Enhanced Tracking System Based on Micro Inertial Measurements Unit to Measure Sensorimotor Responses in Pigeons

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***Abstract*— The ability to orientate and navigate is critically important for the survival of all migratory birds and other animals. Progress in understanding the mechanisms underlying these capabilities and, in particular, the importance of sensitivity to the Earth's magnetic field has, thus far, been constrained by the limited number of techniques available for the analysis of often complex behavioral responses. Methods used to track the movements of animals, such as birds, have varied depending on the degree of accuracy required. Most conventional approaches involve the use of a camera for recording and then measuring an animal's head movements in response to a variety of external stimuli, such as changes in magnetic fields. However, video tracking analysis (VTA) will generally provide only a 2D tracking of head angle. Moreover, such a video analysis can only provide information about movements when the head is in view of the camera. In order to overcome these limitations, the novel invention reported here utilizes a lightweight (<10 g) inertial measurement unit (IMU), positioned on the head of a homing pigeon, which contains a sensor with tri-axial orthogonal accelerometers, gyroscopes, and magnetometers. This highly compact (20.3 × 12.7 × 3 mm) system can be programmed and calibrated to provide measurements of the three rotational angles (roll, pitch, and yaw) simultaneously, eliminating any drift, i.e., the movement of the pigeon's head is determined by detecting and estimating the directions of motion at all angles (even those outside the defined areas of tracking). Using an existing VTA approach as a baseline for comparison, it is demonstrated that the IMU technology can comprehensively track a pigeon's normal head movements with greater precision and in all three axes.**

***Index Terms*— Animal behavior, tracking, inertial measurement unit (IMU), monitoring behavior, image recognition, accelerometer.**

I. INTRODUCTION

THE ability of birds to migrate accurately over large distances is, in part, due to their capacity to use the Earth's magnetic field for orientation. At present, laboratory-based research directed towards understanding the intricacies of migratory and/or homing behaviors (e.g. in response to magnetic cues) is limited by the efficacy of techniques that are suitable for the analysis of complex behavioral responses. An example of one such response is the optocollic reflex (OCR), a sequence of head movements often observed in birds that is analogous to the optokinetic eye movements seen in humans when viewing the world through the window of a moving train. This response in birds comprises an alternation between a 'slow' phase following head movement and a 'quick' saccadic reset head movement. Together, these visually driven head movements act to stabilize the image of the world on the retina to ensure good vision [1].

The neuroanatomy and physiological mechanisms that underlie visuomotor behaviors are highly conserved among vertebrates [2], [3]. Like humans, many avian species also rely on vision as their primary sense. For these reasons, birds can be a particularly good model for investigations of responses to visual and other sensory stimuli. In fact, the results of such studies can be related to other animals. Interestingly, birds largely use head movements to fixate objects of interest rather than eye movements, as in humans. This is primarily due to the fact that the eyes of many bird species take up a far higher proportion of the overall volume of their skull than is the case in many mammals. As a result of the relatively large inertial mass of their eyes, birds exhibit a reduced capacity for eye movements as compared to some mammalian species, including humans. Just as is possible in the study of human eye movements, the intricate dynamics of bird head movements can be used to investigate many aspects of their natural perceptual capabilities. For example, these might include their ability to discriminate different wavelengths of light, motion, different levels of contrast, and changes in magnetic flux (i.e. magnetoreception). Furthermore, such studies are particularly useful in understanding the many visual adaptations evident in birds, which have continued implications for human technological advancements (biomimicry), such as the development of advanced optical systems for use in drones [4].

A. Traditional Tracking Methods

Orientation and navigation skills are crucial for the survival of all organisms that display migratory or homing behaviors. In the field, manual observations of such behaviors continue to be an effective technique for qualitative accounts of an animal's behavior in a given condition. However, such an approach is not suitable for studies that require a more accurate, quantitative account [5].

