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ERROR ANALYSIS IN MARKER-BASED MOTION CAPTURE SYSTEMS

By

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Committee Approval

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My deepest gratitude goes to my parents for supporting me spiritually and financially throughout my life.

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ABSTRACT

One of the most significant and primary parts in the design of exoskeletons and kinematic models of the human body is to obtain a reliable set of data. In mechanical and measurement engineering, there are multiple systems to capture human motion, such as; Leap^{TM} Motion, Data gloves, Motion trackers, and Motion capture systems. One of the most effective systems to capture data is the Vicon^{TM} Motion Capture System. In the process of capturing data, extraneous and unwanted factors present themselves and must be identifiable, measurable, and quantifiable in order to be eliminated via error analysis to achieve the most effective and precise datasets. The present research seeks to determine and measure the effect of extraneous factors via experimental work in the laboratory with regards to the Vicon^{TM} Motion Capture System. The research presents an explanation of the process utilized in this study in quantifying the impact of the extraneous factors on the Vicon Motion Capture System™ output datasets.

Keywords: Motion capture systems; Rigid body motion; Error analysis; Accuracy error; Precision error; Range of error; Error values

CHAPTER ONE – INTRODUCTION

1.1 INTRODUCTION

A variety of different systems introduced and used to capture the motion of the human body in the last decade such as; contact systems (i.e. Data Glove (5DT)[2]), non-contact systems (i.e. RGB-D Cameras (RGB-D)[9]), and marker-based infrared cameras (i.e.Vicon Motion Capture System[6]). Each system offers varying advantageous and disadvantageous of capturing exoskeleton and kinematic data-sets as they differ in the type of movement they measure.

1.2 THESIS GOAL

The primary goal of this study is to identify, and quantify extraneous factors, more specifically, with the intent of minimizing the error of output data. This study seeks to eliminate the impact of extraneous factors on achieving an error-free and effective output from the Vicon Motion Capture System. The reliable set of data is to be obtained with an experienced way of capturing a valid range of data and that induces the process of the design of the kinematic model of the human body, therefore, minimization of error and error-free outputs are important not only in achieving effective designs but also for future advancements in motion capturing.

Capturing effective data pertaining to exoskeleton and kinematic modeling relies on numerous factors such as; physical positioning of the motion camera system, speed of the subject's movement or motion, the optimization of the capture volume, size of the markers under review, as well as the system selected to measure motion. The impact of these extraneous factors varies on a case by case basis. The effective output for error elimination is specifically tied to the subject's motion and not simply the motion.

The research proves that effective data outputs must also identify the source from which each extraneous factor derives in order to offset its' impact on the output. Eventually, the idea of the error combination has been applied to these data to demonstrate the biggest impact of them on each data sets.

1.3 Organization of this thesis

The thesis is organized as follows:

- Chapter 1: Presents organization, methods, and hypothesis
- Chapter 2: Literature review
- Chapter 3: Vicon motion capture system™ and software which is Nexus 2.6.1 and it is more of a handy introduction about how to get the system to work and capture data within a step by step explanation.
- Chapter 4: presents the experimental work and quantify the elemental error components values.
- Chapter 5: Demonstrates the result and also the combination of all elemental errors.
- Chapter 6: Presents the summary, conclusion and the future scope of this research.

CHAPTER TWO - LITERATURE REVIEW

2.1 DEFINING THE PROBLEM

There are so many different ways to capture the kinematic of the human joints that can be explained by measuring the movement of rigid bodies attached to it. One of the most common way is using a set of infrared cameras that circulate around the subject and capture the motion [3], but it is obvious that there is no quantity that can be measured with a perfect certainty, therefore it is necessary to figure out how accurate and precise the measurements are. Experimental error is measured by its accuracy and precision. The difference between the accuracy of the data and their precision, provides a better grasp over the concept. The accuracy measures how close a measured value is to true the value while the precision is about how closely two or more measurements agree with each other.

2.2 SEARCHING FOR THE SOLUTIONS

As it is known, Augmented Reality (AR) has been developed to have enhanced views of the environment. AR systems in general have a display and a motion tracker which is associated with software. A registration is needed to match the geometry of the virtual camera where the augmentation takes place with the real world. The performance of AR systems depend highly on the performance of marker detection, decoding, and pose estimation. In the AR applications, the square shaped vision markers are the most commonly used ones, reason of which is that a square shape provides at least four co-planar corresponding points so that the camera calibration can be carried out with a single marker in the scene [1].

Zhang et al (2002) have evaluated usability, efficiency, accuracy, and reliability in four marker tracking system quantitatively and qualitatively. Figure 2.1 shows the setup which was used for their marker recognizability experiment.

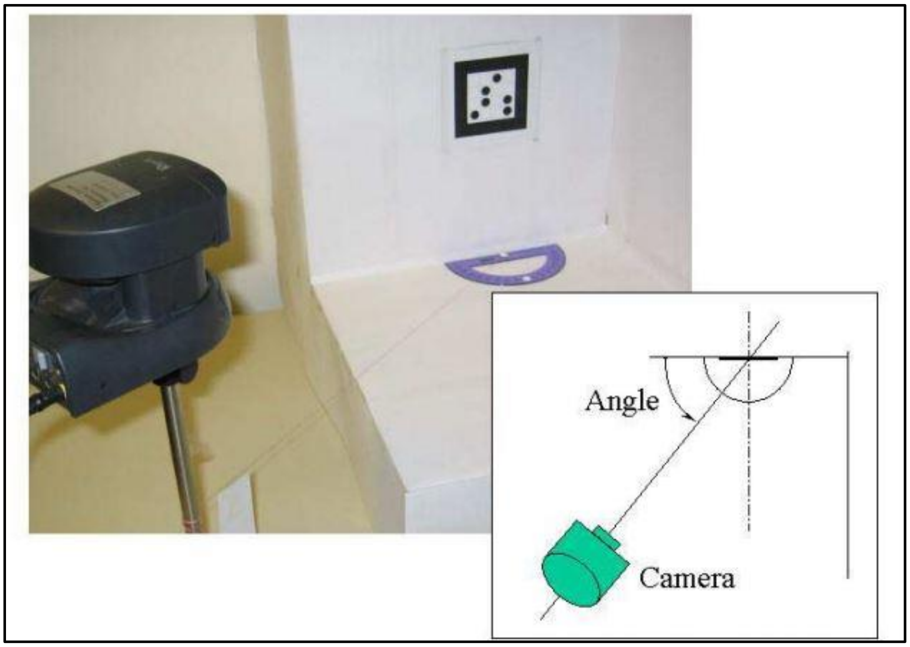


Figure 2.1. Setup for recording videos with different projective distortion [1]

Kuroda et al. (2004) have presented a glove named StrinGlove which used 24 inductocoders and nine sensor were supposed to help recognize body language in the 5th International conference of disability, virtual reality and associated technology which was held in Oxford, U.K. [2]. The glove has a system which includes a gloce shaped device, a computer, and a certain algorithm to translate subject's movements into virtual reality or vice versa. The glove and an overview of its system are demonstrated in Figure 2.2 and Figure 2.3 respectively.

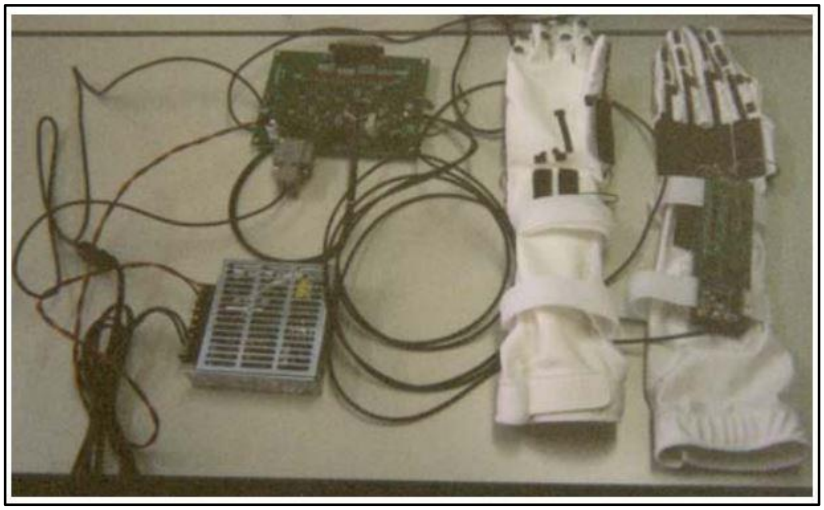


Figure 2.2. Prototype of StrinGlove [2]

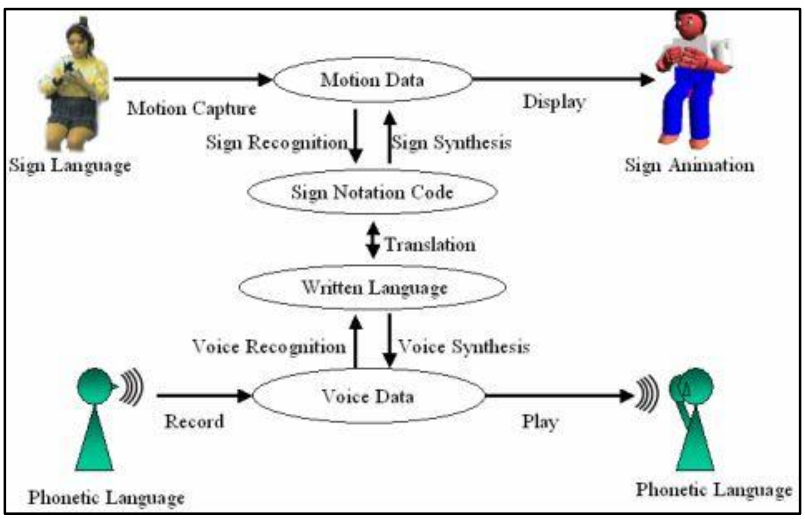


Figure 2.3. General Overview of sign information system [2]

Xu et al. (2012) have worked on a real-time dynamic gesture recognition system based on depth perception for robot navigation. They proposed a new start/end point detection method in which Hidden Markov Models (HMMs) are implemented and its object is to control and convert commands for interactions of the user with the robot. This method's 98.4% recognition rate in complex situations has determined this very effective. The other method uses Dynamic Time Warping (DTW) algorithm to classify gestures. A simple comparison has been done between these two methods and the result is shown in Figure 2.4. Table 2.1 shows the statistics of experimental results for right hand gestures with HMMs modelling and classifying [3].

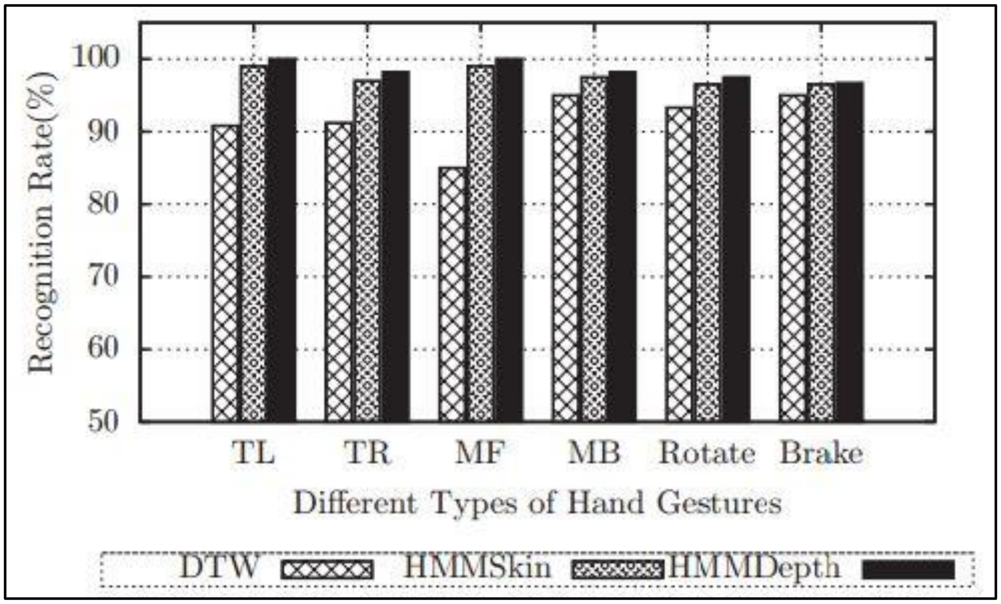


Figure 2.4. The comparison of three different dynamic hand gesture recognition algorithms for six hand gestures. The DTW, HMM Skin and HMM Depth represent the DTW algorithm, the HMMs based the 2D hand tracking using skin color segmentation and the HMMs based the 3D hand tracking using depth perception, respectively. And "TL", "TR", "MF" and"MB" denote the hand gestures "Turn Left", "Turn Right", "Move Forward" and "Move Back", respectively [3]

Table 2.1. The statistics of experimental results for right hand gestures with HMMs modeling and classifying [3]

Gesture Label	#Train	#Test	#Missing	#Accuracy	Recognition Rate(%)
Turn Right	60	112	2	110	98.2%
Turn Left	60	110	0	110	100%
MF	60	111	0	111	100%
MB	60	110	2	108	98.2%
Rotate	80	120	3	118	97.5%
Brake	80	122	4	118	96.7%
Average Recognition Rate					98.4%

As it is obvious in the experiments results do not match the theoretical results 100% and from this, rises a concept called errors in measurements. These errors have different sources and an experimenter has to first find the source and deal with it and also try to minimize these errors so the experiment's results come closer to the reality. As Hoffman has expressed, an error is defined as the real value at the output of a measurement system minus ideal value at the input of a measurement system [4]:

$$\Delta x = x_r - x_i \tag{1}$$

where Δx is the error of measurement, x_r is the real untrue measurement value, and x_i is the ideal true measurement value. Figure 2.5 shows the measurement chain [4].

