Chapter 1

Introduction

1.1 Background to the Study

Human motion capture systems are often very costly and confine the capture area to a certain confined space. These limitations prevent us from understanding bipedal motion in complex environments, knowledge that proves to be critical in the development of functional humanoid robotics. Examples of such systems can be seen in [1] where 8 cameras and stereo vision was used to recreate a 3D model of a walking person and in [2] where 10 Vicon cameras and a full body marked suit was used for the same objective.

A popular approach taken to overcome the spatial limitations inherent in camera based systems is the use of body mounted sensor networks. A commercial sensor suit developed by XSens and demonstrated in [3] can accurately recreate a 3D model of human motion using inertial sensors and data fusion. Similar work completed by Seel et al. [4] further proves the accuracy of such systems. Although the mentioned systems overcome the stated limitations; they do so at increased complexity and cost. They often lack modularity and proprietary software is difficult to adapt.

Recent work [6] completed by the Mechatronics Lab at the University of Cape Town showed data capture with both subject-borne cameras and sensors can be used to better understand unconstrained movement in a natural environment. This was based on research completed by Stocks [7] at the same laboratory. The presented work showed the successful kinematic modelling of a cheetah (Acinonyx jubatus) tail whilst running freely. The importance of understanding motion in the natural world is outlined in [8] and is the cornerstone of biomimicry as defined by [9].

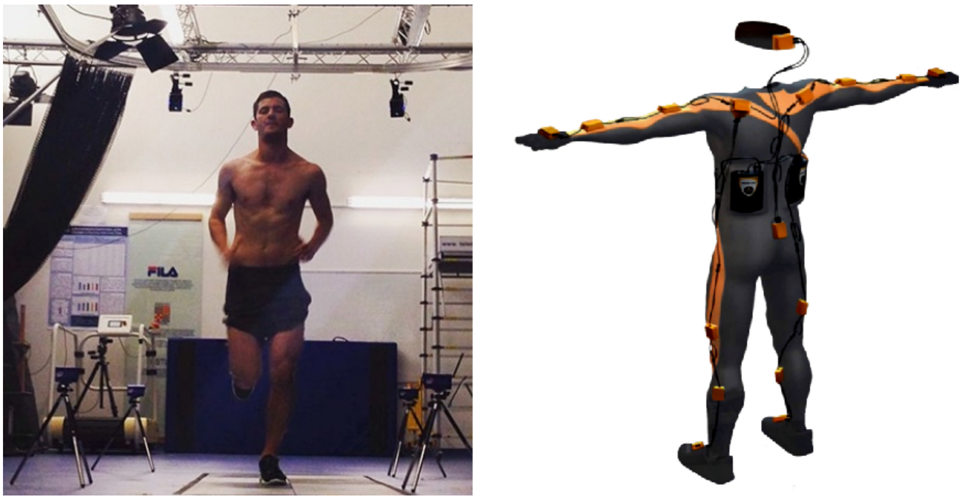

Figure 1.1: Left: Vicon motion capture system tracking the human gait (from [3]) Right: The Xsens MVN motion capture suit (from [5])

1.2 Objectives of the Study

Depth imagery in the field of human motion capture has been extensively reviewed in [10], where the lack of data from complex movements in different environments is listed as a challenge. This reaffirms the difficulty stated in the previous section. Solely relying on motion sensors to understand the gait has been reviewed by [11]. Although this approach was found to be accurate for external environments it has limitation with respect to cost and sensor disturbance. From these reviews it is clear that a middle ground must exist that can combine the strengths of the approaches to provide a holistic solution.

This research project aims to show that subject-borne sensors, primarily a combination of cameras and IMUs, can provide researchers in the field of health sciences, biomechanics and biomimicry with extensive datasets to better understand and model the bipedal motion of humans. It builds on the foundational work presented by Stocks and Patel [7] and envisions to implement a similar system to track data points on the lower limbs of a runner. The original prototype system is shown below.

Finally this thesis will pay close attention to similarities in understanding the human gait using technologies used to control the dynamics of bipedal humanoid robots. Since these robots attempt to imitate human motion many of they key principles in the field of robotics relates directly to to the bio-mechanics of humans.

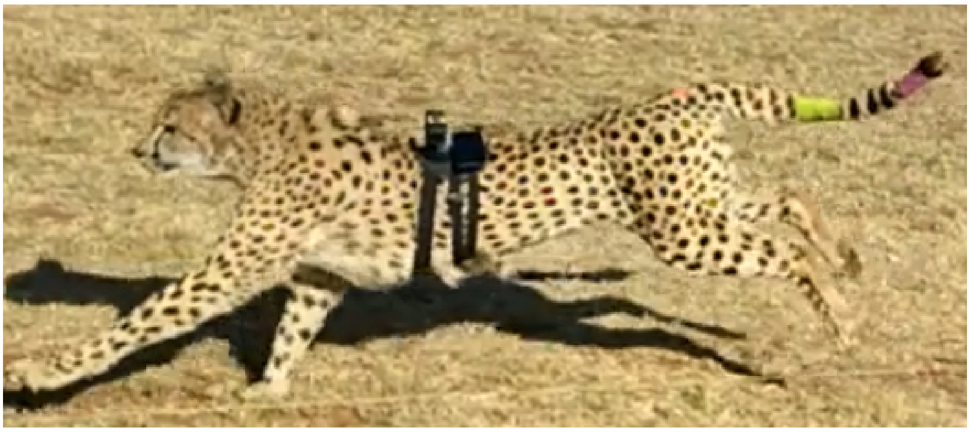

Figure 1.2: A cheetah wearing the wearable motion capture system designed by Stocks [7]

1.3 Scope and Limitations

The scope of this research is to model and estimate the human lower limbs during a flat ground steady state run. The motion will be estimated by determining the different joint angles as well as the motion of the runner w.r.t. the inertial frame. Joint angles are a popular method of quantization and the availability of rich datasets allow comparative analysis on the final findings of this work. This is the first logical step in the iterative design process to eventually understand movement in complex environments using wearable motion capture systems.

The availability of equipment also influenced the quality and accuracy of the system. Due to financial constraints the system was designed to use available hardware and minimize additional expenses. Although the the system designed cannot be classified as low cost, when compared to other methods of motion capture it becomes financially attractive. The components selected are also interchangeable and need not exactly match the specifications presented herein.

It should be noted that the research presented herein does not seek to push the boundaries of modern sensor technology, nor does it wish to re-imagine understood and accepted models of natural phenomena. Instead, a methodology is proposed that brings together systems from exciting disciplines of research such that richer datasets can be generated and studied. This research therefore serves as a proof of concept for a novel wearable motion capture technology.

There is another distinction to make with regard to scope of the project and that is the distinction between kinematics and dynamics. This project is aimed at understanding, modelling and estimating the kinematics of lower limbs, that is to say the movement and motion of the lower limbs but not the forces and torques causing them. These forces are important elements of motion, but require some adoption to the proposed methodology to understand.

Finally a large portion of this project relies on software written for MathWorks' MATLAB [12]. This software is single purpose and serves only this thesis. The software itself is not meant to be modular or generalized, yet can serve as a guideline for research using a similar methodology. The software can be found on the accompanying disc. Some software snippets of critical importance has been added to this thesis to highlight the important aspects of implementing the various mathematical constructs. The various Dassault Systmes SOLIDWORKS [13] models are also present on the same disc. These models are also specific to this thesis and can only provide insight for adoptions.