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At present, the gold-standard technique for the quantitative evaluation of complex behaviors is video tracking analysis (VTA), which, as the name suggests, relies upon *post-hoc* digital signal processing with the aid of sophisticated image processing algorithms [6]. While effective, this technique also has a number of limitations: 1) VTA provides only a two-dimensional view, meaning that data from any out of plane movements, i.e. tilting or rolling of the region of interest, cannot be analysed and such out of plane movements often bring the fiducial mark used to track the head out of the field of view of the camera resulting in the loss of data; 2) VTA has large memory storage requirements, which become even more demanding with the use of high frame-rate cameras; 3) VTA requires time-intensive *post-hoc* frame-by-frame analysis. Reducing the frame rate of the camera can counter the issues of storage and time, however this is often at the expense of the spatial and temporal resolution of the data.

Alternative automated behavioral tracking systems exist. For example, infrared devices for detecting locomotor activity [7], laser-based instruments for recording behavior and providing the location of freely moving animals [8], as well as a microwave Doppler radar activity monitor [9]. Additionally, 3D recording of movements is possible using video tracking systems however complex and expensive multi-camera arrangements are required, which are still limited by many factors (e.g. the size of the field of view, data storage capacity and tracking inaccuracy due to the complexity of synchronising multiple cameras). These alternatives all have associated complex difficulties that are not applicable to the IMU technology used in our study.

B. IMUs as a Precise Tracking Method

Traditionally, accurate but costly and cumbersome stand-alone inertial sensors have been used in aviation, shipping, and aerospace applications. Inertial sensing components have become very small and inexpensive due to the relatively recent development of micro-machined electromechanical system (MEMS) technology. This has been at the expense of reduced accuracy, but as a result of these ongoing developments, many new applications for inertial sensors have been enabled, including the one presented here.

Inertial measurement units (IMUs) contain three dimensional (3D) accelerometers as well as 3D rate gyroscopes, and in many cases 3D magnetometers are also included. The functionality of MEMS sensors are based upon simple mechanical principles. By exploiting the Coriolis effect of a vibrating structure, the angular velocity can be measured; a secondary vibration is induced from which the angular velocity can be calculated when a vibrating structure is rotated whilst with a spring suspended mass, acceleration can be measured, as the mass will be displaced when subjected to acceleration [10].

C. Estimation of Orientation

Rate gyroscopes, magnetometers, and accelerometers comprise the sensing components in an IMU. Angular velocity, or rate-of-turn, is measured by the gyroscopes. The accelerometers measure the outer particular force, a specific force that is contributed to by linear acceleration as well as by the Earth's gravitational field, from which acceleration can then be derived. The local magnetic field is measured by the magnetometers. Both accelerometers and gyroscopes are affected by biases that vary slowly with time (i.e. drift). Information about an IMU's 3D orientation is provided by the combination of all of these sensors. The angular velocity can be integrated to get orientation, which is measured by the gyroscopes. Using the outputs of the accelerometers and magnetometers, the integration drift and noise can be compensated for [10]. Previous research [11] has shown that use of a Normal Kalman Filter in DCM (Direction Cosine Matrix) technique helps to avoid the first order approximation error. In the DCM method (1), which is used for attitude and orientation estimation, vectors are rotated by multiplying them by a matrix of direction cosines:

$$Q_G = RQ_P \tag{1}$$

Q_P = a vector measured in the frame of reference of the plane.

Q_G = a vector measured in the frame of reference of the ground.

R = Rotation matrix

D. Previous Work With IMUs

1) Animal and Human Behavior Measurements: Inertial measurement units have been integrated into a number of devices, e.g. mobile phones, and are now available as chipsets. Similarly, very small wireless IMUs have been produced that can be used as components in an extensive array of applications, including human or smaller animal body-mounted devices, allowing for accurate recording of an animal's responses [10], including, as in this instance, pigeon head movements.

