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.

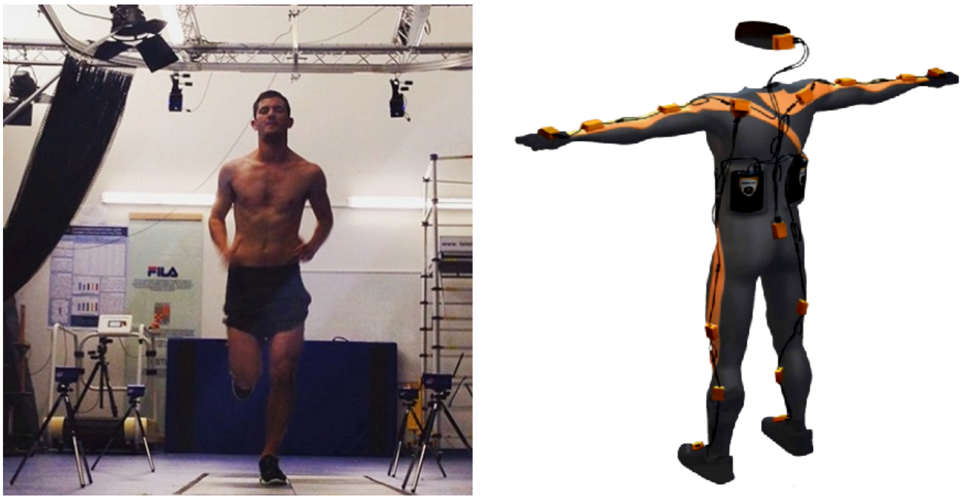

Figure 1.1: Left: Vicon motion capture system tracking the human gait (from [3]) Right: The Xsens MVN motion capture suit (from [5])

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].

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.

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 dataset 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.

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.

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 process 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.

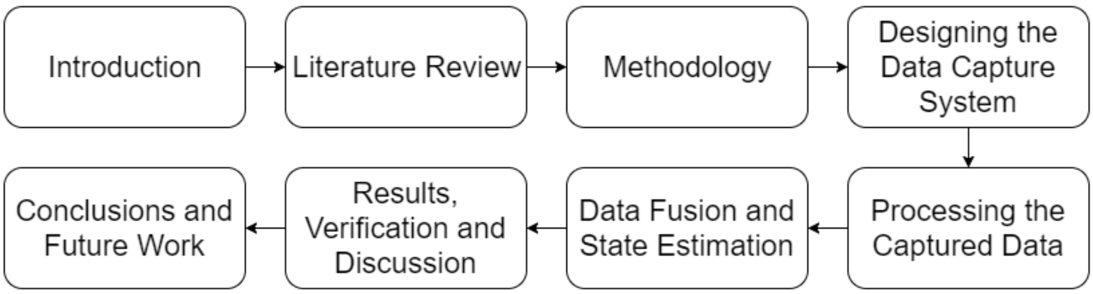

Figure 1.2: Flow chart outlining the report structure

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 biomechanics to form a holistic understanding of the design space. Importantly the technologies discussed will also be related to the field of robotics as

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 intellegence and computer vision have invigorated the persuit of functional humanoid robotics.

Humanoid robotics [12] ... talk about dynamics...

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. [13], 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 [14] (general health) and [15] (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 used and the

Computer vision is a field borne from image processing and artificial intelligence that seeks to replicate the ability of the human visual system.

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 imaeg processing to navigate complex and changing road networks.

Furthermore

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. [16] 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. [17] showed that cameras mounted to dolphins (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 popualr teqnique.

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 [18], but also easy to interface with due to the open source nature of the Android operating system [19].

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

Gyroscope provide rotational data relative to the sensors body. They provide angular accelerations

Magnetometers provide information realting to the macroscopic magnetice fields surrounding the earth

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

Temperature generate local temperature data

2.4.1 Inertial Measurement Units in Robotics

IMUs are integral in the functioning of robotics. Up until very recently intellegent 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.

2.4.2 Human Motion Analysis Using Inertial Measurement Units

[11]

2.5 Mathematical Modelling

The binding element presented in this work is the underlying mathematics.

2.5.1 Mathematical Models of the Gait

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. A popular model of choice is the multi segmented model

Some fundamental work complete by Zajac, Neptune and Winters

[20] interesting to note the how he compared modelling difficulties to that seen in robotics..