1.4 Plan of Development

The following chapter contains an extensive literature review where various methods of modelling and verifying the human gait has been discussed. There are also sections dedicated to subject borne data capture, computer vision, inertial measurement units (motion sensors), humanoid robotics and mathematical modelling.

This is followed by a chapter titled methodology that presents the the planning and ideation of the thesis. It serves as a link between the theoretical work presented in the literature review and the engineering approach and application detailed in the chapters that follow it. It lays out a plan and shows how engineering specifications were generated from a generally defined problem.

The final three chapters that make up the body of this report are titled "Designing the Data Capture System", "Processing the Captured Data" and "Data Fusion and State Estimation" in order of appearance. True to their title they present the processes followed to complete the major milestones of the project.

In closing a chapter is dedicated to presenting and discussing the results obtained, followed by the final chapter that draws conclusions from the presented work and makes recommendations on future work. The following flow digram summarizes the progression of this report.

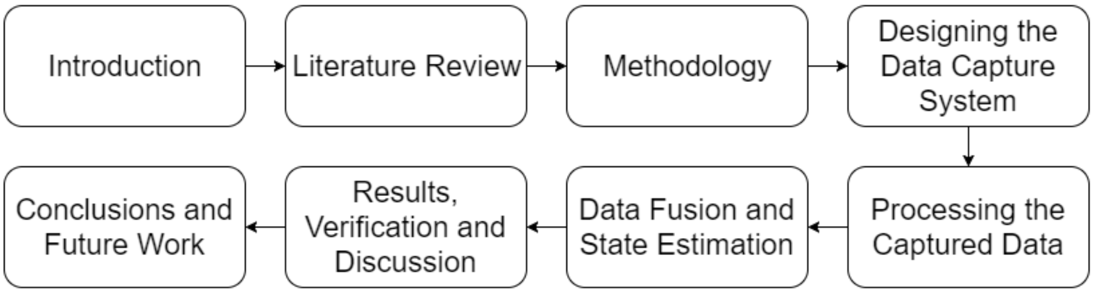

Figure 1.3: Flow chart outlining the report structure

Chapter 2

Literature Review

This section reviews various academic sources related to the methodology proposed. It will look at the various fields of engineering as well as bio-mechanics, biomimicry and applied mathematics to form a holistic understanding of the design space. Importantly the technologies discussed will also be related to the field of robotics as many concepts transfer easily from bipedal humans to bipedal robots.

2.1 Introduction

This research project brings together various disciplines of research. By combining techniques from computer vision, sensors and data fusion we can design and develop new way of capturing human gait data. Whilst the fields of biomimicry and bio-inspired robotics are relatively new, recent advances in related fields such as artificial intelligence and computer vision have invigorated the pursuit of functional humanoid robotics.

kaneko et al. described various components of humanoid robotics in [14].

2.2 Human Motion and Gait

The human gait is well understood and has been studied in detail as it is a fundamental part of human mobility. It is one of the first skills developed in infancy and its importance for healthy develpoment, as outlined by Adolph et al. [15], cannot be understated. Walking and running are also critical factors in transportation and geographical movement of people and goods in developing countries where public transport is underdeveloped and private transport not within the means of the populous. Finally walking and running as exercise has proven benefits as shown in [16] (general health) and [17] (mental health). There is thus clear evidence that the human gait has earned its right as a field of study in academia.

2.3 Computer Vision

While the previous section answers "why" understanding the human gait is important, the following sections will explain fields that contribute to the question of "how" the gait is studied. The technologies and methods used to quantify it. This section titles computer vision should be interpreted within the context of this document. It will be used interchangeable with image processing as the underlying philosophies of both methodologies are algorithmic interpretation of images.

Image processing as a field was born from digital signal processing as it relates to the extraction of critical data from noisy data streams. Computer vision is the use of computational methods to achieve the same end goal. The image processing used in this thesis is basic feature detection and therefore advanced image identification task and

2.3.1 Computer Vision in robotics

Recent improvements to real time computer vision has allowed amazing technological breakthroughs in fields closely related to robotics. One such breakthrough is the rapid improvement of self-driving cars developed by Tesla. These vehicles use vision based technologies and real time image processing to navigate complex and changing road networks. The figure below shows how a Tesla identifies different roadside artefacts.

2.3.2 New Perspectives from Animal Borne Cameras

Patel et al. [6] showed that using animal borne cameras and motion sensors, the tail kinematics of the cheetah (Acinonyx Jubatus) could be tracked. Patel's work was partly inspired by Kane et al. [19] where falcon (Falco Peregrinus) borne cameras were used to better understand airborne pursuit of prey. Giving researchers a new perspective on the behaviour of animals in the natural world.

Further work completed by Pearson et al. [20] showed that cameras mounted to dolphins

Figure 2.1: Insight into object classification by Tesla, image from [18]

(Lagenorhynchus Obscurus) could provide insight into the their movement, social and foraging strategies. Using cameras to study ocean-life has become a popular methodology in recent time due to difficulties imposed by their environment. In essence We struggle to understand flying and swimming animals due to their complex environments.

2.3.3 Human Motion Analysis Using Computer Vision

From Chen et al. [10] using depth imagery to understand human motion we can see that this is a popular technique. Imagery has been a popular approach to interpreting human movement and gesture. Naturally this has formed a foundation of using cameras to capture human movement.

One such system kinect.

2.4 Inertial Measurement Units and Sensors

IMU's are a staple of electrical engineering as applied to dynamic systems. These sensors give us insight as to how an object is moving in space by providing data relating to orientation and acceleration of said system. These data points are created by electronically interpreting signals generated by micro-electromechanical system (MEMS). Modern smartphones have built in IMU's that are not only accurate [21], but also easy to interface with due to the open source nature of the Android operating system [22].

Generally Smartphones contain the following sensors:

- Accelerometer
- Gyroscope
- Magnetometer
- Barometer
- Temperature

Accelerometers provide linear acceleration data; these accelerations may be constant (eg. gravity) or changing (eg. relative motion). In smartphones they are usually based on MEMS that use various mechanical phenomena to determine motion.

Gyroscopes provide rotational data of the sensor relative to the inertial frame. These sensors can generate angular accelerations data.

Magnetometers provide information relating to the macroscopic magnetic fields in a certain area. These sensors can measure the direction, strength, or relative change of fields.

Barometers are finely tuned atmospheric pressure sensors that can determine the relative height of an object with respect to sea-level.

Temperature sensors generate local temperature data of the surrounding environment.

These sensors can be used together to better model the position of a modern smartphone. One example of how this can be done is the fusion of gyroscope and accelerometer.

These se

2.4.1 Global Position System

GPS (Global Position System) is a space based navigational system that uses satellites to determine a receivers absolute position on earth. This system was developed by the United States Air Force and is available freely world wide.

2.4.2 Inertial Measurement Units in Robotics

IMUs are integral in the functioning of robotics. Up until very recently intelligent robotic systems had no sense of vision to provide feedback for their internal control systems.

Instead this feedback was generated by various sensors providing information about the dynamics of these systems.