The implementation of such remote sensor systems allows comprehensive behavioral response data to be collected with minimal involvement of the researcher. Inertial measurement unit (IMU) technology has been used previously in animal behavior research. For example, a data logger incorporating a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer was developed and externally attached to Japanese amberjacks to assess the validity of MEMS technology for monitoring the movement performance of the fast-start behavior of fish in the field [12]. Additionally, 3D accelerometers have been used to enable the monitoring and classification of behavior patterns in cattle, crucially without human interference [13]. Three-dimensional accelerometers have also been used for automated recording and classification of grazing behaviors in goats [14] as well as vertical movement symmetry (MS) in clinically lame horses through attachment of the IMU over the sacrum and the left and right tuber coxae [15]. Similarly, MEMS sensors have been identified as a technical solution to assist clinical research into the early detection of gait disturbance in horses [16]. Finally, recording human movements has proven to be very valuable for the monitoring of personal activity for health purposes, e.g. by detecting steps, estimating stride lengths and the directions of motion, etc. [17], as well as for clinical applications [18] where the clinical specialist or physiotherapist is able to assess the movement of an orthopedic outpatient [19].

2) Bird behavior Measurements: A number of major challenges exist when implementing MEMs technology for the quantification of animal behavioral dynamics, particularly when the species in question place an evolutionary premium on being lightweight. Birds in general are well adapted to flying, e.g. with low bone density as well as an extensive respiratory system that apportions a number of air-filled sacs within the mediastinum. Many birds must also balance their energy intake with their body mass in order to maintain an optimum flying weight. With this in mind, it is necessary, when implementing body or head mounted sensors, to be aware that normal behavioral responses may be significantly affected by the addition of even a small amount of extra weight.

Although a number of studies have used MEM technology to mount devices to the back of pigeons and other birds, without impairing their ability to fly, head mounted devices have been attempted far less often. A study into how pigeons interact with one another in their hierarchies and flocks, for example, involved the use of small backpacks, which housed GPS receivers. Specifically, a backpack weighing 16 grams was attached to pigeons using elasticized fabric bands. Another study, investigating flight dynamics in raptors, used an MTi-G IMU, $58 \times 58 \times 22$ mm in dimensions and 58 gram in mass, which was attached to the birds with Velcro straps [20]. Another example [21] that serves as a useful reference is an investigation of how pigeons navigate through forests. In that study, a GPS recording device, consisting of a hybrid GPS receiver board, a data logger, a GPS patch antenna, a DC-DC converter, a power supply, a status display, and a connector were mounted on the birds' back, all of which had a combined mass of just 33 grams [21]. Additionally, a camera was mounted on the pigeon's head, connected with cables to the body mounted backpack, all of which were found not to impair normal behavior [21].

The present paper describes a reliable, high sample rate and entirely quantitative method for tracking head movements using a small, lightweight head-mounted IMU system, offering live presentation of data, allowing for real-time assessment of behavioral responses. Three-dimensional data acquisition takes place in real-time, eliminating the need for time-consuming *post-hoc* data extraction while avoiding the memory and data storage limitations inherent in video recording methods. Taking advantage of the complex, but highly reproducible, visually induced head movements that comprise the optocollic reflex (OCR), we validate and demonstrate the benefits of this IMU system for tracking head movements.

II. Instrumentation Details

A. VTA System

Video tracking analysis is a method that relies upon *post-hoc* digital signal processing (DSP) of behavioral responses and is often dependent upon sophisticated image processing algorithms [9]. Our custom-designed VTA system comprises a general specification PC (CPU:i5, RAM:8GB) with an SSD (Solid State Drive) to allow saving of video data at speeds of up to 60 fps as well as a digital video camera (FireWire CCD Monochrome DMK 21BF04 [22]) capable of 60 fps, with a specialised lens (M0814-MP). The camera is mounted facing down into the centre of the optocollic reflex (OCR) arena comprising six LCD monitors for presenting visual stimuli (drifting vertical grating). A white hard plastic fiducial marker (14mm × 5mm × 3mm), with parallel, perpendicular black lines offset towards its front end, is affixed to the top of the pigeon's head with double-sided sticky tape. Control of the camera recording during experimental trials and the *post-hoc* frame-by-frame extraction of head angles are performed using custom National Instruments LabView software (see [6] for further details).