[21]

[22]

2.5.2 Linear Kinematics

2.5.3 Rotational Matrices

There is an underlying difficulty in mathematically fusing various data sources and models; the difficulty of finding common frames of reference. The importace of reference einsteins theory of relativity literally changes the game

Rotational marices are mathematical objects that rotate vectors. Since most engineering is constrained to the physical three dismensional world these matrices commonly rotate 3 dimensional vectors.

This is an old problem ask euler.

2.5.4 Kalman FIlter and Extended Kalman FIlter

The Kalman filter is a mathematical tool used to estimate the states of a system using joint

Kalman filters can be broken down into 2 fundamental stages of operation; a prediction and measurement stage. The prediction stage esentially takes the known currernt states of the system and estimates what the measurements should be for the next time interval. The measurement stage takes in measurements and mathematically detemines the states.

The states of the system are user defined parameters that can often not be directly measured.

Closely related to the field of control engineering the kalman filter proves problematic when applied to nonliner systems. From this was born the extended Kalman filter used to beter apply to nonlinear systems

an important elementto understand of these systems is as control ngineers define the cost function. Within the field of optimal control we wnat to control system ebhavious using minial inpu and with minimal error. the cost function is a mathematical representation of these extremes..

2.6 Observing 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. [23] 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

2.7 Conclusion

This chapter has shown the direct pararels of technologies related to gate capture to dynamic robotic systems. With these strong parllels in mind the transferability of these systems from humans to humanoid robots is clear.

ust as we can see the relatoipn work on the human body has to that of robotics we can use engineering methods developed for mechanical systems to understand complex ystems such as the human body.

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.

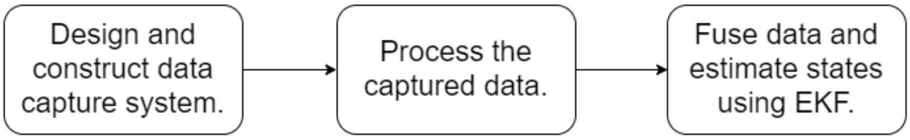

Figure 3.1: Diagram showing the progression and dependence of the major stages of this project

Due to the availability of equipment, financial limitations and time

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 legs of the subject while the IMU will log inertial data from the body of the subject.

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	[24]
IMU	1 Sony Xperia Z3 Compact	[25]
Chest Mount	1 Action Mount Chest Mount	[26]

Table 3.1: The main components used

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

- Stereo housing to hold the cameras.
- Chest mount to hold the cameras and IMU.
-
-

3.2 Modelling the Lower Limbs

talk about the model here

3.3 Experimental Details

The data was captured during a short

3.4 Sensor Fusion

asdfasdkfjasldfk

3.5 Limitations

system shortcomings experimental shortcoming model shortcomings

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 IMU.

4.1 Camera Mount Design

4.2 Designing the Body Harness

sdfgsdfgsdfg

adsfasdfsdfg

sdfgsdfgdsf

sdfgdsfgdsfg

4.3 Vision Calibration

matlab stereo camera calibration software 1. calibrate the cameras 2. get data from the recordings

took some vids

made matlab script to isolate frames in vids

put frames into stereo video camera calibrator

winning at life

Figure 4.1: GoPro Chesty camera mount from [27]

