It used machine vision and force/torque sensor to facilitate system control with the aim to enhance the level of operational safety and achieve easy remote operation. Custom grippers were designed to meet the needs of individual payloads. A number of PCs were deployed to perform data acquisition, processing, supervision and control of the operations remotely. System hardware and software architectures were described.

Xu et al [2.56] introduced a networked smart sensor system for the remote monitoring of a gripper. The system is based on the IEEE 1451 standards used to overcome the cabling problem faced to accomplish the monitoring function remotely. The network architecture is split into two modules; a network capable application processor (NCAP) which runs the network protocol stack and application software, and a smart transducer interface module (STIM) containing a transducer electronic data sheet and sensors. The hardware of the system constitutes a data acquisition card, a NetBox and sensors for the gripper. The NetBox (an embedded microprocessor system) contains a 32-bit Intel 386 board as the NCAP, Ethernet, RS232C, LCD, TCP/IP protocol stack and software including DOS and RTOS. An embedded web server enables the client to communicate with the system through the internet. The gripper system is four-finger gripper with force sensors, proximity sensors, and temperature and displacement sensors.

Grippers in Manufacturing Operations

Quality control in manufacturing is crucial. Some tasks cannot be performed by manual operations. The need to meet the changing demands due to process complexity and consumer requests is the driving force towards automated manufacturing processes. Current advancements in technology and internet communication made possible the integration of robotic devices into many aspects of manufacturing. Robot grippers play a very important role in systems designed to achieve high quality and reproducibility in assembled components. They allow cost and resources to be optimised. Some examples reflecting the considerations given to the deployment of robot grippers in manufacturing are outlined in this section.

Feldmann [2.57] discussed aspects related to the implementation of complete-assembly systems in the automotive industry. The need to eliminate manual labour in the assembly of large components was emphasised. The requirements to realise complete automated assembly systems were also considered. Reductions in production costs combined with quality improvement while keeping process sequences short and robust were the objectives of his research which was designed to attain high degrees of automation. Flexible assembly control software was developed and tested and the need for further development to increase the system availability was expressed.

Rosati et al [2.58] proposed a robotic measurement system for the inspection of small metallic subassemblies for the eyeglasses industry. The system was intended to eliminate manufacturing errors by inspecting components prior to assembly and hence increase the efficiency of the manufacturing process and the quality of the consumer product. The proposed system was based on two CCD cameras and an anthropomorphic robot. One camera provided recognition of a component in a large workspace while the robot picked up and placed the component in a small vision field for the other camera to perform the measurement process. To cope with the variability in the shape and dimensions of the eyeglasses subassemblies, the authors developed a specific shape recognition procedure. A PC acquired and processed the image data and commanded the robot as to what action to take. Communication with the robot was achieved via Ethernet to support on-line measurement and process control. This supports the deployment of robot grippers to carry out delicate and demanding tasks not possible for humans to accomplish to a high degree of accuracy.

To support current trends in manufacturing, Kwon and Chiou [2.59] presented a condition-based maintenance strategy for a robotic system with internet capability. The need to maintain production facilities and systems was addressed. The approach was developed to support an economical maintenance strategy. Issues regarding the implementation of such a strategy were discussed. Optical sensors were used to detect the movement of products on a conveyer and provide guidance for the robot to perform the required operations. It was based upon Yamaha robot which was designed for pick and place operations at high speed and precision. The robot controller was equipped with Ethernet to allow communication with other devices. Three harmonic drives act as a speed reduction gear for x, y and r axes while the z axis has a ball screw type reduction gear. The monitoring system uses a highly advanced "smart" vision sensor (camera), which is web-enabled and self contained and can be accessed over the internet through its IP address. Image processing, inspection, robot guidance and quality checks can be carried out remotely. System parameters are continually updated. A mathematical model of the robot system availability was derived and real time monitoring achieved. It was reported that performance of the system indicated its potential to predict failures and hence improve production efficiency.

The above represents the current state of the art in gripper monitoring and forms the benchmark against which the research reported later in this thesis can be compared.

2.4 Transient-based Monitoring

This section emphasizes the application of transient analysis in various fields as a tool by which faults occurring in the process can be detected and identified. Transient analysis has been shown to be a powerful technique to analyse signals and to study the dynamic behaviour of systems in a variety of relevant application areas. The intention of this research is to deploy a monitoring system based upon a microcontroller. Such devices are becoming increasingly powerful but still have limitations, particularly in terms of available memory. As such the appropriate form of fault diagnosis is real time. In this context the use of transient analysis was adopted as the way forward.

For example, Kaskonas and Nakutis [2.60] considered leak diagnostics in pneumatic cylinders. Flow and pressure transient patterns were monitored while the system undergoes different combinations of calibrated leaks, supply pressure and load mass. Pressure transducers measure the extend line, retract line and supply pressures. A differential pressure transducer was also deployed to obtain flow patterns. Data were acquired by a data acquisition card and a PC. Leakages in the cylinder extend and retract lines in addition to the piston seal were investigated. Diagnostic models representing the relationship between measured process parameters (e.g. supply pressure) and quantities describing the fault (leakage) were obtained and analyzed. Air flow amplitude and consumption were selected as diagnostic features for leaks.

They reported that leaks appearing at various places in the pneumatic system were found to affect these flow features specifically.

Beushausen et al [2.61] addressed transient leak detection in crude oil pipelines. The transient pressure wave generated by leaks when pumps are switched on or off was analysed using a statistical system developed by ATMOS International Limited, UK. Flow, pressure, temperature and density measurements were transmitted to a PC for analysis. Leak detection was based on the probability calculations using mass conservation at regular sampling intervals combined with pattern recognition. The system was said to be capable of detecting leaks to a high degree of accuracy.

Cho et al [2.62] proposed a method for fault detection and isolation in heat, ventilation and air conditioning (HVAC) systems. Transient analysis of residual patterns is the basis of the approach; the residual being the difference between measured variables with a fault and their values in healthy state. The need to improve HVAC systems reliability and safety was emphasised. Faults occurring in the supply fan, flow rate sensor and damper in the variable air volume unit under three different sets of damper controller gains were considered. Output signals from outdoor air damper, indoor temperature sensor, flow rate sensor, supply air temperature sensor and fan were transferred to a PC. Residual patterns for faulty situations were generated and compared to normal conditions. By monitoring the reaction of the system performance to known problems, this residual patterns based approach was shown to be able to identify faults in this HVAC system.

Tan et al [2.63] introduced a condition monitoring and fault diagnosis scheme as applied to hydraulic actuators which are widely used in the food processing and pharmaceutical industries. The actuators under test were based upon both a cylinder and an axial piston motor. Two common faults were simulated; worn rod seals in the cylinder and worn piston shoes in the motor. The actuators were operated to capture the vibration signals arising in their faulty conditions. They were loaded in steps in order to observe any trend reflecting the impact of the faults on their performance. LabVIEW software was used for data acquisition and analysis. The processing method considered both vibration signal and flow rate. It involved the amplification of signals, the filtering of noise, the sampling of data, the performing of a fast Fourier transform (FFT) and finally the spectrum display. They concluded that a change in vibration signal and flow rate exists when more load is added to the actuators. In the deployed solution should a fault (or a change) be diagnosed, the associated LabVIEW software triggers an alarm.

Adewumi et al [2.64] reported an approach to blockage detection in natural gas pipelines. A pressure transient was initiated by altering the mass flux at the inlet. This transient propagates through the pipe and would be partially reflected once it passes a blocked portion of the pipe. A model was proposed to describe the propagation of a pressure pulse through the pipe with multiple blockages. The continuity and momentum equations constitute the model representing the flow through the pipe. Blockages were introduced by varying the cross-sectional area of the pipe. The inlet pressure responses during the transient for the cases with no blockage and those with blockages were analysed to determine the effect of the blockages.

Kim and Daniel [2.65] developed a transient gas flow method for the inspection of fibre pre-forms in resin transfer molding. The mold containing pre-form is pressurised to a certain pressure, and then the gas is suddenly vented to atmosphere. Pressure transducers, placed at different locations, were used to allow pressure variation during the gas release be recorded. A PC with a data acquisition card was deployed. Governing equations of gas flow were derived to validate the experimental work. It was suggested that deviations in the pressures can be detected by comparing the reference and test cases and thus determine the quality of fibre pre-forms.

Paterson and Wilson [2.66] reported on the use of damage monitoring systems for component life optimisation in power plant. In particular, high temperature boiler headers and turbines were considered to be subject to damage by creep and fatigue. The use of monitoring systems to quantify creep damage was highlighted. They stated that the use of such systems demonstrated that faster start-ups and consistent operations can be achieved which provide both life extension and enhanced performance. An example was presented to show the substantial benefits that can be attained from optimised operations due to the deployment of component life monitoring systems.

Brunone et al [2.67] outlined the problems of leaks occurring in water distribution networks. Various traditional methods for leak detection were described. A method was proposed based on the properties of transmission and reflection of pressure waves during transients. They stated that the amplitude of the reflected wave increases with the size of leak. Leaks can also be located. Numerical and experimental evidence of the effects of leaks on the pressure transient were presented. Pressure transducers and a PC were employed for data acquisition and analysis.

Verde et al [2.68] proposed an approach to identify leaks in pressurized pipelines using both transient and static behaviour of fluid. Flow and pressure measurements were considered under various operating conditions. An algorithm combining both transient and steady state measurements was presented. A nonlinear dynamic model of the fluid was used to calculate the parameters associated with leaks from the transient response of the pressure and flow rate at the end of the line. Leaks were introduced into the pipe system using valves. Two flow sensors and two pressure sensors were located at the pipe inlet and outlet. A data acquisition system from National Instruments was used to acquire pressure and flow signals.

The increasing demand for higher operational efficiency, reliability and safety of technical systems requires effective monitoring techniques to be developed not only to detect faults but also to support the capability to predict them. Angeli and Chatzinikolaou [2.69] proposed a knowledge-based diagnostic system that is able to predict faults in hydraulic systems. They suggested that the prediction function incorporated in the diagnostic system offers the benefit of preventing future process failure. Therefore, monitoring the changes in the dynamic behaviour of the system allows the prediction of faults. A data acquisition and control system was developed using a PC. Pressure signals at multiple points in the hydraulic system as well as the angular velocity of the motor and various digital input signals were acquired. The hydraulic system was then modelled using the physical relationships of its components and this was validated with the simulation program.

The authors considered an expert system which compares measured and calculated quantities and translates deviation values into symbolic information based on threshold levels determined from experimental knowledge. Scientific knowledge together with experimental knowledge is used to determine the health of the process. They concluded that dynamic modelling information involved in the fault detection system offers the capability of predicting real time faults.

Kim and Chun [2.70] developed a remote monitoring and control system for application to an agricultural storage facility which can be of great potential benefit to the food industry. Various temperature and humidity sensors were installed; a microcontroller was used to acquire data and transfer it to a PC. A charge coupled device (CCD) video image sensor was also used to capture images of the storage facility to assess current working conditions. The PC connects to the internet via TCP/IP protocols in order to allow a remote supervisor to view the state of the food condition in the storage house. The internet connectivity provides the supervisor with a link to perform the control task of the facility including the capacity to generate signals to the actuators remotely and in real time.

2.5 Embedded Devices-based Monitoring

The following papers were reviewed to reflect the diversity of applications in which embedded systems have been deployed to undertake the monitoring function and are presented in this section. They are based upon microcontroller technology and illustrate an important trend in monitoring system evolution.

The benefits of monitoring in many aspects of life can be attained without the need to deploy high cost systems such as PCs. Postolache et al [2.71] introduced a low cost solution for water quality monitoring based on a microcontroller. The proposed system allows different quantities that characterise the quality of water to be measured remotely. It utilizes a PIC16F877 microcontroller, sensing unit and an Ethernet controller to provide connectivity to the outside world. The microcontroller performs the acquisition and processing of water quality parameters to extract the useful information and transmits it to a remote location.

Cavusoglu et al [2.72] proposed a monitoring system based on a microcontroller that can be of use in the medical field. The system is intended to continuously monitor the respiration patterns of the patients. In so doing, it allows measurement and analysis of breathing dynamics so that breathing disorders such as apnea can be detected. A sensor measures the heat variations in the oro-nazal air flow. A microcontroller (PIC16F877) acquires the heat signal using the on-board ADC converter and performs the analysis. If and when the apnea is detected an alarm is generated. Meanwhile, the microcontroller transfers the data to a PC via the RS232 communication channel for further analysis. Although the approach utilizes a system with limited power it offers a low cost and effective solution to one of the most common sleeping disorders. The authors reported that the performance of the system was evaluated and the results were found to be satisfactory.

It is essential to have power back-up systems especially in the industrial and medical fields. The reasons are: to ensure reliable, stable and continuous operations of critical components such as process controllers and medical equipment. Murad et al [2.73] implemented an online monitoring function for a power back-up system using an 8-bit microcontroller. The microcontroller performs both signal acquisition and control and at the same time provides a link to allow the output voltage from the power back-up system to be displayed on a computer with graphical user interface software. In the event that the system does not sustain the required supply level, a fault signal is indicated on the screen.

Chung and Oh [2.74] developed a wireless sensor module for indoor environment monitoring based on 8-bit microcontrollers that support wireless functionalities. The module contains eight sensors to allow various air quality parameters to be measured. These are converted to analogue if required and transmitted by RF transmitter to the microcontroller. The microcontroller platform has internet capability to provide real time data to a remote client PC or PDA.

Muthukkaruppan and Manoj [2.75] introduced a microcontroller based automated system with application to a multi-station part transfer, drilling and tapping machine using electro-pneumatic system. Signals from sensors and valves were interfaced with an 8-bit microcontroller to perform the control function of the process. Various aspects of the automation process such as time saving, productivity, repeatability, quality of product, etc. were discussed.

Ibanez et al [2.76] reported a DSP based system to monitor hydro-generators. The reliability of these machines is critical to the operation of electrical power plant and hence their monitoring to detect existing faults and/or predict future component failure is essential. To do that, the authors employed a TMS320C30 DSP (Texas Instruments) for signal acquisition and processing. Multiple signals were acquired and several processing algorithms implemented. Data is also transferred to a remote PC through RS422 standard for more analysis and display.

Buizza et al [2.77] presented an instrument with a DSP for monitoring human biological parameters. It contains a TMS320LF2407 DSP with 16 channels, a 10-bit ADC converter. Signals from transducers attached to patients are acquired and processed, and extracted features are displayed on LCD screen in real time. The benefits of this instrument as a monitoring solution were highlighted. They include ease of use, portability, reliability and accuracy.

The dsPIC digital signal controllers were the current devices, available from Microchip Technology, at the start of this research. They overcome the limitations of 8-bit microcontrollers, yet are available at low cost. These devices offer the computational capability to support economical solutions. They are being deployed to perform control and/or monitoring functions in a wide range of applications. For example, Zhang et al [2.78] utilized the dsPIC input capture and output compare modules to design an excitation control system for synchronous generator. The excitation control system is critical to sustain the required performance of the electrical power system. The hardware architecture and characteristics of the designed control system were described. The device used was dsPIC30F6014 which is the one being utilised in this thesis. Its characteristics and technical attributes are provided in Chapter 3.

Chainho et al [2.79] developed and implemented a discrete PID controller with parameter adaptation capability. A simplified algorithm with fuzzy logic system was adopted for parameters adaptation. In this case calibration and adjustment of the PID controller is not required. A first and second order processes were satisfactorily tested. This type of controller is widely used in the control loops of industrial processes. Jayabarathi and Devarajan [2.80] developed and implemented successfully an artificial neural network (ANN) method for reactive power compensation using dsPIC30F2010 device. The load flow was analysed to estimate voltage profile and losses in the investigated system. Capacitors were appropriately connected to the dsPIC to compensate for these losses. The inputs to the ANN network were real power, reactive power, and voltages at the second and eighteenth buses. The ON/OFF positions of the capacitors were taken as outputs. The ANN network was trained while the weights obtained so that mean squared error is minimum. The method was simulated to verify its effectiveness and the result was reported satisfactory.

Dalal [2.81] designed and implemented a digital audio decoder and its associated playback system based on a dsPIC30F4013 digital signal controller. An audio signal generated in Matlab was stored in the dsPIC as lookup table. Huffman decoding was adopted in this approach. The dsPIC's digital converter interface (DCI) connected to a digital to analogue converter was used to playback the audio recording. The author tested the system and good result was obtained. De Capua et al [2.82] reported the realisation of a smart sensor based on dsPIC30F6010 device to monitor the voltage RMS value and extract power quality indexes, thus allowing voltage sags to be detected. Voltage transducer was deployed giving a current output with 25mA maximum. A high precision resistance provided the voltage to be processed by the dsPIC following the required amplification. The acquisition process was controlled by the dsPIC and the sampling rate adopted was 10 kHz. This demonstrated the potential of dsPIC technology in condition monitoring.

2.6 Summary

Condition and process monitoring can be seen to be a vital practice to enhance production quality and reliability in almost every industry. PC based monitoring functions provide an almost limitless means to investigate various fault detection and diagnostic techniques. The need for economical monitoring solutions was expressed throughout the review particularly in pneumatic-based applications. The modern development in electronic and embedded devices provides the foundation to achieve high level of integrity in equipment and processes alike. The dsPIC digital signal controllers have the processing power and computational capability to support the implementation of methods that are capable of detecting and identifying faults occurring in the processes and machines. Moreover, they have the resources required to support evolution in the context of IPMM research as well as the deployment of distributed predictive maintenance architectures to ensure the reliability and effectiveness in production environments.

A distributed monitoring system based entirely on the deployment of dsPIC devices is presented in the next chapter. Technological aspects related to data acquisition and monitoring systems are also described.

References

[2.1] R. Isermann and P. Ball□, "Trends in the application of model-based fault detection and diagnosis of technical processes," *Control Engineering Practice*, vol. 5, May. 1997, pp. 709-719.

[2.2] R. Isermann, "Model-based fault-detection and diagnosis - Status and applications," *Annual Reviews in Control*, vol. 29, 2005, pp. 71-85.

[2.3] P. Jayaswal, A. Wadhwani, and K. Mulchandani, "Machine fault signature analysis," *International Journal of Rotating Machinery*, vol. 2008, 2008. doi:10.1155/2008/583982

[2.4] M. Frankowiak, R. Grosvenor, and P. Prickett, "A review of the evolution of microcontroller-based machine and process monitoring," *International Journal of Machine Tools and Manufacture*, vol. 45, 2005, pp. 573-582.

[2.5] P. Prickett and R. Grosvenor, "Non-sensor based machine tool and cutting process condition monitoring," *Journal of condition Monitoring & Diagnostic Engineering Management*, vol. 2, 1999, pp. 31-37.

[2.6] P. Prickett, "A Petri-net based machine tool maintenance management system," *Industrial Management and Data Systems*, vol. 97, 1997, pp. 143-149.

[2.7] M. Frankowiak, R. Grosvenor, and P. Prickett, "A petri-net based distributed monitoring system using PIC microcontrollers," *Microprocessors and Microsystems*, vol. 29, 2005, pp. 189-196.

[2.8] Q. Ahsan, R. Grosvenor, and P. Prickett, "Distributed on-line system for process plant monitoring," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 220, 2006, pp. 61-77.

[2.9] W. Amer, R. Grosvenor, and P. Prickett, "Sweeping filters and tooth rotation energy estimation (TREE) techniques for machine tool condition monitoring," *International Journal of Machine Tools and Manufacture*, vol. 46, 2006, pp. 1045-1052.

[2.10] R. Siddiqui, W. Amer, Q. Ahsan, R. Grosvenor, and P. Prickett, "Multi-band infinite impulse response filtering using microcontrollers for e-Monitoring applications," *Microprocessors and Microsystems*, vol. 31, 2007, pp. 370-380.

[2.11] W. Amer, R. Grosvenor, and P. Prickett, "Machine tool condition monitoring using sweeping filter techniques," *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, vol. 221, 2007, pp. 103-117.

[2.12] D. Juričić, O. Moseler, and A. Rakar, "Model-based condition monitoring of an actuator system driven by a brushless DC motor," *Control Engineering Practice*, vol. 9, 2001, pp. 545-554.

[2.13] TQC Ltd, "leak testing", [WWW]. <URL: http://www.leaktesting.co.uk/leak_detection.htm>. [Accessed on 11th June 2008]

[2.14] A. Calcatelli, M. Bergoglio, and D. Mari, "Leak detection, calibrations and reference flows: Practical example," *Vacuum*, vol. 81, Aug. 2007, pp. 1538-1544.

[2.15] R. Montague and J. Watton, "Analysis and automated testing of a miniature pneumatic valve for hospital patient support equipment," *International Journal of Fluid Power*, vol. 6, 2005, pp. 57-64.

[2.16] V. Sivaramakrishna, F. Raspante, S. Palaniappan, and M. Pascall, "PET bottles seal quality testing using an on-line pressure differential detector," *Journal of Food Engineering,* vol. 80, 2007, pp. 645-654.
[2.17] C. Boehm, "Self-monitoring pneumatic systems," *Machine Design,* vol. 79, 2007, pp. 70-79.
[2.18] M.A.M. Sharif, "Application of intelligent instrumentation in process plant condition monitoring and fault diagnosis," 1999.
[2.19] V.K. Varma, R. Tucker, S. Kercel, T. Thundat, and A. Passian, "New Acoustic Wave Pipe Inspection System" [WWW]. <URL:http://www.ms.ornl.gov/fossil/Publications/ANNUAL-2003/feab209.pdf>.
[Accessed on 1st June 2006]
[2.20] S. Licciardi, "Quantification and location of leaks by internal inspection," *Tunnelling and Underground Space Technology,* vol. 13, 1998, pp. 5-15.
[2.21] M. Taghvaei, S. Beck, and W. Staszewski, "Leak detection in pipelines using cepstrum analysis," *Measurement Science and Technology,* vol. 17, 2006, pp. 367-372.
[2.22] A. Souza, S. Cruz, and J. Pereira, "Leak detection in pipelines through spectral analysis of pressure signals," *Brazilian Journal of Chemical Engineering,* vol. 17, 2000, pp. 557-563.
[2.23] Sheng Zhang, T. Asakura, and S. Hayashi, "Leakage fault detection of pneumatic pipe system using neural networks," *SICE 2003 Annual Conference,* 2003, pp. 2482-2487 Vol.3.
[2.24] Z. Nakutis and P. Kaskonas, "Pneumatic Cylinder Diagnostics using Classification Methods," *Instrumentation and Measurement Technology Conference Proceedings, 2007. IMTC 2007. IEEE,* 2007, pp. 1-4.
[2.25] G. Bone and Shu Ning, "Experimental Comparison of Position Tracking Control Algorithms for Pneumatic Cylinder Actuators," *Mechatronics, IEEE/ASME Transactions on,* vol. 12, 2007, pp. 557-561.
[2.26] A. Csiszar and V. Andras, "Servo-pneumatic positioning with sliding mode control."[WWW].
<URL: http://iralab.ee.ntu.edu.tw/handson/Winner%20list.doc>.
[Accessed on 22nd February 2007]
[2.27] J. Wang, J. Pu, and P. Moore, "Accurate position control of servo pneumatic actuator systems: an application to food packaging," *Control Engineering Practice,* vol. 7, Jun. 1999, pp. 699-706.
[2.28] T. Guoliang and W. Xuanyin, "RESEARCH ON PNEUMATIC-SERVO CALLIGRAPHY ROBOT."[WWW].
<URL: http://fluid.power.net/techbriefs/hanghzau/3_8.pdf.>
[Accessed on 4th May 2007]
[2.29] R. Richardson, A. Plummer, and M. Brown, "Self-tuning control of a low-friction pneumatic actuator under the influence of gravity," *Control Systems Technology, IEEE Transactions on,* vol. 9, 2001, pp. 330-334.
[2.30] W. Dunbar, R. de Callafon, and J. Kosmatka, "Coulomb and viscous friction fault detection with application to a pneumatic actuator," *Advanced Intelligent Mechatronics, 2001. Proceedings. 2001 IEEE/ASME International Conference on,* 2001, pp. 1239-1244 vol.2.
[2.31] J. [Reference to Pu], P.R. [Reference to Moore], and C.B. [Reference to Wong], "Smart components-based servo pneumatic actuation

systems," *Microprocessors and Microsystems,* vol. 24, Apr. 2000, pp. 113-119.

[2.32] Xiaolin Li and Imin Kao, "Analytical fault detection and diagnosis (FDD) for pneumatic systems in robotics and manufacturing automation," *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on,* 2005, pp. 2517-2522.

[2.33] N. Lehrasab, H. Dassanayake, C. Roberts, S. Fararooy, and C. Goodman, "Industrial fault diagnosis: Pneumatic train door case study," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* vol. 216, 2002, pp. 175-183.

[2.34] W. Xuanyin, G. Lei, and T. Guoliang, "RESEARCH ON FUZZY NEURAL NETWORT FAULT DIAGNOSIS OF PNEUMATIC SYSTEM OF AUTOMATIC PRODUCTION LINE." [WWW]. <URL:http://fluid.power.net/techbriefs/hanghzau/3_7.pdf>. [Accessed on 4th May 2007]

[2.35] M. Karpenko, N. Sepehri, and D. Scuse, "Diagnosis of process valve actuator faults using a multilayer neural network," *Control Engineering Practice,* vol. 11, Nov. 2003, pp. 1289-1299.

[2.36] V. Puig, J. Quevedo, A. Stancu, J. Lunze, J. Neidig, P. Planchon, and P. Supavatanakul, "Comparison of Interval Models and Quantised Syatems in Fault Detection with Application to the DAMADICS Actuator Benchmark Problem", 5th IFAC Symposium on Fault Detection Supervision and Safety for Technical Processes, Washington, USA, 2003, pp 1191-1196.

[2.37] G. Bright and S. Martegoutte, "Generic gripper - grabs your components," *Assembly Automation,* vol. 15, 1995, pp. 24-26.

[2.38] W. Friedrich, P. Lim, and H. Nicholl, "Sensory gripping system for variable products," *Robotics and Automation, 2000. Proceedings. ICRA '00. IEEE International Conference on,* 2000, pp. 1982-1987 vol.2.

[2.39] S. Terada, H. Kobayashi, H. Sengoku, Y. Kato, K. Hara, F. Honma, Y. Ikegami, Y. Iwata, T. Kohriki, T. Kondo, I. Nakano, R. Takashima, R. Tanaka, N. Ujiie, Y. Unno, and S. Yasuda, "Design and development of a work robot to place ATLAS SCT modules onto barrel cylinders," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 541, Apr. 2005, pp. 144-149.

[2.40] E. Ottaviano, M. Toti, and M. Ceccarelli, "Grasp force control in two-finger grippers with pneumatic actuation ," *Robotics and Automation, 2000. Proceedings. ICRA '00. IEEE International Conference on,* 2000, pp. 1976-1981 vol.2.

[2.41] R.C. Luo, "MICROCOMPUTER-BASED INTELLIGENT SENSOR FOR MULTIAXIS FORCE/TORQUE MEASUREMENT.," *IEEE transactions on industrial electronics and control instrumentation,* vol. 35, 1988, pp. 26-30.

[2.42] G. Hirzinger, "Issues in low-dimensional sensing and feedback," *IEEE Transactions on Systems, Man and Cybernetics,* vol. 19, 1989, pp. 832-839.

[2.43] F. Alpek, S. Kovacs, N. Krys, and M. Terbuc, "Multi-sensor systems based on force/torque/pressure sensors for monitoring of grippers,"

Advanced Motion Control, 2002. 7th International Workshop on, 2002, pp. 551-555.
[2.44] N. Tlale, R. Mayor, and G. Bright, "Intelligent gripper using low cost industrial sensors," *Industrial Electronics, 1998. Proceedings. ISIE '98. IEEE International Symposium on,* 1998, pp. 415-419 vol.2.
[2.45] H. Choi and M. Ko□, "Design and feasibility tests of a flexible gripper based on inflatable rubber pockets," *International Journal of Machine Tools and Manufacture,* vol. 46, Oct. 2006, pp. 1350-1361.
[2.46] Y. Ki, S. Tso, and Q. Meng, "Grasping force measurement for dynamic grasp stability assessment ," *Instrumentation and Measurement, IEEE Transactions on,* vol. 47, 1998, pp. 1294-1299.
[2.47] M. Ceccarelli, G. Figliolini, E. Ottaviano, A. Mata, and E. Criado, "Designing a robotic gripper for harvesting horticulture products," *Robotica,* vol. 18, 2000, pp. 105-111.
[2.48] S. Costo, G. Altamura, L. Bruzzone, R. Molfino, and M. Zoppi, "Design of a re-configurable gripper for fast robotic picking and handling of limp sheets," *International Symposium on Robotics,* Stockholm, Sweden: 2002.
[2.49] R. Kolluru, K. Valavanis, and T. Hebert, "A robotic gripper system for limp material manipulation: modeling, analysis and performance evaluation," *Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on,* 1997, pp. 310-316 vol.1.
[2.50] M. Kavoussanos and A. Pouliezos, "Visionary automation of sack handling and emptying," *Robotics & Automation Magazine, IEEE,* vol. 7, 2000, pp. 44-49.
[2.51] E. Holweg, H. Hoeve, W. Jongkind, L. Marconi, C. Melchiorri, and C. Bonivento, "Slip detection by tactile sensors: algorithms and experimental results," *Robotics and Automation, 1996. Proceedings., 1996 IEEE International Conference on,* 1996, pp. 3234-3239 vol.4.
[2.52] S. Ahmad, "A laboratory experiment to teach some concepts on sensor-based robot assembly systems," *Education, IEEE Transactions on,* vol. 31, 1988, pp. 74-84.
[2.53] M. Abu-Hamdan and A. El-Gizawy, "Computer-aided monitoring system for flexible assembly operations," *Computers in Industry,* vol. 34, 1997, pp. 1-10.
[2.54] I. Konukseven and B. Kaftanoglu, "Moving part recognition and automatic pick and place using an industrial robot," *Intelligent Robots and Systems, 1997. IROS '97., Proceedings of the 1997 IEEE/RSJ International Conference on,* 1997, pp. V6-V7 vol.3.
[2.55] W. Drotning, H. Kimberly, W. Wapman, D. Darras, D. Homan, P. Johnson, B. Kast, J. Kuhlmann, R. Lennox, and C. Montoya, "A sensor-based automation system for handling nuclear materials," *Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on,* 1997, pp. 352-358 vol.1.
[2.56] K. Xu, L. Tong, and T. Mei, "A networked smart sensor system for gripper of robots," *Sensors for Industry Conference, 2002. 2nd ISA/IEEE,* 2002, pp. 111-114.
[2.57] K. Feldmann, B. Muller, and T. Haselmann, "Automated assembly of lightweight automotive components," *CIRP Annals - Manufacturing Technology,* vol. 48, 1999, pp. 9-12.

[2.58] G. Rosati, G. Boschetti, A. Biondi, and A. Rossi, "On-line dimensional measurement of small components on the eyeglasses assembly line," *Optics and Lasers in Engineering,* vol. In Press, Corrected Proof.
[2.59] Y.(. Kwon and R. Chiou, "Remote, condition-based maintenance for web-enabled robotic system," *Robotics and Computer-Integrated Manufacturing,* vol. In Press, Corrected Proof.
[2.60] P. Kaskonas and Z. Nakutis, "Leakage diagnostics in pneumatic systems using transient patterns," vol. 2, 2006.
[2.61] R. Beushausen, S. Tornow, H. Borchers, K. Murphy, and J. Zhang, "Transient leak detection in crude oil pipelines," *Proceedings of the Biennial International Pipeline Conference, IPC,* 2004, pp. 2285-2293.
[2.62] S. Cho, H. Yang, M. Zaheer-Uddin, and B. Ahn, "Transient pattern analysis for fault detection and diagnosis of HVAC systems," *Energy Conversion and Management,* vol. 46, 2005, pp. 3103-3116.
[2.63] A. Tan, P. Chua, and G. Lim, "Fault diagnosis of water hydraulic actuators under some simulated faults," *Journal of Materials Processing Technology,* vol. 138, 2003, pp. 123-130.
[2.64] M.A. Adewumi, E.S. Eltohami, and A. Solaja, "Possible Detection of Multiple Blockages Using Transients," *Journal of Energy Resources Technology,* vol. 125, Jun. 2003, pp. 154-159.
[2.65] S. Kim and I. Daniel, "Transient gas flow technique for inspection of fiber preforms in resin transfer molding," *Composites Part A: Applied Science and Manufacturing,* vol. 36, 2005, pp. 1694-1699.
[2.66] I. Paterson and J. Wilson, "Use of damage monitoring systems for component life optimisation in power plant," *International Journal of Pressure Vessels and Piping,* vol. 79, 2002, pp. 541-547.
[2.67] B. Brunone, M. Ferrante, and L. Ubertini, "leak analysis in pipes using transients," *Second Annual Seminar on Comparative Urban Projects,* Rome, Italy: 2000.
[2.68] C. Verde, N. Visairo, and S. Gentil, "Two leaks isolation in a pipeline by transient response," *Advances in Water Resources,* vol. 30, 2007, pp. 1711-1721.
[2.69] C. Angeli and A. Chatzinikolaou, "Prediction and diagnosis of faults in hydraulic systems," *Journal of engineering manufacture,* vol. 216, 2002, pp. 293-297.
[2.70] S. kim and J. Chun, "Remote Monitoring and Control of Agricultural Storage Facility using Internet," Seoul National University, Korea, [WWW]. <URL:;http://zoushoku.narc.affrc.go.jp/ADR/AFITA/afita/afita-conf/2000/part06/p179.pdf>. [Accessed on 10th May 2008].
[2.71] O. Postolache, P. Girao, M. Pereira, and H. Ramos, "An Internet and microcontroller-based remote operation multi-sensor system for water quality monitoring," *Sensors, 2002. Proceedings of IEEE,* 2002, pp. 1532-1536 vol.2.
[2.72] M. Cavusoglu, O. Erogul, and Z. Nakutis, "Design And Implemantation of A Programmable Apnea Monitoring System," Antalya, Turkey: 2005. .[WWW] <URL:http://www.eurasip.org/Proceedings/Eusipco/Eusipco2005/defevent/main/info.pdf>. [Accessed on 16th April 2007].

[2.73] S. Murad, M. Isa, and N. Rahman, "Monitoring system for uninterruptible power supply," *American Journal of Applied Sciences,* vol. 4, 2007, pp. 181-183.
[2.74] W. Chung and S. Oh, "Remote monitoring system with wireless sensors module for room environment," *Sensors and Actuators, B: Chemical,* vol. 113, 2006, pp. 64-70.
[2.75] M. Muthukkaruppan and K. Manoj, "Low cost automation using electro pneumatic system-an online case study in multistation part transfer, drilling and tapping machine," Madras, India: 2007. [WWW]. <URL:http://www.iaarc.org/external/isarc2007-cd/www/PDF/5.2_5_028.pdf>. [Accessed on 20th June 2008]
[2.76] J. Ibáñez, C.J. Pantaleón, I. Santamaría, D. Luengo, M. Lázaro, D. De, and I. De Comunicaciones, "Specific DSP based monitoring system for hydro-generator sets", ICSPAT," 1998. [WWW]. <URL:http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.26.1962> [Accessed on 4th June 2008]
[2.77] A. Buizza, G. Coldani, G. Danese, R. Gandolfi, P. Ghidetti, and R. Lombardi, "An instrument with a DSP for monitoring human biological parameters ," *Electronics, Circuits and Systems, 2001. ICECS 2001. The 8th IEEE International Conference on,* 2001, pp. 757-760 vol.2.
[2.78] W. Zhang, Y. Yang, and J. Wang, "A dsPIC-based Excitation Control System for Synchronous Generator," *Mechatronics and Automation, 2007. ICMA 2007. International Conference on,* 2007, pp. 3844-3848.
[2.79] J. Chainho, P. Pereira, S. Rafael, and A. Pires, "A Simple PID Controller with Adaptive Parameter in a dsPIC; Case of Study." [WWW]. <URL: http://www.aedie.org/9CHLIE-paper-send/337_CHAINHO.pdf>. [Accessed on 4th April 2008]
[2.80] R. Jayabarathi and N. Devarajan, "ANN based DSPIC controller for reactive power compensation. ," *American Journal of Applied Sciences,* vol. 4, Jul. 2007, pp. 508-515.
[2.81] I. Dalal, "A Real-time AAC-type Audio Codec on the 16-bit dsPIC Architecture," Mexico city, Mexico: 2007.
[2.82] C. De Capua, S. De Falco, A. Liccardo, and E. Romeo, "A dsPic-based measurement system for the evaluation of voltage sag severity through new power quality indexes," *Virtual Environments, Human-Computer Interfaces and Measurement Systems, 2005. VECIMS 2005. Proceedings of the 2005 IEEE International Conference on,* 2005, pp 2-6.

Chapter 3

TECHNOLOGY SELECTION AND SYSTEM DESCRIPTION

3.1 Introduction

Today's manufacturing industry can invest in a monitoring system only if it is reliable and can provide an acceptable cost-to-benefit ratio [3.1]. The main attribute of the PC based systems that have been developed to support such functions are related to their computational power and interconnectivity. However a monitoring system that is based on an industrial or commercial PC can become expensive when combined with the necessary software and data acquisition cards and the associated information management functions. For these reasons the practical deployment of PC based systems in today's industrial sector has been limited.

Current technological advancements in embedded devices incorporate processing power and computational speed on a single chip, such as the dsPIC microcontrollers used in this research, makes the development of a distributed process monitoring system, with a plug-and-play capability, a possible solution for a wide variety of applications.

Distributed monitoring systems have been developed over the years and have been deployed in the real world. The term "distributed system" is defined as, "a system in which hardware or software components located at networked computers, communicate and coordinate their actions, only by message passing" [3.2].

Various devices in a distributed system can operate concurrently and tasks are undertaken independently. Actions however are coordinated at well-defined stages by exchanging messages through a digital communication medium such as the Controller Area Network (CAN) bus, which is widely used in many industries.

This chapter describes the development of a distributed process monitoring system based upon Microchip's dsPIC digital signal controllers.

3.2 Monitoring System Architecture

Real-time information about the process and machine components needs to be obtained for effective monitoring. A fundamental aspect of the development process of a monitoring system is the data acquisition, which is normally accomplished through the installation of various sensors and transducers. An industrial application may require a large number of sensors in order to collect data about any process. If this data is collected at a central location, cables will have to be laid down from every sensing element to the central point. This approach can lead to a complex wiring network. Thus yielding a system that is hard to install and difficult to maintain. The cost associated with such systems is an important issue to consider. Signals acquired in this way, in an industrial environment, tend to be noisy; often the effectiveness of the monitoring system may thus be compromised. The idea of deploying this monitoring layout in the present industrial age is no longer attractive. A modular, microcontroller-based, data acquisition and analysis system was therefore developed to provide a more feasible solution.

The essential feature of the acquisition process supporting this development is that analogue signals have to be converted into a more convenient format so that they can be used in a meaningful and effective manner. This is achieved by means of an on board Analogue-to-Digital Converter (ADC). When processed, digital data can then be sent through a Controller Area Network (CAN) bus which connects the different acquisition and processing nodes. This allows information to be shared for collective decision making. This approach will limit if not totally eliminate any wrong decisions from being made. A connectivity node enables the process to be monitored on-line so that concerned parties need not be present on site. When required, actions can be taken as to keep the process running at maximum efficiency.

The main objective of this research was essentially to develop data processing techniques capable of identifying the size of any object being gripped during a "pick and place" like activity, whilst keeping the number of any electronic components and sensors to a minimum. To achieve this, it was decided to employ 16-bit dsPIC microcontrollers in the development of this system. Their built-in digital signal processor (allowing mathematical manipulations to be achieved), computational speed and signal handling (for example via a fast multichannel ADC) capabilities make them superior to the previous generation of microcontrollers, thereby providing considerable additional benefits to front-end processing capabilities. The hardware architecture of the proposed distributed monitoring system is shown in Figure 3.1.

The desired variable (parameter) may be analysed in the front-end node (FEN) to identify known fault symptoms. Signal acquisition and processing are performed in this level of the monitoring system to take advantage of the processing capabilities of dsPIC and to explore its potential in process monitoring and control. The need for a reliable and effective system demands that information be shared, through the CAN bus, between the dsPIC microcontrollers deployed at this level so that a collective decision can be made about the health of the process. This can minimize the number of false alarms being made. The performance of a CAN bus in noisy environments is known to be reliable, hence it is being used to provide the communication medium between devices. Based on the processing capability of the dsPIC, it was expected that most common faults may be identified at this node.

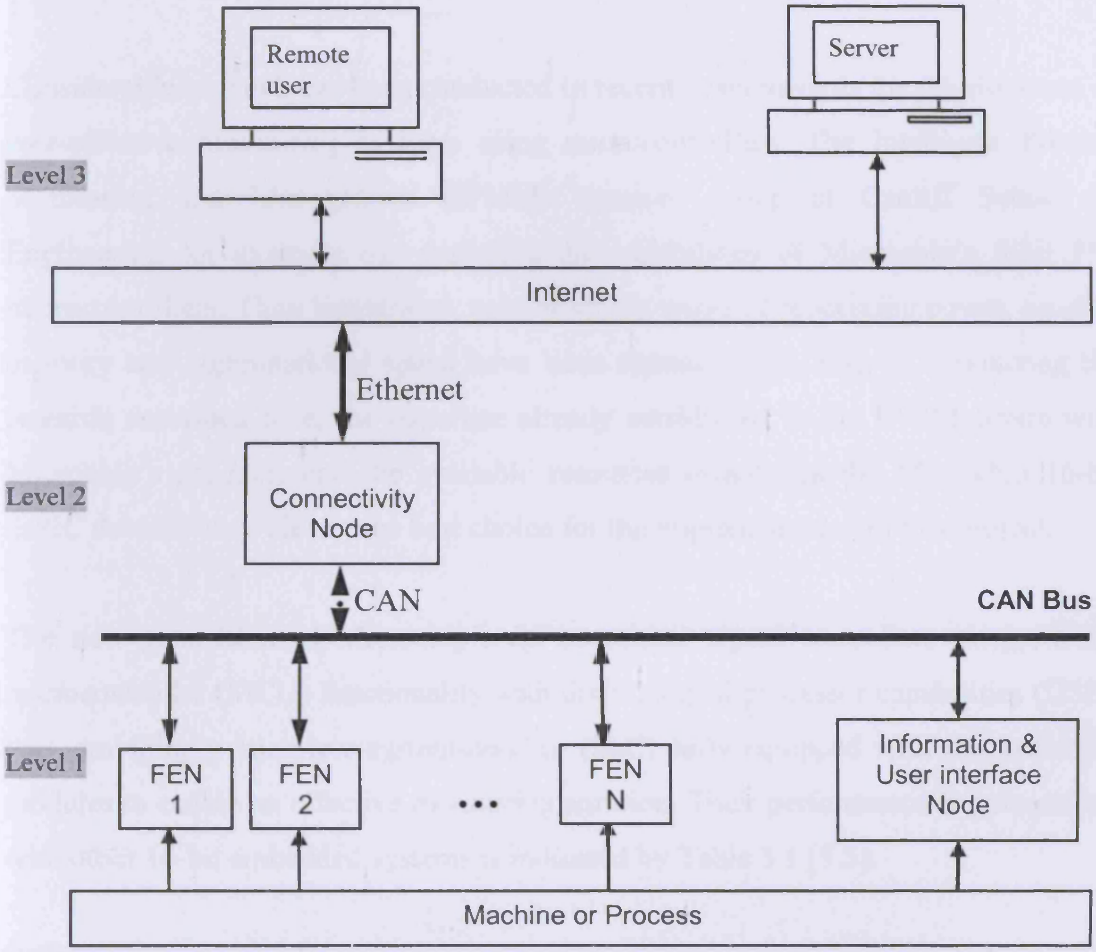


Figure 3.1 Hardware architecture of proposed monitoring system.

The second level in the proposed hierarchy constitutes a synchronisation-connectivity node based also on dsPIC devices. At this stage, if or when required, data from various front-end-nodes (FENs) are combined and analysed. It's believed that all remaining "known" fault conditions will thus be detected at this level. This level also provides a link between FENs on one side to a server on the other side through the Internet, where further analysis tools can be deployed on a computer (personal or industrial) to identify the occurrence of "new" faults as they arise.

It is anticipated that any new faults thus detected and diagnosed may then be added to the list of known faults, and the developed detection process added to the capabilities of the lower nodes.

3.3 Processing and the Selection of Technology

Considerable research has been conducted in recent years towards the development of cost-effective monitoring systems using microcontrollers. The Intelligent Process Monitoring and Management (IPMM) research group at Cardiff School of Engineering for example has exploited the capabilities of Microchip's 8-bit PIC microcontrollers. Their limitations, particularly in terms of processing power, on-chip memory and computational speed have been reported [3.3, 3.4]. In conducting the research described here, the expertise already established in the IPMM centre with Microchip's products and the available resources meant that the Microchip 16-bit dsPIC devices were clearly the best choice for the implementation of this project.

The new generation of Microchip's dsPIC digital signal controllers integrate the microcontroller (MCU) functionality with digital signal processor capabilities (DSP), thus providing a complete system-on-chip (SoC) fully equipped with the necessary modules to enable an effective monitoring solution. Their performance in comparison with other 16-bit embedded systems is indicated by Table 3.1 [3.5].

Company	MCU Family	Instruction Cycle Rate (MHz)	# of Cycles per Instruction	Average Throughput (MIPS)	cost (£)
Microchip	dsPIC30F	30	1-2	28	5.95
Infineon	XC161/166	40	1-6	28	10.9
TI	320LF240x	40	1-4	21	10.28
Motorola	56F80x	40	1-8	19	9.5
Hitachi	H8S/26xx	33	1-7	15	7.25
Infineon	C16x	25	2-4	12	14.3
ST Micro	ST10F269	20	2-4	9	16.89
Mitsubishi	M16C	20	1-8	9	12.60
Motorola	MC9S12D	25	2-6	6	10.08

Key: - dsPIC30F actual, others estimated based on instruction frequency analysis.
- Preliminary results, calendar year 2004.

Table 3.1: The dsPIC30F family as compared to other 16-bit devices.

These devices contain a set of peripherals, a reasonable, sized on-chip data memory, a significant program memory space, CAN bus and I/O ports. Their oscillator system provides various options (of clock sources) and employs a Phase-Locked-Loop (PLL) technique to boost internal operating frequency by 4, 8 or 16 times, making them suitable for many industrial applications. Dynamic systems such as pneumatic grippers and actuators could be considered demanding, particularly in terms of speed and processing power. The author thus only considered the implementation of dsPIC Digital Signal Controllers (DSCs) in this research.

The dsPIC30F6014 was thought to be appropriate for the pursuit of the development process of an integrated monitoring function for pneumatic systems. This device has the stated capabilities required for signal acquisition, processing, and communication within the network and with the outside world. More specifically, it contains a 12-bit ADC, large memory, timers with programmable prescaler, and external interrupts; input capture module, digital I/O ports, and multiple communication modules including CAN, SPI and UART that can be used to implement the RS-232 standard for communication with a PC COM port. The UART and SPI modules helped in the initial development of the proposed system. In the following section, a general overview of dsPIC30F families is provided along with more insight into the capabilities of the particular dsPIC30F6014 digital signal controller.

3.4 The dsPIC30F Digital Signal Controllers

Microchip Incorporation is the leading manufacturer of embedded devices, as indicated by the total number of units shipped in 2006 [3.6]. The introduction of dsPIC30F digital signal controller (DSC) opened new horizons for design engineers in a wide range of applications. In essence these devices provide a computer on a single-chip, which has features that can be adapted for a particular application. The architecture of such devices features a powerful DSP engine, C compiler-friendly design, and familiar microcontroller platform.

The Microchip dsPIC30F consists of three device families:

- General purpose family
- Motor control and power conversion family, and
- Sensor family

In this project, the (most generic) General Purpose Family platform was adopted and many of the available features were utilized in the development of the proposed monitoring system. These devices employ a powerful 16-bit architecture integrating the control features of a microcontroller with the computational capabilities and speed of a digital signal processor. This architecture design leads to an optimum functionality well suited for applications that demand high speed, repetitive computations and control; it was realized by the IPMM research group that robotic gripper applications are challenging and may demand high speed and processing power.

The built-in DSP engine provides the dsPIC30F CPU with extensive mathematical processing capabilities. In addition various full-featured peripherals combined with flexible fast-interrupt handling, renders the dsPIC30F family of devices suitable for control applications. Field programmable Flash program and data EEPROM, coupled with software and hardware tools (from the same supplier) ensures the scalability of applications. Table 3.2 shows a list of variants of the General Purpose Family, with the selected dsPIC30F6014 highlighted.

Device	Pin #	Program Memory		SRAM Bytes	EEPROM Bytes	Timer 16-bit	Input Capture	Output compare	A/D 12-bit (200 ksps)	UART	SPI	CAN	I²C	Max. I/O pins
		Kbytes	Instructions											
dsPIC30F3014	40/ 44	24	8K	2048	1024	3	2	2	13 ch	2	1	-	1	30
dsPIC30F4013	40/ 44	48	16k	2048	1024	5	4	4	13 ch	2	1	1	1	30
dsPIC30F5011	64	66	22k	4096	1024	5	4	4	16 ch	2	2	2	1	52
dsPIC30F6011 dsPIC30F6011a	64	132	44k	6144	2048	5	8	8	16 ch	2	2	2	1	52
dsPIC30F6012 dsPIC30F6012a	64	144	48k	8192	4096	5	8	8	16 ch	2	2	2	1	52
dsPIC30F5013	80	66	22k	4096	1024	5	8	8	16 ch	2	2	2	1	68
dsPIC30F6013 dsPIC30F6013a	80	132	44k	6144	2048	5	8	8	16 ch	2	2	2	1	68
dsPIC30F6014 dsPIC30F6014a	80	144	44k	8192	4096	5	8	8	16 ch	2	2	2	1	68

Note: Maximum I/O pin count includes pins shared by peripheral functions.

Table 3.2: dsPIC30F General Purpose Family variants (compiled from [3.7]).

The dsPIC30F devices support two types of programming methods:

- In-Circuit Serial Programming (ICSP), which allows the device to be programmed after being placed on a circuit board. This was used during the initial development and testing of the monitoring approaches described in the following chapters.
- Run-Time Self-Programming (RTSP) makes it possible to program the device while an embedded program is already in operation. This makes it possible to perform remote software upgrades or update in end-user's applications if and when required. Chapter 7 emphasises the potential use of this programming method.

3.4.1 The dsPIC30F6014 DSC (Digital Signal Controller)

The device selected for both the front-end node and the connectivity node of the distributed process monitoring system was the dsPIC30F6014 MCU. Its selection identified that it has features that provide flexibility and support opportunities to explore the potential deployment of these devices in this research [3.7, 3.8]. The block diagram of the dsPIC30F6014 (General Purpose) digital signal controller is provided in "Appendix A" for reference.

The CPU of this device contains a 16-bit (data) modified Harvard architecture with an enhanced wide instruction set, providing great support for the DSP. The instruction word is 24 bits wide, and the associated program counter (PC) is 23 bits wide. Therefore, it can address up to 4M (that is 2^{22}) instruction words of user program memory. As evident in Table 3.2 the size of program memory implemented varies within the device family. The dsPIC30F6014 contains 144kbytes of program memory, and 4kbytes of data EEPROM memory. The architecture supports program loop constructs through the use of DO and REPEAT instructions, yielding no program overhead. Both instructions can be interrupted at any time.

The dsPIC30F devices have an array of sixteen working registers. Each working register is 16 bits wide and can be used as data, address or address offset registers. The 16^{th} working register (W15) in particular serves as a software stack pointer for interrupts. There are two classes of instruction set, one of which is related to the MCU, the other is concerned with DSP commands. The instruction set is stated to be designed so that C compiler efficiency is optimum.

The data memory space is 16-bit wide, and has a capacity of 32 kwords. It is divided into two sections: X and Y data spaces. An independent Address Generation Unit (AGU) is designated for each section and has its own separate path. This feature is of major importance especially when performing frequency analysis. It allows certain instructions to simultaneously fetch two words from the RAM, thus enhancing the speed of execution. The MCU class of instructions operate completely through the X space AGU that accesses the entire memory map as a single linear data space. Both X and Y AGUs are used during the operation of certain DSP instructions to provide the required support for efficient execution of DSP algorithms such as Fast Fourier Transform (FFT). Most instructions can address data memory either in word or byte formats. The upper 16 kwords of data space can be mapped into program space, if desired. This feature allows any instruction to access program memory as if it was data space.

Circular buffering or modulo addressing, which yields no software overhead and is supported in both X and Y data space, is a unique feature of the dsPIC30F family in general. This feature helps overcoming the software boundary checking overhead associated with DSP algorithms. The X data AGU modulo addressing can be used with any instruction related to the MCU class of instructions. It also supports bit-reversed addressing to simplify the input/output data re-ordering for radix-2 FFT algorithms.

The CPU supports various flexible addressing modes. The dsPIC30F devices have, for most instructions, the capability to perform a data (or a program) memory read, a data memory write, and a working register (data) read in a single instruction cycle.

The DSP engine features a high speed 17-bit by 17-bit multiplier which is shared by the MCU ALU and the DSP engine and can perform multiplications of singed, unsigned and mixed-sign values, two 40-bit saturating accumulators (ACCA and ACCB), and a 40-bit bi-directional barrel shifter capable of shifting the 40 bit value up to 16 bits left or right in one clock cycle. Both DSP and MCU instructions can use the barrel shifter. The DSP class of instructions are stated to have been designed to achieve an optimised performance in real time. The multiply-and-accumulate (MAC) instruction and other instructions associated with it can concurrently fetch two data operands from memory while multiplying two working registers and accumulating the result in the same cycle.

The dsPIC30F family of devices support 16/16 and 32/16 divide operations in both integer and fractional format [3.9]. The divide instructions in these devices are iterative operations and can be interrupted during any of the required 19 instruction clock cycles (total execution time required for division) without loss of data.

Furthermore, the dsPIC30F6014, used in the proposed monitoring system, features 5 external interrupts, and interrupt vector table (IVT) that supports up to 54 interrupt sources. Any source of interrupt can be programmed for one of 7 priority levels, thus providing flexibility and control of target applications. It is in addition possible to interrupt the CPU through an implementation scheme on the rise or fall of signal level of up to 24 digital I/O pins, adding more potential to deploy this device in all kind of applications. The above features of the CPU architecture of such devices enhance the efficiency (in terms of code size and speed of execution) of the C compiler.

3.4.2 Supporting factors for Technology Selection

Microchip has a large portfolio of easy-to-learn development tools for its dsPIC30F families well-suited for embedded monitoring and control solutions. The available software tool-set and online support and product documentations are also very important for a design engineer.

The main hardware components supporting the selection of dsPIC30F devices included:

- The availability of a variety of demonstration boards.
- In-Circuit Debugger 2 (ICD2); this device can be enabled for emulation to test the developed software on the target hardware circuits, or to download it onto the dsPIC DSC.
- MPLAB PM3 is a universal device programmer.
- MPLAB ICE 4000 in-circuit emulator.

The last two items were available for more advanced programming and debugging but were not used in the current research.

The software elements (all of which were used in this research) associated with the dsPIC30F families can be summarized as follows:

- MPLAB IDE Integrated Development Environment; it includes a programmer's text editor, software simulator, assembler and Visual Device Initializer (VDI), which can be utilized for peripherals configuration. MPLAB IDE is powerful software, yet it has a simple and user-friendly Graphical User Interface (GUI). More importantly, it is available for free.
- MPLAB C30 C Compiler; this software development tool is supported by MPLAB IDE. It provides code efficiency and a cost-effective, ANSI-compliant option for writing C or mixed C and Assembly code modules [3.9].
- Digital Filter Design and dsPICworks for data analysis of DSP algorithms.

A number of libraries, designed especially for the dsPIC30F families, were also available and used. They include:

- Math library; functions although written in Assembly, but can be called from either C or Assembly language.
- Peripherals library; it supports the configuration and control of modules like ADC, UART, SPI, and CAN.
- DSP library; all DSP routines are developed and optimized in dsPIC30F assembly language and are callable from both Assembly and C language.

The main development board that was selected and used was the dsPICDEM 1.1™ Development Board. Prior to programming specifically for the current task the use of this helped the designer to become familiar with the dsPIC30F 16-bit architecture, high performance peripherals and powerful instruction set. Microchip provides supporting example software and appropriate documentation. Figure 3.2 shows the dsPICDEM 1.1 board. Related schematics are included in "Appendix B". It proved to be an ideal prototyping tool to develop and validate key design requirements.

Some key features of this platform are listed below [3.10]:

- It supports the dsPIC30F6014 device (implemented in this research).
- CAN communication channel (to allow communication between devices).
- RS-232 and RS-485 communication channels (this provides a link to PC).
- In-Circuit Debugger interface (MPLAB ICD 2).