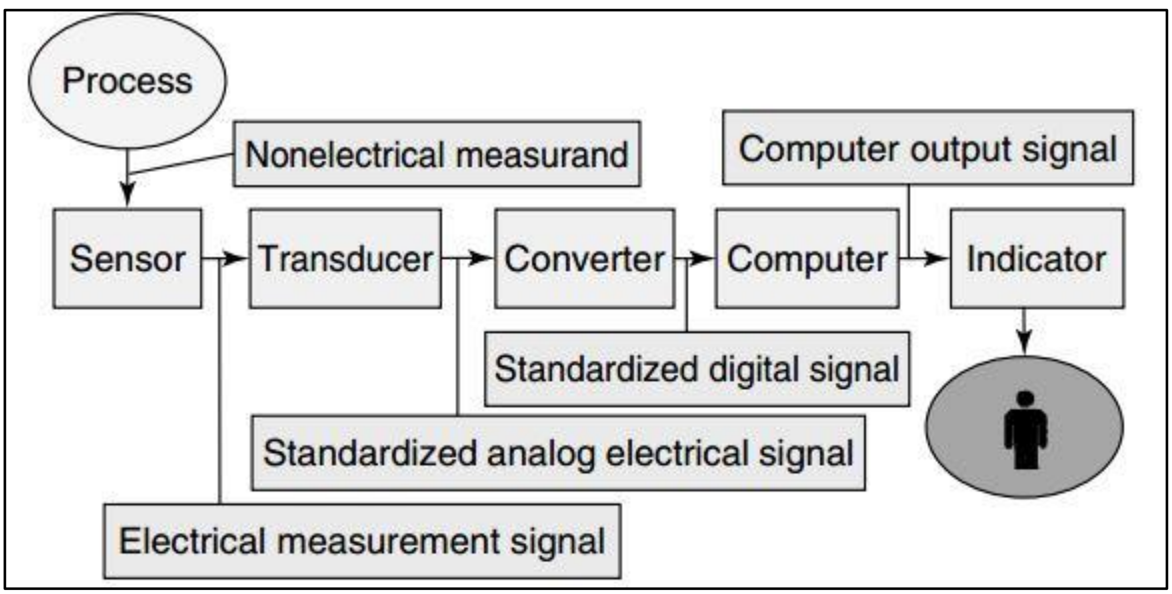


Figure 2.5. Measurement chain [4]

Kinematics of human joints are commonly described by measuring relative motion between two moving bones by applying a series of either passive or active markers to each bone in a fixed orientation to create a rigid body (RB) in vitro studies. Maletsky et al. (2007) have used Optotrak active-marker optical system and claim that the relative positions of the RBs with respect to the camera-viewing plane had a minimal effect on the kinematics and, therefore, for a given distance in the volume less than or close to the precalibrated camera distance, any motion was similarly reliable. For a typical operating set-up, a 10^o rotation showed a bias of 0.05^o and a 95% repeatability limit of 0.67^o. To achieve a high level of accuracy, it is important to keep the distance between the cameras and the markers near the distance the cameras are focused to during calibration. Figure 2.6 shows the set-up which was used for their experiment [5].

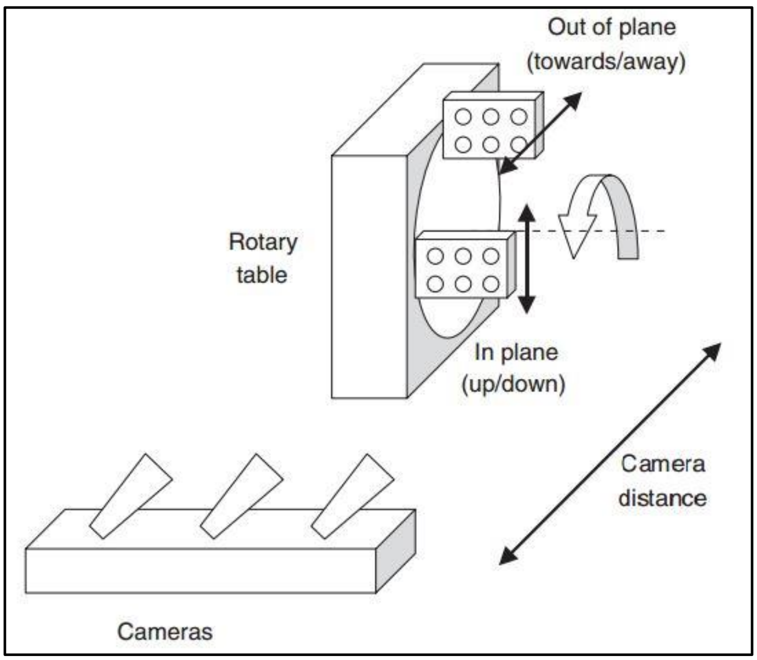


Figure 2.6. Optotrak system set-up [5]

Most of the human body joints cannot be accurately modelled as lower kinematic joints. For this reason, the location of the instantaneous screw axis (ISA) is fundamental in order to generate a kinematic model of the human body which is able to reproduce its movement with the degree of accuracy needed in applications such as prostheses and orthoses design or in diagnosis techniques. Page et al. (2007) used dual vectors to represent and operate with kinematic screws with purpose of locating the ISA which characterized this instantaneous motion. They also utilized a marker based photogrammetry system to obtain the experimental data from which the kinematic magnitude will be obtained. A new method to calculate errors was developed in their research which could obtain expressions of the kinematic parameters and the experimental errors in its determination by using photogrammetry techniques. The previous methods which estimated errors based on an isotropic distribution of markers and which were unfeasible in realistic studies, are obsolete compared to the developed method by Page et al. (2007) which was marker location independent. Figure 2.7 shows marker distribution on a subject to use its data for developing their method [6].

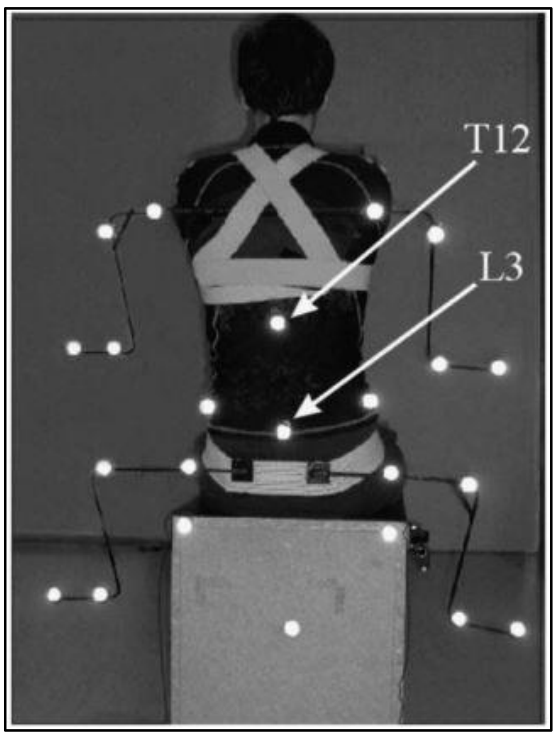


Figure 2.7. Location of markers in thorax, pelvis and seat [6]

Wang et al. (2008) have proposed a new method in AR which helped a lot with solving the issue which old methods had. The issue while constructing an AR system is how to amalgamate the virtual objects and the real environment accurately. They utilized an infrared projector to projects markers which were invisible to the human-eye onto the surface of the equipment. These markers, yet were detectable by the infrared camera. The system's viewpoint could be calculated and the visible image was captured simultaneously when using such a camera system. Figure 2.8 shows the flowchart of the proposed system. From Figure 2.9 it is also seen that the average error of each component of the translation matrix T is round 1%, while the average estimated error of Z component is round 0.24% which is even smaller [7].

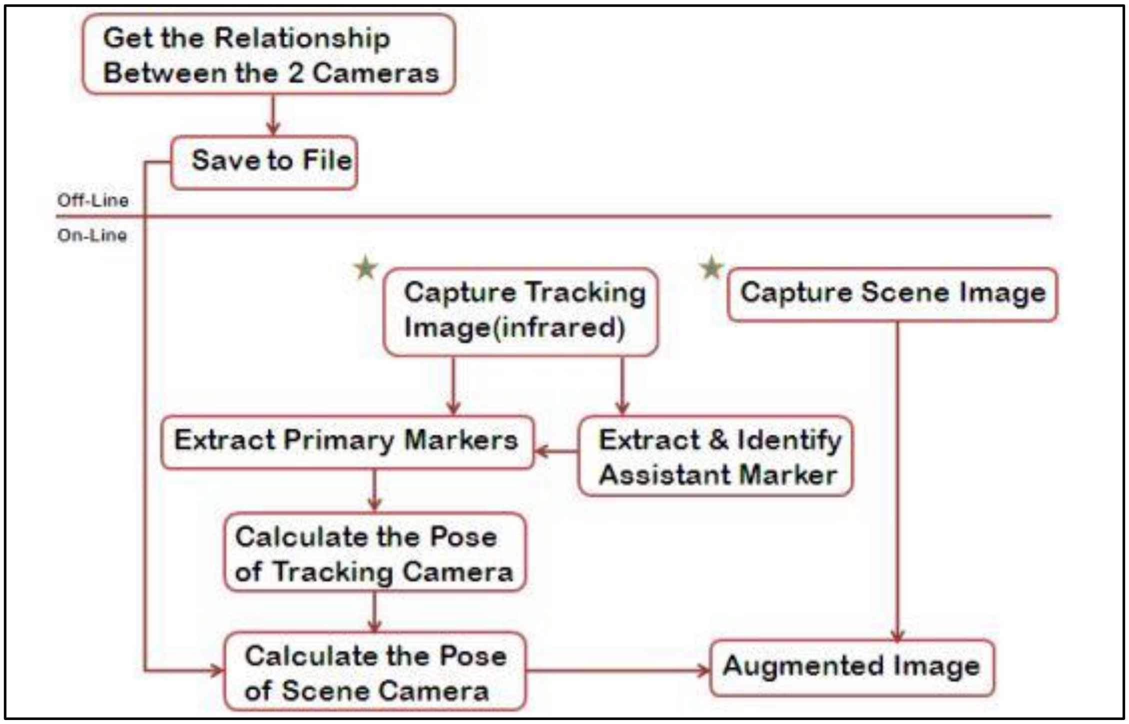


Figure 2.8. Flowchart of the proposed system [7]

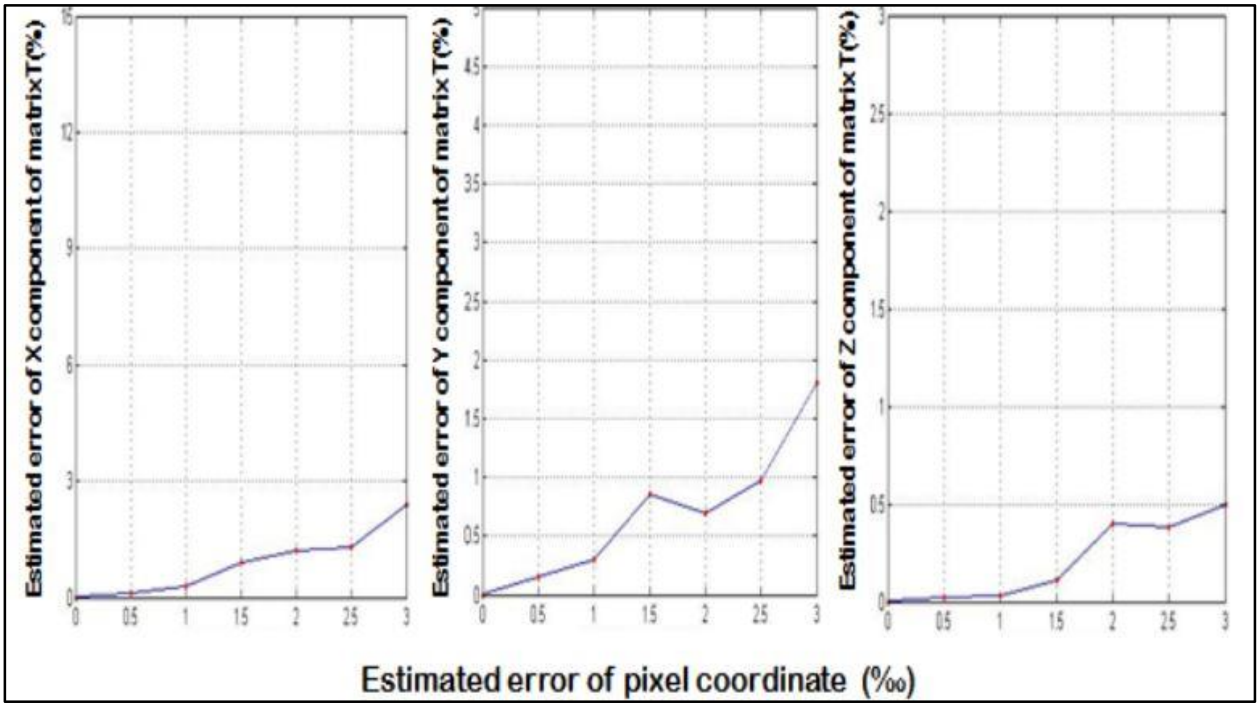


Figure 2.9. Estimated error of pixle coordinate [7]

Another accomplishment of Wang et al.'s research was the sustainability of the norm of rotation matrix R with increasing the estimated error of pixel coordinate which is shown in Figure 2.10.

