Conceptual Design

of

A Gripper for a First-Aid Robot

A thesis

submitted to Cardiff University

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by

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ABSTRACT

First aid is the tentative care for anyone who is injured or ill before definitive medical care arrives. Advancements in technology offer robots the potential to be used extensively in first aid to replace human workers. Currently, many elderly people live alone and absence of care can increase risks of illness- or injury-induced unconsciousness. Due to this, it would be useful to investigate if robots could be employed to perform first-aid care. However, their application in aiding humans in such circumstances is still relatively rare due to complexities concerning safety, communication and ability to interact with humans. This thesis is part of a project to design a first-aid robot to manipulate an unconscious human from any position to the recovery position. The only direct contact with human is through gripper of the robot. An attempt to develop a conceptual design of cost-effective grippers has been undertaken. This will enable a robot to perform the handling and manipulation of human segments to achieve the recovery position. For the purpose of robotic application, a research into the feasibility of human body manipulation is being conducted. Initial stage of research is to identify the limit of physical robot-human interaction; the biomechanical characteristics of human body that decide these limits and essential gripper specifications required to theoretically carry out robot-human interactions to those limits. The research is focused on the geometric properties of various human body parts, defined as body segments, and the minimum gripper specification needed to manipulate these segments.

A novel systematic design approach has been applied to the gripper by utilizing a design tool known as the Theory of Inventive Problem Solving (TRIZ). Results obtained from this study have substantiated design work to derive an enhanced design solution, which will enable the gripper to perform delicate tasks. The gripper’s main priorities have been identified and concluded that fundamental issues are: safely engaging human segments and preventing pain exceeding the recommended pain threshold. This work could form the basis of developing and integrating the First Aid Robotic System (FAROS) and pave a way for further developments and innovations.

This thesis is dedicated to my parents, my late Aunt Dr Kyi Kyi Sein and Pinlon family.

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I would like to take this opportunity to express my sincere gratitude to my supervisor Professor D. T. Pham for his excellent guidance throughout my research, as well as his patience, support and many creative suggestions which was very useful during the difficult stages of my research.

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DECLARATION AND STATEMENTS

DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed ………………………………….. (Saw Min Htet) Date 31/03/2011

STATEMENT 1

This thesis is being submitted in partial fulfilment of the requirements for the degree of Master of Philosophy (MPhil)

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STATEMENT 2

This thesis is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged by explicit references.

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STATEMENT 3

I hereby give consent for my thesis, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available to outside organisations.

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

In recent years, the use of robotics to replace human control has rapidly expanded (Hollerbach, 2008). Current robotic technology is employed in all types of applications to assist people or conduct hazardous tasks in hospitals, homes or work places. The major challenge is to develop robotic systems that can sense and interact with the human world in a wide variety of useful ways. This could result in robot technologies being embedded in thousands of future products (Europe Executive Board Committee 2006).

Rapid advances in technology create unique opportunities to look at new approaches in delivering an effective and sustained first aid health care service. One such opportunity is the concept of a First-Aid Robot System (FAROS); this could potentially lead to developing an advanced cost-effective robotic system to provide first aid. Furthermore, this technology could be used to help elderly persons with impaired mobility in their daily life (Reding, 2007, May, 1999).

To achieve this technology, the challenge is developing a dependable robotic system using advanced robotics and information communication technology to provide first aid services and assist healthcare personnel with the initial diagnosis and treatment of the emergency cases.

Further difficulty is envisaged as many different individual requirements are needed to be designed, developed and integrated for a comprehensive First-Aid Robot System (FAROS). Such requirements include: placing the patient into recovery position, performing Cardio Pulmonary Resuscitation (CPR), dressing a wound, positioning, childbirth, carry out investigative procedures, applying an oxygen mask, measuring pulse rates and all aspects of emergency First Aid. FAROS will also carry out elementary emergency procedures including clearing dangers and raising alarms. It will also need to deliver general domestic assistance. Finally, FAROS will enable medical staff to monitor the patient in real-time and apply more complex medical procedures.

The outcome of FAROS will be a 'home-help' robot capable of first-aid services. Currently, systems with this functionality do not exist. The use of robots to aid humans is still relatively rare due to complexities concerning safety, communication and ability to interact with humans. An initial task of FAROS is to manipulate an unconscious patient from any position to the recovery position. The only direct interaction with humans is through gripper of the robot. It is important that the robot is equipped with grippers that are appropriate for such interaction.

1.2 Aim and Objectives of this Research

The goal of this research project is to develop conceptual designs of cost-effective grippers for FAROS, which are capable of handling an unconscious patient. The research focuses on the development of functions specific to the gripper. This is to allow for easy accommodation and firm gripping action on human body segments of different shapes, sizes and hardness. The gripper should have sufficient versatility to deal with the variety of human body segments which the first-aid robot has to handle. A systematic design approach is applied to the conceptual design of the gripper and the Theory of Inventive Problem Solving (TRIZ) design tool is used for optimising such a conceptual design of a gripper.

The specific objectives of this research are:

- To analyse the geometric shapes, sizes, hardness and pain threshold of various human body segments which will help to implement a gripper suitable for handling human body segments.
- To employ TRIZ inventive principles in the development of the conceptual design of a gripper for a first-aid robot.

1.3 Outline of the thesis

The thesis organised in five chapters. The topics addressed in each chapter are as follows:

Chapter 2: This chapter reviews the current status of emergency First Aid Procedures, conceptual design procedures and the TRIZ technical contradiction problem solving method. In addition, the review chapter addresses the classification and role of the grippers in handling a patient to achieve the recovery position.

Chapter 3: In this chapter, investigations on human body segments, such as shapes, sizes and hardness are presented and safety issues relating to handling different human segments are defined.

Chapter 4: In the first section of this chapter, the implementation of TRIZ trees is described to extract complex features of conceptual gripper design. The final section of chapter 4 analyses and evaluates the result of TRIZ inventive solutions.

Chapter 5: Conclusions and contributions of this thesis are presented in this chapter. Suggestions for future research in this field are also provided.

Chapter 2

Background

2.1 Preliminaries

This chapter gives an overview of emergency first-aid procedures to provide the general context for the research. The chapter also discusses conceptual design and TRIZ as a conceptual design tool. Finally, the chapter reviews the main type of available robot grippers.

2.2 Overview of Emergency First Aid Procedures

First Aid is the immediate and often limited treatment of a victim of sudden illness or injury before the arrival of medical aid. First aid refers to the initial measures which may be instrumental to saving life and ensuring a better and more rapid recovery. The conditions that require immediate attention to avert death include cessation of breathing (asphyxia), severe bleeding, stroke, heart attack and poisoning. First aid comprises of a series of simple life-saving techniques that an individual can be trained to perform with minimal equipment. First aid training is not only for the treatment of initial injury but also responsible for safety (St. John Ambulance, 2009).

2.2.1 Life-Saving Procedures

First Aid is the initial assistance or treatment given to someone who is injured or who has suddenly taken ill (St. John Ambulance, 2009). The first aid learned from a manual or study programme is entirely different from reality. Firstly, the individual performing the first aid would feel apprehensive when faced with “the real thing”. By overcoming these emotional barriers, human are capable of dealing with unexpected injury and illness. It is essential that the robots are capable of handling and performing the First Aid procedures in unexpected situations. Initially, the scene should be assessed to determine whether it is safe for the rescuer. If the situation is not safe, the rescuer should leave the scene for their-own safety. It needs to be established whether the victim is alert, breathing and has circulation (ABCs). If the victim is both alert and an adult, consent should be obtained before performing first aid procedure. For children, it is important to obtain consent from a parent, guardian, or other responsible caregiver. If the victim is not alert, and not breathing, presence of a pulse should be checked for. If there is no pulse, cardiopulmonary resuscitation should be performed. If there is circulation, rescue breathing should be performed. The initial assessment should be done quickly, i.e. within a minute or less. The next step should be alerting trained emergency medical personnel. The emergency services should be called (St. John Ambulance, 2009).

2.2.2 Handling of an Unconscious Adults

There are six main preliminary steps which need to be taken into account when dealing with an unconscious adult. The summary of the sequence is described below.

1. Check casualty's response
    - Try to get response by asking question and gently shaking the casualty's shoulders.
    - Find out if there is any response. If the casualty is responding, leave the casualty in the position they were found in and summon

help if it is necessary. If the casualty is not responding follow the second step.

2. Open the airway; check for breathing
    - Tilt the head back to open the airway.
    - Check for breathing.
    - Is the casualty breathing normally? If yes, check for life-threatening injuries. Place the casualty in the recovery position and summon emergency help. If the casualty's breathing is not normal, follow step three.

3. Call for an ambulance
    - Send a helper to dial 999 for an ambulance.
    - Ask the helper to bring a defibrillator if one is available.

4. Begin chest compression
    - Give 30 chest compressions.

5. Begin rescue breaths
    - Give two rescue breaths.

6. Continue CPR
    - Alternate 30 chest compressions with two rescue breaths until help arrives and the casualty starts breathing normally.

2.2.3 Recovery Position for an Unconscious Breathing Adult

The recovery position is technically known as the lateral recumbent position and is recommended for people who are unconscious but are still breathing. When an unconscious person is lying on their back, there are two main risk factors which can lead to suffocation. Fluids, such as blood but particularly vomit, can collect in the back of the throat, causing the person’s breathing to become restricted. When a person is lying on their back, the esophagus tilts down slightly from the stomach towards the throat. This, combined with loss of muscular control, can lead to the stomach contents flowing into the throat, a phenomenon known as passive regurgitation. Not only does this obstruct the airway, but also fluid which collects in the back of the throat can then flow down into the lungs. As a result stomach acid can attack the inner lining of the lungs and lead to a condition known as aspiration pneumonia. Many fatalities have been known to occur where the original injury or illness which caused the unconsciousness was not itself inherently fatal, but instead the victim suffocated for one of the reasons described above. To an extent, it is possible to protect against risks to the airway by tilting the head back and lifting the jaw. However, an unconscious person will not remain in this position unless held constantly, and most importantly it does not safeguard against risks due to fluids. If the person is placed in the recovery position, the action of gravity will allow any fluids to drain. Also the chest is raised above the ground, which helps to make breathing easier (St. John Ambulance, 2009).

The rescuer needs to perform the preliminary first aid steps before implementing the recovery position described in the previous section, 2.2.2. The recovery position is done by straightening the victim's legs and pulling the closest arm out from the body with the elbow at a right angle or 3'o clock position and the other arm across the victim's body with the hip and knee bent. This allows for the victim's body to be rolled on its side. The head should be tilted back slightly to keep the windpipe open. Note that the head should not be propped up. Airways should always be open. If the casualty is unconscious, unresponsive and not breathing, then CPR should be initiated.

The recovery position is simple to implement, very effective and can save lives. The step by step procedures of the recovery position are as follows:

1. Kneel beside the casualty. Remove any spectacles and bulky objects, such as mobile phones and large bunches of keys from the pockets. Do not search the pockets for small items.
2. Make sure that both of the casualty's legs are straight.
3. Place the arm that is nearest to you at right angles to the casualty's body with the elbow bent and the palm facing upwards.
4. Bring the arm that is farthest from you across the casualty's chest, and hold the back of his hand against the cheek nearest to you. With your other hand, grasp the far leg just above the knee and pull it up, keeping the foot flat on the ground.
5. Keeping the casualty's hand pressed against his cheek, pull on the far leg and roll the casualty towards you and on to his side.

6. Adjust the upper leg so that both the hip and the knee are bent at right angles.

7. Tilt the casualty's head back so that the airway remains open. If necessary, adjust the hand under the cheek to make sure that the head remains tilted and the airway stays open.

8. If it has not already been done, dial 999 for an ambulance. Monitor and record vital signs level of response, pulse and breathing.

9. If the casualty has to be left in the recovery position for longer than 30 minutes, roll him on to his back, and then turn him onto the opposite side, unless of course other injuries prevent from putting the casualty's into the recovery position.

In the early stage, FAROS focuses on putting an unconscious patient into recovery position. Figure 2.1shown the recovery position of an unconscious casualty.

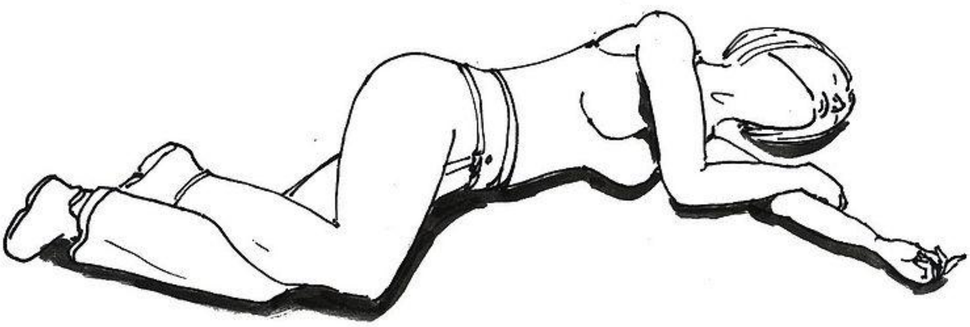


Figure 2.1: The recovery position

2.3 Conceptual Design

Conceptual design is an initial phase of the design process and is the thought process of generating and implementing the fundamental ideas that characterize a product or system. The design process affects the product performance, robustness, novelty, development time, value and cost. Conceptual design commences with 'need identification and analyses' which make up the initial stage of the design process. Need analysis transforms the often vague statement of a design task into a set of design requirements. Conceptual design encompasses the generation of concepts and integration into system-level solutions, leading to a relatively detailed design (Kroll, 2001). A good conceptual design comprises of the creation of an idea, the exploration of the intentions of an idea and the representation of an idea. If the concepts and the idea are not clear, the end result will always be compromised. In previous literature articles, the conceptual design is defined as:

- High-level descriptions of requirements and proceeds with a high level description of a solution.
- The phase where engineering science, practical knowledge, production methods, and commercial aspects need to be brought together.
- Therefore, conceptual design is imperative task in an engineering product development.

2.3.1 Conceptual Design Process

Figure 2.2, represents a block diagram of the conceptual design process adapted from the work of Pahl & Beitz, French, and B O'Sulivan'. The left block diagram represents four stages of the design process. Novel product development initially started from analysing the problems and requirements. Conceptual design plays an important role in the early stage of design and creates new ideas that satisfy the design requirements. In this phase, demand on the designer is at its greatest and where there is the most scope for remarkable improvement. It is also a phase where all practical knowledge, production methods, engineering science and commercial aspects are combined together and important decisions are taken in order to fulfil the design requirements. The outcome of conceptual design comprises of one or more new design concepts that can be used as a basis for embodiment and detail design for the later phase of design. The right diagram of the block diagram indicates four sub-stages in the phase of conceptual design. The purpose of the conceptual design stage is to generate inventive ideas and solutions to evaluate throughout the process.

There are many techniques which support the conceptual design in current literature. Some literature state that the supporting techniques for conceptual design stage are classified into two groups which are modelling issues and reasoning issues. The modelling issues usually occur at the early phase of the conceptual design while the reasoning issues are employed for supporting concept generation, selection and evaluation (O'Sullivan, 2002).

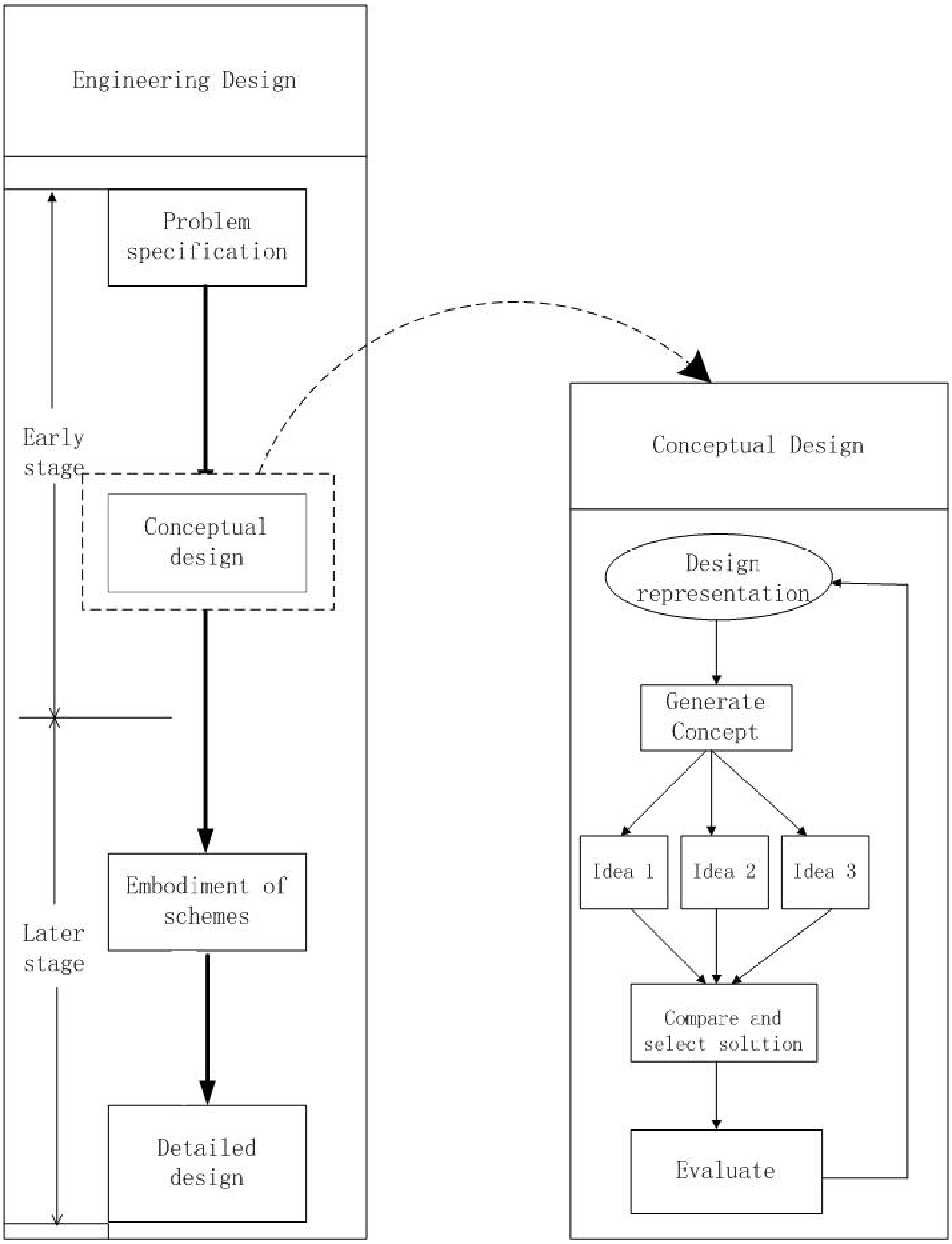


Figure 2.2: Process of design and conceptual design

In design literature, there are varieties of tools or techniques for supporting the conceptual design phase. Concept generation is the most important phase. The technique can be divided into two groups: human-oriented creative thinking tools and computer aided tools. The former approach is emphasis on assisting designers to generate ideas while the computer aided approach focus on generating concepts automatically.