- 4 line- LCD display. It provides a significant tool as a user/designer interface to monitor and control, the application process. Messages may be displayed to inform the operator about the health of the process.
- A prototype area and header emulator to facilitate any required expansion.
- Various LEDS, switches and analogue potentiometers.

All of the above features were utilized in this research during the initial development and final deployment of the monitoring approaches. More available features, although not used in this research, include:

- Voice band codec interface with line in/out jacks.
- ICE 4000 Emulator interface
- Microchip temperature sensor
- Microchip Digital Potentiometer

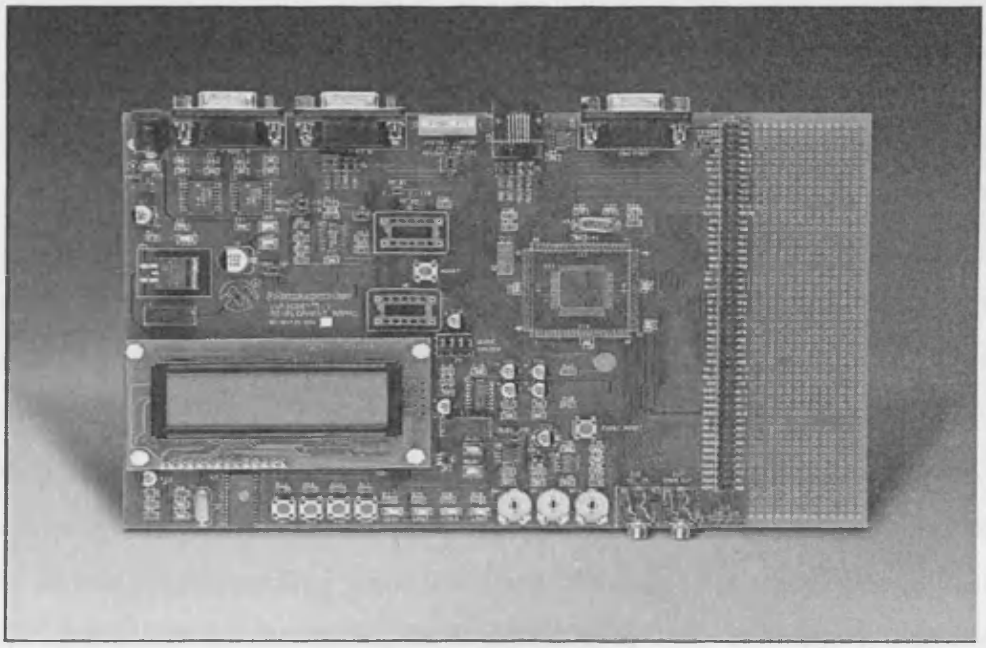


Figure 3.2: The dsPICDEM 1.1 Development Board [3.7].

3.5 Data Acquisition

The use of the dsPIC6014 DSC in the front-end-nodes (FENs) to acquire desired physical variable (pressure signal) and digital signals from different sensors and transducers is detailed in the following sections.

3.5.1 Analogue Signal Acquisition

Analogue variables include measurable physical quantities such as pressure, temperature, flow and human speech. Processing analogue signals, as they are, requires special electronic circuitry that is often difficult to design, expensive, and its component accuracy can be affected by age [3.11]. Hence these signals are frequently converted to digital form so that some processing method can be applied to them to extract information about a particular process. This information is normally contained in the form of signal amplitude, frequency, phase, or timing relationship with respect to other signals [3.12].

It is first necessary to convert the physical quantities being measured into (analogue) electrical signals. Various sensors are usually installed in the process or machine to perform such a task. In many cases, the output measurement of a sensor requires signal conditioning to conform with the requirements of the data acquisition hardware. In the context of this research for example, the pressure transducer (an industrial heavy duty pressure sensor with spring movement) output is a 4-20 mA current signal. This signal had to be converted to voltage in the range 0 to 5 VDC as required by the dsPIC. The parameters of the process being monitored are thus normally initially represented by analogue signals, which have to be converted into digital format for processing. An Analogue to Digital Converter, such as the ADC module embedded in the dsPIC, is responsible for this conversion operation. It employs the concept of successive approximation, which is the fastest and most commonly used technique in analogue to digital conversion [3.13].

When using ADC some parameters have to be considered in order for a process monitoring and control system to be most effective and robust. Those of major importance include resolution, sampling rate, linearity, repeatability and the range of input signals. Resolution is usually expressed by the number of bits used to represent an analogue signal. The greater the number of bits the better the resolution of ADC. For example, the ADC converter available on dsPIC30F6014 has a 12-bit resolution, which provides 4096 levels of representation of the analogue signal. This would mean that the ADC has 0.0012 V/level of full-scale resolution.

Another consideration is the sampling rate, which indicates how often data is read from the ADC and passed along to other application components [3.14]. Nyquist theory states that sampling rate would have to be at least twice the maximum frequency content of the signal to avoid aliasing [3.15]. This is a lower bound and for practical reasons, analogue signals should be sampled at an even higher rate to account for the differences in performance between real-world ADC and the ideal one [3.11]. A higher sampling rate provides a better quality reproduction than a lower sampling rate and should be considered for fast changing signals. In the proposed system, the pressure signal was sampled at 2 kHz, which is five times the highest frequency content (as was empirically determined in preliminary testing).

The integrity of the relationship between the analogue signal and its discrete representation over the full input range is determined by its linearity. The range of input voltages that are supported by the device or analogue channel characterizes input signal range. The smaller the deviation between successive measurements or tests, the better repeatability is. Linearity and repeatability may be affected by changes in operating conditions such as ambient temperature, environmental noise, signal type, etc. [3.16].

The selected dsPIC DSC was recognised as being a solution capable of providing the general data acquisition requirements. The ADC converter, embedded in the dsPIC6014 DSC is briefly reviewed next section.

3.5.2 The 12-bit ADC Module

The ADC module has a 12-bit resolution. This device is limited to one sample-and-hold amplifier, but can sequentially sample up to 16 analogue inputs. At the full supply voltage (5 V), a maximum sampling rate of 100,000 sample-per-second (sps) is possible. This sampling bandwidth, however, is "spread" over all 16 channels, so each channel can sample at a maximum of 6,250 sps, when all channels are used. The designer however must also ensure sufficient time for processing and analysis as required by the application in between successive ADC samples. Figure 3.3 shows a block diagram representation of the 12-bit ADC.

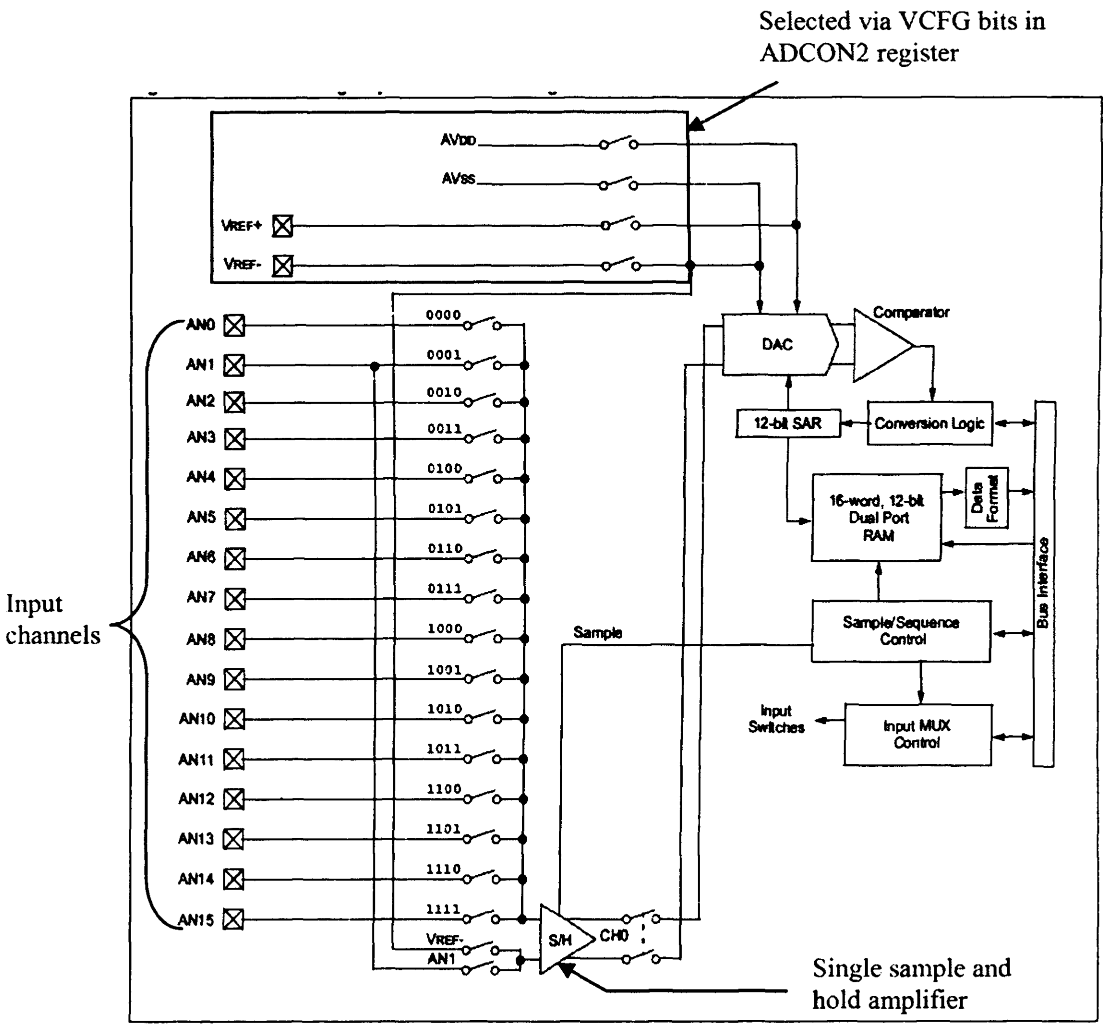


Figure 3.3: The ADC block diagram [3.17].

The analogue reference voltage is software selectable and follows the configuration of VCFG bits in the ADC control register 2 (ADCON2) as shown in Table 3.3. It is easier for the designer to configure ADC for the full range of the supply voltage (AVSS to AVDD) as no external supply need to be facilitated. However, it is sometimes important to limit the reference voltage to the range Vref- to Vref+, for better resolution of measurements. This can significantly improve the ADC's ability to measure limited-range input signals when the conversion is performed only over the voltage range of interest [3.11].

Other major features of the ADC module are listed below [3.17]:

- It has six 16-bit registers for operation control, selection of input channels, input pins configuration as analogue or digital I/O, and selection of which inputs to scan.
- It contains sixteen16-bit read only buffers.
- The ADC can convert an input signal manually (the conversion trigger is under software control) or automatically (conversion trigger is under ADC clock control.
- Other sources of conversion can come from an external interrupt (INT0) or timer 3 (TMR3). The latter was used to trigger conversion during the acquisition of pressure signal while implementing the proposed monitoring systems as discussed in the following chapters.
- Number of samples per interrupt can be set between one and sixteen. In this way, it can scan all 16 channels before an interrupt occurs (multiple settings were used in this research).
- It has the ability to operate while the device is in SLEEP mode with RC oscillator selection (was not used in this research).

ADCON2 register setting of VCFG<2:0> bits	ADC upper reference voltage	ADC lower reference voltage
000	AVDD	AVSS
001	Vref+	AVSS
010	AVDD	Vref-
011	Vref+	Vref-
1xx	AVDD	AVSS

Vref+ = External upper reference voltage
Vref- = External lower reference voltage
AVDD = Analogue positive power rail (5 V)
AVSS = Analogue negative power rail (ground)

Table 3.3: ADC Reference Voltage Configuration Values [3.17].

3.5.3 Digital Signal Acquisition

The term "digital" or "discrete-time" signal refers to a signal defined only at a particular set of instants in time. A simple example would be the midday temperature at a specified place, measured on successive days [3.18]. Digital signals provide information about discrete events in the process or machine like the on/off state of a valve or a limit switch. In many situations it may be necessary, to apply appropriate signal conditioning to a digital signal. In this work it was necessary to make signals TTL compatible (0 to 5 V) so that they may be interfaced with the dsPIC. In the developed system, an operational amplifier was used to adjust the limit switches true voltages to 4.5 V (within the TTL tolerance levels). The Timer 1 module on the dsPIC30F6014 was used to measure for example the time taken by the slide unit in the actuator system to either extend (from the home position to the end position) or retract. More detail is provided in Chapter 5. Polling the input pins to detect the rising/falling state indicates the event to be recorded. The simplest way was to implement the timer as a counter. The 16-bit Timer 1 was used to count the number of instruction cycles consumed between the falling state (off state) of the "home position" sensor and the rising (on state) of the "end position" sensor, according to the following formula:

Travel time = (TMR1* prescaler)/Fcy, where

TMR1 = Timer1 counter value,

Fcy = chip's clock frequency = PLL* oscillator frequency/4,

Permissible values:

PLL = 4, 8 or 16

Prescalar = 1, 8, 64 or 256

At an oscillator frequency of 7.3728 MHz and PLL = 4, Fcy = 7.3728 MIPS. For the 16-bit Timer 1, TMR1 counter can have values between 1 and 65535, and the prescaler was set to 256. These settings were sufficient to cover the complete operation cycle of the actuator, giving a maximum measurable timer period of:

Timer period = (65535*256)/7372800 = 2.275 seconds.

The selected dsPIC has five Timers, two of which can be combined to form a 32-bit counter or timer whenever required, and would provide flexibility for future applications requiring differing periods and/or resolutions.

3.6 Technology Selection for Level 2– Connectivity node

This level in the distributed monitoring system is dedicated to cases where processing and analysis is found to be challenging and may require that information from various FENs, be shared, in order to reach a conclusive decision about the health of monitored parameters. Additionally it has the capabilities and the required facilities such as Ethernet to provide a communication link with the outside world and the server-side PC in particular. Communication between the first and second levels is made possible through a built-in CAN module.

After a survey of commercially available technologies to support the objectivity of this level, the author selected another of the Microchip development boards, namely the dsPICDEM.net platform. This platform can deliver the processing power and communication requirements required by the application. Moreover, the well-established experience and knowledge amongst the IPMM research group with Microchip's hardware and software as well as the resources available "in-house" deemed this platform a sensible option. A brief overview of the supporting factors and a detailed insight into Ethernet connectivity, Internet Protocols and CAN controller are presented in the following sections.

3.6.1 The dsPICDEM.net™— Supporting Elements

The selection of the dsPICDEM.net platform as the second level is supported by many factors. Its hardware schematic diagrams are provided in "Appendix B" for reference. The major features and attributes include [3.19] a powerful device (dsPIC30F6014) with many modules well suited for a wide range of applications. The processing capabilities of dsPIC30F6014 at this level when combined with the functionality and power associated with FENs may eliminate the need for third level in many applications (i.e. processing and analysis at Server level would not normally be required). The availability of a 10BASE-T Ethernet Network Interface Controller (NIC) and connection provides a link between the second level and the internet, thus allowing remote users to interact with the application. It also supports MPLAB ICD2 for device programming and code debugging. It provides the required serial communication capability; RS-232 and CAN. This allowed data transmission to a PC during the initial development of the system and communication with FENs devices. A 7.3728 MHz crystal oscillator is also included. Two analogue potentiometers and LEDs are available on this board and were used during initial testing. The board incorporates a 32 Kbytes EEPROM where constants such as web pages can be stored. It can be programmed via I^2C interface on dsPIC30F6014. A 64 kwords (128 kbyte) data RAM is provided onboard and is accessible via PORTD on the dsPIC30F6014. An LCD screen and a prototyping area are available for the developer to ease the design process.

The dsPICDEM.net development board, shown in Figure 3.4, can act as a stand-alone system, by which a small application can be monitored and controlled via the internet as illustrated in Chapter 7. The dsPIC30F6014 device has all the capabilities to acquire signals and process them, and make decisions about the process. Ethernet connectivity can then be implemented in conjunction with the TCP/IP stack software (provided from Microchip at no cost) to send data to interested remote users (clients). Data can also be transmitted to the server for further analysis as to identify new "unknown" faults if and when they occur. In this case the distributed monitoring system architecture is reduced to two levels.

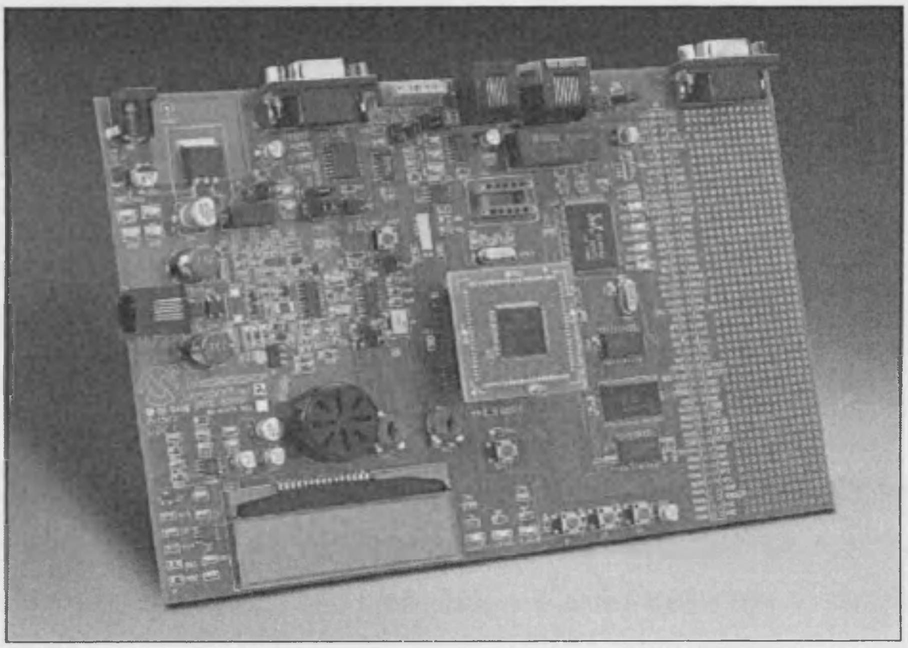


Figure 3.4: The dsPICDEM.net Development Board [3.7].

3.6.2 Ethernet connectivity

The Ethernet is described by [3.20] as "the dominant cabling and low level data delivery technology used in Local Area Networks (LANs), and is more correctly known as the IEEE 802.3 standard. It forms the lower two layers of the Open System Interconnection (OSI) model adopted by the International Standards Organisation (ISO). This model is a 7 layer protocol architecture representing information in a network. Layers and their functionalities are outlined in Table 3.4.

Layer	Name	Function
7	Application	Provides the meaning of data; application services such as file transfer, e-mail, authentication. FTP is an application example that exists entirely in this layer.
6	Presentation	Formats and encrypts data to be sent across a network
5	Session	Control opining and closing of communication paths
4	Transport	Responsible for data transmission and flow control
3	Network	Create logical paths for transmitting data from one node to another
2	Data Link	Provides reliable transfer of data blocks
1	Physical	Decodes data and produces signal levels that drive cables

Table 3.4: The OSI layers and their functions (compiled from [3.21, 3.22]).

There are different rates, at which data can be transmitted using Ethernet. The developer must make sure that it is supported by the cabling of the communication network. For instance, a network built with a twisted-pair cable is supported by 10BASE-T Ethernet, where data is transmitted or received at up to 10 Mbps. The main features and benefits of Ethernet connectivity in embedded applications include [3.20, 3.23, 3.24] its wide deployment, especially the 10BASE-T Ethernet considered in this research. Applications of Ethernet include industrial monitoring and control, security systems, and automation. It is stated that its protocol is easy to understand, implement, manage and maintain. It allows low cost communication network implementation. It also supports a wide array of data types such as TCP/IP, and Apple Talk. Ethernet networks are scalable, thus providing flexibility to system installation. Products that are standards-compliant will operate successfully regardless of manufacturer. The IEEE 802.3 standards ensure reliability mainly in terms of network connection and data transmission. It detects data collisions, when more than one device attempts to send data at the same time, so as preventing loss of information. A device can be monitored or controlled through the Internet once it is connected to an Ethernet network. Moreover, data collection and data sharing are also benefits from deploying Ethernet in embedded applications.

3.6.3 Internet Protocols

There are various Internet protocols, but the most commonly employed protocol today is the Transmission Control Protocol/Internet Protocol (TCP/IP protocol). During the 1970s, the need to share computer resources in a cooperative way led to the development of this software-based protocol [3.25, 3.26]. This protocol is reliable, thus data delivery is guaranteed [27]. Many implementations follow a software structure known as "TCP/IP reference model" in which software is divided into multiple layers stacked on top of each other and each layer accesses services from one or more layers directly bellow it. Microchip developed its own "TCP/IP stack" of programs, that provide services to TCP/IP-based applications such as HTTP and FTP servers, suitable for the deployment of its devices in embedded solutions. It is implemented in a modular fashion. Unlike the reference model, one layer can access services from one or more layers not directly below it as illustrated in Figure 3.4. The Microchip TCP/IP protocol is designed to be independent of operating systems and is capable of cooperative multitasking [3.26]. It is written in the C programming language and is designed to run on the dsPICDEM.net Internet/Ethernet development board. An in-depth discussion about this software is available in application notes AN833 and AN870 on the company's web site. Without getting into further details about the Microchip TCP/IP stack, its implementation with HTTP server may be considered in this research.

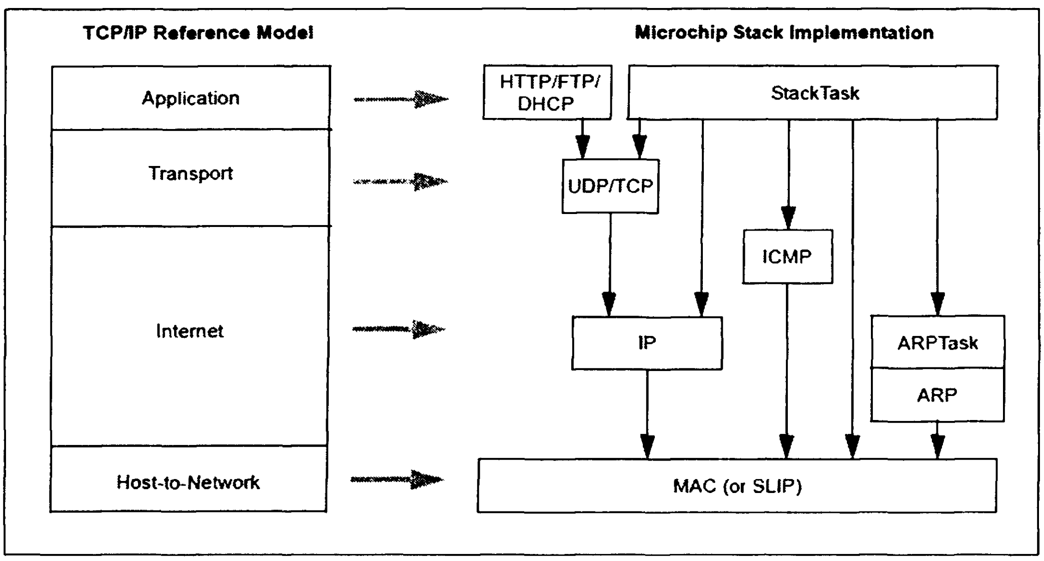
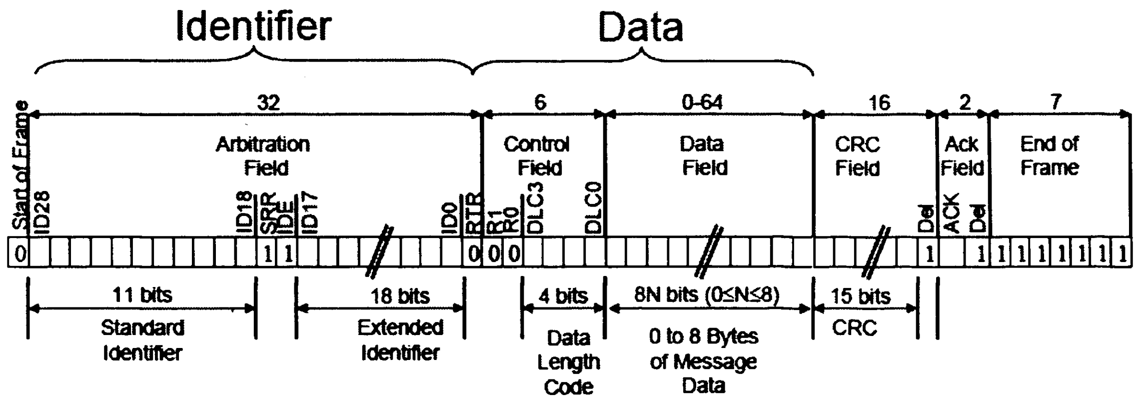


Figure 3.5: Illustration of Microchip TCP/IP stack software [3.26].

3.6.4 Controller Area Network (CAN)

CAN bus networks were initially deployed in automotive applications, requiring predictable and error-free communications. It was used then so that mission-critical real time control systems such as engine management systems and gearbox controls can exchange information [3.28]. Today, it is widely employed as a serial communication network in many application areas, including industrial automation, medical equipments, building services control and facility management. The cost associated with a CAN bus network is low, while providing a robust and simple communication between microcontrollers and peripherals at a bit rate of up to 1 Mbps, depending on the length of the bus (e.g. 1Mbps at 30m maximum). It features a multi-master system, which broadcasts messages to all nodes and each node filter out unwanted messages. Moreover, CAN is message-based, not address-based, thus allowing nodes to be added or removed with minimal software impact. Communication through CAN bus is achieved using message frames that has internal fields to distinguish the frame being sent [3.29]. These frames can either be data, remote, error, or overload. A message consists of several fields including a start bit; a numerical identifier; a Control Field; a Data Field; a Cyclic Redundancy Check (CRC) field; an Acknowledge Field; and End of Frame Field as shown below. The start bit indicates the start of transmission, while the identifier that is either 11bit (standard) or 29bit (extended) describes the meaning of transmitted data to enable all connected nodes to decide whether to use it or to filter it out [3.28]. The Control Field specifies the number of bytes of data contained in the message. Subsequent to the Data Field, the CRC field is sent to ensure that the message is not corrupted, adding extra reliability to CAN protocol. It is then followed by an Acknowledge Field that allows all nodes on the bus to acknowledge receiving the message. The End of Frame Field marks the end of the message being sent and returns the bus to an idle state [3.30].

The dsPIC30F6014 has two integrated CAN modules, therefore, making it a feasible choice for the implementation of the proposed monitoring system.



The built-in CAN controller consists of a protocol engine and a set of buffers. It supports data transfer with built-in hardware error detection, a sophisticated message prioritisation scheme, and has the ability to set filters that allow only messages of interest to be received. CAN module has two receive buffers.

The CAN protocol engine receives all bits of transmitted messages and places them into the Message Assembly Buffer (MAB). Once a message is completely placed into the MAB, its identifier field (specified by the user) is matched against a filter value, in conjunction with a mask value, and if there is a match it's then moved into the corresponding receive buffer. The module will subsequently generate an interrupt and set the receive buffer full (RXFUL) bit, located in a particular receive buffer control register (C1RX0CON). The application software can then clear this bit, indicating that the module has read the buffer and it is ready to receive the next message. There are two receive (or acceptance) filters associated with receive buffer 0 (RXB0), and four associated with receive buffer 1 (RXB1). One mask is also designated for each receive buffer. A block diagram of CAN controller is provided in "Appendix A".

If buffer 0 happens to be full when a message is accepted, it has the capability to store that message in buffer 1, assuming that buffer 1 is available. This feature is enabled by setting the DBEN bit in its control register (C1RX0CON). Additionally, if every bit of received identifier field either matched the corresponding filter bit or was ignored, the message is automatically sent to the appropriate receive buffer, otherwise it is rejected as indicated by the truth Table 3.5 below.

Mask bit n	Filter bit n	Message Identifier bit n	Accept or Reject bit n
0	x	x	Accept
1	0	0	Accept
1	0	1	Reject
1	1	0	Reject
1	1	1	Accept

Table 3.5: CAN Controller Filter/Mask Truth Table.

There are three transmit buffers in the module, only one of which is allowed to send data at any given time. Whenever the module initiates a transmission from a specific buffer, the bits of that buffer are sent to the CAN protocol engine to begin transmission on the bus and perform error checking. In general the user application determines when a message is to be sent. For instance, if the cylinder node in the pneumatic system determines that air pressure is too low, a message may be sent to notify other modules (or nodes) in the system. Once the message is assembled in the transmit buffer, the user application can request its transmission by setting the transmit request bit (TXREQ) in the associated control register (C1TX0CON). If the bus is busy, the module will wait until the bus is idle before attempting the transmission. When the module completes the transmission, it automatically clears the TXREQ bit and generates an interrupt. Only then, can the application software request another transmission. It is possible for all transmit buffers to request transmission, at any time. When the bus is free, the module will then decide the order in which messages are sent based on a user-specified priority level for each buffer. One of four transmit priority levels (0 to 3) can be assigned for each buffer, with 3 being the highest and 0 the lowest, thus providing an additional degree of flexibility to the user application. Meanwhile, if two buffers have the same priority level, their indices will then resolve the issue. In simple terms, buffer 2 (TXB2) is given the highest priority over buffer 0 (TXB0). This mechanism enhances the module capability to ensure that messages are delivered to intended nodes and no message is lost, and hence proving the CAN protocol a more reliable serial network well-suited for monitoring and control applications.

3.7 Summary

The development of a low-cost monitoring system that has adequate capabilities in terms of signal acquisition and processing was essential. The emerging technologies can help make the realisation of such a system a reality. New embedded devices with a high level of integration, processing power, and communication facilities can greatly contribute to the development of a reliable distributed monitoring system. A distributed system based upon the 16-bit dsPIC digital signal controllers was proposed. A general overview of the proposed system was provided along with various aspects in signal acquisition, processing and communication. Communication protocols that are efficient and reliable (e.g. CAN) became a necessity to enable the integration of intelligent devices in such a distributed environment.

Microchip Corporation has developed a TCP/IP protocol designed to ensure optimal performance requirements of the dsPIC devices. This may be implemented in this research, in conjunction with the Ethernet Protocol, to enable access via the internet. In this way, a common interface was established and user applications can therefore be monitored and/or controlled.

The technology supporting the deployment of what was essentially a two-level distributed system to monitor an actuator (or gripper) based upon dsPIC technology has been established in this chapter. To test the applicability and effectiveness of the system, an actuator and a gripper were monitored and several techniques capable of identifying the end of stroke or the size of objects to be gripped were created and implemented. This research will be presented in the following chapters.

References

[3.1] S. Dunn, "Condition Monitoring in the 21st Century", Plant Maintenance Resource Center [WWW]. <URL:http://www.plant-maintenance.com/articles/ ConMon21stCentury.shtml> [Accessed on 20th August 2005].

[3.2] G. Coulouris, J. Dollimore, T. Kinberg, "Distributed Systems- Concepts and Design, 2001, ISBN 0201-619-180.

[3.3] Q. Ahsan, "Compact Information Technology Enabled Systems For Intelligent Process Monitoring", PhD Thesis, Cardiff School of Engineering, Cardiff University, UK, 2006.

[3.4] M. R. Frankowiak, "Intelligent Distributed Process Monitoring and Management Sytem", PhD Thesis, Cardiff School of Engineering, Cardiff University, 2004.

[3.5] Microchip Technology Incorporation, "Microchip WebSeminars- dsPIC digital signal controller", [WWW]. < URL: http://techtrain.microchip.com/webseminars/documents/ dsPICIntro_111204.pdf> [Accessed on 10th January 2005]

[3.6] A. Chandler, "Microchip technology Ships 400,000th Development Tool", The free library [WWW]. <URL:http://www.thefreelibrary.com/Microchip+Technology+Ships+ 400,00 0th+Development+Tool.-a0141165863> [Accessed on 2nd May 2007].

[3.7] Microchip Technology Inc.,"The dsPIC30F Family Overview", 2005, DS70043F.

[3.8] Microchip Technology Inc., "The dsPIC30F6011/6012/6013/6014 Data Sheet", 2004, DS70117E.

[3.9] Microchip Technology Inc., "MPLAB C30 C Compiler User's Guide", 2004. DS51284C.

[3.10] Microchip Technology Inc.," dsPICDEM™ 1.1 Development Board User's Guide", 2005, DS70099B.

[3.11] C. Huddleston, "Intelligent Sensor Design Using the Microchip dsPIC", 2007.,ISBN: 0-7506-7755-4.

[3.12] W. Kester, "Mixed Signal and DSP Design Techniques", [WWW]. <URL: http://www.analog.com/processors/learning/training/ design_techniques.html> [Accessed on 10th May 2005]

[3.13] T. R. Kuphaldt, "Lessons In Electric Circuits, Volume IV-Digital: Successive Approximation ADC", [WWW]. <URL: http://www.allaboutcircuits.com/vol_4/chpt_13/6.html> [Accessed on 7th March 2006].

[3.14] D. Stewart, "Sampling rates for analog sensors", Embedded Systems Design [WWW]. <URL: http://www.embedded.com/story/OEG20030610S0038> [Accessed on 30th June 2006]

[3.15] S. W. Smith, "The Scientist and Engineer's Guide to Digital Signal Processing",1999, ISBN: 0-9660176-6-8.

[3.16] Hyadraulics & Pneumatics, "Pressure Transducers", [WWW].
<URL: http://www.hydraulicspneumatics.com/200/TechZone/
SystemInstrumen/Article/True/6439/TechZone-SystemInstrumen>
[Accessed on 4th April 2007].

[3.17] Microchip Technology Inc., "dsPIC30F Family Reference Manual", 2004, DS70046C.

[3.18] P. Lynn, W. Fuerst, "Introductory Digital Signal Processing with Computer Applications", 2000, ISBN:0-471 97631-8.

[3.19] Microchip Technology Inc., "dsPICDEM.net 1 and dsPICDEM.net 2 Connectivity Development Board User's Guide", 2004, DS51471A.

[3.20] Indiana University website, "University Information Technology Services:What is Ethernet?", [WWW].
<URL: http://kb.iu.edu/data/aesi.html>
[Accessed on 8th May 2007]

[3.21] Webopedia web site, "The 7 Layers of the OSI model", [WWW].
<URL: http://www.webopedia.com/quick_ref/OSI_Layers.asp
[Accessed on 17th May 2007].

[3.22] E. Simon, "Distributed Information Systems",1996, ISBN: 0-07-709076-4.

[3.23] Cisco Systems, "Internetworking Technologies Handbook- Ethernet", [WWW].<URL: http://www.cisco.com/en/US/docs/internetworking/
technology/handbook/Ethernet.html
[Accessed on 5th May 2007]

[3.24] N. Smith-Microchip Technology Inc., "Embedded Ethernet Made Easy", [WWW]. <URL:http://techtrain.microchip.com/webseminars/
ArchivedDetail.aspx?Active=126>
[Accessed on 15th April 2007]

[3.25] A. K. Kochhar, N. D. Burns, "Microprocessors and their Manufacturing Applications", 1983, ISBN: 0-71-313470-4.

[3.26] N. Rajbharti-Microchip Technology Inc., "Microchip TCP/IP Stack Application Note", AN833.

[3.27] Microchip Masters -857 TCP module, 2004, "Connectivity Solutions for the dsPIC30F", [WWW]. <URL:http://techtrain.microchip.com/
masters2004/ (m4klpwnelumu3o3dth10rnqb)/downloads/
classes/857/857.htm>
[Accessed on 7th July 2005].

[3.28] CAN in Automation (CiA), "CAN Protocol", [WWW].
<URL: http://www.can-cia.org/index.php?id=170>
[Accessed on 2nd May 2007]

[3.29] B. C. Baker-Microchip Tech. Inc., "Ease into the Flexible CANbus Network".Analog Design Note (ADN004). [WWW].
<URL: http://ww1.microchip.com/downloads/en/DeviceDoc/
adn004.pdf>
[Accessed on 10th September 2006].

[3.30] Microchip Tech. Inc., "Serial Communication using the dsPIC30F CAN module",[WWW].<URL:http://techtrain.microchip.com/
webseminars/ArchivedDetail.aspx?Active=92>
[Accessed on 25th May 2005].

Chapter 4

A PIPE QUALITY ASSESSMENT TASK

4.1. Introduction

This chapter considers the development of a microcontroller-based system to detect leaks in gas pipes using pressurised air. The intention of this work was to explore the potential of microcontroller-based quality assessment systems in the context of a production environment. The deployed microcontroller based approach acquires and analyses transient data related to the testing by pressurisation of corrugated gas pipes such as the one shown in Figure 4.1. Two techniques for leak identification are implemented and compared. The work clearly identifies the potential of microcontroller based systems as very powerful yet affordable real-time quality management tools.

The identification of leaks can be of the utmost importance in certain manufacturing industries. The presence of leaks in general may be of tremendous concern as they may affect human health and the environment in today's industrial world. Identifying leaks during the manufacturing cycle can lead to flaws and defects arising due to the manufacturing process being identified. The effectiveness of manufacturing plant and processes may thus be assured. This is essential if reliability improvement is being addressed and quality assurance is emphasised [4.1]. It is also essential to assess the integrity of commercial products so that their reliability and quality can be assured.

In general gas leaks can be a significant hazard to human safety, via poisoning and/or explosion. They can also represent the source of higher than required energy consumption and can lead to excessive operating costs. Their effect on the environment can also be enormous. In the application being considered here the leakage of gas from a consumer unit connecting pipe could obviously lead to very dangerous accumulations of gas. For this reason the prevailing requirement in this industry is that 100% quality checks are performed on each component immediately following its manufacture and subsequent to its final installation.

Any component designed to contain or carry a gas may be subject to a manufacturing or material fault causing it to exhibit a leakage problem. Test procedures must therefore be enacted to ensure all manufactured and assembled parts meet the standard set by the industry and the government. These tests may be conducted upon the final installation, or more sensibly, upon the components and or the subassemblies as they are manufactured.

The most common sources of leakage that have been identified [4.2, 4.3] include:

1. Filter/ regulator/lubricator assembly
2. Joints and couplings
3. Control valves
4. Fittings, hoses, and pipes
5. Thread sealants and defects arising during manufacturing processes
6. Pneumatic cylinder and pressure regulator

Many techniques have been introduced in recent years to detect and quantify the rate at which a product leaks [4.4]. Others can also locate leaks. This was evident in the review presented in Chapter 2. They can be either hardware-based or software-based techniques. Some examples of hardware-based methods include acoustic, reflected wave, bubble testing, and sniffing. Volume (or mass) balance, pressure (or flow) deviation, frequency analysis, and pressure point analysis are examples of software-based methods. However, no single method can always meet operational needs in terms of accuracy and cost. For instance, an ultrasonic-based detector can pick up ultrasound signals, usually higher than 19 kHz, generated by gasses escaping through a leak. It can however be affected by surrounding environment due to its high sensitivity. In addition, high flow rate may cause a hissing sound, which could be recognized as leak, leading to false alarms. This is very important consideration in this application. Not every technology has the capability to determine all leaks, every time in all situations [4.5]. A technique may be practical in one situation while impractical in another. Furthermore, most of the technologies available today are either expensive or time consuming. The users must be aware of the capabilities (accuracy, tolerance to environmental conditions) and limitations (response time, allowable pressure, part volume, and leak size) of each leak detection method [4.4, 4.6]. In addition, it is intended that any system produced should be capable of being located within the process manufacturing such parts. Thus the leakage detection system becomes part of the system managing the process.

In the case of the family of corrugated stainless steel gas fittings being tested in this application, leaks are currently detected using two methods; immersion in water or sniffing. In the first method pipes are placed into a tank of water, pressurized and manually inspected to identify any escaping air. This is a cheap but manually intensive system, which presently requires between thirty and sixty seconds to detect leaks. This testing has been incorporated into the operator's working cycle to reduce costs. It can however be subject to human error and may miss some very small leaks; thus the method is restricted to low pressure products which will be tested in situ upon their subsequent assembly into consumer units. This ensures that all resultant systems leaving the factory should reach the 100% quality levels required by their customers.

The current system does not however record failures; all reject products are retained for inspection to identify possible failure modes, but there is a delay between failure and diagnosis that can result in any process or material related problems being allowed to continue to cause quality problems. In addition no trend analysis or in depth investigation relating to the possible cause of a disturbance in the process can be enacted since the rejects are not linked to the acquisition of any process information pertaining to the conditions present at the time of the fault.

In the second, "sniffing" method, more specialised, higher value high pressure pipes are placed into a vacuum chamber and pressurised with a selected gas. Leaks are then detected using a gas spectrometer. This is a more expensive and time consuming activity, with tests taking between one and two minutes. It is however capable of providing 100% accuracy, which is a requirement in the case of these high pressure high value systems. The major concern arising from this type of system is normally related to their capital cost, with each installation costing up to £10k. This test facility should ideally be located next to the production process to support the timely diagnosis of process failings. In this instance the test facility can serve more than one manufacturing cell. Once again the approach adopted requires that the operator who oversees the automatic robotic welding processes takes responsibility for the test procedure. In this way a greater amount of information can be gathered locally regarding the test results, and necessary process adjustments made. However more advanced integrated information management is recognized as being desirable.

To satisfy the needs of this particular installation, and more general manufacturing operations, what is needed is the development of a low-cost, effective and reliable integrated monitoring system. Such a system can be deployed on individual processes and networked to support factory wide quality management. The distributed system outlined in Chapter 3 of this research considers how the system requirements needed to support such activities can be accomplished using the currently available dsPIC Digital Signal Controllers.

4.2. Corrugated Gas Pipe Test-rig Development

The particular corrugated stainless steel flexible pipes used in this experiment were developed for a wide range of applications across the manufacturing spectrum. They are designed to transfer or to contain safety critical gases and their integrity should thus be assessed for quality assurance. The standards sat by the industry and the government in regard to the amount of permissible leakage must be met. The objective of this work is to effectively determine the health of corrugated gas pipes in terms of leak occurrence as fast as possible using pressurised air. The employment of minimal electronics and transducers are emphasised.

To achieve the aforementioned objective, a test rig was designed and constructed. The monitoring method developed is based upon a leak test which considers the pressure response inside the pipe during a rapid pressurization cycle; for speed of response it was determined to base this approach on transient events. The general scheme of the leak detection system is shown in Figure 4.1(a). Its pneumatic circuit diagram is illustrated in Figure 4.1(b). The main components of this system are:

A. An air preparation unit
B. An air receiver model CRVZS-2L (FESTO Ltd., Fleet, UK).
C. A solenoid valve to control the flow of the compressed air.
D. A pressure transducer (BR 3300/1 model, Kobold Instruments Inc., UK) used to monitor air pressure inside the pipe.
E. Gas pipe under test.
F. Microchip's dsPICDEM 1.1 platform containing dsPIC30F6014 Digital Signal Controller (DSC).

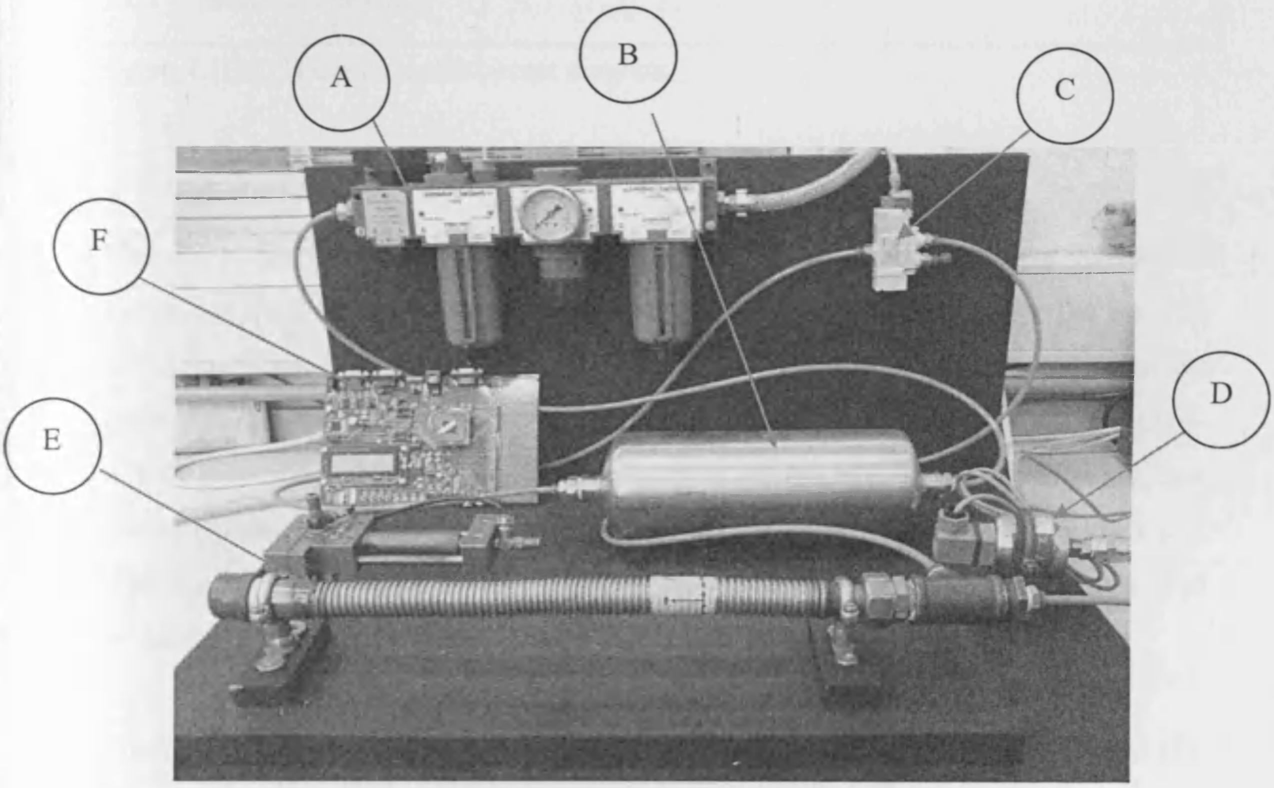


Figure 4.1(a): General scheme of the leak detection system

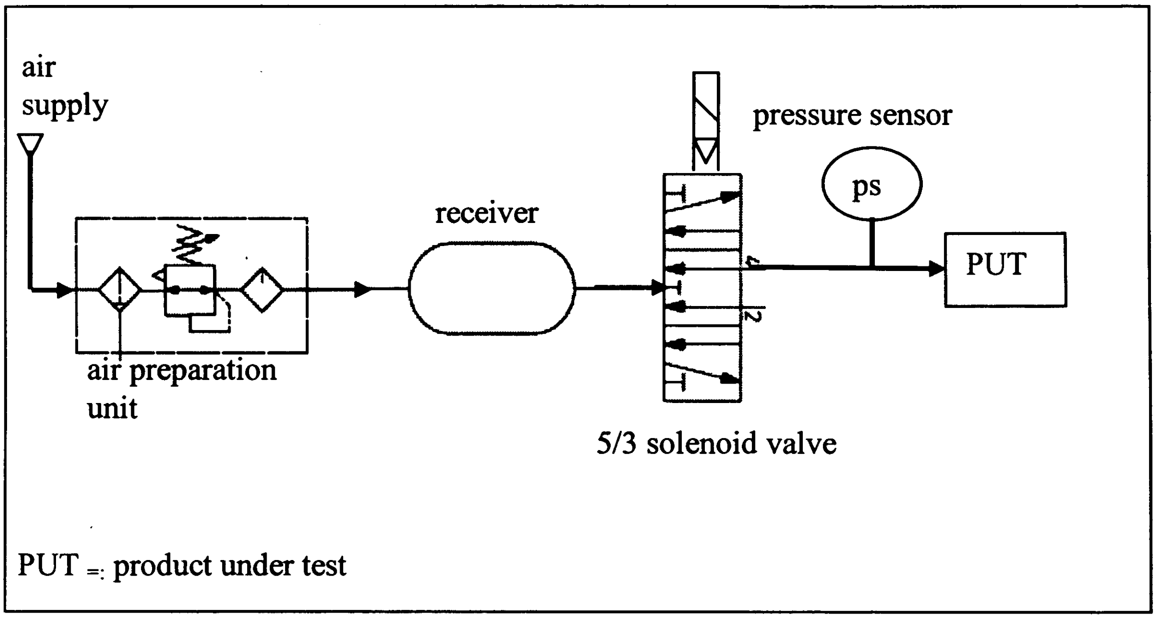


Figure 4.1(b): The pnuematic circuit diagram

The air preparation unit (A) comprises a filter to trap moisture and to remove impurities from the pressurized air; a lubricator to oil the air and hence the valve to avoid stickiness as encountered in preliminary tests; and a regulator to maintain the supply pressure at a constant level. The solenoid valve (C), model SY7120-5LOU-02F-Q (SMC Pneumatics LTD), has a compact design with high flow capacity, low power consumption and long life exceeding 50 million cycles. It is a 3 way- 5 port type but for the purpose of this experiment only two ports (inlet/outlet) were used while the remaining ports were sealed.

The most important part of this test rig is the dsPICDEM1.1 development board (F). Details of this platform along with the dsPIC30F6014 DSC device have been provided in Chapter 3. It is being used as a front-end node (or FEN) in the proposed system.

The pressure transducer (D), model BR 3300/1 from Kobold Instruments Inc., converts the motion of a spring into an electrical signal (a 4-20 mA analogue signal) which is then converted into a voltage in the range 0-5 V by means of an RCV420 current-loop receiver, and subsequently measured by the microcontroller using the internal ADC converter. Fact sheets about the pressure sensor are attached in Appendix E. The output voltage from the current-loop receiver is connected to the ADC converter and the pressure signal is sampled at a rate of 256 samples-per-second. The ADC is configured for one sample per interrupt, and its clock is derived from the system's oscillator. Therefore, data is transmitted as soon as a value becomes available. One of the microcontroller's digital outputs is used for the switch controlling the valve. LEDs on the expansion board are used to represent the status of the valve and to indicate faults to the operator whenever they occur. An electronic switch using an NPN transistor was designed to control the operation of the valve. A diode was connected appropriately across the valve in order to protect both the transistor and the chip from any damage that could be caused by reverse current. The switch is controlled by the dsPIC30F6014 Digital Signal Controller. A 15V DC supply is used to power the solenoid valve.

In this application, the device clock was configured for 7.3728 MHz, yielding 7.3728 MIPS. The SPI2 module is used to send data to the LCD controller, at a rate of 230 kHz generated from the system clock. The output sample from the ADC is scaled for display on an on-board LCD screen. Furthermore, data can be transmitted to a PC at a rate of 19.2 kHz, by implementing the UART2 module. This link allowed Microsoft Excel to be used for off-line data analysis, initially to develop the monitoring system and subsequently to evaluate the effectiveness of the monitoring system in determining the health of the process. MPLAB and an ICD 2 were used for the debugging and programming of the device. A simple control algorithm is implemented in "C" language to perform this testing sequence. If the drop in pressure exceeds a threshold value, an alarm is generated to notify a local operator, and a text message showing the condition of the pipe is displayed.

4.3. Leak Detection Methodology

To develop and test the monitoring system a series of experiments were undertaken by applying four different supply pressures (1.5, 2, 3 and 4 bar) to a known "no leak" pipe. This was to investigate the effect that supply pressure had upon the set-up; the actual testing pressure inside the pipe was restricted to approximately 1 bar to protect the product from over pressurisation. When the pressure inside the pipe reaches 1 bar the valve is closed. This testing sequence was programmed into and enacted by the dsPIC30F6014 DSC.

To simulate faults occurring during manufacturing cycles a series of pipes were drilled with calibrated holes of 0.4, 0.8, and 1.2mm. Diameter confirmation tests were also later conducted on factory supplied "reject" pipes which had been identified as faulty by the industrial standards. The acquired data for each test performed was transmitted to a PC to support the evolution of the fault detection methodologies.

The object of the approach was to determine as quickly as possible the state of the pipe under test. This was aimed, in part, at reaching a conclusion in as short a time as feasible and also at exploring the capabilities of the approach. Of these two aims the second was seen as being more informative; it is anticipated that the approach taken may be deployed to solve quality related problems under many different conditions, including some high speed applications.

Figure 4.2 shows the transient responses acquired for the tests conducted at 1.5 bar for the "no leak" case and for each of the calibrated leak pipes. Similar tests were conducted at 2, 3 and 4 bar and their transient pressure responses are shown in Figures 4.3, 4.4, and 4.5 respectively. This approach was designed to represent situations where the available air pressure may vary. The regulated test pressure however is kept constant.

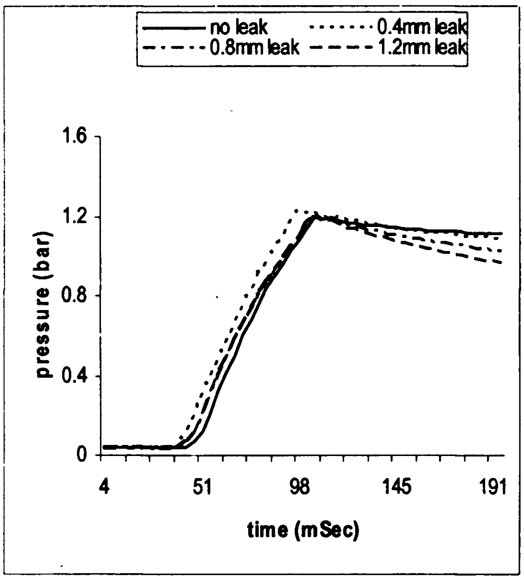


Figure 4.2: Transients of 1.5 bar supply pressure.

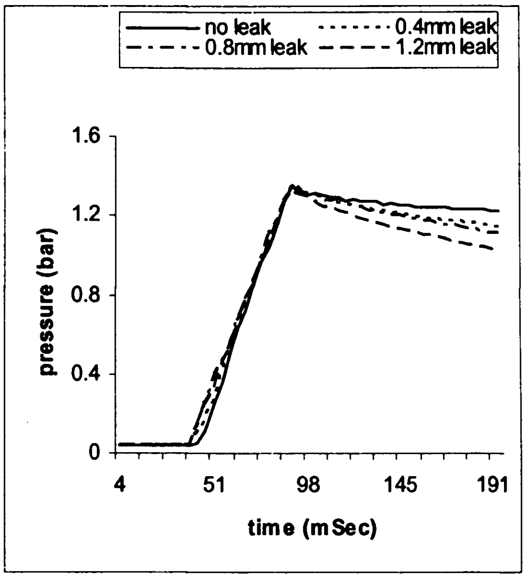


Figure 4.3: Transients of 2 bar supply pressure.

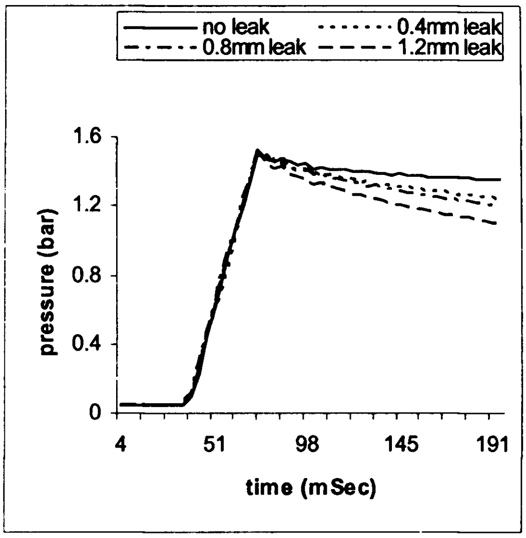


Figure 4.4: Transients of 3 bar supply pressure.

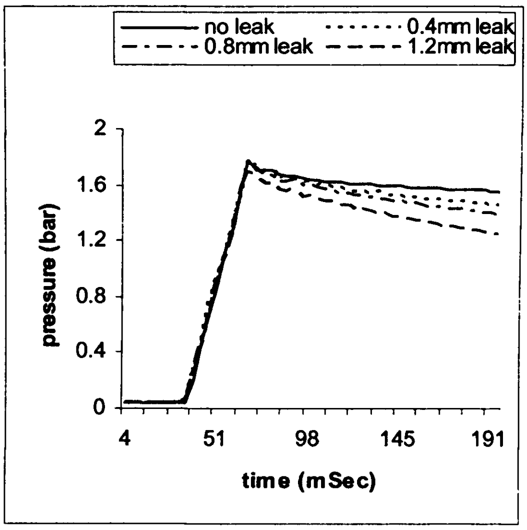


Figure 4.5: Transients of 4 bar supply pressure.