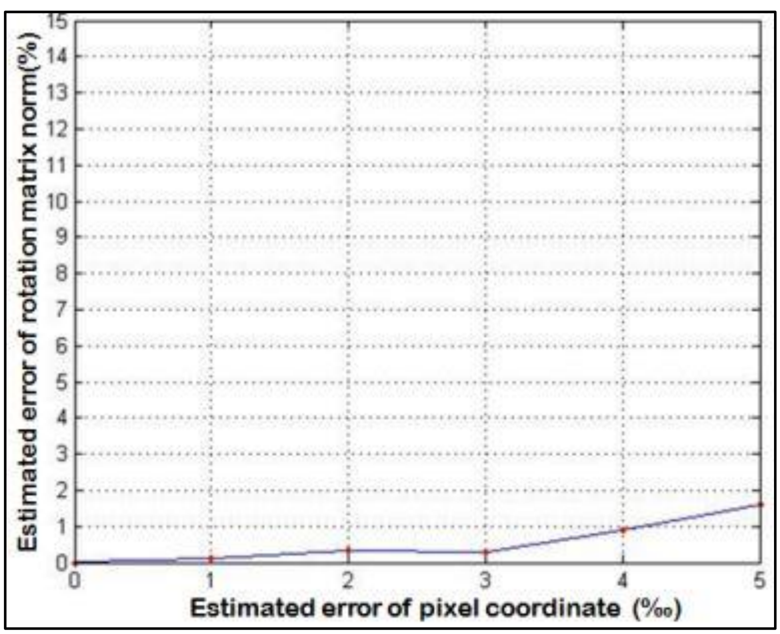


Figure 2.10. Sustainability of the norm of rotation matrix R [7]

Schmidt et al. (2009) have worked on Optotrak optical motion tracking systems and has showed that the distance between the camera systems and the rigid body, as well as the tilt angle of the rigid body, did affect the resulting precision, repeatability and accuracy of the camera systems. Their study was to evaluate the limitations of three- dimensional motion tracking systems in order to understand the validity of the results achieved through their use. The set-up they used can be seen in Figure 2.11. They have showed that all Optotrak camera systems tested in their study produced precision, repeatability and accuracy appropriate for use in large- and small- scale studies. One limiting factor for the near-focus camera system would be the measurement volume, since there was a significant decrease in precision when operated outside the recommended 3.0 m range. In addition, all Optotrak systems would be appropriate for use in micron-level experiments, although additional considerations should be taken to ensure the best possible results [8].

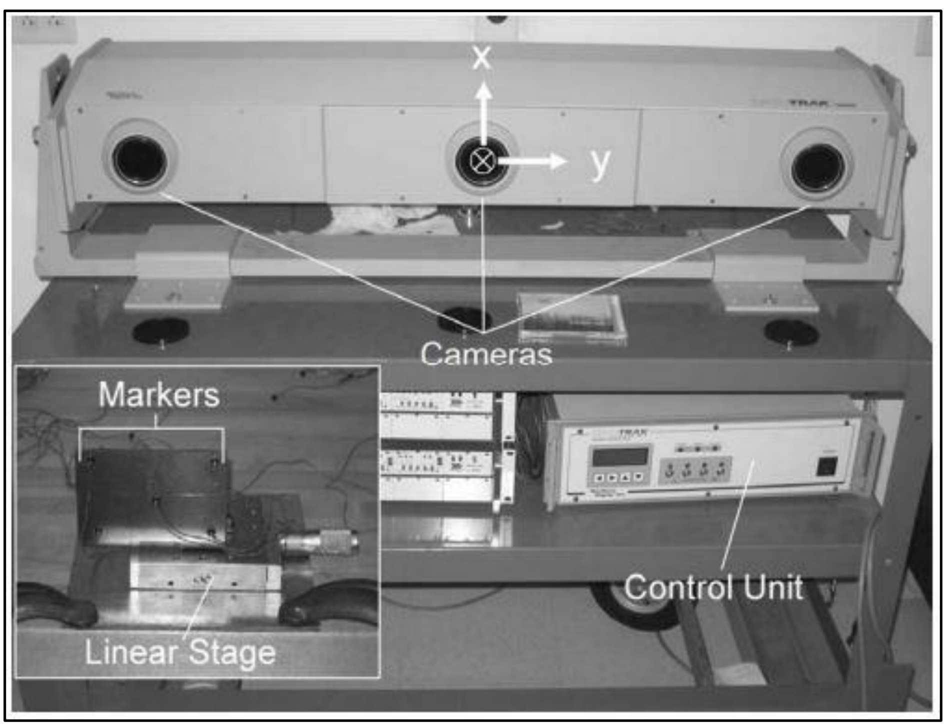


Figure 2.11. Experiment set-up [8]

Staranowicz et al. (20015) presented a novel RGB-D camera-calibration algorithm which is easy to use and can be utilized with any arrangement of RGB and depth sensors, for the estimation of the full set of intrinsic and extrinsic parameters. Their method only requires that a spherical object is moved in front of the camera for a few seconds. Their calibration method uses all the frames of the detected sphere and leverages novel analytical results on the multi-view projection of spheres to accurately estimate all the calibration parameters. The flowchart of their proposed method is shown in Figure 2.12. Also other calibration methods that had been developed since the time they published their paper can be seen in Table 2.2. A comparison between the set-up which other methods use and the one Staranowicz et al. use is also demonstrated in Figure 2.13 [9].

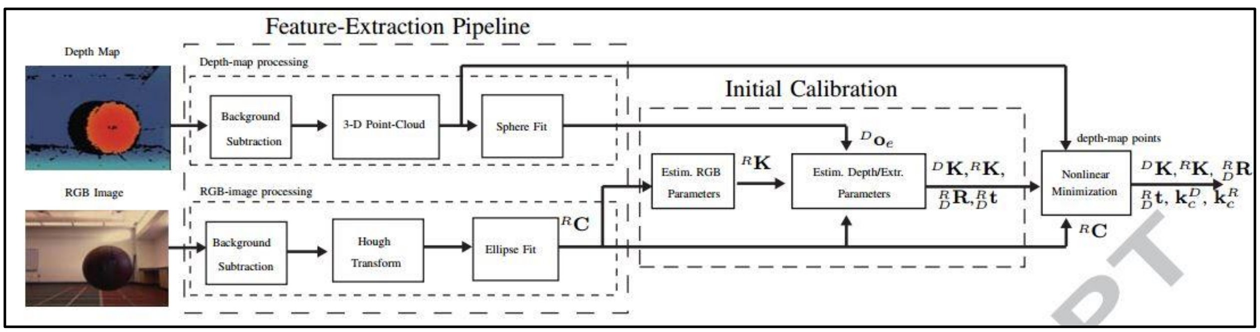


Figure 2.12. Work-flow diagram of the RGB-D camera-calibration algorithm [9]

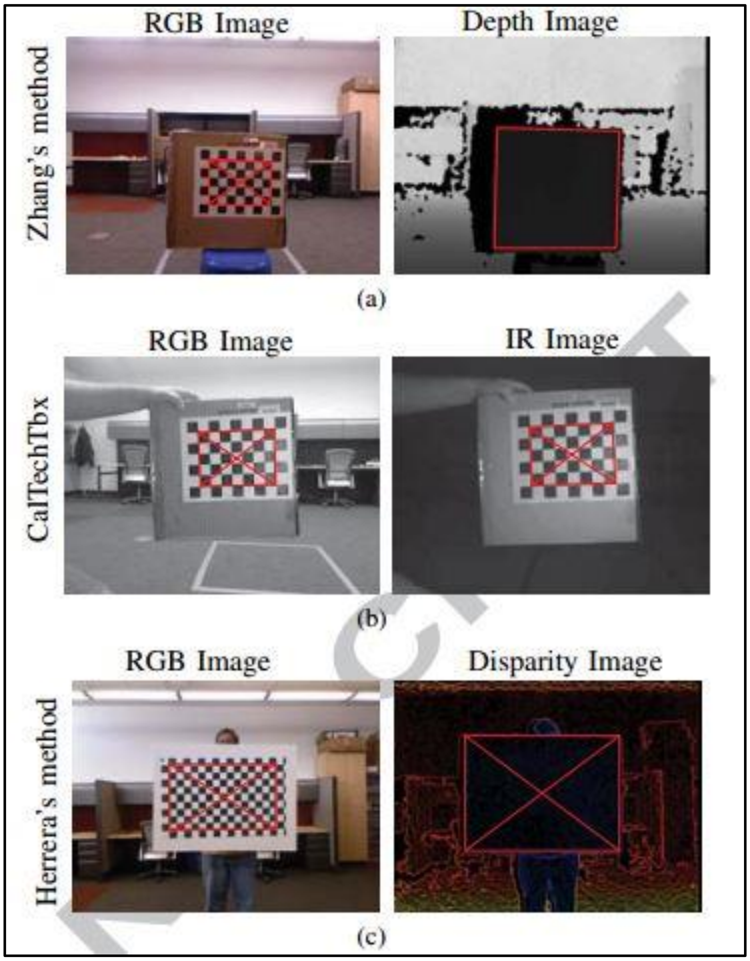


Figure 2.13. Feature extraction: (a) Zhang's Method (RGB + Depth); (b) ROSCalTbx. and CalTechTbx. (RGB + IR); (c) Herrera's Method (RGB + Disparity [9]

Table 2.2 Main features of the existing calibration methods for kinect-like sensors, listed in chronological order [9]

Method	Calibration object(s)	Parameters estimated	Correction of depth distortion	Typology of sensors	Toolbox developed (Matlab)
Zhang *et al.*	Planar surf., checkerboard	Ext./Int. (D)	No	Kinect	–
Jung *et al.*	Custom Planar surf.	Ext./Int. (D)	No	Any RGB-D pair	–
Burrus /ROSCalTbx	Checkerboard	Ext./Int. (D)	No	Kinect	–
Khoshelham *et al.*	Planar surf., checkerboard	Ext./Int. (RGB, D)	Yes	Kinect	–
Herrera *et al.*	Planar surf., checkerboard	Ext./Int. (RGB, D)	Yes	Kinect	Kinect Calibration Tbx
Smíšek *et al.*	Checkerboard	Int. (RGB, D)	Yes	Kinect	–
Raposo *et al.*	Planar surf., checkerboard	Ext./Int. (RGB, D)	Yes	Kinect	–
Teichman *et al.*	Natural environment	Int. (D)	Yes	Any RGB-D pair	–
Mikhelson *et al.*	Checkerboard	Ext./Int. (D)	No	Any RGB-D pair	CalibRT Tbx
Basso *et al.*	Planar surf., checkerboard	Ext./Int. (D)	Yes	Any RGB-D pair	–
Our method	Sphere	Ext./Int. (RGB, D)	Yes	Any RGB-D pair	RGB-D Calibration Tbx

Quantitative gait analysis allows clinicians to assess the inherent gait variability over time which is a functional marker to aid in the diagnosis of disabilities or diseases. Gonz´alez et al. (20016) have compared passive vision-based system and a wearable inertial based system for estimating temporal gait parameters related to the GAITRITE electronic walkway. They have chosen two low-cost systems for quantitative gait analysis, a wearable inertial system that relies on two wireless acceleration sensors mounted on the ankles; and a passive vision-based system that externally estimates the measurements through a structured light sensor and 3D point-cloud processing. Both systems are compared with a reference clinical instrument using an experimental protocol focused on the feasibility of estimating temporal gait parameters over two groups of healthy adults (five elders and five young subjects) under controlled conditions. The vision-based system, which has been precisely detailed in their work, and the wearable system included in the comparison are proof that the design of technologies for QGA should be supported. The vision-based system is expected to be installed in an elderly home and adapted to provide long-term gait monitoring in future steps. Besides, the estimation of spatial parameters as step/stride length and walking speed is envisaged for both systems [10].

It has been shown that anatomical marker placement is the largest source of inter examiner variance in gait analyses. Osis et al.'s research addresses the disparities such as inter-examiner variance or other deviations by applying a simulation of marker placement deviations to a large (n = 411) database of runners; evaluating a recently published method of morphometric-based deviation detection; and pilot-testing a system of location-based feedback for marker placements. Median deviation in kinematic variables between Novice testers and the Expert trended towards zero in 7 of the 9 kinematic variables after feedback is given in Figure 2.14 in which, Bars indicate the signed median difference between the group of n = 6 Novices and the Expert, both before and after receiving feedback, and * indicates significant differences from the Signed Wilcoxon Rank test (family-wise $p < 0.05$) [11].

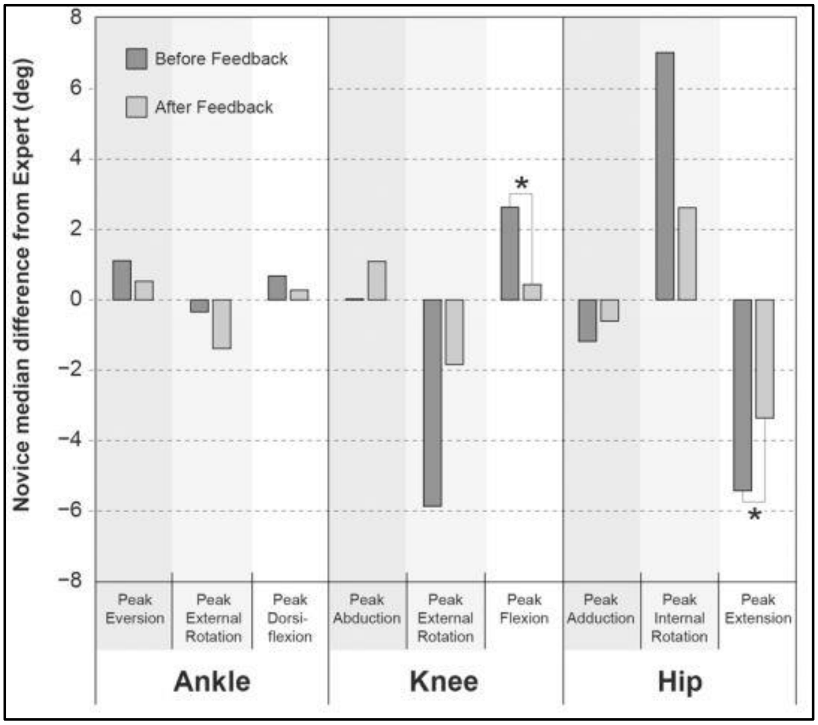


Figure 2.14. Results of the pilot study [11]

There is no study that focused on the optical motion capture and its accuracy in large volumes or how the accuracy of the measurements is different in the different spots of the workspace. Aurand et al. (2017) found the range of error for 97% of the capture volume areas are under 200 µm if 42 cameras triangulate to obtain data. They also repeated same experiment with only using half (21) of the cameras, and this time range of error for 91% of the capture volume area was below 200 µm(10^{-6}m) of error [2]. Figure 2.15 shows how they rounded 42 and 21 cameras in two different experiments respectively. As it is obvious, the areas that have less error in the first experiment with 42 cameras are less than the second experiment with 21 cameras [12].