There are a number of techniques to help engineers generate new design ideas which are Morphological Analysis, Brainstorming, Lateral Thinking, Attribute Listing, Check Listing, Brain Writing, Interviewing and Surveying etc. Concept generation solutions tool can be classified into two groups such as disciplined thinking and 'out-of-the-box' or divergent thinking. Disciplined thinking focuses on logical or structured ways of creating a new product or service. Morphological Analysis is an example of disciplined thinking. Divergent thinking, or 'out-of-the-box' thinking methods is lateral thinking, which breaks out of patterned ways of thinking and that moves away from diverging to involve a variety of aspects, which sometimes leads to novel ideas and solution. However, each type of approach has its strengths and weaknesses (Figure 2.3).

Disciplined or logical thinking is an effective way of making products and can provide better services. Divergent thinking can generate novel ideas and concepts. It can create exceptional improvements to existing systems. However, it can create unnecessary disruption.

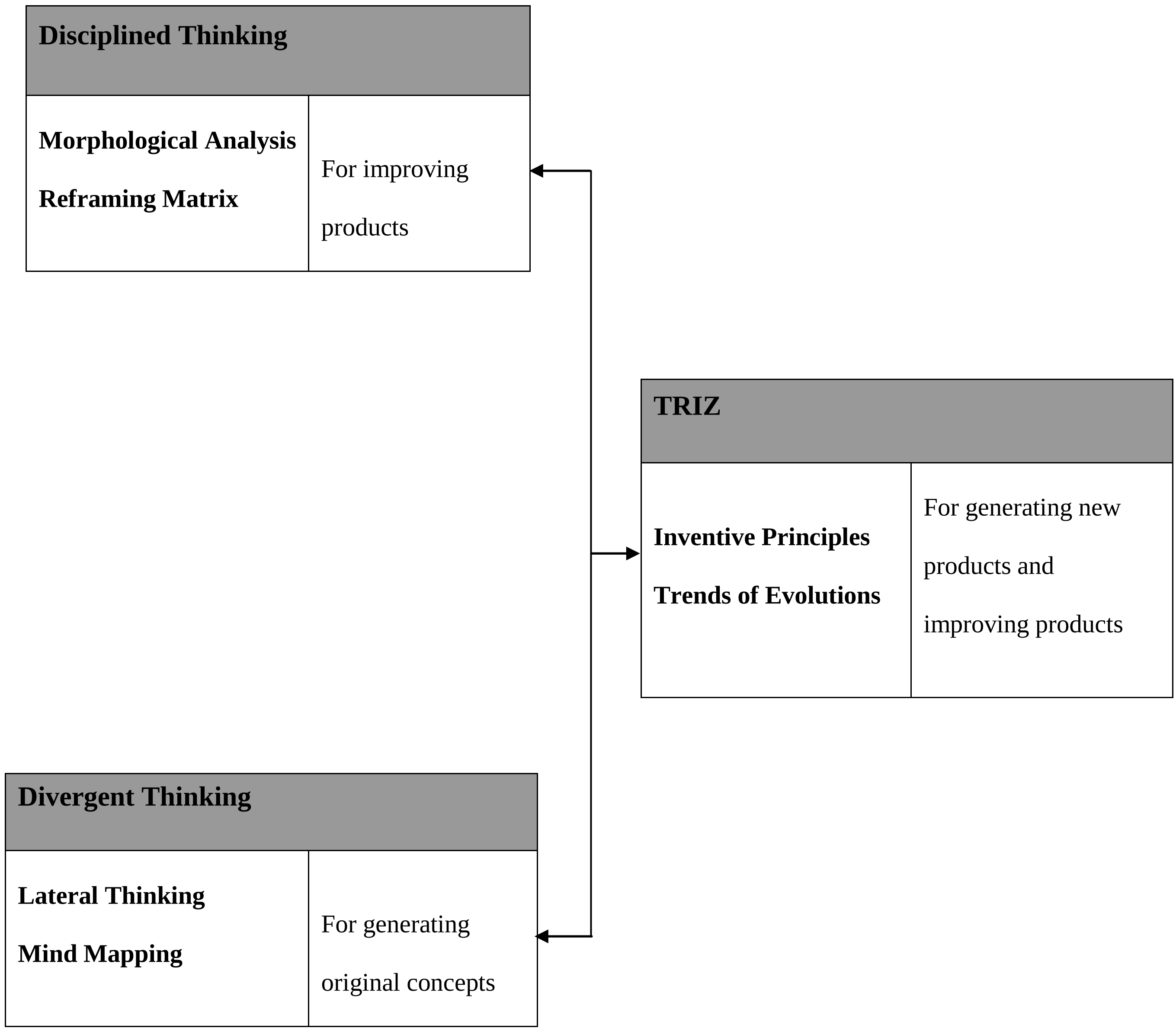


Figure 2.3: Comparison of Creative Thinking Tools

TRIZ (Altshuller, 1988) is the acronym for "Theory of Inventive Problem Solving," in Russian. It integrates the advantages of disciplined and divergent thinking. A contradiction matrix provides a structured way of solving technical problems while the 'Ideal Final Result visioning method' is a divergent thinking technique based on the philosophy of "breaking psychological inertia". TRIZ was developed by Genrich Saulovic Altshuller and his colleagues in the former USSR in 1946 and based on more than 50 years of research. The theory is still being developed and practiced all over the world.

TRIZ provides a systematic analysis of the system to be improved and the application of guidelines for problem definition. With TRIZ, ideas can be generated faster, problems solved more effectively and form a basis for further improvements. TRIZ is the theory based on features of great inventions and patterns of the evolution of systems (Rantanen, 2008). Albeit, TRIZ provides a number of tools to help a designer generate new ideas, it has its limits. TRIZ tools are still difficult for people to understand in a short period of time and apply in practice. However, among the creative thinking tools, TRIZ is still one of the most powerful tools for generating ideas during conceptual design for both novice and experienced designers.

It is very important to achieve the best solutions in every aspect of conceptual design. A good solution resolves the contradiction that is the cause of the problem. TRIZ is the theory that provides the basis for the model of successful problem solving. In general, there are two kinds of contractions: 'Trade-off contradictions' and 'Inherent contradiction'. A trade-off contradiction means that if something good happens, something bad happens. Alternately when something good gets better, something undesirable gets worse. Inherent contradiction means that one thing has two opposite properties. For example, the product should be thick (to get strength) also should be thin (to be light). The idea of a system is a measure of how close it is to the perfect system. The perfect system, also known as ‘ideal final result’, in TRIZ has all the benefits to the customer at no cost, without harmful effects. Unseen idle resources of the system are used to reach these seemingly incompatible goals. These resources include energy, objects, information, materials or things that can be made easily from the resources that are in the system (Rantanen, 2008).

The set of 40 inventive principles of classical TRIZ was extracted and derived from thousands of patents in the Russian patent database. The 40 inventive principles can be employed to solve all design problems. The conventional technical contradiction matrix of TRIZ is a matrix consisting of 39 improving features and 39 worsening features. In Altshuller’s TRIZ problem solving method (Altshuller, 1997), the designer needs to identify a list of improving and worsening features from the technical contradiction matrix. The cell, containing each improving and worsening feature, will have a list of solution or inventive principles. That list has a restriction and contains a maximum of four possible inventive principles in the conventional matrix. However, there are two weaknesses in the matrix. Empty cells can be seen in the matrix which are due to non-recommended inventive principle in some cells and cells that coincide with the same improving and worsening feature are always empty and have no solution principle recommended (Pham, 2009).

2.3.2 Modified TRIZ's Technical Contradiction Matrix

Genrich Altshuller created and completed the TRIZ technical contradiction matrix in 1985 (Altshuller, 1997). The new contradiction matrix has 48 improving features and 48 worsening features but the number of inventive principles remains unchanged. The new contradiction matrix is developed based upon new patents and contains some improvements in new contradiction matrix. Table [2.1] indicates the 40 inventive principles recommended by TRIZ. The new contradiction matrix is still non-recommendation of inventive principles when the same improving and worsening features coincide, however the other cells are filled unlike the conventional matrix. Table [2.2] illustrates all the 48 improving and worsening features of the new matrix by Mann. The new contradiction matrix provides more design related knowledge and better design support compared to the old version of TRIZ (Mann, 2003).

Inventive Principles
1. Segmentation
2. Taking Out
3. Local Quality
4. Asymmetry
5. Merging
6. Universality
7. ‘Nested Doll’
8. Anti-Weight
9. Preliminary Anti-Action
10. Preliminary Action
11. Beforehand Cushioning
12. Equipotentiality
13. “The other way round”
14. Spheroidality – Curvature
15. Dynamisation
16. Partial or Excessive Actions
17. Another Dimension
18. Mechanical Vibration
19. Periodic Action
20. Continuity of Useful Action
21. Skipping
22. “Blessing in Disguise”
23. Feedback
24. “Intermediary”
25. Self-Service
26. Copying
27. Cheap Short-Living Objects
28. Mechanics Substitution
29. Pneumatics and Hydraulics
30. Flexible Shells and Tin Films
31. Porous Materials
32. Colour Changes
33. Homogeneity
34. Discarding and Recovering
35. Parameter Changes
36. Phase Transitions
37. Thermal Expansion
38. Strong Oxidants
39. Inert Atmosphere
40.Composite Materials

Table 2.1: The 40 Inventive Principles of TRIZ

(Mann, 2003)

Improving and Worsening Feature
1: Weight of moving object
2: Weight of stationary object
3: Length/Angle of moving object
4: Length/Angle of stationary object
5: Area of moving object
6: Area of stationary object
7: Volume of moving object
8: Volume of stationary object
9: Shape
10: Amount of substance
11: Amount of information
12: Duration of action of moving object
13: Duration of action of stationary object
14: Speed
15: Force/Torque
16: Energy used by moving object
17: Energy used by stationary object
18: Power
19: Stress/Pressure
20: Strength
21: Stability of the object
22: Temperature
23: Illumination intensity
24: Function Efficiency
25: Loss of Substance
26: Loss of Time
27: Loss of Energy
28: Loss of Information
29: Noise
30: Harmful Emission
31: Other harmful effects generated by system
32: Adaptability/versatility
33: Compatibility/Connectivity
34: Trainability/Operability/Controllability/Ease of operation
35: Reliability/Robustness
36: Reparability / Ease of repair
37: Security
38: Safety/Vulnerability
39: Aesthetics/Appearance
40: Other harmful effects acting on system
41: Manufacturability/Ease of manufacture
42: Manufacturing precision/Consistency
43: Automation/Extent of automation
44: Productivity
45: Device complexity
46: Control Complexity
47: Ability to detect/Measure/Difficulty of detecting
48: Measurement accuracy/Measuring Precision

Table 2.2: The 48 Improving and Worsening Features of TRIZ Contradiction Matrix by Mann (Mann, 2003)

2.3.3 TRIZ in Conceptual Design

TRIZ is a great tool for generating good ideas; it has been widely employed in the design process (Pham, 2009) (Mann, 2002, Souchkov, 1998, Rantanen, 2008) have showed a variety of ways to solve design problems using the contradiction matrix. TRIZ contradiction matrix is not easy to use and it can cause confusion to the novice user (Pham, 2006). Altshuller stated that all TRIZ problem solving tools, including the contradiction matrix support the aim of solving a design problem which is to achieve the ideal final result (IFR). IFR is a description of the best possible design solution to a technical problem, regardless of the resources or constraints of the original problem. IFR is one of the basic terms in TRIZ. It has all useful functions aspired and has neither harmful functions nor weakness. The IFR helps a designer to break 'psychological inertia' that would hinder chances of deriving an innovative design solution and breakthrough solutions by thinking about the solution, but not the intervening problem. It only focuses on functions requirement, not the current process or equipment (http://www.triz-journal.com/archives/1997/02/a/index.html).

Since TRIZ is a great tool for generating inventive ideas, it has been applied in the design process. Valeri Souchkov (Souchkov, 1998) developed a TRIZ-based conceptual design model, which integrated inventive principles and evolutionary trends for supporting the following two phases of conceptual design: concept generation and concept evolution. Darrel Mann built a general systematic creativity process consisting of four phases: define, select tool, evaluate, and generate solutions, which can be applied in the phase of concept generation. Different TRIZ tools have been discussed to fit in each phase in his systematic creativity process. Application of technical contradiction matrix in solving design has been employed for many years. Most of design problems involve driving solutions that solve one or more contradiction features. In this thesis, it has been decided that TRIZ is suitable method to apply to generate a conceptual design for a first-aid robot gripper.

2.4 Gripper Classification

Grippers will be essential in the implementation of a first aid robot. Current available grippers can be categorized into four main groups according to their physical principle of operation (gripping methods). The four gripping methods are- impactive, ingressive, contigutive and astrictive (Monkman, 2007b).

2.4.1 Clamping (Impactive) Grippers

A clamping gripper is a type of mechanical gripper where the object prehension is achieved by the direct mechanical force from two or more directions. It is a force applied against the surfaces of the object to be gripped. The clamping (Impactive gripping) method requires solid jaw movement to produce the desired firm grasping force (Monkman, 2007b). Clamping grippers normally contain between two to four fingers and belong to the most widely used implemented gripper designs. The two jaw gripper motions are synchronized so that the closure is achieved towards the centre in a uniform manner. Some designs rely on the movement of only one jaw. The advantages of independent jaw motion are where the object centre point is required as the gripper jaws control and adjust themselves with respect to the exact grip position. The two jaws clamping gripper is shown in figure 2.4.

Other types of clamping grippers are angular gripper and radial gripper. The angular gripper can open and close along a curved path and operates with ranges that are as wide as 90 degree. The gripper has the advantage of accommodating a wide range of objects and also contains limitations when operating in restricted space. Angular grippers are capable of grasping a variety of object shapes and sizes by finger shape matching. Radial clamping grippers are the self-centering grippers and mostly consist of three jaws capable of aligning the object along the gripper axis. They are commonly used for the handling of cylindrical work pieces in loading and mounting operation.

Another kind of clamping gripper is internal gripper which grasps the work piece internally depicted in Figure 2.5(a). The gripper allows the robot to grasp and manipulate the object by an internal cavity. Internal clamping gripper mainly consists of two types. One type of gripper provides an actuator connected by a linkage with a number of fingers which can move outward. Another type of gripper is the inflatable bladder gripper. This contains a bladder which is inserted within the cavity of the part and either a hydraulic or pneumatic system is provided for inflating the bladder. The cavity is filled and presses against the walls of the work piece. Friction between the bladder and cavity walls provide resistance against slippage when the component is lifted. Due to contact between the bladder and component being spread across a large area, the gripping pressure can be kept small, which makes the gripper suitable for handling fragile objects. The bladder grippers cannot be used in operation where high positional accuracy is required. This disadvantage is due to the flexibility of the bladder which provides uncertainties in the position of the object being gripped (Monkman, 2007b, Lundstrom, 1977, Brandy, 1989).