The techniques proposed were intended to identify leaks based upon observing the transient "diagnostic" region of the pressure signal. To illustrate the approach used, a pair of typical pressure transients (for tests using the "no leak" and 1.2mm calibrated leak pipes for a supply pressure of 2 bar) are shown in Figure 4.6. This more detailed figure zooms in on the intended diagnostic region. The initial transient region (approximately 40 to 90 msec in Figure 4.6) can be seen to rise until the pressure in the pipe has reached and exceeded the 1 bar cut-off pressure at which point the solenoid valve was closed and the pressure supply is cut off. There was a delay after this cut-off and any pressure drop-off in the closed system (above a certain rate) could be used to determine the presence of any leaks. The idea was to compare the pressure behaviour in "a good pipe" to those under the influence of leakage without having to analyse the dynamics of the system. The observed delay and increasing pressure phases (whilst control valve open) and the small reduction in pressure with time (post-valve closure) are however consistent with compressible flow into a volume.

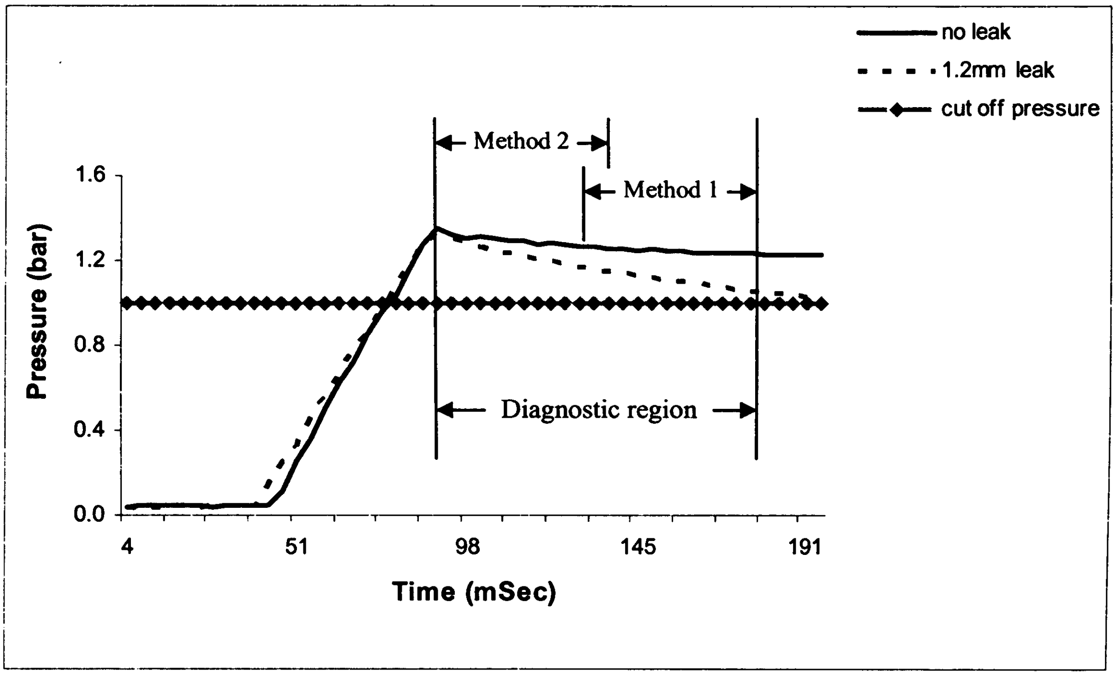


Figure 4.6: A comparison of a pair of transient signals for 2 bar pressure tests.

Thus, the pressure rises to a maximum depending upon the supply pressure and the response time of the solenoid valve. The "no leak" condition is reflected by a slow decay to a level pressure; the leak condition gives rise to a steady fall (to zero if tested for sufficiently long periods) over time. The previously stated aims of this research were to determine how fast and accurately the dsPIC microcontroller could be programmed to detect leaks. In so doing it was intended that the efficacy of deploying dsPIC based monitoring systems should also be demonstrated. The underlying procedure was implemented in two ways:

- Method 1 developed using a pressure drop-based approach, and
- Method 2 a curve fitting-based approach.

4.3.1 Method 1: A pressure drop-based approach

In order to develop a diagnostic tool the acquired data was initially analyzed using Microsoft Excel. Before observing the difference in pressure values measured immediately after the peak value, it was found to be necessary to allow time for the transient itself to stabilize. To avoid the possibility of generating false alarms due to the noisy variations arising around the peak, a compromise was made between speed and accuracy in detecting leaks. The tenth sample from the peak, as shown in Figure 4.6, was empirically determined to be suitable as the high value from which the pressure drop can be measured over time. Method 1 was therefore started following this period of ten samples, which represents a delay of some 0.04 seconds, and the pressure drop parameter used was simply obtained by subtracting the on-going pressure values from the pressure value recorded at sample 10 post-peak.

This modified set of data based was generated using a simple algorithm programmed, using the "C" language, into the microcontroller. Using this approach data samples were acquired and the difference between the tenth sample and the current sample was measured progressively to create new set of data. Figure 4.7 shows an example of a set of modified data produced for various supply pressures applied to a known "good" pipe and a pipe with a 0.4mm leakage. The data shown also indicates the determinations made of the repeatabilities of the results at the 2 different conditions. Similar results, and clear separations of trends, were obtained for the other test conditions used.

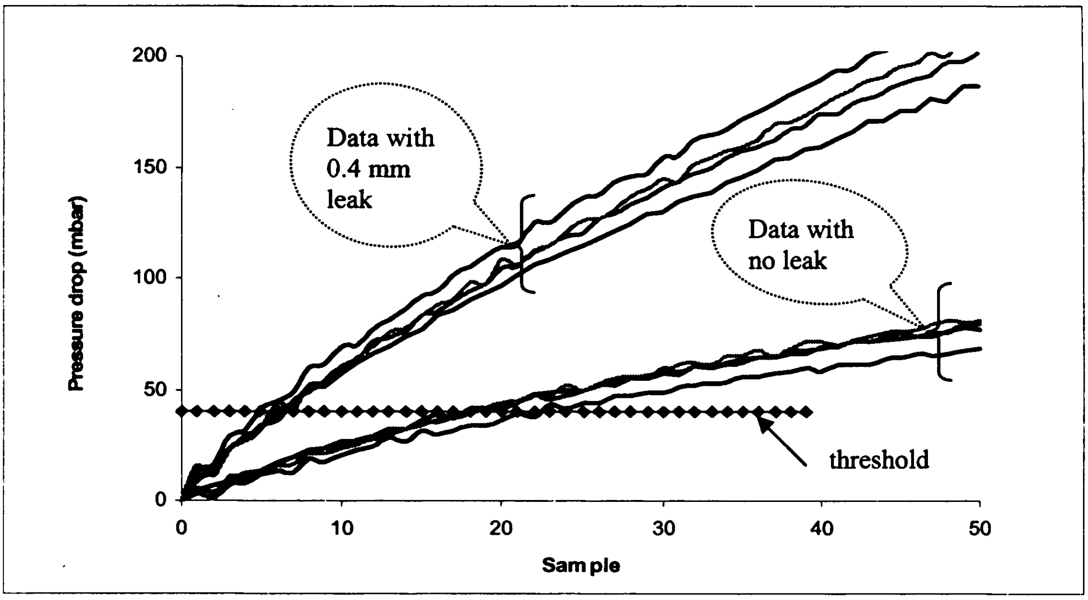


Figure 4.7: Modified transient data analysis.

The particular case shown in Figure 4.7 was selected since it represents the situation arising for the most challenging diagnosis conditions; various supply pressures (1.5, 2, 3, and 4 bar) combined with the smallest leak (0.4mm). The Figure shows a threshold projection established for and applied to all of the different pressures used in these experiments. This threshold was determined empirically, and was selected to enable the clear separation between "healthy" and "leaking" pipes. It was determined that, using this threshold, the shortest threshold crossing period arising for pipes without leaks was fourteen samples (i.e. 24 samples post-peak) assuming no change in environmental conditions (ambient temperature in particular). To evaluate the health of the pipes it then becomes necessary to compute the pressure drop for the first fourteen samples following the tenth sample after the peak amplitude. If the set threshold was not crossed within this period a "good" pipe result was confirmed.

To test this approach a large number of experiments were performed for different configurations and the results all gave positive identifications; no healthy pipe was diagnosed as leaking and any leaking pipe condition was detected. Results of these tests are summarized in Table 4.1.

Pressure ↓ (bar)	Condition of the pipe			
	No leak	0.4mm leak	0.8mm leak	1.2 mm leak
1.5	identified	detected	detected	detected
2	identified	detected	detected	detected
3	identified	detected	detected	detected
4	identified	detected	detected	detected

Table 4.1: Results of the pressure drop-based method.

This work indicated that the microcontroller deployed could acquire, process and compare data quickly; no test result took longer than 200 milliseconds. As a consequence of this it was clearly demonstrated that a simple but effective method of fault detection could reliably be deployed using the dsPIC30F6014 based approach in conjunction with the dsPICDEM 1.1 development board. The conditions of the pipes under test were reflected on the LCD display and LEDs present the status of the solenoid valve and indicate the presence of leak if occurred for the operator. To further prove the applicability of a microcontroller in the context of automatic testing a more computationally challenging data modelling and analysis method was also developed and is described in the following section.

4.3.2 Modelling of Transient Response

Following an examination of the transient pressures arising for a range of test conditions, it was clear that the presence of a leak changed the nature of the data. It was thus decided to attempt to model these changes, in order that a more sophisticated leak detection process could be enacted on the dsPIC. Using a "least-squares" methodology, the transients of the pressure samples acquired under different configurations were modelled using a PC based data analysis tool. The modelling was done by dividing the response into three segments as shown in Figure 4.8.

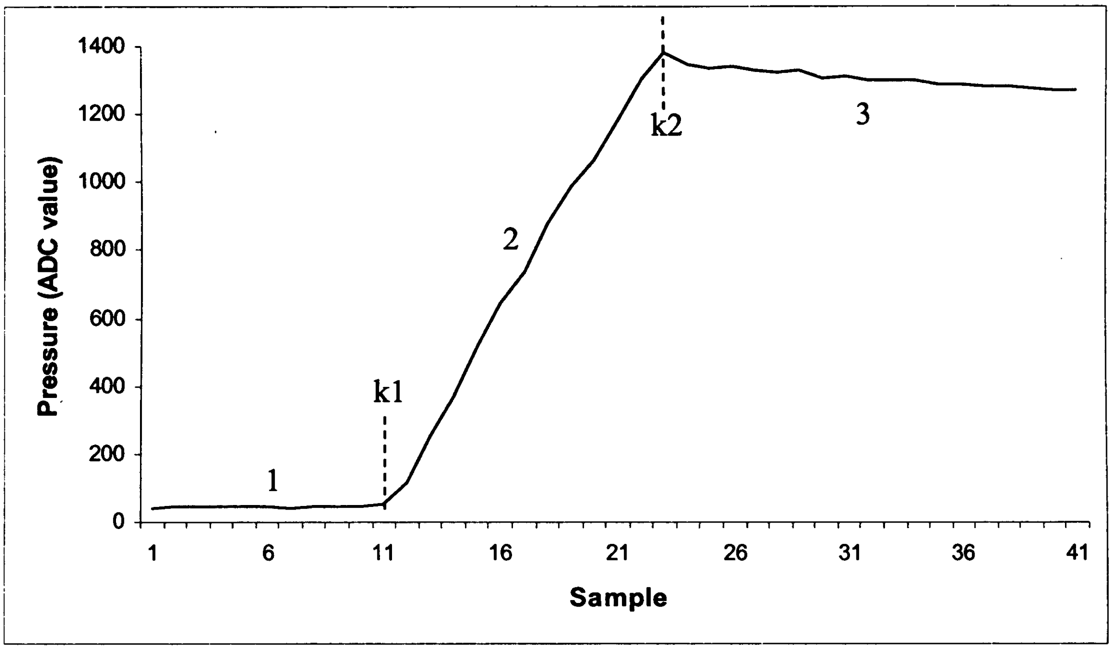


Figure 4.8: Modelling procedure of pressure response.

In this approach different equations are to be fitted into three portions of the data as described below. It should be noted that this modelling method was carried out only on the first 51 samples of the pressure behaviour inside the pipes for each supply pressure. Segment 3 is equivalent to the range shown on Figure 4.6 for "method 2". The aim previously set was to develop an algorithm based on the best possible fit of the response so that the health of the pipes under test can be determined in as short a time as possible. The pressure signal was sampled at 256 Hz.

Segment 1:

This portion of observed data can be described by a constant which varies slightly in amplitude and duration depending upon the applied pressure and the health of the pipe. That is, pressure inside the pipe

$$P_k = \text{Constant} \qquad \text{for} \quad 1 \leq k < k1$$

Segment 2:

Attempts were made to fit the second portion of data to various models. It was then found to be adequately modelled by a quadratic equation of the form

$$P_k = a.(k-k1)^2 + b.(k-k1) + c \qquad \text{for} \quad k1 \leq k \leq k2$$

Segment 3:

This portion of observed data can be best predicted by an exponential equation. Hence,

$$P_k = m.(k-k2)^{\alpha} e^{-\beta(k-k2)} \qquad \text{for} \quad k > k2$$

The modelling software provided a good indication of what type of formula was best suited for the expression of pressure behaviour inside the pipe under different operational conditions. Microsoft Excel was then used to tune the parameters a, b, c, m, α, and β in order to achieve the best possible curve fitting using which the sum-squared error ($\varepsilon = \sum$ [data-model]^2) is minimised. To illustrate this approach the generated models of the pressure responses for the 1.5 bar applied pressure tests are shown along with the measured values in Figures 4.9 through 4.12 respectively.

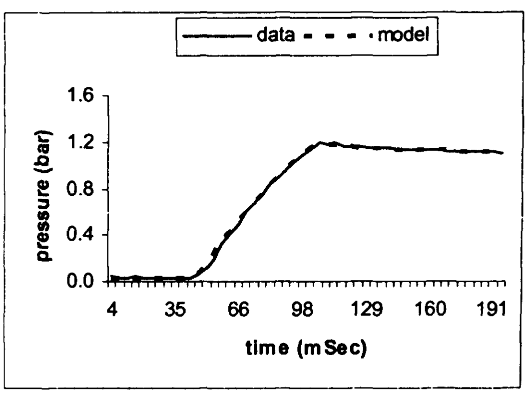


Figure 4.9: model of 1.5 bar without leak

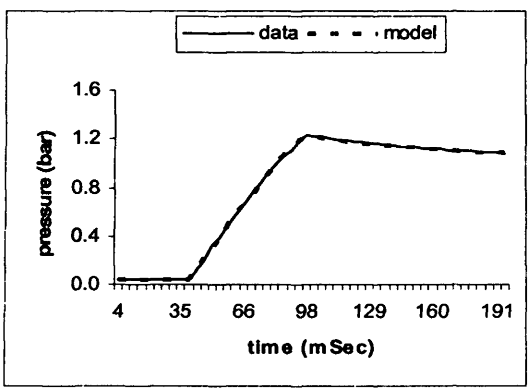


Figure 4.10: model of 1.5 bar with a 0.4mm leak

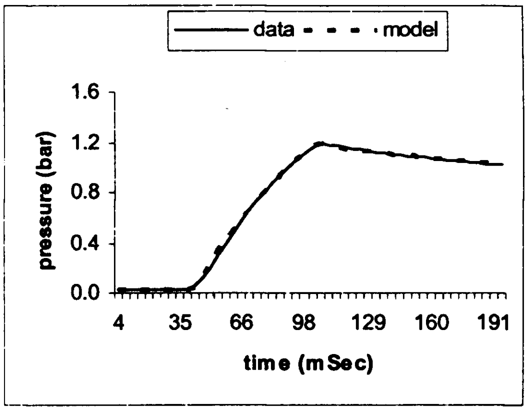


Figure 4.11: model of 1.5 bar
with a 0.8mm leak

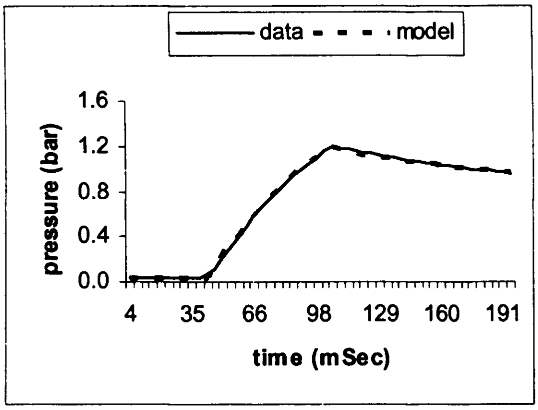


Figure 4.12: model of 1.5 bar
with a 1.2mm leak

The mathematical representations produced for each of the three segments using the modelling approach outlined above are shown in Table 4.2. Figures similar to those shown in 4.9 to 4.12 were produced for test pressures of 2, 3 and 4 bar. These Figures are included in Appendix B, and clearly illustrate that the developed technique can reliably model the responses occurring under each experimental set-up.

Leak (mm)	Equations		Parameters
Nil	$p_k = 38$ $= a.(k-12)^2 + b.(k-12)+c$ $= m.(k-26)^{\alpha}\, e^{-\beta(k-26)}$	for $1 \le k \le 11$ $12 \le k \le 26$ $k \ge 27$	$a = -1.5$, $b = 100$, $c = 65$, $m = 1230$, $\alpha = -0.02$, $\beta = 0.00045$
0.4	$p_k = 40$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-25)^{\alpha}\, e^{-\beta(k-25)}$	for $1 \le k \le 10$ $11 \le k \le 24$ $k \ge 25$	$a = -1.16$, $b = 100$, $c = 112$, $m = 1270$, $\alpha = -0.02$, $\beta = 0.0027$
0.8	$p_k = 37$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-26)^{\alpha}\, e^{-\beta(k-26)}$	for $1 \le k \le 10$ $11 \le k \le 26$ $k \ge 27$	$a = -1.55$, $b = 99$, $c = 49$, $m = 1230$, $\alpha = -0.02$, $\beta = 0.0035$
1.2	$p_k = 36$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-26)^{\alpha}\, e^{-\beta(k-26)}$	for $1 \le k \le 10$ $11 \le k \le 26$ $k \ge 27$	$a = -1.72$, $b = 102$, $c = 40$, $m = 1230$, $\alpha = -0.02$, $\beta = 0.0061$

Table 4.2: Models' equations describing transients of 1.5 bar.

For the experiments performed when 2 bar is applied to the system, the pressure responses and their corresponding models can be seen in Table 4.3.

Leak (mm)	Equations		Parameters
Nil	$p_k = 44$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-22)^{\alpha}\, e^{-\beta(k-22)}$	for $1 \le k \le 10$ $11 \le k \le 22$ $k \ge 23$	$a = -0.24, b = 117,$ $c = 45, m = 1384,$ $\alpha = -0.02, \beta = 0.0014$
0.4	$p_k = 42$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-22)^{\alpha}\, e^{-\beta(k-22)}$	for $1 \le k \le 10$ $11 \le k \le 22$ $k \ge 23$	$a = 0, b = 108,$ $c = 108, m = 1384,$ $\alpha = -0.02, \beta = 0.0039$
0.8	$p_k = 44$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-22)^{\alpha}\, e^{-\beta(k-22)}$	for $1 \le k \le 10$ $11 \le k \le 22$ $k \ge 23$	$a = -1.55, b = 125,$ $c = 117, m = 1400,$ $\alpha = -0.02, \beta = 0.0052$
1.2	$p_k = 43$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-22)^{\alpha}\, e^{-\beta(k-22)}$	for $1 \le k \le 10$ $11 \le k \le 22$ $k \ge 23$	$a = -1.6, b = 123,$ $c = 120, m = 1370,$ $\alpha = -0.02, \beta = 0.0075$

Table 4.3: Models' equations describing transients of 2 bar.

Models of the responses of 3 and 4 bar applied pressures are detailed in Tables 4.4 and 4.5.

Leak (mm)	Equations		Parameters
Nil	$p_k = 48$ $= a.(k-10)^2 + b.(k-10)+c$ $= m.(k-18)^{\alpha}\, e^{-\beta(k-18)}$	for $1 \le k \le 9$ $10 \le k \le 18$ $k \ge 19$	$a = 0, b = 162,$ $c = 100, m = 1545,$ $\alpha = -0.02, \beta = 0.0014$
0.4	$p_k = 45$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-22)^{\alpha}\, e^{-\beta(k-22)}$	for $1 \le k \le 10$ $11 \le k \le 22$ $k \ge 23$	$a = 1.11, b = 153,$ $c = 90, m = 1546,$ $\alpha = -0.02, \beta = 0.0045$
0.8	$p_k = 44$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-22)^{\alpha}\, e^{-\beta(k-22)}$	for $1 \le k \le 10$ $11 \le k \le 22$ $k \ge 23$	$a = 0, b = 162,$ $c = 133, m = 1564,$ $\alpha = -0.02, \beta = 0.0061$
1.2	$p_k = 44$ $= a.(k-11)^2 + b.(k-11)+c$ $= m.(k-22)^{\alpha}\, e^{-\beta(k-22)}$	for $1 \le k \le 10$ $11 \le k \le 22$ $k \ge 23$	$a = 0, b = 159,$ $c = 107, m = 1531,$ $\alpha = -0.02, \beta = 0.0083$

Table 4.4: Models' equations describing transients of 3 bar

Leak (mm)	Equations		Parameters
Nil	$p_k = 46$ $= a.(k-10)^2 + b.(k-10) + c$ $= m.(k-16)^{\alpha} e^{-\beta(k-16)}$	for $1 \le k \le 9$ $10 \le k \le 16$ $k \ge 17$	$a = 0$, $b = 240$, $c = 202$, $m = 1810$, $\alpha = -0.027$, $\beta = 0.0015$
0.4	$p_k = 45$ $= a.(k-9)^2 + b.(k-9) + c$ $= m.(k-16)^{\alpha} e^{-\beta(k-16)}$	for $1 \le k \le 8$ $9 \le k \le 16$ $k \ge 17$	$a = 0$, $b = 214$, $c = 80$, $m = 1815$, $\alpha = -0.02$, $\beta = 0.0045$
0.8	$p_k = 45$ $= a.(k-9)^2 + b.(k-9) + c$ $= m.(k-16)^{\alpha} e^{-\beta(k-16)}$	for $1 \le k \le 8$ $9 \le k \le 16$ $k \ge 17$	$a = 0$, $b = 215$, $c = 58$, $m = 1805$, $\alpha = -0.02$, $\beta = 0.0057$
1.2	$p_k = 45$ $= a.(k-10)^2 + b.(k-10) + c$ $= m.(k-16)^{\alpha} e^{-\beta(k-16)}$	for $1 \le k \le 9$ $10 \le k \le 16$ $k \ge 17$	$a = 0$, $b = 218$, $c = 241$, $m = 1740$, $\alpha = -0.02$, $\beta = 0.0076$

Table 4.5: Models' equations describing transients of 4 bar.

The models produced in this approach can be used to accurately represent the transient responses occurring at the different pressures. However, in the context of the wider aims of this research, they were perceived as being too detailed; it is evident that the models are very sensitive to test pressure. In the context of the flexibility required in the approach being developed this was seen as being perhaps a limitation to its application in an industrial environment where fluctuations in supply pressure may arise.

It became apparent that sufficiently accurate curve fitting could be achieved using samples of the transient response following the peak. In this way the model algorithm is simplified but the efficacy of the method is maintained, thus achieving the objective of this work.

From the peak sample, the pressure transient could be represented by an equation of the following form:

$$P_k = m.k^{\alpha} e^{-\beta.k} \qquad (1)$$

Where P_k is the sampled pressure signal,

m = peak amplitude and

k = sample number.

This is a more adaptable approach which can be used to facilitate the speedy diagnosis of the leak for different pressure applied to the process at different configurations. The resulting method was developed based upon keeping the value of "α" constant throughout the modelling process, whilst adjusting the decay rate "β". This can then be used as a measure for leak detection by observing the pattern discrepancy between modelled and measured transient values.

Taking natural logarithm of both sides in and rearranging equation (1) gave:

$$\beta = \frac{\ln(m) - 0.02\ln(k) - \ln\left(P_k\right)}{k} \tag{2}$$

It was determined experimentally that after setting α = -0.02, the values of "β" could be tuned in order to achieve the best fit for the above model as close to the peak sample as possible to identify the pipe condition as fast as possible. The resulting methodology is actually based upon acquiring and analysing eleven samples after the peak, as indicated in Figure 4.6. This means that k = 12 in equation (2) where P_k is the corresponding sampled pressure value (or P_{12}). It was decided to initially consider the modelling of "no leak" situations for the development and implementation of this technique. The values of "β" for different pressures assuming no leaks were then determined. These are shown as the "pre-set" values in Table 4.6. An attempt was made to establish the relation between the decay rate and supply pressure as shown in Figure 4.13. This allows the distinction between the no leak situations and the leaking ones, but can not quantify the leak. An equation illustrating the changes in β with respect to supply pressure for the non leaking pipe was obtained. It was found to have the form;

$$\beta = 0.0006p^3 - 0.0047p^2 + 0.0127p - 0.01 \tag{3}$$

where p is the supply pressure in bar.

It is possible to apply any pressure in the range 1.5 to 4 bar to inspect the integrity of pipes, but performed tests to validate Method 2 were limited to those pressure levels listed in the table.

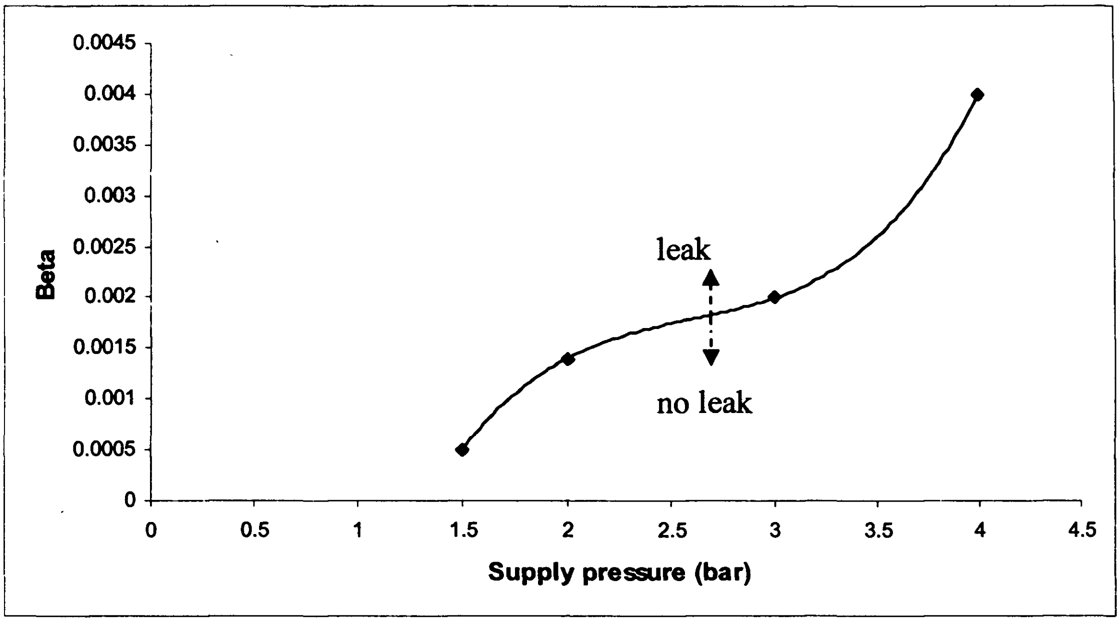


Figure 4.13: Changes in decay rate at no leak situations.

		Pipe Condition			
Supply Pressure (bar)	Pre-set β value	No leak	0.4mm leak	0.8mm leak	1.2 mm leak
1.5	0.00005	identified	detected	detected	detected
2	0.0014	identified	detected	detected	detected
3	0.002	identified	detected	detected	detected
4	0.0042	identified	detected	detected	detected

Table 4.6 Results of deploying the modified modelling method.

Equation (3) may be used to calculate the pre-set threshold (for no leak situations) at any given supply pressure. The method proposes that, by comparing the calculated value of "β" using equation (2) to the pre-set "no-leak" threshold value, a decision can be made about the condition of the pipe. The implementation of this technique was limited here to the simple detection of leaks. The limited number of data points precluded its implementation to determine leak size. This was because it was extremely difficult to drill wide range of holes of such small sizes. It can however be proposed that this approach may be extended to include the capability required to determine the size of the leak.

Taking all models into consideration and applying the same methodology adopted here, the values of "β" for a speedy diagnosis are determined and plotted against the leak size as shown in Figure 4.14. It can be seen that data points of leak size with respect to decay rate (or β) at each pressure supplied to the system are scattered and do not provide clear indication of their relationship. The obtained data are not adequately sufficient to draw a precise conclusion of how one affects the other.

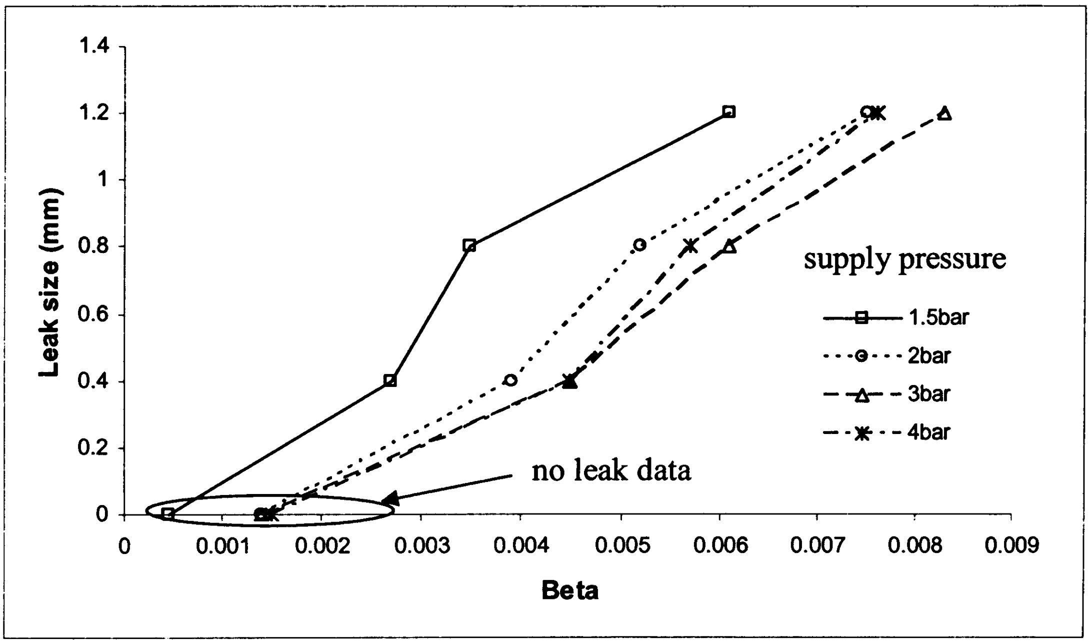


Figure 4.14: Relationship of β with leak size for all supplied pressures.

The transient pressure traces produced by the model for each test pressure can be included within the memory of the dsPIC as a "look up table". The actual pressure values can then be compared against those values predicted by the model, associated with a given supply pressure, stored in the microcontroller memory. For instance, if 2 bar supply pressure is used to test the pipes for leak, the values generated by the associated model at no leak are evoked to see whether they match the actual traces or not. A match indicates the non-existence of leak. The only requirement is to configure the monitoring system for 2 bar applied pressure. However, to facilitate the speedy diagnosis of a leak, this approach was evolved. The modelling technique was transferred onto the microcontroller using MPLAB C30 "C" programming compiler. Once the method was deployed on the dsPIC, pipes were tested at different pressures, and results are summarized in Table 4.6. In implementing this approach it was determined that the method was shown to be capable of detecting leaks faster than the previous one; the response time was found to be less than 150 milliseconds

4.4 Discussion and Conclusion

In this chapter, two techniques for leak detection in corrugated gas pipes, based upon the transient analysis of pressure signals have been developed and tested. Experimental tests were conducted on calibrated pipes for various pressure and leakage configurations. To validate the proposed leak detection techniques, gas pipes identified as faulty by tests undertaken to industrial standards were also been installed into the rig and tests were performed. Eight rejected pipes were tested using both methods. These pipes were tested at 3 bar and their transient responses are shown in Figure 4.15. The outcome of these tests was found to be satisfactory. An example set of result to tests carried out on a rejected pipe is shown in Table 4.7. Method 1 was examined for supply pressures ranging from 1.5 to 4 bar, while Method 2 is tested at the modelled pressures supplied to the system during the initial development of the monitoring techniques (i.e. 1.5, 2, 3 and 4 bar). If an accurate relationship between "β" and leak size was possible to obtain as shown otherwise in Figure 4.14 above, a surface model governing pressure, decay rate and leak size can then be derived. Only then the method can be used to quantify the leak size. Both Methods can be validated over a wide range of testing pressure, providing the user the flexibility to choose supply pressure as required or based on what is available on the shopfloor. The main feature of the system is its fast response time. The condition of the pipe could be determined in 0.20 seconds using Method 1 and in less than 0.15 seconds using Method 2. There is thus practically no difference between the two methods. In fact the flexibility of the dsPIC implementation is such that both methods can be deployed and an "agreed" conclusion reached. A customized leak detection system can be made in which the dsPIC30F6014 device has two functionalities: one is based on pressure drop; the other is based on decay rate. The LCD display provides information to local operator (health of the pipes and detection time) and facilitate a user interface so that the system can be configured for supply pressure, pressure drop and decay rate thresholds. The on-board switches are used to select the method to perform.

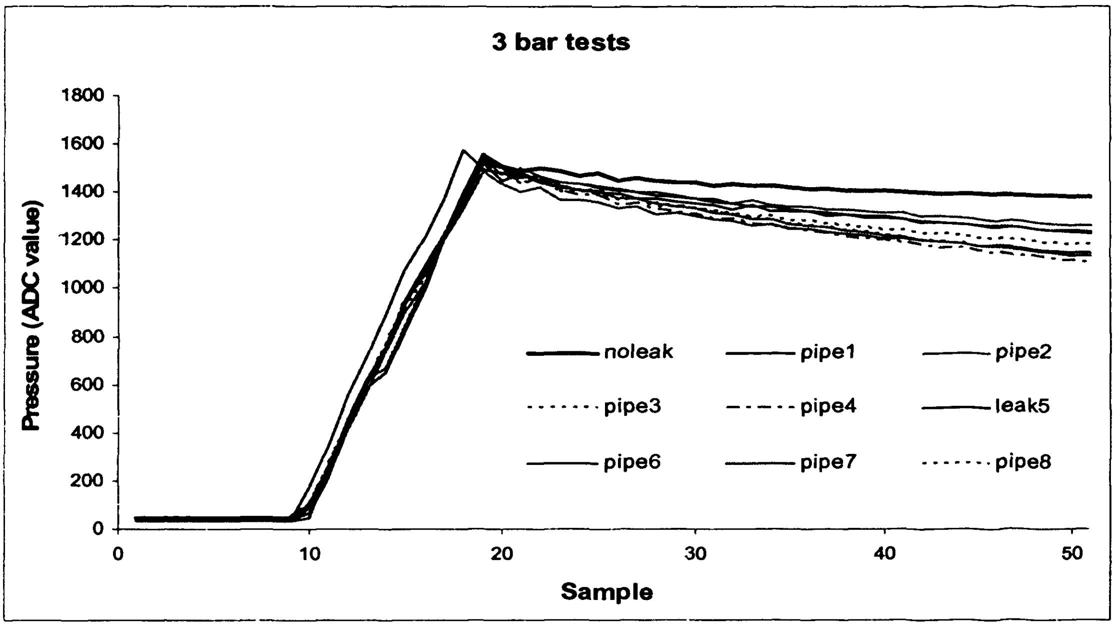


Figure 4.15: Pressure transients for rejected pipes tested at 3 bar.

Method 1

Pressure (bar)	Fault	Detection time (msec)
1.5	detected	199
2	detected	180
2.5	detected	172
3	detected	164
3.5	detected	160
4	detected	156

Method 2

Pressure (bar)	Fault	Detection time (msec)
1.5	detected	148.4
2	detected	132.8
3	detected	117.2
4	detected	109.4

Table 4.7 Comparison of the two developed pipe testing methods.

In this way a synergy of effort is afforded; if both methods indicate a leak then it is certain that there is one. The pipe leak test may then be halted, saving time and resources. It should be noted that strict testing procedures may be applied to such products. It is not intended that the method developed here should replace such tests; the aim was to stop the test if a leak was present, on the basis that it is pointless completing what may be a time consuming and expensive test if the pipe has a leak. If both methods indicate that there is no leak then the test can be allowed to run for a complete cycle as required by any associated testing procedure and or standards. Such procedures and standards may of course be modified over time to recognise the efficacy of this test as confidence in this method grows. Should the methods not agree, then again a full cycle test may be required to reach an accurate conclusion. The effect of this is that no expensive test, such as one that may use the detection of a leakage of a known gas, is undertaken on a component or assembly that has no realistic chance of passing it.

The proposed techniques, together with dsPIC platform, can thus provide a simple, economical and effective solution for detection of leaks. This research has shown much more than this however; it has demonstrated that microcontrollers, particularly the current range of dsPIC devices, have a potentially important role to play in the context of quality management systems. In this application the device acts as an autonomous fault diagnosis system. Once primed with a pipe for testing, the dsPIC initiates and controls the pressurisation process, activates the solenoid at the required test pressure, acquires and processes data, identifies the occurrence of a peak value (the trigger for the two analysis methods) and completes the test analysis. This is achieved using the analogue and digital input and digital output facilities built into the dsPIC.

When required the microcontroller can communicate with other devices in the front-end-nodes (FENs) and/or more powerful computer resources. Thus the developed system can operate either alone or in collaboration with similar systems to assess product quality and quantity, levels of faults and be used to identify failures and possible trends in manufacturing processes [4.7]. By integrating systems assessing product quality with those monitoring the process, using the architecture described in Chapter 3, it becomes feasible to have complete access all of the information needed for effective process management. The design of each dsPIC based "node" can be matched against the monitoring and control requirements associated with its function. The number of such nodes can be varied depending upon the application being considered. Thus a truly flexible and integrated system can be deployed.

Similar systems have been developed based upon the deployment of 8 bit PIC microcontrollers. Their only shortcoming lay in the relative lack of processing power. The evolution of these devices into the much more powerful range of dsPIC microcontrollers used in this work promises to be the basis of a major step forward in automatic testing and monitoring. The adaptability and effectiveness of such an approach can thus form the basis of the next generation of quality assessment methodologies.

It is intended that in the future the deployed system can become the front end of a productive maintenance approach, under which potential process failures can be predicted and prevented. Thus the leakage detection system becomes part of the system managing the process; the faulty operation of say the robot welding station which is leading to the production of reject parts can be detected in time to prevent the manufacture of further products until the problem is removed. Local operators can be notified to take the necessary actions and/or data could be communicated via Ethernet, as suggested by the system proposed in Chapter 3, to a higher supervisory level for further fault analysis. In this way the leakage detection system can become part of an internet-enabled process monitoring and management system. This can lead to improved component reliability and reduced downtimes, thus maximizing system performance and throughput.

References

[4.1] S. Dunn, "Condition Monitoring in the 21st Century". Plant Maintenance Resource Center [www],<URL: http://www.plant-maintenance.com/articles/ConMon21stCentury.shtml> [Accessed on 20th Aug 2005].

[4.2] "Compressed Air System Leaks", [www]. <URL: http://www.plantsupport.com/download/CompAirSysLeaks.pdf> [Accessed on 28th Dec 2005].

[4.3] SDT North America Inc., "Industrial Compressed Air Ultrasonic Leak Detection Survey Guide", [www], <URL:http://www.sdtnorthamerica.com/PDFs/Leak_Survey_Handbook.pdf> [Accessed 15 Nov 2005].

[4.4] Future Technologies, Inc., "Production Leak Detection Systems", [www], <URL: http://www.futuretechnologies.com/leak_testing.htm> [Accessed on 18th June 2005]

[4.5] P. Tashian, "Successful Leak Detection using Ultrasonics", [www], <URL: http://www.superiorsignal.com/usndacr.pdf> [Accessed on 14th Oct 2005].

[4.6] Forward Technology, "Leak & Burst Testers", [www]. <URL: http://www.forwardtech.com/PlasticAssembly/Testers/> [Accessed on 3rd June 2006].

[4.7] D.R Eyers, R.I Grosvenor, and P.W. Prickett (2005) "Welding station condition Monitoring using Bluetooth enabled sensors and intelligent data management", Sensors & their applications XIII, IOP, University of Greenwich, September 2005, pp 143-148.

Chapter 5
MONITORING OF A LINEAR ACTUATOR

5.1 Introduction

Pneumatic systems retain a dominant and important role in the field of automation for a number of reasons. They provide; low cost-to-benefit ratio, high power-to-weight ratio, fast speed of operation and are easy to maintain. Since air is the energy source, pneumatic systems provide a clean and safe environment when compared to hydraulic and electric systems [5.1]. A pneumatic or compressed air system can either be oil-free or lubricated, depending on air purification and industry requirements. The application dictates whether or not a lubricant is to be used. Oil-free applications require that oil aerosols (generated by the compressor), vapours, and moisture are removed since the oil can carbonize and form a solid substance causing air devices to malfunction [5.2]. Lubricated systems on the other hand use oil to alleviate friction between moving parts. An air receiver is a fundamental component in pneumatic systems to stabilize pressure.

Traditionally, the main purpose of deploying pneumatically driven systems in the industry is to perform position control, especially in robotic manipulators, end effectors and grippers. However, pneumatics exhibit highly nonlinear characteristics resulting from the compressibility of air and friction which arises in cylinders. Valves, in general, contribute further nonlinearity to the system. Moreover, the compressibility of air introduces a dead time (or delay) in the system's response [5.1, 5.3]. Air losses in cylinders and transmission lines add more complexity to such systems [5.4]. These factors can make it difficult to achieve accurate position control without the use of some added sensors.

Recent advancements in pneumatic technology along with the technological advancement in embedded systems such as the Microchip's dsPIC digital signal controllers make it possible to consider that control algorithms can be employed to control actuator motion. It may represent an ideal solution for applications in confined and hazardous spaces. This chapter describes research undertaken to engineer such a system.

A pneumatic actuator is “a device which translates the energy from a compressed air supply into a linear or rotary movement” [5.5]. It provides the means by which specific tasks such as clamping, pressing, lifting, picking and placing, filling and ejecting are performed. Rapidly changing market requirements in recent years are a driving force towards the introduction of a wide range of actuators that are compact, powerful and efficient devices [5.5, 5.6]. These include single and double acting cylinders, single and twin rod slide units and rotary actuators. The movement may be linear (on a single axis) or rotary. In a single acting cylinder, air is applied to the piston on one side while a spring on opposite side of piston provides the return motion. In the case of double acting cylinder, air pressure is applied on one side for extracting and the opposite side for retracting. Pneumatic actuators are suitable for light-to-medium loads and are widely used in many applications. They can be found in manufacturing performing tasks like the movement of parts and in assembly operations. In the medical sector, they may be part of drilling or cutting tools. Moreover, suction and clamping functions in medical systems are often carried out by means of pneumatic actuators. Robotics also employs these devices to perform specific tasks. For instance some robots use a linear actuator for leg-lifting and arm-extending during its movement [5.7,5.8]. Pneumatic actuators are deployed in the agricultural sector for harvesting. Modern pneumatic systems areas of activity include the food industry, the milk-processing industry as well as the packaging and material-handling industry, electronic and pharmaceutical industries.

Figure 5.1 shows a variety of current pneumatic actuators. The cost of such devices varies with the size of cylinder, the stroke length and other add on features including cushions, stop screws, sensors and connecting cables. The impact of hard metal-to-metal contact manifests in the form of wear, vibration or bouncing of surfaces and noise which can be irritating. These factors can be eliminated by decelerating the piston at the end of stroke using cushions, thus enhancing the operating life of the actuator’s components and improving its performance [5.9]. Sensors on the other hand provide the required information about the process.

The piston-type double acting is amongst the most commonly used linear actuators and is thus the type of device being considered in this research [5.10]. This device costs around £444, inclusive of cushions.

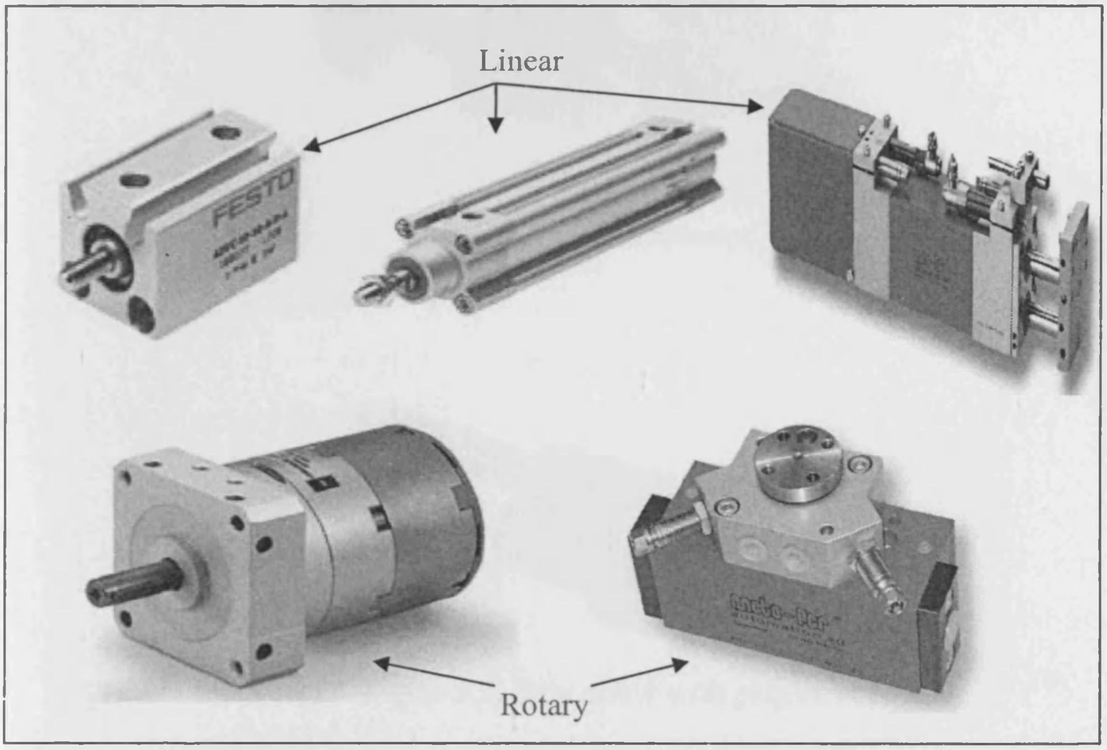


Figure 5.1: Various types of pneumatic actuators; adopted from [5.6,5.11,5.12].

This research project considers the development of a monitoring system for a linear actuator which is able to identify the precise end of slide or size of products in an automated process. Minimizing the number of sensors used by making it intelligent and cost-effective are fundamental requirements.

5.2 Experiment set-up

The test rig designed to support this work has been introduced in Chapter 4, with the addition of the actuator device shown in Figure 5.2. The linear actuator used is a Meto-Fer ® slide unit (mini linear unit ML13). Its supporting fact sheet is listed in Appendix C.

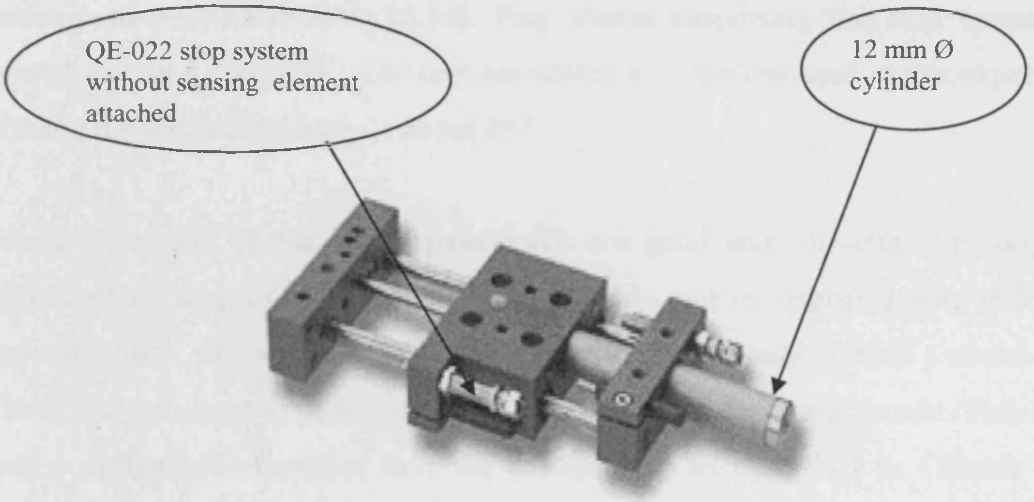


Figure 5.2: Linear actuator.

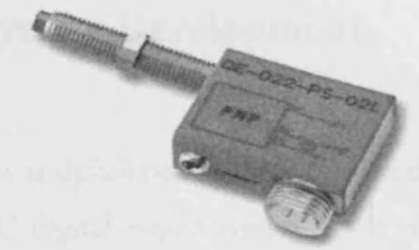


Figure 5.3: Stop screw with plug on sensor.

This unit has low friction, can operate at high speed and has a precision in slide motion, providing repeatability equal to ± 0.01 mm. It can provide a stroke up to 100mm, apply loads up to 196 N, and operate at pressures in the range 3 - 8 bar. It has a piston diameter of 12 mm [5.13]. In addition, the manufacturer has a patented "*stop system*", which is shown in Figure 5.3, consisting of a stop screw with a locknut and a dedicated sensing element. The stop screw is made with fine threads allowing precise adjustment of the mechanical end-position of the slide motion, while a locknut is used to secure the screw in its adjusted position. It contains a spring and a hardened stopping pin, which operates the plug-on sensing unit once it's driven to the defined end-position. The sensing element, however, has to be powered. The electronic sensor used in this experiment operates with a supply voltage ranging from 8 to 30 VDC, with a maximum load current equal to 200 mA. The proximity switch (sensor) provides a simultaneous feedback and has options to provide an output in electrical, electronic or pneumatic form [5.14]. Fact sheets supporting the stop system are demonstrated in Appendix C. The cost associated with the one used in this experiment including the connecting cable is about £87.

The stated features of the *stop system* make it a good and cost-effective choice to facilitate monitoring of the positioning of the slide unit or gripper during pick-and-place operations. The actuator used in this experiment can only provide a stroke up to 75 mm, and the sensor type (QE-022) gives an output in electronic format. This linear actuator system was installed into the existing rig, as described in Chapter 4. A solenoid operated on/off control valve permits the flow of air into one chamber of the cylinder allowing the extension of the slide unit. Air flows into a second chamber for the return of the slide unit.

5.3 Monitoring System Development

The monitoring system was developed based upon the data acquisition and processing capabilities of the dsPIC digital signal controller. It was intended that the resulting system would be flexible and provide monitoring information for a range of applications and configurations.

As previously outlined the operating pressures for the chosen actuator range from 3 to 8 bar. It was possible to carry out this work at supply pressures of 3 to 7 bar (gauge), the highest available pressure, to investigate the performance of the slide unit (or actuator) over a range of pressures. The intention of this research was to produce a monitoring system that operates at any pressure within the range. This accommodates any possible set-up of the system. The experimental procedure adopted in this work requires that supply pressure is initially set to a specific level. A set of objects with various lengths are used to simulate the end of stroke or end position as shown in Figure 5.4. The object is placed to limit the stroke and the end position is measured from the left (from point "A"). To clarify, zero end position means full stroke. At a given supply pressure, the time taken by the slide unit to reach an object is measured. A relationship between the travel time and end of stroke can then be realised. In this way, a time based monitoring system can be developed. If the travel time at a specific supply pressure and intended end position does not match to a defined tolerance the pre-set value, assuming the same operating conditions, a faulty situation is indicated to the operator.

To develop a robust and flexible monitoring solution, the system was evolved through three stages;

- In the first case, two limit-switches (S1 and S2 in Figure 5.4) are used to monitor home and end positions of the actuator.
- In the second, one limit-switch (S1) monitoring the home-position in addition to the pressure response at the inlet of the actuator.
- Finally, the pressure transient signal alone is monitored. Each approach is discussed in detail in the following subsections.

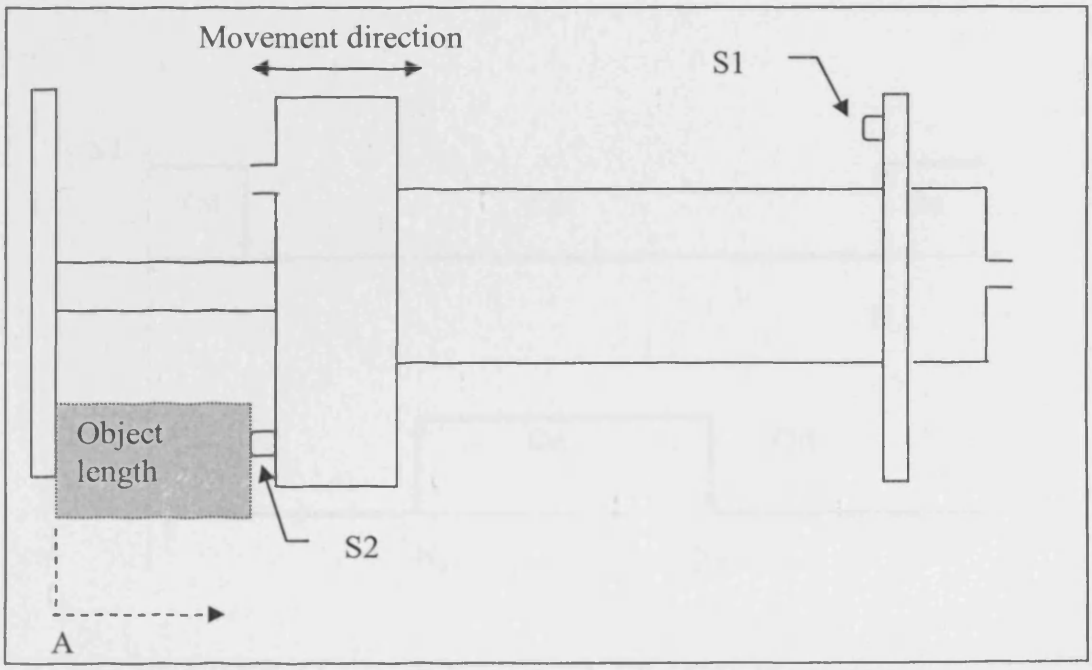


Figure 5.4: The actuator set-up.

Key: End position measured from "A"; the zero coordinate.

S1 and S2 indicate home and end positions respectively.

5.3.1 The two limit switch based approach

In this approach, both extension and retraction times were monitored. The dsPIC30F6014 device was configured to operate at a 7.3728 MHz clock frequency (Fcy). Signals from the limit switches installed on the slide unit were also monitored. An operational amplifier was used to make these signals TTL compatible and suitable for interfacing to the dsPIC. The Timer 1 module on the dsPIC30F6014 was used to measure either the time taken by the slide unit in the actuator system to extend from the home position to the end position or to retract back to its home position. The measured time interval was sent to the LCD display on the dsPICDEM 1.1™ development board. Polling the input pins to detect the rising and or falling state indicated which event was to be recorded. Timer 1 (16-bit) was used to count the number of instruction cycles consumed between the falling state (off state) of the "home position" sensor (S1) and the rising (on state) of the "end position" sensor (S2), as shown in Figure 5.5.

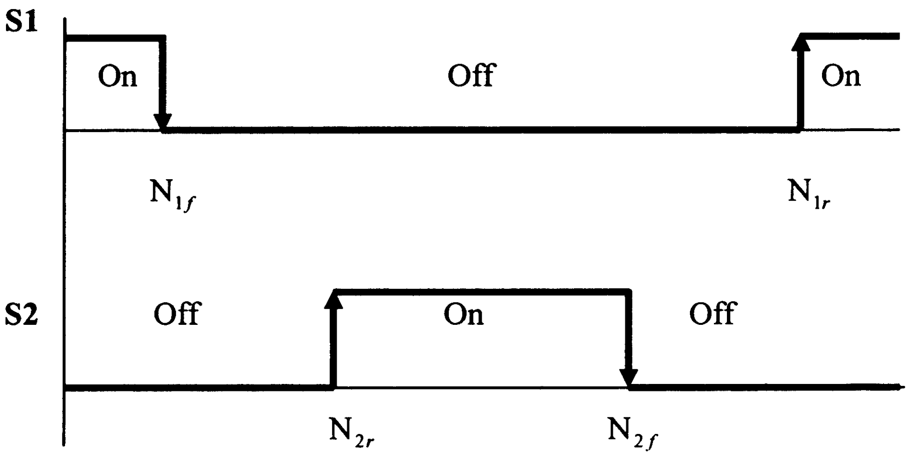


Figure 5.5: Limit switches states during cycle operation.