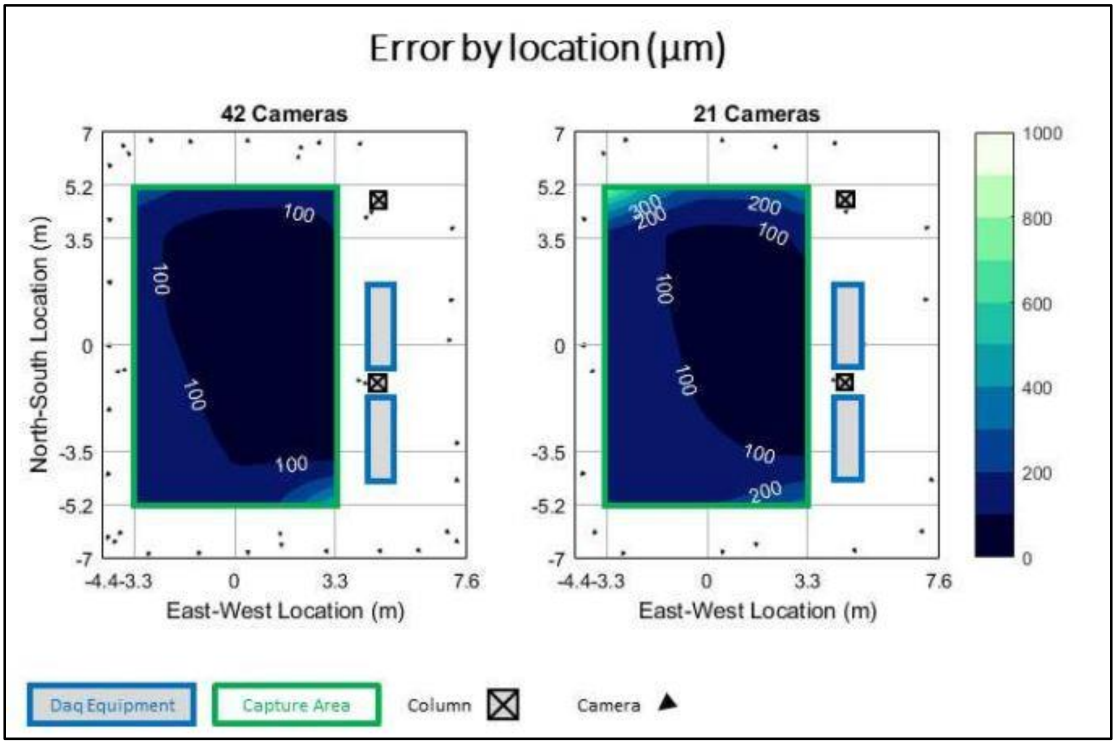


Figure 2.15. Error distribution in different area of the capturer volume [12]

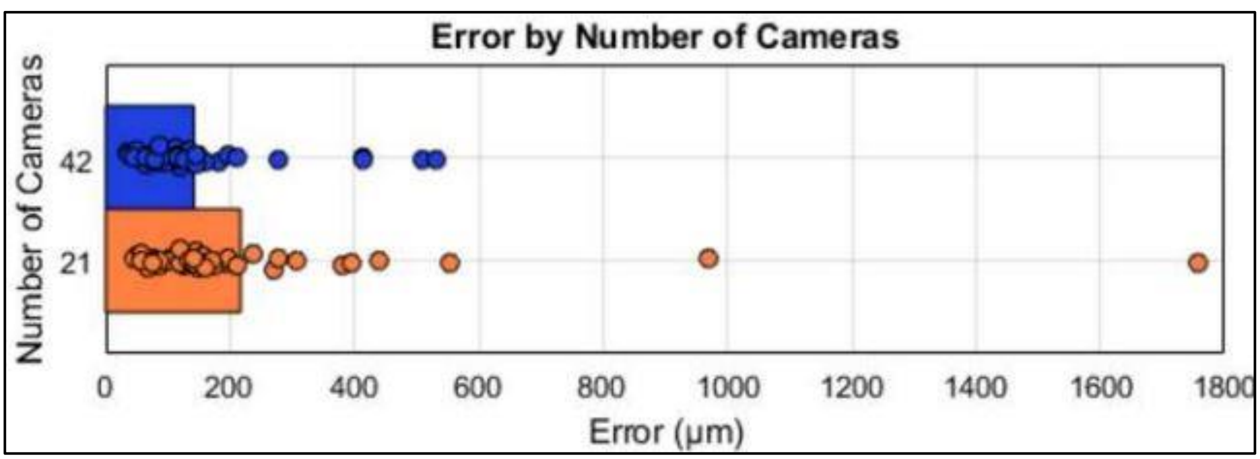


Figure 2.16. Error with respect to the number of the cameras [12]

Figure 2.16, demonstrates the error by number of the cameras and bars show the mean and each circle represent a capture. According to the author in 2017, the numbers of cameras do plays a significant role in terms of error reduction. The more cameras included in circuit, the less error output data might have [12,13].

Very few studies investigate the positioning performance of motion capture setups. Merriaux et al. (20017) have studied the positioning performance of one player in the optoelectronic motion capture based on markers which is the Vicon System™. They have introduced a new setup that enables directly estimating the absolute positioning accuracy for dynamic experiments contrary to state-of-the art works that rely on inter-marker distances. The system performs well on static experiments with a mean absolute error of 0.15 mm and a variability lower than 0.025 mm [13].

2.3 ADAPTING FOR THE FUTURE

Now the different subcategories of the systematic errors that can affect the accuracy and precision of the experimental data can be huge. There are different factors such as the different locations of the capture volume, number of cameras, and size of markers attached to the body, and distance of the markers to the center of the capture volume, speed of the motion and system calibration that might have a big impact on the precision of the data. There is no studies about the effect of motions' speed, non-rigidity of human body and error distribution in different area of capture volume by using eight infrared cameras, therefore it has been tried to concentrates on these areas of uncertainty and their impact on the precision of data obtained from Vicon motion capture system™.

CHAPTER THREE – INTRODUCTION TO VICON MOTION CAPTURE SYSTEM™ AND NEXUS

3.1 INTRODUCTION

As previously mentioned, the Vicon Motion Capture system™ has been used in the laboratory to obtain data. In this chapter, a detailed glossary is provided about both the system (Vicon Motion Capture) and software (Nexus2.6.1) which can come to handy for new users who are interested in working with the system and learn it.

All the steps need to be done before running the system and obtaining data have been explained pretty straightforward along with figures to makes it easier to understand. There are different systems of motion capture and the focus of this chapter is on the Vicon motion capture system™ at Idaho State University motion capture laboratory. This information makes the job easier for the future users so that they can get to know how to work with the system and software faster and provides a better grasp for the readers over this study as we go further in the following chapters.

3.2 SYSTEM COMPONENTS AND THE SOFTWARE

Figure 3.1 shows all systems' components and how they are connected with each other.

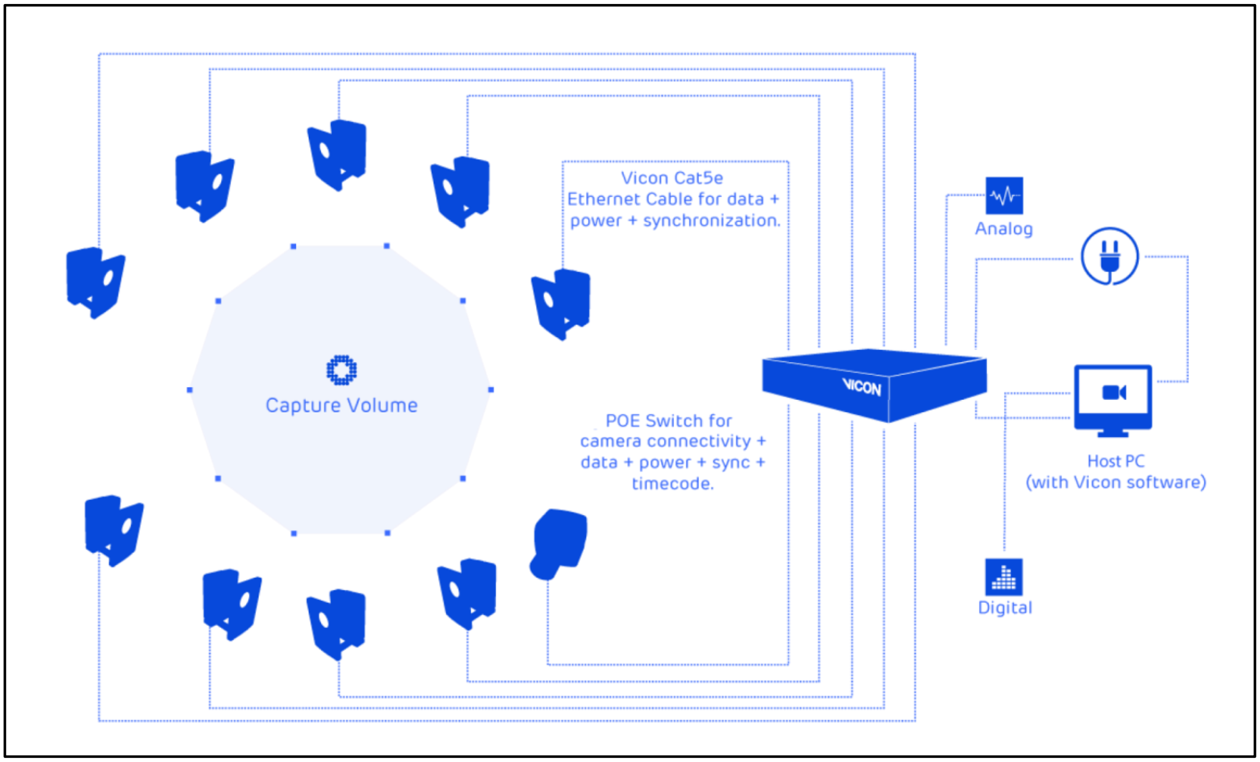


Figure 3.1. System and its components

The Vicon Motion Capture System™ in the motion capture laboratory consists of four major parts. A set of eight infrared cameras, a calibration wand and the lock box. Figure 3.2 to 3.5 not only shows the system components but also demonstrates the connections between these parts.

Figure 3.2. Bonita cameras

Figure 3.3. Calibration wand

Figure 3.4. Lock box connection to power box and cameras

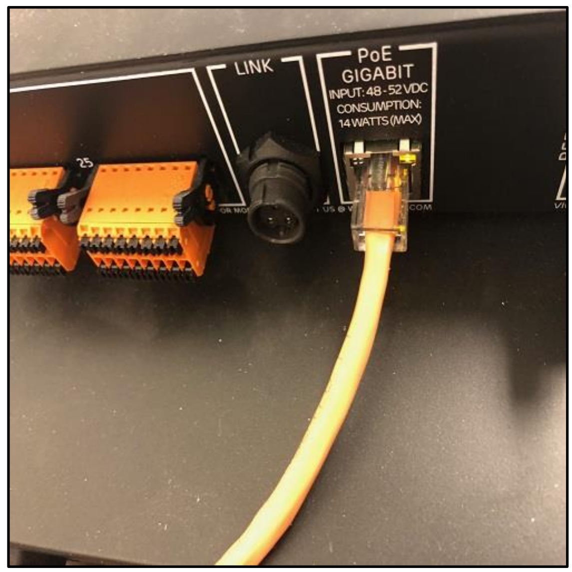


Figure 3.5. Power box connection to the lock box

As the figures shows, the set of cameras connect to the D-Link power supply through eight LAN cables. Then the power supply itself connects to the lock box and the PC through two different LAN cables.

3.3 PC SETUP FOR THE SYSTEM

Once everything is connected as it is shown above, network configuration settings and connecting network ports has to be done so that the PC and software identify the system.

3.3.1 PORT CONFIGURATION

In order to enable the Bonita cameras talk with each other and communicate with the Vicon lock box and software, the advanced adaptor setting should be configured correctly. To do that, different steps should be followed.

1. Open the network connection window by double click on it.
2. Open the properties for the first network port by right click on it and the following window should appear, Figure 3.6.