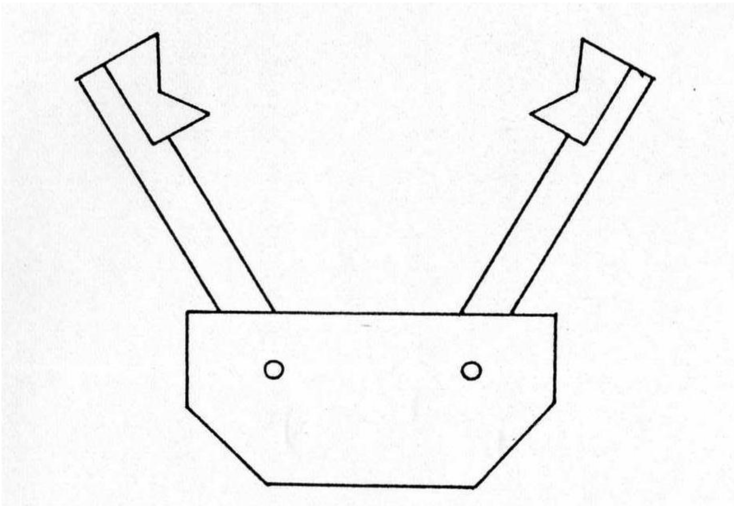
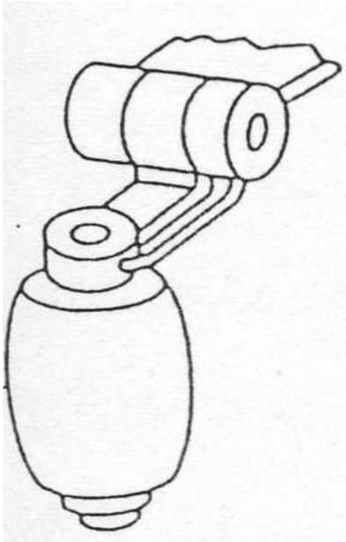


Figure 2.4: Schematic of the Impactive Two Finger Gripper

(Monkman, 2007a)



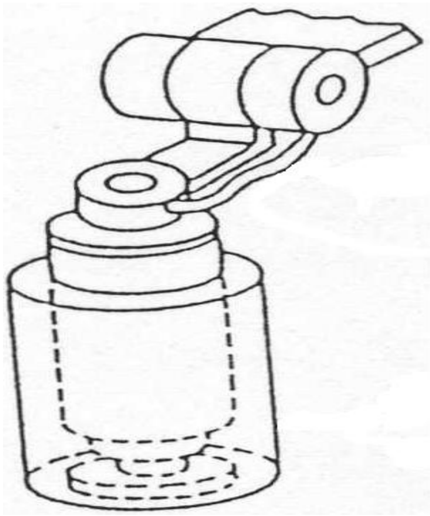


Figure 2.5 (a): Schematic of the Impactive Internal Bladder Gripper

(Jacobsen, 1983)

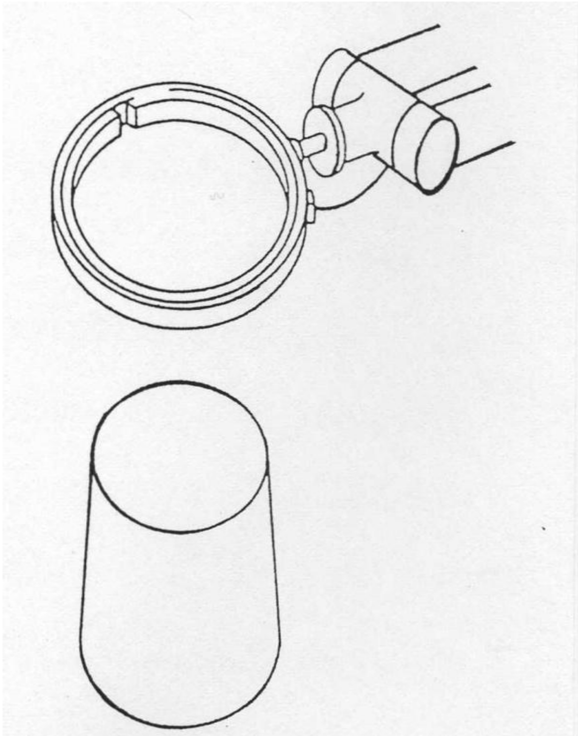


Figure 2.5 (b): Schematic of the Impactive External Bladder Gripper

(Jacobsen, 1983)

2.4.1.1 Three Finger Grippers

The three finger grippers are employed for grasping objects of more complex shapes that can be handled by two finger jaw devices. Three fingers offer good centring possibilities for the adjustment of the work piece on the gripper axis (Monkman, 2007a) pg153). The grippers provide a higher degree of safety when compared to the two-finger grippers due to more constraints on the movements of the work piece. There are numerous designs for grippers with three fingers. Figure 2.6 illustrates the schematic of a three finger gripper. Most of the three-finger grippers are well suited for assembly operations with cylindrically shaped objects. The cup-shaped gripper jaw provides lower surface pressure compare to prismatic jaw grippers. This can be a useful criterion when handling thin-walled, delicate or brittle work pieces. However, three finger grippers are generally more complex and more expensive than two finger grippers.

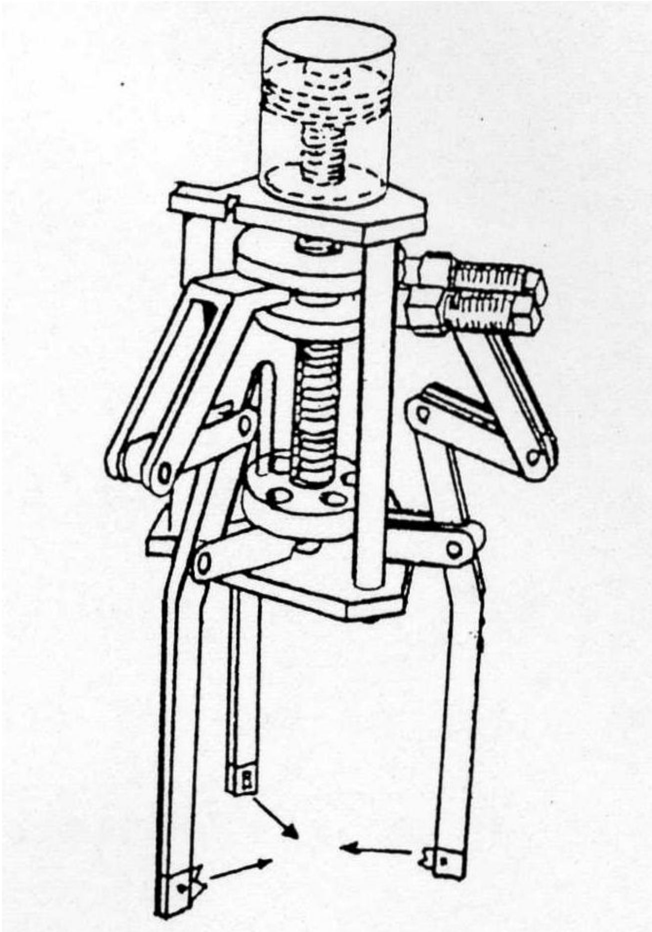
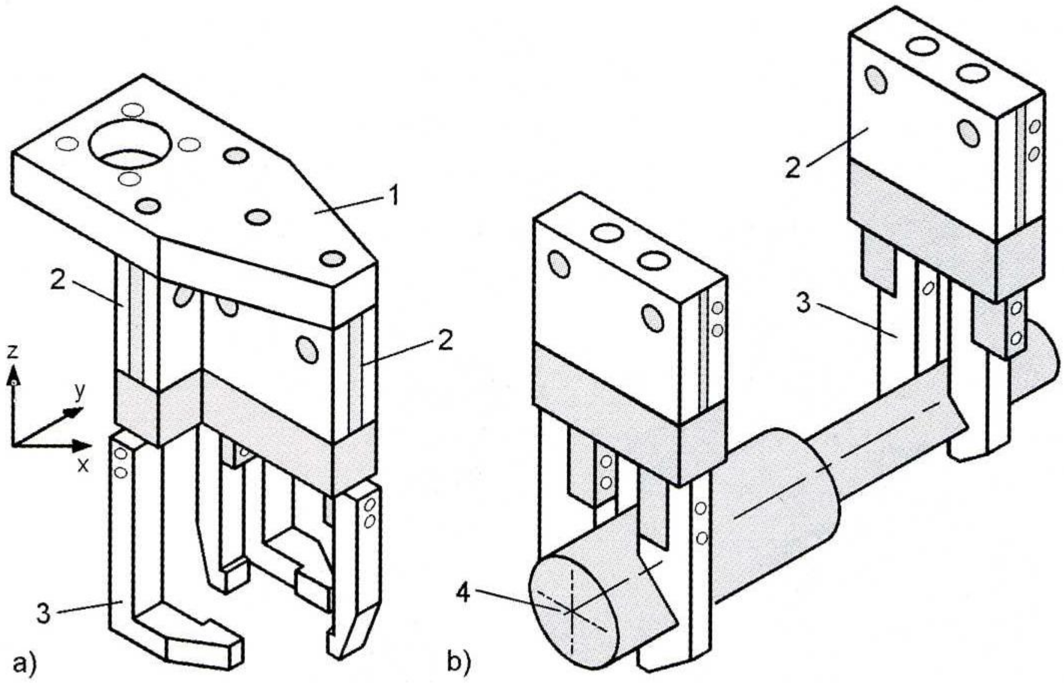


Figure 2.6: Schematic of a Three-Finger Gripper (Lundstrom 1977)

2.4.1.2 Four Finger Grippers

Four finger grippers are designed especially for the prehension of long objects. Current four-finger grippers can grasp both rectangular objects and objects with various diameters along their length. Four-finger grippers with hydraulic drive are preferable for large and heavy work pieces as the force is sub-divided amongst multiple pieces. Some four-finger grippers can prehend large cylindrical work pieces internally (Monkman, 2007b, Brandy, 1989, Groover, 1986, McKerrow, 1998). Figure 2.7 (a) and (b) illustrates the schematic of a four-finger gripper.

The majority of industrial grippers are impactive grippers. Most available industrial used grippers are mainly clamps with external fingers, internal fingers, chucks and spring clamps. Also tongs with parallel, shear and radial grippers are used heavily implanted in industrial applications. The impactive grippers are suitable for large, heavy rigid objects. It is useful for industrial application. Due to its design complexity and higher cost, it man not be taken into account for first-aid gripper design.



2. Flange Plate
3. Parallel Gripper
4. Gripper Jaw
5. Workpiece

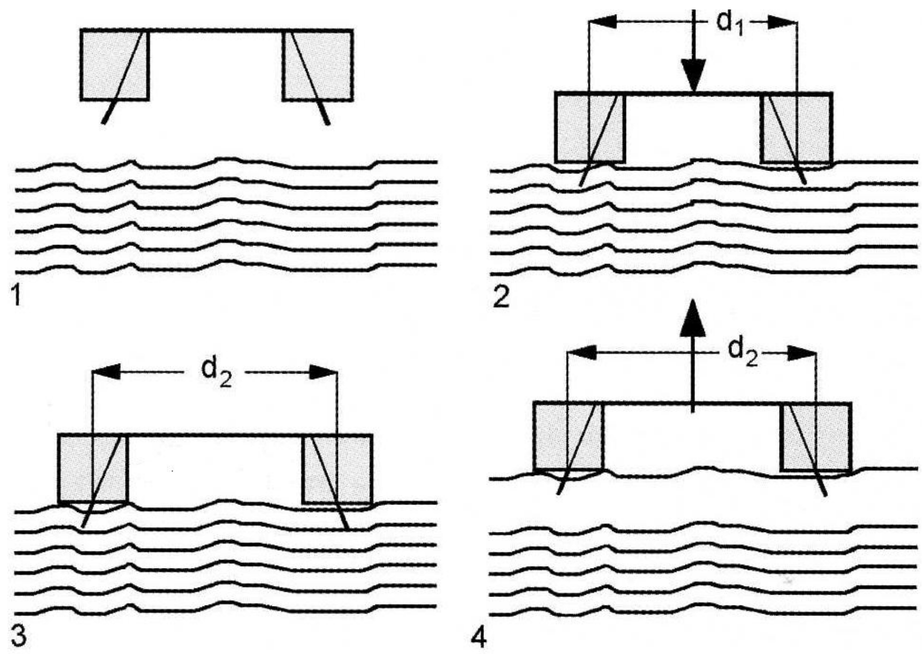
Figure 2.7: Schematic of the Four-Finger Gripper

a) Gripper for rectangular parts, b) Gripper for long cylindrical parts

The above diagram is taken from ‘Robot Grippers’ book(Monkman, 2007a)

2.4.2 Ingressive Grippers

Ingressive gripping involves penetrating or deforming the object to be gripped. The technique can be intrusive, as in the case of pins which can permeate through the materials or non-intrusive as in the case of mechanisms which do not penetrate and merely pinch the material. Ingressive methods are normally used on a single surface and hold the object without the need to maintain an applied force. Most ingressive grippers are designed to separate flat objects from a stack. The separation is obtained by means of intrusion into the top object to a controlled depth. Figure 2.8 shows the application of needle gripper to ply separation. Ingressive techniques are also suitable for soft materials which include fabric, foam and fibrous components such as textile, carbon and glass fibre (Monkman, 2007b). They are mainly used in the garment industry and, therefore, may not be of interest to the gripper for first-aid robot project.



1. Approaching the stack
2. Contact and penetration
3. Stretching of material between needles
4. Removal from stack

Figure 2.8: Schematic of the Ingressive Gripper, application of needle gripper to ply separation(Monkman, 2007a)

2.4.3 Single Surface (Astrictive) Grippers

Astrictive means a binding force produced by a field. The field can be vacuum suction (air movement), magnetism or electrostatic charge displacement. Vacuum suction magnetic and electrostatic adhesion can lift most objects without direct initial contact. Astrictive grippers have the ability of providing a continuous holding force without the application of compressive stress. Vacuum suction method is used extensively in industry and is one of the oldest gripping methods. Astrictive grippers rely on continuous energy supply to maintain object retention. The loss of that supply could result in loss of retention (Monkman, 2007b, McKerrow, 1998). This type of gripper is for any situation where only one surface of the work piece is accessible or available for gripping.

2.4.3.1 Vacuum Grippers

Vacuum grippers employ vacuum suction cups for pick and place applications shown in Figure 2.9. It holds and lifts the object through the astrictive surface force produced by the pressure difference between the cups and surrounding atmosphere. Vacuum cups are generally made of polyurethane, silicon rubber, nitrile rubber, natural rubber, fluorine rubber, chloroprene and PVC and they could be used at a large temperature range between -40˚C to 200˚C. The suction cup material can be selected according to charts which take into consideration resistance to oil, weather, high/low temperatures, chemicals and wear and tear. Vacuum grippers can be used for large and heavy parts. It can also be used for very small components in the semiconductor industry and micro-assemblies. The essential requirement for using vacuum end-effectors is to have a clean, dry and impermeable gripping surface. Vacuum end-effectors are light, cheap, and reliable. It also provides contact pressure distribution (Monkman, 2007b).

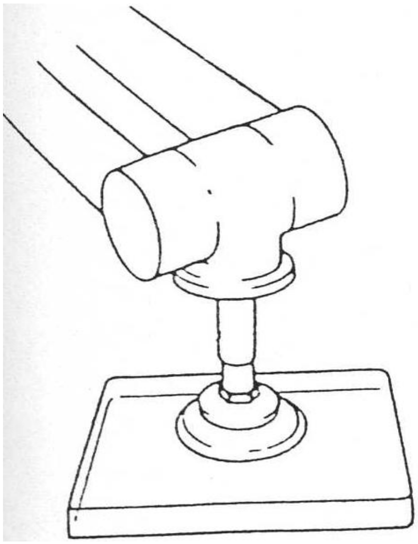


Figure 2.9: Schematic of a Vacuum Gripper

(Jacobsen, 1983)

2.4.3.2 Passive Suction Caps

Passive suction caps create a vacuum by pressing a disk sucker with a relatively soft rim against a flat surface. Mechanical pressure can be applied by means of machine or hand and the suckers do not require further operational force. Passive suction caps depicted in Figure 2.10 can also be applied to slightly curved surfaces. These grippers are considered to be very secure in terms of leakage losses which cannot be compensated and are not affected by a failure of power supply. In order to release the object, air inlet valve must be included in an actuator. Releasing objects can be achieved by pressing the sucker against a surface where an internal piston is pushed up and allows air to escape. Some passive suction caps grippers design employ an electromagnet. In this particular design, the sucker is released by lifting the internal piston through electromagnetic force which in turn connects the air duct with the atmosphere. The passive suction caps grippers (end-effectors) can be used in an environment where a power source is not readily available (Monkman, 2007b, McKerrow, 1998). Industrial use suction cup grippers are shown in Figure 2.11 (a) and (b).

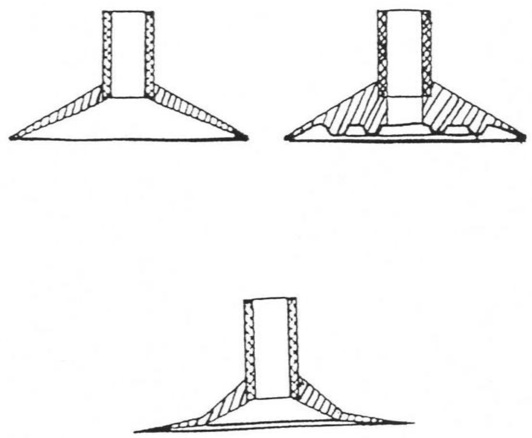


Figure 2.10: Schematic of Suction Cup

(Jacobsen, 1983)

Figure 2.11 (a): Box and carton handling with suction cup gripper (Reference from Liftrite special material handling and lifting equipment)

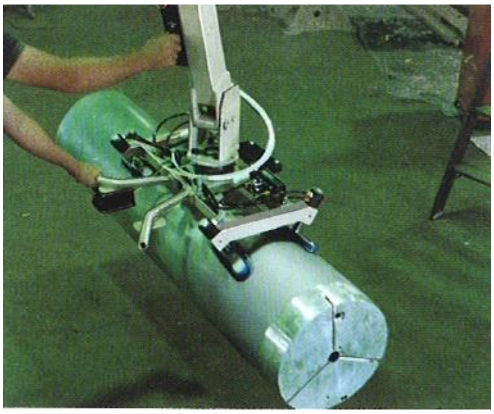


Figure 2.11 (b): Suction cup gripper handling cylindrical shape object. (Reference from Liftrite special material handling and lifting equipment)

2.4.3.3 Magneto Adhesion

Magneto adhesion grippers (end-effectors) are suitable for grasping ferrous objects. They are made of either permanent or electro magnets. Figure 2.12 illustrates the schematic of a principle of the permanent magnet gripper. The electro magnet grippers have the advantage of ease of control in pick and place operations and are suitable for non explosive environment. Permanent magnets can be employed which do not present the risk of failure, if power is removed, unlike electro-mechanical mechanisms. However, permanent magnets require a mechanism to release the component. This could be in the form of a cross polar magnet. It is important to note that whilst humans obviously do not contain magnetic elements, it is wrong to dismiss the use of magneto adhesion for grippers (end-effectors). It is conceivable that the magnets could be placed on clothes or placed on straps around the body (McKerrow, 1998, Monkman, 2007b).