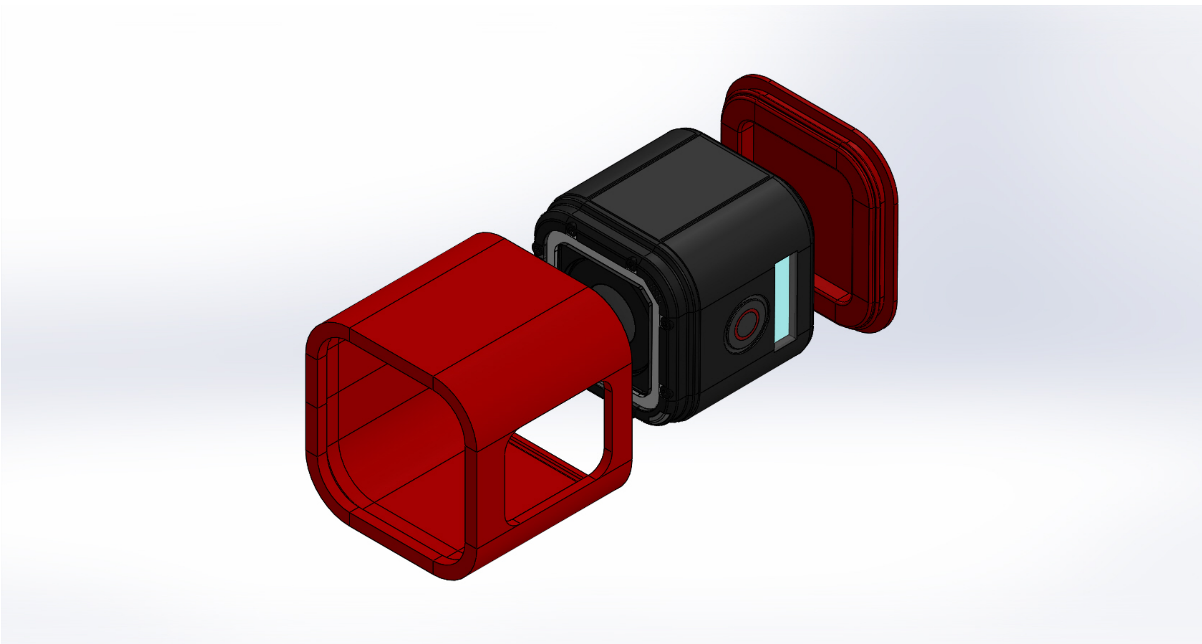

Figure 4.2: Solidworks model of the GoPros Hero 4 Session

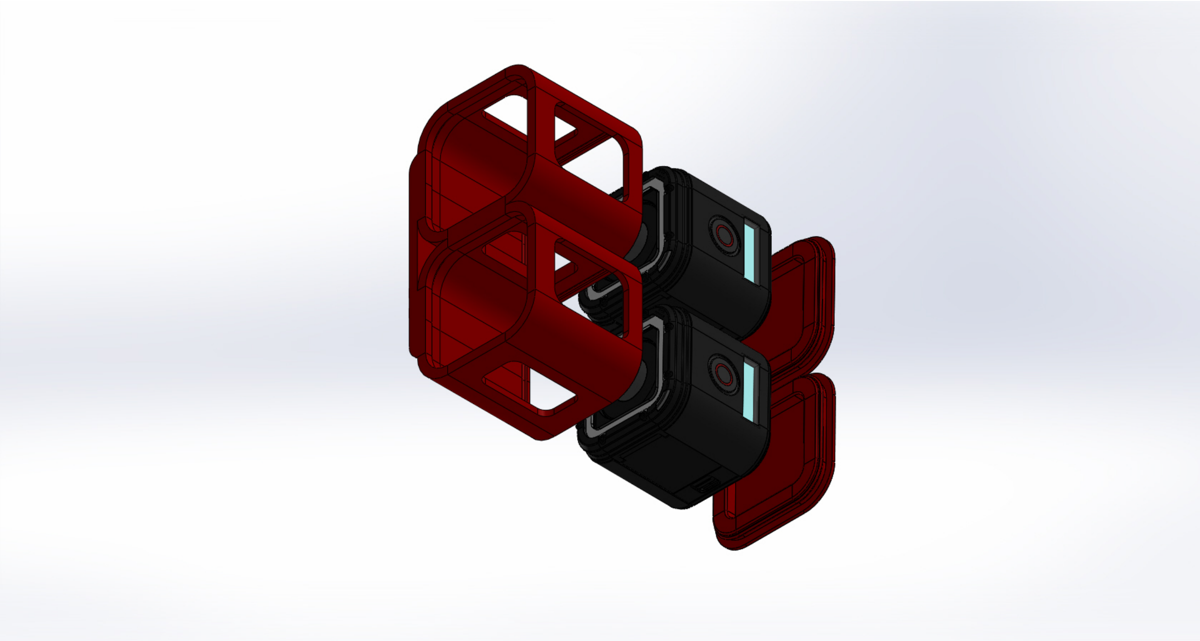

Figure 4.3: angle 1

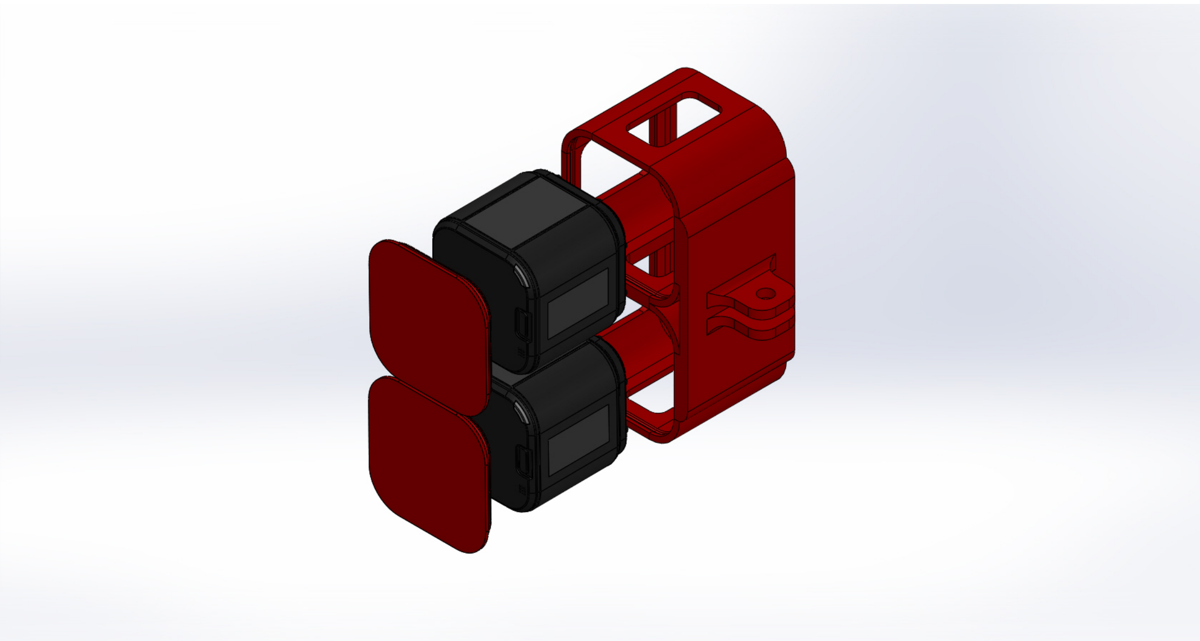