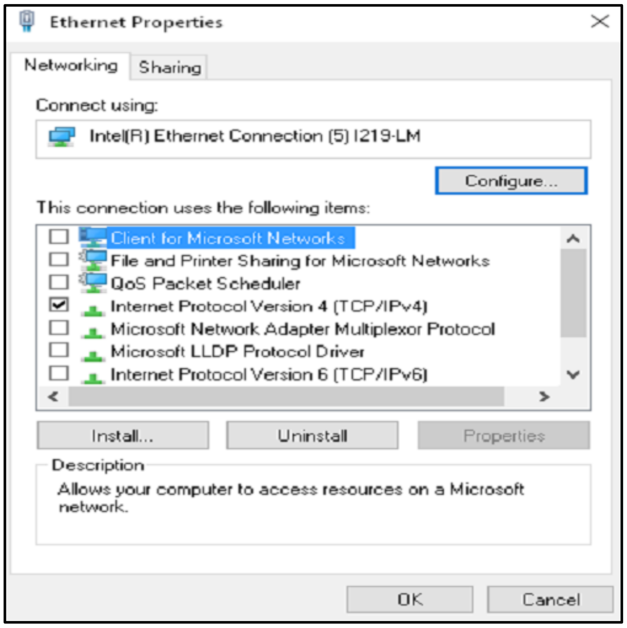


Figure 3.6. Properties dialog box

3. In the properties dialog box the configuration button should be selected, Figure 3.7.

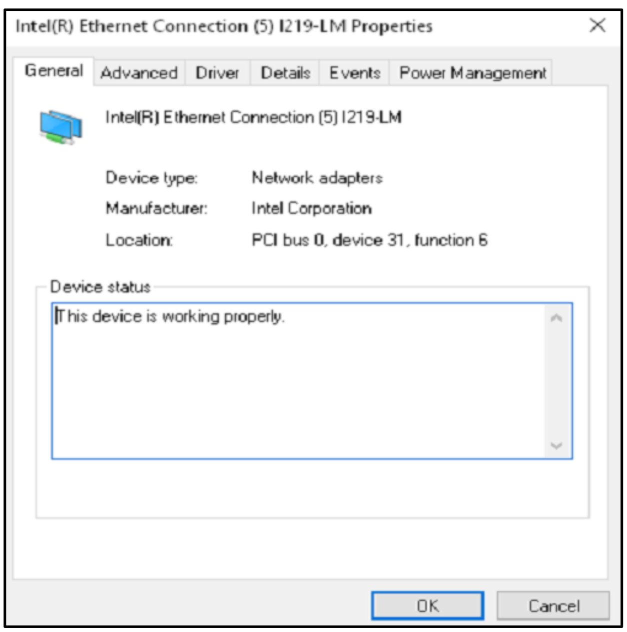


Figure 3.7. Ethernet connection properties

4. Once this window appeared, click on advanced button.

5. From the advanced window, different settings should be configured including:

A. Interrupt moderation should be disabled as it is shown in the following figure. The interrupt moderation choice should be selected in the property list and then disabled through the value option in front of it, Figure 3.8.

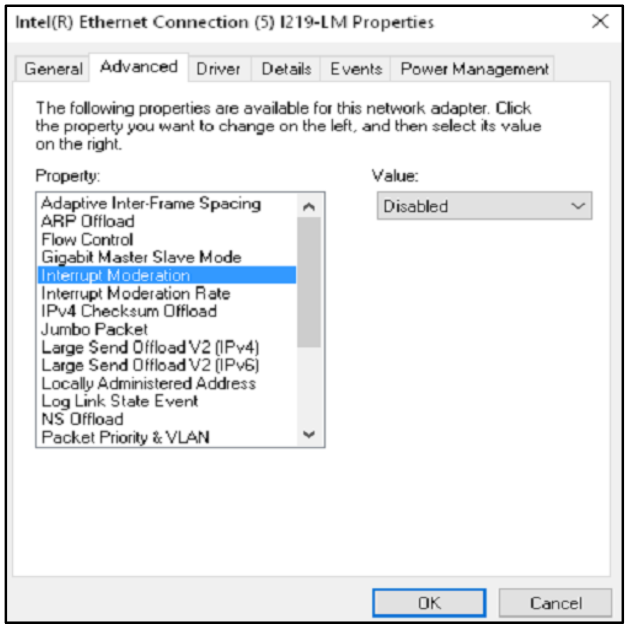


Figure 3.8. Disabling interrupt moderation

B. Change the value of Jumbo Packet from the property list to 9014 Bytes, Figure 3.9.

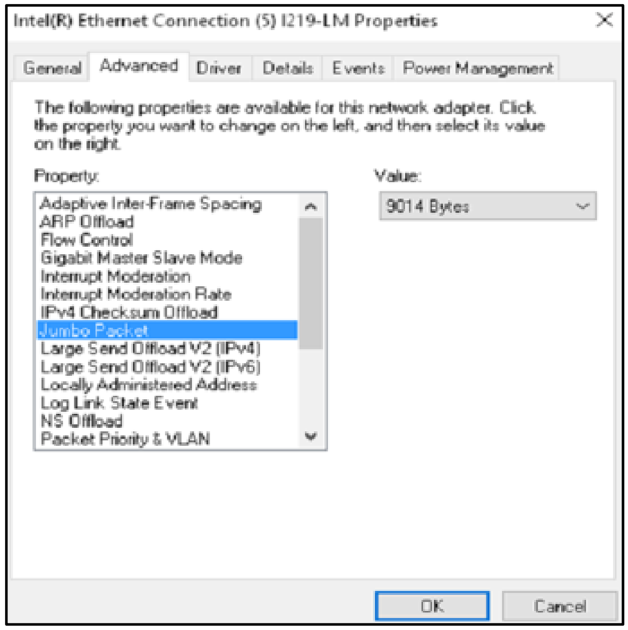


Figure 3.9. Jumbo Packet in maximum value

C. Click on the receive buffers in the property list and select the maximum possible value of 2048, Figure 3.10.

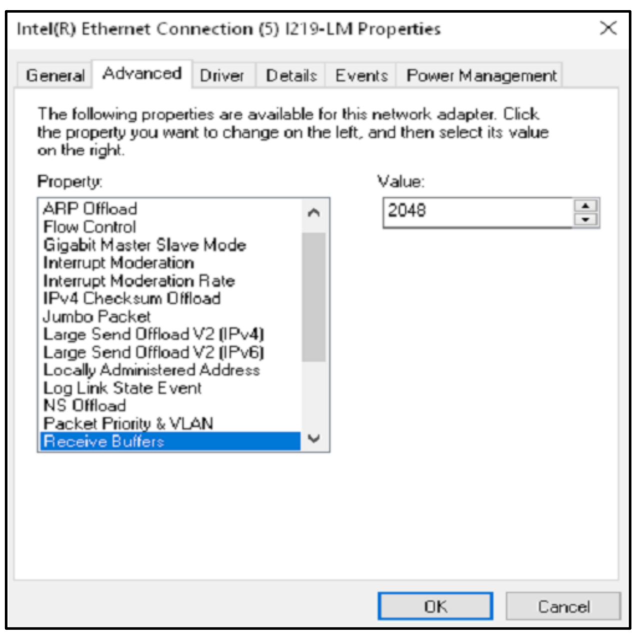


Figure 3.10. Maximize receive buffers

D. Enable receive side scaling first and then for the receive scale side queues, pick the maximum value of 8 Queues. Figure 3.11 and 3.12 demonstrates the process respectively.

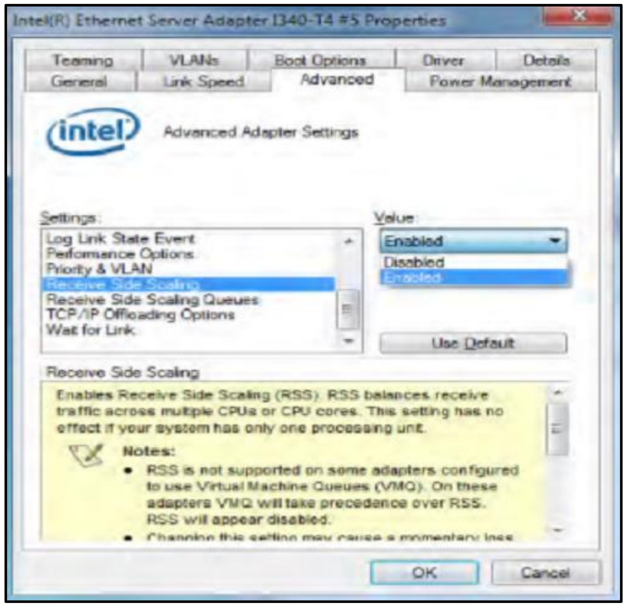


Figure 3.11. Enabling receive side scaling

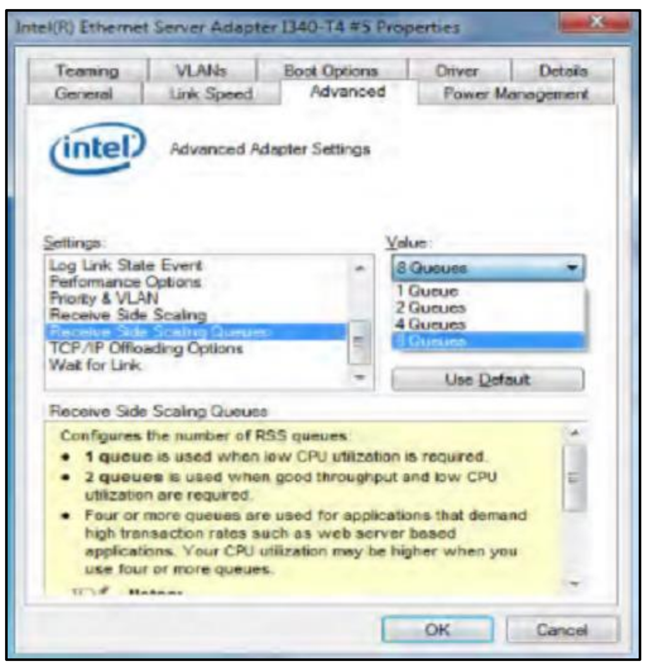


Figure 3.12. Maximize receive side scaling queues

E. Finally, simply click OK to update all the changes.

3.3.2 ASSIGNING IP ADDRESS TO THE PORT

To assign an IP address to the port, open the network and sharing center window again and right click on the port that has been just created and then select property. Clear and unmark all items except the Internet Protocol Version (TCP/IPv4), Figure 3.13.

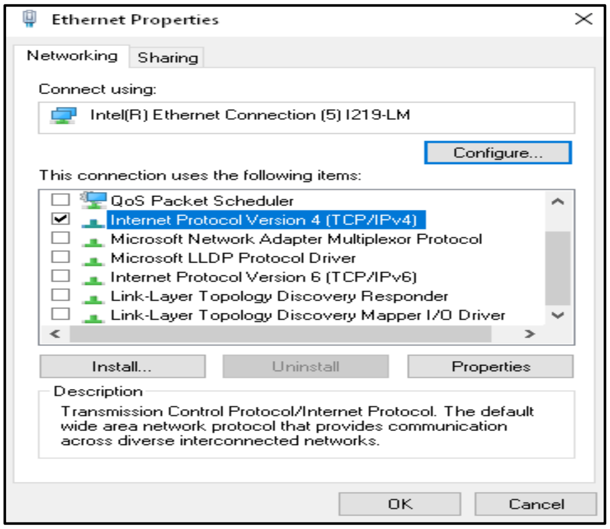


Figure 3.13. Mark the 4 (TCP/IPv4) and unmark all others

After that, click on the properties and then use the same IP addresses and then click OK, Figure 3.14.

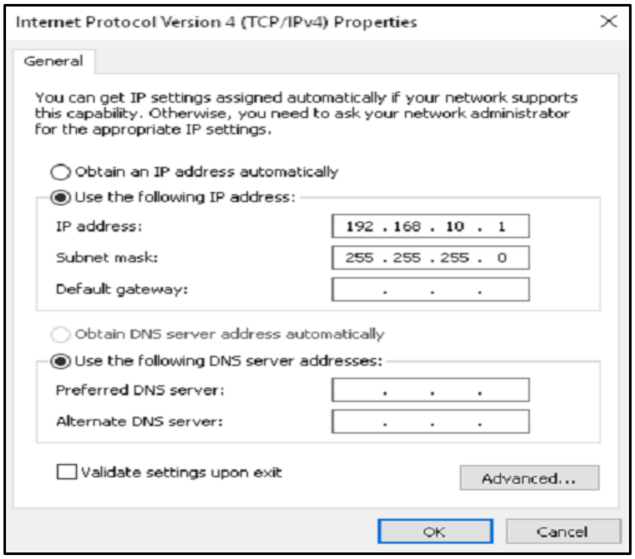


Figure 3.14. Assign IP addresses

3.4 SOFTWARE

3.4.1 SOFTWARE INSTALLATION

To run the software, the following steps should be taken.

A. Launch the Vicon core page at https://www.vicon.com/downloads/core-software, and download nexus 2.6.1 software installer.

B. Search in the browser for the folder that has been used to save the software installer file and double click on it to run.

C. Note that, if you already have the older version of the software installed, it is better to contact Vicon support team for the advice.

3.4.2 LICENSING

Complete information about licensing is provided at www.vicon.com/faqs/licensing. To revoke the license, it is better to contact the Vicon support team.

3.4.3 SOFTWARE

Next step is to get to know how to work in software environment. Since Nexus may not be a user friendly software to everyone, all the steps to obtain data has been explained as follow. There are different steps need to be taken, respecting the order.