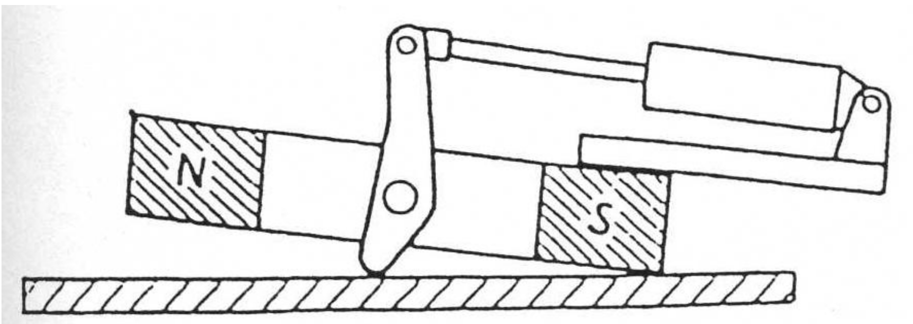


Figure 2.12: Schematic of a Principle of the Permanent Magnet Gripper

(Jacobsen, 1983)

2.4.4 Adhesive (Contigutive) Gripper

Contiguive prehension refers to direct contact between the gripper and object's surface. The nature of the contact holding force can be chemical and thermal adhesion (Monkman, 2007b). Figure 2.13 shows the schematic of adhesive gripper.

2.4.4.1 Chemical Adhesion

In chemical adhesion, both permanent and temporary surface bonding is extensively applying for the purpose of adhesions. However, in terms of robot grippers (end-effectors), only the temporary surface bonding scenario is applicable.

The use of a paper sheet feeding mechanism using adhesive surfaces was designed in 1941 (Monkman, 1991b, Monkman, 1991a). Both designs achieved continuous usage by automatically winding adhesive tapes. For the robotic prehension application, the adhesive tapes provide an activated retention force and for non-reusable adhesives can be replaced after their adhesive properties have expired. In recent research, polymer chemistry has led to the development of adhesives which have re-useable characteristics. In some applications, such as permatack adhesive, the application must be provided enough adhesive power to be capable of several hundred operations before cleaning is required. In addition, the chemical must be risk assessed to ensure it is safe to use on humans. However, not so much adhesion that it becomes difficult to remove the object when release is necessary. Moreover, robustness requires sustaining several tens of thousands of pick and place operations before replacement of the adhesive head is desired. Some adhesive compounds are made of plasticized polyurethane and can be permanently tacky and durable and also exhibit elasticity. This elasticity can be considered to be a disadvantage in robot grippers in first aid applications.

2.4.4.2 Thermoadhesion

Thermoadhesion prehension method involves freezing small droplets of water suspended between the surfaces of objects and gripper heads by means of a small quantity of liquid carbon dioxide or nitrogen. The ice, formed between the gripping head and object, acts as an adhesive layer and also prevents direct contact with the grippers. After prehension, increasing the temperature of the gripping surface melts the ice which releases the object. The retention force is larger than a similar sized vacuum suction head. The thermoadhesion gripping method is most suitable for handling textile fabrics, polymer and composite materials; the former being of most use to the first aid robot application as the gripper could attach to clothing. However, this type of gripper might be of limited use for robot-human interaction, as liquid nitrogen can burn human skin, when applied in large quantities.

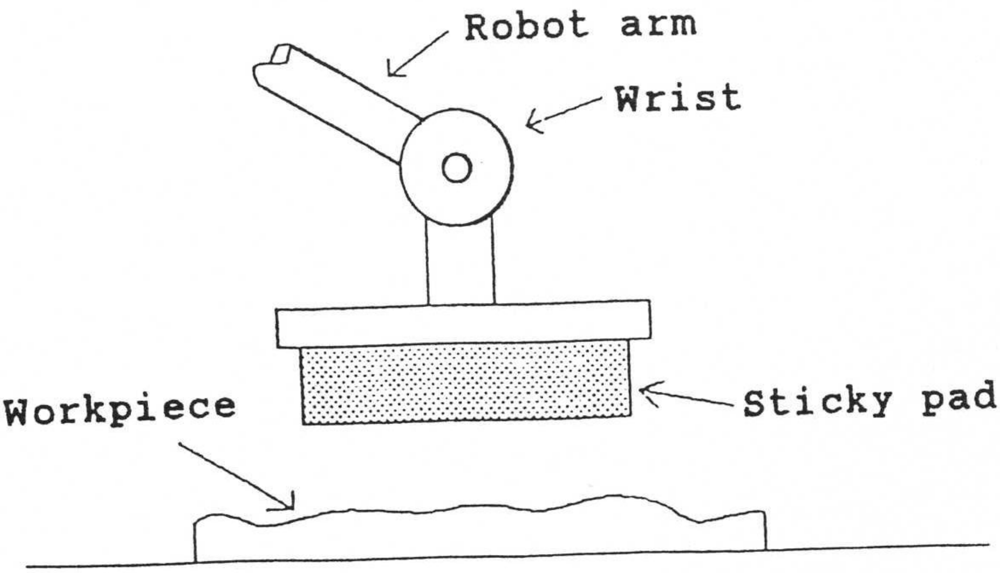


Figure 2.13: Schematic of an Adhesive Gripper

(Jacobsen, 1983)

As previously mentioned, gripper technique may be categorised in four main groups which are Clamping (Impactive), Ingressive, Vacuum (Astrictive) and Adhesive (Contigutive). The summary of advantages and disadvantages of each type of gripper are listed in table 2.3.

Gripper technique	Advantage	Disadvantage
Clamping (Impactive) 2 fingers	- Flexible - Commonly used - Can adjust themselves easily - Angular and radial operation possible	- Less safe due to constraints on movement - High surface pressure
Clamping (Impactive) 3 fingers	- Complex shapes possible - Higher degree of safety - Lower surface pressure	- More complex and expensive than 2-finger
Clamping (Impactive) 4 fingers	- Useful for long objects - Suitable for large/heavy objects - Useful for industrial applications	- Complex and expensive
Ingressive	- Suitable for garments	- Sometimes not suitable for humans - Suitable only for specific applications
Vacuum (Astrictive)	- Can be suitable for large/heavy parts as well as very small components - Requires suction - Can be reliable - Not suitable for all robot human interactions - Can be cheap - Even pressure distribution	- Loss of force of vacuum is inadvertently removed
Passive suction (Astrictive)	- No additional machinery is required for vacuum - Suitable for flat surfaces - Can be secure	- Inlet valve needed to release force
Magnetic (Astrictive)	- Reliable - Magnet can be permanent (so no risk of force loss)	- Release mechanism needed - Need magnet attached to patient
Chemical (Contigutive)	- Cheap - temporary bonding allows for automatic release	- Can require cleaning - Chemicals could be unsafe - Could be limiting for applications (as retention time low)
Thermo adhesion (Contigutive)	- Large retention force (compared to vacuum) - Suitable for clothing	- Requires potentially dangerous levels of liquid nitrogen

Table 2.3: Summary of advantages and disadvantages with each type of gripper

2.5 Robot Gripper-Human Interaction

Grippers can be categorised into two groups; grippers and tools. The gripper is the mechanical device which interfaces between the robot and its working environment (Pham, 1991). It is an attachment to the robot arm that has to grasp and manipulate objects without causing damage to the object being handled or drop it accidentally while handling (Engelberger, 1980). Grippers can be used in many applications where the human hand is unsuitable, such as working in dangerous environments and lifting heavy or sharp objects. In general, a gripper has to be specifically designed to handle specific tasks. These tasks are to perform gripping, holding and manipulation tasks. For those reasons the more generic term "End-Effector" is often used (Monkman, 2007b). The primary task of the end-effector is to hold the work piece firmly and securely relative to the wrist of the robot. It is important for the designer to develop a correct design as the use of the gripper is essential to the success of the robot's operation.

Grippers are generally employed to grasp an object, and hold it during the robot work cycle. There are a number of holding methods in robotic technology; these were discussed in the previous section. Conventional grippers using gripper jaws are shaped according to the work piece profile and grasping the part between two or more fingers. However, as discussed, there are other additional methods including the use of suction cups, magnets, hook and scoops.

A tool can be used as an end-effector in order to perform specific applications. Such applications which have already been demonstrated include spot welding, arc welding, spray painting and drilling. In each case, the particular tool is attached to the robot's wrist to accomplish the application (Groover, 1986). Empirical studies have indicated that, in the future, flexible end-effector designs for assembly equipment are required in order to respond to practical demand. Assembly consists not only grasping and manipulations of the objects but also pressing, fitting and joining operations. Recently a new miniaturized gripper has been designed for applications in the production and assembly of minuscule components. Also, it has increased a vast number of grippers used in other areas such as in civil engineering, handicraft, space research, medical and pharmaceutical applications. In general, the designing of a gripper depends on the specific requirements. From this review, it can be seen that existing grippers are not applicable in robot human interaction. Therefore, it is necessary to design and develop a special gripper for first-aid robot applications.

2.6 Summary

In this chapter, the current status of first-aid has been reviewed. Lives saving procedures were studied initially. Subsequently, details were given for the handling of an unconscious patient and how to move them into the recovery position. In this project, the information on the current status of first aid was used to clarify procedures which the robot will need to accomplish, and to guide the concept design of a suitable gripper. An overview of the conceptual design process has been addressed. A review of TRIZ and its application in conceptual design has also been given. It can be seen that with the aid of TRIZ it is possible to generate a conceptual design for a first-aid robot gripper.

In the last section of this chapter, the different types of gripper, for possible implementation in first aid robots, have been identified and discussed. These included the most commonly used end-effector grippers in industry. Other applications were reviewed from multiple literature sources (Groover, 1986, Engelberger, 1980, Lundstrom, 1977, Monkman, 2007b). It is important to use this data for deciding the final gripper for the first-aid robot concept data. Table 2.3 summarises the main advantages and disadvantages of each type of gripper.

Chapter 3

Biomechanical Analysis of Human Body Segments in Robot-Human Interaction

3.1 Preliminaries

This chapter focuses on analysing the shapes, sizes and hardness of various segments of human bodies which help to implement a gripper suitable for handling body parts. The purpose of this gripper is to allow easy accommodation and firm gripping action on human body segments of different geometrical features. During direct, physical interactions with humans, it is vital to avoid physical damage on the human body; thus both safety and comfort issues become major concerns. It is essential to specify human body segments, shapes, sizes and hardness in order to implement safe and painless handling.

With the rapid advances in technology, unique opportunities arose to allow consideration of new approaches in delivering an effective and sustained first aid health care service. This could potentially lead to the development of an advanced cost-effective robotic system in order to assist the provision of first aid. Furthermore, this technology could be used to assist elderly people with impaired mobility in their daily living (Fiorini, 1997, Meng and Lee, May, 1999). One of the major difficulties in such implementation is a versatile gripper capable of carrying out both delicate and heavy-duty tasks, such as moving an unconscious casualty into the recovery position (i.e. arranging limbs and torso into desirable positions for further medical assistance).

This chapter is organised as follows: section 3.2 presents a segmentation and geometric model of human body, followed by section 3.3 the Three-Dimensional Anthropometry, section 3.4 discuses hardness/rigidity of human segments, section 3.5 defines the pain threshold of different human segments and section 3.6 summarises this chapter.

3.2 Segmentation and Geometric Model of Human Body

The human body can be represented by a set of rigid bodies of simple geometric shapes. Whitsett (1962) refined the geometrical model of human body segments developed by Simons and Gardner which comprised 14 body segments. Whitsett's model consisted of spheres, ellipsoids, cylinders, frustums of cones and rectangular parallelepipeds and allowed estimation of the mass distribution, centre of mass, mass moments of inertia and mobility of the human body. The model was primarily based on the body segment data from Dempster, 1955 and the regression equations from Barter, 1957. Hanavan (1964) proposed another geometric model similar to Whitsett's, consisting of 15 segments as the torso was modelled as two segments. In Hanavan's geometric model, the human body segments are a series of cylinders, frusta and ellipsoids (Bjornstrup, 1995, Kwon, 1998).

Throughout the current stage of this research Hanavan's geometric model has been adopted and modified as reference for determining the shape of the human body segments. Modified Hanavan's segmentation system of the human body consists of 16 segments, namely head, two forearms, two upper arms, two palms, fingers (all 10 fingers count as one segment), upper torso, lower torso, two thighs, two shanks, and two feet. The geometric shapes of these segments were concluded from data collected during an evaluation conducted on a sample group containing 20 females and 20 males aged between 18 and 50.

Hanavan (1964) developed a geometric model of the human body, modelling segments as a series of cylinders, frusta and ellipsoids. The human body can be represented by a set of rigid bodies of simple geometric shape and uniform density. The limbs move about fixed pivot points when the body changes position. The head is a right circular ellipsoid of revolution, the upper and lower torsos are right elliptical cylinders, the hands are rectangular parallelepiped, and the foot and thigh are elliptical solids with one face being circular and the remaining segments are the frusta of right circular cones.

The head was defined as ellipsoids of revolution while other body segments were defined as variations of elliptical solid such as truncated circular cones (forearm, upper arm and shank), elliptical cylinder (upper torso and lower torso), and elliptical solids with one face being circular (foot and thigh) (Hanavan, 1964, Dempster, 1955).

3.2.1 Groupings of Human Segments Geometry

Three geometric groups commonly used in defining the human body segments are cylindrical, ellipsoid and rectangular parallelepiped. The cylindrical group consists of elliptical cylinder, elliptical solid, truncated circular cone, elliptical cylinder and circular cylinder. The members of the ellipsoid group are the semi ellipsoid, sphere and ellipsoid of revolution. The rectangular parallelepiped group consists of parametric solid, prismatic and stadium solid (Young 1988). These three groups and their constituent members are presented in table 3.1. The geometric shapes of human body segments were concluded from information collected in a review of the published literature supplemented by an evaluation of a sample group of subjects. The results of this geometric shape definition are shown in the table 3.2. The segmentations and geometric model of human body segments are presented in figure 3.1.

Geometric Group	**Member of Geometric Shapes**
Cylindrical (C)	Elliptic Cylinder Elliptical Solid Truncated Circular Cone Elliptical Disks Circular Cylinder
Ellipsoid (E)	Semi Ellipsoid Sphere Ellipsoid of Revolution
Rectangular Parallelepiped (R)	Parametric Solid Prismatic Stadium Solid

Table 3.1: Geometric group and member of geometric shapes table

Segment	Geometric Shape	Geometric Group
1xHead	Ellipsoid	E
2xFore Arm	Truncated Circular Cone	C
2xUpper Arm	Truncated Circular Cone	C
2xPalm	Rectangular Parallelepiped	R
1xFinger	Cylinder with Semi Ellipsoid Top	C
1xUpper Trunk	Elliptical Cylinder	C
1xLower Trunk	Elliptical Cylinder	C
2xThigh	Elliptical Solid	C
2xShank	Truncated Circular Cone	C
2xFoot	Elliptical Solid with Circular Base	C

Table 3.2: Definition of human body segment with regard to their geometric shapes

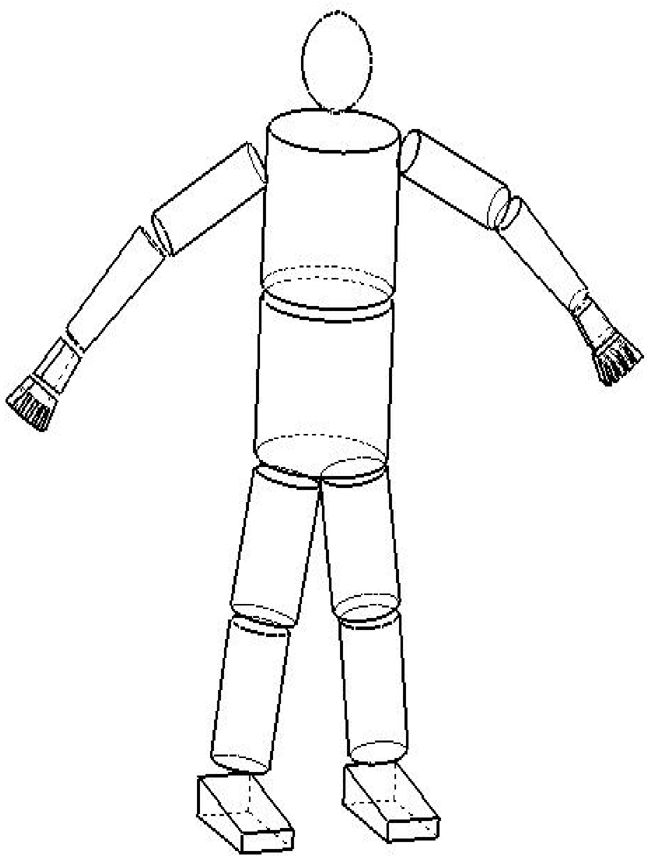


Figure 3.1: Schematic showing the human body divided into 16 segments

It is also possible to study the distribution of geometric groups in terms of a number of shapes. Table 3.3 presents the percentages of the geometric shapes involved in the human body segment. It is obvious that the cylindrical shape is the most common, which is to be anticipated as a large proportion of these shapes occur in limbs, which tend to be long and slender.

Geometric group	**Number of shapes**	**Percentages (%)**
Cylindrical (C)	22	88
Ellipsoid (E)	1	4
Rectangular Parallelepiped (R)	2	8
Total	25	100

Table 3.3: Percentages of the geometric shapes which constitute the human body

3.3 Three-Dimensional Anthropometry

Anthropometry refers to the measurement of living human individuals for the purposes of understanding human physical variation. Anthropometric measurements are usually done through the use of bony landmarks to which heights, breadths, depths, distances, circumferences, and curvatures are measured. For engineers, the relationships of these dimensions to skeletal "link-joint" systems are of importance, so that the human body can be placed in various positions relative to workstations and equipment (Kroemer, 1986).