2.4.3 Human Motion Analysis Using Inertial Measurement Units

Picerno completed and extensive review of motion sensor based data capture for human motion in [11].

2.5 Mathematical Modelling

The binding element presented in this work is the underlying mathematics. Using various mathematical tools and methods known to robotics and bio-mechanics it is possible to transform various data types in various frames of reference to a singular model.

2.5.1 Mathematical Models of the Gait

Before exploring complex methods and tools used to analyze the human gait, it is important to select and understand the model they are derived from. Due to the large amount of existing research related to the human gait some models have been well established. These models are capable of quantifying important elements of the human gait such as gait period, dynamic joint forces and neuromuscular control.

Some fundamental work complete by Zajac, Neptune and Winters will be discussed to better understand existing models.

In work completed by Zajac et al. [23] iy is interesting to note the how he compared modelling difficulties to that seen in bipedal robotics. In this work he also places some important bounds on human joints. He argues that the maximum DOF (Degrees of Freedom) that any single joint can have is 6; 3 for translation and 3 for rotation. He also constrains body segments as rigid and that the internal happenings of a body segment is insignificant.

In further papers published by these authors [24] and [25] various dynamic simulations are tested against proposed methods and subject studies. These papers confirm the multi rigid segment model for studying human dynamics. Since this study is only concerned with the kinetics the assumption can be made that the model is adequate in kinematic analysis.

2.5.2 Linear Kinematics

By using kinematics we can quantify and understand the movement of the lower limbs. Kinematics is a branch of mechanics that fully defines the motion of a point with respect to position, velocity and acceleration (be it linear, rotational or a combination). Kinematics does not however describe the forces, torques or other variables that may affect that point. This is due to a fundamental assumption in kinematics that the point is massless.

Kinematics can be broken up into 2 main branches: *forward* and *inverse*. To illustrate the matter the following diagram is that of a basic kinematic model.

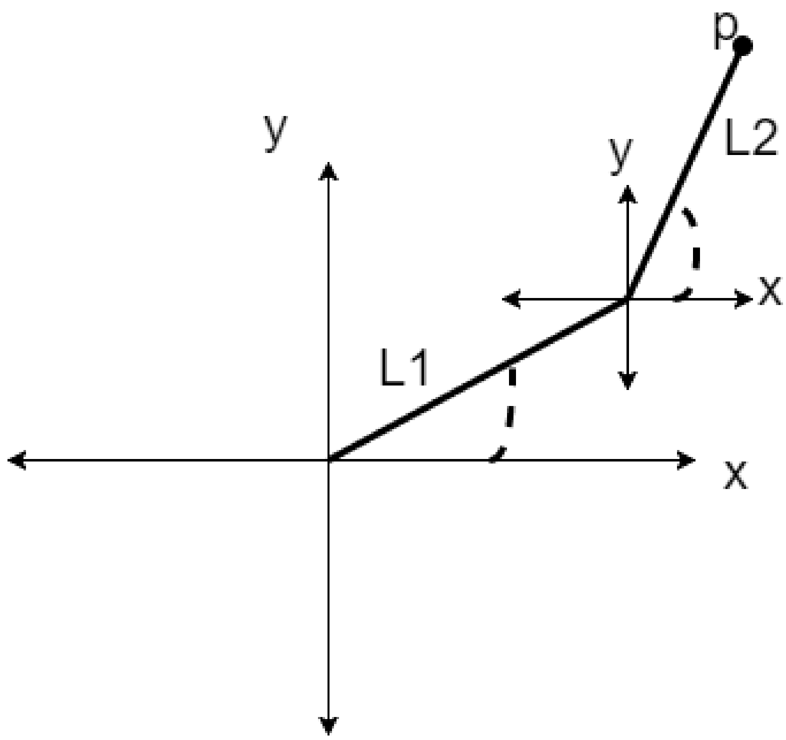

Figure 2.2: Basic kinematic model to demonstrate

In this figure the position of point P is defined by 2 lengths, L1 and L2 with different lengths and angles from a set of shared axis. In forward kinematics we can find P if we know the angles and lengths of the different links in the system. The motion of point P can then be described by looking at how the angles and lengths of the links in the system change over time.

Inverse kinematics uses knowledge of different points in the system, such as the origin and P and the lengths of the links in the system to determine the angular offsets of each length. Since these produce a set of linear equations, the more unknowns we are faced with the more possible solutions we can generate.

As discussed in the previous section a common method of modelling the human lower limbs is to use a collection of rigid beams.

2.5.3 Rotational Matrices

There is an underlying difficulty in mathematically fusing various data sources and models; that of finding a common frame of reference. With the intent of using Lagrangian mechanics good definitions for the different frames are critical. This thesis will primarily use 2 different frames of reference. The inertial frame and the body frame.

The inertial frame (or world frame) can be defined in different ways as seen in [26], for the purpose of this study the NED (North East Down) definition is used. This configuration is also known as the local tangent plain and is often used in aviation.

Rotational matrices are mathematical objects that rotate vectors in three dimensional space. Since most engineering is constrained to the physical three dimensional world these matrices commonly rotate 3 dimensional vectors with a 3x3 sized matrix.

2.5.4 Kalman FIlter and Extended Kalman Filter

The Kalman filter is a mathematical tool used to estimate the states of a system. All measurements contain some unwanted elements of noise that produce uncertainty. Another source of uncertainty is the imprecision in the model. Simplifying assumptions disregard the minute details that when summed can have an effect on the interpretation of the data. To minimize these uncertainties it is important to filter the datasets correctly. Fortunately, estimation can be used as a form of filtering to reduce the impact of these uncertainties.

Another powerful element of the Kalman filter is its ability to fuse data from different sources to compute a more holistic picture of the underlying system. Fusion allows us to interpret sensor data within constraints of other sensors, creating a more accurate dataset. For example we can negate the drift of an accelerometer if we have absolute positional data provided by a GPS.

There is also an important distinction to be made between the KF and the EKF. To briefly explain this it should be understood that the Kalman filter was the original concept as developed by Rudolf E. Klmn and he EKF the extension of said work. The KF has an inherent limitation that it can only be applied to linear systems, whereas the EKF can be applied to non-linear system operating within a certain defined range.

The KF itself can be broken down into 2 fundamental stages of operation; a prediction stage and update stage. The prediction stage takes the known current states of the system and estimates what the measurements should be for the next time interval. The measurement stage takes in current measurements and mathematically determines the states. The states of the system are user defined parameters that can often not be directly measured.

2.6 Natural Solutions for Robotic Shortcomings

Naturally the question arises: why would we want to better understand the dynamics of animals? A persistent problem in the field of modern robotics is that of mobility; robots struggle to navigate real world surfaces and obstacles. Work by Patel et al. [27] shows how we can look towards nature for inspiration to solve this mobility problem.

As demonstrated by various prototype robots built by Boston Dynamics bipedal robots are severely limited in manoeuvrability when compared to animals. This is due to the longest iterative design process known to man, evolution. Pictured below is a collection of bio-inspired robots build by Boston Dynamics.

Figure 2.3: Different bipedal and quadroped robots created by Boston Dynamics, image from [28]

2.7 Conclusion

This chapter has shown the direct parallels of technologies related to gate capture to dynamic robotic systems. With these strong parallels in mind the transferability of these systems from humans to humanoid robots is clear. In the same manner we are able to take a bio-mechanical look at the human body and treat it as a dynamics mechanical system instead of the complex bio-chemical and physiological system it really is.