This gives;

$$\text{Travel time (milliseconds)} = (N_{2r} - N_{1f}) * prescalar / F_{cy} \qquad (5.1)$$

where N_{2r} and N_{1f} are the integer timer values.

While Fcy = 7372.8 kHz, the pre-scalar was set to 256 in this experiment to achieve a maximum possible timer period of 2.27 seconds (that is 65535*256/7372800). The dsPIC30F6014 has five Timers, two of which can be paired to form a 32-bit counter or timer if required. The 16-bit timer however was more than sufficient for the entire cycle period in this application. The measurements indicating the relation of travel time to the end position at specific supply pressures are plotted in Figure 5.6. Each test was repeated a number of times to confirm consistency in measurement. The measurement was observed to be repeatable. Thus, the curves produced are the result of single measurements.

The UART1 module on the dsPIC was implemented to send counter values to the PC to verify various events occurring during the cycle operation of the slide unit. LEDs on the dsPICDEM 1.1 development board were used to indicate the occurrence of events such as the state of the solenoid valve and proximity sensors. The solenoid valve is controlled by the dsPIC through an electronic switch. The on-board switches were also used to select program functions via a menu displayed on the LCD screen.

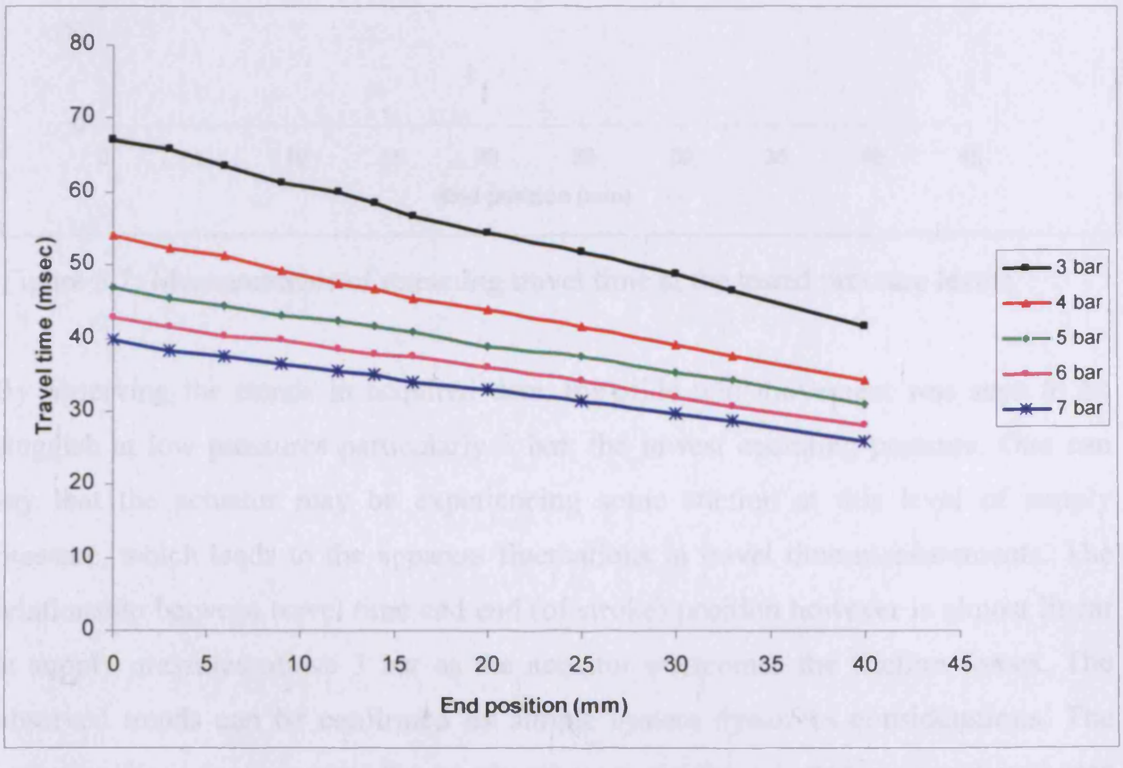


Figure 5.6: Extending travel time measurements at various supply pressures.

The time taken by the slide unit to retract to its original position (or home position) was also measured, and calculated using:

$$\text{Return time (milliseconds)} = \left(N_{1r} - N_{2f}\right) * prescalar / F_{cy} \qquad (5.2)$$

The curves representing the return time intervals of the slide unit as measured by the dsPIC at various pressures applied to the system are shown in Figure 5.7.

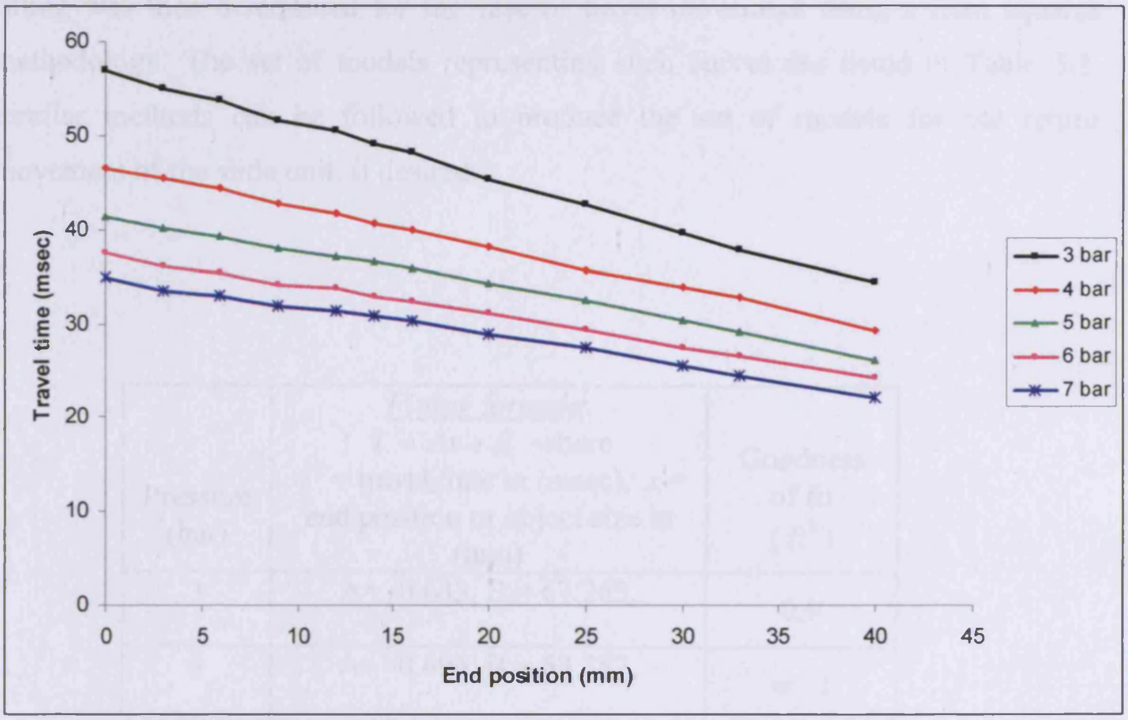


Figure 5.7: Measurements of retracting travel time at the tested pressure levels.

By observing the trends in acquired data, the slide unit movement was seen to be sluggish at low pressures particularly 3 bar, the lowest operating pressure. One can say that the actuator may be experiencing some stiction at this level of supply pressure, which leads to the apparent fluctuations in travel time measurements. The relationship between travel time and end (of stroke) position however is almost linear at supply pressures above 3 bar as the actuator overcomes the friction forces. The observed trends can be confirmed by simple system dynamics considerations. The actuating force depends upon the supply pressure and the actuator cross sectional area (constant). The movement can be considered to be opposed by a viscous damping effect, with no spring return force in this case. These considerations thus confirm that the actuator velocity will be constant and that the travel time reduces with increased supply pressure, assuming the load force does not change. The travel time also increases with the length of stroke at any given supply pressure.

To simplify the implementation of the system to detect the size of the object (or end position), it was decided to model only the trends in travel time with respect to the end position for each of the particular pressures applied to the system as indicated in Figure 5.6. This was accomplished using Excel software. The best possible curve fitting was then determined for the case of travel movement using a least squares methodology. The set of models representing such curves are listed in Table 5.1. Similar methods can be followed to produce the set of models for the return movement of the slide unit, if desired.

Pressure (bar)	*Fitting formula*: $T = Ax + B$ where T = travel time in (msec), x = end position or object size in (mm)	Goodness of fit (R^2)
3	A= -0.633, B = 67.265,	0.9
4	A= -0.495, B = 53.787,	$\approx$ 1
5	A= -0.39, B = 46.91,	1
6	A= -0.36, B = 42.93,	1
7	A= -0.335, B = 39.656,	1

Table 5.1: Models of travel time measurements at various supply pressures.

The correlation between actual and predicted values was found to be very strong especially at supply pressures above 4 bar. The linear model represents the actual measurements accurately. This method is limited to the pressures applied to the actuator system. In other words, this approach applies only to those levels of supply pressure used in the initial development and testing of the monitoring system. However, a generic monitoring system is conceived and presented in the next subsection. This approach considers modelling the data obtained to yield a "surface model". Hence, the monitoring system is not restricted to the specific operating pressures used in this experiment. Any pressure in the range 3-7 bar may be applied to the pneumatic system.

The developed mathematical formulae may be implemented in several ways. One approach that was taken was to form lookup tables which are stored in the dsPIC memory for a set of particular objects or end positions. For each supply pressure, a lookup table may be generated and programmed onto the microcontroller. Whenever the actuator is to perform an operation, the monitoring system can be configured for a specific supply pressure and part sizes or end positions. The measured time can then be compared to those in the lookup table to identify the end position or object size. To implement the associated formula of a particular supply pressure for a desired end (of stroke) position in a repeated process is another way in which an algorithm containing this formula may be downloaded into the dsPIC memory. For instance, if the actuator system operating at 5 bar is to slide up to a limit of 5 mm, the best and easiest way to implement it is to use the designated (or prediction) formulae in a simple program to create a pre-set travel/return time values and compare them against the actual measurement. If they agree to within an acceptable tolerance the object or end position can then be recognized as the correct or desired one.

It is to be noted that the actuator inhibits high uncertainty in predicted values at 3 bar. In many industrial applications it is however possible that the slide unit travels a fixed distance, keeping the object size or end position the same at all time. The only requirement is to set end position and operating pressure. An algorithm based up on multiple supply pressure along with various end positions may also be implemented if required.

In order to increase the flexibility of this process, an attempt was made to fit the data into a single formula representing the travel/return time behaviour with respect to the end of slide position at any supply pressure. This leads to a comprehensive surface model for the actuator's travel and return time; thus allowing even for a wider range of pressures to apply to the pneumatic system. In simple terms, 4.25 bar or 5.5 bar may be used as the operating pressure. Furthermore, this approach provides the capability to detect faults in the process whenever they arise before the cycle is repeated; hence, saving energy, time and providing the potential to optimize performance. When required to act the operator can halt the operation and make the required inspection. The fault may be a result of the process undergoing leakage, blockage or end of stroke and/or operating pressure need to be correctly reset. There is also a possibility that the object operated on is being the wrong one.

Curve-fitting software was used to obtain the surface model through a least squares technique [5.15]. The software implements Levenberg-Marquardt (LM) algorithm, which is an iterative method, to fit the actual data to a model while the mean squared residual is kept optimum [5.16]. The surface model function was found to be of the form,

$$z = \frac{A + x}{B + Cy} + Dy \tag{5.3}$$

Where,

x = end position in millimetres,

y = applied pressure in bar, and

z = travel time in milliseconds.

The modelling procedure converges after eight iterations, and the parameters were estimated. It was then exported to Excel to tune the parameters so that the best possible fit is achieved. Figure 5.8 shows the surface of travel time measurements. The estimated parameters are listed below:

A = -97 mm,

B = -0.176 mm/msec,

C = -0.456 mm/(bar.msec),

D = 1.48 msec/bar.

A quantitative value or goodness of fit (R^2) that describes how well the model fits the data is calculated. This measures the correlation between observed data and predicted ones and was found to be equal to 0.998. It indicates that the variation of the actual data to the estimated model curve is very small. To evaluate the surface model further, one can look at a critical value table of the correlation coefficient (r).

If a probability (p) level of 0.05 is assumed in this research experiment, as commonly used in academic research, it can be said that repeating the experiment a 100 times would lead to the same value for the correlation coefficient 95% of the times [5.17]. In other words, the likelihood that the same value of (r) occurred by chance is 5%. To verify the goodness of fit, there is a need to determine degree of freedom. That is the number of data sets (60 in this experiment) minus the number of parameters (4 parameters) used to fit the data to the model formula (equation 5.3). The calculated r value ($r = \sqrt{R^2} = 0.999$) exceeds the tabulated one (0.250) at 0.05 probability level. It also exceeds the tabulated value for $p = 0.01$(that is 0.325) [5.17]. Therefore, it can be stated as 99% confident that the model performance is highly efficient.

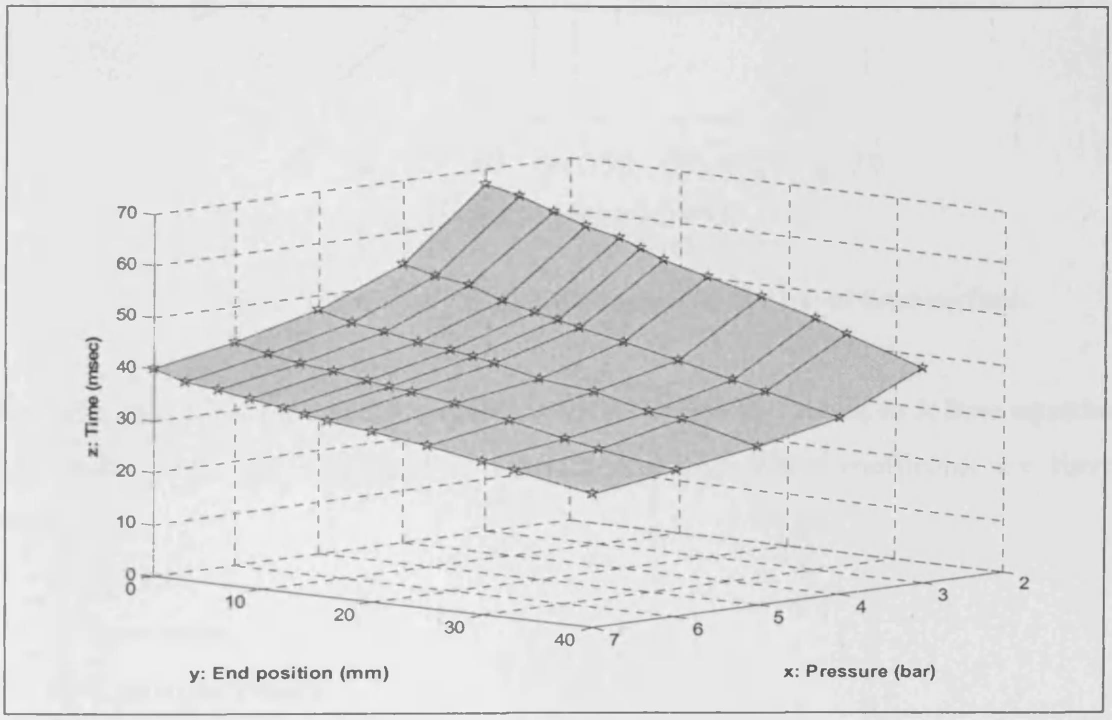


Figure 5.8: Surface of travel time measurements.

A plot of the actual measurements against expected values provides further evidence that equation (5.3) gives an adequate description of the actual data. This is illustrated in Figure 5.9. The linear relationship reflects the superiority of the fit. The maximum difference obtained was ± 1.1 msec. A tolerance of ± 1.5 msec indicates that any measured time lies within an acceptable band as shown in the Figure.

This model was then deployed onto the dsPIC in order to achieve an on-line, real-time system and tests were performed at the stated tolerance, yielding positive outcomes. However, its sensitivity to operating conditions, particularly ambient temperature and the operator setting of applied pressure should be recognised.

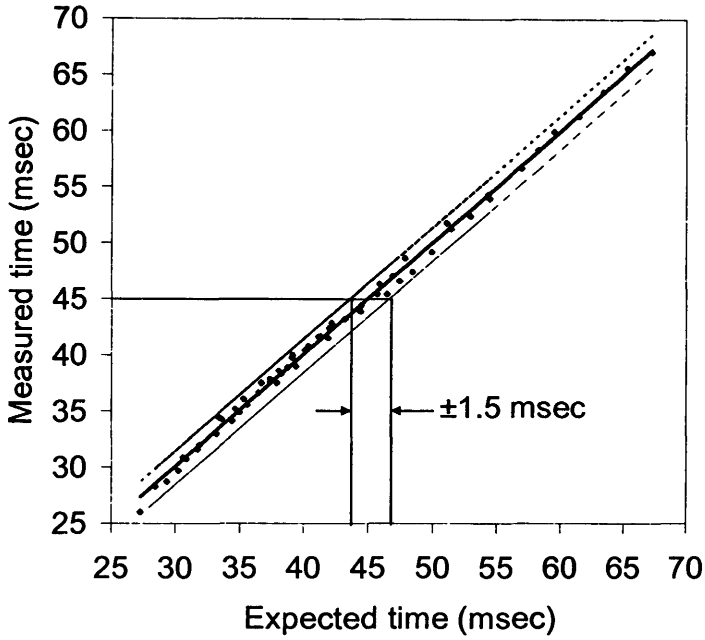


Figure 5.9: Quality of the fitting model for travel time surface.

Similarly, the return time measurements were modelled and found to follow equation (5.3) really well. The estimated parameters and correlation coefficient are listed below.

A = -95.14 mm,

B = -0.5 mm/msec,

C = -0.42 mm/(bar.msec),

D = 1 msec/bar, and r = 0.999 which is highly significant from a statistical point of view. The surface representing the return time measurements as well as the variations between actual and estimated time values are shown in Figures 5.10 and 5.11 respectively. It shows that the model fits the retraction time intervals of the slide unit precisely. The tolerance in this case was set to ±1 msec as shown in Figure 5.11.

This approach has the advantage of allowing the process to be monitored during both extension and retraction of the linear actuator. Based upon the tolerances established, if a fault occurs, an alarm is generated to bring it to the operator's attention before the cycle is repeated. The process can be inspected to rectify what went wrong at an early stage, thus improving productivity and optimise operational cost.

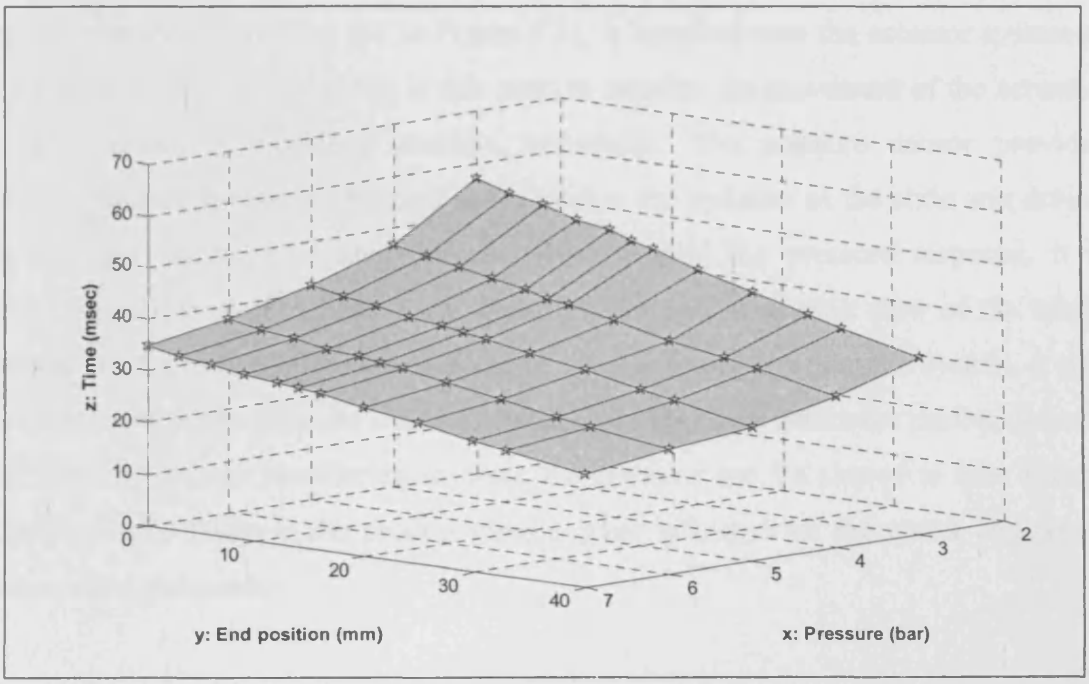


Figure 5.10: Surface of the return time measurements.

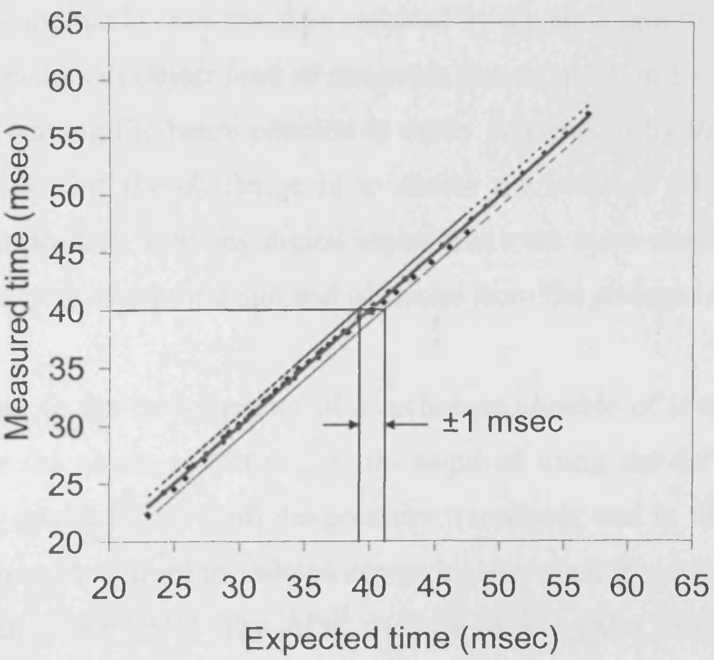


Figure 5.11: Model variation with actual measurements of the return movement.

5.3.2 One limit switch and pressure based approach

This approach was conceived to deal with the case where only one limit switch, representing home-position (S1 in Figure 5.4), is installed onto the actuator system or if the user prefers such a set up. In this case, to monitor the movement of the actuator, it is necessary to install a pressure transducer. The pressure sensor provides measurement of the pressure signal at the inlet to the cylinder of the slide unit during its operation in an automated process. By acquiring the pressure response, it is actually possible to determine many important features. It gives a view of the whole process. If, for example, there is leakage or blockage in the pneumatic system, it will be manifested in the pressure signal. Leakage and blockage affect the performance of the system, but with monitoring in place the operator can be alerted to take action. These possible faults in the process have a great influence on the travel and return times of the slide unit.

The author considered the extension movement of the actuator; the retraction movement may be investigated if required, but was not considered in this research. The stated aim is to detect the end position or size of object being operated on in the process. That is attainable once the time required by the slide unit to travel from home to the point it reaches an object (end of stroke) is measured. In this set up, the moment the slide starts leaving the home position is easily determined by the signal from the proximity switch. But the challenge is to detect the instance when the slide unit reaches its final position with any digital input. It is even more challenging to be able to decide the possible beginning and end of stroke from the pressure response alone.

The data leading to the development of a technique capable of identifying the slide end position or the object size was initially acquired using the dsPIC digital signal controller. The output signal from the pressure transducer was in the form of a 4-20 mA current signal. A current-to-voltage converter was used to convert the signal has to be in the range 0-5 VDC. The ADC module on the dsPIC30F6014 device was configured for a sampling rate of 2 kHz. The sample value at which the limit switch (S1) changes state, as previously described and shown in Figure 5.5, is recorded and stored as a variable in the dsPIC memory. In addition, the pressure samples were recorded and stored in an array. Data was then transmitted to a PC for analysis. This was accomplished by configuring the dsPIC serial communication module (UART1) to send data to the PC once an individual test is complete. Tests were carried out on supply pressures ranging from 3 to 7 bar using various object sizes.

An example cycle with the linear actuator tested at 5 bar supply pressure, while the object operated on at the end position of 20 mm dimension, is illustrated in Figure 5.12. The LCD display in conjunction with press button switches available on the dsPICDEM 1.1™ demonstration board provided an interface with the rig and the acquisition system (the dsPIC30F6014 chip) to initiate the test, and monitor various stages in the process such as the state of the proximity switch. LEDs represent the state of the valve and indicate when data collection was complete and ready for transmission.

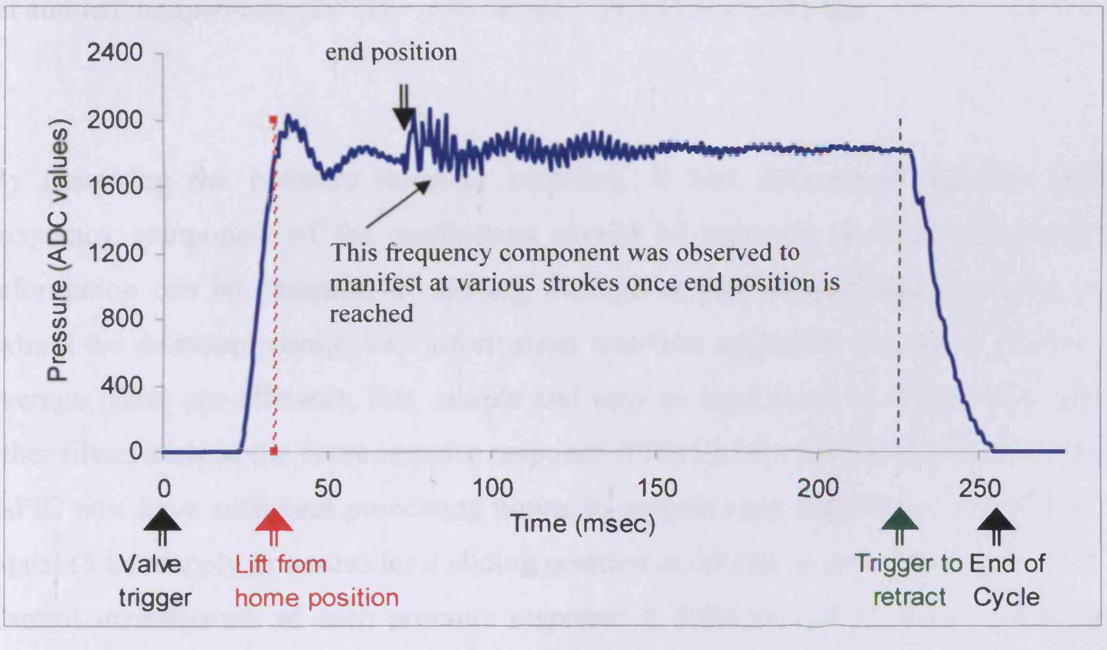


Figure 5.12: Data at 5 bar and 20 mm end position.

The effect that compressibility of air has on the response is apparent. It leads to a delay in pressure transient response. The response time of the solenoid valve also contributes to the delay. Once the valve is triggered, it can be seen that air pressure takes some time to build up to provide sufficient force to push the slide piston from its home position (the home-position change of state as shown in the example of Figure

5.12 occurred approximately 30 msec post-triggering). The transient overshoots, then settles during the motion, but once it reaches an object a resistance is created. The bouncing of metal surfaces generates a decreasing oscillation in the pressure signal, which dies out with time. As soon as the valve receives the signal to close (after approximately 225 msec for the Figure 5.12 example), air exits the cylinder to the atmosphere depending on the valve's response time and the measured inlet pressure falls rapidly to zero. Reflection points in the pneumatic circuit such as valves and joints generate pressure waves which propagate in the opposite direction. It was observed that 400 Hz was the dominant frequency component in the pressure transient response. This frequency can be roughly computed as

$$f = \frac{c_0}{2L}$$

Where "c_0" is the velocity of sound in air; "L" may be considered as the length of connecting tube between the valve and the sensor which is about 45 cm. Hence, at ambient temperature (20°C), $f = 343\,ms^{-1}/2(0.45\,m) = 381$ Hz

By observing the pressure transient response, it was determined that the high frequency component of the oscillations should be removed, so that more useful information can be obtained. A moving average or smoothing filtering process to extract the dominant component information was thus applied to the signal. Moving average filters are efficient, fast, simple and easy to implement in comparison with other filters such as the finite impulse response (FIR) [5.18]. And devices such as the dsPIC now have sufficient processing power to support such algorithms. The filtered signal (5 bar supply pressure) for a sliding position of 20 mm is shown in Figure 5.13. Careful investigation of each pressure response at different end of stroke positions (point of contact with various objects) led to the realisation that the squared rate of change values (considered only from the first detected minimum point "m1", in the TT_1 zone, onwards) rise above a certain level. This important calculated parameter, shown as the (r.o.c)^2 trace on Figure 5.13, proved to be useful in this and later sections of the research. For example, they seem to exceed the proposed 400 (ADC value) threshold level once contact with an object is made (when the slide unit undergoes a test at 5 bar in this case). The minimum point "m1" can easily be determined by observing the first sign change in the rate of change value within TT_1 zone. Therefore, the extension time (TT_1) is computed as the difference between contact time and home position time. That is,

$$TT_1(m\sec) = \left(\frac{N_c - N_h}{sampling\_rate} \right) \tag{5.4}$$

Where, N_c = sample number when (r.o.c)² ≥ threshold; N_h = sample number at home position and sampling rate = 2 kHz.

This procedure was applied to the data file for each supply pressure acting upon multiple objects. Different threshold levels, according to the prevailing test conditions, implemented in this technique are summarised in Table 5.2. The travel time (TT1) intervals were computed and plotted against end position or object size as shown in Figure 5.14. This indicates that the travel time follows an almost linear trend as a function of the end position. There however exist small variations at some end positions.

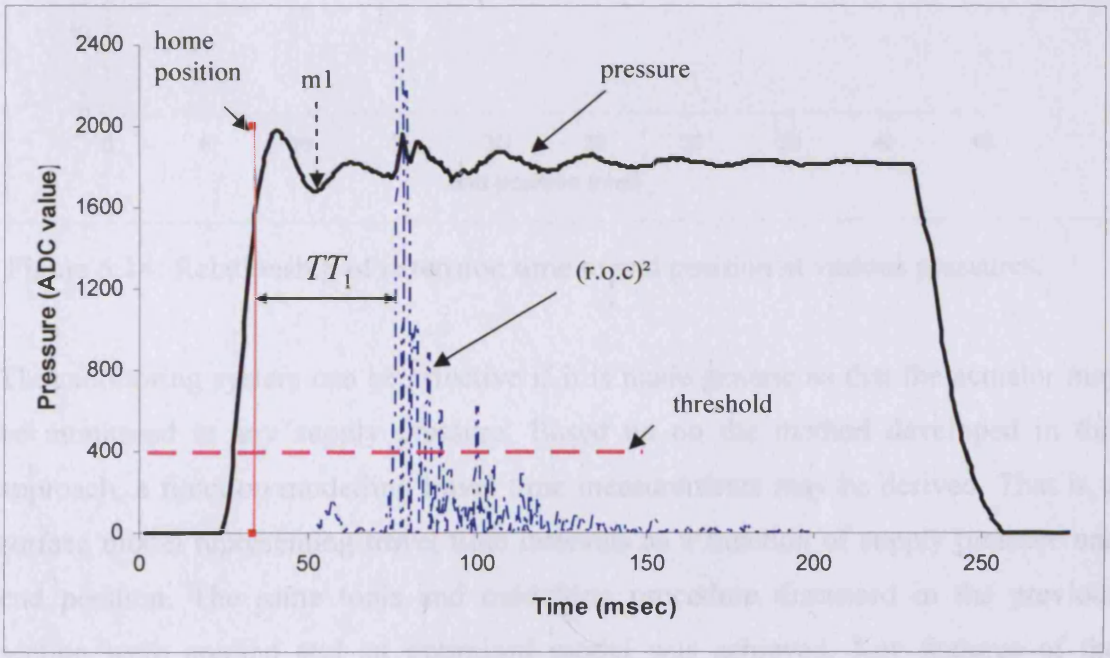


Figure 5.13: Processed data at 5 bar and 20 mm end position; TT_1 = travel time.

Pressure (bar)	Threshold (ADC unit)
3	250
4	300
5	400
6	400
7	400

Table 5.2: Threshold levels applied in data analysis.

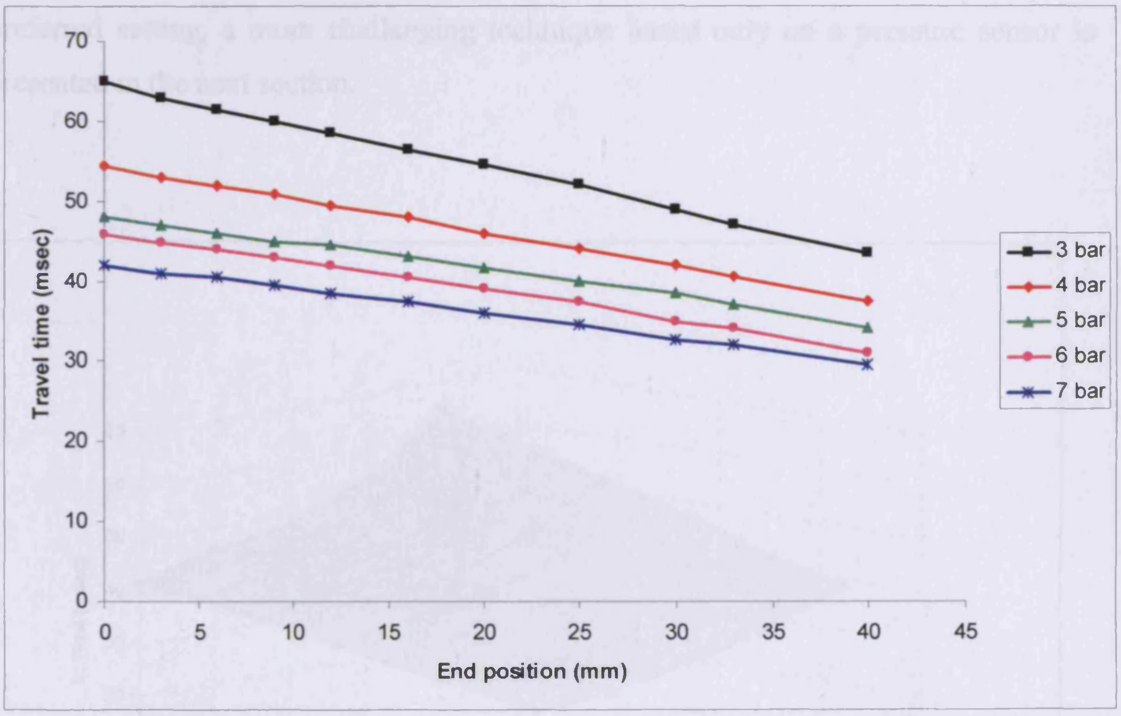


Figure 5.14: Relationship of extension time to end position at various pressures.

The monitoring system can be effective if it is made generic so that the actuator may be monitored at any supply pressure. Based up on the method developed in this approach, a function modelling travel time measurements may be derived. That is, a surface model representing travel time intervals as a function of supply pressure and end position. The same tools and modelling procedure discussed in the previous section were applied and an optimised model was achieved. Key features of the surface model include a highly significant correlation coefficient of 0.998. An adjusted correlation determination (or R^2) close to unity was determined. The formula representing the surface was found to be similar in structure to equation (5.3). The parameter estimation led to the following values; A = -111.5 mm, B = -0.544 mm/msec, C = -0.4376 mm/(bar.msec), and D = 1.6 msec/bar. Figure 5.15 and Figure 5.16 illustrate the surface and the quality of its model, respectively. The maximum variation was found to be ±1.2 msec. Therefore, a reasonable tolerance was established and is shown in Figure 5.16. Testing this approach was performed at ± 1.5 msec tolerance and the outcome was positive. This approach still has some disadvantages especially in terms of configuration (or set up) cost. A proximity sensor plus a pressure sensor add more to the operational cost. Each sensor required some conditioning circuitry. To provide some flexibility and allow the user to choose the preferred setting, a more challenging technique based only on a pressure sensor is presented in the next section.

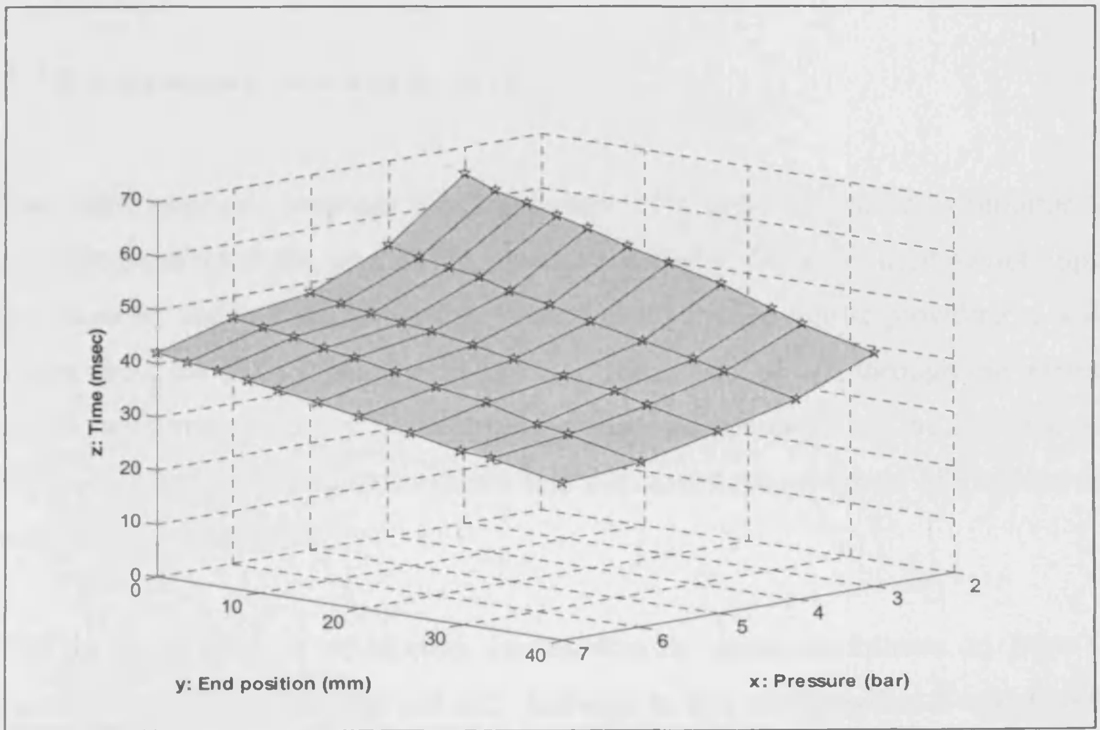


Figure 5.15: The surface representing extension movement.

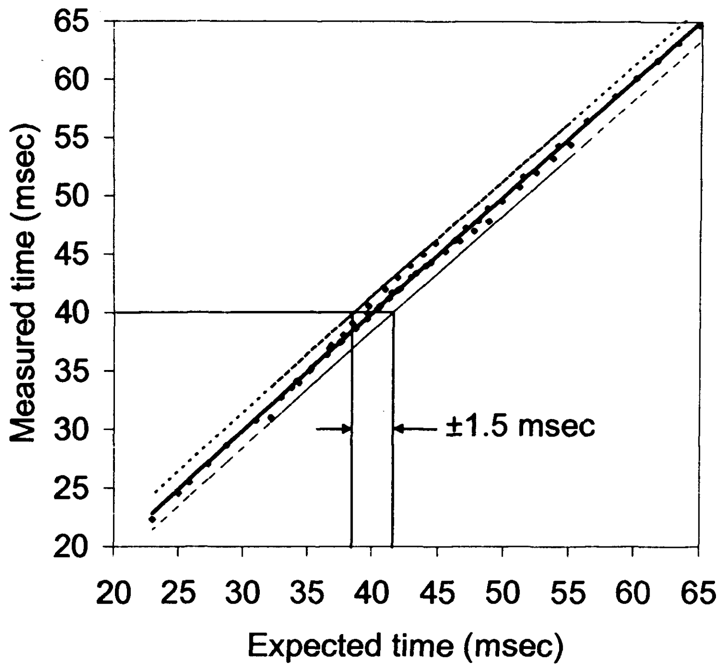


Figure 5.16: Model quality as compared to the actual measurements.

5.3.3 A pressure based approach

This third approach proposes the deployment of a pressure sensor to monitor the pressure transient at the inlet to the actuator's cylinder. Since no limit switch inputs are required, the cost of monitoring system is minimised whilst providing a wider vision about the process being monitored. As mentioned earlier, through the pressure signal measurement, many faults arising during an operation can be detected and isolated. It should be emphasised again that the extension movement of the slide unit only is being considered.

The approach taken to developing this monitoring approach follows on from the previous ones. The additional and real challenge in this configuration is to determine from the transient response a point where the process (motion) may start. That is the possible beginning of the movement of the actuator. The travel time intervals can then be computed as the difference between the point of contact and this point. The dsPIC device has the processing power and mathematical capability to easily identify the peak sample. As a rule-of-thumb, the author assumes that the peak sample of the pressure signal can be used to mark the start of the motion. It was observed in the acquired pressure signals that the peak sample occurs at an almost fixed time, assuming same pressure is applied to the system. It is accepted that this represents a slightly different point in time to that at which the home limit switch changed state. However the consistency of the results and the need to calculate the overall response surface are deemed to make this an acceptable approach. Therefore, the travel time of the slide unit is computed as indicated in Figure 5.17. The Figure shows both the filtered pressure profile and the computed squared rate of change (r.o.c)² parameter.

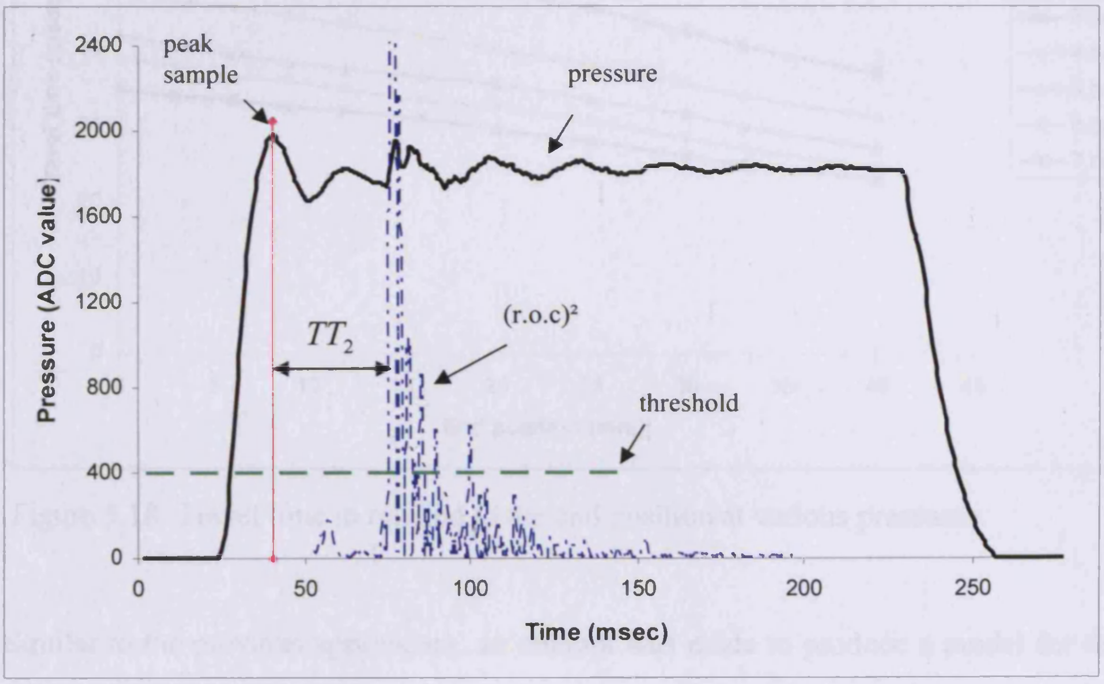


Figure 5.17: Travel time (TT_2) computation at 5 bar and 20mm end position.

This gives;

$$TT_2(m\sec) = \left(\frac{N_c - N_p}{sampling\_rate} \right) \quad (5.5)$$

Where, N_p = peak sample number; N_c = sample number when (r.o.c)² ≥ threshold.

The trends in the computations of travel time in relation to the end position for the various supply pressures are shown in Figure 5.18. It is clear that the variation in the dependant variable (travel time) with the changes in the independent variable (end position) is largely linear. The plots demonstrate that the technique can work well in situations where only the pressure transient signal is available. This is probably the normal case in applications involving such devices in the industry.

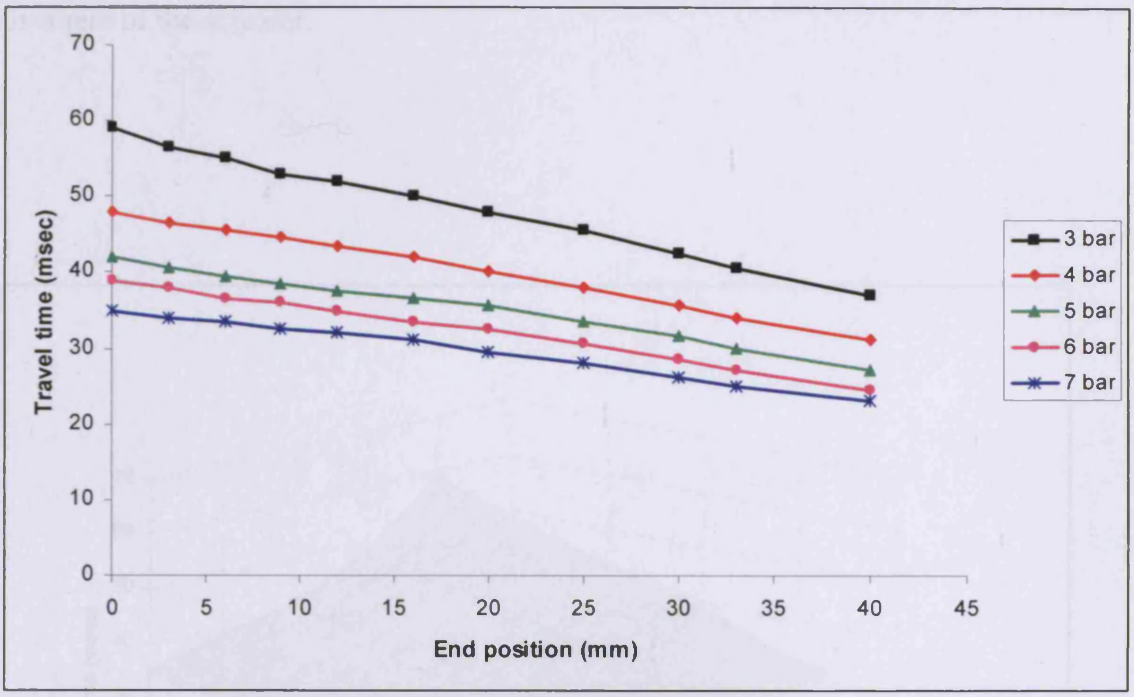


Figure 5.18: Travel time in relation to the end position at various pressures.

Similar to the previous approaches, an attempt was made to produce a model for the conceived surface that represents the extension movement. Figure 5.19 shows such a surface, which relates travel time of the slide unit to the changes in its end position and the supply pressure. The best fit was attained and found to obey equation (5.3) precisely. The fitting parameters are: A =-102.34 mm, B = -0.534 mm/msec, C=-0.433 mm/(bar.msec) and D = 0.9 msec/bar. The actual surface and the model were found to be correlated rather well. Their computed correlation coefficient is 0.998, which signifies the model performance. The model performs well in the estimation of travel time as compared to the time obtained from information extracted from the pressure transient. In addition, more statistical quantities that solidify the quality of the fit include a standard deviation in actual measurements equal to 8.468 msec while that in estimated ones equates to 8.471 msec. Further evidence to illustrate the effectiveness of the fitting process may be induced from Figure 5.20. It shows that the deviation between predicted travel time and the time obtained from real data is very small. The maximum was found to be equal to ±0.9 msec, but testing to validate this method was carried out, with ±1.2 msec tolerance as shown in the Figure, giving a good outcome. These features support the deployment of a simple pressure based algorithm implemented on the dsPIC as a potential solution in order to monitor the movement of the actuator.

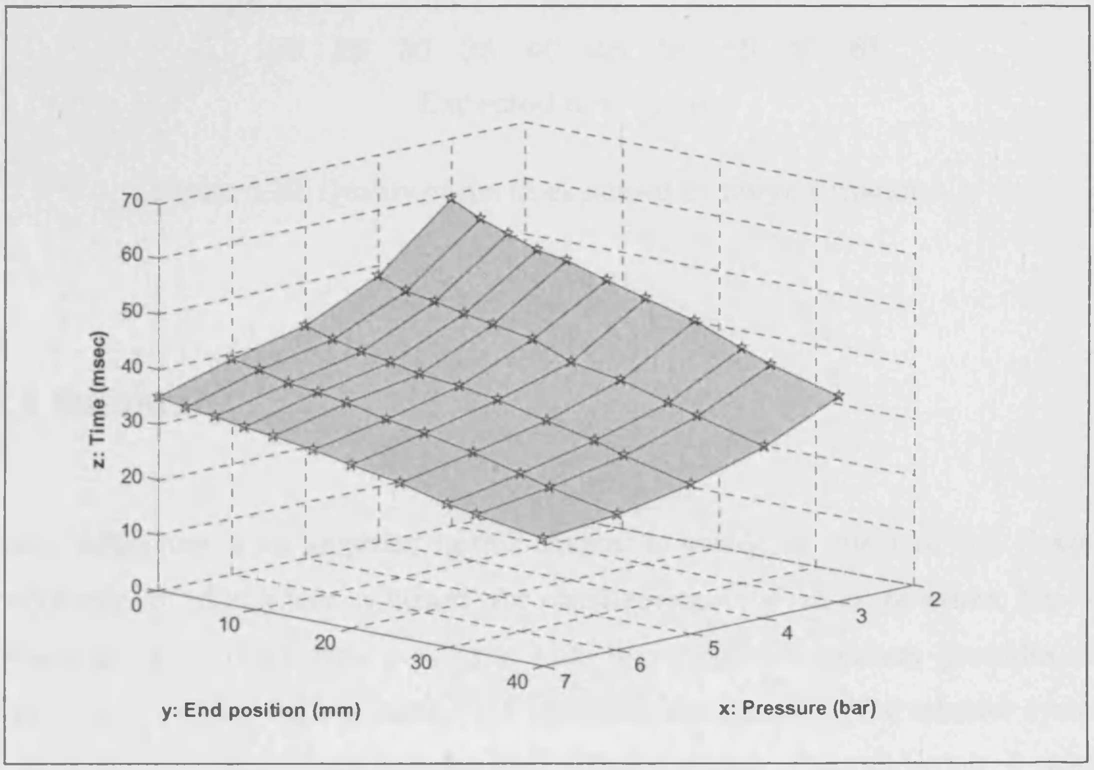


Figure 5.19: Surface obtained from the pressure based methodology.

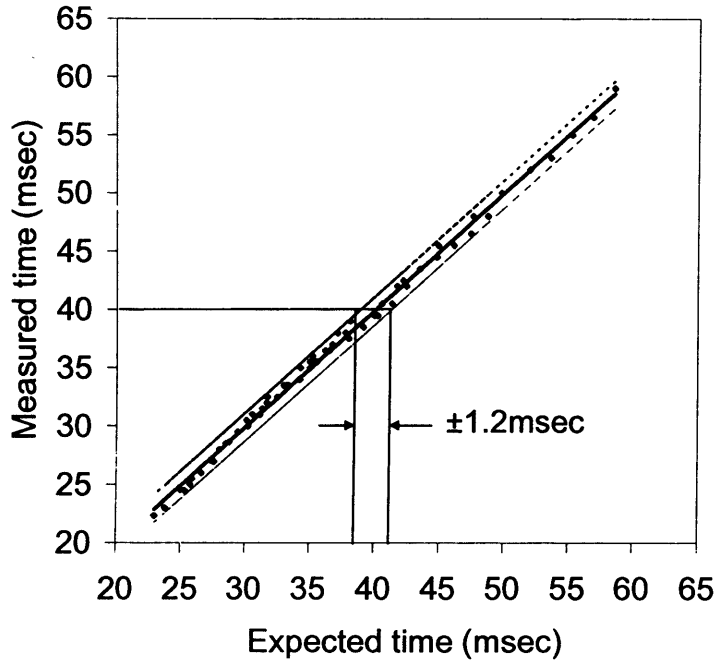


Figure 5.20: Quality of the fit explained by minor variations.

5.4 Summary

Three techniques were proposed in this chapter to enable an effective and flexible monitoring of the linear actuator; the configuration of each however has its advantages and limitations. The first with two proximity sensors provides the capability to monitor both extension and retraction movements of the actuator system or slide unit. If a fault is not detected during the extension of the slide unit, it would be spotted in the return motion. The process may then be stopped and wasted energy is avoided, while the quality of products is maintained. The second method proposes the deployment of a single proximity sensor in addition to a pressure sensor; thus adding more to the cost of the system monitoring the process. The third approach being, a pressure dependant method only, optimises overall cost through reduction in electronic circuitry and sensors. Observing the pressure signal is argued to give more insight into the whole process. Additionally trends in pressure response may lead to symptoms of various known faults such as leakage and blockage, which hinder process performance.

A dsPIC-based system can be an effective and cost-optimized solution in the monitoring of the actuator systems deployed in industrial environments. It is actually an ideal and well suited solution for applications in confined spaces and in situations where human life could be harmed. The proposed methods provide the basis for a low cost, intelligent, compact, and generic system to monitor linear actuators. It has the capability to identify the size of the object it is dealing with, and to recognise the precise end of stroke or end position.

Upon deployment the operator can run some test cycles to calibrate the system and if required make adjustment to the estimation parameters to suit the application in hand. The proposed monitoring system may represent a work cell on the factory floor and is connected to the system managing the process. It may also represent one of many actuator systems performing variety of tasks; all are linked to a management system via a LAN network or the internet. Any fault arising in the process is reported to the operator so that a prompt action can be taken, thus reducing operational cost and optimizing performance.

References

[5.1] R. B. Van Varseveld, G.M. Bone (1997), "Accurate Position Control of a Pneumatic Actuator Using on/off Solenoid Valves". IEEE/ASME Transactions on Mechatronics, vol. 2, no. 3, pp 195-204.

[5.2] eCompressedair, "Types of Compressed Air Systems", [WWW]. <URL:http://www.ecompressedair.com/library/compressedairsystems. shtml> [Accessed on 10th October 2007]

[5.3] J. Wang, J. D. Wang, N. Daw, Q. H. Wu (2004), "Identification of Pneumatic Cylinder Friction Parameters using Genetic Algorithm". IEEE/ASME Transaction on Mechatronics, vol. 9, no. 1, pp 100-107.

[5.4] A. Messina, N. I. Giannoccaro, A. Gentile (2005), "Experimenting and Modeling the Dynamics of Pneumatic Actuators Controlled by the Pulse Width Modulation (PWM) Technique", Mechatronics 15, pp 859-881.