There are four different ways to measure the stature. In general, the subject standing naturally upright, but not stretched; standing freely but stretched to maximum height; leaning against a wall with the back flattened and stretched to maximum height; and lying supine. The differences between the measures when the subject stretches to maximum height either standing freely or leaning are within 2cm. Lying supine results in a taller measure, but standing slumped reduces stature by several centimetres.

The body measurements are usually defined by the two end-points of the distance measured, such as elbow-to–fingertip. The stature starts at the floor on which the subject stands and extends to the highest point on the skull. There are seven different terms which are used in anthropometry they are height, breadth, depth, distance, curvature, circumference, and reach. Brief descriptions of these terms used in anthropometry are as followed:

- Height is a straight-line, point to point vertical measurement.
- Breadth is a straight-line, point to point horizontal measurement running across the body or a segment.
- Depth is a straight-line, point to point measurement between landmarks on the body.
- Distance is a straight-line, point to point measurement between landmarks on the body.
- Curvature is a point to point measurement following a contour; this measurement is neither closed nor usually circular.
- Circumference is a closed measurement that follows a body contour; hence this measurement usually is not circular.
- Reach is a point to point measurement following the long axis of the arm and leg.

For the purpose of this study, the age of people whose body dimensions measured were limited to a range of ages between 18 years to 65 years old. Data included in this document have been taken reference from 'National Aeronautics and Space Administration' (Jeeverajan, 2008), research project 'DINBelg 2005', 'National Anthropometry survey of Fire-fighters, UK and United States' (CACFOA), and Advances in Human Factors/Ergonomics 4, K.H.E. Kroemer, H.J. Kroemer, and Kroemer-Elbert (Kroemer, 1986, Kroemer, 1988). These documents provided comprehensive human body dimensional specifications which were used in the research. Anthropometric dimensional data from various ethnic backgrounds of both male and female are given in table 3.4. Dimension values are given in millimetre (mm) scale.

Segment	Dimension	Minimum value	Maximum value
Head	Head length	169	211
	Head breadth	130	168
	Head height	190	261
	Circumference	516	623
	Bitagion arc length	304	372
	Sagital arc length	304	374
	Face breadth	123	151
	Jaw width	103	135
Upper Arm	Shoulder to elbow length	272	418
	Upper arm circumference	219	408
Forearm	Elbow to wrist length	215	297
	Forearm circumference	119	327
	Wrist circumference	137	193

Table 3.4: Anthropometric Dimensional Data Collected from Multiple Sources (a)

Segment	Dimension	Minimum value	Maximum value
Hand(Palm+Fingers)			
Hand length	Hand length	158	179
	Hand thickness maximum	35	63
	Hand thickness	19	36
Palm	Palm length	87	119
	Palm breadth maximum	69	107
	Palm breadth	69	94
	Circumference	165	234
Finger	Thumb length	44	65
	Thumb width	17	25
	Finger length	65	94
	Finger width	16	22

Table 3.4 Continued: Anthropometric Dimensional Data Collected from Multiple Sources (b)

Segment	Dimension	Minimum value	Maximum value
Upper Torso/trunk	Bi-acromial width	305	443
	Neck circumference	304	419
	Chest circumference	732	1215
	Upper torso height	317	516
	Chest breadth	245	367
	Waist circumference	553	1080
	Abdominal depth	167	307
Lower Torso/Trunk	Length(waist to crouch)	210	273
	Hip breadth	305	390
	Hip circumference	799	1244
	Waist circumference	553	1080
	Vertical trunk circumference	1369	1826

Table 3.4 Continued: Anthropometric Dimensional Data Collected from Multiple Sources (c)

Segment	Dimension	Minimum value	Maximum value
Thigh	Thigh clearance	112	191
	Circumference	418	736
	Crotch to knee height	237	324
	Crotch to calf height	397	533
	Torchanteric to tibiale height	351	397
Shank	Calf circumference	303	414
	Knee circumference	429	310
	Knee to ankle height	364	451
	Calf to ankle height	203	380
Foot	Foot length	209	293
	Foot breadth	79	111

Table 3.4 Continued: Anthropometric Dimensional Data Collected from Multiple Sources (d)

3.4 Hardness/Rigidity of Human Segments

Size, shape and non-linearity in the human form are important for a robot interaction, the hardness and rigidity of various human segments is a vital characteristic in this research. In this section, these effects are studied in more depth.

3.4.1 Determining Hardness/Rigidity of Human Segments

In this research, it is imperative to avoid physical damages to the human during robot/ human interaction. For security and safety reasons it is necessary to determine the hardness of the human body. In this study, hardness of the human body is divided into three categories namely soft, medium and hard. Whilst three categories might over-generalise the hardness of the human body in the first instance, it will be possible to add more categories or sub-categories in the future. Hard parts are more sensitive to pressure and pain, while medium and soft parts are less sensitive to the same amount of pressure and pain. It is important to develop the gripper with a measurement sensor (tactile/force sensor) to detect the maximum allowable force to avoid any pain and damage whilst the gripping action is occurring.

Human have an estimated average weight between 60 to 100 Kg (Kroemer, 1986). The gripper must be able to securely hold the load in any position. The gripping surface must have a large area in contact with human body segments to reduce the stress caused by manipulator.

The design methodology will be treated as an optimization problem to search for the optimal material arrangement which will be suitable for the purpose of handling.

The basic design requirement of the gripper is that there must be physical connections between the input actuator, output gripper and ground supports to allow the transmission of force and motion. The hardness data of the human body segment are described in table 3.5. It is evident that most segments are defined as medium hardness (73%). However, it is critical to the design for the extremes as well.

Segments	**Hardness**
Head	Hard
Upper arm	Medium
Forearm	Medium
Hand	Medium
Palm	Medium
Fingers	Hard
Upper Torso	Medium
Lower Torso	Soft
Thigh	Medium
Shank	Medium
Foot	Medium

Table 3.5: Illustrate Hardness of Human Body Segments

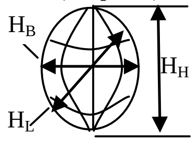
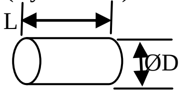
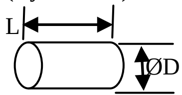
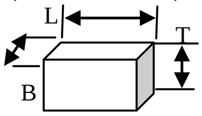
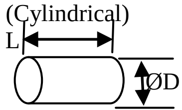
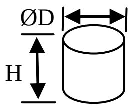
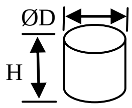
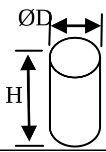
Segment and shape description	Dimension	Min. value	Max. value	Part Count	Hardness
Head (Ellipsoid) 	Head length (H_L) Head breadth (H_B) Head height (H_H)	169 130 190	211 168 261	1	Hard
Upper Arm (Cylindrical) 	Shoulder to elbow length (L) Upper arm diameter (ØD)	272 69.7	418 129.87	2	Medium
Forearm (Cylindrical) 	Elbow to wrist length Forearm diameter (ØD) Wrist diameter (ØD)	215 37.87 43.61	297 104.09 61.43	2	Medium
Palm (Parametric solid) 	Palm length (L) Palm breadth maximum (B) Thickness (T)	87 69 19	119 107 36	2	Medium
Finger (Cylindrical) 	Finger length (L) Diameter (ØD)	44 16	94 25	1	Hard
Upper Torso (Cylindrical) 	Diameter (ØD) Upper torso height (H)	218 317	386.75 516	1	Medium
Lower Torso (Cylindrical) 	Length (waist to crotch) (H) Diameter (ØD)	210 165	273 396	1	Soft
Thigh(Cylindrical) 	Thigh height (H) Diameter (ØD)	324 133.05	397 234.28	2	Medium

Table 3.6: Summary of Human Body Segments Geometric Shape, Size and Hardness

(a)

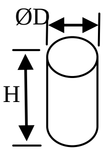
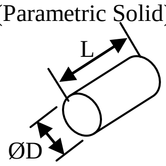
Segment and shape description	**Dimension**	**Min. value**	**Max. value**	**Part Count**	**Hardness**
Shank(Cylindrical) 	Shank height (H)	364	451	2	Medium
	Diameter (ØD)	96.45	136.55		
Foot (Parametric Solid) 	Foot length(L)	209	293	2	Medium
	Foot breadth(ØD)	79	111		

Table 3.6 Continued: Summary of Human Body Segments Geometric Shape, Size and Hardness (b)

Shape		Cylindrical	Ellipsoid	Rectangular Parallelepiped
Count		88%	4%	8%
Size [a] (in mm)	0 - 36	40%	-	8%
	36 - 261	40%	4%	-
	261 - 516	8%	-	-
Total		88%	4%	8%
Hardness	Hard	40%	4%	
	Medium	44%	-	8%
	Soft	4%	-	-
Total		88%	4%	8%

Table 3.7: Percentage data of Human Body Segments Geometric Sizes, Shape, and Hardness

[a] For any body segments other than head, only diameter/ breadth/thickness were considered since it is not likely that an gripper will be needed to cover the full length/height of these body segments during operation.

3.5 Defining the Pain Threshold of Different Human Body Segments

Another important factor in physical robot-human interaction, especially human body manipulation, would be the force and pressure directly applied on human body. Take the ‘recovery position’ in first aid procedures for example; the most likely and frequent contact areas where gripping action would take place on the human body are shoulder, upper arm, forearm, hand, knee and shank. It is imperative that the gripping force does not exceed the pain threshold, which is the maximum pressure that can be applied to human body before causing painful sensation; and in a less favourable situation where the pain threshold had to be reached in order to carry out essential tasks, it is desired that the pressure can be kept below pain tolerance, which is the maximum pressure that can be applied to a human body before the pain becomes intolerable.

The pressure being applied to human body surface or human interface pressure as it is often referred to, is considered to be an important parameter in comfort evaluation. Ideally, the contact surface between gripper and the human body should be kept as large as possible in order to minimize pressure. Pressure at the human interface is unavoidable for various physical interactions; however it is also dangerous since too much of it may cause discomfort, pain, damage and injury and discomfort.

Human interface pressure is an important consideration in the development of robotic applications. It is essential to understand the pressure patterns that are appropriate of the human body which is the pattern that reduce discomfort or enhance comfort. The understanding of pressure pattern can make product design and usage very safe and satisfying.

Pain or discomfort occurs when the special nerve endings, nociceptors, detect an unpleasant stimulus. Human body consists of millions of nociceptors in skin, muscles, joints, bones and internal organs. These nociceptors use nerve impulse to relay pain messages to networks of nearby nerve cells. The detected impulses are transmitted instantaneously from cell to cell and are facilitated by neurotransmitters. Transmitted messages travel along nerve system to the spinal cord and central nervous system, brain. There are some predictions that the pain signals must reach a threshold before they are relay.

As aforementioned, there are two important pressure threshold values, namely the pain threshold and pain tolerance. Here are their more precise definitions. The term pain threshold is defined as the minimum pressure that induces pain and involves measurement of stimulus intensity, whereas pain tolerance is the maximum pressure a person can tolerate without excessive effort. In other words the pain threshold is the point at which stimulus is reported by a person as pain and the pain tolerance is the amount of pain a person can withstand before breaking down either emotionally or physically (Stirling, 2008, Winson, 2005, Wilson, 2006, Jones et al., 2007, Karwowski, 2006).

In this study, it is decided to use pain threshold as a guideline pressure limit. This means avoiding causing pain to human at all. A number of investigations have been done to study the pain response to pressure applied onto human limbs. In human body, some regions with a thicker layer of soft tissue had lower pain thresholds than those with a thinner tissue layer. The patellar tendon and distal end of the fibula were the best and the worst pressure tolerant regions. The pain threshold could be age dependent. One of the methods researchers have applied to find pain threshold was to apply pressure to the test regions through a circular, flat ended indenter of 10mm diameter connected to a force transducer until the subjects claimed not being able to stand the pressure. In some methods indenters of 5mm and 13mm diameters were used. The peak threshold pressure for 10mm diameter indenter is 0.81 MPa (Karwowski, 2006, Wilson, 2006, Winson, 2005).

Given the pain threshold values, and the definition of pressure (Eq. 3.1)

$$p = \Delta F / \Delta A \qquad (3.1)$$

Where:

p is the pressure (in Pascal)

F is the normal force (in Newton)

A is area (in Meter square)

The maximum force which can be safely applied to a human is only decided by the size of contact area between the gripper and human body. The introduction of a second end-effector, which essentially increases contact area by supporting the segment being handled, will consequently decrease the force required to perform these handling tasks and thus lessen the possibility of inflicting pain.

3.6 Summary

In this section, the geometric shapes, sizes, hardness and pain threshold for different human body segments have been analysed and identified which will help to implement a gripper suitable for handling an unconscious human casualty.

Chapter 4

Design of Gripper to Achieve Recovery Position

4.1 Preliminaries

Engineering design involves the formulation of a plan to assist an engineer to create a new product. The design process mainly involves the application of human intelligence. Conceptual design is very important in early stages of design. Conceptual design involves generating a solution, evaluating the outcome of the generated solution and exploring the best alternatives (Pham, 2006). The generation of solutions requires creativity to achieve the design goals while satisfying the constraints (Hyman, 1988). The most basic functions of a new product and design solutions are generated in this conceptual design stage, which affect later detailed design stages. Many tools and techniques are available to generate conceptual design solutions. Researchers are focused on developing solutions, including computer-aided techniques and human-oriented creative thinking tools (Pham, 2006). This chapter develops conceptual designs of mechanical robot grippers for a first-aid robot. The approach of generating a conceptual design of first aid robot grippers employs TRIZ methodology.

4.2 Conceptual Design

Engineering design generally starts with a requirement and may be met by existing designs. In such cases, the designer is trying to improve the existing design and trying to meet the requirement more efficiently. The designer ends up with a set of drawings and information to enable the design to be made. Design is a very complex process according to empirical and theoretical studies (Lawson, 1997, Dym, 1994, Pahl, 1996). "Designing is a complex process and is not a simple hierarchical process where the designer needs to present a set of requirements. The requirements are processed steadily through a decomposition strategy from abstract concepts to the final concrete product" (Hudson, 1995). Design problems are generally solved iteratively by proposing and refining solutions rather than by a purely sequential methodology. However, design does not iterate around a single solution but rather around a range of acceptable solutions and every partial solution will influence the final solution. Decisions made in early stages influence the later stages. In addition, there are different models in the engineering design process, but they all include the following elements:

- Conceptual design: this is a stage to create new ideas that satisfy the need. The most important factor in conceptual design is the consideration of alternatives while developing a working solution.

- Embodiment design: in this stage, the schemes are worked up in greater detail and if there is more than one, a final choice between them is made. The end product is usually a set of drawings. Generally, it is the part of the design process where starting from the concept of a technical project, the design developed to where subsequent detail design can lead directly to production.

- Detail design: the final stage where the embodiment design is developed. In this stage, quality of this work must be efficient, otherwise it will delay and be costly or even failure can occur at this stage. Many algorithms have been created to aid design (Pahl, 1996).

This research will only consider the conceptual design stage because the embodiment and detailed design have been extensively studied and are suited to classical/procedural approaches. Conceptual design is characterised by the lack of information available to the designer, however, a TRIZ technical contradiction problem solving method is adopted in searching such solution spaces.

Conceptual design commences once a problem has been identified and a vague description of a solution has been generated. Although these solutions are based on limited information, they will determine most of the major design parameters. The conceptual design stage contributes to 70 or 80 percent of project resources that are committed (Pahl, 1996).

Conceptual design is also considered to be one of the most difficult and challenging stages for designers because of the range of possible options. Therefore, only experienced designers carry out conceptual design tasks due to the lack of initial information (Pham, 2009). This limits the effectiveness of procedural techniques to assist more novice designers. A good source of design knowledge and expertise is the patent office. The patent offices collect a vast number of idea and solutions for design problems from a broad range of domains. However, the information in patent offices is not well structured for the purpose of supporting designers in solving design problems. In order to address this issue, the 'Theory of Inventive Problem Solving' (TRIZ) tool has been developed. TRIZ is a philosophy, a process and a series of problem solving tools based on years of studies on patent information (Pham and Ng, 2009). TRIZ is a very powerful problem solving tool, especially for product innovation design in conceptual design stage to provide the engineers with breakthrough thinking. It has been widely applied in the design process. TRIZ provides a systematic analysis of the system to be improved and the application of guidelines for problem definition. With TRIZ, idea can be generated faster, solve the problem effectively and form a basis for further improvements. It is important to achieve the best solution in conceptual design. A good solution resolves the contradiction that causes the problem (Mann, 2002). TRIZ is the theory that provides the basis for the model of successful problem solving. It has been decided that TRIZ is a suitable method to apply to solve this problem of developing the conceptual design of first aid robot grippers.

4.3 Design Requirements

The design of highly dexterous robot hands has been a major research and development objective for at least the past two decades (Pons, 1999). Many institutions have subsequently developed a large number of robot grippers, to varying degrees of complexity. Current robot hands have the general objective of achieving a high degree of dexterity in a wide variety of situations. However, their objective may sometimes lessen their effectiveness in specific categories of applications. The goal of this project is to develop conceptual designs for cost-effective gripper that are versatile and able to grip and manipulate non-rigid human body segments, such as a leg or hand to accomplish the task of positioning an unconscious casualty into the recovery position.

4.4 Ideal Functional Result

The gripper is the mechanical interface between the robot and casualty to be handled (Pham, 1991). More precisely, it is the system that physically interacts with the human casualty. Therefore, conceptual design of the gripper should reflect this extremely important role and match the capabilities of the robot to the requirements of the intended task.

The objective is to meet the requirements for safety and firm grip of the gripper while at the same time minimizing the weight, size, complexity and cost. Therefore, it is necessary to design a robot gripper with the following generic features:

- Ability to grip and hold different shapes, sizes and weights of the human segments safely.
- An ability to support the human segment safely.
- Easy to implement and maintain.