This technique of abstracting systems to different domains of knowledge allows us to apply engineering methods and design to complex problem spaces. As mechanical engineers have used resistive networks to understand thermodynamics [29] and control engineers have used mechanical models and electrical models interchangeably to apply control principles [30], there is power in this methodology. Fusing different methods from different fields has proven its usefulness and this work will use this approach of horizontal thinking to create its own unique methodology.

As discussed in this chapter the importance of understanding the human gait cannot be understated. The recent breakthroughs in computer vision and neural networks has reignited a field that has potential to truly change our day to day life. The ever increasing ability of sensors technology and data capture systems allow us to quantify what we have never been able to and the underlying fundamental mathematical methods never seem to fall short.

The future of humanoid robotics sits at the overlap of computer vision, IMUs and biomimicry; add to this some form of general intelligence and the world reaches a stage of automation and transformation only imagined by authors such as Asimov and Wiener. Perhaps this work could contribute to that future.

Chapter 3

Methodology

To ensure the success of this project a basic plan of action was created. The following diagram shows the critical phases of the project.

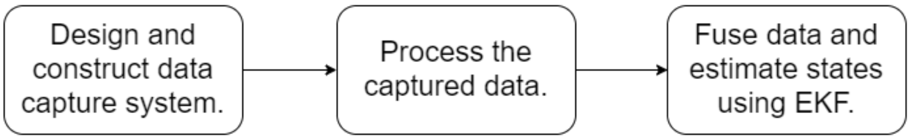

Figure 3.1: Diagram showing the progression and dependence of the major stages of this project

Due to the availability of equipment, financial limitations and time constraints various design parameters where predetermined. These known design elements are discussed in the following section.

3.1 System Design

This section is dedicated to defining and understanding the specifications of the data capture system. The system will consist of 4 cameras and an IMU mounted to the torso of the subject. The cameras will record the lower limbs of the subject while the IMU will log inertial data from the body of the subject. The video data from the cameras will provide information about the kinematics of the lower limbs with respect to the cameras while the IMU will provide motion data of the body with respect to the inertial frame. As discussed in the previous chapter the inertial frame and the world frame are equivalent in this project.

Due to the availability of equipment provided by the Mechatronics Lab the following equipment was chosen as the main components to use in the system:

Item	Selected Equipment	From
Camera	4 GoPro Hero Session Cameras	[31]
IMU	1 Sony Xperia Z3 Compact	[32]
Chest Mount	1 Action Mount Chest Mount	[33]

Table 3.1: Known design elements of the project

The specifications of this data capture system has been defined as:

- 2 stereo housings to hold the cameras
- Chest mount to hold the cameras and IMU
- Connecting hardware to mount camera housing to the chest harness.
- Cameras must be stable during running
- IMU must be rigidly mounted to front cameras
- Cameras must capture full lower limb motion
- Harness must be comfortable during running.
- Harness must not impede natural gait of subject
- Harness must be as light as possible
- Harness must fit different size torsos and for different sexes
- system must be remote controlled as far as possible

These specifications ensure a system that can be used by a large demographic of people.

3.2 Modelling the Lower Limbs

To interpret the data and the underlying mathematics a model of the human torso and lower limbs must be created. This model consist of the lower limbs being represented as rigid links. Each leg is comprised of three different links: thigh, calf and foot. The joints connecting the links have been limited degrees of freedom to simplify the model. The ankle (serving as the joint between the foot and calf) is assumed to have a single rotational degree of freedom (pitch). The knee (serving as a joint between the calf and the thigh) has also been limited to only have a pitch element. Finally the hip (joining the thigh to the body) has been given 2 rotational degrees of freedom: pitch and yaw. This rigid model can be seen in the following figure.

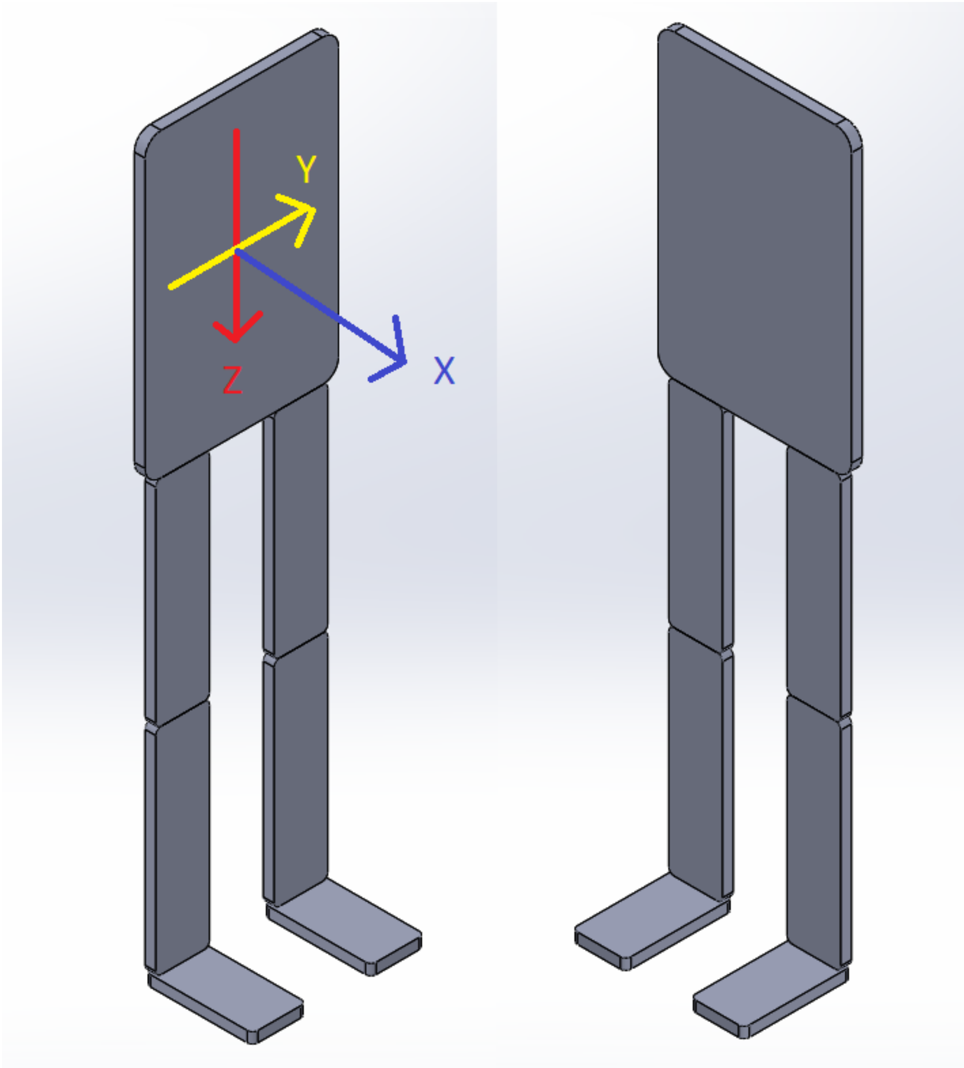

Figure 3.2: Rigid beam model used in this thesis

3.3 Experimental Details

The data was captured during a short straight road run where the runner started from a standing position and accelerated to a steady state running pace. This allowed us to capture some transients (accelerations) from the run that can be used to initialize the propowed EKF.