[5.5] SMC Corporation, "Pneumatic Actuators Technology", [WWW]. <URL:http://www.smc.eu/portal/WebContent/local/UK/Pneu_Book/ Pneumatic_Actuators.jsp?tree_title=Products&tree_image=menu_ products.jpg&tree_options=tree_products.js&box=box_locations.htm> [Accessed on 2nd February 2007]

[5.6] Festo, "Pneumatic Drive Units", [WWW]. <URL:http://www.festo.com/INetDomino/coorp_sites/en/ 3800097483cb57c2c12571000035e536.htm [Accessed on 20th August 2007]

[5.7] J. P. Fernandes, J. C. Claro, F. Ribeiro, "Design of a Hexapod Robotic System", [WWW]. <URL: http://www.robotica.dei.uminho.pt/robocup/documents/ DESIGN%20OF%20A%20HEXAPOD%20ROBOTIC%20SYSTEM.pdf> [Accessed on 12th June 2007]

[5.8] "A quadruped legged robot driven by linear actuators", [WWW]. <URL:http//www.wipo.int/pctdb/en/wo.jsp?IA=IL2008000044&WO= 2008084480&DISPLAY=CLAIMS> [Accessed on 25th June 2008]

[5.9] Hydraulics & Pneumatics, "Avoiding the Bounce", [WWW]. <URL:http://www.hydraulicspneumatics.com/200/Issue/Article/ False/17815/Issue> [Accessed on 10th July 2007]

[5.10] Hydraulics & Pneumatics, "Machine Design: Cylinders" [WWW]. <URL:http://www.hydraulicspneumatics.com/200/GlobalSearch/Article/ True/6423/machine+design > [Accessed on 3rd May 2007]

[5.11] SMC Corporation, "Rotary Actuators", [WWW]. <URL:http://www.smceu.com/Prod/NEW_EBP/Level1EU.jsp?ctry=1& id=9760&pos=Rotary%20Actuator> [Accessed on 8th May 2007].

[5.12] Meto-fer Automation, "Automation Components", [WWW]. <URL:http://www.meto-fer.com/2ACsub.html> [Accessed on 1st May 2007]

[5.13] Meto-Fer Automation, "Pneumatic Linear Actuators", [WWW]. <URL: http://www.meto-fer.com/SECT1.PDF> [Accessed on 10th December 2006]

[5.14] Meto-Fer Automation, "Stop Screws, Sensors, Cables, and Gauges",

[WWW]. <URL: http://www.meto-fer.com/SECT8.PDF>
[Accessed on 10th December 2006]
[5.15]. "LAB Fit Curve Fitting Software", [WWW].
<URL: http://www.angelfire.com/rnb/labfit/>
[Accessed on 10th March 2007]
[5.16] A. Ranganathan, "The Levenberg-Marquardt Algorithm", [WWW].
<URL:http://www.cc.gatech.edu/~ananth/docs/lmtut.pdf>
[Accessed on 10th March 2007]
[5.17] University of Connecticut website, "Using a Critical Value Table for Pearson's r",[WWW].
<URL: http://www.gifted.uconn.edu/Siegle/research/Correlation/alphaleve.htm> [Accessed on 20th March 2007]
[5.18] S. W. Smith, "The Scientist and Engineer's Guide to Digital Signal Processing",1999, ISBN: 0-9660176-6-8.

Chapter 6

PARALLEL GRIPPER MONITORING TASK

6.1 Introduction

Advances in automatic control together with developments in the design of automation systems led to the evolution of robotics. The term "robotics" implies the study, design, manufacture and application of robots [6.1]. A robot is defined as "a reprogrammable multifunctional manipulator, designed to move materials, parts, tools or specialized devices through variable programmed movements to carry out specified tasks [6.2]. For the performance of repetitive tasks in particular, it was thought that robots could be ideal solutions through which workers are ity of robots [6.3,6.4].

Robot systems were typically deployed in automotive and manufacturing industries; thus allowing for many production processes to become automated. The integration of robots into a production line offered many advantages. It raised the quality of end (consumer) products, and led to better quality control and provided increased adaptability to ever changing demands. Additionally, major advantages are seen in the use of robots in the area of exploration which may involve work being carried out reliably in harsh environments such as outer space, radioactive regions, underwater and environments of unendurable temperatures [6.5,6.6,6.7]. Some robots are made for general-purpose use where they can be reprogrammed to perform an array of tasks. Others are special-purpose robots that although fast and efficient, can only carry out a very limited number of tasks [6.2]. In most cases, sensors must be installed into a robot system to provide it with the capability to react and adapt to varying conditions.

Technological advancements have led to the application of robots in almost every industry including medical, pharmaceutical, agricultural, packaging and electronics.

The diversity of tasks assigned to a robotic gripper include, but are not limited to, surgery, drug discovery, parts assembly, pick-and-place operations, welding, painting, harvesting, cleaning, product inspection, and testing [6.8,6.9,6.10]. This proliferation in the deployment of robots can be attributed to a number of factors, including their ability to undertake tasks on high speed/high volume production lines in a safe and cost effective manner. Advances in robotics leading to improvements in accuracy and efficiency increased robot multitasking and flexibility (or adaptability) [6.10,6.11].

An important component of a robot system is the gripper, which is connected to the end of its arm and is often called the end-effector. It is defined as "the device that enables the holding of a part or an object to be manipulated" [6.12]. It actually provides the robot with the capability to interact with other objects, thus allowing for the grabbing and moving of a part from one place to another. Grippers can be pneumatic, vacuum, hydraulic, or electric depending on the source of power by which they operate. The most widely used however are pneumatic [6.1,6.10]. Each category has its advantages and limitations and their adoption is usually determined by the application. For example, hydraulic grippers offer the strongest grasping force so care must be taken when handling the part so as not to harm it or the gripper fingers. They can be slow when compared to pneumatic ones. Both types require that part and gripper are precisely aligned, while an electric gripper can be programmed to grab an object positioned not necessarily at the gripper's centreline.

Grippers or end-effectors come in different styles (2 or 3 fingers), and sizes (length of stroke or opening) that allow for the selection of a design as required by the application. They can also vary with regard to the gripping force that can be applied. This is governed by the shape of the gripping fingers which may form either an encompassing or a friction grip. A friction grip relies entirely on the force exerted (by the air pressure supplied to a pneumatic system for instance) by the gripper fingers on the part being grasped. The contact it makes with a part is less as compared to an encompassing grip and therefore usually requires more force to hold the part. An encompassing grip adds stability and strength by encircling the part with its fingers, creating more contact with it [6.13]. In either case, to release a part the fingers would have to be driven open.

Grippers can also be differentiated in terms of the motion of their fingers or jaws in relation to the gripper body. Possible options include parallel, angular, or rotary which combines a rotation function to motion. Figure 6.1 illustrates various types of grippers. Angular grippers, whose jaws move to open or close in an arc type of motion toward the central axis of the gripper, are suited for applications where space is limited. A two-finger parallel gripper, similar to the one used in this research with encompassing grip, is the most popular design, particularly for the gripping of round objects. In a parallel gripper, the jaws or fingers move linearly (on the same axis) and simultaneously, to open or close. They are suited for a large number of applications due to their accuracy [6.12]. Additionally, parallel or linear grippers are versatile, and can be assigned to pick up parts of various size and shape to and from a variety of places [6.16]. The implementation of linear grippers in a production line can lead to reductions in production time and can increase throughput. In addition, product quality and profits can be enhanced due to the deployment of such grippers [6.17].

The selection of gripper to be deployed is mainly determined by the application. One type may be right for a specific application, but would not be preferred for another. Grippers can also be custom made to suit the requirements set by specific tasks. Gripper features such as style, type of motion, speed, gripping force and the ability to "hold on" to the part being grasped are major considerations involved in the process of design [6.16]. This level of detail is considered to be beyond the scope of this research project. The focus of this work is to develop a cost effective and intelligent monitoring technique allowing the detection of objects being gripped and the identification of their size. The methodology to attain this objective is based upon the use of a dsPIC digital signal controller, and is presented in the forthcoming sections. The approach makes use of an industrial pressure sensor which is deployed to measure air pressure at the inlet (this will be clarified in the next section) of a two-finger gripper. The system monitors the performance of the gripper undertaking an assembly or pick-and-place task. It is proposed that such an operation could be affected by faults arising during the process. Effects of known faults that might occur in pneumatic systems such as leakage, blockage, and defect seals are considered and the efficacy of the monitoring system in fault detection is explored.

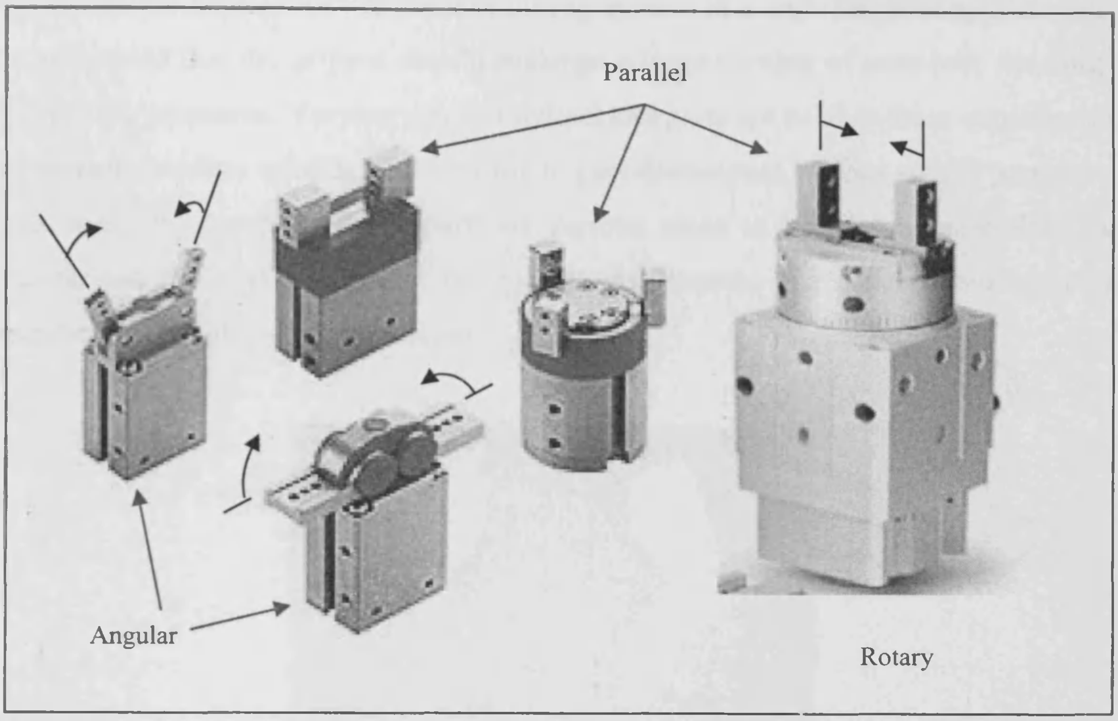


Figure 6.1: Various types of pneumatic grippers [6.14,6.15].

6.2 Monitoring Technique Development

Using the previously defined test rig (Chapter 4), an experimental procedure was developed in order to develop a system capable of detecting the presence of parts and of identifying their diameters during a pick-and-place or assembly operation performed by a pneumatically-driven gripper. A parallel gripper with v-type jaws was installed into the test rig. The dsPICDEM 1.1™ Development Board equipped with dsPIC30F6014 device (described in Chapter 3) was used in the conduct of these experiments to develop an intelligent, and cost effective approach well suited for the monitoring of a gripper deployed in an industrial environment. It should be emphasised that, to reduce costs a single industrial pressure sensor combined with minimal electronic circuitry is adopted, which made this dynamic application quite challenging. The gripper used in this experiment is shown in Figure 6.2. It has two grips as indicated; both are suitable for round-section workpieces or parts. The motion of this type of gripper is linear (i.e. the jaws move in a straight line). The typical operating pressure range of the gripper is 3 to 8 bar.

To validate the deployment of the monitoring system in a wide range of applications, it was decided that the gripper should undergo a large number of tests over the range of operating pressures. Varying sizes of cylindrical parts are used in these experiments to generate a surface relating closure time to part diameter at various supply pressures. Tests were thus performed on parts of various sizes to initially acquire data for analysis and the development of the monitoring system. The procedure adopted is described in the following subsection.

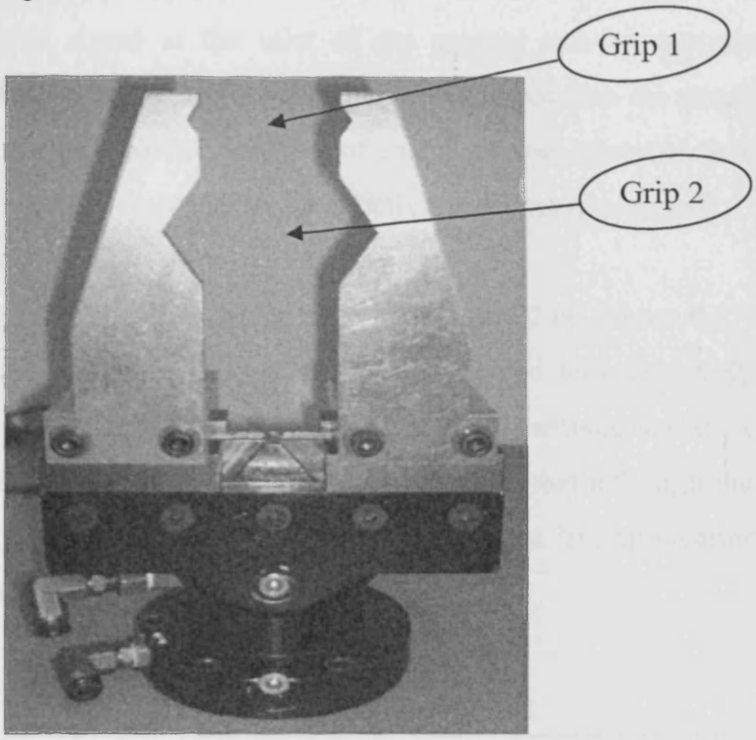


Figure 6.2: The parallel gripper used in this experiment.

6.2.1 Testing Procedure

The aim of this research is to develop a system that can monitor the pneumatic gripper over a wide range of supply pressures. It is necessary for the system to have the capability to identify parts being gripped. If a part is not the correct one, it should be detected. In a repeated process such as commonly arises in actual robotic applications, the gripper could be operating on the same size of workpiece over and over or may be picking parts of specific sizes (or diameters). A range of cylindrical test pieces were manufactured in the School of Engineering workshop to support the experiments. The aim, as stated, was to derive a surface model of the gripper relating part diameter and supply pressure to the time taken for the gripping operation.

Air pressure was supplied to the pneumatic system at various levels from 3 bar up to and including 7 bar (gauge pressure). In this case the gripper contains a double acting cylinder with two chambers; air passes through port A into one chamber providing the closing motion while it enters the other chamber via port B for the opening movement. The measured pressure, in these experiments, is that at port A as per the setup shown in Figure 6.3. From this point forward, the word "inlet" refers to port A in this Figure. At each level of supply pressure, tests were carried out on a series of parts so that the pressure signal at the inlet of the gripper can be captured and transmitted to a PC. Tests were repeated a number of times to confirm the consistency of the obtained responses. Subsequent analysis of raw data was executed to extract information required for the development of an effective monitoring approach.

The gripper has two gripping locations, denoted by Grip 1 and 2 on Figure 6.2. Grip 1 deals with parts of small diameters while Grip 2 is concerned with relatively large ones. It was decided to conduct tests on each grip so that a realistic surface can be deduced representing each individual grip. It may be assumed that although the cycle operation is limited in time and may not fully represent a real life application, it is deemed sufficient to meet the purpose of this research.

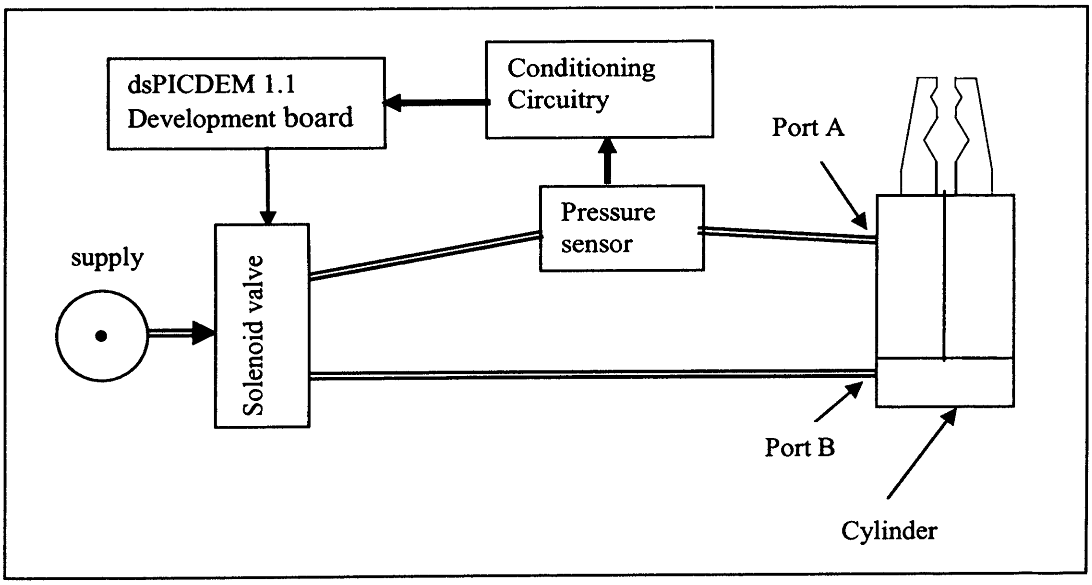


Figure 6.3: The measurement system set up.

6.2.2 Acquisition of the Pressure Signal

The pressure sensor installed measures the pressure at the inlet of the gripper, with its output being converted, as previously, to a voltage in the range 0 to 5 V. A current-loop receiver (RCV420) provides this function. The sensor signal was connected to an input/output (I/O) pin on the dsPIC30F6014 digital signal controller. The particular pin (AN7) of the analogue-to-digital (ADC) converter was configured as an analogue input, thus converting a pressure response to its digital equivalent. This digital signal can then be processed to extract useful information about the process. The pressure signal was sampled at 2000 samples-per-second. Each test was performed using a specified and set supply pressure to produce a gripping operation of an object. Data was collected and stored in an array on the dsPIC memory and, when initiated, data was transferred to the PC for analysis. The RS232 serial communication port available on the dsPIC board was used for this function to make possible the investigation of the relation between gripping time and diameter of part at any given supply pressure. An example of acquired pressure response (for a 6 bar applied pressure when a 14 mm part was grasped using Grip 1) can be seen in Figure 6.4. The switches on the dsPICDEM 1.1 platform were used (as menu select keys) to facilitate the use of LCD screen as an interface tool with the process. Monitoring of the execution of the code was also accomplished on this display. A switch is used to initiate data transmission to the PC. Others are used to reset and or repeat the operation cycle or test. LEDs are used to represent various states in the process such as the state of the valve (ON/OFF), and completion of data transfer.

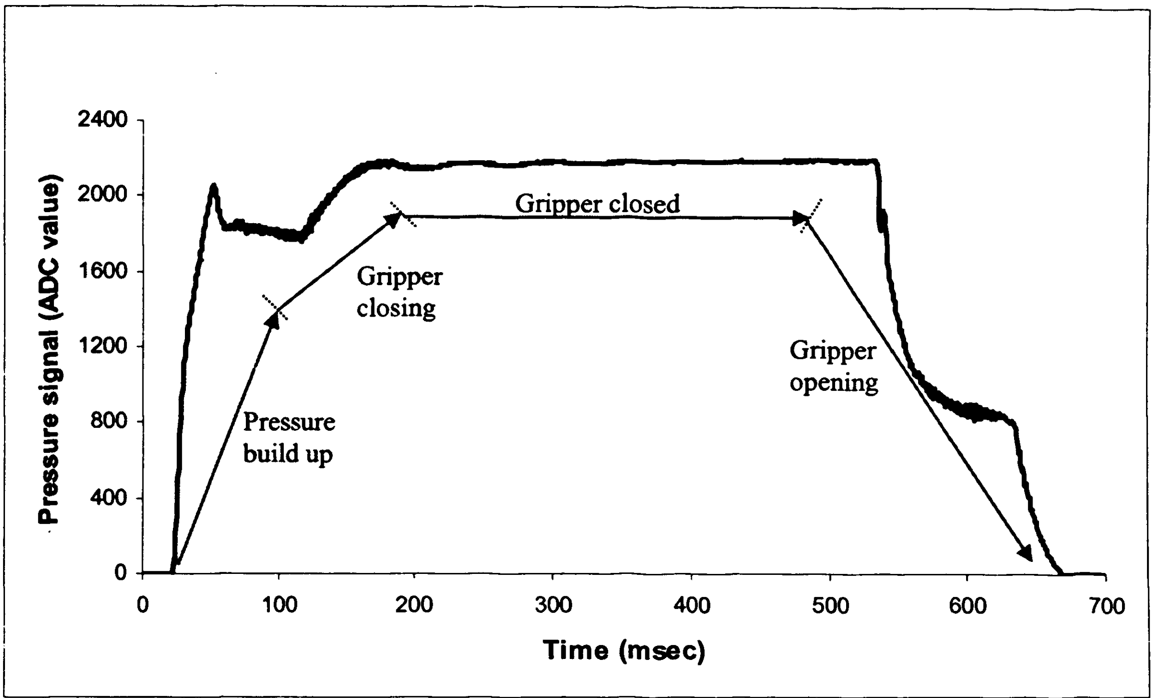


Figure 6.4: Pressure response when a 14 mm workpiece is tested at 6 bar.

6.2.3 Pressure Transient Analysis

The pressure transient response acquired during the operation of the gripper exhibits some nonlinearity presumed to arise from the compressibility of air. A delay or dead time is also manifested in the response, as is commonly observed in pneumatic systems. However, sufficient features describing the performance of a pneumatically-driven gripper can be extracted from the pressure signal. When compressed air is applied to the gripper, the pressure takes time to build up to a level sufficient to overcome the frictional resistance to piston movement in addition to residual pressure and compressibility in the cylinder. This time is reported to be dependant on the cylinder size and the friction due to transmission lines, fittings and valves [6.18]. The gripper jaws starts closing on the workpiece freely with minimal effort, during which the air flow rate depends on the pressure difference between the supply line and the cylinder as well as any resistance to flow. An overshoot is a common feature generally observed in the pressure transient response, as seen in Figure 6.4. Once the jaws reach the part, an opposing force (or reaction) is created; thus giving rise, with slight oscillation, to the transient response settling to its final amplitude.

After the workpiece is transferred to the desired place, the valve is triggered to close via a signal sent by the dsPIC digital signal controller. The pressure supply is then cut off. Although the response initially falls rapidly, the figure indicates that the signal inhibits some obscure fluctuations. These may be attributed to friction effects and residual pressure; or instability in the gripper's movement; or a combination of both. Nonlinearity in transmission lines as a result of the compressibility of air may contribute to such phenomenon. It may also be observed that relatively short strokes lead to air getting trapped, generating more residuals than usual and hence produce an effect on the behaviour of pressure transient particularly during the return of gripper jaws to their original position. Observations indicate an increase in pressure residuals dependant on the size of exhaust ports. The rise in the oscillation also increases with the size of the part as the response falls down to zero, as is clearly shown in Figure 6.5.

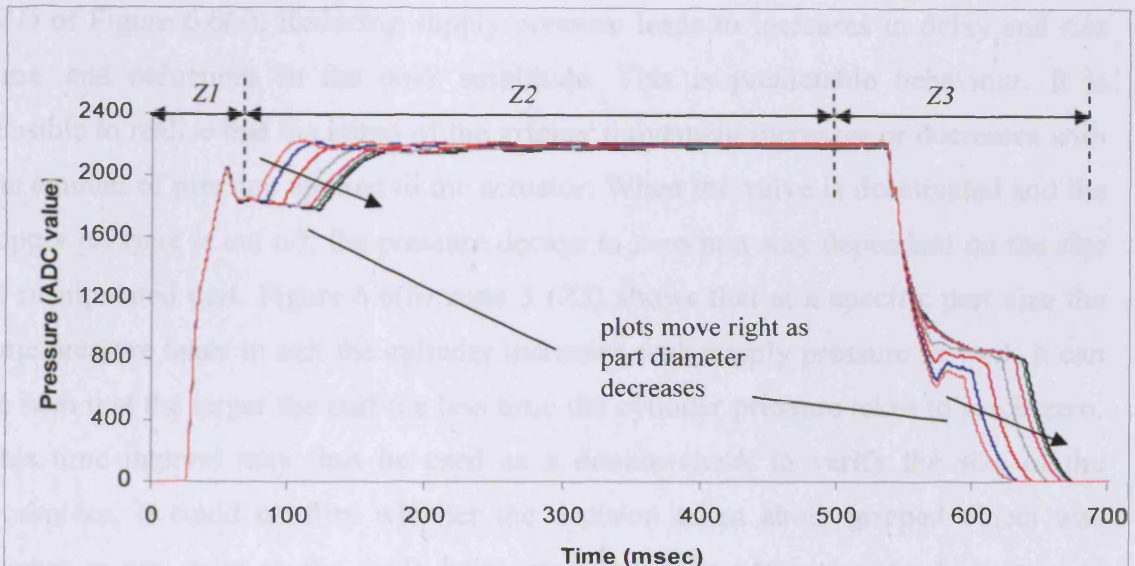


Figure 6.5: Transient responses for tests performed at 6 bar using Grip 1.

The transient response contains variations in its amplitude. It was empirically determined that the high frequency component should be removed via filtering from the pressure signal in order to obtain meaningful information about the process. The dsPIC capabilities in this respect were discussed in Chapter 3. Moving-average were applied to each test performed using either grip. A typical family of plots are shown in

Figure 6.5. These individual profiles are for tests, using different diameter test pieces, all conducted at 6 bar supply pressure and Grip 1 in this example. Filtered pressure transients for tests conducted at 6 bar using Grip 2 are posted in Appendix D. Figure 6.5 shows that, typical responses for tests undertaken at a specific supply pressure (6 bar for this set) share many common features. The time delay, peak amplitude, and rise time, all manifested in zone 1 (*Z1*), appear to be the same. The time air takes to evacuate varies with the size of the workpiece as shown in zone 3 (*Z3*). The smaller the part diameter, the larger the evacuation time. The patterns observed in the pressure transients, shown as zone 2 (*Z2*), identify clearly the potential for detecting the presence of different sized parts. As well as the desired change with part diameter these features, however, differ with the value of the supply pressure.

In related experiments using a single test piece an increase in supply pressure causes decreases in delay and rise times while the peak amplitude increases as shown in zone (*Z1*) of Figure 6.6(a). Reducing supply pressure leads to increases in delay and rise time, and reductions in the peak amplitude. This is predictable behaviour. It is sensible to realise that the speed of the gripper movement increases or decreases with the amount of pressure applied to the actuator. When the valve is deactivated and the supply pressure is cut off, the pressure decays to zero in a way dependant on the size of manipulated part. Figure 6.6(b) zone 3 (*Z3*) shows that at a specific part size the time pressure takes to exit the cylinder increases with supply pressure as well. It can be seen that the larger the part the less time the cylinder pressure takes to reach zero. This time interval may thus be used as a double check to verify the size of the workpiece. It could confirm whether the decision taken about gripped object was correct or not, prior to the cycle being repeated; thus optimising productivity and saving energy.

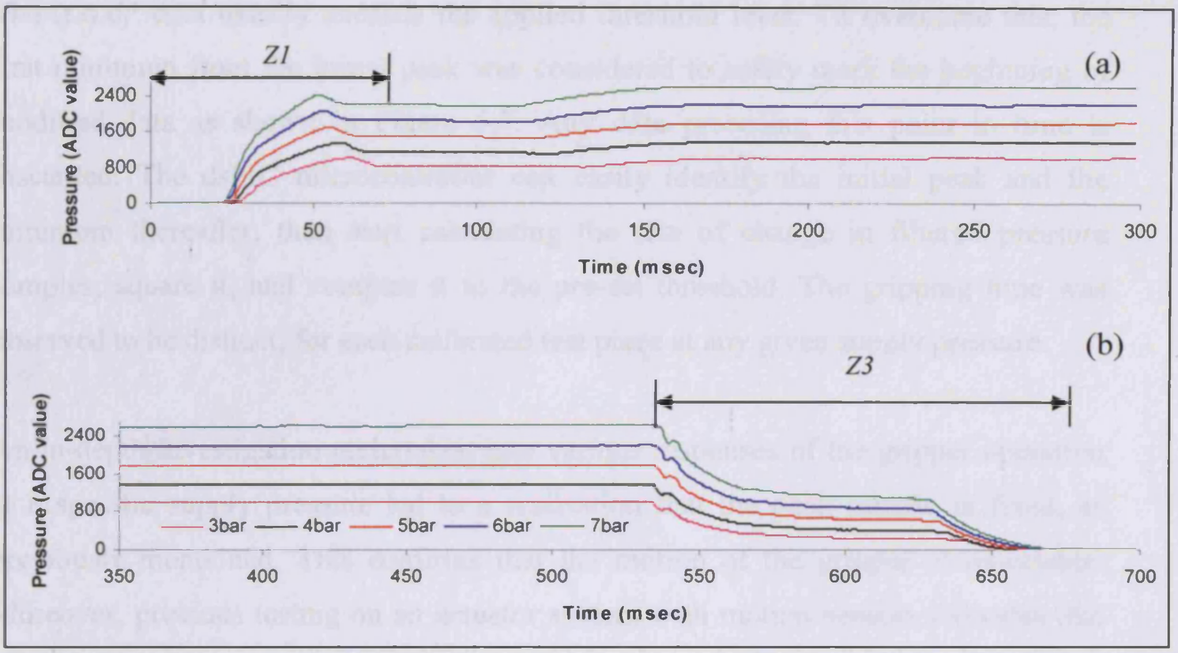


Figure 6.6: Transients for tests carried out for a 16 mm piece using Grip 1.

6.2.4 Gripping Time Estimation

An extensive investigation of the transient response for different diameter parts at different supply pressures was conducted. To facilitate diagnosis of the motion it was necessary to identify key points which could be subsequently recognised and assessed. In order to identify these critical points, the calculated rate of change (r.o.c.) of filtered pressure responses was observed. In the example test shown in Figure 6.5, it is clear that in the first portion of the response, designated as zone 1 (*Z1*) the r.o.c itself changes from positive to negative as the pressure is either rising or falling on either side of the peak value. In the next phase, the signal changes less indicating the movement of the gripper. The rate of change rises again signifying the possible instant an object is reached. In order to use this information as a means of determining the duration of the gripper's motion it was decided to again use the $(r.o.c)^2$ to generate a new set of data as shown in Figure 6.7. The concept deployed was to utilise this $(r.o.c)^2$ data to identify when significant changes occur; it is assumed that changes such as the gripper starting and stopping will in this way be identified. To aid this process a threshold was established with regard to the $(r.o.c)^2$ data, as indicated in Figure 6.7.

The $(r.o.c)^2$ data usually exceeds the applied threshold level. To overcome this, the first minimum from the initial peak was considered to safely mark the beginning of modified data as shown in Figure 6.7. Any data preceding this point in time is discarded. The dsPIC microcontroller can easily identify the initial peak and the minimum thereafter; then start calculating the rate of change in filtered pressure samples, square it, and compare it to the pre-set threshold. The gripping time was observed to be distinct, for each calibrated test piece at any given supply pressure.

An in-depth investigation undertaken into various responses of the gripper operation at a specific supply pressure led to a realisation that the peak sample is fixed, as previously mentioned. This confirms that the motion of the gripper is repeatable. Moreover, previous testing on an actuator system with motion sensors indicates that piston movement occurs slightly prior to the peak sample. The peak sample is easily distinguishable (from a programming standpoint) and hence may be considered as the reference point for the computation of closure or gripping time of the gripper jaws. The same threshold value was found to be applicable to all tests under any operational conditions, and was determined to be equal to 20 (ADC unit). Figure 6.7 illustrates the use of this concept to estimate the gripping time when 6 bar is supplied to the gripper system and a 14 mm part is gripped. It was determined that gripping time could be represented by;

$$GT(m\sec) = \frac{(Nc - Np)}{sampling\_rate} \qquad (6.1)$$

Where, GT = gripping or closure time in milliseconds;

Nc = sample number when $(r.o.c)^2 \geq 20$,

Np = sample number at the initial peak and sampling rate = 2 kHz.

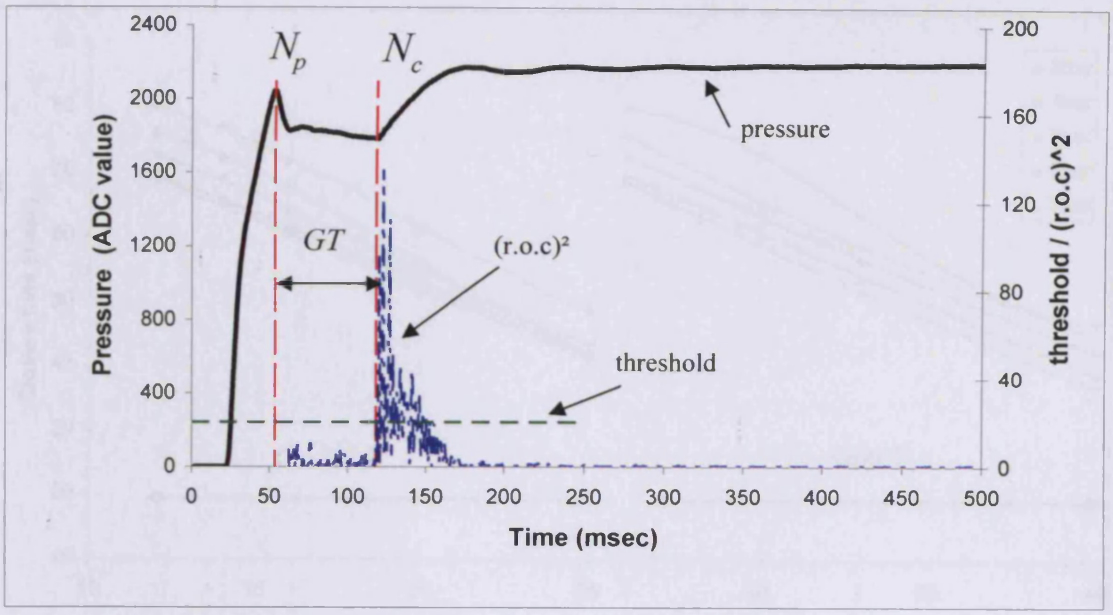


Figure 6.7: Gripping time estimation when a test is performed at 6 bar for a 14 mm workpiece.

The gripper design restricted the use of Grip 2 to parts as large as 26 mm. Thus testing on this grip was limited between 26 and 40 mm while Grip 1 can handle parts of 12 to 25 mm diameters. For parts within these ranges, tests were undertaken at supply pressures of 3, 4, 5, 6 and 7 bar, using each gripping location. A thorough analysis of their transient responses following the above procedure was conducted. Calculated closure (gripping) times using equation 6.1 were then plotted against part diameter for each grip as shown in Figure 6.8. The trends clearly illustrate their variability with respect to the size of gripped object. This process led to the evolution of a surface representing each grip as demonstrated in figure 6.9. From this, a possible relation between gripping time and part diameter at any given supply pressure may be obtained.

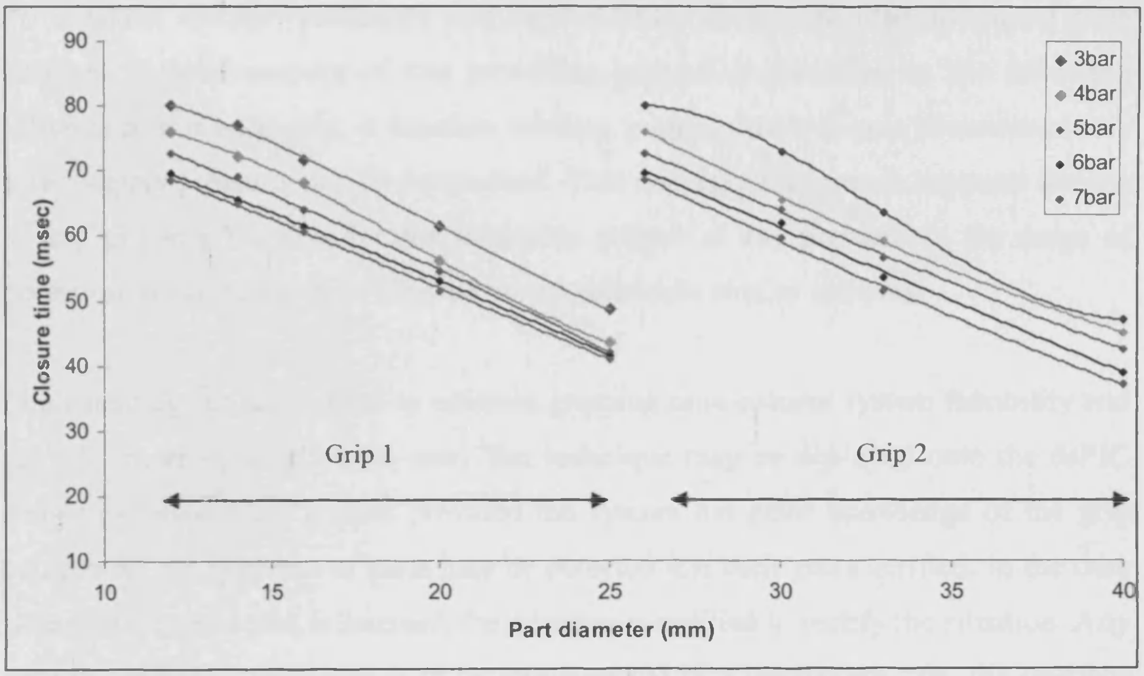


Figure 6.8: Closure time estimations for a variety of parts at different pressures.

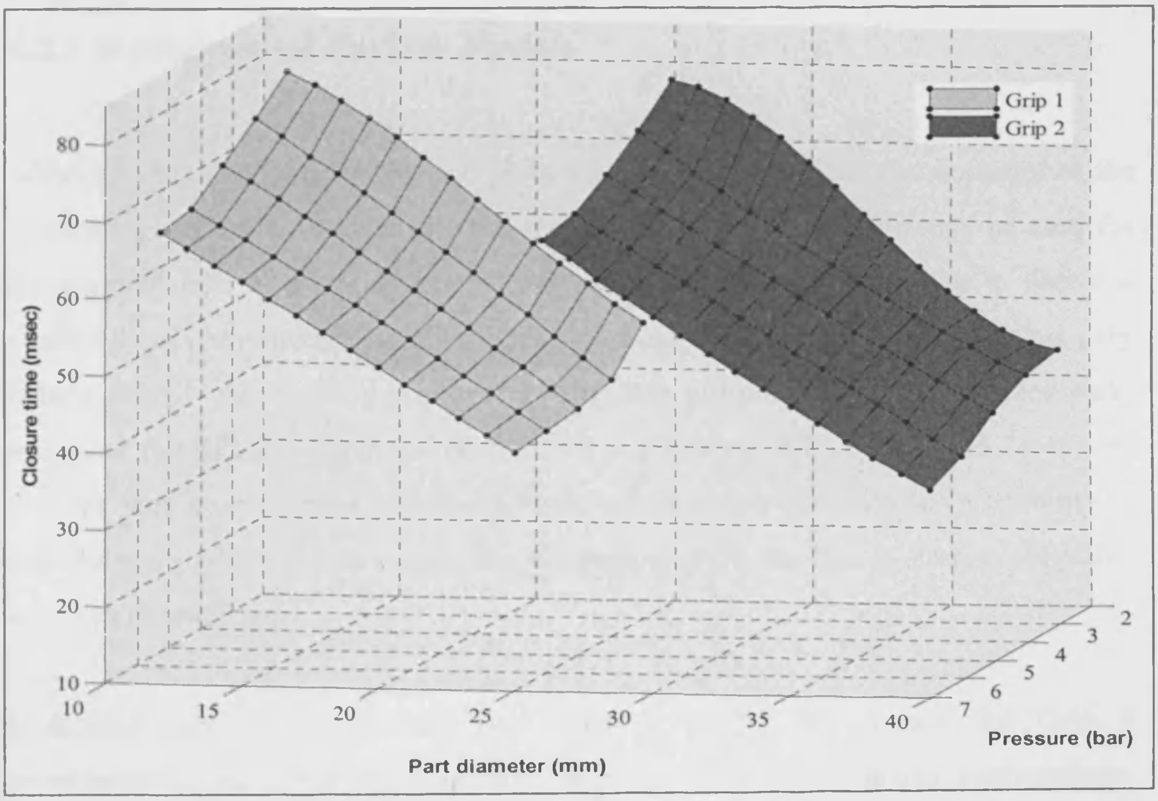


Figure 6.9: The surfaces representing measurements based upon the use of both grips.

To enhance system practicality and applicability, it was decided to model both surfaces. A brief account of this modelling process is presented in the following subsection. For each grip, a function relating gripping time to part diameter at any given supply pressure may be determined. This conceptual approach supports the use of any gripping location for this particular gripper at any pressure in the range of operation. It can however be adapted to accommodate similar grippers.

Implementing surface models to estimate gripping time ensures system flexibility and provides more options for the user. The technique may be deployed onto the dsPIC device to monitor the gripper provided the system has prior knowledge of the grip being used; the presence of parts may be detected and their sizes verified. In the case where an incorrect part is detected, the operator is notified to rectify the situation. Any time the proposed technique is to be implemented in a production line, the operator could run some test cycles to calibrate the system and if required adjustments may be made to the surface model to keep it in line with the process.

6.2.5 Mathematical Surface Models

Although only certain pressures and parts were used in the initial development of the monitoring system, in practice any pressure in the range of operation may be used for the manipulation of many different workpieces. Modelling the surface to derive a single relationship through which gripping time may be estimated would be thus very helpful. It will make the monitoring of a pneumatic gripper during an automated pick-and-place operation a simple task to undertake. Moreover, the surface model provides the user with more options concerning the level of supply pressure and variability in manipulated parts. It makes monitoring the gripper a process that is simple, adaptable and easy to implement.

Dedicated curve-fitting software was used to model the surface for Grip 1 measurements; the modelling procedure is based on a least squares methodology. Fitting observed measurements into a model capable of estimating closure time with a reasonable degree of accuracy was undertaken using an Levenberg-Marquardt (LM) iterative algorithm [6.19]. The convergence happened after fifteen iterations with a tolerance equal to 0.00001. Keeping mean squared error to a minimum was essential to ensure the validity of the model. A single formula expressing closure time as a function of part diameter and supply pressure was obtained. Its parameters were tuned further to attain the best possible match to the actual data measurements using Microsoft Excel. The model can be represented by

$$z = \frac{A_i + B_i x}{1 + C_i y + D_i y^2} \tag{6.2}$$

Where,

$x =$ Part diameter in millimetre,

$y =$ Pressure in bar, and

$z =$ Closure time interval in milliseconds; i represents the grip being used.

The values of the fitting parameters were determined as;

A_1 = 162.84 msec,

B_1 = -3.75 msec/mm,

C_1 = 0.1835/bar, and

D_1 = -0.012/bar^2.

These parameters were obtained so that the model on which a generic monitoring system is based could sustain high quality performance. The model function (equation 6.2) was tested and its performance estimated using a quantitative measure or goodness of fit (R^2). This was found to equal to 0.998, which indicates its highly significant effectiveness, from a statistical standpoint. It actually describes how well the model performs. Supporting evidence in terms of minor variations between observed and predicted measurements can be drawn from Figure 6.10. A tolerance or threshold of ±1.5 msec, as shown in the Figure, was tested providing a good outcome.

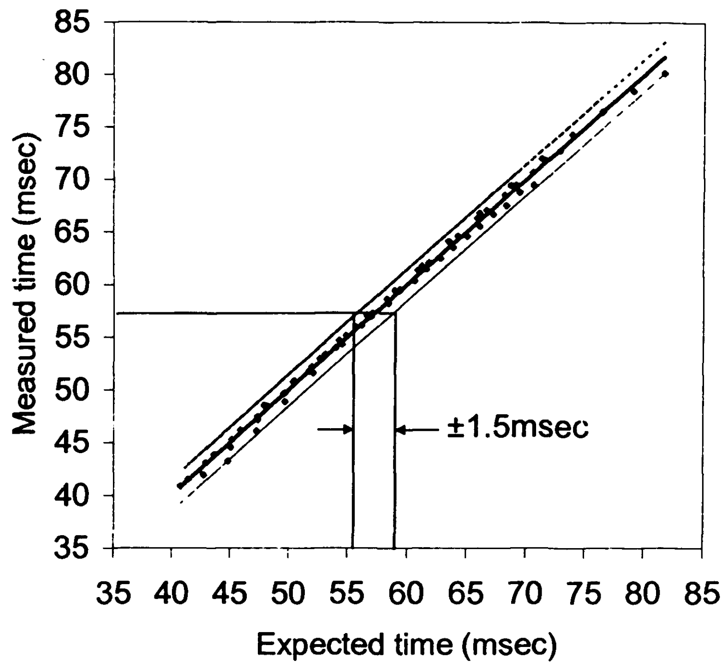


Figure 6.10: Evidence to the quality of the model for Grip 1 movement.

The same approach was followed to model the surface representing measurements when Grip 2 is used. This surface was modelled using an equation similar to (6.2), but governed by different parameters. Another subscript was adopted to refer to the grip being used. Therefore, the parameters obtained to support the use of Grip 2 were found to be,

A_2 = 187 msec

B_2 = -3.25 msec/mm

C_2= 0.098/bar

D_2 = -0.0035/bar^2

In this case a value of R^2= 0.992 was determined; again indicating a good fitting model.

Figure 6.11 shows that the resulting model follows actual measurements well, and preserves the effectiveness and reliability in the prediction of closure time. In this case, a worst case tolerance of ±2.5 msec, as shown in the Figure, was found to be reasonable. It supports the potential of the model equation to monitor the behaviour of Grip 2 movement. Together these models whenever implemented on the dsPIC memory allow the deployment of a compact and low-cost system on an industrial environment where a gripper of such type may efficiently be monitored. By adopting this model and deploying it within the gripping operation means that faults can be detected; the presence of parts and the identification of their sizes may be realized.

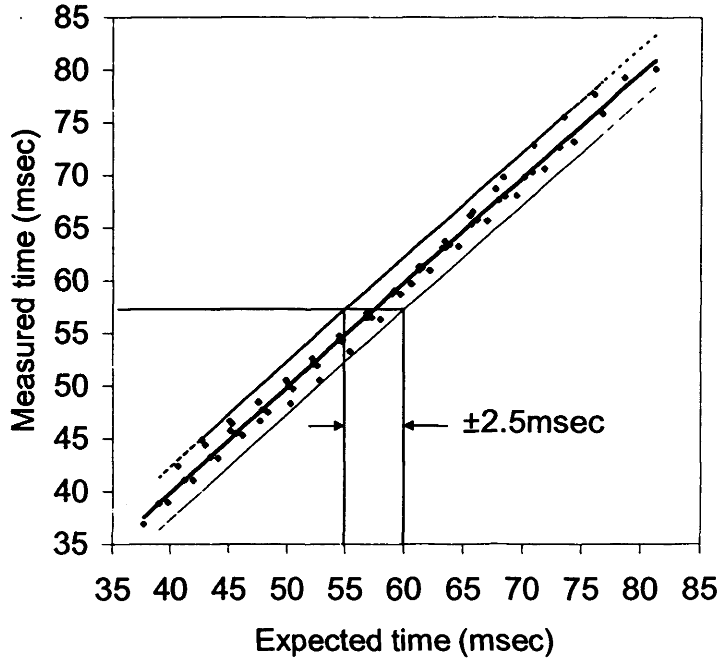


Figure 6.11: Illustration of the model behaviour for Grip 2 movement.

Common faults occurring in such processes include picking the incorrect part, which could sometimes be catastrophic. In an assembly operation, for instance, picking a smaller or a bigger piece than required may impact upon the quality of product being assembled and hence productivity may be hindered. Therefore, assessing the quality in a production environment can be vital. In such situations the proposed monitoring system generates an alarm so that the operator can take action at an early stage in the production process. This makes this process monitoring system of a great potential to all kind of industries. Additionally, fault detection and isolation can improve productivity and lead to reduction in operational costs and downtime. Saving in energy resources can also be significant.

6.3 Fault Simulation Tests

Monitoring the pressure response in pneumatic systems can lead to the possibility of various types of faults being detected and isolated. "Hard faults" such as gripping the wrong part and mishandling the correct one as well as faults in the form of leakage and blockage for instance will affect the characteristics of the response. To this end, a set of in-line calibrated valves were used to simulate air blockages so that the performance of the gripper could be investigated. These valves were located at the inlet (port B) to the chamber responsible for the opening movement of the gripper while the pressure at the other inlet (port A) is being monitored (this is the inlet to the chamber providing the closing motion of the gripper) as shown in Figure 6.12. To simulate the effect of a leak, a needle was also used to pierce a number of holes into the transmission line to simulate leakage in the actuator system. Analysis of the effects of these simulated faults on the gripper operation is reported in the following subsections.

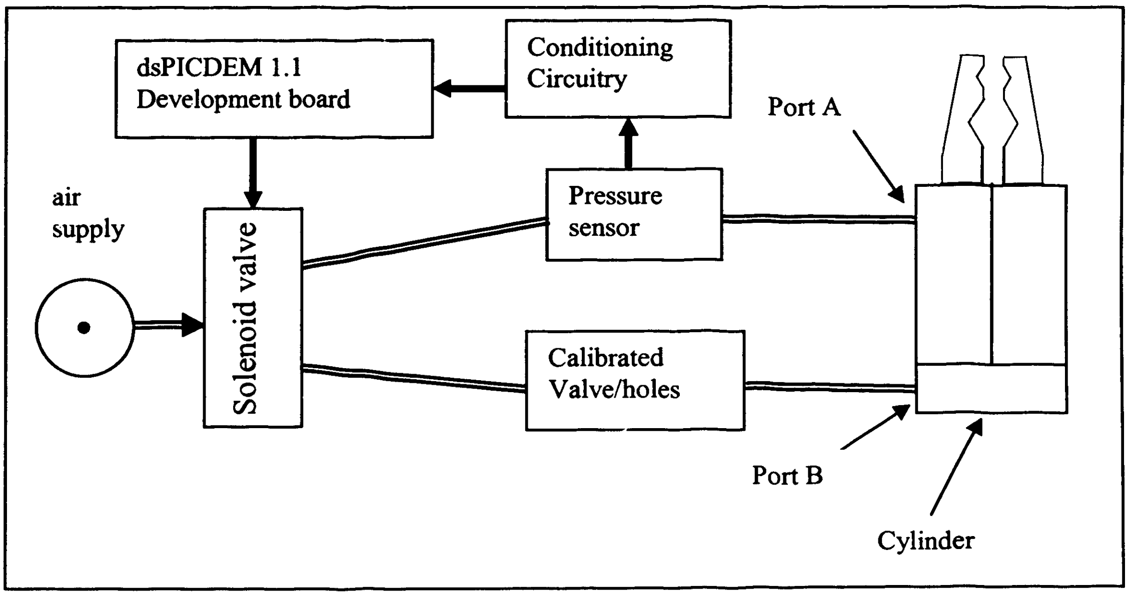


Figure 6.12: System arrangement to simulate leakage and blockage faults.

6.3.1 Effects of gripping the wrong part on the gripper performance

Analysing the pressure response during an assembly or a pick-and-place operation can lead to the detection of faults arising in the process on time before the cycle is repeated. "Hard faults" such as picking the wrong part or mishandling the correct one normally happen in a production line. To simulate this, tests were carried out on two parts (16 mm and 20 mm) at a supply pressure of 4 bar. If the proposed gripper monitoring system is configured to pick a 20 mm part, the pressure response will thus be analysed as discussed before. The gripping time (GT_2) in this case was determined to be 56 milliseconds as would be estimated by the model.

Suppose that a 16 mm part is incorrectly present on the feeding line, the gripping time (GT_1) would be measured and computed to be 68 milliseconds. This differs with the estimated gripping time (that is 56 msec), thus leading to an alarm indicating the picking of a wrong part. Figure 6.13 illustrates the pressure behaviour simulating the gripping of 16 and 20 mm parts at 4 bar. The cycle time is longer for the 16 mm (the wrong part in this given example). Any discrepancy in the characteristics of the pressure response indicates the occurrence of a faulty situation. Data analysis however revealed that the minimum difference in part diameter, at any given supply pressure, that is detectable was approximately 0.9 mm.

This simulates picking a wrong part; further insight on the developed part detection system could be gained through the implementation phase which is introduced in Chapter 7 which follows.

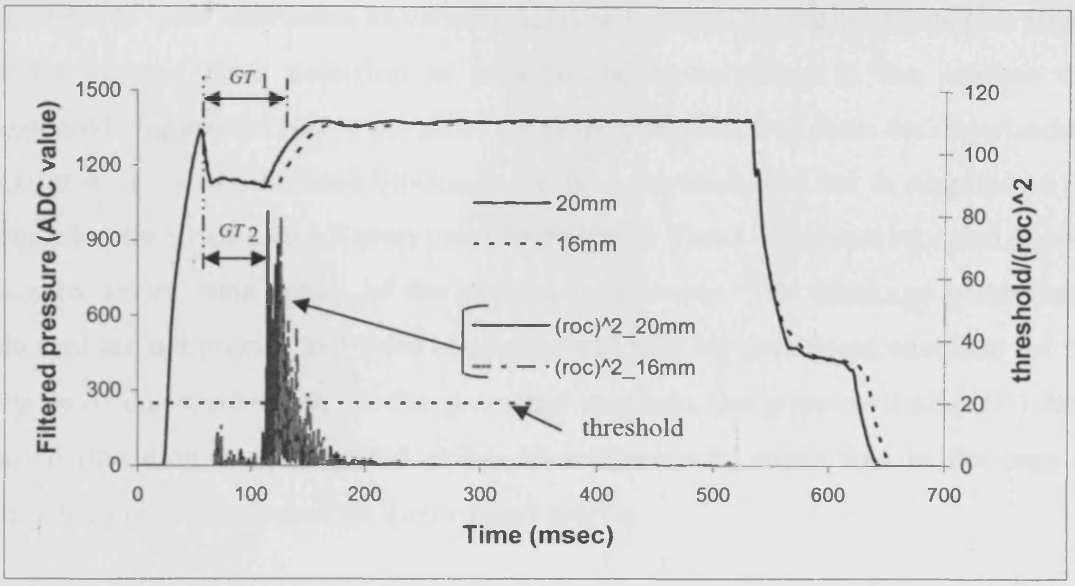


Figure 6.13: Pressure response simulating the gripping of 16 and 20 mm parts.

Since the gripper actions are repetitive and often fast it is critical that any system deployed to monitor gripper operation should be capable of being located within the manufacturing process. Thus the work piece detection system becomes part of the system managing the process; the faulty operation of say a robotic assembly station which is leading to the production of reject products can be detected in time to prevent the manufacture of further products until the problem is removed. Data identified as being "different" may be communicated to a higher supervisory level for further fault analysis. Trends arising, indicating the presence of so called "soft faults" can thus be identified and appropriate maintenance action can be undertaken. Local operators can be notified to take the necessary actions. In this way the gripper error work piece detection system can become part of a condition monitoring process and support a predictive maintenance strategy through which faults can be detected and potential failures can also be predicted. This can lead to improved component reliability and reduced downtimes, thus maximizing system performance and throughput [6.20].

6.3.2 Effects of blockage on the gripper performance

A blockage in the transmission line was simulated to illustrate its effect on the pressure response during the pick-and-place operation. In-line valves (shown in

Figure 6.14) were calibrated to various degrees to simulate partial blockages in the gripper system. Their detection as possible faults occurring in the process was considered. Figures 6.15(a) to (d) show the responses produced from the experimental data for 4 levels of simulated blockages, when a pressure of 4 bar is supplied to the system for the picking of a 20 mm part using Grip 1. These tests were repeated several times to assure consistency of the obtained responses. The blockage percentages indicated are not precise, but were consistent and may be considered adequate for the purpose of this experiment. In the given test example, the gripping time (GT) for a normal operation was computed to be 56 milliseconds, while that in the case of simulated faults is indicated on their related graphs.

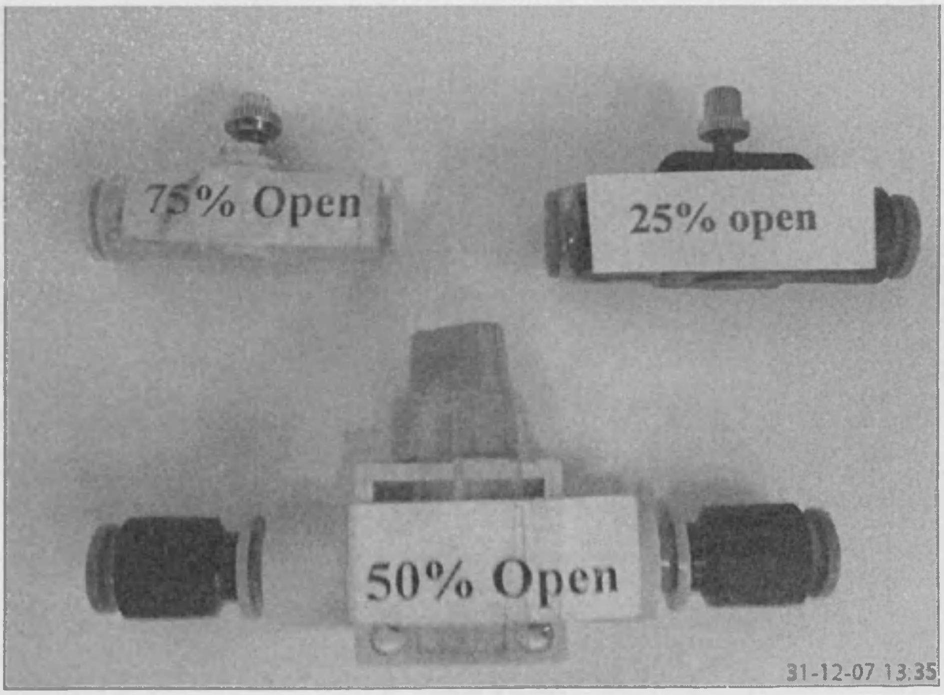


Figure 7.14: Calibrated valves to simulate blockage.