A. Run the software and make sure that all the cameras are in green state while the software is in online mode.

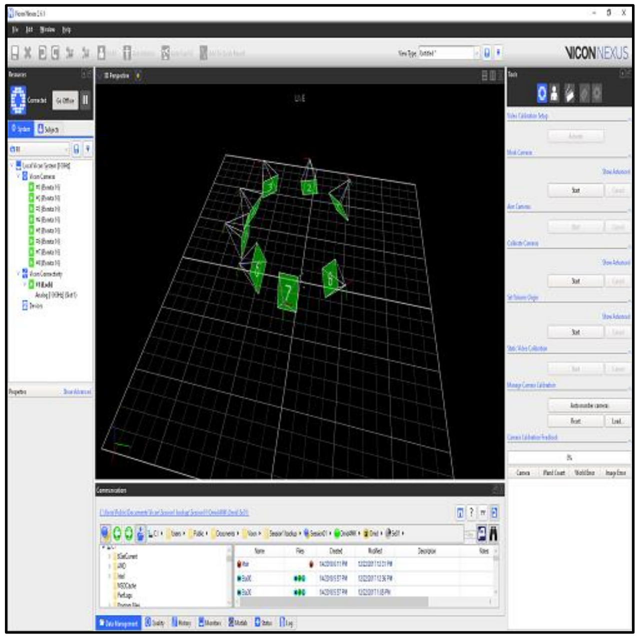


Figure 3.15. Cameras in green state

Figure 3.15 shows how all the cameras should turn green at the beginning. For some reasons, the cameras may appear in red, which means the system is not ready to capture. It is good to double check the connection of the cameras to the system and if the problem is still there, it is also a good option to close the software and run it again or even restart the PC.

B. Once all the cameras are in green mode, it is time to prepare the system for aiming.

3.4.4 AIMING

To do the aiming, there is a tab on the top right hand side of the window and that should use to aim the cameras.

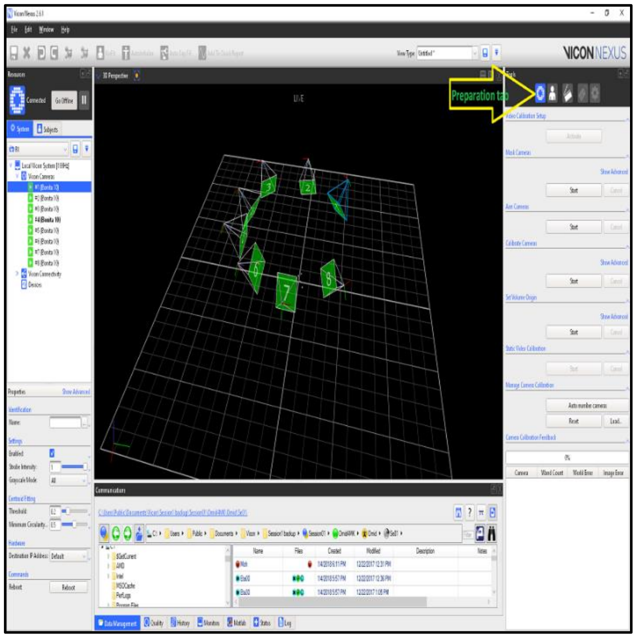


Figure 3.16. Preparation tab

Figure 3.16 demonstrates where the preparation tab is located. After clicking on this tab, all the cameras should be aimed one by one. To do so, the 3D perspective view should change to the camera view and there is a tab for that purpose.

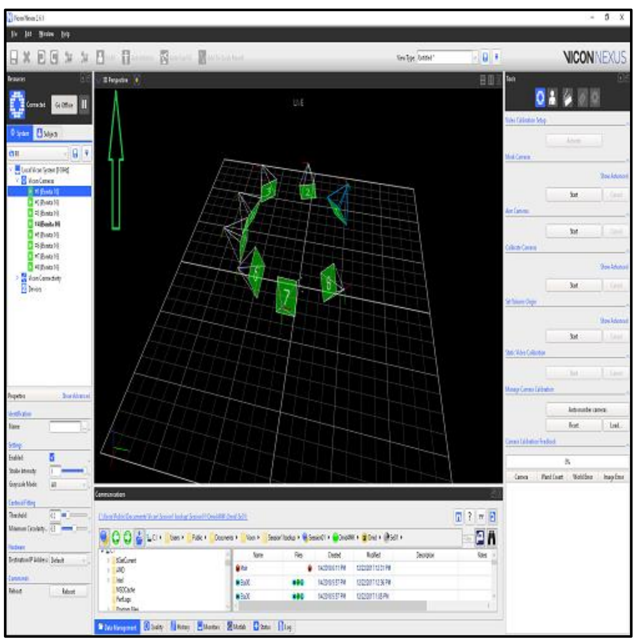


Figure 3.17. Changing Tab

The button to switch from 3D perspective or 3D orthogonal to camera view is located in the software, see Figure 3.17.

Next, the calibration wand should be placed in the middle of the capture volume so that the cameras can be aimed based on the markers sitting on the calibration wand. There are three different screws on the head of each of them to aim:

1. The first screw, closest to the head of the camera, is the focus screw which enables the system to focus on the objects at different distances and goes from infinity to near (∞ to N).
2. Aperture screw is the middle screw that goes from open to close (O to C). Open means more light into the cameras whereas close means there is less light allowed to the camera.
3. The last one is the zoom that goes from telephoto to wide (T to W) where Telephoto means the system is zoomed closer to the capture volume.

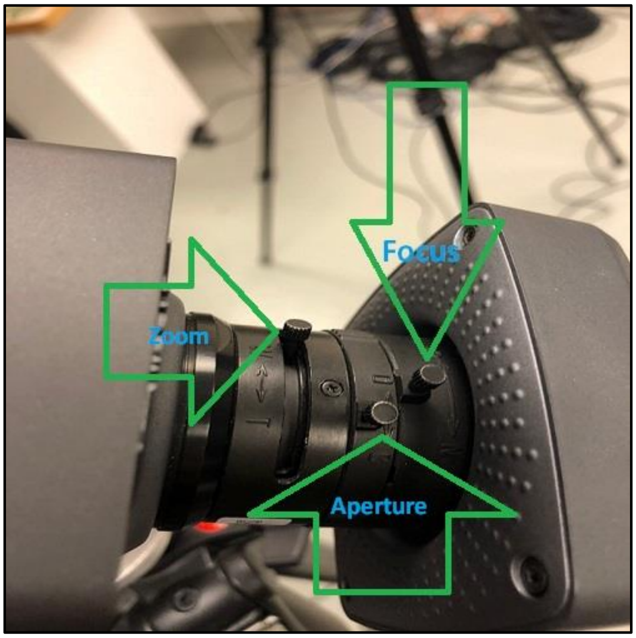


Figure 3.18. Focus, Aperture and Zoom screw

Figure 3.18 shows the position of each screw on top of each camera. These three screws are the tools to aim the cameras. There are signs that guide the user how to manipulate the cameras with these screws. Figure 3.19 and 3.20 distinguish a good aiming from a bad one.

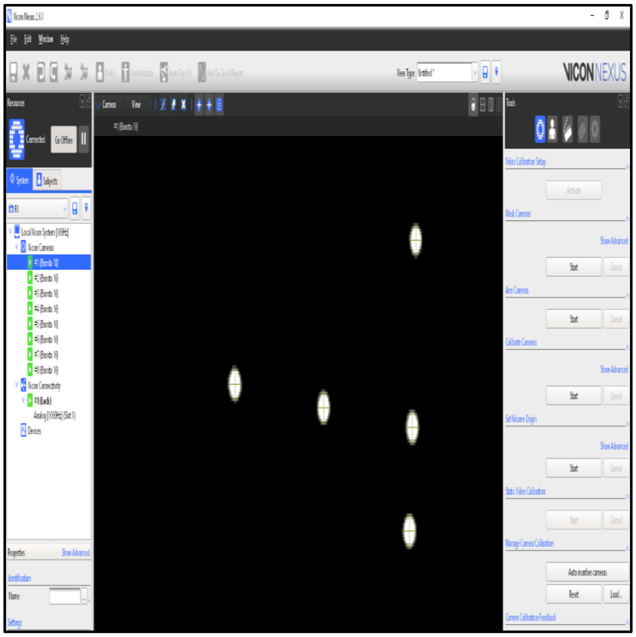


Figure 3.19. Good aiming

As the Figure 3.19 shows, the markers on calibration wand which have been used to aim the cameras, should have three major specifications. Circularity and the gray shadow around them and having the plus sign inside of the circle are the signs that every user should look for to make the cameras well-aimed. Therefore, the screws should be used and play with until the markers are circular and have the plus sign well fitted in them as well as having a gray shadow around themselves. Any deformed shape is the result of a bad aiming.

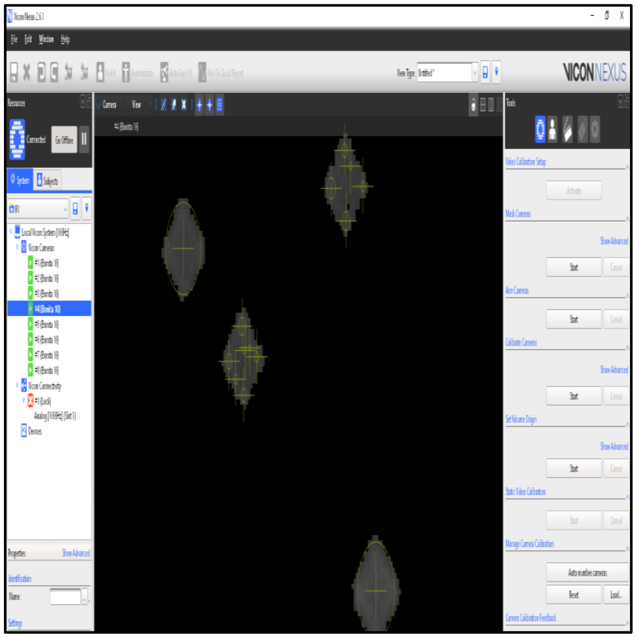


Figure 3.20. Bad aiming

As shown in figure 3.20, the plus sign is not well fitted within the circle, there is no gray shadow around the markers and they are not circular at all. Therefore, the cameras are not well aimed and the measurements and obtained data from this kinds of aiming includes big amount of error which is not ideal at all.

3.4.5 MASKING

Once aiming is done, the capture volume should be masked. The masking button is also in the preparation tab. A camera mask can be defined as an area on the sensor that does not collect data. Masking stops permanent reflection of some objects and cameras interrupting each other with results in bad tracking.

An ideal option is to minimize these camera masks as much as possible especially in the middle of the capture volume so that they cannot be detrimental to the 3D reconstructions.

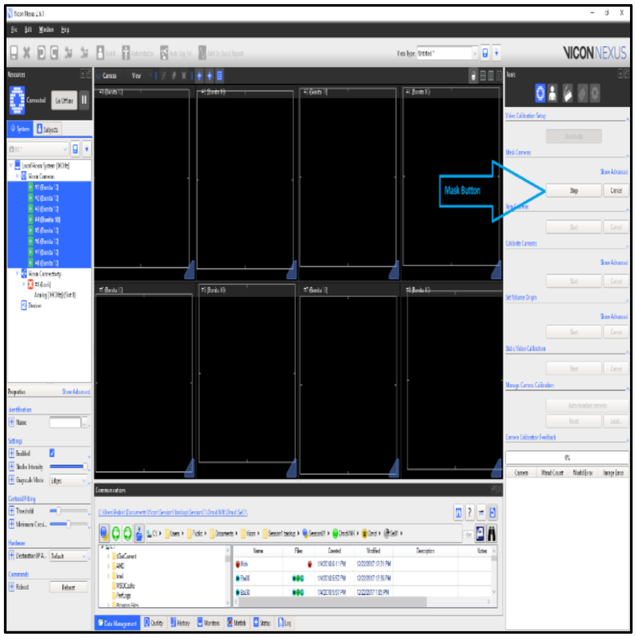


Figure 3.21. Mask Button

Figure 3.21 demonstrates the mask button location in the software. The system starts to mask the capture volume by click on the mask button and some small triangles appear on the bottom right hand side of each camera meaning that each one is under the masking process. The process of masking is straightforward. It starts with clicking on the start button, waiting for three to five seconds and then pressing the stop button. It should be noted that the calibration wand must be removed from the capture volume, otherwise the system masks a huge area of capture volume and capturing process may not be feasible.

If some areas of the capture volume are masked, some blue dots appear on the screen. Blue dots in the capture volume means the system is not able to track the markers if they pass through those areas.

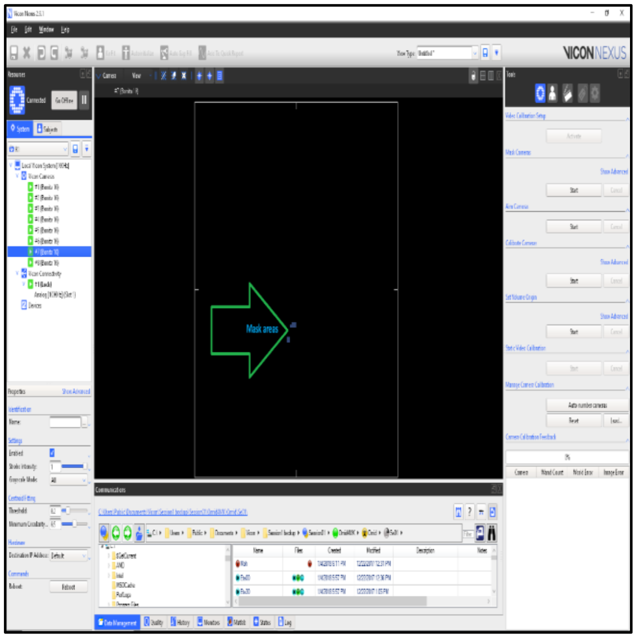


Figure 3.22. Mask areas

Figure 3.22 shows the areas that are under the mask; if the markers pass through those areas, the system is not able to follow the trajectory of markers and the software does not provide any data for markers positions through masked area.