In order to design robot gripper for the first aid robot, it is necessary to address the required interaction between the robot and environment in order to grasp and hold human body segments safely, securely and execute the operation (Bicchi, 2000). Since human body segments are of different shapes and sizes the friction method is essential where the human body segments are restricted from moving by the friction present between the fingers and gripping object. The fingers exert sufficient force to hold the part against gravity, acceleration and any other force that might arise during the holding portion of the work cycle. The most vital task is to avoid any danger and harm to the casualty caused by the gripper during the gripping and holding work cycle.

4.5 Conceptual Design Approach

TRIZ has been employed to solve the problem of developing the conceptual design of robot gripper for the first aid robot. It is required to identify possible contradictions before developing the conceptual design of gripper. In the case of first-aid robot gripper, the fundamental design trade-off may seem to be a conflict between functionalities and safety features in order to achieve safety, firm gripping and cost effective gripper. Robot gripper functionalities involve prehension and retention of various size, shapes, hardness and delicate human body. It is necessary to address the entire possible parameters which are typically expected when designing a system. The physical parameter involves speed, weight, size, shape and strength of the gripper. These parameters plays important role during the conceptual design process because it can cause harm and danger during robot/human interaction. If the movement of the gripper speed is too fast, it can be harmful to the casualty.

If the weight and size of the gripper is too large, it can be difficult to allocate in small confines. In addition, if the strength of the gripper is higher, it can be thicker than the size of the gripper and it can be relatively bulky and produce extra payload to the first aid robot. The shape of the gripper fingers is important because the fingers will be in direct contact with the casualty. Sharp edges can be harmful and damage the casualty during retention and prehension tasks which have been undertaken by the robot. It is imperative to design light and medium size robot gripper together with low speed gripper movement, to avoid any harm and danger. The contradiction lies between the functionalities and safety features.

Technical Contradiction Problem Solving tools offer a start point to generate conceptual design of first-aid robot gripper and advocate eliminating a contradiction. One simple strategy to tackle the contradiction is to work through the list of 39 parameters until one appears to fit the problem (Mann, 2003). First, the right engineering parameters should be chosen to describe the contradiction.

Since robot end-effectors interact with humans, it is vital to avoid danger and harm to the casualty from the robot end-effectors. It also requires generating a minimum weight of gripper while grasping and moving the casualty. Every robot has a fixed payload capacity and heavier tooling causes larger overshooting. Some of the currently available gripper that handle light plastic parts are made from aluminium or steel and are much stronger than necessary and overly heavy(Brandy, 1989). Multifunctional robot gripper will provide greater flexibility and avoid danger to the casualty(Brandy, 1989, Groover, 1986). Improved functionality is the key to accommodate new types and designs for gripper.

In terms of the targeted desire to reduce danger and harm to the casualty there is not a parameter explicitly called ‘avoid danger and harm’, there is one called ‘other harmful effects generated by system’ in TRIZ contradiction matrix by Mann (Mann, 2002). The mapping between the specific (‘avoid danger and harm’) and generic (‘other harmful effects generated by system') is quite straightforward in this instance. Another two parameters to improve are weight and functionalities of the gripper. There is parameter called 'weight of moving object' in the TRIZ contradiction matrix. However, for functionality, there is no direct parameter in the TRIZ contradiction matrix. A parameter called, 'Adaptability/Versatility' in the TRIZ contradiction matrix. The meaning for 'Adaptability/Versatility' is a system/object which is able to respond to external changes. It also relates to a system capable of being used in multiple ways or under a variety of circumstances (Mann, 2003). The corresponding inventive principles can be obtained by the Altshuller's Matrix.

Tables 4.1 and 4.2 illustrate how inventive principles are determined from the requirements of a conceptual design to improve weight of moving object, other harmful effects generated by system and the adaptability/versatility of a design to the worsening feature for area of moving object, device complexity and control complexity.

In table 4.1, the first 12 inventive principles determined from improving feature other harmful effects generated by system and worsening feature device complexity. Also, the second nine inventive principles (in table 4.1) resolute from the improving feature other harmful effects generated by system and worsening feature area of moving object. It also described the nine inventive principles from the bottom row of worsening feature's control complexity and a design problem to improving feature for other harmful effects generated by system.

Improving Features			Worsening Features		IP	Description
No.	***IF***	***Description***	***WF***	***Description***		
1	31	Other harmful effects generated by system	45	Device complexity	19	Periodic action
					31	Porous Materials
					1	Segmentation
					23	Feedback
					2	Taking Out
					10	Preliminary Action
					4	Asymmetry
					17	Another Dimension
					3	Local Quality
					12	Equipotentiality
					35	Parameter Changes
					26	Copying
			5	Area of moving object	12	Equipotentiality
					4	Asymmetry
					3	Local Quality
					17	Another Dimension
					26	Copying
					10	Preliminary Action
					23	Feedback
					2	Taking Out
					19	Periodic Action
			46	Control Complexity	19	Periodic Action
					26	Copying
					23	Feedback
					10	Preliminary Action
					12	Equipotentiality
					4	Asymmetry
					17	Another Dimension
					3	Local Quality
					2	Taking Out

Table 4.1 Resolving the Problem with Corresponding Inventive Principles

Table 4.2 represents how the inventive principles are determined from the requirements of a design problem. This is to improve other harmful effects generated by system of a design to the worsening feature for device complexity, area of moving object and control complexity (one improving feature and three worsening features). The inventive principles proposed by the technical contradiction matrix from above table 4.1 and 4.2 are 19, 23, 31, 17, 2, 10, 4, 1, 12, 3, 26 and 35. After comparing the above tables 4.1 and 4.2 it can be noted that inventive principles 19, 23, 17, 2, 10, 4, 12, 3, 26 are recommended in both tables. Therefore these inventive solution principles are chosen to be considered emphatically because of the most possibility of relevancy to the problem.

Improving Features			**Worsening Features**		**IP**	Description
No.	***IF***	***Description***	***WF***	***Description***		
1	31	Other harmful effects generated by system	45	Device complexity	19	Periodic Action
					23	Feedback
					31	Porous Materials
					17	Another Dimension
			5	Area of moving object	2	Taking Out
					10	Preliminary Action
					4	Asymmetry
					1	Segmentation
			46	Control Complexity	12	Equipotentiality
					3	Local Quality
					26	Copying
					35	Parameter Changes

Table 4.2 Resolving the Problem with Corresponding Inventive Principles

Table 4.3 and 4.4 represent how inventive principles are determined from the requirements of a design problem. In both tables, improving feature is weight of moving object and worsening features are device complexity, area of moving object and control complexity (one improving feature and three worsening features). It can be seen the proposed inventive solution principles by the technical contradiction matrix from the left hand column of table 4.3 and 4.4.

Improving Features			Worsening Features		IP	Description
No.	***IF***	***Description***	***WF***	***Description***		
2	1	Weight of moving object	45	Device complexity	35	Parameter Changes
					2	Taking Out
					19	Periodic Action
					40	Composite Materials
					10	Preliminary Action
					23	Feedback
					29	Pneumatics and Hydraulics
					26	Copying
					12	Equipotentiality
					17	Another Dimension
					30	Flexible Shells and Thin Flims
					28	Mechanics Substitution
			5	Area of moving object	17	Another Dimension
					29	Pneumatics and Hydraulics
					28	Mechanics Substitution
					35	Parameter Changes
					23	Feedback
					10	Preliminary Action
					12	Equipotentiality
					19	Periodic Action
					2	Taking Out
			46	Control Complexity	2	Taking Out
					19	Periodic Action
					12	Equipotentiality
					10	Preliminary Action
					23	Feedback
					28	Mechanics Substitution
					29	Pneumatics and Hydraulics
					35	Parameter Changes
					17	Another Dimension

Table 4.3 Resolving the Problem with Corresponding Inventive Principles

Improving Features			**Worsening Features**		**IP**	Description
No.	***IF***	***Description***	***WF***	***Description***		
2	1	Weight of moving object	45	Device complexity	35	Parameter Changes
					29	Pneumatics and Hydraulics
					2	Taking Out
					10	Preliminary Action
			5	Area of moving object	23	Feedback
					26	Copying
					19	Periodic Action
					17	Another Dimension
			46	Control Complexity	30	Flexible Shells and Thin Films
					28	Mechanics Substitution
					40	Composite Materials
					12	Equipotentiality

Table 4.4 Resolving the Problem with Corresponding Inventive Principles

Table 4.5 and 4.6 represent how inventive principles are determined from the requirements of a design problem. The inventive principles are generated from improving feature ‘Adaptability/Versatility’ against worsening features ‘Device Complexity and Control Complexity’. The inventive solution principles proposed by the technical contradiction matrix from the tables 4.1 and 4.2 are 28, 29, 19, 35, 37, 6, 25, 31, 23 and 17. This inventive solution can be relevant to the problem.

Improving Features			Worsening Features		IP	Description
No.	***IF***	***Description***	***WF***	***Description***		
3	32	Adaptability/versatility	45	Device complexity	28	Mechanics Substitution
					29	Pneumatics and Hydraulics
					23	Feedback
					19	Periodic Action
					17	Another Dimension
					25	Self-Service
					6	Universality
					37	Thermal Expansion
					31	Porous Materials
					35	Parameter Changes
			46	Control Complexity	28	Mechanics Substitution
					25	Self-Service
					37	Thermal Expansion
					19	Periodic Action
					29	Pneumatics and Hydraulics
					23	Feedback
					17	Another Dimension
					35	Parameter Changes

Table 4.5: Resolving the Problem with Corresponding Inventive Principles

Improving Features			Worsening Features		IP	Description
No.	***IF***	***Description***	***WF***	***Description***		
3	32	Adaptability/Versatility	45	Device Complexity	28	Mechanics Substitution
					29	Pneumatics and Hydraulics
					19	Periodic Action
					35	Parameter Changes
					37	Thermal Expansion
					6	Universality
			46	Control Complexity	25	Self-Service
					31	Porous Materials
					23	Feedback
					17	Another Dimension

Table 4.6: Resolving the Problem with Corresponding Inventive Principles

4.6 Analysis of Chosen Inventive Solution

Tables 4.1 to 4.6 give an indication of details of improving and worsening features identified and inventive principles recommended by the contradiction matrix. Among the recommended inventive principles from the above tables, inventive principles No. 35 'Parameter Changes', No. 17 'Another Dimension', No. 28 'Mechanics Substitution', No.10 'Preliminary Action' and No. 40 'Composite Material' are considered emphatically because of their relevance to the problem. The next task is to translate these generic solution triggers into a specific solution to conceptual design of the robot gripper problem. The headings below are the interpretations of inventive principles.

4.6.1 Parameter Changes

Inventive Principle No. 35, 'Parameter Changes' occurs several times and should suggest it is likely to be highly relevant to the problem at hand. Parameter Changes, emerging from the contradiction associated with all improving features, 'other harmful effects generated by system', 'weight of moving objects, adaptability/versatility' and worsening features of 'device complexity/area of moving object/control complexity'. It offers a direct lead into the conceptual gripper design problem solution. From a patent information perspective, parameter change a means change of object's physical state, degree of flexibility and other parameters. In the case of robot gripper, degree of flexibility is relevant to the problem. The flexibility of grippers includes shape adjustment and adjustment of the gripping range. According to the analysis of gripping objects, the flexible gripper is necessary and it can avoid physical damage on human body. It can also provide easy accommodation and firm gripping action on human body segments of different geometrical features. Two-jaw gripper can be used to grasp components externally or internally depending on the jaw design. It can securely and accurately handle components ranging from small shapes with different dimensions that have to be gripped. It can also be handled variety of dimensions. Jaws are designed to handle cylindrical objects with the same two jaw concept.

Since, the majority of human body segments are of cylindrical shapes, the two jaw grippers are suitable to handle human body segments. Jaws are the main part of the gripper that performs the task of gripping and holding the object to be grasped. The shape of contacting surfaces jaws have to be suitably curved for better grasp stability, it can provide the capability to achieve the basic function of grasping, holding, shape adjustment and gripping range adjustment. According to the analysis of gripping objects, the flexible grippers are necessary and can avoid physical damage to the human body. It can also provide easy accommodation and firm gripping action on human body segments of different geometrical features.

4.6.2 Another Dimension

The recommendation of the No. 17 ‘Another Dimension’ solution is particularly interesting. From the 40 inventive principles solutions, another dimension stated as ‘changing dimension or move into a new dimension’, can be interpreted as creating a number of dimensional contacts between gripper finger(s) and the object being gripped. The gripper fingers (jaws) are the appendages that make actual contact with the object. The active gripper finger surfaces are designated according to their shape. The types of contact between a gripper finger (jaw) and the cylindrical object being gripped is ideally classified into three categories. This depends on whether the contacts occur at a single point of contact (one dimensional contact), along a straight line contact (one dimensional contact) and surface contact (two dimensional contacts)(Monkman, 2007b). Figure 4.1 illustrates possible contact methods for the cylindrical shape object. Gripping stability plays important role in robot gripper object prehension and retention. The stability of grip should be ensured by the effective gripping force at the active surfaces between object and gripper jaws (the contact point). Large active contact surfaces improve the gripping as well as holding stability, and at the same time, it can allow for a reduction in gripping forces (Brandy, 1989). It can be achieved by increasing the number of active surfaces, which means using more gripper jaws or an adequate gripper jaw profile.

Hence, the gripping objects of human body segments are a set of rigid bodies and the majority of segments are cylindrical shapes. It is necessary to achieve stability grip and avoid damage to gripping object (human body segments). From the recommendation of the 'Another Dimension' solution triggers, it has been decided to use two dimensional surface contacts. Two dimensional surfaces improve the stability of grip. It also improves the holding stability and allow for a reduction in gripping forces. One dimensional single point contact and line contact to cylindrical objects are not stable in terms of holding. Both point and line contact surface reduce the grip stability and require high gripping forces. It will result in harm and danger to the gripping object. Thus, to avoid harm to the casualty, the two dimensional surfaces contact is the best option in order to achieve a stable and safe grip.

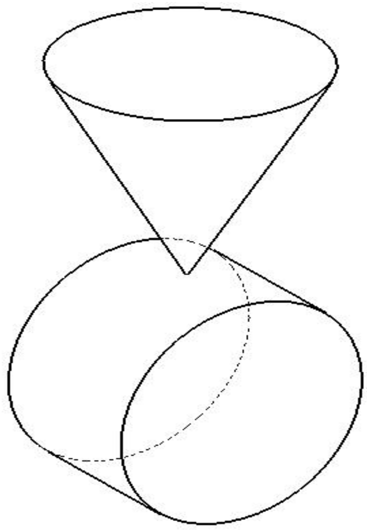


Figure 4.1: a) Point Contact

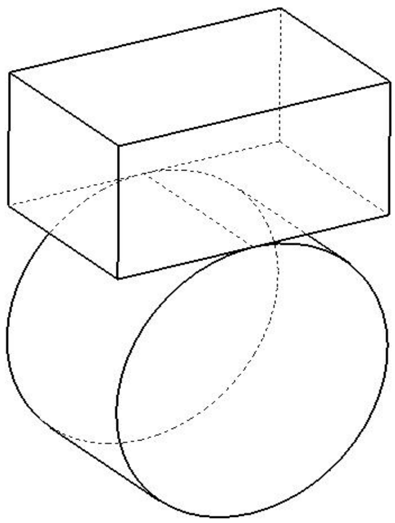


Figure 4.1: b) Line Contacts

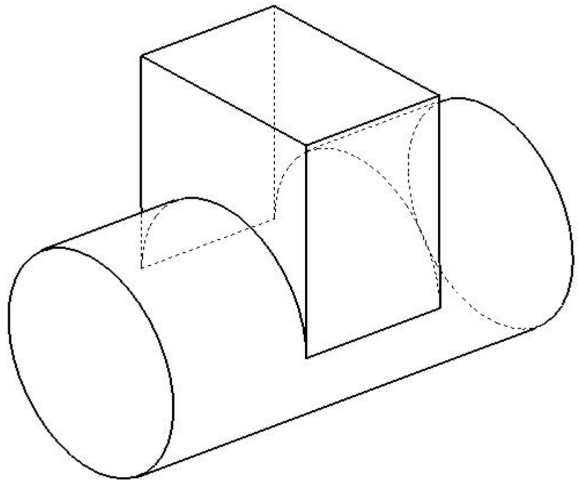


Figure 4.1 c) Surface Contacts

Figure 4.1 Number of Contact Points between the Gripped Cylinder Object including (a) Point (b) Line and (c) Surface Contacts

4.6.3 Mechanics Substitution

The recommendation of the No.28 ‘Mechanics Substitution’ inventive principle implies replacing a mechanical system with a sensory one (consider sensors application). Important applications of sensor technology in human robot interaction are safety and hazard monitoring which concerns the protection of human casualty (human body segments) from danger (Groover, 1986).

Sensors are important to the task of grasping an object. For robotic grasping applications, sensors are normally built into gripper with integrated data pre-processing for position detection, registration of object approach, determination of gripping force, path and slippage detection (Groover, 1986, Brandy, 1989, Monkman, 2007b). In robot gripper technology, only very simple task can be performed without the assistance of a sensor. The sensors used in robotic end-effectors are tactile sensors, proximity sensors, measurement sensors and miscellaneous sensors; all of these sensors are discussed in brief detail in the following section.

4.6.3.1 Tactile Sensors

Tactile sensors are devices that react to physical contact. Tactile sensing can be divided into two main categories; touch sensors and force sensors. Touch sensors indicate whether the contact has been made between two objects regardless of the magnitude of the contacting force. Force sensors indicate the magnitude of contact force between two objects. The force sensors allow the robot to perform a number of tasks which include the capability to grasp objects of different sizes in material handling, machine loading and assembly work and applying the appropriate level of force for a given part (Brandy, 1989).

4.6.3.2 Proximity Sensors

Proximity sensors are non-contact sensors that indicate when one object is close to another object. Proximity sensors are normally attached to the wrist or end- effectors (Monkman, 2007b).