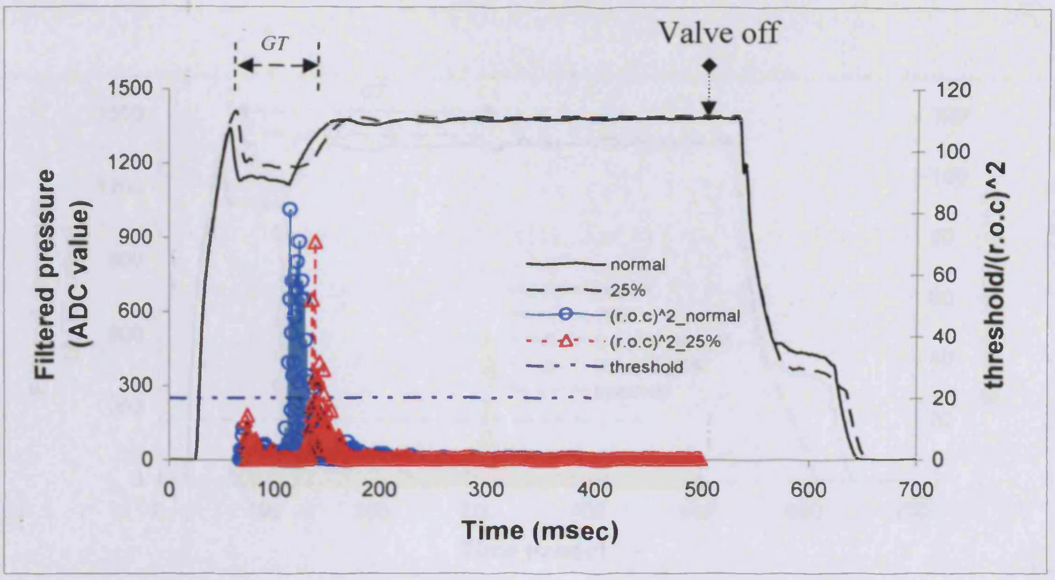


Figure 6.15(a): Pressure responses for normal and 25% blockage tests; GT =72.5 msec.

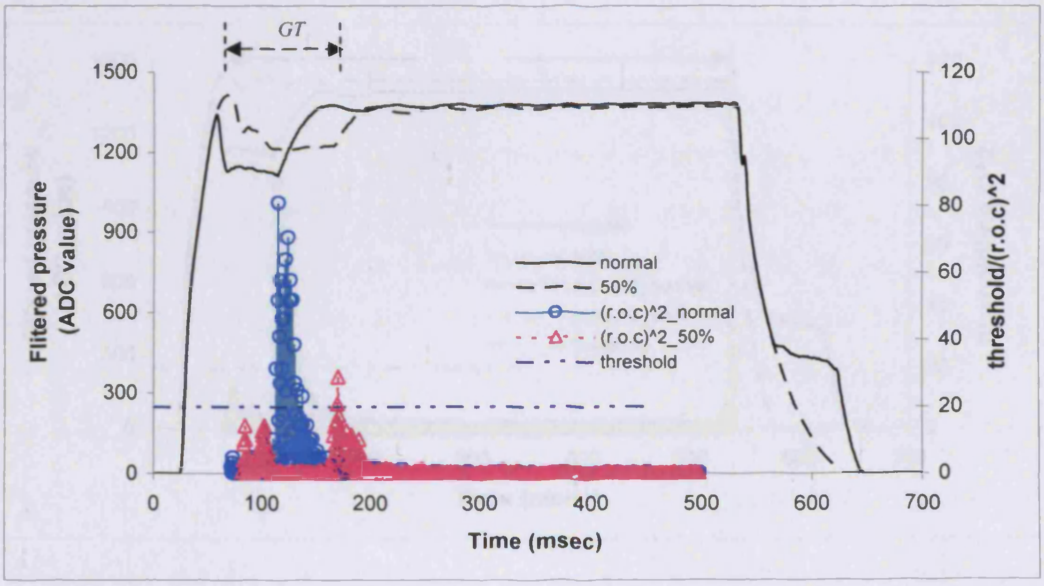


Figure 6.15(b): Pressure responses for normal and 50% blockage tests; GT =102.5 msec.

actually increase with the degree of blockage thus yielding higher values in the rise time of the response. The response also inhibits more fluctuations as the percentage of blockage increases. This led to an increase in settling time. The observed fluctuations in the cases where the blockage exceeds 25%, led to an unrealistic rise in closure (gripping) time (GT). Overall this indicates that the jaws are moving slowly and hence the system would signal the occurrence of a faulty situation. For an operation requiring a certain part to be picked the closure time would be already pre-set from the model and an estimated time set. This will lead to an alarm being generated even though the correct piece is present for manipulation. The operator is then informed to inspect the process to rectify the situation. For the case where the transmission line is 90% blocked, the response oscillates in a decreasing fashion to its steady-state before it falls rapidly down to zero (air has entirely escaped from the cylinder). This behaviour led again to the closure time being unrealistically too large, and lies in fact outside the surface. In this case the presence of the workpiece would not be identified since no movement has occurred. The system would alarm the operator to conduct further analysis in order to identify and isolate the fault.

Other measures may be considered to resolve such issues before the cycle is repeated. For example, the above graphs indicate that once the valve is switched off, assuming the part is placed, the time the pressure response takes to reach zero varies inversely with the degree of blockage. From these experiments, the statistical properties of the pressure may be considered for fault detection and are summarized in Table 6.1. Their computation was based on the set of pressure samples in the region within which the gripping time (GT) is estimated (i.e. between N_p, initial peak sample number, and N_c). Again N_c refers to the sample number when the square rate of change in the pressure exceeds threshold (that is $(\text{r.o.c})^2 \geq 20$), as illustrated in Figures 6.15(a) through (d).

Pressure (ADC value)	Normal process	25% blockage	50% blockage	75% blockage	90% blockage
Mean	1148.55	1205.37	1247.64	1410.47	1419.6
Peak amplitude	1341.4	1411.2	1414.6	1443.2	1451
Variance	2174.46	2278.3	2965.04	118	66.75
Standard deviation	46.63	47.73	54.45	10.86	8.17

Table 6.1: Statistical properties of the response under various degrees of blockage.

For effective fault detection, it is necessary to compare these statistical properties in order to produce more distinguishable criteria. Referring to Table 6.1, it is evident that the mean and peak values of the pressure increases with the amount of blockage as compared to that of normal process (or no blockage). A decision about the health of the process based on the mean value can be conclusive. The increase in variance however is great up to some level of blockage, but it falls drastically for levels beyond 50% blockage. Similarly, it is difficult to discriminate between standard deviations particularly at a blockage level of or below 50%. The blockage could not be quantified due to the discrepancy in the variance and standard deviation factors. But as far as the process concerns, a decision about its health can be accurately determined. The mean value and variance differ clearly with those of a normal process, thus indicating a fault has occurred.

6.3.3 Effects of leakage and faulty seal on the gripper performance

It is possible that leakage and faults arising in the seals within the cylinder can affect the gripper action and thus impact on any pick and place operations. To test this in practice two holes were pierced in the flexible transmission line, as shown in Figure 6.12 above, so that the effect of a small leak could be analysed. The variation in the pressure response was monitored when 4 bar is applied to the system for the gripping of a 20 mm part. This is illustrated in Figure 6.16, together with the response obtained for a non-leaking operation.

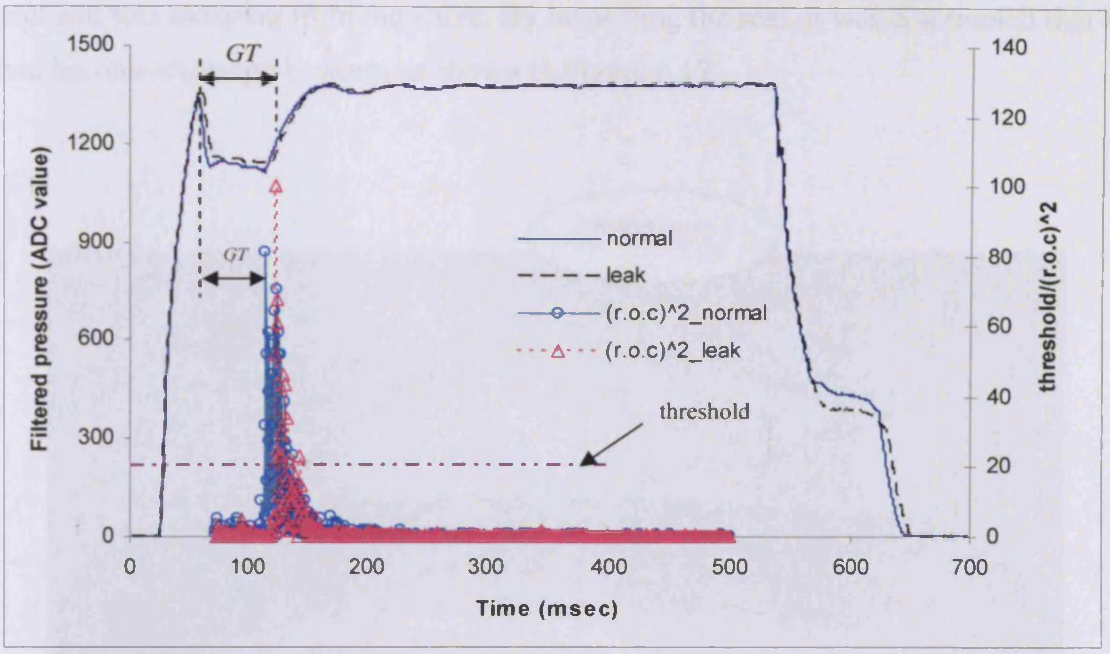


Figure 6.16: Pressure responses for normal and leaking operations; GT = 62 msec.

The transient responses do not provide a clear distinction between normal process and those under faulty conditions, but can be determined analytically. It can be seen that leak led to an increase in peak amplitude. Closure time also increases due to the leak since the square rate of change $(r.o.c)^2$ exceeds threshold later than that of a normal operation. In the given test example, the part has 20 mm diameter and the gripping time would be estimated to be around 56 milliseconds (msec) while that due to the leak was found to be 62 (msec), thus indicating a "wrong" part had been picked. The increase in gripping time would mean that a smaller part is being picked. Consequently, the monitoring system will recognise the situation as indicating fault and hence alarm the operator to inspect the process. The part being operated on is correct (20 mm) nonetheless and the condition can be accurately identified as leak if other measures are considered. The rate at which the response decays is slow as compared to normal case, thus yielding an increase in length of cycle.

The "quad ring seal" on the piston divides the cylinder to two chambers. Upon actuation, pressurised air passes into one chamber pushing the jaws open. When the valve is actuated, air on the other side passes into the other chamber causing the jaws to close. During one phase of testing it was realised that air was passing through the seal and was escaping from the valve. By inspecting the seal, it was determined that it had become excessively worn, as shown in Figure 6.17.

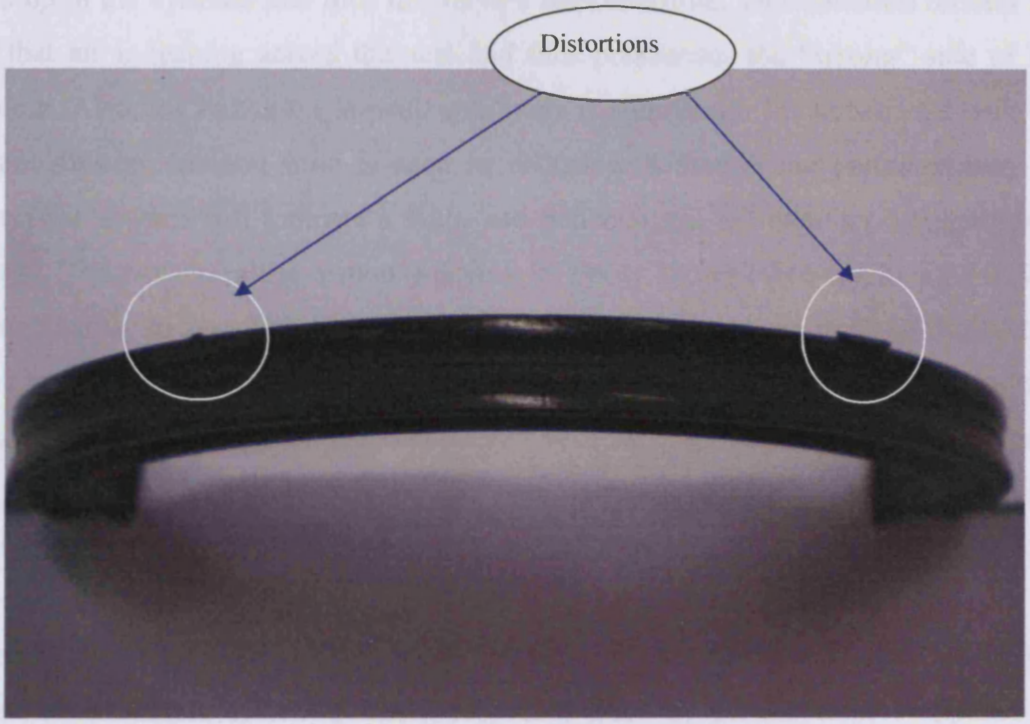


Figure 6.17: The faulty quad ring seal on the piston.

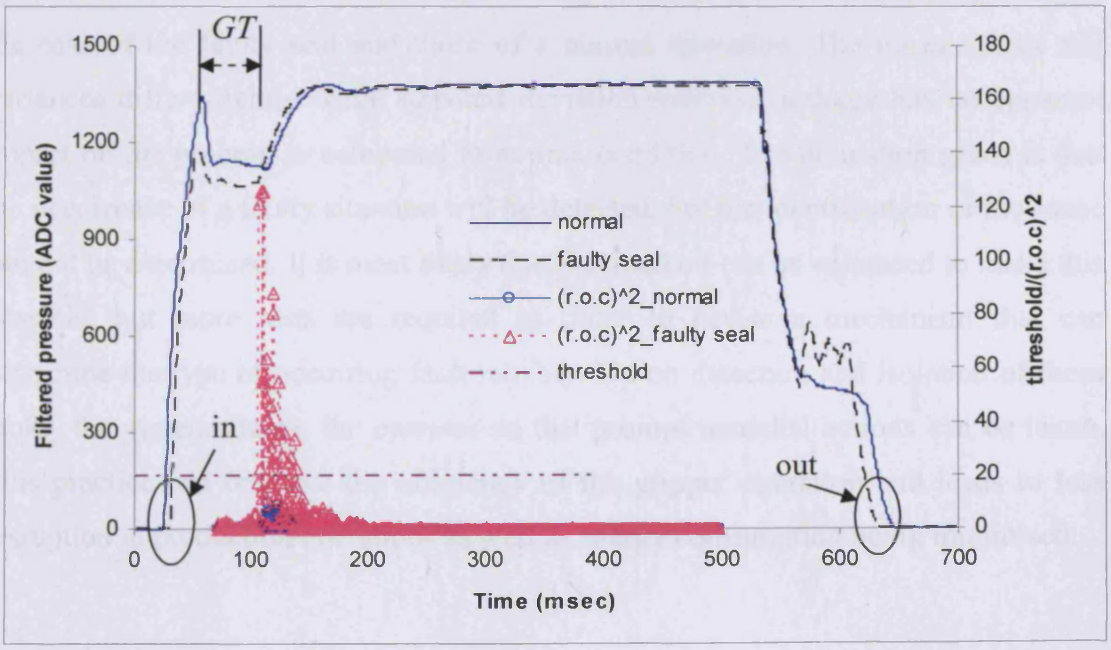


Figure 6.18: Pressure responses demonstrating the effect of a faulty seal; GT = 52 msec.

Figure 6.18 shows that the pressure response produced for the case of a faulty seal is clearly distinctive. It can be seen that the delay or dead time (a common feature in pneumatic systems) has increased corresponding to the slow rate of relative pressure build-up in the cylinder and thus the valve's response time. This situation reflects the fact that air is leaking across the seal and thus pressurises the "wrong" side of the cylinder. Also, the reduction in peak amplitude is significant. In comparison with the normal process, closure time is seen to decrease. Although the part size may be correct the system will indicate a fault, and hence signal the operator to inspect the process. The pattern in the response during its decay shows more oscillations before falling sharply to zero, which is a clear indication to air passing through the seal in conjunction with increased pressure residuals after closing the valve and the cutting off the supply. The faulty seal affects the rate of flow of air into or out of the cylinder (this is indicated on Figure 6.18 by "in" and "out"). The response exhibits a short cycle time as a result of degenerate seal.

Other factors supporting detection of possible faults can be deduced from the statistical properties of the transient response. Such properties were computed as described in the previous subsection and are listed in Table 6.2. A combination of multiple measures could lead to detection of faults occurring during a pick and place operation. By reference to Table 6.2, it is easy to discriminate between properties for the case of the faulty seal and those of a normal operation. The mean values and variances differ slightly while standard deviation indicates leakage has no apparent impact on the process as compared to normal condition. The indication given is that the occurrence of a faulty situation will be detected, but the identification of the cause can not be determined. It is most likely that this method can be enhanced to make this possible, but more tests are required in order to devise a mechanism that can determine the type of occurring fault reliably. Up on detection and isolation of these faults, the system alarms the operator so that prompt remedial actions can be taken. This practice can improve the efficiency of the gripper operation and leads to less disruption in production operations as well as energy consumption being minimised.

Pressure (ADC value)	Normal	Worn out seal	Leak
Mean	1148.55	1078.92	1161.81
Peak amplitude	1341.4	1171.8	1361.8
Variance	2174.46	653.93	2166.79
Standard deviation	46.63	25.57	46.55

Table 6.2: Statistical properties of the response under various conditions.

6.4 Cycle Time Consideration

In automated pick and place processes, the gripper performs the gripping action of a part while a second device (a robot or actuator) provides the required movement to the desired location to place the part and return to the original position. The time taken to accomplish this sequence of events is called the cycle time of operation. It determines the rate at which a product is produced. The production rate can in turn be affected by the feed rate. If the cycle time requires 5 seconds for instance, parts will have to be presented to the gripper in at least 5 seconds for optimum productivity [6.21]. The main elements of a successful pick and place operation may be divided into pick up, transfer and placement of a part which constitute the cycle time. The typical cycle time requires several seconds. The part's weight as well as the complexity of the task can lead to an increase in cycle time [6.22, 6.23].

The capability of a dsPIC based monitoring system for the detection of parts during a pick and place operation is investigated in the following Chapter. The requirements to accommodate the cycle time in order to attain successful operations are also emphasised.

6.5 Summary

The detection of known faults that may occur during the gripper operation such as leakage, blockage and deteriorate seal was considered. Their effect on the performance of the gripper was clearly recognised when diagnostic tests were carried out on the experimental test rig. A method to isolate various faults which may arise in the process was established. In order to diagnose faults accurately, it was also deduced that, a combination of measures must be considered. This method requires a fair amount of tests to ensure clear distinction of symptoms appearing in the process variable, which in this work was the pressure transient.

A generic diagnostic technique was developed based on the measurements of a pressure signal at the inlet of the gripper. This method offers cost effectiveness through the use of dsPIC devices and an industrial pressure sensor. The proposed system can provide useful information about the condition of the gripping operation. The presence of parts being grasped can be detected while their sizes are identified. The gripper may form a work cell in a production line where all processes are linked to a process and condition monitoring and management system. The proposed system has the capability to be deployed in an industrial environment as a plug & play system, thereby enabling the monitoring of a number of grippers. Diagnostic results may be communicated to the system managing the process via either a local area network (LAN) or the internet.

The mathematical surface model-based system allows speedy diagnosis. It is simple and easy to implement. Determining whether or not the picked part is correct could lead to faults being detected before the cycle is repeated, thus saving time, energy resources and maintaining quality levels. The feasibility of using the dsPIC as transient response analysis tool in real-time applications has thus been demonstrated. The implementation of the proposed technique on the dsPIC digital signal controller is presented in the following chapter. Its effectiveness to detect the presence and identify the size of a part being gripped is also explored. The "e-monitoring" capability of the system is possible and may be considered.

References

[6.1] Central Connecticut State University, "Industrial Applications of Computers: Robotics", [WWW].<URL:http://www.technology.ccsu.edu/personnel/information/it500/CH8_PowerPoint_Robotics.ppt#5> [Accessed on 19th October 2007].

[6.2] J. L. Fuller, "Robotics: Introduction, Programming, and Projects", 1991, ISBN 0-13-095543-4.

[6.3] Industrial Robots and Robotics Automation Systems, "Pick and Place Automation", [WWW].<URL:http://www.robots.com/applications.php?app=pick+and+place> [Accessed on 14th July 2007].

[6.4] "Monitoring Control Systems",[WWW]. <URL: http://www.geocities.com/it_khs_2002/control_systems.htm> [Accessed on 5th August 2007].

[6.5] P. Coiffet, M. Chirouze,"An introduction to Robot Technology", 1983, ISBN 0-85038-637-3.

[6.6] G. H. Massiha, "Industrial Applications", [WWW]. <URL: http://vedcc.org/Robotics/itec424/lec5-industrial_application.ppt> [Accessed on 26th October 2007].

[6.7] IntelliDrives Inc., "linear Actuators Blog: Robotic Arms and Robotics", [WWW]. <URL:http://www.intellidrives.com/robots-blog/?m=200607> [Accessed on 30th May 2007].

[6.8] V. Kumar, "Introduction to Robotics",[WWW]. <URL: ftp://137.204.212.13/electronics/robotic/introduction%20to%20robotics.pdf> [Accessed on 3rd April 2007].

[6.9] Wikipedia- the free encyclopedia, "Industrial Robots", [WWW]. <URL: http://en.wikipedia.org/wiki/Industrial_robots> [Accessed on 17th April 2007].

[6.10] D. Hardin, "Designers make robotic grippers with productivity, energy saving in mind", [WWW]. <URL:http://www.industrialcontroldesignline.com/howto/roboticsprototyping/172301304> [Accessed on 23rd December 2007].

[6.11] J. Halka, "Innovations in Robotic Technology and Implementation: Understanding growth in robotics purchasing, and evaluating advances in robotics technology, vision, and multitasking reinforced through an examination of the SIG Pack Delta robot",[WWW]. <URL:http://www.iopp.org/files/Halka_John_Clemson_Robotics.pdf?pageid=pageid> [Accessed on 2nd September 2007].

[6.12] Applied Robotics, "Grippers", [WWW]. <URL: http://www.arobotics.com/technical/tutorials/index.cfm> [Accessed on 5th March 2007].

[6.13] T. Zajac, Jr., "Robotic Gripper Sizing: The Science, Technology and Lore",[WWW]. <URL: http://www.grippers.com/size.htm> [Accessed on 20th July 2007].

[6.14] SMC Pneumatics, "Rotary Gripper", [WWW]. <URL: http://www.smc.eu/portal/NEW_EBP/Level1EU.jsp?ctry=1&id=

9786&pos=Air%20Gripper> [Accessed on 10th December 2007].
[6.15] Festo-Automation, "Standard Grippers", [WWW]. <URL:http://www.festo.com/INetDomino/coorp_sites/en/a4f028c63370f821c1257100003c2a6f.htm> [Accessed on 10th December 2007].
[6.16] FIRSTnemo, "Vex for the Technically Challenged", [WWW]. <URL: http://www.firstnemo.org/PDF/Vex_for_the_Technically_Challenged.pdf> [Accessed on 7th November 2007].
[6.17] D. Collins, "Total cost of ownership for linear motion", [WWW]. <URL:http://www.industrialcontroldesignline.com/showArticle.jhtml?articleID=205208132> [Accessed on December 2007].
[6.18] Trade & Technical Press LTD., "Principles of Pneumatics", 1966, Modern, Surrey.
[6.19] A. Ranganathan, "The Levenberg-Marquardt Algorithm", [WWW].<URL:http://www.cc.gatech.edu/~ananth/docs/lmtut.pdf> [Accessed on 10th March 2007]
[6.20] S. Dunn, "Condition Monitoring in the 21st Century". Plant Maintenance Resource Center [WWW]. <URL:http://www.plant-maintenance.com/articles/ ConMon21stCentury.shtml> [Accessed on 20th Aug 2005].
[6.21] M. P. Groover, M. Weiss, R. N. Nagel, N. G. Odrey, "INDUSTRIAL ROBOTICS: Technology, Programming and Applications", 1986, McGraw-Hill Inc., Singapore. ISBN: 0 07 100442 4.
[6.22] S. Y. Nof, "Handbook of Industrial Robotics", 1985, John Willy & Sons Inc.,USA. ISBN: 0 471 89684 5.
[6.23] H. Makino, M. Tominaga, "Estimation of Production Rate in Flexible Assembly Systems", CIRP Annals-Manufacturing Technology, January, 1995, Volume 44, pp7-10.

Chapter 7

SYSTEM IMPLEMENTATION

7.1 Introduction

The deployment of computer based monitoring is becoming a requirement in many automated activities. The aim is to support the effective management of production equipment and machines. The cost associated with installing and operating these monitoring systems can be high. The aim of this research is to produce a monitoring system that is capable of being placed within the work cell. In this way, data can be collected and analysed close to the signal source. This ensures the integrity of the signals being measured and avoids the need of expensive and complicated wiring.

The developed solution should be compact and cost effective, yet be capable of supporting production, maintenance and management functions in the industrial environment. The solution proposed uses a dsPIC microcontroller device that embodies the processing power and resources and hence can offer a low cost solution to meet the requirements for effective monitoring schemes.

The reliability and repeatability of a system monitoring a pick and place operation in a production environment is essential. In order to prevent incorrect operations it has to be able to detect the presence of parts and identify their sizes in real time before the cycle is repeated. Picking the wrong part can lead to jamming of parts and assembly errors in the product being produced thus affecting the factory throughput, operational cost and profit. The integrity of the pick and place operation should always be maintained at a high level. This chapter describes the implementation of the technique presented in the previous chapter; extracting key features of the pressure transient response which is the basis of this approach.

7.2 Monitoring Approach Adaptability

The essence of the developed monitoring system is adaptability; it must respond to changes arising in the gripper performance. This must provide robustness when faced with changes in the response due to the deployment of a new gripper. The system will also need to manage changes arising as a result of performing any maintenance on the existing grippers. The applicability and ability to learn new gripper properties of the system over a wide range of pneumatic gripper applications is also important.

After the initial development outlined in Chapter 6 the gripper was not in use for sometime. Testing was then resumed to implement the developed system and it was realised that the pressure behaviour had changed. Following a complete overhaul it is believed that the lubricant dried out and the gripper movement was thus slowed due to high friction forces that impeded the motion of the piston. It should be noted that this phenomenon was not planned by the author. But given that it occurred, it was a fortunate situation since it allowed the system's adaptability to be tested and proved. It also provided the opportunity to enhance the dsPIC based solution being engineered.

The gripper was stripped apart, cleaned and oiled, and reassembled. When tested the pressure response was found to behave different than previously reported (Chapter 6). Figure 7.1 shows the response to an example test carried out at 4 bar and a 20 mm work piece. It shows that the transient response was now under damped which reflects changes in the gripper performance. It oscillates with decreasing amplitude until it reaches equilibrium or steady state. The motion is also faster than observed earlier. Such change in behaviour is bound to happen if and when the gripper is replaced or maintained.

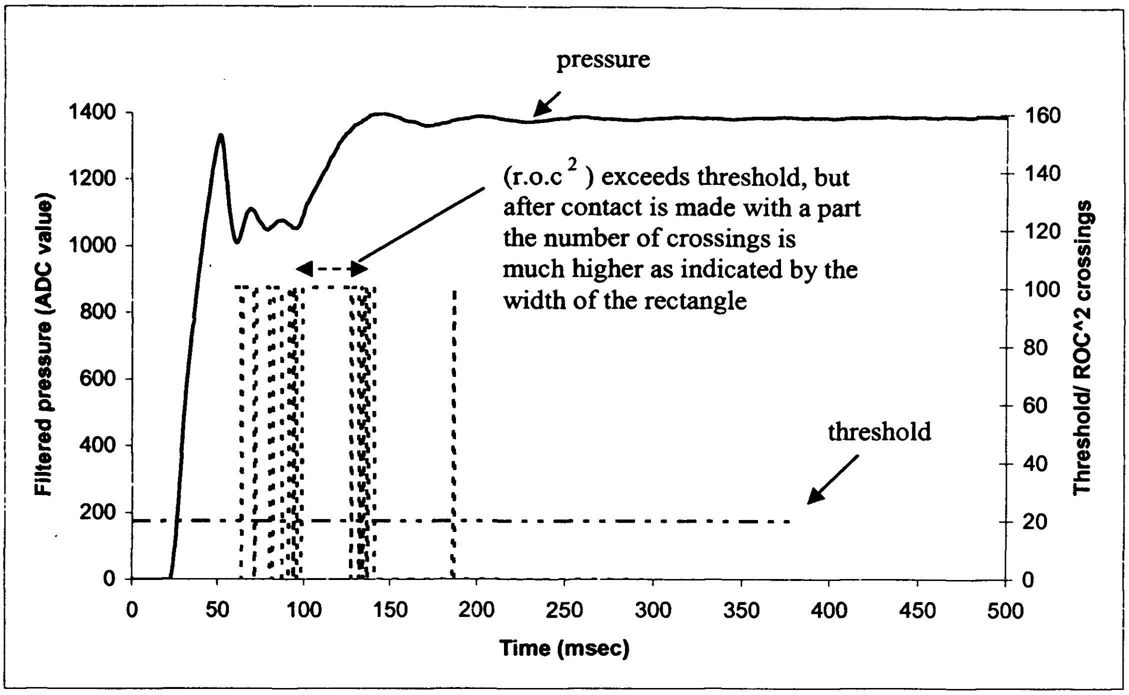


Figure 7.1: Pressure response when a 20 mm work piece is tested at 4 bar.

The algorithm presented in Chapter 6 for the estimation of closure time is still applicable to the new response but with minor modifications. The oscillation between the first minimum from the initial peak and the point when contact is made with the part can lead to false alarms being generated. To avoid this, the number of threshold crossings by the square rate of change (r.o.c^2) was considered as an additional measure to ensure the correct determination of gripping time and eliminate false alarms. This is represented by the width of rectangles between maxima and minima in Figure 7.1. It can be seen that the width of the rectangle or number of threshold crossings is higher as the pressure rises to its steady state (or between final minimum and maximum amplitude). The threshold can thus be changed if required to accommodate any changes in pressure behaviour, so indicating adaptability of this monitoring approach.

Attempts were made to perform a sufficient number of tests in order to reproduce the surface model. That is, the fitting parameters to the equation illustrating the surface. It was decided to obtain the new surface parameters which represent the use of Grip 1 and implement it on dsPIC to monitor the gripper performance. A number of tests were conducted and the same model produced previously was used in the reproduction process. Equation (7.1) represents the surface.

$$z = \frac{A_1 + B_1 x}{1 + C_1 y + D_1 y^2} \tag{7.1}$$

where,

$x =$ Part diameter in millimetre,

$y =$ Pressure in bar, and

$z =$ Closure time interval in milliseconds.

The fitting parameters were determined as;

$A_1 =$ 94.4576 msec, $B_1 =$ -2.309 msec/mm, $C_1 =$ 0.0245/bar, and $D_1 =$ -0.0017/bar^2. The goodness of fit was found to equal 0.995, which indicates a good fit.

7.3 Alternative Filtering Scheme

The oscillations observed after the first minimum must be dealt with carefully to avoid false alarms. The previously applied moving average filtering can only smooth the pressure response. To overcome this, a low pass infinite impulse response (IIR) filter was designed and applied. In general, an IIR filter is a recursive digital filter. Its output depends not only on inputs but also on at least one previous output or feedback. It has at least one pole dependant on the feedback coefficient which should be chosen carefully; otherwise the filter may become unstable. It requires less computation as compared to non-recursive filters [7.1]. The general transfer function has the form;

$$H(z) = \frac{\sum_{k=0}^{k=m} b_k z^{-1}}{1 + \sum_{k=1}^{k=n} a_k z^{-1}} \tag{7.2}$$

where, m (number of zeros) ≥ 0 and n (number of poles) > 0.

The filter designed for this application was aimed at the removal of all unwanted frequency components leading to the observed oscillation. It was empirically determined that this frequency was about 60 Hz. The filter should eliminate this oscillation and still reveal enough information about pressure variations for part size detection. The dsPIC (Filter Design Lite) software (available from Microchip Technology website) was used. A number of attempts were made until the desired filter was achieved to fulfil the requirements set forth. It has two cascaded second order sections as illustrated in Figure 7.2.

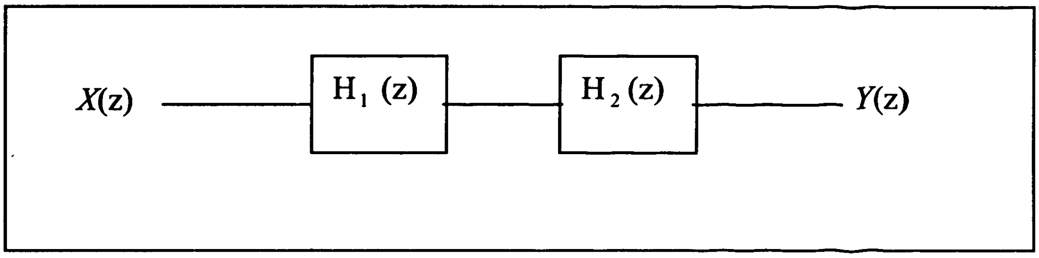
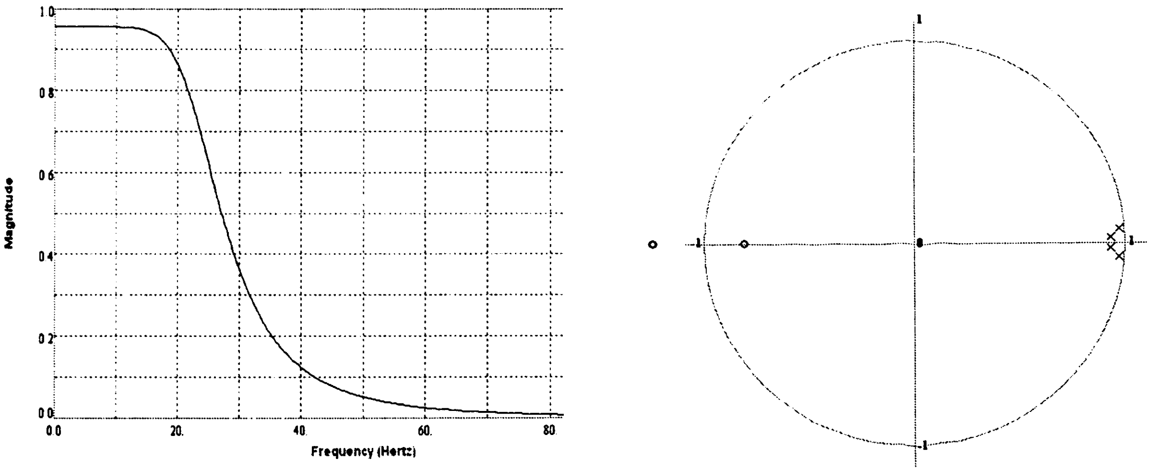


Figure 7.2 Cascaded IIR filter block diagram

The transfer function of this IIR filter can be written as;

$$H(z) = \frac{Y(z)}{X(z)} = K\frac{(z-z1)(z-z2)(z-z3)(z-z4)}{(z-p1)(z-p2)(z-p3)(z-p4)} \tag{7.3}$$

It has 4 poles/zeros as indicated in Figure 7.3 (b). It can also be deduced that the filter is clearly stable so long as all poles (the roots of the denominator in equation 7.3) lie within the unit-circle.



(a) Magnitude vs Frequency Plot; (b) Pole/Zero Plot

Figure 7.3: IIR filter's related plots

Figure 7.3 (a), the magnitude verses frequency plot, shows that 98% of the response was attenuated at 60 Hz while 95% was allowed through the filter at a frequency of approximately 16 Hz. This is the frequency component of the response when it oscillates to its steady state giving a sharp rise to the response peak as shown in Figure 7.4. In simple terms, the magnitude of the denominator in equation (7.3) becomes small at this frequency, which is highly desirable in determining a clear and accurate detection of the gripper-end movement.

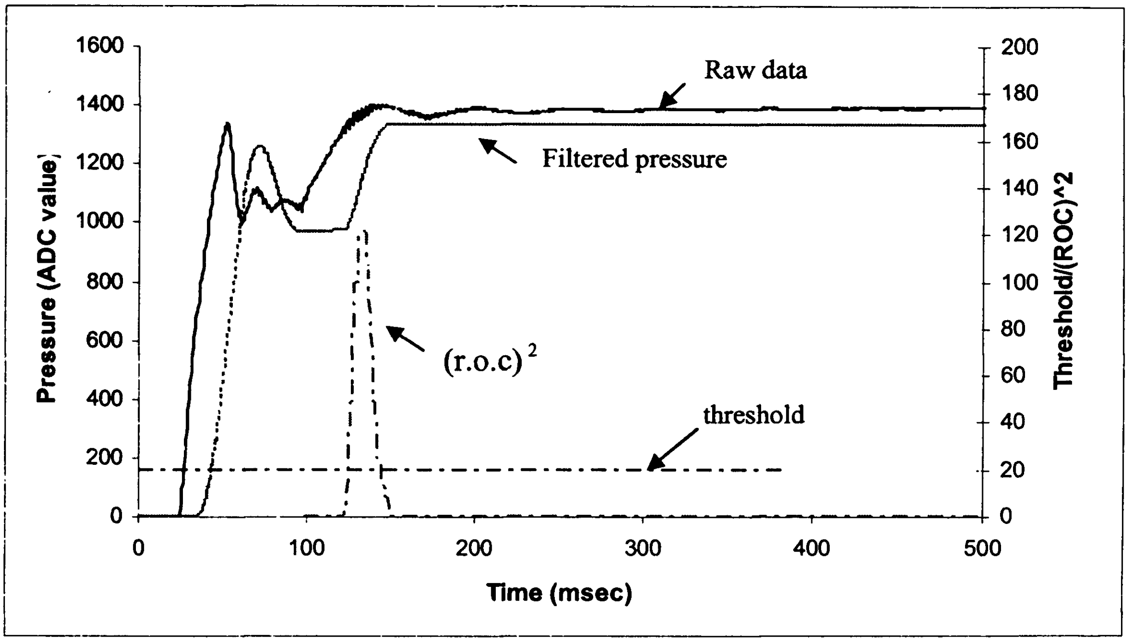


Figure 7.4: Raw and filtered pressure for a test carried out at 4 bar and a 20 mm Part.

It worth noting that this filter was applied to both previous and current tests and its performance was found to be equally good. The performance of the designed filter is demonstrated in Figure 7.4. Once the low pass IIR filter was applied to the response, the $(r.o.c)^2$ was observed to exceed threshold exactly when the gripper made contact with the part or work piece. The dsPIC Filter Design software has the advantage of being able to produce code in the C language so that filters can easily be integrated into a condition monitoring regime. The dsPIC microcontroller has the capability to perform IIR filtering as was shown by research work involving the detection of tool breakage within the IPMM research group activities [7.2]. Nevertheless, moving average filtering process was implemented in this work.

7.4 Surface Reproduction (Updating)

The ability to update surface parameters as quickly and efficiently as possible is of major importance in considering the practical implementation of this approach. Disruption to production can lead to undesired downtimes and loss of profits. Such disruption is unacceptable generally, but even more so should it be caused by failings in the system being used to monitor the quality of the process. Various combinations of pressures and parts were thus investigated to determine the optimum number of tests required to regenerate the fitting parameters. The speed and adequacy of this process need to be balanced; the accuracy of the fit should be maintained. Each combination was tested in order to obtain the surface and a comparison procedure was then carried out in terms of quality of the fit and speed of execution. The outcome to this process is outlined in Table 7.1. It shows that combination 3, which involves the possible minimum number of tests (12 tests) and can be performed over a short period of time to update surface parameters with little loss in accuracy. The system adaptability to changing behaviour was therefore confirmed and it was established that a testing set can be performed and experimental data gathered in a matter of seconds following either a gripper change or some other maintenance related activity.

Combination	Part (mm)	Pressure (bar)	No. of tests	R^2
1	12,14,16,20	4,5,6,7	16	0.995
2	12,16,20	4,5,6,7	12	0.994
3	12,14,16,20	3,5,7	12	0.994

Table 7.1: Optimal testing sets to regenerate the surface.

7.4.1 A dsPIC Modelling Capability Test: A Case Study

To determine the capabilities of the dsPIC an attempt was made to fit a portion of the surface data to a polynomial model. It should be noted that this was not meant to replace the model implemented to monitor the gripper motion, but was undertaken to investigate the dsPIC capability in curve-fitting operations. The model deployed took the form;

$$\hat{z} = A(y+1)^3 + B(y+1)^2 + C(y+1) + Dx + E \tag{7.4}$$

where, x is part size (mm), y is pressure (3-7 bar) and $\hat{z}$ is estimated gripping time (msec), while A, B, C, D and E are the fitting parameters.

To simplify the analysis, suppose (y+1) is replaced by Y. Then the equation becomes;

$$\hat{z} = AY^3 + BY^2 + CY + Dx + E \tag{7.5}$$

For a given set of data (x_i, Y_i, z_i), the best fitting curve $\hat{z}_i$ has the least square error;

$$J = \sum_{i=1}^{n} [z_i - \hat{z}_i]^2 \tag{7.6}$$

where, n = data points or tests and z_i is the measured gripping time.

To obtain the least square error, the fitting parameters must yield zero first derivatives. That is; $\frac{\partial J}{\partial A} = \frac{\partial J}{\partial B} = \frac{\partial J}{\partial C} = \frac{\partial J}{\partial D} = \frac{\partial J}{\partial E} = 0$

Hence, $\frac{\partial J}{\partial A} = -2\sum_{i=1}^{n}[z_i - (AY_i^3 + BY_i^2 + CY_i + Dx_i + E)]Y_i^3 = 0$

$$\frac{\partial J}{\partial B} = -2\sum_{i=1}^{n}[z_i - (AY_i^3 + BY_i^2 + CY_i + Dx_i + E)]Y_i^2 = 0$$

$$\frac{\partial J}{\partial C} = -2\sum_{i=1}^{n}[z_i - (AY_i^3 + BY_i^2 + CY_i + Dx_i + E)]Y_i = 0$$

$$\frac{\partial J}{\partial D} = -2\sum_{i=1}^{n}[z_i - (AY_i^3 + BY_i^2 + CY_i + Dx_i + E)]x_i = 0$$

$$\frac{\partial J}{\partial E} = -2\sum_{i=1}^{n}[z_i - (AY_i^3 + BY_i^2 + CY_i + Dx_i + E)] = 0$$

After expanding and rearranging the above equations, they can be written as;

$$\upsilon = \Phi\beta \tag{7.7}$$

Therefore, the unknown coefficients, β, can be obtained by solving the above linear system. That is;

$$\beta = \Phi^{-1}\nu \tag{7.8}$$

The above algorithm was implemented on the dsPIC and the fitting parameters (equation 7.8) were computed. Similarly, Matlab was used to verify the dsPIC analysis capability and the same solution determined. Tests indicated that the ability of this model to predict gripping time was not as good as the previous solution and hence was not considered for the monitoring of the gripper. The purpose of this task was to investigate the dsPIC capability as a modelling tool.

This case study is not intended to investigate the power of dsPIC. It illustrated limitations, particularly in terms of the resolution (16-bit). Curve-fitting to a polynomial-type model of more than 5 parameters (coefficients) could not be realised to a high degree of accuracy. Higher order matrix inversion requires better resolution. Therefore, dsPIC microcontrollers may not be suited for modelling which involves high order matrices. Personal computers are better choice to undertake such operations. The proposed system outlined in Chapter 3 constitutes a server level is thus recommended for the modelling process. As far as monitoring concerns, the dsPIC is superior to its previous generation of microcontrollers and has the processing capability to offer an alternative economical solution to detect and identify faults which may arise in the process, but it is not able to replace the PC server as the modelling host.

7.4.2 Modelling Mode

The required optimal testing set needed to reproduce the surface parameters has been established above. The tests also indicated that the required data can be gathered. The gripping times for all tests in any proposed combination were computed and stored in the dsPIC memory. The next step now was to determine how to best implement the modelling algorithm. The dsPIC device has a 16-bit processor and accurate curve-fitting in most cases requires more powerful machines with high resolution, especially if the model, such as the one developed in this research work, demands numerical and iterative procedures. The process will also be time consuming. The approach taken was therefore that it is not necessary to generate the surface parameters on the dsPIC. The monitoring task requires that the dsPIC based solution is capable of monitoring the gripper action to determine the integrity of the process. There is no reason why the surface model needs to be calculated within the dsPIC. Indeed the design of the distributed monitoring system proposed in Chapter 3 was based on providing easy access to a server where more advanced software is available whenever further signal analysis and/or modelling is required. It was therefore decided that the surface updating task would be better assigned to the server. Data from the process can be immediately transmitted to the server to perform the modelling function using the architecture shown in Figure 7.5. The parameters can then be sent back to the dsPIC based monitoring system. This solution provides for better utilisation of resources since the server can also be used to maintain surfaces related to all the grippers used within the cell.

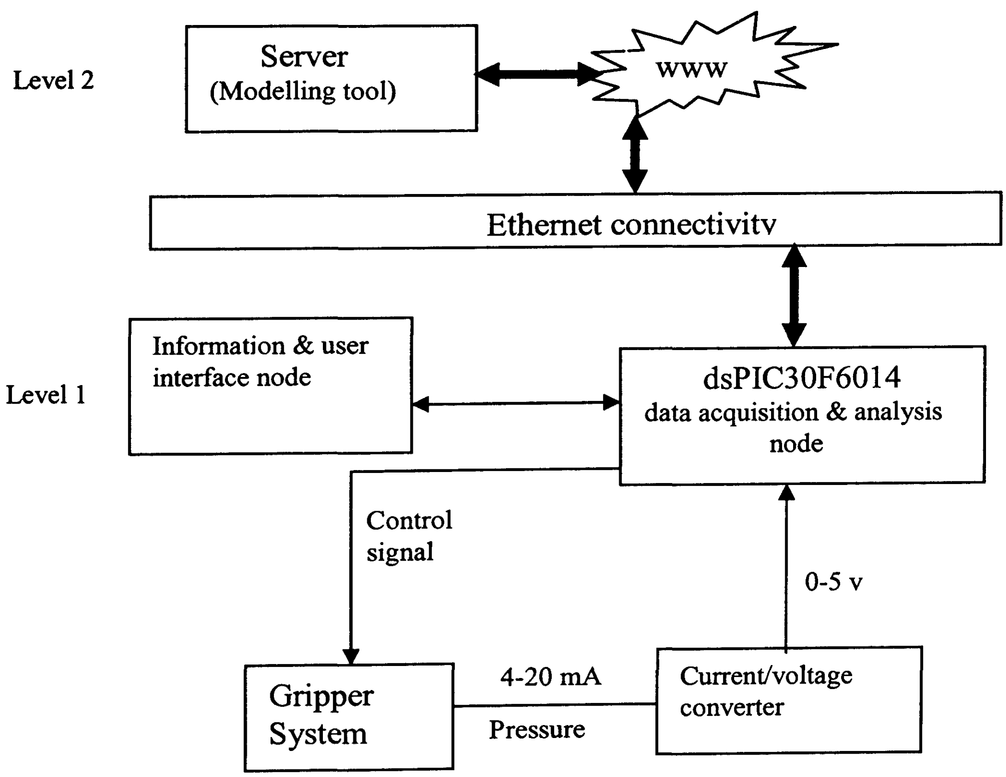


Figure 7.5: Architecture of surface reproduction scheme-Modelling mode.

The developed approach is supported by dsPIC technology called run-time self-programming (RTSP). This method enables changes to be made to an existing program held by a dsPIC device while the device remains in-circuit using a bootloader [7.3]. This program typically requires less than 100 words and remains in the microcontroller memory. Any time the device resets, the bootloader first checks any configured port of communication such as UART, CAN, etc., to see if another device (the server in this case) is attempting to communicate with the target application so as to write new constants to its program memory [7.4]. After a short delay it launches the execution of the user program with the new changes. In this way surface parameters modelled on the server but held in the dsPIC can be updated as soon as they become available.

The developed solution requires that the dsPIC initiates and controls this testing sequence following a perceived change in the gripper performance. The time required for this calibration process would be minutes. This may be justified in order to maintain the required levels of quality control and efficiency. To undertake this process it is recommended that the operator selects an appropriate pressure/dimension combination and performs a gripping operation. This process is repeated until an acceptable model is evolved. The process can be completed over the operational period of the gripper. Each time a change in process occurs, most likely to be related to the part dimension, a "test" cycle can be undertaken by the operator to add to the surface definition. This will cause minimal disruption to the production process since production will be halted to allow for the gripper change. The software flow chart to execute this procedure is shown in Figure 7.6.

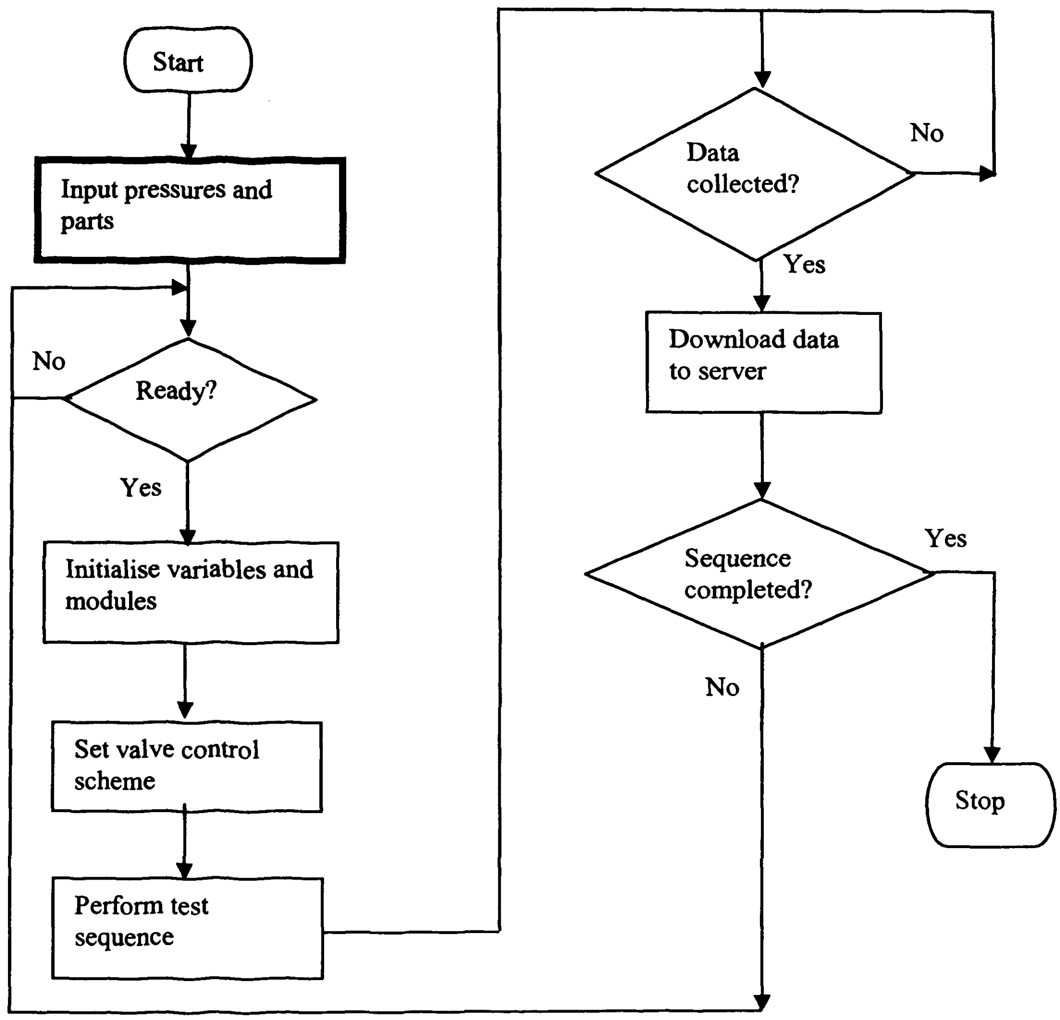


Figure 7.6: Flow chart of data gathering code to update the surface-Modelling mode

7.5 System Implementation

The gripper monitoring system considers the variations in the pressure transient be analysed so that key features about the process can be obtained. The time taken by the gripper jaws to grasp a part during a pick and place operation may be measured. The size of the part being gripped may be accordingly determined. If a wrong part when compared with the model prediction is detected, an alarm is generated to the operator and immediate action is taken to rectify the situation. The system supports data transmission to a higher level so that further analysis can be undertaken whenever required. It should be emphasised that the implemented system supports two functionalities; modelling and monitoring. Figure 7.7 represents the overall system software hierarchy. Upon system power up the device resets, performs the necessary initialisation and waits for functionality mode selection. The mode of operation can be selected as required through the information and interface node available on the dsPIC development board. Selecting mode 1 allows modelling or surface updating to be performed as explained in section 7.4.2. Mode 2 can be chosen to start the monitoring regime of the gripper. Preceding execution of the developed monitoring algorithm, the parameter sequence has to be set. That is, the desired operating pressure and parts required in a pick and place task. Following this stage, the ADC module is reconfigured for monitoring of the pressure response.

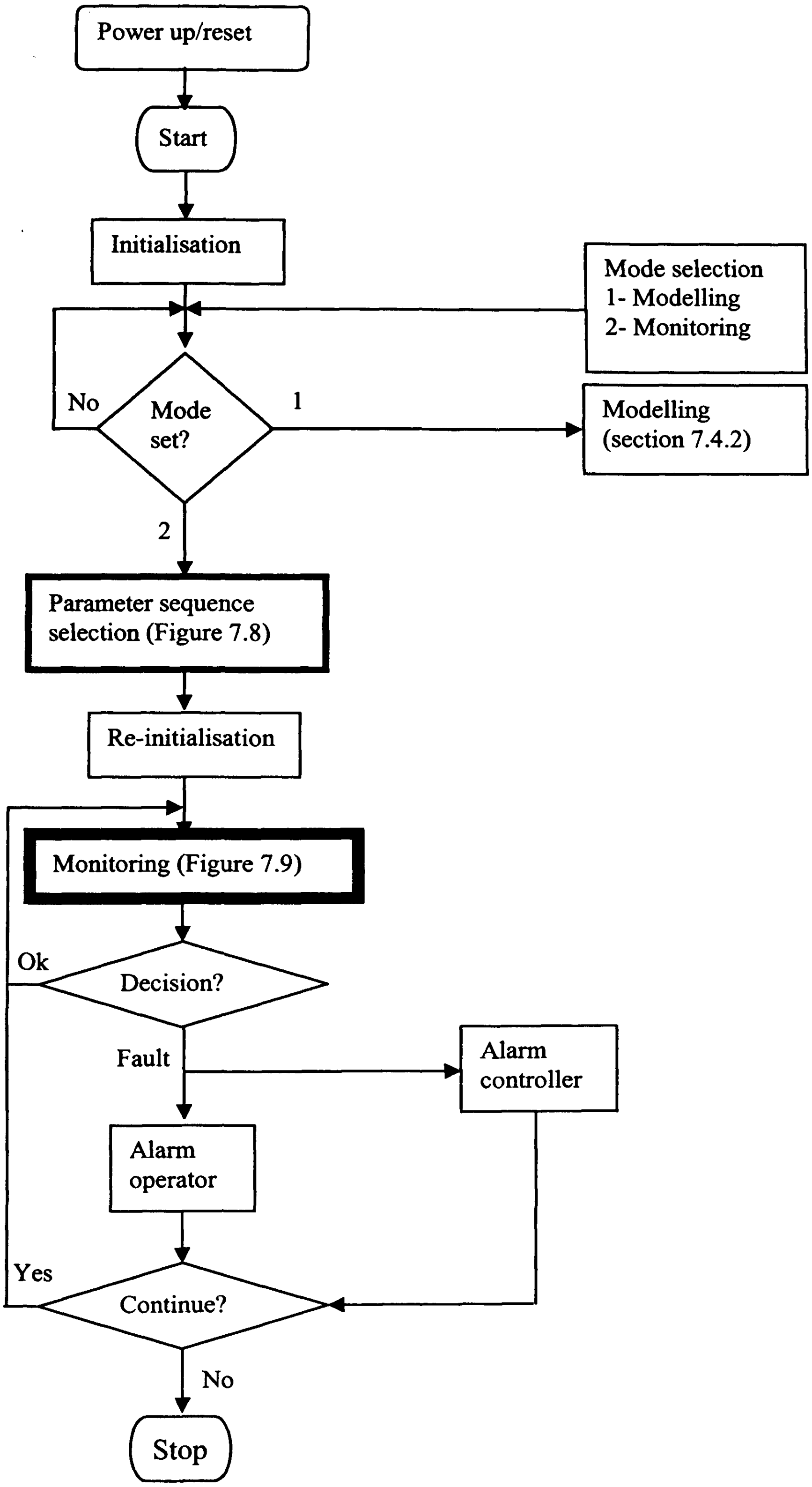


Figure 7.7: Overall system software hierarchy.