3.4 Limitations

The scope of this research does not include runs over rough terrain as this is the logical next step after flat ground steady state running is modelled and estimated. It is assumed that given robust EKF and complete image processing solution the system would work for running on various terrains.

Another source of limitations is the nature of the rigid beam model. This non elastic model does not take in to account the slight change in lengths of the limbs during running. The model also omits yaw and roll parameters about the knee and ankle as well as roll parameters about the hip. Finally the model assumes a rigid stationary chest that introduces some error relating the the camera data.

Since the chest swings proportional to the gait period this could be modelled as a harmonic oscillator. It would also be possible to interpret the rotational rates of the chest from the IMU data.

Chapter 4

Designing the Data Capture System

To obtain data for the Extended Kalman Filter, a data-capture system needed to be designed. Since the data sources have been identified as multiple video sources and a 9-DOF IMUthe equipment has been selected as follows.

4.1 GoPro Hero Session Camera

Due to the availability of GoPro Hero Session cameras the wearable motion capture system was designed with these in mind. These cameras only take up a volume of $250cm^3$ and has a square housing measuring $6.3cm$ on all sides. The following figure presents a visual of the camera.

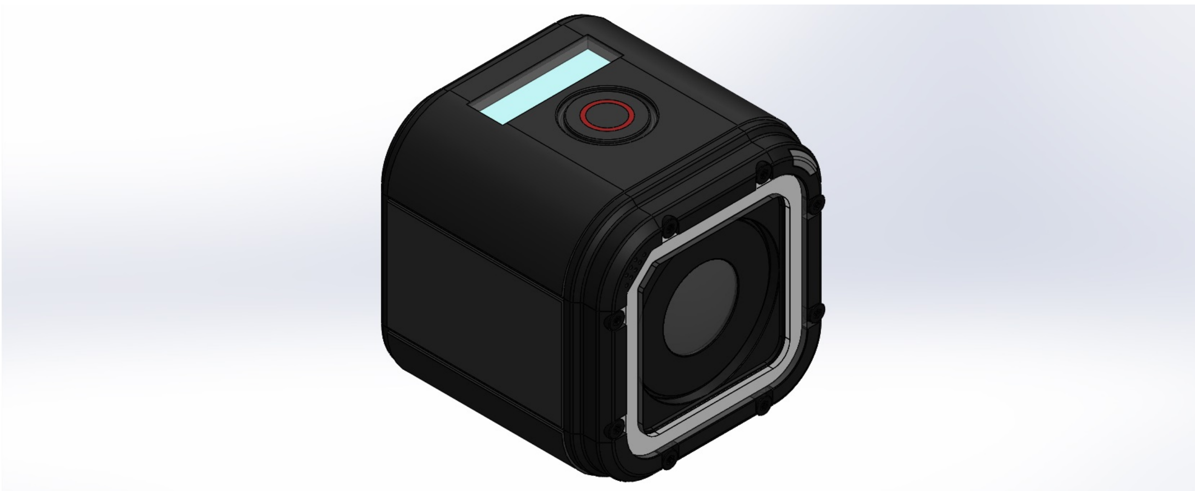

Figure 4.1: 3D CAD rendering of the GoPro Hero Session action camera

The camera can capture videos at a variety of frame rates and a variety of resolutions.

These settings are limited as the software that controls the camera is proprietary.

These set frame rates and resolutions are presented in the table below.

Resolution	Frame Rates
1920 x 1440	30 fps, 25 fps
1920 x 1080	60 fps, 50 fps, 48 fps, 30 fps, 25 fps
1280 x 960	60 fps, 50 fps, 30 fps, 25 fps
1280 x 720	100 fps, 60 fps, 50 fps, 30 fps, 25 fps
848 x 480	120 fps, 100 fps

Table 4.1: Possible frame rate and resolution combinations on the GPHS camera

The relative motion of the lower limbs appeared to move rapidly and therefore the highest possible framerate with the best resolution was chosen. The camera was therefore configured to record at 100Hz and a resolution of 1280 x 720 pixels. This was chosen as the quality of the 848 x 480 video was simply to low to analyse using computer algorithms.

The camera also has the ability to record using a normal lens or a wide angle lens. The field of view of the camera greatly increases with the wide angle lens but its focal length decreases proportionally. The wide lens also produces more distortion when compared to the normal lens. Due to the relatively narrow area of capture needed the camera was configured to use the normal lens as it would decrease distortion without compromising the area of interest.

4.2 Camera Mount Design

Some initial work on modelling a housing for the camera was completed by the Mechatronics Lab. This was a 2 part 3D printable enclosure with no mounting points. The enclosure is pictured below.

This model was heavily modified using Dassault Systems SOLIDWORKS software to enclose 2 cameras mounted side by side. The bracket also needed a mounting point to join to the chest mount. Finally the bracket needed to be lightweight, provide access to the camera controls and not obscure the built in status screen of the cameras. The following figure shows the final dual camera bracket that was 3D printed.