4.6.3.3 Measurement Sensors

It is vital to know the exact distance to the object in any gripping procedure. Gripper jaw separation measurements can be useful in determining object dimensions and identity (Monkman, 2007a). Distance measurement systems also assist in avoiding obstacles. Another interesting sensor is the slip sensor. Slipping of an object between the gripper jaws can be detected by specially designed slip sensors. Objects can be retained with the smallest possible force and upon detection of slip; the holding force can be automatically increased. Slip sensors are intended for the manipulation of sensitive, easily deformable and rigid objects as well as materials that are soft and limp (Monkman, 2007a).

4.6.3.4 Miscellaneous Sensors

The miscellaneous sensors can be categorised for use in interlocks and other purposes in robotic work cells. The devices are capable of sensing variables such as temperature, pressure, fluid flow and electrical properties. Other available sensors are vision sensors. These have the ability to see and recognize objects (Monkman, 2007a, Brandy, 1989).

After analysing the types of sensors, it can be concluded that tactile sensors, proximity sensors, measurement sensors and slip sensors are suitable and an ideal solution for the problem faced in this thesis.

The pressure sensor will also be of use to assist the robot end-effectors to ensure they do not to exceed the human pain threshold pressure during gripping and holding tasks. According to previous chapter, the maximum force which can be safely applied to human is determined by the size of the contact area between the end-effectors and the human body. Employment of these sensors will assist to avoid harm and danger to the casualty during gripping and handling tasks performed by the robot gripper (Brandy, 1989, Monkman, 2007b).

4.7 Preliminary Action

Inventive principle No. 10 'Preliminary Action' implies to introduce a useful action into an object or system before it is needed or place objects in advance. It can go into action immediately from the most convenient position (Mann, 2002).. The conceptual design of gripper system has to provide the basic means of grasping and object motion in a useful way. The conceptual design of gripper will be used to develop and evaluate different approaches of stable grasping and object manipulation. It is important to avoid danger and harm to the human body segments during grasping and manipulation. For example, to take the recovery position in first procedures, the most frequent contact areas where gripping action would take place on the human body are the shoulder, upper arm, forearm, hand, knee and shank. In order to achieve stable grasping and to handle a variety range of sizes and shapes, a complex multi-finger hand is required. Also, to obtain certainty about a grasp, it will require a special purpose gripper.

To overcome the poor stability of grip on human body segments, it has been decided to introduce a third finger which will perform a support action to stabilise the gripping object and avoid slippage. Introduction of the third finger will ensure the gripper remains versatile and provides extra support during grasping and manipulation tasks. From the recommendation of the preliminary action solution trigger, a third finger is introduced and will perform a support action to stabilise and avoid slippage during the gripping action.

4.8 Composite Materials

The recommended principle No.40 'Composite Materials' means changing from uniform to composite (multiple) materials where each material is optimised to a particular functional requirement. The desire gripper is made from light but strong, rigid materials. Therefore, lighter and stronger material would be beneficial, if used throughout the entire design. The use of available composite materials would greatly decrease the weight of the device. Inner contact surfaces of the gripper can be covered in a silicon rubber like substance; it can be used for gripper fingers to ensure a better gripping capability. It can also adopt the inflatable rubber pockets that are adjustable to handle different sizes, shapes and weight by changing the rubber-pocket pressure. Inflatable rubber pockets are embedded on the inner contact surfaces of the gripper (Choi, 2005, Alqasemi, 2007, McKerrow, 1998).

After analysing all the chosen principles, the gripper for robot-human interaction should be composed of two fingers with suitably curved and contacting surfaces for better grasp stability, shape adjustment and adjustment of gripping range (Principle No.35 'Parameter Changes'). Principle No.17 'Another Dimension' suggests that, two dimensional surface contacts are required, in order to achieve a stable grip of human-body rigid cylindrical objects. The gripper should also include a mechanical sensory system according to Principle No. 28 'Mechanics Substitution'. The employment of a sensory system will provide safety and hazard monitoring which will protect the human casualty from danger. Introduction of a third support finger is essential according to principle No. 10 'Preliminary Action'. The third finger will stabilise the gripping object and avoid slippage during holding and manipulation tasks. Finally, gripper should be made from composite materials (from principle No. 40 'Composite Materials') in order to develop light weight and strong material end-effectors. The composite material would greatly decrease the weight of the device. The inner contact surfaces should be covered in a silicon rubber like substance which will provide a better gripping capability.

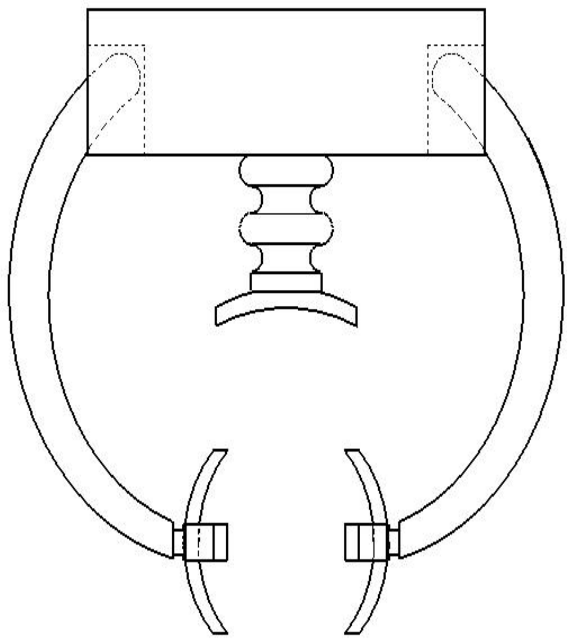


Figure 4.2 a): The Final Conceptual Design of a Gripper for FARO’s System

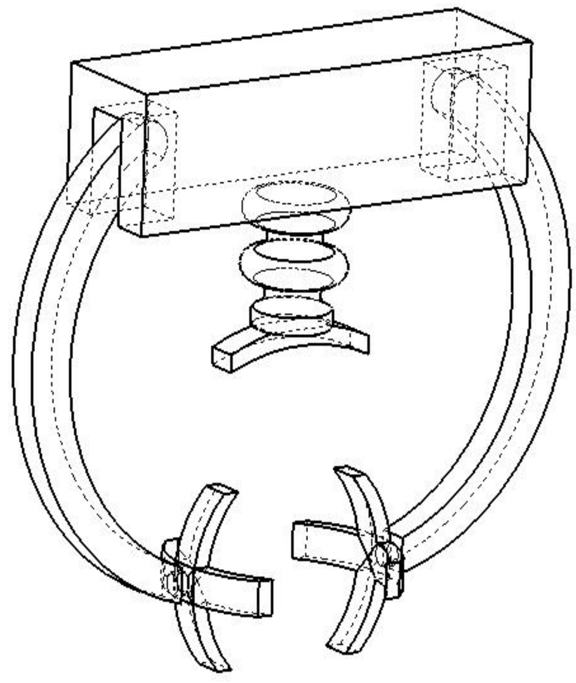


Figure 4.2 b): The Final Conceptual Design of a Gripper for FARO’s System

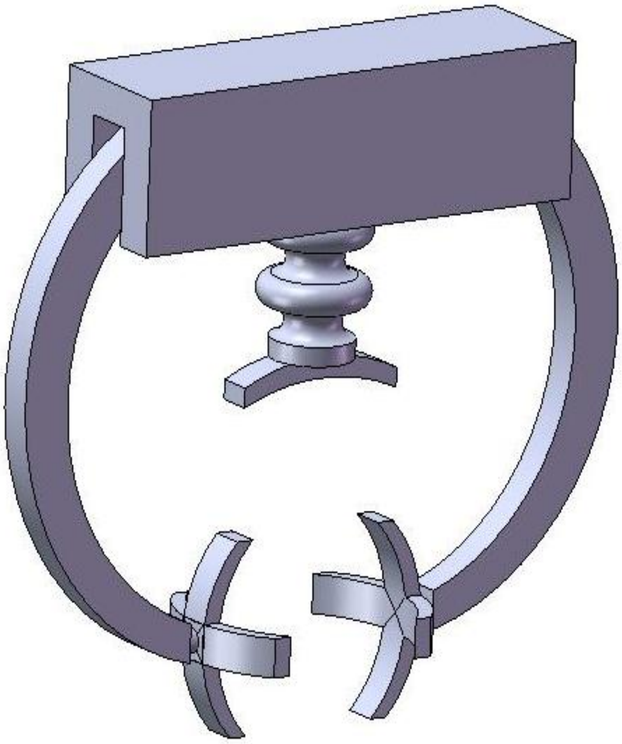


Figure 4.2 c): The Final Conceptual Design of a Gripper for FARO's System

4.9 Evaluation of TRIZ Inventive Solutions

Evaluation is a systematic determination of the value, usefulness or strength of a solution with respect to a given objective (Pahl, 1996). An objective is essential in evaluating the solution since the value of a solution is not absolute and it must be standard in terms of certain requirements. Objectives are mainly derived from the requirements list and from general constraints. A set of objectives include a number of elements which comprise of a variety of technical, economic and safety factors. The objectives must cover the decision-relevant requirements and constraints to ensure no essential criteria are ignored. The evaluation of individual objectives must be independent of one another, as far as possible to increase the value of one variant with respect to one objective. Increasing variant value to an objective must not influence its values with other objectives. The properties of the system to be evaluated must be expressed in quantitative or qualitative terms (Pahl, 1996). It is important to establish the evaluation criteria first in order to evaluate any solution and then make the evaluation (Rantanen, 2008). Kalevi Rananen and Ellen Domb stated that 'the basic concepts of TRIZ are translated into seven evaluation criteria that are used to evaluate proposed solutions with respect to the best conventional solution' (Rantanen, 2008). The seven evaluation criteria stated are as follows:

1. All harmful features vanish.
2. All useful features are retained and new benefits appear.
3. New harmful features do not appear.
4. The system does not get more complex.
5. The primary tradeoffs and contradictions are removed.
6. Idle, easily available, but previously ignored resources are used.
7. Other requirements related to the developed system are fulfilled.

The evaluations of these solutions are presented in table 4.7. The table includes two columns. The left column indicates the criteria and the right column indicates the evaluation. The result of the evaluation column produces five ‘yes’ answers (1, 2, 5, 6, 7) and two ‘no’ answers (3, 4), thus it can be assumed that the solution is nearly an ideal final result.

Criteria		Comparison with known solution
1.	Do the harmful features disappear?	Yes. Able to avoid slippage and maintain stable grip.
2.	Are the useful features retained? Will new benefits appear?	Yes. The sensory system will provide safety and hazard monitoring which protect the human casualty from danger
3.	Will new harmful features appear?	No.
4.	Does the system become more complex?	No. Conceptual design of end-effectors is simple. It can be complex in detail design.
5.	Is the inherent, primary contradiction resolved?	Yes. All the conflict is solved.
6.	Are idle, easily available, resources used?	Yes. Mechanical sensory system is used.
7.	Other Criteria: Easy to implement?	Yes.

Table 4.7 Evaluation Table

(Adapted from Rantanen and Domb 2008)

It can be clearly seen that five ‘Yes’ answers and two ‘No’ answers are in table 4.7 which indicates the solution is considered to be an ideal final result. The final solution meets the majority requirements of the objectives. However, this final solution should always be improved and developed further, to totally avoid harmful to the casualty. It should be able to be employed in any weather condition, any environment, more flexibility, durability, to take the maximum load of the human body segments, easy to implement and maintainable gripper.

4.10 Summary

Conceptual design and TRIZ technical contradiction problem solving methods have been briefly addressed in this chapter. To accomplish the conceptual design of a first-aid robot gripper, the TRIZ method was employed. This helped to eliminate the contradiction of a conceptual design problem. The outcome of inventive solutions principles from the TRIZ Contradiction Matrix were analysed and evaluated. Moreover, the final conceptual design model of robot gripper was presented. TRIZ inventive solutions principles were evaluated using basic concepts of TRIZ’s seven evaluation criteria in the final part of this chapter.

Chapter 5

Conclusion

This chapter presents conclusions of this thesis, outlines contributions of the research and provides suggestions for future work.

5.1 Conclusions

In Chapter 1, the goals of this research were presented. These were to generate conceptual designs of a robot gripper for a First Aid Robot System (FAROS), which was capable of handling unconscious patients. This project focuses on the development of functions which were specific to the gripper, in order to allow for easy accommodation and a firm gripping action on human body segments of different shapes. Moreover, the Theory of Inventive Problem Solving (TRIZ) was used for optimising the concept design of the gripper.

In order to further expand robotic applications, research into the feasibility of human body manipulation was conducted. In this stage, the research was focusing on the geometric properties and pain thresholds of various human body segments. Throughout the research on geometric properties of human body segments, it became apparent that cylindrical shapes were the most likely contact areas. Sizes varied from 16 mm to 235mm in diameter. It can be concluded that end-effectors, capable of gripping cylindrical-shaped objects within this diameter range, will be sufficient to perform the majority of human body manipulation. As far as the pain threshold is concerned, the pressure reduction problem can possibly be remedied by increasing the contact surface between the end-effectors and the human body. Other possible options, such as the introduction of additional end-effectors and the application of deformable material layers on contact surface, remain to be evaluated in-depth in the future.

Conceptual design is a highly significant and difficult task in an engineering design. The conceptual design stage requires expertise because most of the important decisions taken at this stage are based on imprecise and incomplete knowledge of the design requirements and constraints. Furthermore, conceptual design is a crucial stage when designing a new and innovative product. Currently, there are many tools to support conceptual design. TRIZ is a very powerful tool when an innovative idea is required. In this research, it has been applied to generate new design concepts for a robot gripper.

The TRIZ method helped to eliminate contradictions of a conceptual design problem. After analysing the results of the TRIZ Contradiction Matrix, five solutions were used to generate the conceptual design model of the robot gripper. The improving and worsening features provide a designer to drive their ideal final results systematically. As the TRIZ recommendations did not take into consideration the cost of the final product, the recommendation of mechanics substitution and composite materials are costly. The inventive solutions are also evaluated using basic concepts of TRIZ's seven evaluation criteria in this thesis. The evaluation indicated that the inventive solutions meet the conceptual design objectives.

The following recommended inventive principles provide a simple solution to the problem. These are No.35 'Parameter Changes', No. 17 'Another Dimension', No. 28 'Mechanics Substitution', No. 10 'Preliminary Action', and No. 40 'Composite

Materials'. Based on the above principles, the robot gripper should be made from composite materials with two flexible fingers, a support finger and a built-in mechanical sensory system. A two fingers jaw will provide the capability to achieve the basic function of grasping, holding, shape and gripping range adjustment. The third finger will ensure that the whole gripper remains versatile and provides extra support during grasping and manipulation. In order to achieve holding stability and a reduction in gripping forces on a human body segment, the decision is to use two dimensional surface contacts. The inner contact surfaces of the gripper should be covered in a silicon rubber like substance, which will provide a better gripping capability.

Application of mechanical sensory system in grippers can help to avoid harm and danger to the casualty during gripping and handling tasks performed by the robot gripper. A composite material is required in developing a light, rigid and strong gripper. The final results generated from TRIZ, meet the objectives of the work and should yield a gripper suitable for the task of moving a casualty to the recovery position.

5.2 Contributions

The main contributions of this research are:

- Analysis of human body segments in robot-human interaction. This research particularly addresses the identification of human body segments' geometric shape, size, hardness and pain threshold.
- The implementation of TRIZ tree to extract complex features of conceptual design and robot grippers in a more effectual manner.
- The improvement of the two finger jaw's flexibility by using optimal parameters identified by the TRIZ tree. This ensures the capability of the grippers to handle different dimensions and shapes of human body segments.
- The improvement of the jaw's dimension and the surface contacts to create better grasp and avoid slippage of cylindrical objects.
- The development of an effective and efficient mechanism for the mechanical substitution of the sensory system to avoid exceeding the human pain threshold.
- The design and introduction of a third finger on the gripper to ensure stability, versatility and the provision of extra support in grasping tasks.
- The results of the design analysis evaluated against the design criteria. This indicated that the conceptual design of this thesis met the minimum strength and overall design requirements. This helped to identify the best solution from a range of pre-determined options as the final solution.

5.3 Future Work

The research work in this thesis has explored in detail the analysis of human body segments from the perspective of shape and has the analysis has significant contribution and influences to the design of the gripper. However, the analysis was focused on identifying and grouping the human body segment into shapes that ease the derivation of a suitable design concept gripper. Future research work to realise the final gripper for a human body segment requires further progression into detailed design of the gripper from this design concept which include the gripping mechanism, the material selection, the appropriate sensors and others. Hence, the possible future research work for the continuation of this research work would be from two perspectives, namely advanced analysis of the human body to substantiate the detailed design of the gripper and the actual design process of the gripper itself using multiple design tools.

In summary the future work for this research include:

- Advanced analysis on human body segments.

  Unconscious people can be positioned in a variety of configuration. When people become unconscious, it is common to find them falling down onto the floor as well as on any obstructing object within range thus causing a large variation in the position configuration. For example, an unconscious person maybe found laying head down with their torso pressing against their hands or their head leaning against their hands. Therefore, the position of their hands, legs, torso and head can be of a variety of position that may obstruct the access of grippers to grab and manipulate these human segments into the recovery position. Current research work presumes the people casualty is laying a face-up position with and hands and legs straight. In view of this, the gripper may have to deal with gripping other locations of the human segments instead of just the hand and the knee. In addition to that the advanced analysis of human segments should also include possible shape of human segments covered with clothing or fabric.

- Detailed design with design tools

The proposed design concept was developed with TRIZ assistance. However, work is needed to decomposed the proposed design concept into details to include components, links, actuators, power transmission, sensors etc.. In addition, TRIZ tools known as Algorithm of Inventive Problem Solving (ARIZ) can be utilised to improvise and refine the current design concept (Fey, 2007). ARIZ is a logical structured process that incrementally evolves a complex problem to a point where it is simple to solve. ARIZ is the central analytical tool of TRIZ. The concept of ARIZ is a sequence of logical procedures for the analysis of a vaguely defined initial problem and transforming it into a distinct system conflict. ARIZ consists of a set of guidelines that utilises multi-step process of asking series of questions that reformulate complex design problems to simpler problems that are solvable using TRIZ tools.