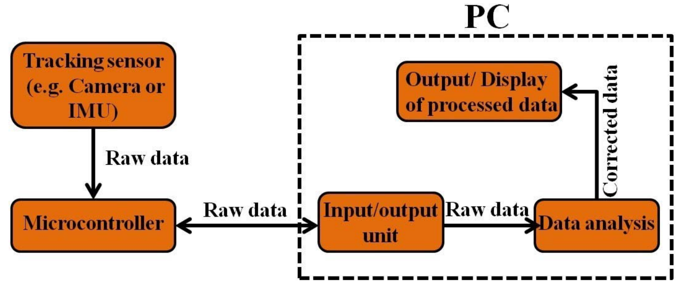

Fig. 1. General schematic diagram of a tracking systems (camera or IMU) which are used in this research.

VTA has proven to be particularly effective in the analysis of complex head movement responses but, as described previously, has a number of inherent limitations. Fig. 1 depicts the general operation of the tracking system used in this research. The microcontroller is used to acquire the signal, which has been obtained from the tracking system (IMU or camera), and which is then passed to the PC where the data can be analysed, calibrated and displayed for the user.

B. Inertial Measurement Unit (IMU) System

To address these limitations, we have developed a novel method that is based on the use of an IMU with 9 degrees of freedom (DOF), i.e. a triple axis gyroscope (G) measuring angular velocities around Gx, Gy, and Gz; a triple axis accelerometer (A) measuring acceleration along Ax, Ay, Az; and a triple axis magnetometer (M) measuring magnetic field along Mx, My and Mz, all of which are required for the IMU unit to be able to detect and measure the orientation of the pigeon's head in 3D space. Real time measurements are obtained at 512 Hz (128 samples/sec) from the combined data of all of these sensors, encased within the IMU.

In order to ensure that the Attitude and Heading Reference System (AHRS) algorithms are able to function correctly, all three sensors (magnetometer, accelerometer and gyroscope) must be correctly calibrated. Hard-iron calibration has been established for the magnetometer to compensate for the hard-iron biases introduced to the magnetometer by any surrounding metal or electronic devices. The IMU was calibrated based upon a maximum angular velocity head movement of 200°/s, and thus, the measurement range of the gyroscope has been set to ±2000°/s. This value was chosen as this easily deals with the maximum head movement speed.

These algorithms have been programmed to use the outputs from the gyroscope, accelerometer and magnetometer to

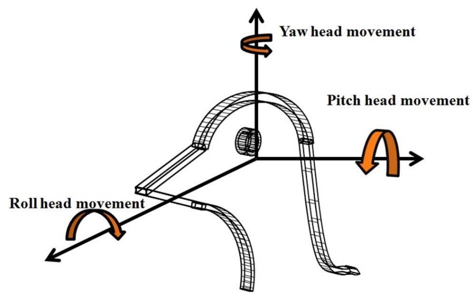

Fig. 2. The three axes of pigeon head movement.

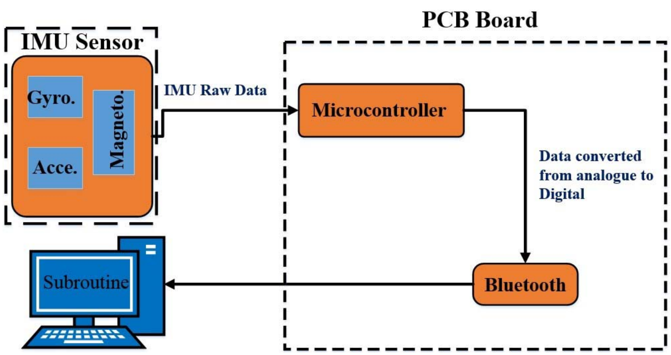

Fig. 3. A schematic illustration of the new tracking system. The IMU sensor is placed on the head of the pigeon, and the PCB is placed on the back of the pigeon. The microcontroller is used to acquire the raw data (signal), which are obtained from the IMU. The microcontroller then converts the signal from analogue to digital. In turn, the data (in digital format) are passed to the PC via a Bluetooth connection.