7.5.1 Hardware Architecture

The proposed part detection technique is based on the two level system architecture as shown in Figure 7.5. It has the flexibility to be extended to three levels if required by the production management. In this way nodes can communicate with each other. The dsPIC monitoring the gripper may need to communicate with the device controlling the process for instance. The front end node is based on a dsPIC30F6014 digital signal controller to monitor variations in the pressure transient signal. The hardware architecture and detailed features of this device have been reported in Chapter 3. This node connects to the server via an Ethernet link. This allows data to be stored and analysed in the event of an abnormal situation developing. In addition, it provides the means by which surface parameters can be updated as described in section 7.4.2. Before interfacing the pressure signal to the dsPIC, it has to be converted to the correct format. A current to voltage converter is used to perform this function. An information display and interface node enables mode selection to be made; that is modelling or monitoring.

7.5.2 Software Architecture

The software for the transient analysis of acquired pressure response is organised to support the monitoring of one individual gripper. The ADC module is configured for one sample per interrupt. As soon as a sample becomes available, it is processed so that appropriate decision is made about the health of the process in real time. The sampling rate applied in this application is 2 kHz, which yields a 0.5 millisecond sampling period. Therefore, the required processing must be completed before the next sample becomes available (in less than 0.5 millisecond) to avoid false diagnosis results as register values are updated after each interrupt, thus supporting real time monitoring.

The parameter sequence selection may be keyed in using a keypad or other means. It was implemented in this work using the available resources on dsPIC platform. The analogue potentiometers (RP1, RP2 and RP3) were chosen to represent pressure, part size and maximum number of parts in a sequence, respectively. For example, if the desired operating pressure is 4 bar, RP1 would have to be set to 4. The sequence of parts has to be determined and RP2 is set for a particular size using a switch on the board. Another switch is used to confirm that all parts are set. The corresponding gripping times as predicted by the model are then calculated and stored in the dsPIC memory. The ADC module was configured to perform this procedure. The program flow chart of this routine can be seen in Figure 7.8.

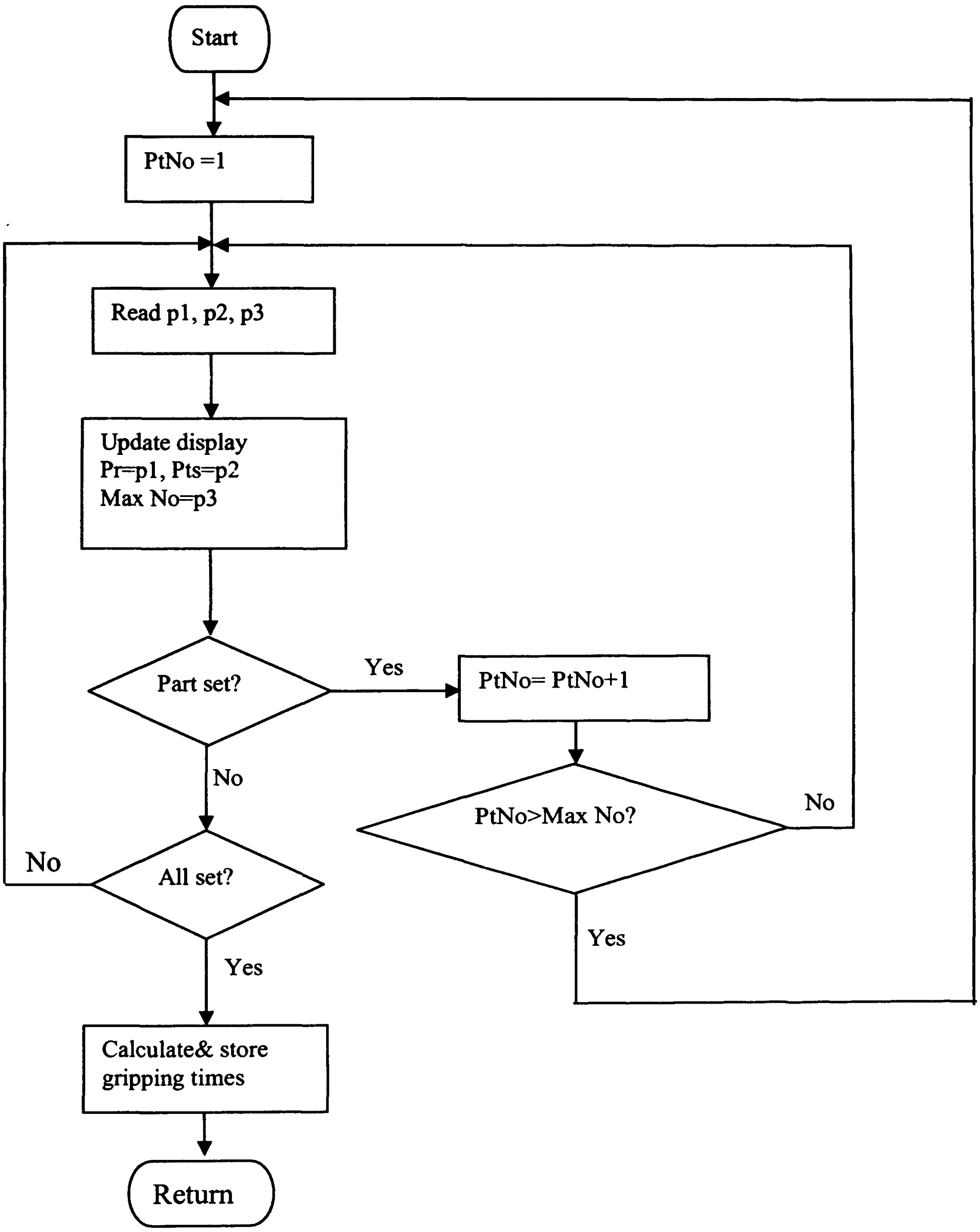


Figure 7.8: The program flow chart- parameter sequence selection.

Key: p1, p2, p3 refer to RP1, RP2, RP3, respectively.
Pr =pressure, Pts= part size; and PtNo= part number in the sequence

The developed monitoring technique uses a moving average filter to remove unwanted noise and random variations in the signal. The high frequency component should also be attenuated in order to obtain reliable information. Laboratory testing revealed that a 5-point moving average filtering process provided a smooth signal. The output, y(n), of this filter can be mathematically expressed as a function of its input, x(n), as;

$$y(n) = \frac{1}{5}\sum_{k=0}^{4} x(n-k)$$

The flow chart to execute this monitoring routine is shown in Figure 7.9. This can be thought of as a convolution of the filter's input with a rectangular pulse having an area of one. The monitoring system waits for five samples to be collected before filtering is applied. The consequent filtering process requires around 20 instruction cycles which amounts to approximately 2.7 microseconds at 7.3728 MHz oscillator frequency. The start of the process is determined by the significant increase in the pressure (state 0). Once this state is realised the system tracks variations in the pressure transient until the initial peak is identified (state 1). The ADC index is then captured and stored in the peak sample (Np) variable which is considered as the possible start of motion. The system keeps observing changes in the pressure until a minimum is identified (state 2). From this point forward, the square rate of change is calculated, while another peak is determined (state 3). It compares square rate of change and counts the number of times it exceeds the preset threshold (state 4). When this point is identified and the number of threshold's crossing exceeded a preset value, the ADC index associated with the first crossing is recorded as "Nc" (the sample number when a part is gripped), and the gripping time is calculated.

Subsequently, the gripping time is compared to the model prediction for the associated part, if there is an agreement within a reasonable tolerance the process is regarded as healthy and the next cycle is executed. Otherwise, a wrong part is detected leading to an alarm being generated and the process halted. It is suggested that in this situation the system waits for instructions from the controller as to whether to remove the part or to proceed with or stop the operation. The operator may remove the part and allow the continuation of the operation.

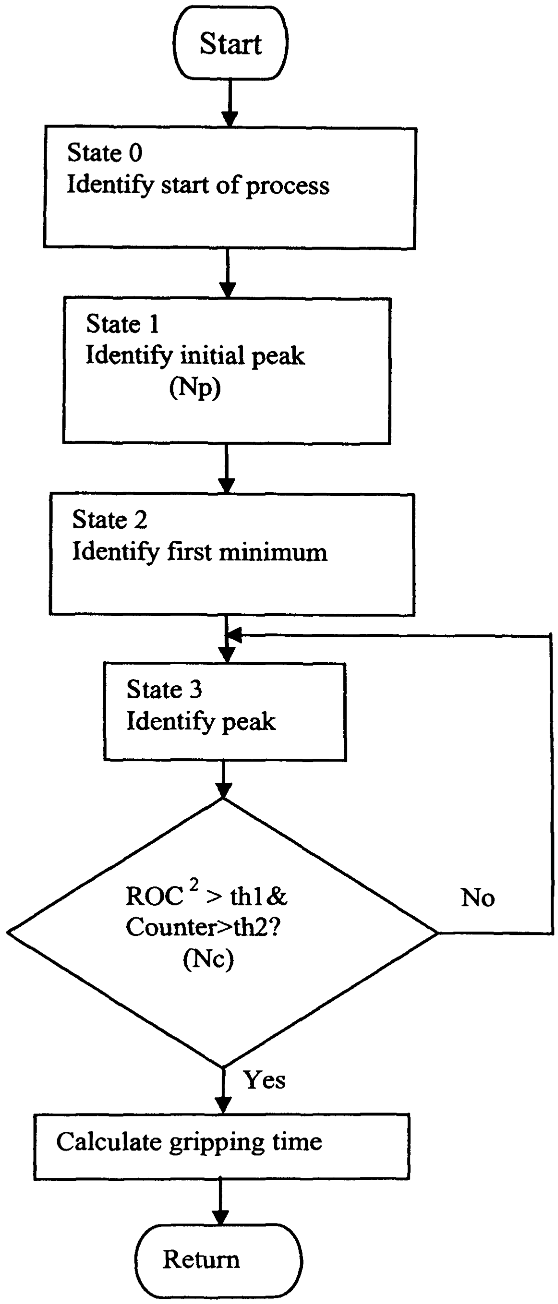


Figure 7.9: Software flow chart- Monitoring mode routine.

7.6 Discussion and Results

The gripper fingers or jaws can either be an integral part of its mechanism or are attached to it. The gripper used in this work is of the latter. The advantage of this is that these fingers can be replaced to accommodate a range of parts. In this way, various sets of fingers can be used to handle different parts. To monitor any situation a surface would have to be generated in order for the gripper performance to be monitored. This may be a new surface or an updated version of a previously developed one.

An effective and reliable monitoring system should be designed to satisfy the required cycle time. Although the part size is determined during the pick up portion of the cycle time, monitoring the pressure response during transfer and placement times may also reveal any faulty situation occurring in the process. It is extremely important to detect faults before the cycle is repeated to maintain high level of quality and efficiency. It is also important that the monitoring device should be able to manage the task.

The dsPIC30F6014 digital signal controller used here contains a 12 kB (RAM); about 4 kB were used for stacking and routine calling leaving the remaining 8 kB of data space available for the execution of the target application. This allows for 4000 samples (integer) to be stored; an equivalent to 2 seconds worth of data at a sampling rate of 2 kHz. If a pick and place operation requires more than 2 seconds, additional data memory would have to be facilitated to allow for effective continuous monitoring in order to achieve a successful operation. To overcome this limitation the dsPIC30F6014 was used. One of dsPIC30F6014 main attributes is a program memory of 144 kB; of which 32 kB can be mapped into data space, thus allowing for an additional 16000 samples to be stored if required. Altogether, a total of 10 seconds of data can be stored.

As far as the processing requirements, one major consideration is the device frequency or speed. This device operates at 7.3728 MHz which yields 7.3728 million instructions per second. Hence, the time required to execute one instruction is 0.135 microseconds.

At the above mentioned sampling rate, data has to be processed and any decision made in less than 0.5 milliseconds. The required communication activities must also be completed within this sampling interval. This is clearly dependant on the number of instructions required by the processing mechanism. If and when required, the device frequency can be increased by a multiple of 4 or 8, thus yielding a minimum 0.034 microseconds per instruction. This allowed the monitoring technique to be improved to detect various faults which may occur during a pick and place operation or an assembly task. Furthermore, faster operations requiring lesser cycle times can be accommodated with this device. A sampling rate up to 100 kHz can be achieved, but data would have to be processed in less than 10 microseconds.

To assess the effectiveness of the developed technique, a number of tests were conducted at various supply pressures. At first the operating pressure was set to 3 bar while the sequence of parts to be manipulated was set to 14, 15, 16, 20 and 25 mm. Among the expected parts, a 15mm part was imposed upon the model to evaluate the accuracy of the monitoring system. In reality this part did not exist. The system compares actual and expected gripping times for each part. Based upon the analysis carried out in Chapter 6, the tolerance was, in this case, set to 1.5 msec. The actual parts presented to the gripper were 14, 16, 20 and 25 mm. The process was initiated depicting a pick and place operations. The testing procedure was set so that a 14 mm part is presented five times. The same procedure was followed with every part, thus yielding 20 tests for 3 bar supply pressure. This was repeated for 4, 5 and 6 bar supply pressures. The results of the monitoring system are shown in Table 7.2.

Pressure (bar)	Actual part size (mm)	Expected part size (mm)				
		14	15	16	20	25
3	14	i	c	i	i	i
	16	i	i	c	i	i
	20	i	i	i	i	i
	25	i	i	i	i	i
4	14	i	i	i	i	i
	16	i	i	c	i	i
	20	i	i	i	c	i
	25	i	i	i	i	c
5	14	c	i	i	i	i
	16	i	i	c	i	i
	20	i	i	i	c	i
	25	i	i	i	i	c
6	14	c	i	i	i	i
	16	i	i	c	i	i
	20	i	i	i	c	i
	25	i	i	i	i	c

Table 7.2: Results of the monitoring system.

Key: c = correct part is detected
i = incorrect part is detected
false detection   correct diagnostics

In the event that an incorrect part was detected, an alarm was generated and a message was sent to the LCD display on the dsPIC platform, thus indicating a wrong part was being gripped. It can be seen that false alarms were generated at low pressures particularly at 3 bar, the lowest operating pressure. It is possible that the effect of friction forces on the gripper movement limits the accuracy of the monitoring system at low pressures. In total 80 tests were performed in these pick and place operations. The results indicate that the monitoring system was capable of making the correct diagnostics about the gripper performance as required with 93.75% accuracy. This however can be improved by performing experiments on a large number of parts with small variations so that the surface model can be optimized.

7.7 Summary

The adaptability of the gripper monitoring system was illustrated and proven to be capable of detecting faults arising in the process and in real time. The means by which surface parameters can be updated in a speedy process was also proposed.

The capability of the dsPIC microcontroller as a modelling tool was investigated. It shows that the complexity of a surface model may restrict the use of this device to model real life applications.

The monitoring system hardware and software architectures were discussed. It was deployed in a situation depicting pick and place operations and the outcome was promising. The system was shown to be able to detect the part being processed and identify its size before the cycle is repeated. It is anticipated however that operational and environmental conditions may lead to changes in the behaviour of pressure transient and hence affect the accuracy of the system. Non sufficient lubrication for instance was observed to cause a significant drift in the transient from normal conditions. Dirt and moisture in transmission lines in addition to ambient temperature may also contribute to the sensitivity of the system.

Cycle time is a crucial consideration in automated pick and place applications for effective and reliable monitoring. It can lead to other aspects in a production environment being emphasised to optimize productivity. The dsPIC capability in terms of data memory and processing speed to satisfy cycle time requirements has been assured and its suitability verified.

References

[7.1] W. Kester, "Mixed Signal and DSP Design Techniques", [WWW]. <URL:http//www.analog.com/static/ imported- files/tech_docs/MixedSignal_Sect6.pdf> [Accessed on 4th April 2008]

[7.2] R. A. Siddiqui, W. Ameer, Q. Ahsan, R. I. Grosvenor, P. W. Prickett, "Multi-band Infinite Impulse Response Filtering using Microcontrollers for eMonitoring Applications", Journal of Microprocessor and Microsystems, September, 2007, Volume 31, pp370-380.

[7.3] "Tiny PIC bootloader", [WWW]. <URL:http://www.etc.ugal.ro/cchiclita/software/picbiitloader.htm>. [Accessed on 18th July 2008]

[7.4] L. Elevich, V. Kudva, "Bootloader for dsPIC30F/33F and PIC24F/24H Devices", Application note (AN1094), Microchip Technology Inc.

Chapter 8

DISCUSSION

8.1 Summary

Three applications were researched in this work. Compressed air provides the power by which these applications are driven. The first considered leak detection in gas fitting pipes. The second aimed at monitoring of a linear actuator so that end of slide (stroke) may be determined as required by its application. If an undesired position is detected, the monitoring system generates an alarm to the person attending the process. The final application was the monitoring of a two-finger parallel gripper during pick and place operations. A technique capable of making the correct diagnosis about the part being gripped was developed and validated. One dsPIC device was used in each application as a standalone system. The speed at which the health of the process can be determined and the amount of data required for the diagnosis were principal requirements. Therefore, pressure transient analysis was the basis of the developed techniques.

The approach adopted throughout this research was aimed at the deployment of minimal sensors and electronic circuitry. The cost and effectiveness of each of the developed monitoring system supports its possible deployment in industrial processes. In addition each monitoring function considered varying the operating pressures, thus adding flexibility to the system. The monitoring system is in this sense generic. In the case of linear actuator and parallel gripper, the developed monitoring system considered all levels of pressure within the range of operation. In other words the pneumatic system could be monitored at various supply pressures.

8.2 A Process Management System

Although each application dictated the development of a designated monitoring system, they can be integrated together to form one distributed modular system. A pick and place station such as the one shown in Figure 8.1 consists of two linear actuators (similar to the one used in this research) and a gripper. It is proposed that the developed systems can be deployed as modules or front-end- nodes supporting the distributed architecture shown in Figure 8.2. This allows for the monitoring of a number of stations in a production line. Upon detection of faults, it could be brought to the attention of operators, to take the appropriate remedial action, in real-time. Faults may also be reported to the system managing the process. When required, data can be transmitted to the higher level where advanced tools are available for analysis and/or record keeping. The server level also provides the developed monitoring system with advanced modelling software to support the reproduction of surfaces produced in this research. If the monitoring system was unable to detect a fault occurring in the process, further analysis can be performed and new fault symptoms defined and sent to the low level nodes (monitoring nodes) to update the monitoring capabilities using the run-time self programming as described in Chapter 7.

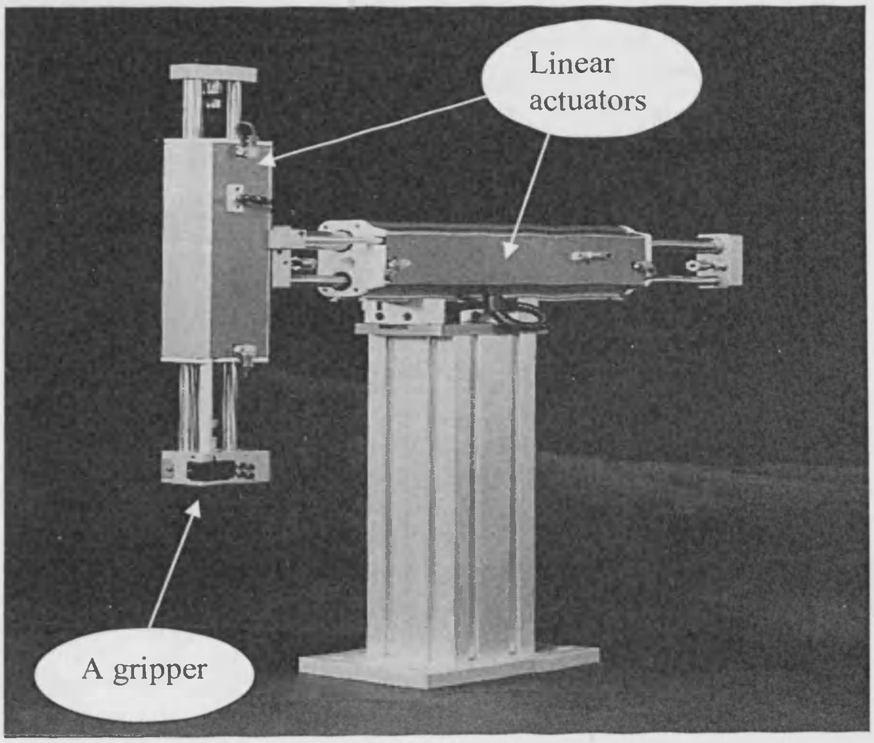


Figure 8.1: Pick and Place station [8.1].

The information and user interface node facilitates process parameter setting and manages the message display for the operator. Operating pressure, surface parameters and part size can be set through this node or downloaded from the server level. Nodes may need to communicate with each other (via CAN bus) to allow for a collective decision to be made. The linear actuator node may signal the controller once the end of stroke is confirmed to trigger the motion of the gripper. The gripper node could then be suitably informed to start monitoring its performance. CAN bus is a reliable and fast medium to facilitate such communication amongst nodes.

The connectivity node (middle node) provides the system with more processing power whenever local advanced analysis is required. This node also supports the synchronisation of data transmission and message passing between monitoring nodes and the server. The technical attributes and features of the dsPIC controller as well as the information related to CAN and Ethernet protocols, which were covered in Chapter 3, can be utilized to implement this system. The HTTP/FTP web servers can be implemented with TCP/IP protocol to enable e-monitoring of the production environment. In this way a predictive maintenance and management strategy may be realised.

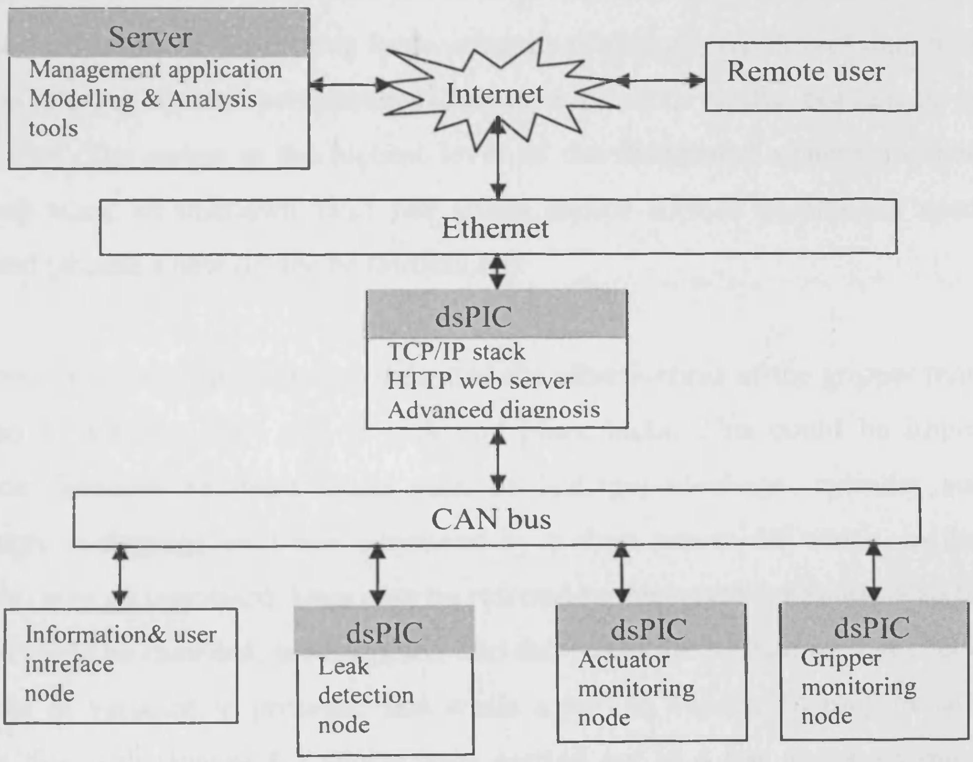


Figure 8.2: Architecture of the process management system.

The literature review, provided in Chapter 2, identified that no monitoring system based entirely on microcontrollers has been developed. That is a system in which data acquisition and analysis are accomplished using microcontrollers in order to determine the health of the process. The use of microcontrollers was limited to data acquisition and/or control functions. The potential benefits for low cost, yet effective monitoring systems, was evident throughout the review.

This research investigated the deployment of a powerful microcontroller (the dsPIC) with digital signal processing capability to undertake the monitoring solutions in industrial applications in general and pneumatics in particular. The capability and suitability of such a device was demonstrated through the monitoring of pneumatic systems. Higher production efficiency and reductions in operational costs may be achieved by deploying these small devices, since they are well suited for noisy and space limited environments.

The dsPIC devices were considered in this research for their processing potential in order to bring to the front-end-nodes the capability to detect and diagnose most known faults. This allows the connectivity node to be used only to communicate messages and process status and eliminates the need to transmit large amounts of data unless deemed necessary. Transmitting large volumes of (largely repetitive) data may affect the monitoring system performance due to a possible traffic bottleneck in some situations. The server at the highest level of the distributed system architecture is utilised when an unknown fault has arisen and/or surface parameters need to be updated (should a new device be introduced).

The results reported in Chapter 7 indicated the effectiveness of the gripper monitoring system in detecting part size in pick and place tasks. This could be improved to include detection of more faults such as leakage, blockage, cylinder seals and slippage. A slippage fault was simulated by a short power off which, in the actual system, may go unnoticed. Data may be referred to the server for analysis so that such a fault could be recorded. Investigation into this led to the realisation that checking the average or variance in pressure data while a part is transferred may be utilised to detect this fault. Figure 8.3 shows tests carried out at 4 bar and a 16 mm part to simulate the possibility of a part slipping during pick and place operations.

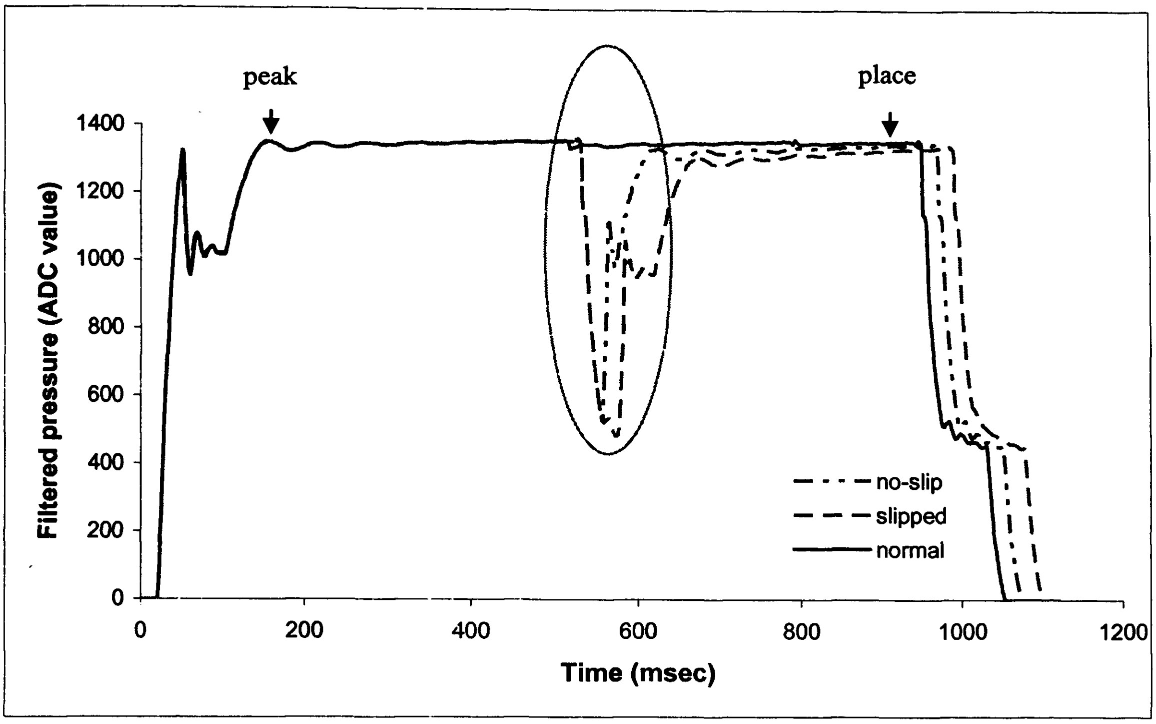


Figure 8.3: Simulation of slippage performed at 4 bar and a 16 mm part.

The circled fault was created by switching the valve off for periods of 40 msec and 60 msec. The first did not result in the part being dropped; the second however did result in the dropping of the part. This situation may arise in the process if the power goes off for any reason or a part is greasy for example. In these tests, the average and variance of data set between the peak amplitude and the placing of a part as indicated in the Figure (the set of data during part transfer) were calculated and are listed in Table 8.1. It can be seen that such measures may be used to indicate a fault had arisen and may provide its identification before the cycle is repeated. At this instance, the system would generate an alarm and data for the cycle could be sent to the server to investigate the matter further. The ON/OFF switching of the valve may indicate a fault related to the valve or the system controlling the process. More testing could be performed for further analysis as to identify the fault which led to the dropping of a part.

Pressure (ADC unit)	Normal	Part not slipped	Part slipped
Average	1350.1	1310.4	1270.6
Variance	48.6	14429.6	32525.8

Table 8.1: Statistical parameters of the process simulating slippage.

Other possible faulty operations were considered. If, for example, the pneumatic circuit is running out of lubricant, capturing and analysing the pressure signal can lead to its detection. Under such conditions, it was found that a decision made identifying the gripping of a correct part as being incorrect is a clear possibility as shown in Figure 8.4. This was recognised when experiments were resumed after a period of non-use of the gripper system, as described in Chapter 7.

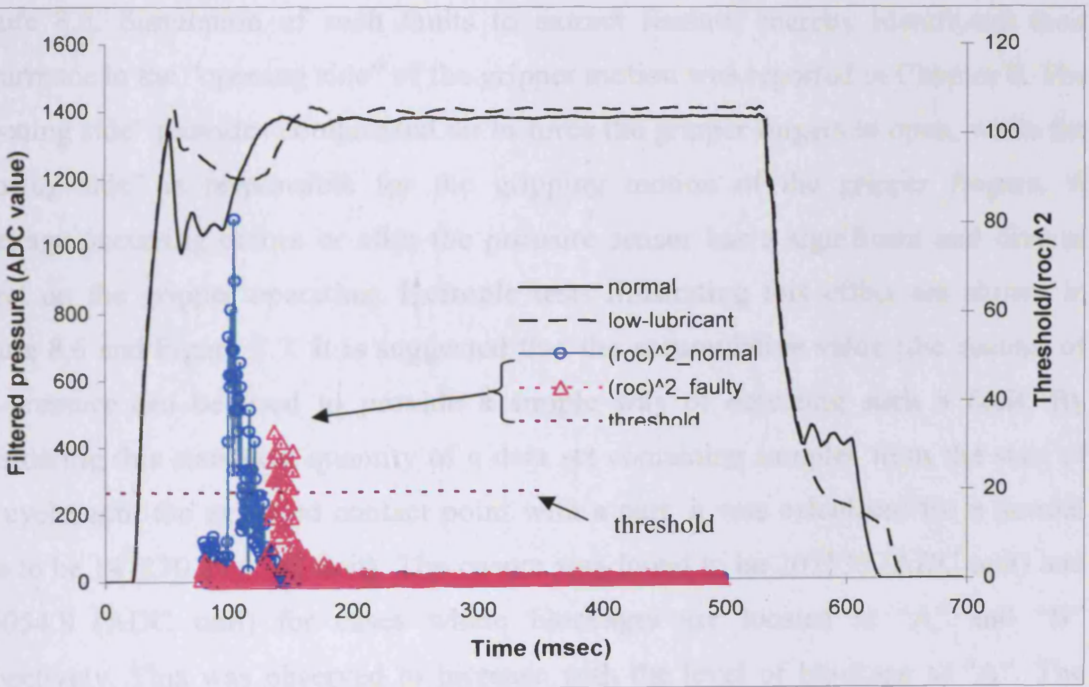


Figure 8.4: Tests carried out at 4 bar and a 20 mm part, with low lubrication.

The pressure behaviour clearly indicated a wrong decision would be made about the process due to the effect of low lubrication which led to high friction inside the cylinder. The initial peak is higher than normal as more force was required to overcome the friction and start the movement of the gripper. This will obviously occur in real life applications when a gripper is replaced or a system is shutdown for a period of time. The system can be utilised to adapt to start-up procedures that will be undertaken following such events. In practice it is likely that initial operations will be closely supervised by the operator who may determine the point at which automatic monitoring can be commenced. This is different to a "soft" fault that develops over time. Degradation in performance linked to lack of lubrication could be identified using the developed system following a period of monitoring and fault classification. The capability of the monitoring system would be enhanced as commonly occurring faults may be predicted and the required maintenance identified. The gripper operation will in turn be made more reliable and efficient.

Furthermore, leakage and blockage may develop in the pneumatic circuit. The location of such faults has different affects on the gripper performance. They may, for example, occur in the closing or opening side of the gripper fingers as shown in Figure 8.5. Simulation of such faults to extract features thereby identifying their occurrence in the "opening side" of the gripper motion was reported in Chapter 6. The "opening side" provides compressed air to force the gripper fingers to open, while the "closing side" is responsible for the gripping motion of the gripper fingers. A blockage occurring before or after the pressure sensor has a significant and diverse effect on the gripper operation. Example tests illustrating this effect are shown in Figure 8.6 and Figure 8.7. It is suggested that the accumulative value (the cusum) of the pressure can be used to provide a simple way of detecting such a fault. By considering this statistical quantity of a data set containing samples from the start of the cycle until the expected contact point with a part, it was calculated for a normal case to be 147230.2 (ADC unit). The cusum was found to be 207535 (ADC unit) and 126054.8 (ADC unit) for cases where blockages are located at "A" and "B" respectively. This was observed to increase with the level of blockage at "A". The reverse effect was however observed for blockages located at "B". That is, as the degree of blockage increases the cusum value decreases. A proper algorithm relating various features obtained from the required tests may lead to detection of these faults. Their locations may also be identified. Leakage can also be investigated in the same manner and a detection mechanism may be derived and implemented on the monitoring node, thus allowing the detection of most possible faults. This supports the efficiency of a predictive maintenance and management program as the monitoring system capabilities keep improving. The detection method of any identified fault signature is added to the front-end-nodes (FENs) of the system monitoring the process to make it more reliable and effective. In other words, more analysis and diagnosis are assigned to the lower level while the server is more suitably used for the identification of new faults and surface modelling.

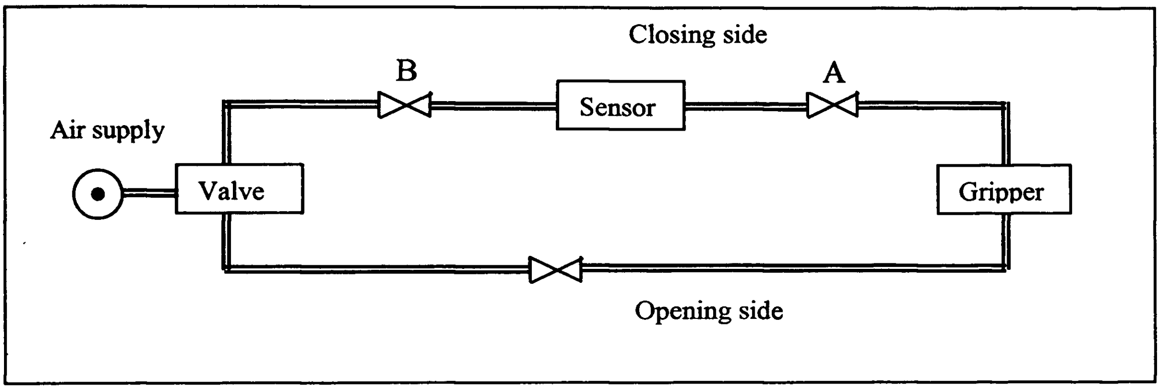


Figure 8.5: Pneumatic circuit. ⋈ Manual valve simulating blockage.

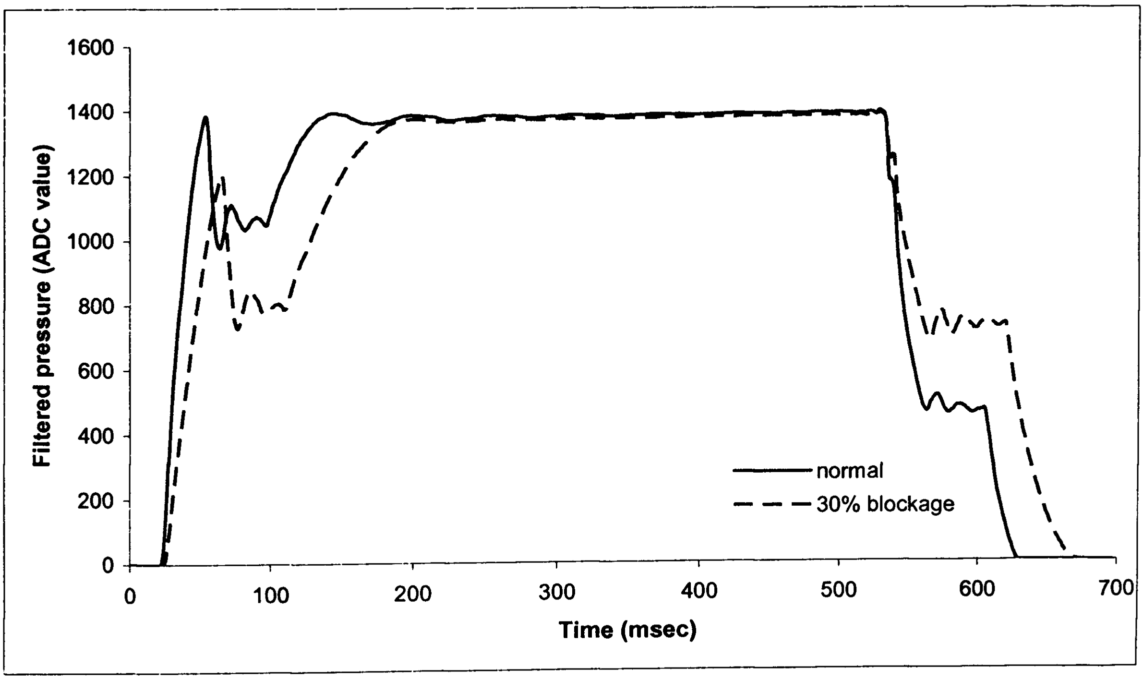


Figure 8.6: A test, simulating a blockage located at "B", at 4 bar and a 20 mm part.

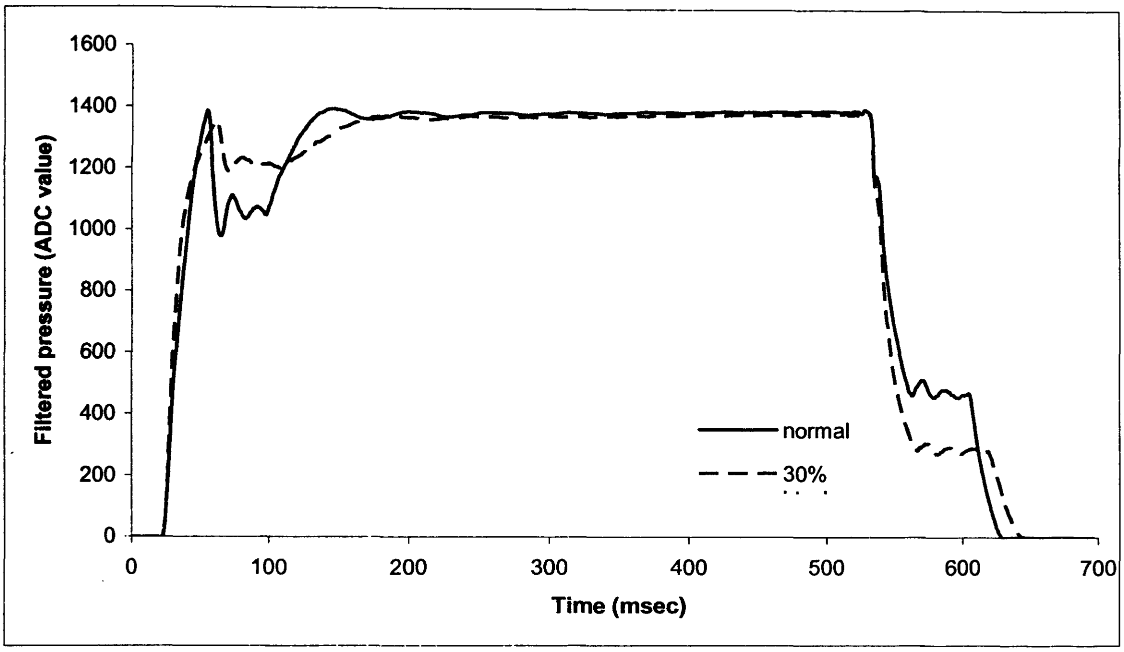


Figure 8.7: A test performed at 4 bar and a 20 mm part to simulate a blockage located at "A".

References

[8.1] Meto-fer Automation, "Automated assembly systems", [WWW]. <URL: http://www.meto-fer.com/SECT17.PDF> [Accessed on 8th July 2008]

Chapter 9

CONCLUSIONS AND FURTHER RECOMMENDATIONS

9.1 Conclusions

The research described in this thesis was aimed at investigating the feasibility and deployment of microcontrollers for the monitoring of pneumatic processes. The potential of dsPICs, as a distributed monitoring solution, was explored.

The speed of the applications which were the subject of this research and the limitation in memory of the monitoring tool were initially identified as a challenge to be overcome. Therefore, the developed monitoring methods were based on transient analysis. In each researched application, the monitoring system was made generic. It can be deployed in a wide range of applications.

Leak detection techniques were developed with application to gas fitting pipes. The speed at which correct decisions are determined was the essence of this method. The solutions were tested, compared and their capability validated using pipes which had been rejected according to industrial standards. In this application a dsPIC digital signal controller and a pressure sensor were deployed, thus ensuring a low cost monitoring solution. A method was proposed to implement both of the developed techniques on a single dsPIC so that a conclusive diagnosis can be reached.

Linear actuator "end of stroke" monitoring was made possible using limit switches. A more challenging method based only upon the deployment of a pressure sensor was accomplished. This proved the effectiveness of the approaches in terms of cost, and time and space limitations.

With regard to the gripper monitoring, a surface by which the gripper action can be monitored was obtained. In addition, various faults were simulated and their effect on the gripper performance was investigated. Leakage and blockage were also investigated at various places in the pneumatic circuit to allow for an algorithm to be devised. Faults may be detected and isolated and their locations identified to allow for timely recovery treatment, thus supporting an energy saving strategy. A possible mechanism to identify these faults was proposed. The need for more testing to further enhance there capabilities was reported.

Individual dsPIC controllers although superior to the previous generation of microcontrollers may be limited in resources as compared to PCs but much higher capabilities would be attained in the overall distributed system. Effective fault detection and diagnosis was achieved in a number of pneumatic applications. The main benefit of such an approach is the ease with which the developed devices can be integrated to form powerful monitoring systems.

9.2 Further Recommendations

The developed monitoring systems were tested on the applications for which they were designed and were shown to be capable of making the correct decisions about the health of the process at various operating conditions. Further enhancements can be achieved by incorporating to the overall system the following suggestions.

Leak size in pipes can be quantified through a relationship with the decay rate. More tests on pipe with small varying holes are required to reach a conclusive and reliable formula in order to quantify leaks at various supply pressures.

During a pick and place operation, it is possible to encounter obstruction which may cause the part to slip. An instantaneous power cut-off could lead to the occurrence of such phenomenon. Monitoring the pressure during transfer period of parts is crucial. A simple detection method was proposed, but more tests and analysis are required to devise a mechanism capable of its detection at any given supply pressure.

Low lubrication is bound to happen in pneumatic circuits. This was observed as previously stated. Further testing and analysis could be carried out in the future to obtain a diagnostic regime to identify the occurrence of such fault.

Leak and blockage are faults which may develop with time and a monitoring system should be able to detect them. Simulation of these faults was provided in Chapter 8 which indicated that the location of such faults have diverse effects on the pressure behaviour and hence the performance of the pneumatic system. Other statistical measures may be developed to enhance the detection algorithm. It is recommended that this is investigated further not only to allow their detection but also to locate them to make the process recovery a simple task to undertake.

The pressure signal was analysed for each simulated and observed (low lubricant) faults individually. The occurrence of multiple faults should be investigated to study their effect on the process performance. Different faults may be present at the same time. Their symptoms could be combined to obtain a comprehensive method with the capability to detect and isolate such faults.

9.3 Research Contributions

This research has made the following main contributions towards knowledge:

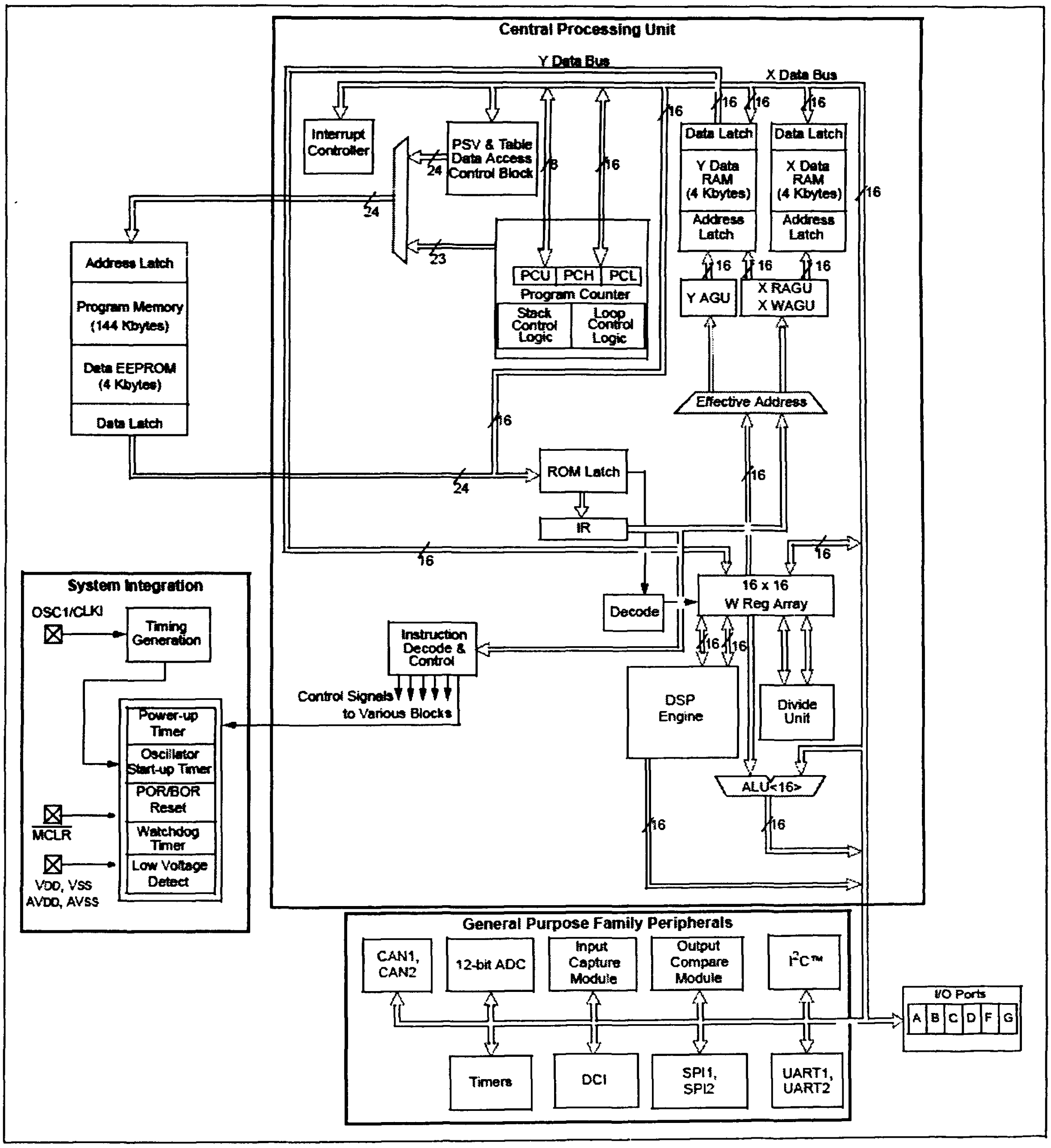
- **Pressure transient-based diagnosis**
    - A low cost, process and condition monitoring system applied to pneumatic systems was developed using a single pressure transducer.
    - The integrity of products can be assessed in a wide range of applications using the developed method.
    - Utilising the squared rate of change to detect faults arising in the process is a novel approach.
- **Process performance surface**
    - The surface based monitoring supports the aim for generic and real-time monitoring of a wide range of applications.
    - The surface provides the detection of faults occurring in the process which then leads to their isolation through the transient analysis.
    - An optimum method was proposed in order to update the surface (in a speedy way) whenever required. This supports the system adaptability to changing conditions and helps reducing the development time-constraint.

- **dsPIC deployment**
  - The use of dsPIC allows the implementation of the developed techniques and provides the required communication (CAN and Ethernet) capability. A web-enabled distributed architecture, based solely on dsPICs, as a process monitoring and control solution can be realised.
  - Capturing all significant events via continuous monitoring for off-line analysis and diagnosis. This reporting process allows development of diagnostic systems.
  - The capability of this device as a modelling tool was examined and its limitation was revealed.
  - The feasibility of dsPIC to undertake the monitoring function in processes operating at high speed was demonstrated.