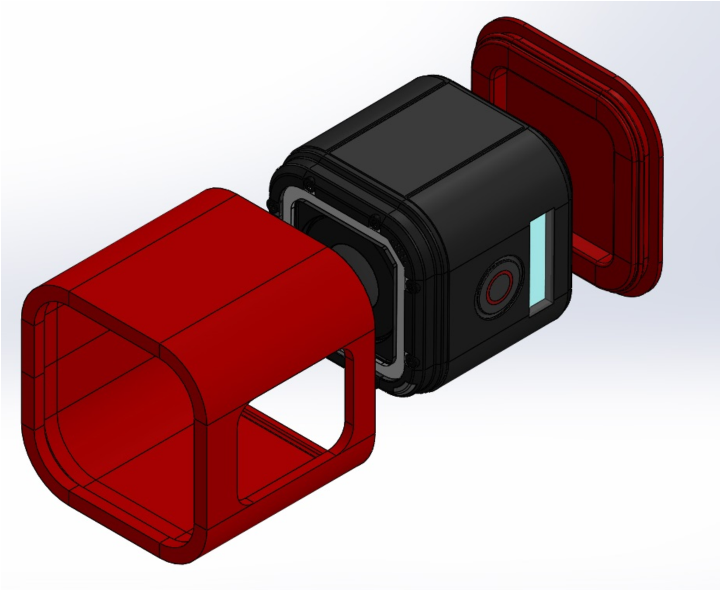

Figure 4.2: Initial camera enclosure designed by the mechatronics lab

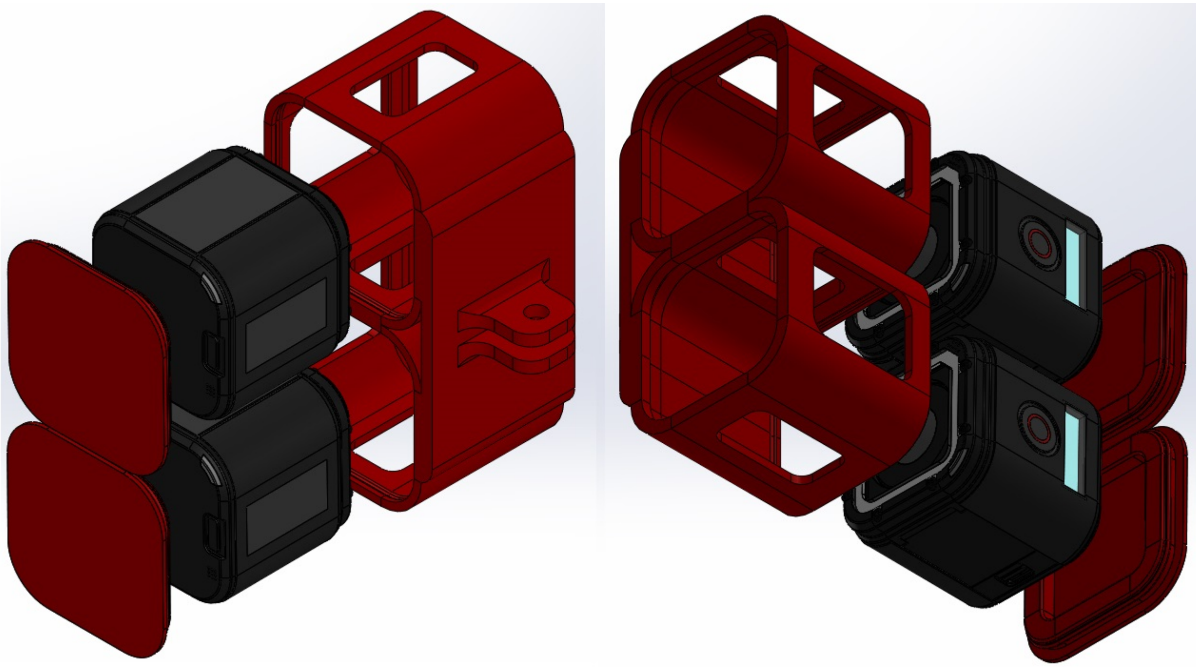

Figure 4.3: Final dual camera enclosure designed by the author

4.3 Vision Calibration

In order to obtain accurate positional information from the video cameras calibration was performed. MATLAB has a built in stereo camera calibration application that can calibrate a set of cameras and create an object containing all the essential parameters, including the individual camera intrinsics.

To calibrate the cameras pictures of a white and black chequerboard is fed in to the calibration application that then mathematically determines the camera parameters. In order to make this process more efficient a video of the the moving chequerboard was taken and various frames of importance extracted using a simple MATLAB script.

Chapter 5

Processing the Captured Data

This chapter is dedicated to the complex process of extracting critical data from the video files. The following digram shows the process of converting a data heavy video file to a more lightweight .csv (Comma Separated Values) file.

5.1 Processing the IMU Data

5.1.1 Capture IMU Data

To use the smartphone as an IMU a free application ”AndroSensor” was installed. This application could log parameter from all the availible sensor s and could be configured in various ways

[34]

The IMU data logged by the smartphone was saved as a .CSV file with the first row containing the headings of various variables. These headings were

All these variables have been recorded with respect the smartphone frame of reference as shown below

5.2 Processing the Video Data

The following flowcharts depicts the procedural processing of video data.

Heading
ACCELEROMETER X
ACCELEROMETER Y
ACCELEROMETER Z
GRAVITY X
GRAVITY Y
GRAVITY Z
LINEAR ACCELERATION X
LINEAR ACCELERATION Y
LINEAR ACCELERATION Z
GYROSCOPE X
GYROSCOPE Y
GYROSCOPE Z
MAGNETIC FIELD X
MAGNETIC FIELD Y
MAGNETIC FIELD Z
ORIENTATION Z
ORIENTATION X
ORIENTATION Y
ATMOSPHERIC PRESSURE
LOCATION Latitude
LOCATION Longitude
LOCATION Speed
LOCATION ORIENTATION

Table 5.1: My caption

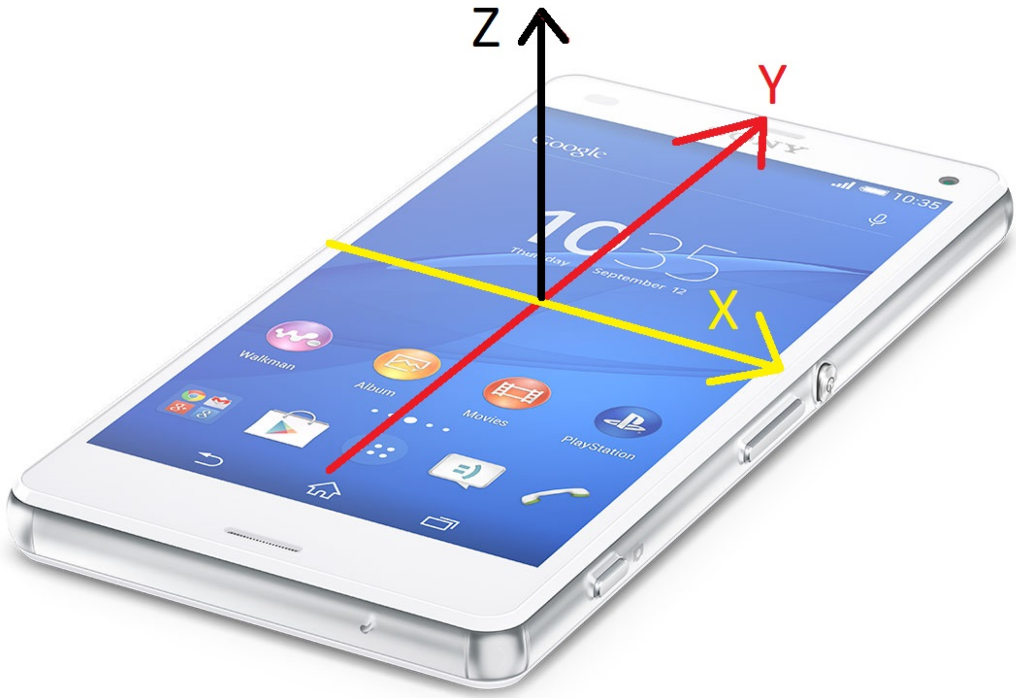

Figure 5.1: Figure demonstrating the frame of reference of the smartphone

5.2.1 Obtaining Video Data

Using the chest mounted cameras detailed in the previous chapter we can generate raw video data. The GPHS cameras can be configured to record at different frame rates and resolutions as discussed in the previous chapter. The video files where stored in an .MP4 format. This meant that during recording the video was compressed and the

5.2.2 Synchronizing Video Sources

I typical problem faced when working with different sources of data is that of synchronization. Since this project used 4 different cameras, synchronizing the video sources are critical to generate accurate stereo vision data.

The problem of synchronization was overcome by using a audio cue to align the video data post capturing. With all systems recording, a simple hand clap can serve as a spiking audio input easily identified in the audio track of the video streams. The frame associated with this audio spike can be identified using SVP (Sony Vegas Pro) video editing software as shown in the figure below.