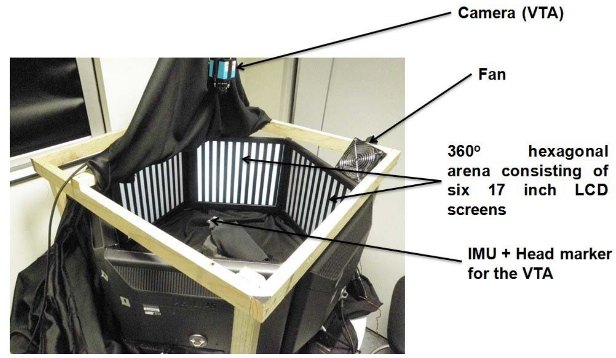

Fig. 4. Experimental apparatus to elicit the optocollic reflex (OCR) consisting of a ring of 6 LCD monitor screens on which square wave grating stimuli are presented to pigeons retrained on a central platform.

obtain angular velocities of the pigeon's head (gyroscope), the direction of gravity (accelerometer), and the Earth's magnetic field (magnetometer) in the x, y and z axes. The measurements derived from these three components contribute to an overall 3D representation of the IMU unit (in space). Angular velocity measurements derived from the gyroscope are used to filter errors in the estimated orientation, i.e. those caused by linear accelerations and temporal magnetic distortions. In parallel, accelerometer measurements provide an absolute reference for the pitch and roll components of the estimated orientation. Earth's magnetic field measurements, obtained from the built in magnetometer, are used to provide an absolute reference for the heading component of the estimated orientation.

The IMU device outputs 12 variables in total: three rotational angles (roll, pitch and yaw (Fig. 2), as well as acceleration, angular velocity and magnetic field density, all of which are output in three dimensions and are free from drift. Custom software has been designed to display real-time raw and calibrated data graphically to allow the experimenter to be able to monitor the behavior of the subject in real time.

The size limit of the IMU, imposed by both the biological and physical constraints of the pigeon, is found to be $20.3 \times 12.7 \times 3$ mm. The basis of this limitation is derived from the aforementioned adverse influences there might be on normal behavior if the device were to hang over the edge of the head and obstruct vision. A weight limit of $\leq$10 grams is imposed for similar reasons.

As illustrated in Fig. 3, the IMU board communicates with the microcontroller, which processes the raw data from the three sensors within the IMU and derives an estimate of the IMU's absolute orientation. In turn, these data are output through the microcontroller's serial interface. In order to minimize any disturbance of the normal behavior of the pigeon, the system is fully managed via wireless communication. Power is provided to the system by lightweight rechargeable lithium polymer cells (400mAh). In order to create a backpack unit as small and light as possible and with no unnecessary wires, a PCB board was printed to host all of the components, including the batteries, independently of the IMU. As with the size and weight restrictions associated with the IMU, a weight restriction of $<$30 grams is imposed on the backpack.

C. Experimental Set-Up

An optocollic reflex (OCR), which comprises a 'slow' (tracking) phase and a 'quick' reset phase (or saccade) in response to optic flow Fig. 4, was elicited in two restrained adult homing pigeons using a 0.16 cycle/° square-wave stimulus at different levels of contrast, presented within a 360° hexagonal arena consisting of six 17 inch LCD screens. The angular velocity of the stimulus was increased from stationary to 60°/sec stepwise in 4°/sec increments every 20 seconds. All stimuli were generated and controlled using custom MATLAB code. Food and water were constantly available *ad libitum* other than the duration of stimulus presentation, which did not exceed 10 minutes. Pigeon restraint was in the form of an elasticated tubular bandage. Once restrained, the pigeon was placed on a firm foam base and covered with a matte black sheet, except for its head. Two computer fans were used to generate airflow through the arena to prevent the pigeon from overheating. All blinds and doors in the laboratory were shut in order to eliminate any natural light, and the entire arena was covered with a black matte drape. All experimental procedures involving animals complied with the U.K. Home Office legislation and the European Communities Council Directive 86/609/EEC (1986).