Appendix A

DsPIC RELATED DIAGRAMS

The Block Diagram of dsPIC30F6014 DSC



The dsPIC30F features

High Performance Modified RISC CPU:

- Modified Harvard architecture
- C compiler optimized instruction set architecture
- Flexible addressing modes
- 84 base instructions
- 24-bit wide instructions, 16-bit wide data path
- Up to 144 Kbytes on-chip Flash program space
- Up to 48K instruction words
- Up to 8 Kbytes of on-chip data RAM
- Up to 4 Kbytes of non-volatile data EEPROM
- 16 x 16-bit working register array
- Up to 30 MIPs operation:
  - DC to 40 MHz external clock input
  - 4 MHz-10 MHz oscillator input with PLL active (4x, 8x, 16x)
- Up to 41 interrupt sources:
  - 8 user selectable priority levels
  - 5 external interrupt sources
  - 4 processor traps

DSP Features:

- Dual data fetch
- Modulo and Bit-reversed modes
- Two 40-bit wide accumulators with optional saturation logic
- 17-bit x 17-bit single cycle hardware fractional/integer multiplier
- All DSP instructions are single cycle
  - Multiply-Accumulate (MAC) operation
- Single cycle ±16 shift

Peripheral Features:

- High current sink/source I/O pins: 25 mA/25 mA

• Five 16-bit timers/counters; optionally pair up 16-bit timers into 32-bit timer modules

• 16-bit Capture input functions

• 16-bit Compare/PWM output functions:

• Data Converter Interface (DCI) supports common audio Codec protocols, including I2S and AC'97

• 3-wire SPI™ modules (supports 4 Frame modes)

• I2C™ module supports Multi-Master/Slave mode and 7-bit/10-bit addressing

• Two addressable UART modules with FIFO buffers

• Two CAN bus modules compliant with CAN 2.0B standard

Analog Features:

• 12-bit Analog-to-Digital Converter (A/D) with:

- 100 Ksps conversion rate
- Up to 16 input channels
- Conversion available during Sleep and Idle

• Programmable Low Voltage Detection (PLVD)

• Programmable Brown-out Detection and Reset generation

Special Microcontroller Features:

• Enhanced Flash program memory:

- 10,000 erase/write cycle (min.) for industrial temperature range, 100K (typical)

• Data EEPROM memory:

- 100,000 erase/write cycle (min.) for industrial temperature range, 1M (typical)

• Self-reprogrammable under software control

• Power-on Reset (POR), Power-up Timer (PWRT) and Oscillator Start-up Timer (OST)

• Flexible Watchdog Timer (WDT) with on-chip low power RC oscillator for reliable operation

• Fail-Safe Clock Monitor operation:

- Detects clock failure and switches to on-chip low power RC oscillator

• Programmable code protection

• In-Circuit Serial Programming™ (ICSP™)

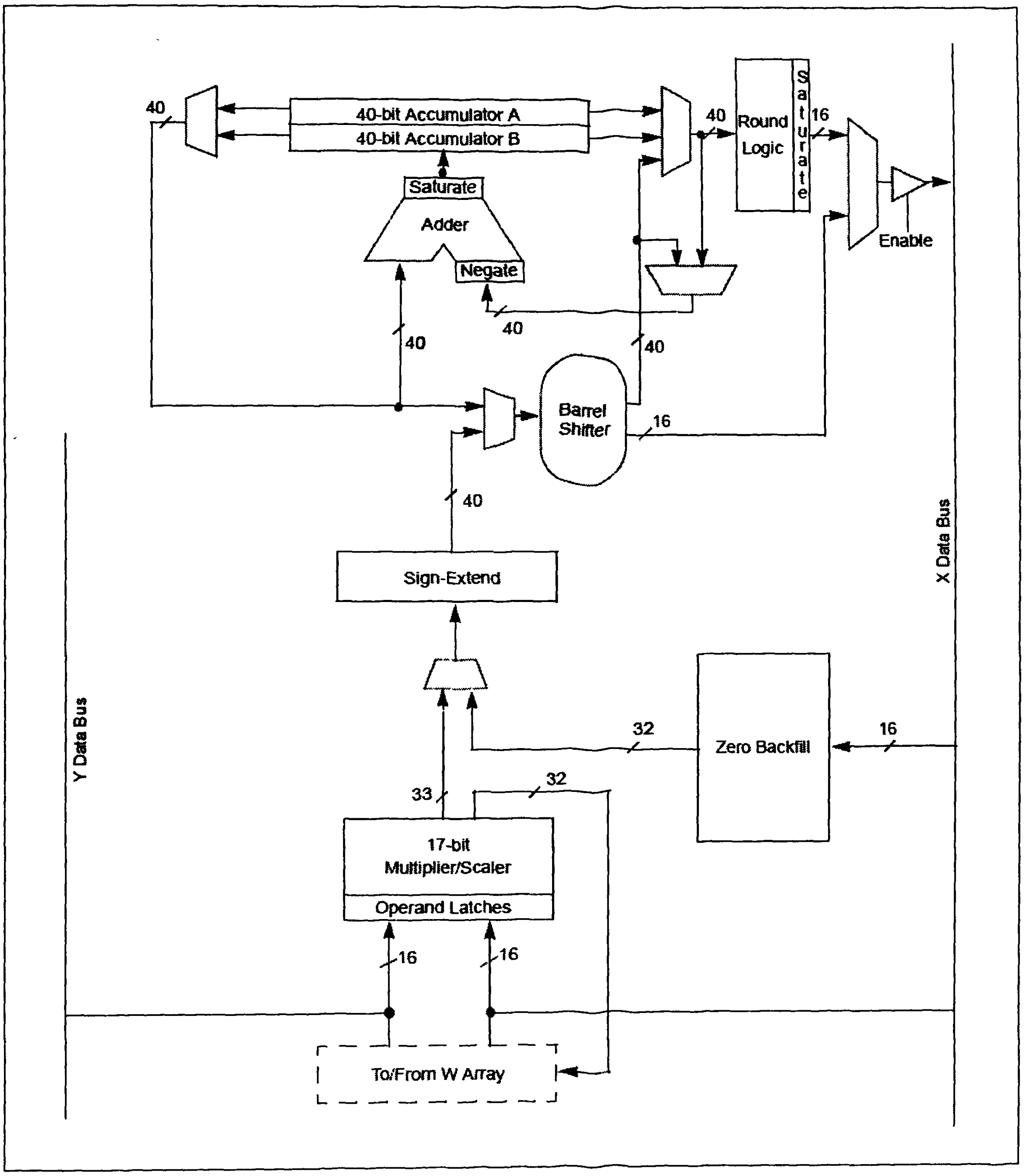
• Selectable Power Management modes:

- Sleep, Idle and Alternate Clock modes

CMOS Technology:

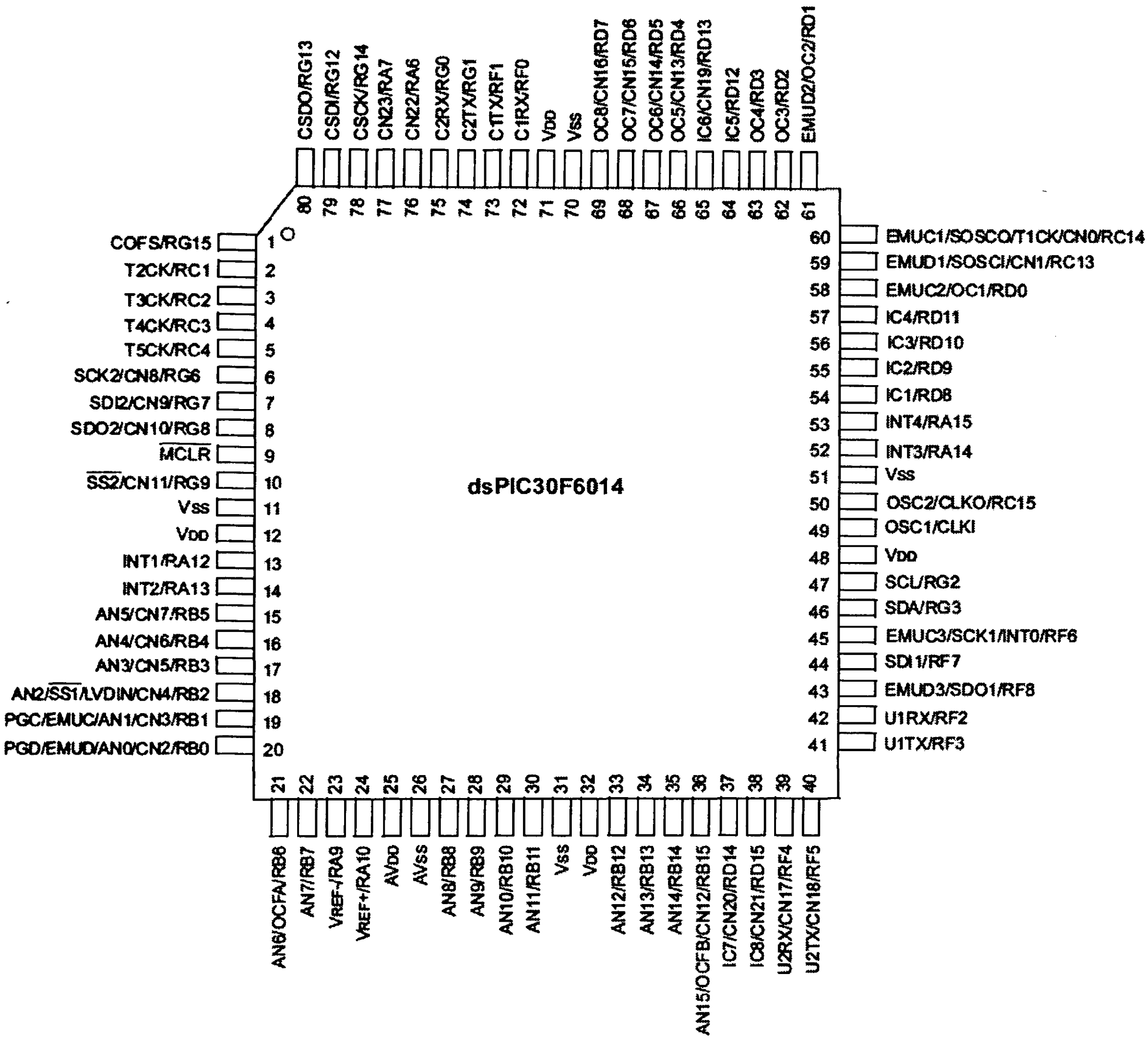
- Low power, high speed Flash technology
- Wide operating voltage range (2.5V to 5.5V)
- Industrial and Extended temperature ranges
- Low power consumption

The DSP Engine Block Diagram

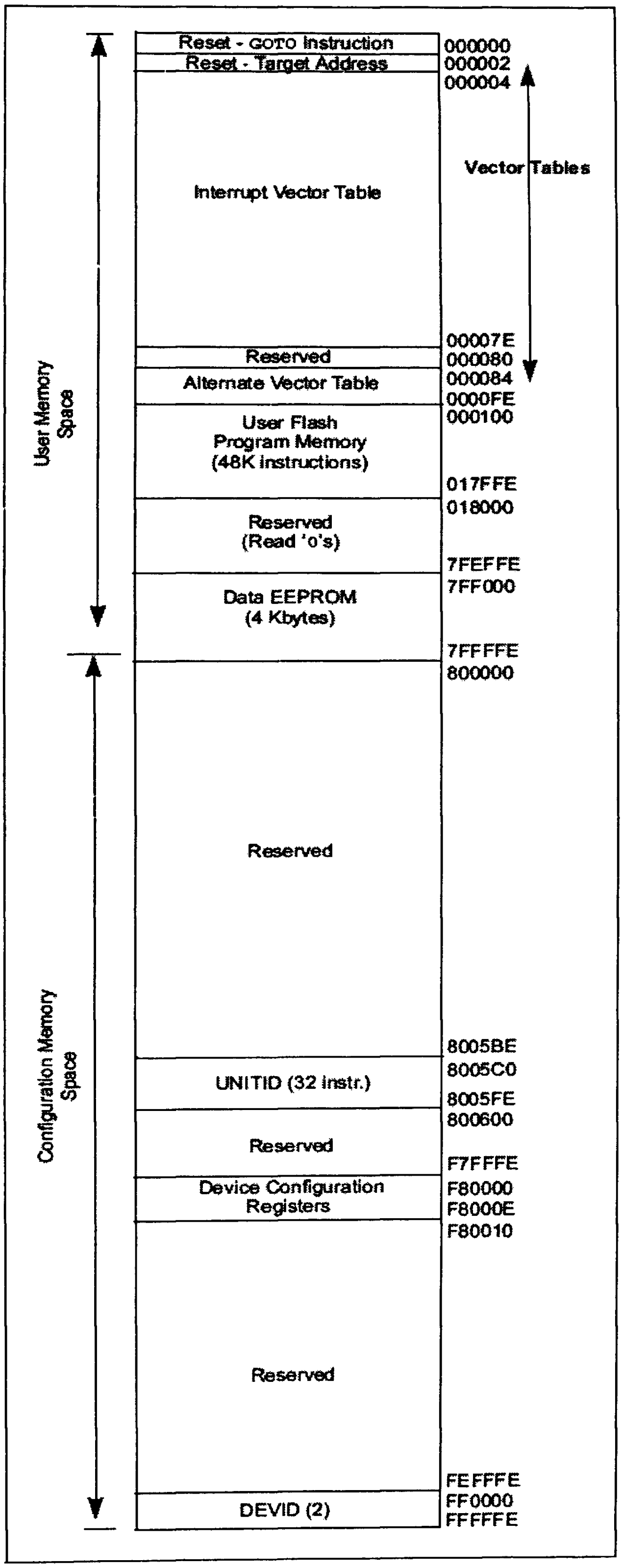


The dsPIC30F6014 Pin Diagram

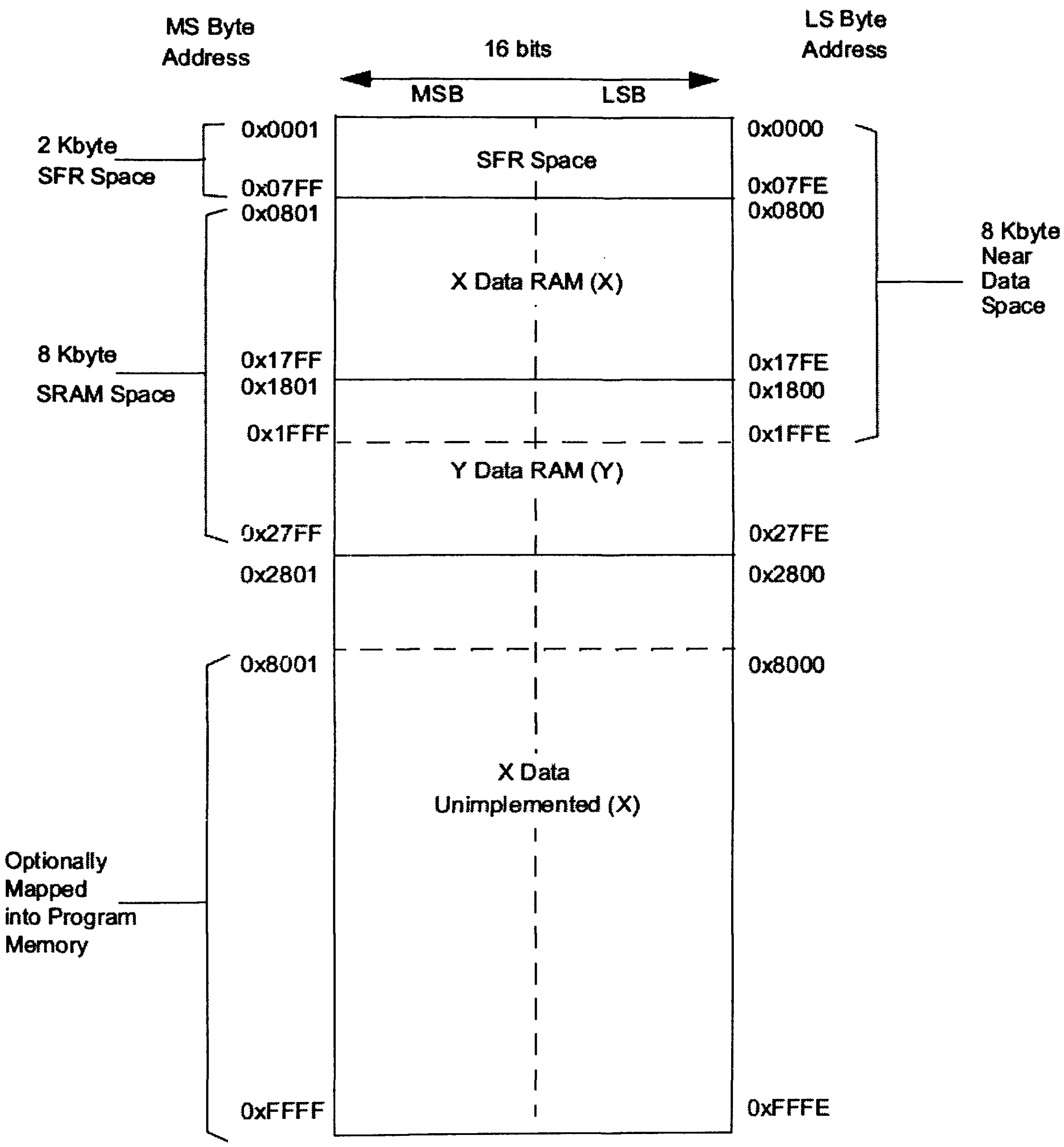
80-Pin TQFP



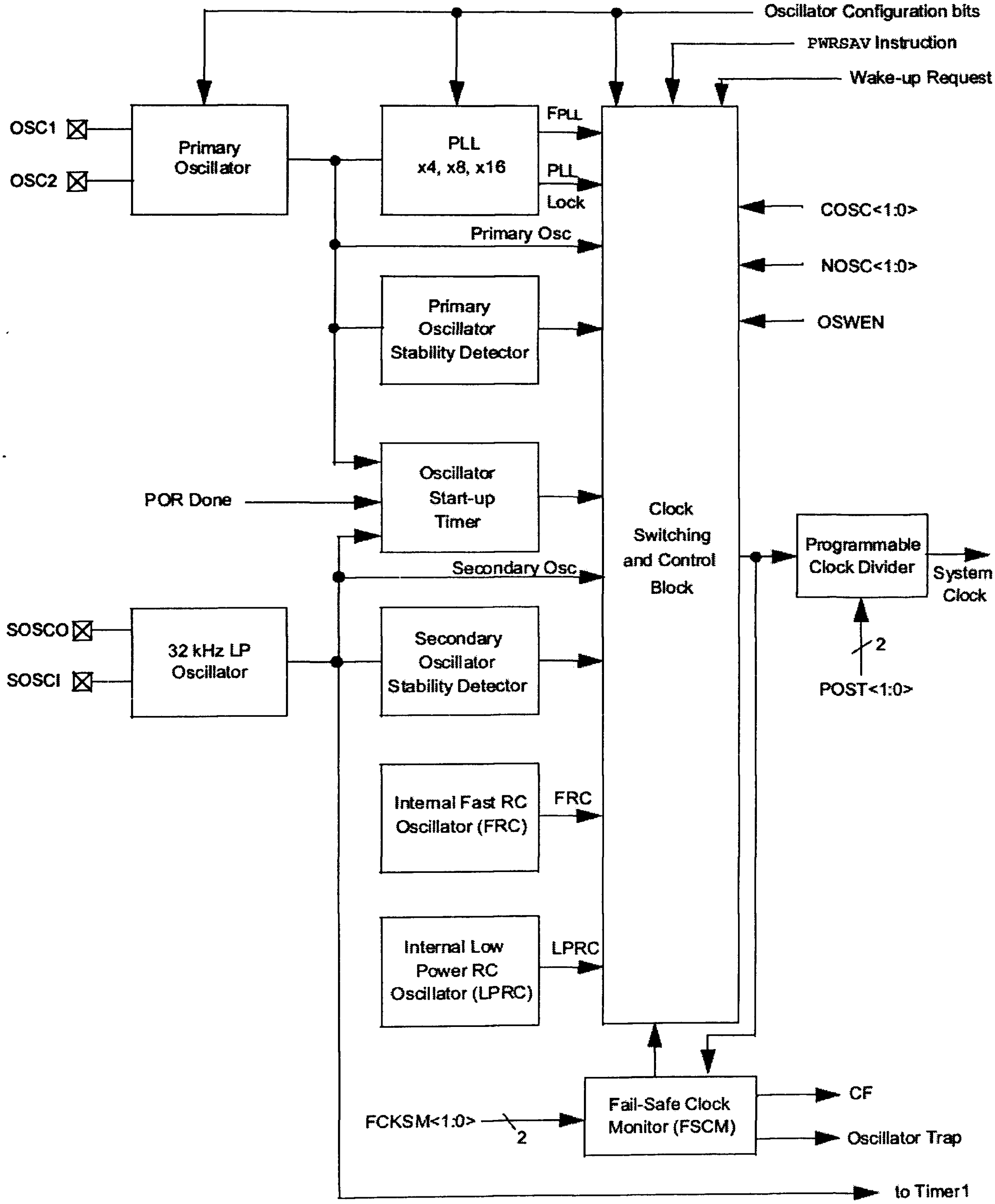
Program Space Memory Map



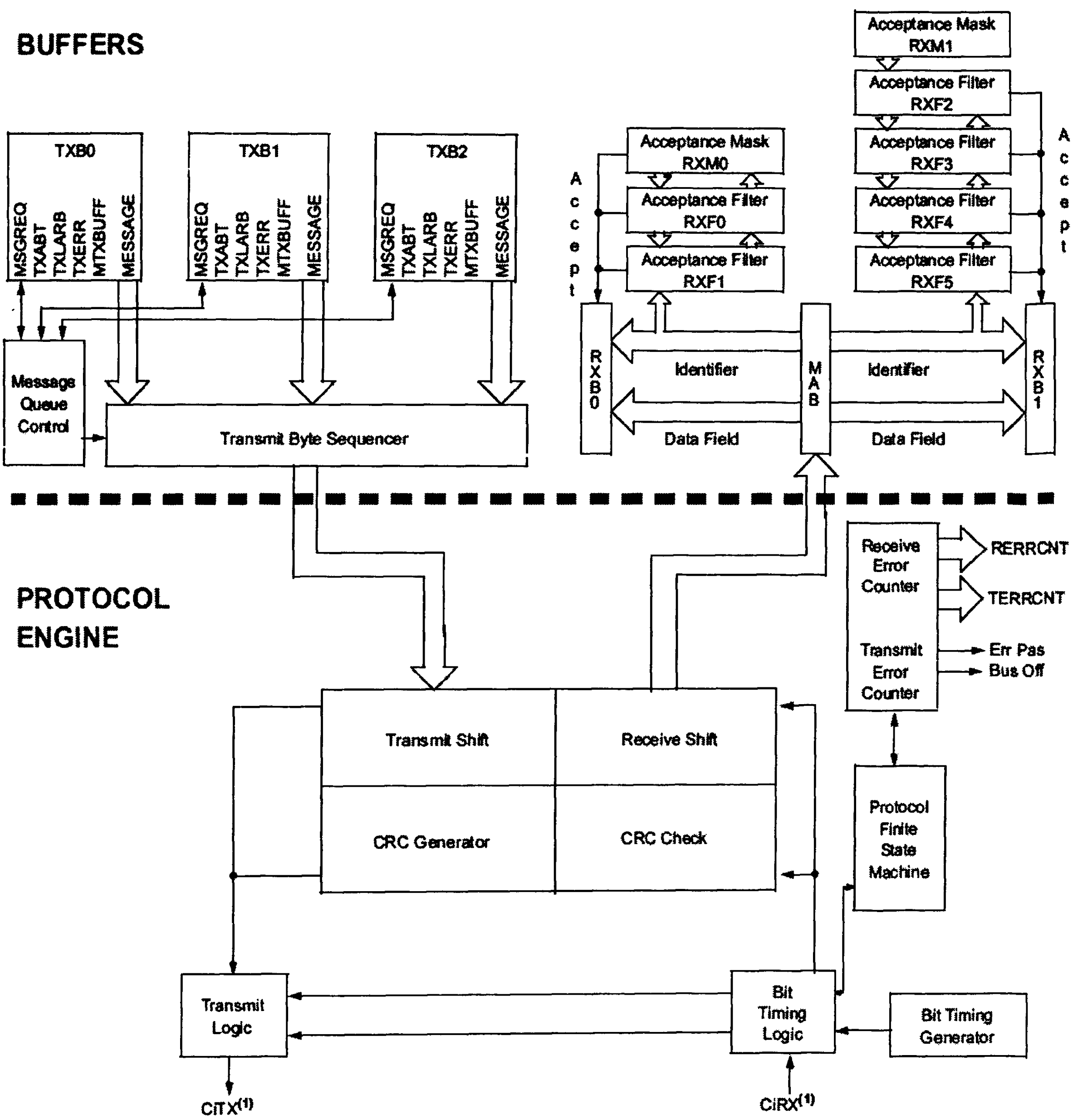
Data Space Memory Map



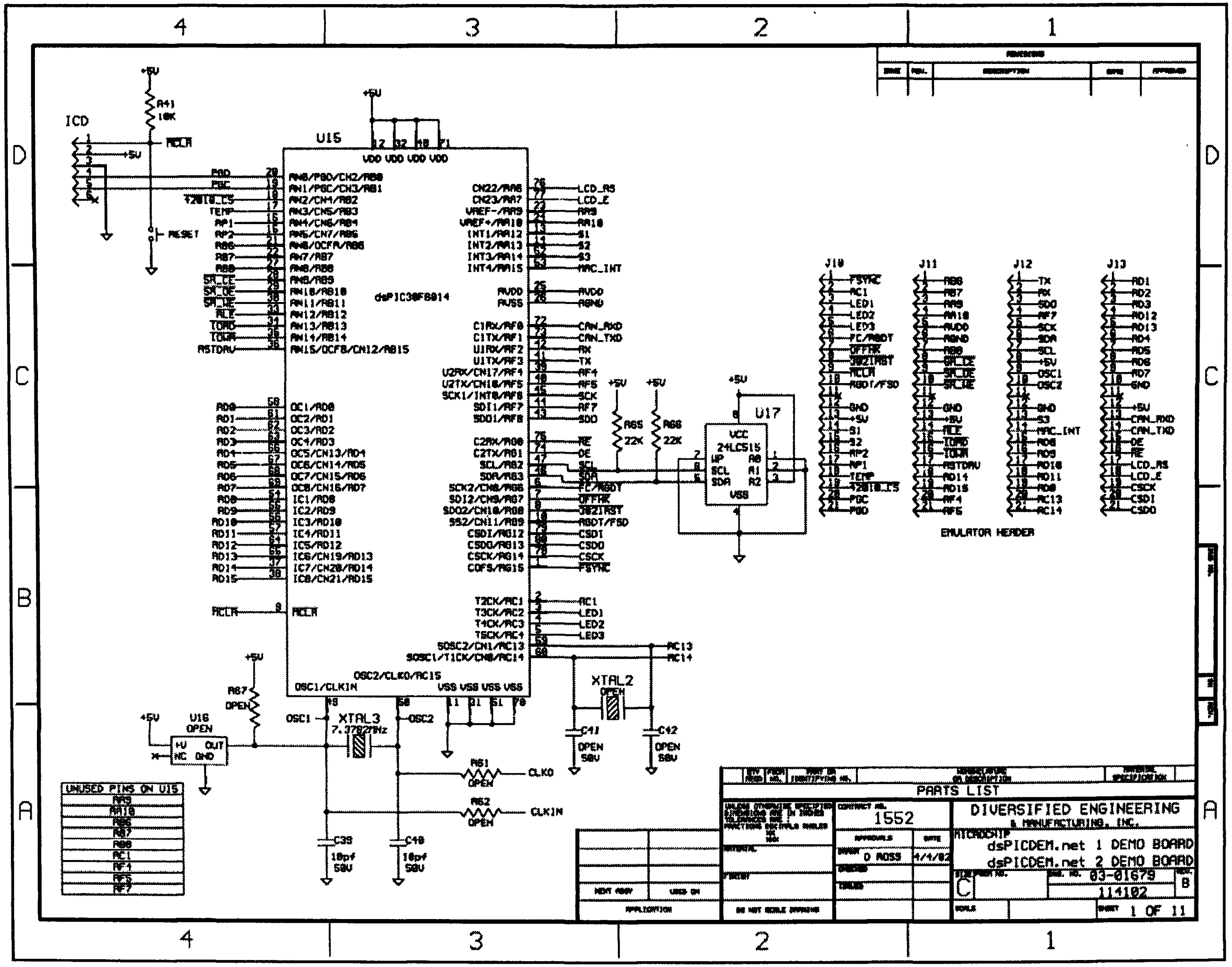
Oscillator System Block Diagram



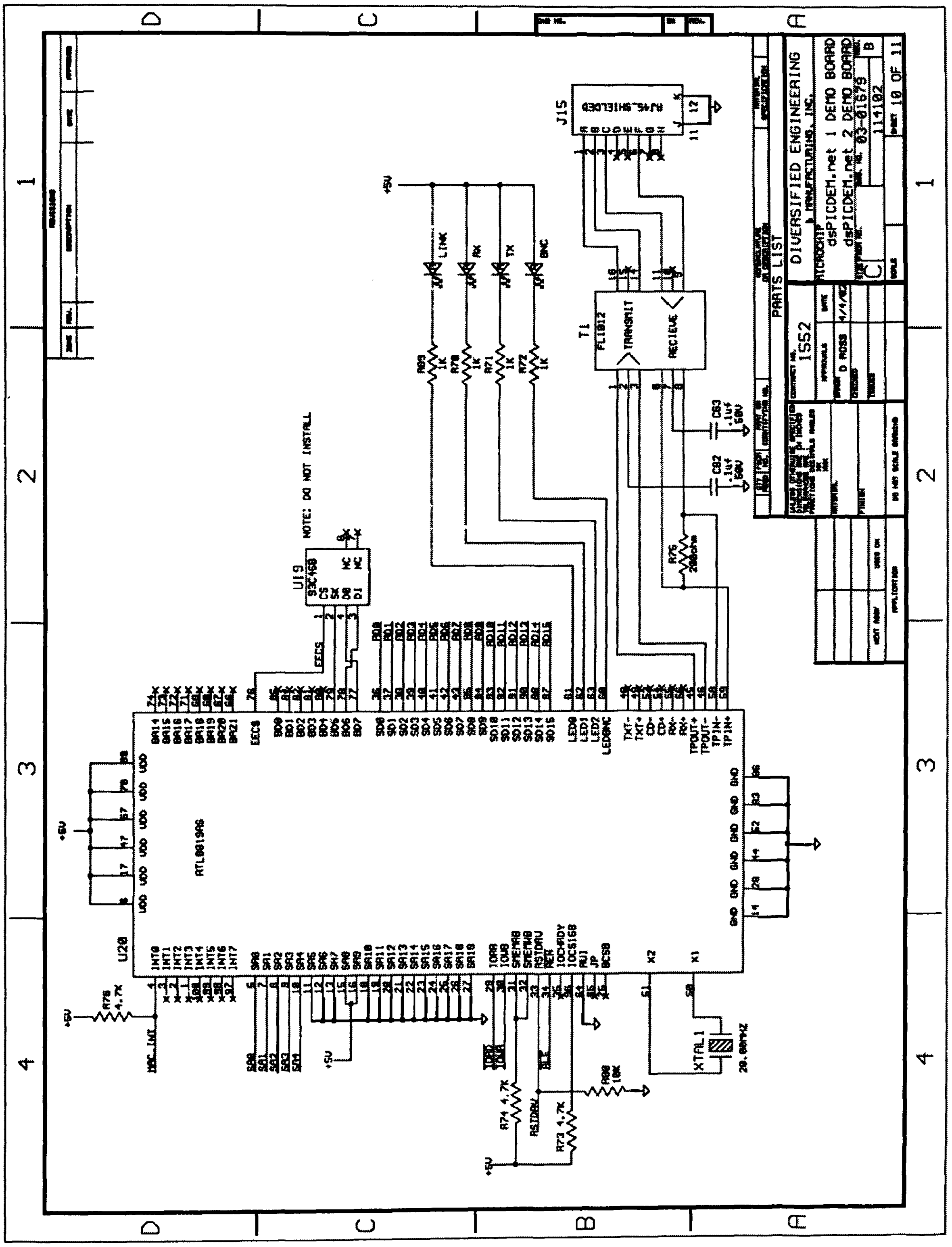
CAN Buffers and Protocol Engine Block Diagram



Note 1: i = 1 or 2 refers to a particular CAN module (CAN1 or CAN2).

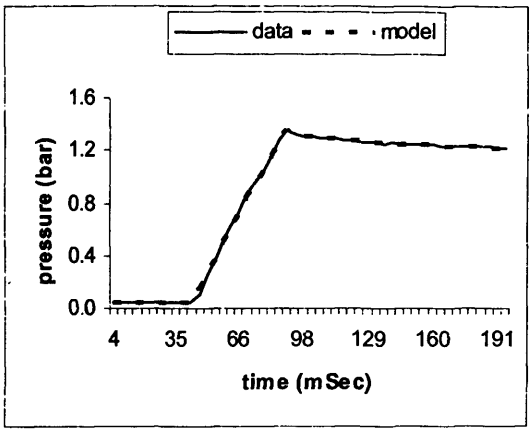

U15
dsPIC30F6014
U17
24LC515
XTAL3
7.3728MHz
XTAL2
ICD
EMULATOR HEADER
UNUSED PINS ON U15
PARTS LIST
DIVERSIFIED ENGINEERING
& MANUFACTURING, INC.
1552
D ROSS
4/4/02
MICROCHIP
dsPICDEM.net 1 DEMO BOARD
dsPICDEM.net 2 DEMO BOARD
03-01679
114102
1 OF 11

Ethernet Hardware Schematic Diagram

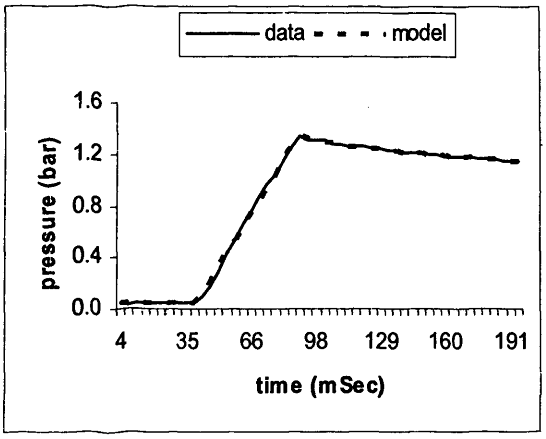


Appendix B

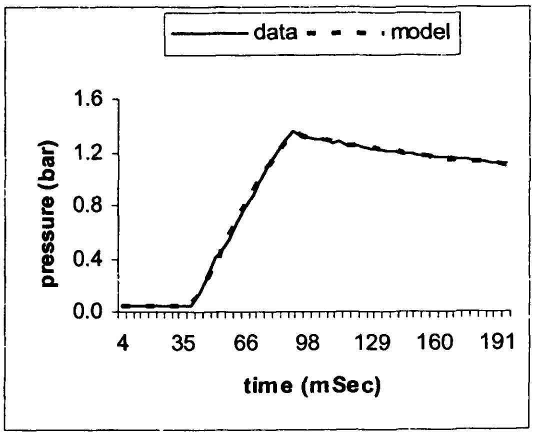
TRANSIENTS AND THEIR MODELS FOR 2, 3 AND 4 BAR



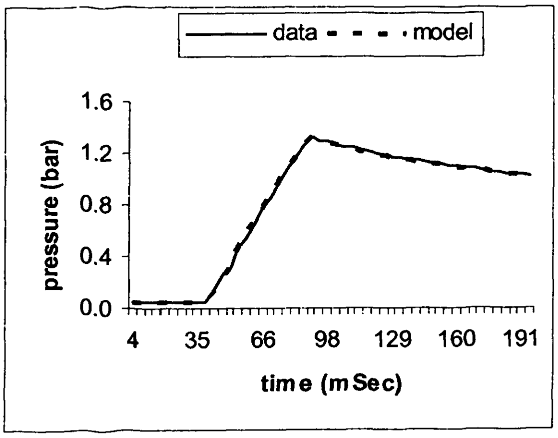
Transient model of 2 bar at no leak



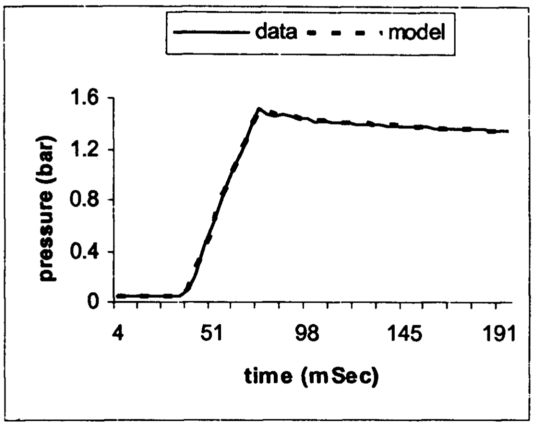
Transient model of 2 bar at 0.4 mm leak



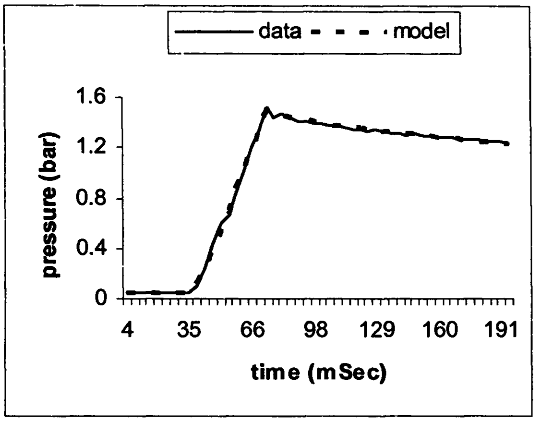
Transient model of 2 bar at 0.8 mm leak



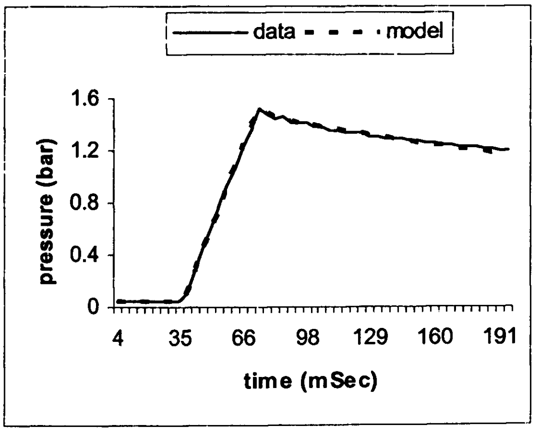
Transient model of 2 bar at 1.2 mm leak



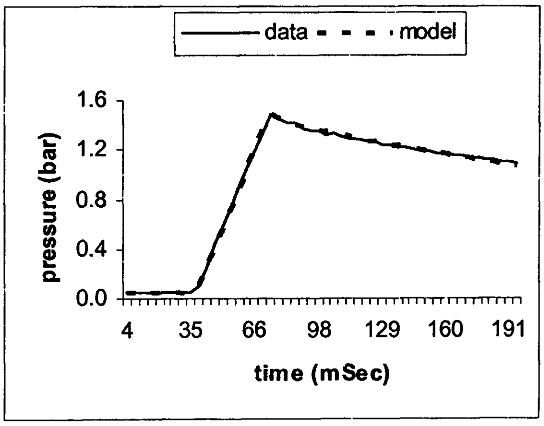
Transient model of 3 bar at no leak



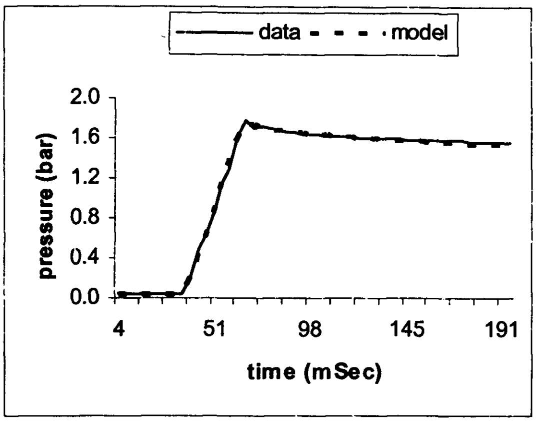
Transient model of 3 bar at 0.4 mm leak



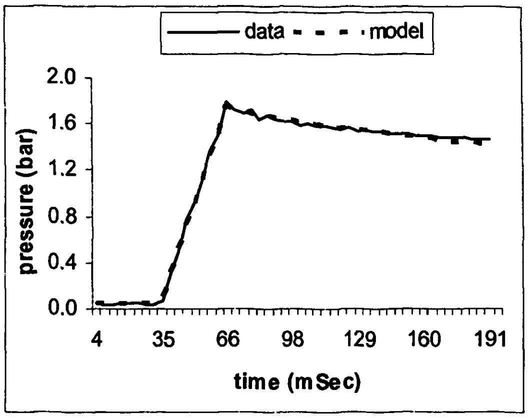
Transient model of 3 bar at 0.8 mm leak



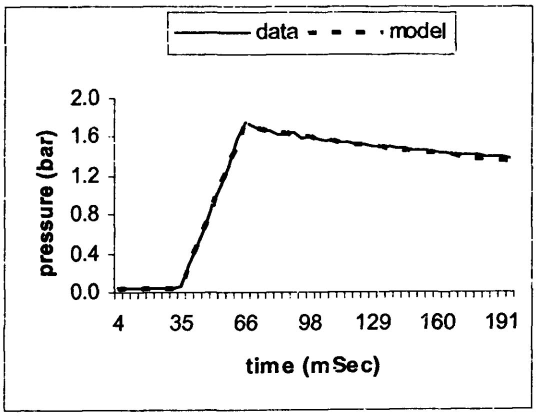
Transient model of 3 bar at 1.2 mm leak



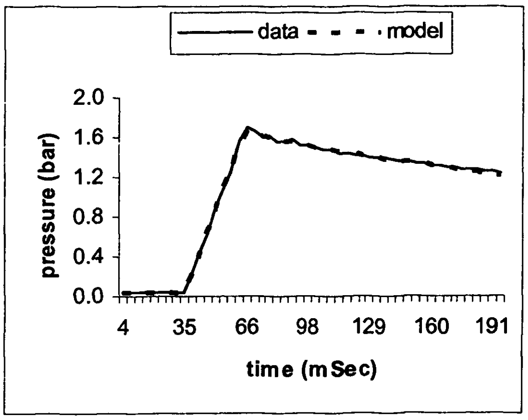
Transient model of 4 bar at no leak



Transient model of 4 bar at 0.4 mm leak



Transient model of 4 bar at 0.8 mm leak

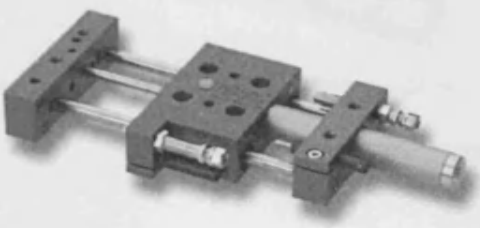


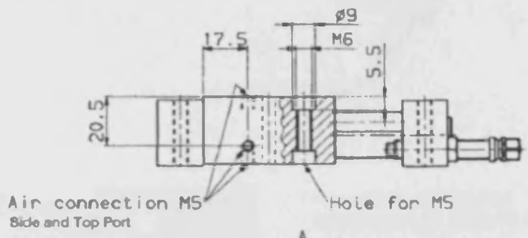
Transient model of 4 bar at 1.2 mm leak

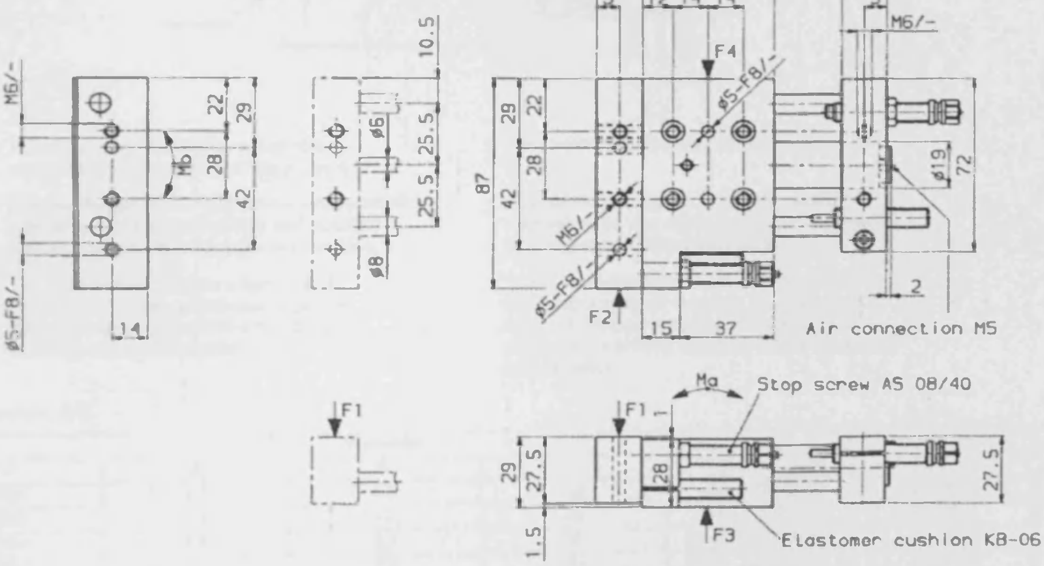
Appendix C

LINEAR ACTAUTOR FACT SHEETS

Mini linear unit ML13







Type	Stroke (mm)	Adjusting range (mm)	A	Piston force at 72.5 psi (5 bar)	Max. load stat./dyn. lb (N)				Ma lb.in (Nm)	Mb lb.in (Nm)	Air consumption for each double stroke at 72.5 psi (5bar)	Weight lb (kg)
					F1	F2	F3	F4				
ML13-25	0-25	0-25	115	7lb (32N)	29 (131)	31 (137)	38 (167)	44 (196)	40 (4.5)	84 (9.5)	0.001scf (0.03NL)	1.5 (0.70)
ML13-50	0-50	13-50	140	7lb (32N)	19 (84)	20 (88)	43 (190)	44 (196)	40 (4.5)	84 (9.5)	0.002scf (0.06NL)	1.7 (0.76)
ML13-75	0-75	38-75	165	7lb (32N)	14 (62)	15 (65)	43 (190)	44 (196)	40 (4.5)	84 (9.5)	0.003scf (0.09NL)	1.8 (0.82)
ML13-100	0-100	63-100	190	7lb (32N)	9 (41)	10 (43)	43 (190)	44 (196)	40 (4.5)	84 (9.5)	0.004scf (0.12NL)	1.9 (0.88)

Order No. ML13 - . . . - . . .

O = Without cushions
A = Elastomer cushions (Standard M6x1 / KB 06)

Stroke

Technical data:

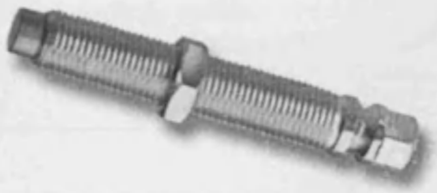
- Built in stop screw with fine threads provide adjustable stroke.
- The stop screws can be fitted with patented sensing elements. (see section 8 "Stop system with plug-in sensing elements").
- End position damped with elasotmer cushions KB 06.
- Bearing: Precision linear ball bearings

-Operating medium	Compressed air oiled/ not oiled
-Operating pressure	43.5 - 116 psi (3 - 8 bar)
-Piston diameter	12mm
-Repeatability	+/- 0.01mm (0.0004")
-Air connection	M5

Precision Stop System With Sensing Element

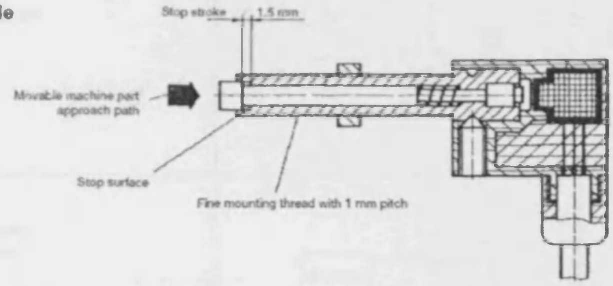
For monitoring mechanical motions, Meto-Fer has a patented Stop System that provides fine stroke adjustment of the stop position and simultaneously provides an output in electrical, electronic, or pneumatic form to confirm that the stop position has been met.

Stop screw with locknut



Plug-in sensing element

Functional Principle

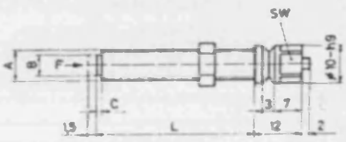


* Please note additional information on page 12 / 13

- The stop screw is used to adjust the mechanical end-position of the motion.
- The fine thread of the stop screw allows exact adjustment of the mechanical end position. The locknut secures the adjusted position.
- The stop screw contains a spring and hardened stop pin, which operates the attached sensing element when the pin is driven to the end position.
- The stroke of the hardened stop striker is 1.5 mm.
- This combination eliminates the need for a secondary sensor adjustment after the hard stop adjustment has been made.
- They come standard on all our rotary and linear actuators, or they can be integrated into your design as stand alone products whenever precision feedback and adjustment are required.

Stop Screw AS

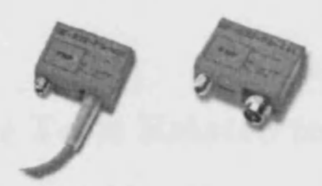
Dimension						Part No.
A	B	C	L	LB	(N)	
M8x1	5.5	1.5	15	450	(2,000 N)	AS 08/15
M8x1	5.5	1.5	40	450	(2,000 N)	AS 08/40
M10x1	7.5	2.5	50	2,135	(9,500 N)	AS 10/50
M12x1	9	2.5	60	4,600	(20,500 N)	AS 12/60
M12x1	9	2.5	80	4,600	(20,500 N)	AS 12/80
M18x1	14	2.5	100	10,100	(45,000 N)	AS 18/100
1/2-20	9	2.5	60	4,600	(20,500 N)	AS 1/2-20
5/16-24	5.5	1.5	40	450	(2,000 N)	AS 5/16-20



F = force or load (N) F = m x a
M = mass (kg) a = acceleration (m/s)

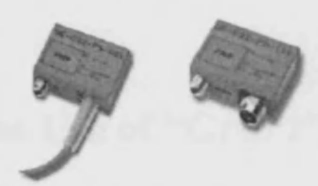
- mechanically adjust stroke limit with electronic or pneumatic sensing device
- element can be plugged on
- Type ..-NS,-PS.: sense with inductive proximity switch
- Type ..-EB: electro-mech. switch
- Type P: 3/2 directional control valve

electronic NAMUR

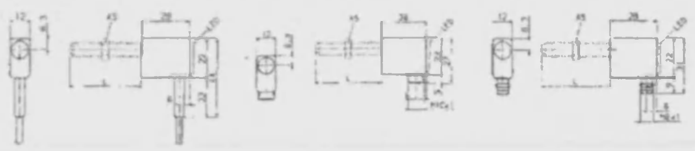
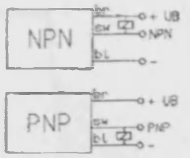


sensor for stop screw

electronic NPN / PNP



sensor for stop screw

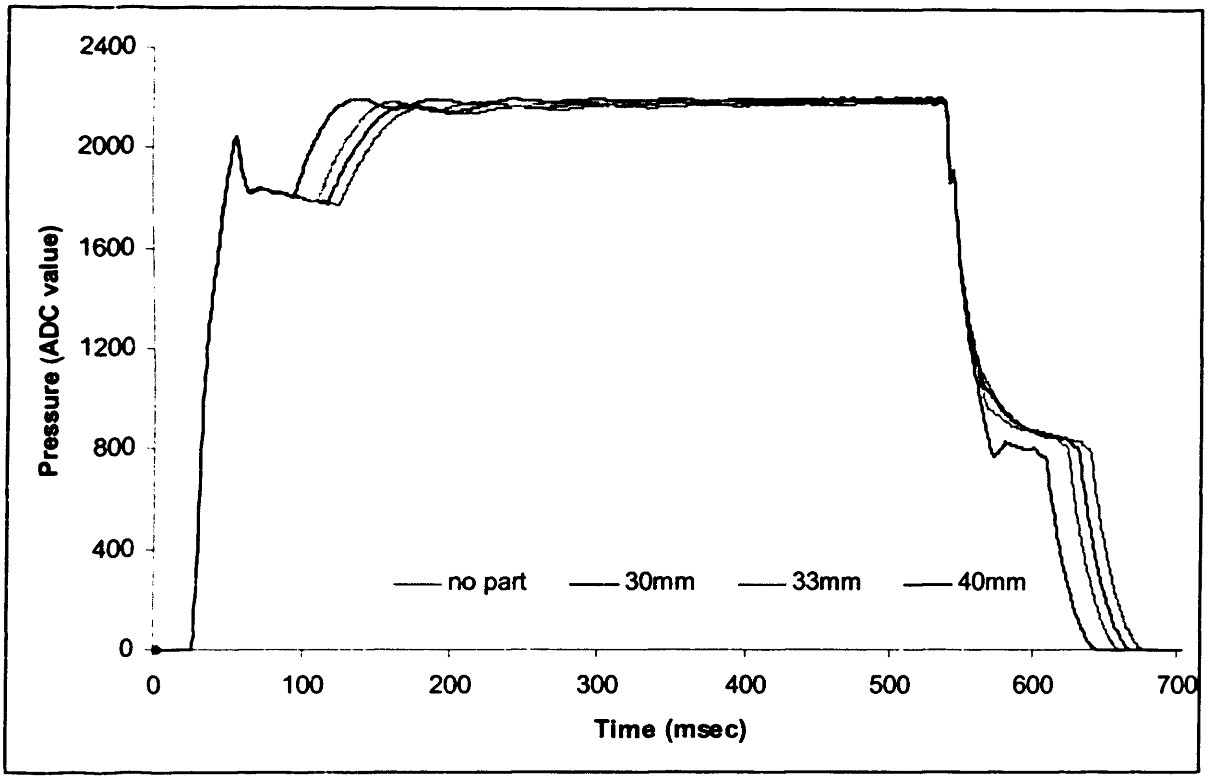
	22 x 12mm NAMUR	22 x 12mm LOGIC
Plug on to any stop screw and secure with set screw.	 U20 02 11	
wiring diagram br = brown sw = black we = white bl = blue wires are color coded according to EN 50044		
TECHNICAL DATA		
supply voltage	5V.....24V DC	8V.....30V DC
residual ripple per DIN 41755	10%	10%
load current		200mA
current drain, activated	<1mA	<15mA
current drain, not activated	<4mA	<2mA
Max. switching current (AC and DC)		
Max. switching voltage DC		
Max. switching voltage AC		
polarity protection		yes
short circuit prot. / overvoltage prot.		yes
switching function	analog	normally open
output type	NAMUR	NPN or PNP
LED status indicator		yes
switching rate	2 kHz	2 kHz
operating temperature range	-20°C.....+70°C	-20°C.....+70°C
casing material	plastic	plastic
cable cross section	$0.14mm^2$	$0.14mm^2$
cable: - PUR cable is standard -cable info - (see page 4)	integral molded cable or cable with plug (see page 4)	integral molded cable or cable with plug (see page 4)
system of protection per DIN 40050	IP 67 (plug version = IP 65)	IP 67 (plug version = IP 65)
signal transmitter	stop screw	stop screw

remarks to the part number	**Part Number**	**Part Number** Sensor / Cable (2m.6FT)
Reference codes see page 1	**QE-022-AX-110** **QE-022-AX-020** **QE-022-AX-U20**	*5m and 9m also available

Sensor	Cable (2m.6FT)
QE-022-NS-11L QE-022-PS-11L	ST-11G-3B-U2X
QE-022-NS-02L QE-022-PS-02L	ST-02G-3A-U2X
QE-022-NS-U2L QE-022-PS-U2L	INTEGRAL MOLDED CABLE

Appendix D

Example Tests Related to the Use of "Grip 2"



Pressure transients for tests performed at 6 bar using grip 2.

Appendix E

Fact sheets related to the pressure sensor

Industrial Heavy Duty Pressure Sensors with Internal Membrane

Output signal: 0 ... 10 V, 4 ... 20 mA
0 ... 100 mV, 1 ... 5 V

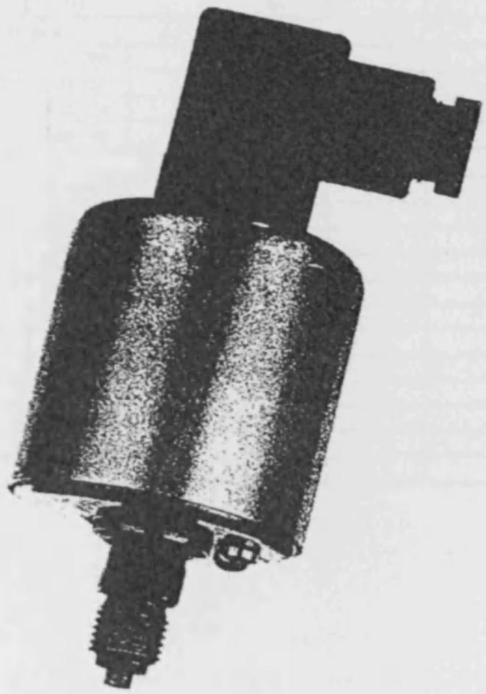
Measuring ranges

Min. −1 ... 0 bar, max. 0 ... 600 bar

Application Range

Pneumatic and hydraulic control technology;
General machinery;
Engines and generators.

Together with diaphragm seals (DAS-Programme) also suitable for application in high viscosity, aggressive or crystallising media.



Features

- O Housing ABS or stainless steel
- O Economically priced
- O Contactless electrical pickup
- O Space saving design
- O 1.3- or 2 fold overloading
- O Measuring systems of copper alloy or stainless steel 1. 4571
- O High sensitivity
- O Insensitive to shocks

Description

The Pressure Sensors convert the motion of a spring movement (Bourdon tube) into a pressure proportional output signal.

The conversion of the motion into an electrical signal is achieved by means of the "Hall" effect.

Due to the contact-free conversion, no wear is experienced.

This sensor represents an economic solution for measurement applications where an electrical signal is necessary and a local indication is not possible or unnecessary.

With an accuracy class of ± 1 %, it is possible to cover a large spectrum of measurement applications.

The pressure connection is available with a G ¼ male thread. Other connections on enquiry.

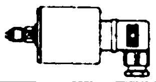
A choice of two materials is available, copper alloy or stainless steel (1.4571).

All system components are enclosed in a spacesaving housing of stainless steel (1.4301) with IP 65 protection.

The electrical connection is led axially out ot the housing and is provided with a plug in accordance with DIN 43650. Optional 1 metre cable can also be supplied.

Operating temperature: −40 ... +80 °C
Storage temperature: −40 ... +80 °C

Industrial Heavy Duty Pressure Sensors with Spring Movement Brass design

Series	3300/1		3300/2		3300/3		3300/4		
									
Accuracy %	1,0		1,0		1,0		1,0		
Output	4 ... 20 mA		0 ... 10 V		0 ... 100 mV		1 ... 5 V		
Housing	Stainless steel 1.4301 2) 3)								
Pressure connection	Brass								
Thread	G ¼ A								
Supply volt.	12 ... 36 VDC		12 ... 36 VDC		12 ... 36 VDC		8 ... 36 VDC 1)		
Electrical connection	Plug in accordance with Din 43650 with socket				1 m cable				
Measuring range bar	Code No.		Code No.		Code No.		Code No.		
Price Group A									
-1 ... + 3	044 007		044 107		044 704		044 504		
-1 ... + 5	045 007		045 107		045 704		045 504		
-1 ... + 9	046 007		046 107		046 704		046 504		
-1 ... +15	049 007		049 107		049 704		049 504		
Price Group B									
0 ... 4	073 007		073 107		073 704		073 504		
0 ... 6	074 007		074 107		074 704		074 504		
0 ... 10	075 007		075 107		075 704		075 504		
0 ... 16	076 007		076 107		076 704		076 504		
0 ... 25	078 007		078 107		078 704		078 504		
0 ... 40	079 007		079 107		079 704		079 504		
0 ... 60	080 007		080 107		080 704		080 504		
0 ... 100	081 007		081 107		081 704		081 504		
0 ... 160	082 007		082 107		082 704		082 504		
0 ... 250	084 007		084 107		084 704		084 504		
0 ... 400	086 007		086 107		086 704		086 504		
0 ... 600	087 007		087 107		087 704		087 504		

1) Aux. supply < 12 V accuracy 1,6 %.
2) Also available with ABS housing.
3) Also available with zero point adjustment.

Appendix F

List of Publications

Published Papers

1. M. Alyami, R. A. Siddiqui, R. I. Grosvenor and P.W. Prickett, "A Pressure-based Approach to the Monitoring of a Pneumatic Parallel Gripper" *in proceeding of COMADEM 10-13th June 2008, 21st International Congress on Condition Monitoring and Diagnostic Engineering Management, Prague Czech Republic.* ISBN 978 80 254 2276 2, pp. 33–42.

2. Q. Ahsan, W. Amer, R. A. Siddiqui, M. Alyami, R. I. Grosvenor and P.W. Prickett, "Distributed Process Monitoring and Management," *In proceeding of IEEE International Conference on Engineering of Intelligent Systems, ICEIS 2006*, 22- 23 April 2006. Islamabad, Pakistan.

3. R. A. Siddiqui, M. Alyami, R.I. Grosvenor and P.W. Prickett, "On-line Measurement of Process Parameter for e-Monitoring Applications" *in proceeding of COMADEM 10-13th June 2008, 21st International Congress on Condition Monitoring and Diagnostic Engineering Management, Prague Czech Republic.* ISBN 978 80 254 2276 2, pp. 435–444.

Submitted and Accepted for Publication

4. M. Alyami, R.I. Grosvenor, P.W. Prickett, "A Microcontroller-based Approach to Monitoring of Pneumatic Actuators" *International Journal of Production Research (IJPR).*