Appendix A TRIZ Inventive Principles with Examples

Principle 1. Segmentation

A. Divide an object into independent parts.
    - Replace mainframe computer by personal computers.
    - Replace a large truck by a truck and trailer.
    - Use a work breakdown structure for a large project.

B. Make an object easy to disassemble.
    - Modular furniture
    - Quick disconnect joints in plumbing

C. Increase the degree of fragmentation or segmentation.
    - Replace solid shades with Venetian blinds.
    - Use powdered welding metal instead of foil or rod to get better penetration of the joint.

Principle 2. Taking out

A. Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.
    - Locate a noisy compressor outside the building where compressed air is used.
    - Use fibre optics or a light pipe to separate the hot light source from the location where light is needed.
    - Use the sound of a barking dog, without the dog, as a burglar alarm.

Principle 3. Local quality

A. Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.
    - Use a temperature, density, or pressure gradient instead of constant temperature, density or pressure.
B. Make each part of an object function in conditions most suitable for its operation.
    - Lunch box with special compartments for hot and cold solid foods and for liquids
C. Make each part of an object fulfill a different and useful function.
    - Pencil with eraser
    - Hammer with nail puller
    - Multi-function tool that scales fish, acts as pliers, a wire stripper, a flat-blade screwdriver, a Phillips screwdriver, manicure set, etc.

Principle 4. Asymmetry

A. A. Change the shape of an object from symmetrical to asymmetrical.
    - Asymmetrical mixing vessels or asymmetrical vanes in symmetrical vessels improve mixing (cement trucks, cake mixers, blenders).
    - Put a flat spot on a cylindrical shaft to attach a knob securely.
B. If an object is asymmetrical, increase its degree of asymmetry.
    - Change from circular O-rings to oval cross-section to specialized shapes to improve sealing.
    - Use astigmatic optics to merge colours.

Principle 5. Merging

A. Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.
    - Personal computers in a network
    - Thousands of microprocessors in a parallel processor computer
    - Vanes in a ventilation system
    - Electronic chips mounted on both sides of a circuit board or subassembly

B. Make operations contiguous or parallel; bring them together in time.
    - Link slats together in Venetian or vertical blinds.
    - Medical diagnostic instruments that analyze multiple blood parameters simultaneously
    - Mulching lawnmower

Principle 6. Universality

A. Make a part or object perform multiple functions; eliminate the need for other parts.
    - Handle of a toothbrush contains toothpaste
    - Child's car safety seat converts to a stroller
    - Mulching lawnmower (Yes, it demonstrates both Principles 5 and 6, Merging and Universality.)
    - Team leader acts as recorder and timekeeper.
    - CCD (Charge coupled device) with micro-lenses formed on the surface

Principle 7. "Nested doll"

A. Place one object inside another; place each object, in turn, inside the other.
   - Measuring cups or spoons
   - Russian dolls
   - Portable audio system (microphone fits inside transmitter, which fits inside amplifier case)

B. Make one part pass through a cavity in the other.
   - Extending radio antenna
   - Extending pointer
   - Zoom lens
   - Seat belt retraction mechanism
   - Retractable aircraft landing gear stow inside the fuselage (also demonstrates Principle 15, Dynamism).

Principle 8. Anti-weight

A. To compensate for the weight of an object, merge it with other objects that provide lift.
   - Inject foaming agent into a bundle of logs, to make it float better.
   - Use helium balloon to support advertising signs.

B. To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).
   - Aircraft wing shape reduces air density above the wing, increases density below wing, to create lift. (This also demonstrates Principle 4,

Asymmetry.)

- Vortex strips improve lift of aircraft wings.
- Hydrofoils lift ship out of the water to reduce drag.

Principle 9. Preliminary anti-action

A. If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.
   - Buffer a solution to prevent harm from extremes of pH.

B. Create beforehand stresses in an object that will oppose known undesirable working stresses later on.
   - Pre-stress rebar before pouring concrete.
   - Masking anything before harmful exposure: Use a lead apron on parts of the body not being exposed to X-rays. Use masking tape to protect the part of an object not being painted

Principle 10. Preliminary action

A. Perform, before it is needed, the required change of an object (either fully or partially).
   - Pre-pasted wall paper
   - Sterilize all instruments needed for a surgical procedure on a sealed tray.

B. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.
   - Kanban arrangements in a Just-In-Time factory
   - Flexible manufacturing cell

Principle 11. Beforehand cushioning

A. Prepare emergency means beforehand to compensate for the relatively low reliability of an object.
    - Magnetic strip on photographic film that directs the developer to compensate for poor exposure
    - Back-up parachute
    - Alternate air system for aircraft instruments

Principle 12. Equipotentiality

A. In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).
    - Spring loaded parts delivery system in a factory
    - Locks in a channel between 2 bodies of water (Panama Canal)
    - "Skillets" in an automobile plant that bring all tools to the right position (also demonstrates Principle 10, Preliminary Action)

Principle 13. 'The other way round'

A. Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).
    - To loosen stuck parts, cool the inner part instead of heating the outer part.
    - Bring the mountain to Mohammed, instead of bringing Mohammed to the mountain.
B. Make movable parts (or the external environment) fixed, and fixed parts movable).

- Rotate the part instead of the tool.
- Moving sidewalk with standing people
- Treadmill (for walking or running in place)

C. Turn the object (or process) 'upside down'.

- Turn an assembly upside down to insert fasteners (especially screws).
- Empty grain from containers (ship or railroad) by inverting them.

Principle 14. Spheroidality - Curvature

A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.

- Use arches and domes for strength in architecture.

B. Use rollers, balls, spirals, domes.

- Spiral gear (Nautilus) produces continuous resistance for weight lifting.
- Ball point and roller point pens for smooth ink distribution

C. Go from linear to rotary motion, use centrifugal forces.

- Produce linear motion of the cursor on the computer screen using a mouse or a trackball.
- Replace wringing clothes to remove water with spinning clothes in a washing machine.
- Use spherical casters instead of cylindrical wheels to move furniture.

Principle 15. Dynamics

A. Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.

- Adjustable steering wheel (or seat, or back support, or mirror position...)

B. Divide an object into parts capable of movement relative to each other.

- The "butterfly" computer keyboard, (also demonstrates Principle 7, "Nested doll".)

C. If an object (or process) is rigid or inflexible, make it movable or adaptive.

- The flexible boroscope for examining engines
- The flexible sigmoidoscope, for medical examination

Principle 16. Partial or excessive actions

A. If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.

- Over spray when painting, then remove excess. (Or, use a stencil--this is an application of Principle 3, Local Quality and Principle 9, Preliminary anti-action).
- Fill, then "top off" when filling the gas tank of your car.

Principle 17. Another dimension

A. To move an object in two- or three-dimensional space.

- Infrared computer mouse moves in space, instead of on a surface, for presentations.
- Five-axis cutting tool can be positioned where needed.

B. Use a multi-story arrangement of objects instead of a single-story arrangement.

- Cassette with 6 CD's to increase music time and variety

- Electronic chips on both sides of a printed circuit board
- Employees "disappear" from the customers in a theme park, descend into a tunnel, and walk to their next assignment, where they return to the surface and magically reappear.

C. Tilt or re-orient the object, lay it on its side.

- Dump truck

D. Use 'another side' of a given area.

- Stack microelectronic hybrid circuits to improve density.

Principle 18. Mechanical vibration

A. Cause an object to oscillate or vibrate.

- Electric carving knife with vibrating blades

B. Increase its frequency (even up to the ultrasonic).

- Distribute powder with vibration.

C. Use an object's resonant frequency.

- Destroy gall stones or kidney stones using ultrasonic resonance.

D. Use piezoelectric vibrators instead of mechanical ones.

- Quartz crystal oscillations drive high accuracy clocks.

E. Use combined ultrasonic and electromagnetic field oscillations.

- Mixing alloys in an induction furnace

Principle 19. Periodic action

A. Instead of continuous action, use periodic or pulsating actions.

- Hitting something repeatedly with a hammer
- Replace a continuous siren with a pulsed sound.

B. If an action is already periodic, change the periodic magnitude or frequency.

   - Use Frequency Modulation to convey information, instead of morse code.
   - Replace a continuous siren with sound that changes amplitude and frequency.

C. Use pauses between impulses to perform a different action.

   - In cardio-pulmonary respiration (CPR) breathe after every 5 chest compressions.

Principle 20. Continuity of useful action

A. Carry on work continuously; make all parts of an object work at full load, all the time.

   - Flywheel (or hydraulic system) stores energy when a vehicle stops, so the motor can keep running at optimum power.
   - Run the bottleneck operations in a factory continuously, to reach the optimum pace. (From theory of constraints, or takt time operations)

B. Eliminate all idle or intermittent actions or work.

   - Print during the return of a printer carriage--dot matrix printer, daisy wheel printers, inkjet printers.

Principle 21. Skipping

A. Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

   - Use a high speed dentist's drill to avoid heating tissue.
   - Cut plastic faster than heat can propagate in the material, to avoid

deforming the shape.

Principle 22. "Blessing in disguise" or "Turn Lemons into Lemonade"

A. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.
    - Use waste heat to generate electric power.
    - Recycle waste (scrap) material from one process as raw materials for another.
B. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.
    - Add a buffering material to a corrosive solution.
    - Use a helium-oxygen mix for diving, to eliminate both nitrogen narcosis and oxygen poisoning from air and other nitrox mixes.

Amplify a harmful factor to such a degree that it is no longer harmful.

- Use a backfire to eliminate the fuel from a forest fire.

Principle 23. Feedback

A. Introduce feedback (referring back, cross-checking) to improve a process or action.
    - Automatic volume control in audio circuits
    - Signal from gyrocompass is used to control simple aircraft autopilots.
    - Statistical Process Control (SPC) -- Measurements are used to decide when to modify a process. (Not all feedback systems are automated!)
    - Budgets --Measurements are used to decide when to modify a process.

B. If feedback is already used, change its magnitude or influence.

  - Change sensitivity of an autopilot when within 5 miles of an airport.
  - Change sensitivity of a thermostat when cooling vs. heating, since it uses energy less efficiently when cooling.
  - Change a management measure from budget variance to customer satisfaction.

Principle 24. 'Intermediary'

A. Use an intermediary carrier article or intermediary process.

  - Carpenter's nailset, used between the hammer and the nail

B. Merge one object temporarily with another (which can be easily removed).

  - Pot holder to carry hot dishes to the table

Principle 25. Self-service

A. Make an object serve itself by performing auxiliary helpful functions

  - A soda fountain pump that runs on the pressure of the carbon dioxide that is used to "fizz" the drinks. This assures that drinks will not be flat, and eliminates the need for sensors.
  - Halogen lamps regenerate the filament during use--evaporated material is redeposited.
  - To weld steel to aluminum, create an interface from alternating thin strips of the 2 materials. Cold weld the surface into a single unit with steel on one face and copper on the other, then use normal welding techniques to attach the steel object to the interface, and the interface to the aluminum. (This concept also has elements of Principle 24,

Intermediary, and Principle 4, Asymmetry.)

B. Use waste resources, energy, or substances.
   - Use heat from a process to generate electricity: "Co-generation".
   - Use animal waste as fertilizer.
   - Use food and lawn waste to create compost.

Principle 26. Copying

A. Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.
   - Virtual reality via computer instead of an expensive vacation
   - Listen to an audio tape instead of attending a seminar.
B. Replace an object, or process with optical copies.
   - Do surveying from space photographs instead of on the ground.
   - Measure an object by measuring the photograph.
   - Make sonograms to evaluate the health of a foetus, instead of risking damage by direct testing.
C. If visible optical copies are already used, move to infrared or ultraviolet copies.
   - Make images in infrared to detect heat sources, such as diseases in crops, or intruders in a security system.

Principle 27. Cheap short-living objects

A. Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).
   - Use disposable paper objects to avoid the cost of cleaning and storing durable objects. Plastic cups in motels, disposable diapers, many kinds

of medical supplies.

Principle 28 Mechanics substitution

A. Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.
    - Replace a physical fence to confine a dog or cat with an acoustic "fence" (signal audible to the animal).
    - Use a bad smelling compound in natural gas to alert users to leakage, instead of a mechanical or electrical sensor.
B. Use electric, magnetic and electromagnetic fields to interact with the object.
    - To mix 2 powders, electrostatically charge one positive and the other negative. Either use fields to direct them, or mix them mechanically and let their acquired fields cause the grains of powder to pair up.
C. Change from static to movable fields, from unstructured fields to those having structure.
    - Early communications used omnidirectional broadcasting. We now use antennas with very detailed structure of the pattern of radiation.
D. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.
    - Heat a substance containing ferromagnetic material by using varying magnetic field. When the temperature exceeds the Curie point, the material becomes paramagnetic, and no longer absorbs heat.

Principle 29. Pneumatics and hydraulics

A. Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).

- Comfortable shoe sole inserts filled with gel
- Store energy from decelerating a vehicle in a hydraulic system, then use the stored energy to accelerate later.

Principle 30. Flexible shells and thin films

A. Use flexible shells and thin films instead of three dimensional structures
   - Use inflatable (thin film) structures as winter covers on tennis courts.

B. Isolate the object from the external environment using flexible shells and thin films.
   - Float a film of bipolar material (one end hydrophilic, one end hydrophobic) on a reservoir to limit evaporation.

Principle 31. Porous materials

A. Make an object porous or add porous elements (inserts, coatings, etc.).
   - Drill holes in a structure to reduce the weight.

B. If an object is already porous, use the pores to introduce a useful substance or function.
   - Use a porous metal mesh to wick excess solder away from a joint.
   - Store hydrogen in the pores of a palladium sponge. (Fuel "tank" for the hydrogen car--much safer than storing hydrogen gas)

Principle 32. Colour changes

A. Change the colour of an object or its external environment.
   - Use safe lights in a photographic darkroom.

B. Change the transparency of an object or its external environment.

- Use photolithography to change transparent material to a solid mask for semiconductor processing. Similarly, change mask material from transparent to opaque for silk screen processing.

Principle 33. Homogeneity

A. Make objects interacting with a given object of the same material (or material with identical properties).
    - Make the container out of the same material as the contents, to reduce chemical reactions.
    - Make a diamond cutting tool out of diamonds.

Principle 34. Discarding and recovering

A. Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
    - Use a dissolving capsule for medicine.
    - Sprinkle water on cornstarch-based packaging and watch it reduce its volume by more than 1000X!
    - Ice structures: use water ice or carbon dioxide (dry ice) to make a template for a rammed earth structure, such as a temporary dam. Fill with earth, then, let the ice melt or sublime to leave the final structure.
B. Conversely, restore consumable parts of an object directly in operation.
    - Self-sharpening lawn mower blades
    - Automobile engines that give themselves a "tune up" while running (the ones that say "100,000 miles between tune ups")

Principle 35. Parameter changes

A. A. Change an object's physical state (e.g. to a gas, liquid, or solid.
    - Freeze the liquid centres of filled candies, then dip in melted chocolate, instead of handling the messy, gooey, hot liquid.
    - Transport oxygen or nitrogen or petroleum gas as a liquid, instead of a gas, to reduce volume.
B. Change the concentration or consistency.
    - Liquid hand soap is concentrated and more viscous than bar soap at the point of use, making it easier to dispense in the correct amount and more sanitary when shared by several people.
C. Change the degree of flexibility.
    - Use adjustable dampers to reduce the noise of parts falling into a container by restricting the motion of the walls of the container.
    - Vulcanize rubber to change its flexibility and durability.
D. Change the temperature.
    - Raise the temperature above the Curie point to change a ferromagnetic substance to a paramagnetic substance.
    - Raise the temperature of food to cook it. (Changes taste, aroma, texture, chemical properties, etc.)
    - Lower the temperature of medical specimens to preserve them for later analysis.

Principle 36. Phase transitions

A. Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).

- Water expands when frozen, unlike most other liquids. Hannibal is reputed to have used this when marching on Rome a few thousand years ago. Large rocks blocked passages in the Alps. He poured water on them at night. The overnight cold froze the water, and the expansion split the rocks into small pieces which could be pushed aside.
- Heat pumps use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work.

Principle 37. Thermal expansion

A. Use thermal expansion (or contraction) of materials.
   - Fit a tight joint together by cooling the inner part to contract, heating the outer part to expand, putting the joint together, and returning to equilibrium.

B. If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.
   - The basic leaf spring thermostat: (2 metals with different coefficients of expansion are linked so that it bends one way when warmer than nominal and the opposite way when cooler.)

Principle 38. Strong oxidants

A. Replace common air with oxygen-enriched air.
   - Scuba diving with Nitrox or other non-air mixtures for extended endurance

B. Replace enriched air with pure oxygen.
   - Cut at a higher temperature using an oxy-acetylene torch.

- Treat wounds in a high pressure oxygen environment to kill anaerobic bacteria and aid healing.

C. Expose air or oxygen to ionizing radiation.

D. Use ionized oxygen.

- Ionize air to trap pollutants in an air cleaner.

E. Replace ozonized (or ionized) oxygen with ozone.

- Speed up chemical reactions by ionizing the gas before use.

Principle 39. Inert atmosphere

A. Replace a normal environment with an inert one.

- Prevent degradation of a hot metal filament by using an argon atmosphere.

B. Add neutral parts, or inert additives to an object.

- Increase the volume of powdered detergent by adding inert ingredients. This makes it easier to measure with conventional tools.

Principle 40. Composite materials

A. Change from uniform to composite (multiple) materials.

- Composite epoxy resin/carbon fibre golf club shafts are lighter, stronger, and more flexible than metal. Same for airplane parts.
- Fibreglass surfboards are lighter and more controllable and easier to form into a variety of shapes than wooden ones.

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