D. IMU Placement

For data collection using the IMU, a custom-made lightweight leather hood was placed over the head of the restrained pigeon and gently secured with adjustable straps. In turn, the IMU was attached to the hood with Velcro, Fig. 5.

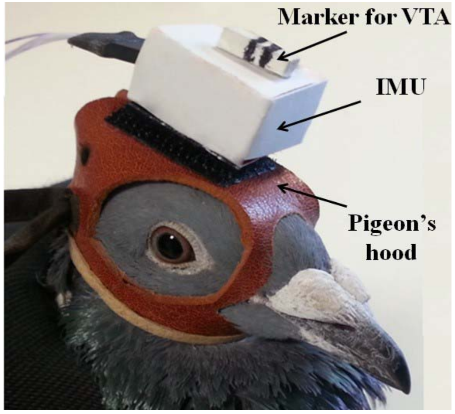

Fig. 5. IMU placement on the pigeon's head. A custom made leather hood is used to Velcro-mount the IMU to the pigeons head without obscuring its field of view.

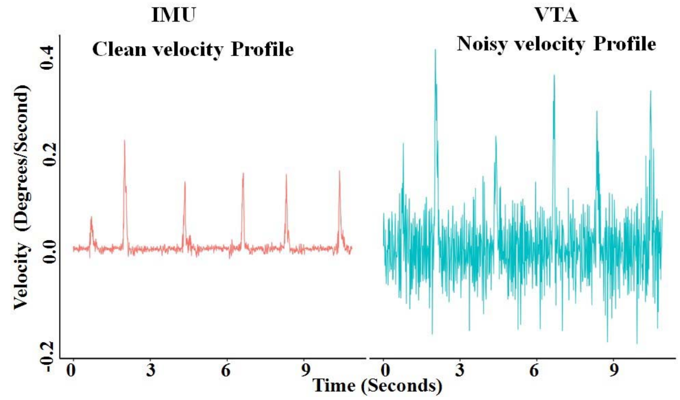

Fig. 7. A comparison of velocity profiles recorded by the IMU (left facet) and VTA (right facet). The data from the IMU have a considerabley higher signal-to-noise ratio.

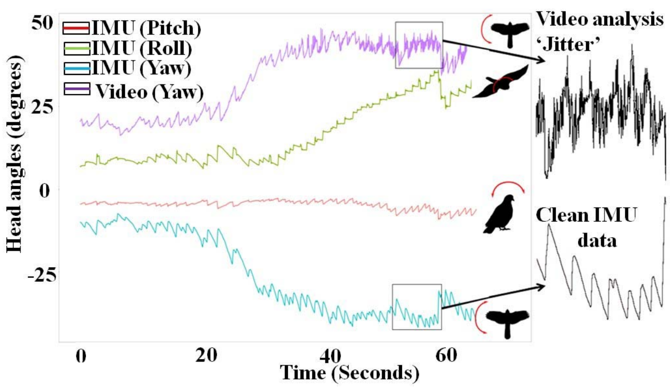

Fig. 6. Comparison of raw head angle data from both systems: VTA (purple- YAW) and IMU (red- PITCH; blue- YAW; green- ROLL). VTA data exhibit noticeable jitter that is not apparent in that derived from the IMU.

The backpack unit (PCB board), connected to the IMU, was placed in a lightweight casing, which was gently strapped to the back of the pigeon. For trials in which both IMU and VTA analyses were carried out simultaneously, the hard plastic fiducial marker was attached to the top of the IMU. Note that the pigeon's eyes were completely unobstructed.