Figure 4.4: angle 2

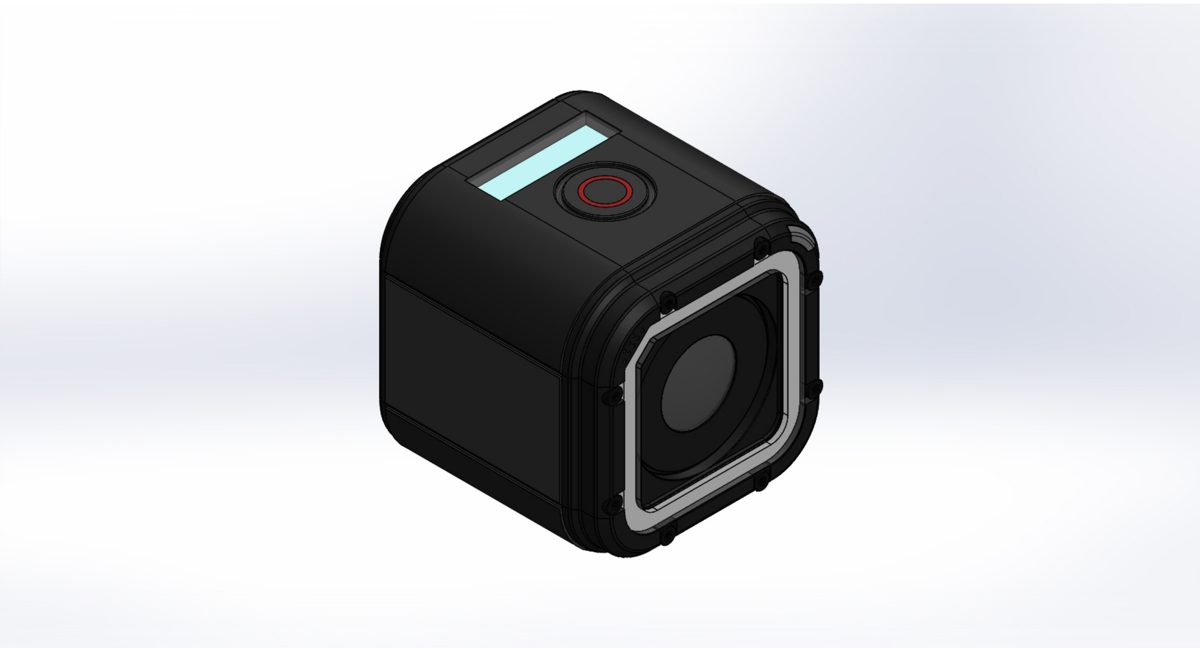

Figure 4.5: Solidworks model of the GPHS Action Camera from [28]

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.