3.4.6 CALIBRATION

The next step after masking is calibration. To do the calibration, the wand calibration should be placed in the middle of the capture volume. Next, in the preparation tab there is a button for calibrating the system. After pressing the start button, the user should wave the wand in infinity-like path until all the cameras reach 1,000 of wand count. Once all of them reach that number, the system automatically stops the process. There is a significant point about how to do the calibration. Once the calibration is done, systems announces the corresponding world error and image error to that calibration. The image and world errors are different. The image error is a comparison of two markers, one marker is the 2D camera image and the other is the projection of the 3D reconstruction back onto that specific camera sensor. Therefore, if there are eight cameras, and we are looking at camera 1, it compares the image of a marker from camera 1 to the 3D reconstructions of cameras 2-7 projected back onto that 2D image. The world error then takes this image error, the focal length of the camera and the mean distance of all cameras to the middle of the volume to predict a real-world error in mm (millimeter). With Bonita cameras, it is good to have the image error less than 0.3. Each time we calibrate, we are given the opportunity to provide the cameras with information that it can use to help with these calculations. If the wand has been waved differently, this provides different results every time. The best way to wave the wand is to follow an infinity path in the capture volume and make sure that all the cameras reach the 1,000 wand count all together; this is the most important point about calibration process. Considering this significant point, the image error and world error are supposed to be less than 0.3. This means that if seven cameras reach 1,000 wand count and one of them is still around 500 wand counts, then the user have to wave the wand in front of that camera for longer periods of time to make calibration process complete. This causes a higher image error and word error for that specific camera.

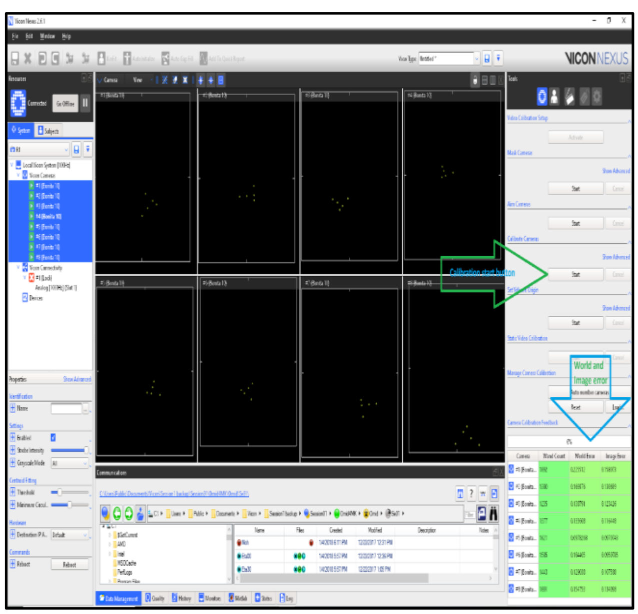


Figure 3.23. Calibration button, world and image error

Figure 3.23 illustrates where the calibration button is located and also shows an acceptable range for the world and image error for each camera. A good criteria for a good calibration can be the table color of image error and world error. If it is green like the color shown in Figure 23 then they are in an acceptable range.

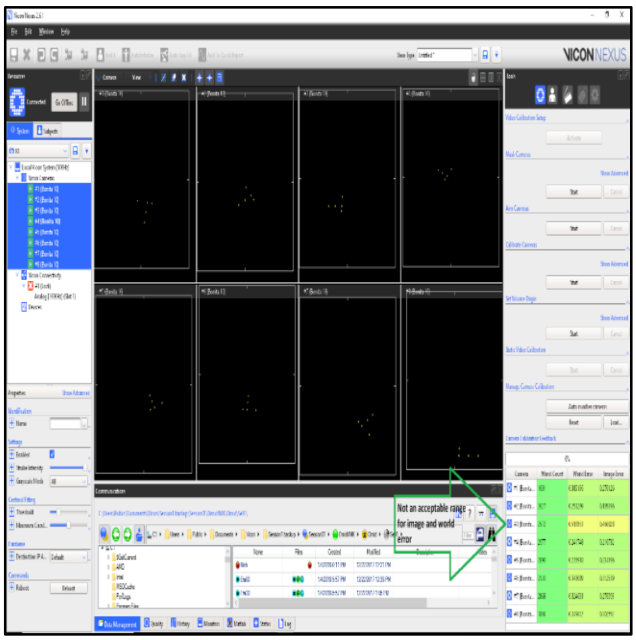


Figure 3.24. Unacceptable Image and world error

Figure 3.24 demonstrates that if the image and world error is not in an acceptable range, then the green color switch to light green and dark yellow and if it is too bad they appear in dark red which means the calibration process has to be redone.

3.4.7 SET UP THE CAPTURE VOLUME ORIGIN

After calibrating the system, the origin of the capture volume has to be set. To this end, the calibration wand has to be in the middle of the capture volume and balanced. One important point here is to set the origin based on the range of the motions that are supposed to be captured. If the motions are occurring in a lower level, then the origin should set at that low level as well. If they are wider and higher range of motions, then the origin has to be set at a higher level accordingly meaning that the height between calibration wand and the head of the camera should not be too much. Setting the capture volume origin is strictly depending on the type of motions and it becames one of the user abilities as becoming more experienced with capturing different motions.

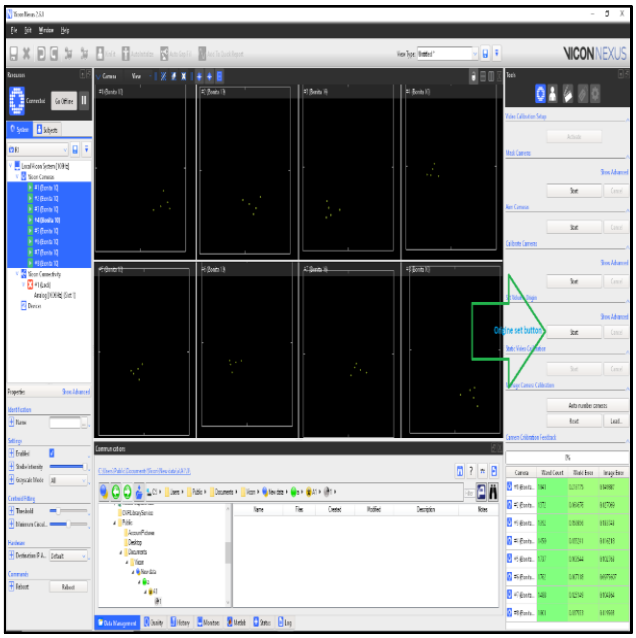


Figure 3.25. Origin set button

Figure 3.25 shows the origin set button and the user has to press the start button twice to set the origin.

3.4.8 CREATE A SESSION

In order to capture the data, a path has to be created through the software to save the files. To do that, user has to do it through the data management area located on the bottom left hand side of the software.

After clicking on that button, the user has to follow the path where the data has to be captured. It saves in C:\Users\Public\Documents\Vicon. A new folder should be created for each round of capture. One important point here is that after creating a new folder for the capture, it has to be registered in the data management through the main Pro Eclipse menu button, otherwise the software dose not identify that folder and it becomes impossible to create a subject and start the capturing process.

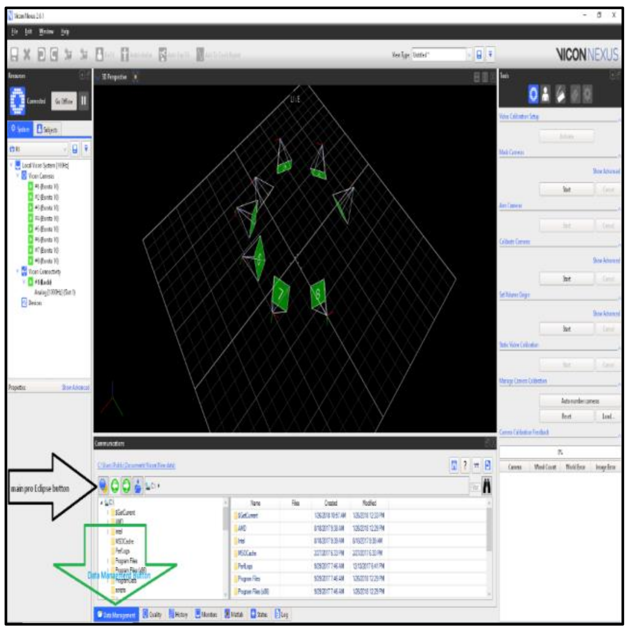


Figure 3.26. Data Management Button

Figure 3.26 demonstrates where the data management and main pro eclipse menu button is located in the software. To register the new folder, the user should click on the main Pro Eclipse button and then click on manage eclipse database.

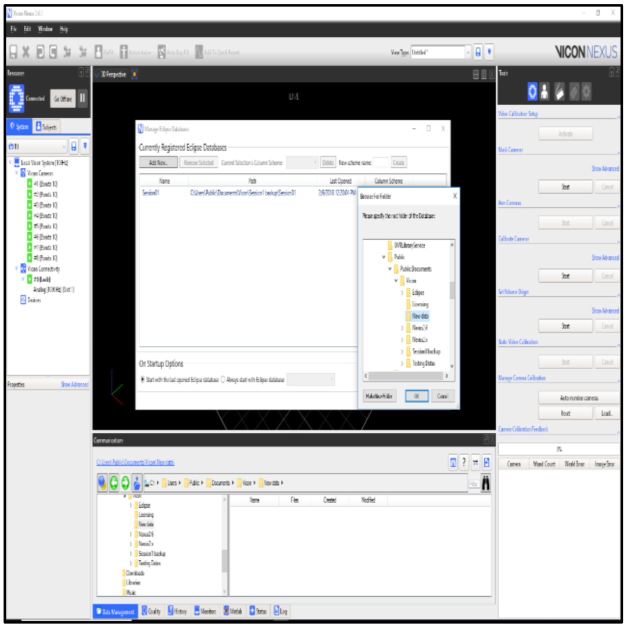


Figure 3.27. Manage Eclipse database

Figure 3.27 shows the manage eclipse database window along with the small window that appears and by clicking on add new button, registering the new folder to save data at is possible.

Next step is to click on the create new patient classification button and assign a name for it and then double click on the name and click on the create new patient button and assign a name for that too and double click on it. Following these steps, the session button appears and by clicking and assigning a name for the session, the software lets the user to start the capturing process. Figure 3.28, 3.29 and 3.30 show the location of patient classification button, patient button and new session button respectively.

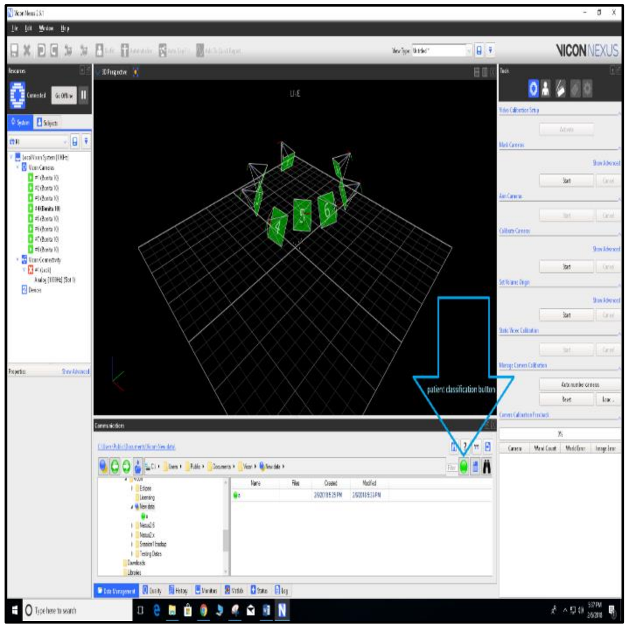


Figure 3.28. Patient classification button

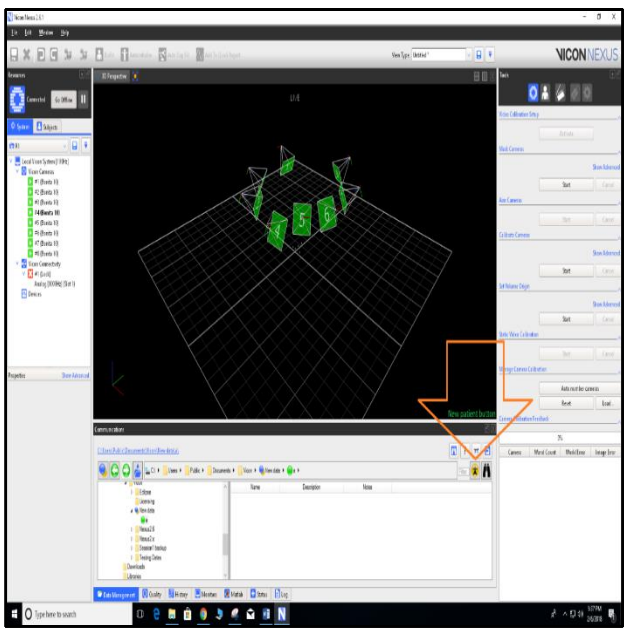


Figure 3.29. New patient button

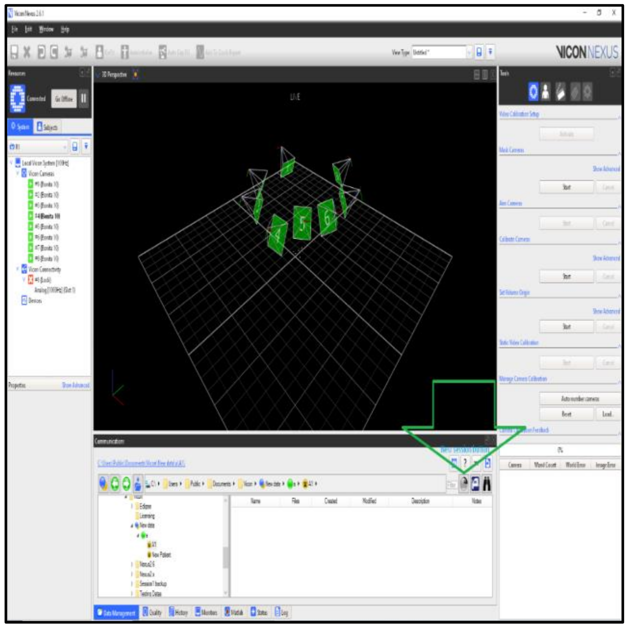


Figure 3.30. New session button

If any of these steps that are mentioned above are misses by the user, then the capturing button remains off. Once all the steps followed exactly as above, the software turns the capturing button to blue and let the software to start the capturing process.