The red track in the above figure shows the recorded audio stream while the corresponding frames are displayed in the blue track above that. The cursor is aligned with the audio

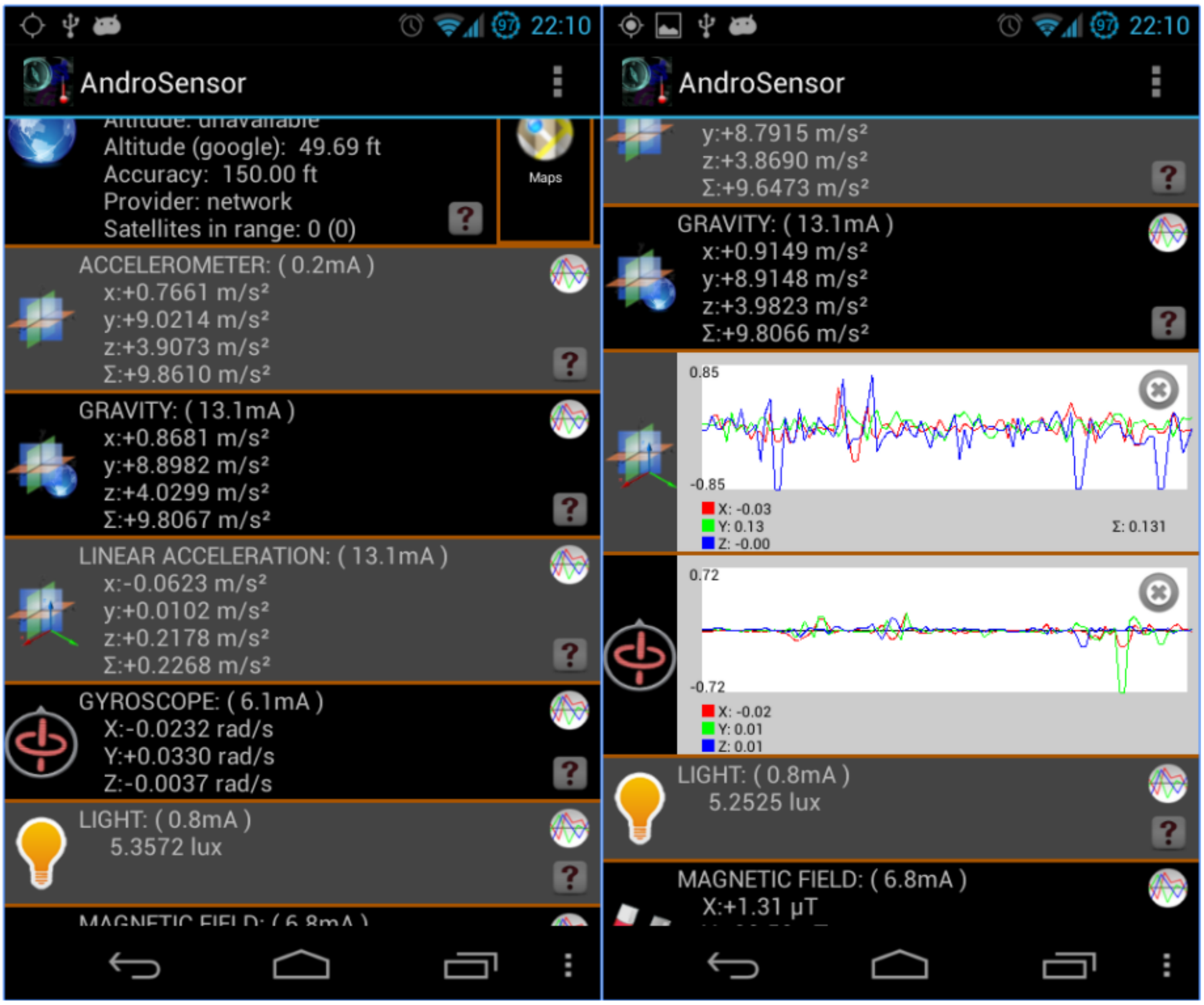

Figure 5.2: Androsensor Screenshots

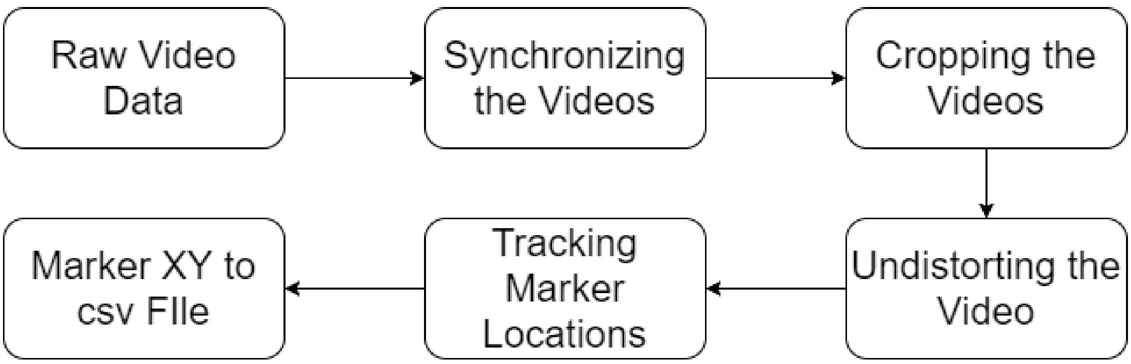

Figure 5.3: Diagram showing the progression and dependence of the major stages of video processing in the project

spike caused by the clap with the corresponding frame number displayed below the playback controls.

This method was repeated for every video stream such that a common starting point was

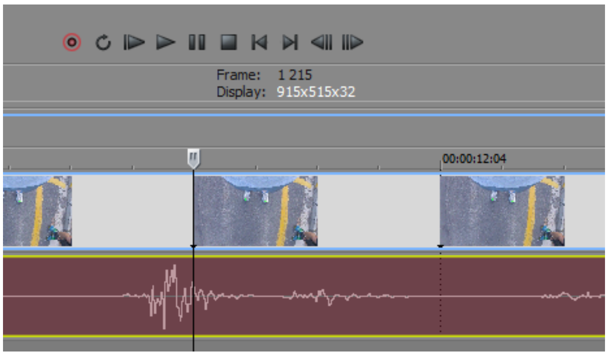

Figure 5.4: Figure showing the user interface of SVP video editing software

generated.

5.2.3 Cutting Critical Video Data

With the video data synchronized the next step was to generate a subset of video demonstrating a transient period and steady state period of running. From accelerometer readings we can easily determine the gait cycle period of our subject; that is the amount of time take between the same foot impacting the ground. These impacts are visible as spikes as seen in the accelerometer data.

5.2.4 Undistorting the Video Data

To generate accurate distances using stereo vision the video frames need to be undistorted.

Distortion of the frames is a result of the

[35]

5.2.5 Tracking and Exporting Marker Positions in the Frame

using work from [36]

Chapter 6

Data Fusion and State Estimation

This chapter is dedicated the explaining the mathematical methods and models used to fuse data generated by the cameras and IMU.