III. Validation of the New System

Even with the limitations described previously, VTA is the gold-standard tracking method used to record behavioral responses in the yaw plane. As a result, it was important to first determine whether the IMU effectively replicates this capability. Critically, this validation was necessary to determine whether the position of the mounted IMU on the pigeon's head affected the activity of the pigeon, in addition to checking the overall reliability. As VTA measures only horizontal movements, this validation stage involved comparing the yaw angle measurements using both approaches. To compare the two approaches effectively, data were obtained using both VTA and IMU measurements during the same behavioral session, as well as independently.

Fig. 6 illustrates that the signal-to-noise ratio is better from the IMU as compared with VTA, as VTA is influenced by roll head movements. Data obtained from VTA were found to be much noisier than IMU data (Fig. 7), largely as a result of tracking inaccuracies, i.e. 'jitter'. Furthermore, atypical head movements (e.g. the bird turning its head to look up) resulted in significant loss of VTA data. Crucially, these did not affect IMU analysis, and indeed, this change in head position could be documented.

The adverse effects of tracking jitter in head angle waveforms, which resulted from differences in tracking accuracy between the two systems, were compounded by the inferior rate of data capture in the VTA system, i.e. the camera delivers images at a constant frame speed of 60 fps whereas the data obtained using the IMU captures 128 readings/second. While this issue could be overcome by using a higher frame rate camera, the benefits would be offset by increased data storage demands as well as considerably increased time required for *post-hoc* image analysis, all of which are not applicable when using the IMU.

In general, *post-hoc* analyses revealed that the IMU system approach is capable of giving far more precise data with considerably less tracking 'jitter'. Moreover, the IMU provided positional information about the pigeon's head movements along an additional two axes of motion (i.e. pitch and roll; Fig. 6), providing data that greatly facilitate and enhance the analysis of behavioral responses.

Post-hoc analyses of behavioral responses recorded using any given tracking method is often dependent upon the identification of saccadic movements and subsequently, in the case of the optocollic reflex, the separation of saccadic and slow phase movements. Given that 'tracking jitter' often has saccade-like characteristics, it is necessary to apply a filter to the data in order to remove this noise. Inevitably, however, during this process true data, e.g. low amplitude saccades or microsaccades, are lost. Through circumventing this issue with the use of the IMU, no such filter is necessary and the output information becomes both more accurate and comprehensive. The presence of jitter in head movement data is of even greater detriment to the analysis of head movement velocity plots (Fig. 8), the profiles of which can be used to provide insight into both the nature of the response and the impact of the stimulus presented. Again, these issues are typically overcome

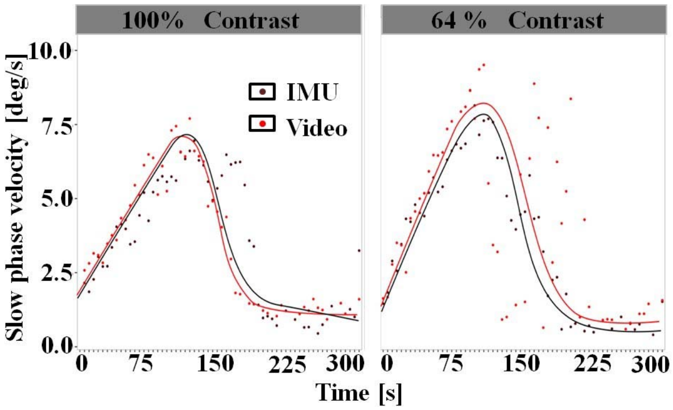

Fig. 8. Validation of agreement between YAW data from the IMU (black) and VTA (red) systems at two different visual contrasts.