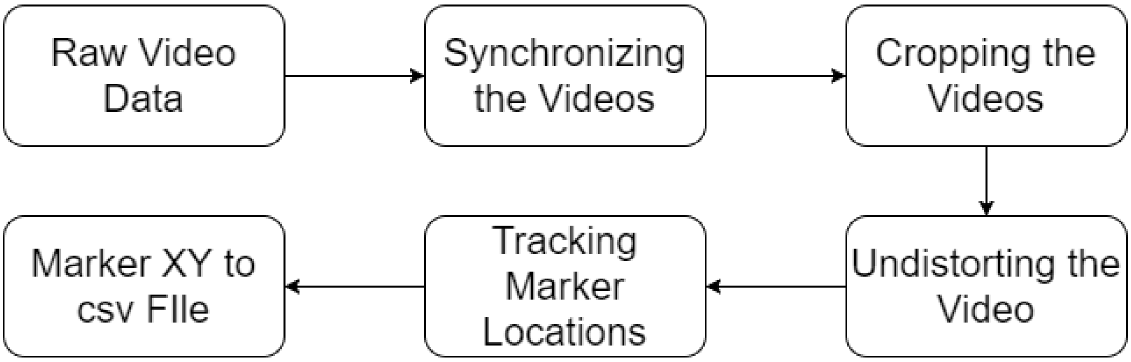

Figure 5.1: Diagram showing the progression and dependence of the major stages of video processing in the project

5.1 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.

5.2 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.

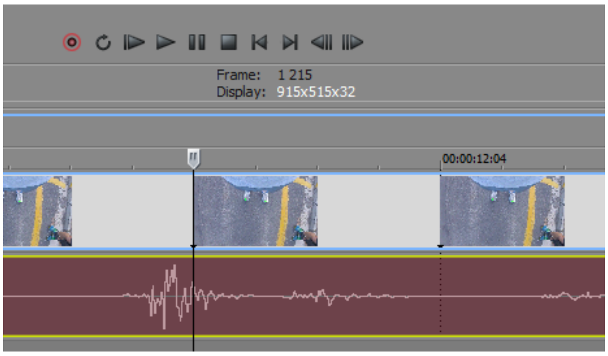

Figure 5.2: Figure showing the user interface of SVP video editing software

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 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 generated.

5.3 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.

5.4 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

[29]

5.5 Tracking and Exporting Marker Positions in the Frame

using work from [30]

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

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

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

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

angular

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

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

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

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 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 varaible 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

Chapter 7

Results, Verification and Discussion

Chapter 8

Conclusions and Future Work

Bibliography

[1] M. Sandau, H. Koblauch, T. B. Moeslund, H. Aanæs, T. Alkjær, and E. B. Simonsen, "Markerless motion capture can provide reliable 3d gait kinematics in the sagittal and frontal plane," *Medical engineering & physics*, vol. 36, no. 9, pp. 1168–1175, 2014.

[2] A. Pfister, A. M. West, S. Bronner, and J. A. Noah, "Comparative abilities of microsoft kinect and vicon 3d motion capture for gait analysis," *Journal of medical engineering & technology*, vol. 38, no. 5, pp. 274–280, 2014.

[3] D. Roetenberg, H. Luinge, and P. Slycke, "Xsens mvn: full 6dof human motion tracking using miniature inertial sensors," *Xsens Motion Technologies BV, Tech. Rep*, 2009.

[4] T. Seel, J. Raisch, and T. Schauer, "Imu-based joint angle measurement for gait analysis," *Sensors*, vol. 14, no. 4, pp. 6891–6909, 2014.

[5] VICON, "Vicon motion capture system," https://www.vicon.com/motion-capture/biomechanics-and-sport, [Online; accessed 16-October-2017].

[6] A. Patel, B. Stocks, C. Fisher, F. Nicolls, and E. Boje, "Tracking the cheetah tail using animal-borne cameras, gps, and an imu," *IEEE Sensors Letters*, vol. 1, no. 4, pp. 1–4, 2017.

[7] B. Stocks, "Cheetah motion analysis," Master's thesis, University of Cape TOwn, South Africa, 2016.

[8] A. Patel and M. Braae, "Rapid acceleration and braking: Inspirations from the cheetah's tail," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*. IEEE, 2014, pp. 793–799.