State	Description
x_{body}	x Position of body w.r.t. the inertial frame
y_{body}	y Position of body w.r.t. the inertial frame
z_{body}	z Position of body w.r.t. the inertial frame
θ_{body}	Pitch of body w.r.t. the inertial frame
ϕ_{body}	Roll of body w.r.t. the inertial frame
ψ_{body}	Yaw of body w.r.t. the inertial frame
θ_{LH}	Pitch of left thigh w.r.t. left hip
ψ_{LH}	Yaw of left thigh w.r.t. left hip
θ_{LK}	Pitch of left calf w.r.t. left knee
θ_{LA}	Pitch of left foot w.r.t. left ankle
θ_{RH}	Pitch of right thigh w.r.t. right hip
ψ_{RH}	Yaw of right thigh w.r.t. right hip
θ_{RK}	Pitch of the right calf w.r.t. right knee
θ_{RA}	Pitch of the right foot w.r.t. the right ankle

Table 6.1: Table showing the different states of the model to be determined by the kalman filter.

we will use derivatives

al the derivatives

$$q = [x_{body}\ y_{body}\ z_{body}\ \theta_{body}\ \phi_{body}\ \psi_{body}\ \theta_{LH}\ \psi_{LH}\ \theta_{LK}\ \theta_{LA}\ \theta_{RH}\ \psi_{RH}\ \theta_{RK}\ \theta_{RA}]$$

all the states totalling 42 states

$$Q = [q\ \dot{q}\ \ddot{q}]$$

all 42 and their equations

positional

$$\ddot{x}_{k+1} = \ddot{x}_k + \sigma^2_{\ddot{x}}$$

$$\dot{x}_{k+1} = \dot{x}_k + \ddot{x}_k T + \sigma^2_{\dot{x}}$$

$$x_{k+1} = x_k + \dot{x}_k T + \sigma^2_{x}$$

angular

$$\ddot{\theta}_{k+1} = \ddot{\theta}_k + \sigma^2_{\ddot{\theta}}$$

$$\dot{\theta}_{k+1} = \dot{\theta}_k + \ddot{\theta}_k T + \sigma^2_{\dot{\theta}}$$

$$\theta_{k+1} = \theta_k + \dot{\theta}_k T + \sigma^2_{\theta}$$

since all states are either positional(body) or angular(body and limbs) matrices: rotational matrices

$$\text{x axis} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

$$\text{y axis} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$\text{z axis} \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

solving for the angles

front cameras

point 1 right knee

point 2 left knee

point 3 right foot

point 4 left foot

back cameras
point 1 right calf
point 2 left calf
point 3 right heel
point 4 left heel

front
right knee

$$p1xyz = bodyY + bodyZ + R1 * Thigh$$

left knee

$$p2xyz = bodyY + bodyZ + R1 * Thigh$$

right foot

$$p3xyz = bodyY + bodyZ + R1 * Thigh + R2 * Calf + R3 * Foot$$

left foot

$$p4xyz = bodyY + bodyZ + R1 * Thigh + R2 * Calf + R3 * Foot$$

back
right calf

$$p1xyz = bodyY + bodyZ + R1 * Thigh + R2 * 0.5 * Calf$$

left calf

$$p2xyz = bodyY + bodyZ + R1 * Thigh + R2 * 0.5 * Calf$$

right heel

$$p2xyz = bodyY + bodyZ + R1 * Thigh + R2 * Calf$$

left heel

$$p2xyz = bodyY + bodyZ + R1 * Thigh + R2 * Calf$$

6.1 Understanding the Data Sources

It is important to understand the different parameters that mathematically quantify cameras. These parameters can be devided into *extrinsic* and *extrinsic*. Extrinsic camera variables related to the cameras position in the inertial frame and the direction the camera is facing. These can be summarized by the extrinsic camera matrix

$$[R \,|\, \boldsymbol{t}] = \left[\begin{array}{ccc|c} r_{1,1} & r_{1,2} & r_{1,3} & t_1 \\ r_{2,1} & r_{2,2} & r_{2,3} & t_2 \\ r_{3,1} & r_{3,2} & r_{3,3} & t_3 \end{array}\right]$$

6.2 State Estimation

This section will mathematically explain the Kalman filter and its implementation in this project.

Process equation of the kalam filter. from states to emasurements

$$X_{k+1} = FX_k + w_k$$

our state, contained in the vector X can be estimated by applying the process matrix F to our current known state. the term w is the noise variable that accounts for process noise.

Measurement equations from measurements to states.

$$Y_k = H_k X_k + v_k$$

w will be contained int he matrix Q

while v will be contained in the matrix R1

linearizing nonlinear system we get the EKF

6.3 Q Matrix, R Matrix and Initialization

This section will discuss the final components of the EKF namely the Q matrix containing the various process noise variations, R matrix containing the various measurement noise variances and the initial state values.

Chapter 7

Results, Verification and Discussion

This chapter is dedicated to discussing the results generated and their verification.

7.1 Results

7.2 Verification

7.3 Discussion

Chapter 8

Conclusions and Future Work

This chapter is dedicated to drawing conclusions based on results found and make recommendation on future iterations of this project. Since the underlying methodology is quite novel this system should serve as the foundational step to a fully automated motion capture system.

8.1 Conclusion

Due to the relatively small dataset used in this project it serves cannot serve as more than a proof of concept.

8.2 Future work

The system was originally designed with four cameras due to the availability of equipment and the assumption that stereo vision would be implemented. From this a set of front and rear mounted cameras would be necessary. Originally there was an intention to reduce the total amount of cameras.

The iterative design would have followed the following mapping. Initially using 4 cameras and an smartphone as a sensor. reducing the system to two cameras (one mounted to the back of the runner and one mounted to the chest of the runner) and a smartphone as a sensor. The next iteration would use the the smartphone camera at the front and a single camera at the back whilst using the smartphone as a sensor as well. This system greatly reduces the cost of the original design philosophy, even given that a powerful and modern smartphone would be used. The final iteration would use only the smartphone at the front as a single camera and sensor. For this method to work the estimation algorithm would need to better understand the periodic motion of the human gait and the model would need to increase in complexity.

Due to the labour intensive approach taken to image processing a further avenue for improvement is the automation of feature detection. The progression would start from the current implementation of markers and use a semi-automatic toolbox to identify critical points on the image. Next computer algorithms should be created to automate the image processing with markers. This could allow for much longer runs and larger datasets to be studied, introducing elements such as fatigue and other running modifiers. THe next iterative step would be to remove the markers from the runner such that the setup time of the system is reduces. This is a difficult problem to solve using classical image processing as the variables relating to the runner and the environment are not constant. Perhaps a neural network can be trained to identify the different elements of the lower limbs.

These improvements would decrease the overall cost of the system and optimize the the process substantially. This decrease in hardware does imply that the complexity of the underlying algorithms and models would increase. This trade-off can be considered for future work.

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data.The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook**(available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/usr/ebe/research/ethics.pdf

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Johann Hendrik Joosten
Department		Electrical and Electronics Engineering
Preferred email address of applicant:		joostenhendrik@gmail.com
If a Student	Your Degree: e.g., MSc, PhD, etc.,	B.Sc(Eng) Mechatronics
	Name of Supervisor (if supervised):	Dr. Amir Patel
If this is a researchcontract, indicate the source of funding/sponsorship		-
Project Title		Modelling the Kinematics of the Human Lower-Limbs using Cameras and an IMU

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Johann Hendrik Joosten		22/08

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	AMIR PATEL		22/08/2017
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours).	S. CHOWDHURY		11/10/17

Figure 8.1: ethics clearance

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