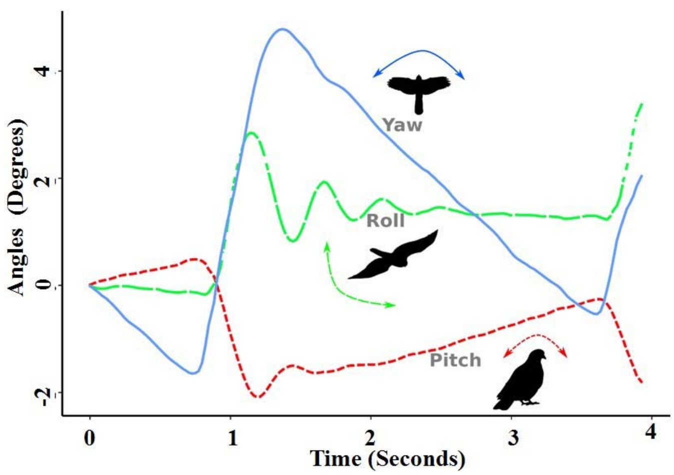

Fig. 9. Three rotational angles: YAW (blue), ROLL (green long dashed) and PITCH (red dashed) obtained from IMU tracking. Only yaw data are obtained from video tracking analysis.

through discarding sections of particularly noisy data but such non-ideal removal of data is made unnecessary with the IMU.

Subroutines written for the analysis of the slow phase velocity showed that the yaw angle produced by the IMU exhibited an almost identical measurement of the bird's head movements, spatially and temporally, Fig. 8, but without data loss and with greater precision, smoothness and appreciably fewer anomalies.

IV. Additional Benefits of IMU Tracking

Head movements, like eye movements, consist of multiple components, i.e. yaw, pitch and roll. While VTA is limited to a single dimension, i.e. yaw, the IMU has the capability of recording movements in all three planes. Analysis of these additional pitch and roll components in a typical optocollic reflex reveal their temporal and spatial characteristics in ways that were not previously possible with conventional VTA, Fig. 9.

Indeed, temporal analysis of the yaw, roll and pitch components together, within a complete optocollic reflex, reveals a far more complex sequence of events than previously appreciated. It is apparent from the 3D data obtained from IMU tracking (Fig.9) that, when a saccade initiates, the dominant yaw movement is accompanied by a roll movement in the same direction of the saccade as well as a vertical pitch movement that resets during the course of the slow phase movement.

V. Conclusion

The present study describes the novelty of using inertial measurement technology to detect behavioral responses in pigeons. The IMU approach was validated through a comparison with VTA, the current gold standard in quantitative behavioral analyses. The results demonstrate not only that the IMU is a fully capable alternative to the conventional VTA approach but also that it offers considerably more information (in the form of extra dimensions) as well as far greater accuracy and precision.

Inertial measurement technology holds great promise for the accurate, quantitative measurement of complex head movements, which, in turn, provide important information relating to how animals, including humans, respond to sensory stimuli and, ultimately, navigate. Our preliminary investigation confirms the potential of inertial measurement technology, which clearly overcomes many, if not all, of the limitations and shortcomings of video recording technology, while providing a range of additional benefits, including:

- Generating far more precise data, i.e. no jitter, by removing the requirement for the *post-hoc* frame-by-frame analysis of video recordings of a fiducial marker.
- Providing lossless data sets, i.e. generating data from the entirety of each behavioral trial and not being limited by the need to keep the head in a set field of view.
- Minimising the requirement for large amounts of data storage
- Eliminating the need for *post-hoc* data extraction and enabling near real-time observations.
- Providing head angle measurements in all 3 dimensions (pitch, roll and yaw) rather than being limited to just one plane
- Producing additional outputs, such as acceleration, angular velocity and magnetic field flux measurements

The improvement in temporal precision achieved by IMU can be calculated by

$$(60_{sample/sec} - 128_{sample/\mathrm{sec}})/128_{sample/sec} \quad (2)$$

and is determined from (2) to be 53%.

Moreover, the provision of head angle data in 3D is critical to understanding the complexities of sensorimotor responses that are not confined to the yaw plane, e.g. head bobbing and orientation responses to changes in magnetic fields.

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