[9] J. M. Benyus, "Biomimicry: Innovation inspired by nature."

[10] L. Chen, H. Wei, and J. Ferryman, "A survey of human motion analysis using depth imagery," *Pattern Recognition Letters*, vol. 34, no. 15, pp. 1995–2006, 2013.

[11] P. Picerno, "25 years of lower limb joint kinematics by using inertial and magnetic sensors: A review of methodological approaches," *Gait & posture*, vol. 51, pp. 239–246, 2017.

[12] K. Kaneko, F. Kanehiro, S. Kajita, K. Yokoyama, K. Akachi, T. Kawasaki, S. Ota, and T. Isozumi, "Design of prototype humanoid robotics platform for hrp," in

Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on, vol. 3. IEEE, 2002, pp. 2431–2436.

[13] K. E. Adolph and S. R. Robinson, "The road to walking: What learning to walk tells us about development," *Oxford handbook of developmental psychology*, vol. 1, pp. 403–443, 2013.

[14] S. Hanson and A. Jones, "Is there evidence that walking groups have health benefits? a systematic review and meta-analysis," *Br J Sports Med*, vol. 49, no. 11, pp. 710–715, 2015.

[15] K. R. Fox, "The influence of physical activity on mental well-being," *Public health nutrition*, vol. 2, no. 3a, pp. 411–418, 1999.

[16] S. A. Kane and M. Zamani, "Falcons pursue prey using visual motion cues: new perspectives from animal-borne cameras," *Journal of Experimental Biology*, vol. 217, no. 2, pp. 225–234, 2014.

[17] H. C. Pearson, P. W. Jones, M. Srinivasan, D. Lundquist, C. J. Pearson, K. A. Stockin, and G. E. Machovsky-Capuska, "Testing and deployment of c-viss (cetacean-borne video camera and integrated sensor system) on wild dolphins," *Marine Biology*, vol. 164, no. 3, p. 42, 2017.

[18] V. Gikas and H. Perakis, "Rigorous performance evaluation of smartphone gnss/imu sensors for its applications," *Sensors*, vol. 16, no. 8, p. 1240, 2016.

[19] Google, "Sensors overview," https://developer.android.com/guide/topics/sensors/sensors_overview.html, [Online; accessed 11-October-2017].

[20] F. E. Zajac and J. M. Winters, "Modeling musculoskeletal movement systems: joint and body segmental dynamics, musculoskeletal actuation, and neuromuscular control," *Multiple muscle systems: Biomechanics and movement organization*, vol. 8, pp. 121–148, 1990.

[21] F. E. Zajac, R. R. Neptune, and S. A. Kautz, "Biomechanics and muscle coordination of human walking: Part i: Introduction to concepts, power transfer, dynamics and simulations," *Gait & posture*, vol. 16, no. 3, pp. 215–232, 2002.

[22] ——, "Biomechanics and muscle coordination of human walking: part ii: lessons from dynamical simulations and clinical implications," *Gait & posture*, vol. 17, no. 1, pp. 1–17, 2003.

[23] A. Patel and M. Braae, "Rapid turning at high-speed: Inspirations from the cheetah's tail," in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*. IEEE, 2013, pp. 5506–5511.

[24] GOPRO, "Hero session," https://shop.gopro.com/EMEA/cameras/hero-session/CHDHS-104-master.html, [Online; accessed 10-October-2017].

[25] SONY, "Xperia z3 compact," https://www.sonymobile.com/za/products/phones/xperia-z3-compact/, [Online; accessed 10-October-2017].

[26] ACTIONMOUNTS, "Chest mount," http://action-mount.com/products/chest-mount/, [Online; accessed 10-October-2017].

[27] GOPRO, "Gopro chesty (chest harness)," https://shop.gopro.com/EMEA/mounts/chesty-chest-harness/GCHM30-001.html, [Online; accessed 6-October-2017].

[28] M. Christensen, "Gopro hero4 session," https://grabcad.com/library/gopro-hero4-session-1, [Online; accessed 6-October-2017].

[29] R. I. Hartley and A. Zisserman, *Multiple View Geometry in Computer Vision*, 2nd ed. Cambridge University Press, ISBN: 0521540518, 2004.

[30] T. L. Hedrick, "Software techniques for two-and three-dimensional kinematic measurements of biological and biomimetic systems," *Bioinspiration & biomimetics*, vol. 3, no. 3, p. 034001, 2008.