3.4.9 BUILDING THE LABELING SKELETON

The user needs to make a labeling skeleton through the software. To do that, after attaching the markers on the subject body, there is a tab in the software called subject preparation that is used for this purpose.

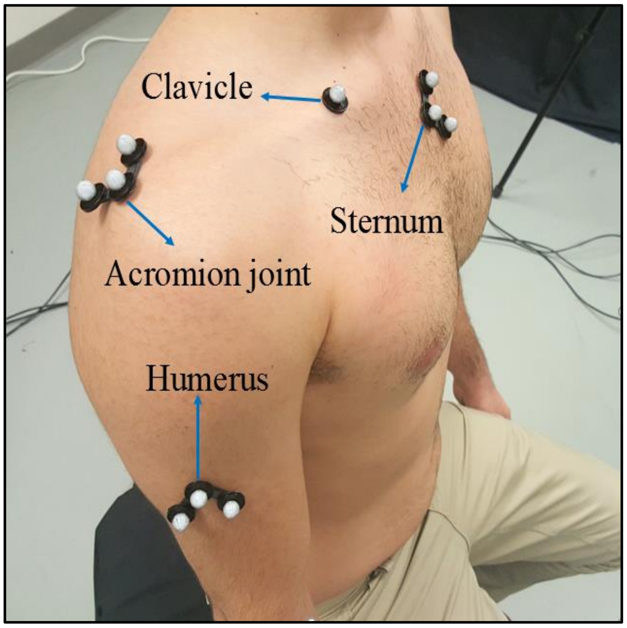


Figure 3.31. Markers on the subject body

Figure 3.31 shows the L-frame markers attached on the subjects' body. While the subject is in the middle of the capture volume, all the user can see in the software is shown in the following figure.

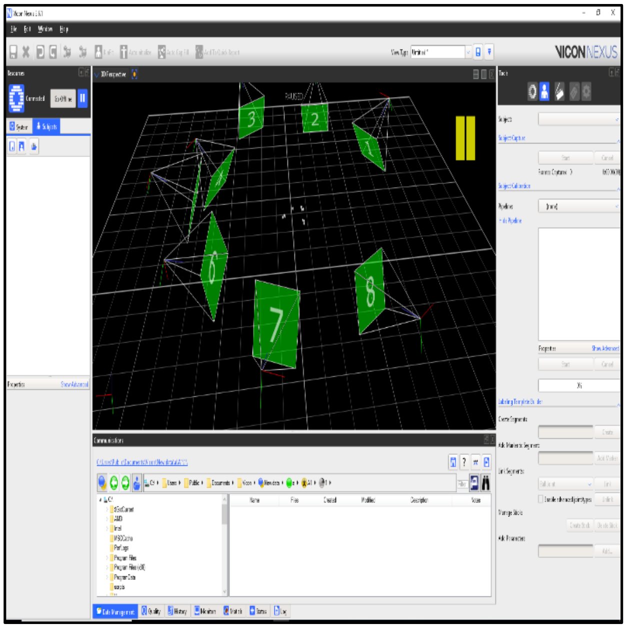


Figure 3.32. Software's view of the marker

Figure 3.31 demonstrates the markers attached on the subject's body. The user has to make the labeling skeleton by making different segments and then link them together so that the software identifies it as a whole unit and template.

To do that, the user has to pause the system from live mode and click on the subject preparation tab. As the Figure 3.31 shows, the subject tab is located on top right hand side of the software. While the system is paused, the user has to go to the subject preparation tab.

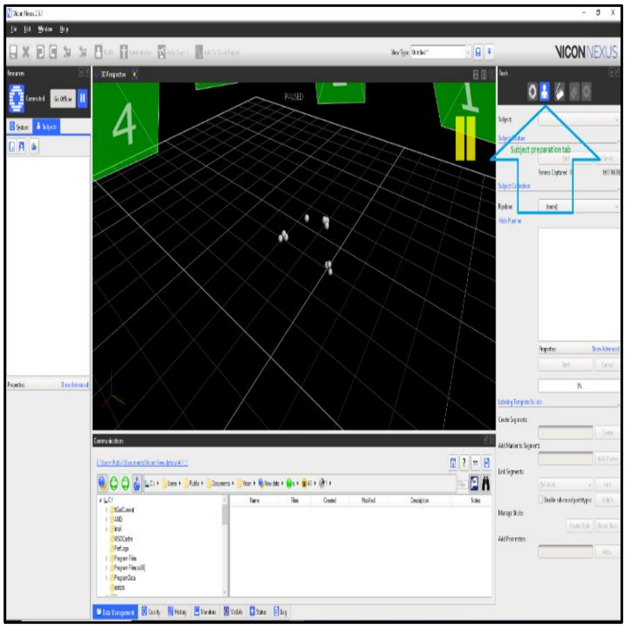


Figure 3.33. Subject preparation tab

Figure 3.32 shows where the subject preparation tab is located. The user has to click on the subject button to select an active subject and both name and save it prior to clicking on subject preparation tab. The subject button and subject preparation tab are totally different from each other and it is vital not to get confused with them.

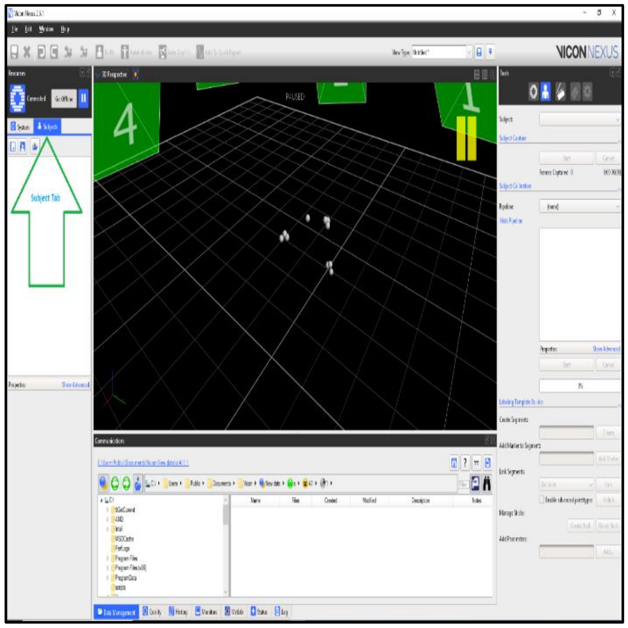


Figure 3.34. Subject Tab

Figure 3.33 shows where the subject tab is located. Once the user is there, a new blank subject has to be created with the tab underneath the subject tab and then name of subject. Once these steps are done, the subject name appears in the list in red with a star on top of it. Red means the subject has no segments and they are not linked together and star means the subject is not saved through the software. Segments can be created through the create button in the subject tab and name of the segments assigned based on the name of the bones that markers attached to them. Each segment has to be created with putting a name for that segment and then clicking on create and pick all the markers associated with that segment and finally hit the create button again. This process need to be repeated until all the segments are created. After all segment has been created, they need to be linked together and it is doable by pressing the link button and then select the parent joint and then child joint. The user can do it by selecting joints in 3D perspective or go to the subject tab and click on subject name and then select the segments tab and then click on their names. It is easier and recommended to do it through the subject tab.

3.5 SOME VITAL POINTS

There are some small details that help the user to have better view over the capturing process and makes the motion capture process easier in some cases, explained as follows.

3.5.1 EXTRA MAKER

Sometimes the template that has been made may have a long distance between its markers and this causes the software to lose the link between the segments and does not record data for those frames. To fix this, the user can attach an extra marker in between of segments that have long distances to each other and then link those segments through that markers by making it a unique segment so that the software be able to identify the template during the capture in all frames. At the end, when the Excel spreadsheet of the data has been exported, the data that is related to the extra marker can be removed manually.

3.5.2 COLORING

The other notable point is that the user can color all the markers and it helps to prevent mislabeling and ghosting. Mislabeling is when the software swipes the markers and it may happen and if the markers are in the same color, then it may be hard to identify this problem and data that obtained might have a significant amount of error. Ghosting means losing markers position in the space and the software knows that there is marker, but it doesn't know the exact position of it. It is hard to identify the ghosting and mislabeling while capturing if all markers are in the same color. To color the markers, the user simply has to go to the subject tab, click on the arrow on the left hand side of the subject's name and click on the arrow appears on the left hand side of the markers.

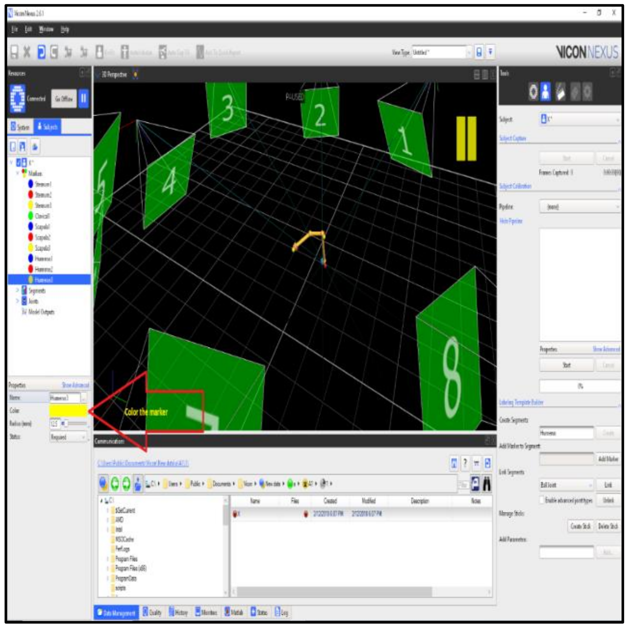


Figure 3.35. Color the marker

Figure 3.34 demonstrates where to color markers. Once the user clicks on the color area, a tab opens that let the user to pick from different color for that specific marker. Also the yellow lines between the segments shows that all the segments are linked together properly.

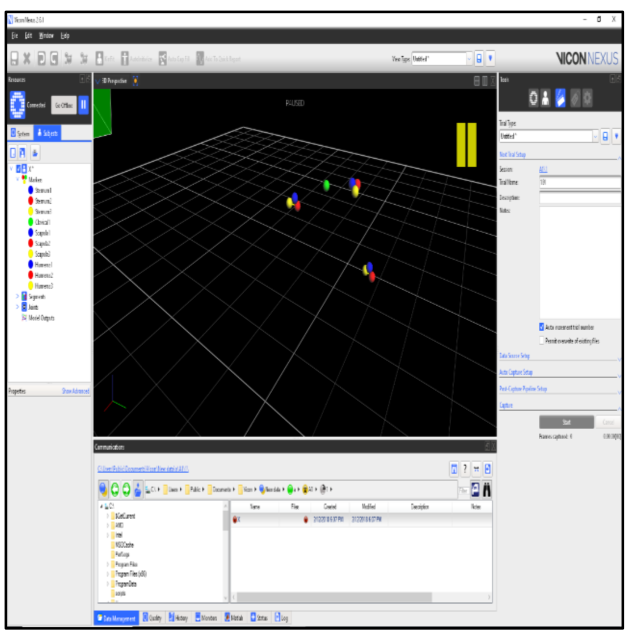


Figure 3.36. 3D perspective of markers after coloring

As the Figure 3.35 shows, each marker has been colored, and the green marker represent that extra marker to prevent the software losing the whole template.

Now the system is ready to capture. To start capturing, the user has to go to the capture tab and simply press the start when the subject is ready. Figure 35 shows the start button is off in the capture tab and this is due to the paused mode. The user has to switch to the live mode and then start button turns blue and ready to capture.

3.6 EXPORTING DATA

The last step is exporting data. When the data trial has been captured, the trial appears in the communications window. The user has to double click on it and then run the pipeline on it.

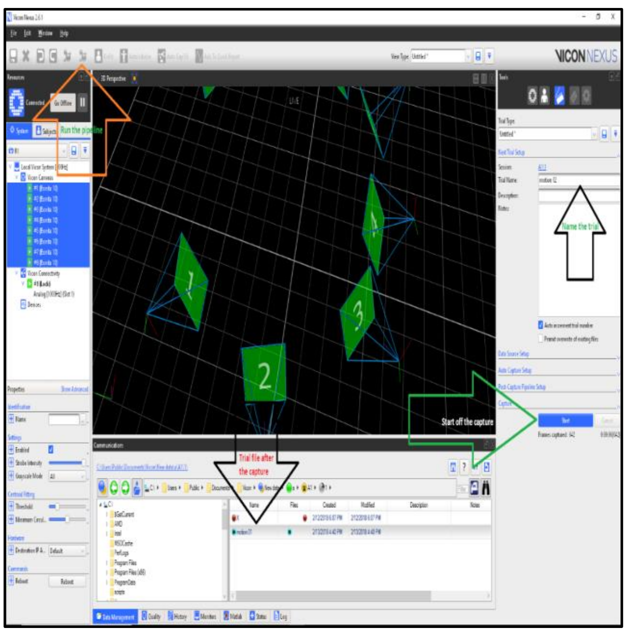


Figure 3.37. Pipeline, capture trial name

Figure 3.36 shows where the pipeline and capture button is located, along with the location of captured file and also the tab that user can change the name of the trials.

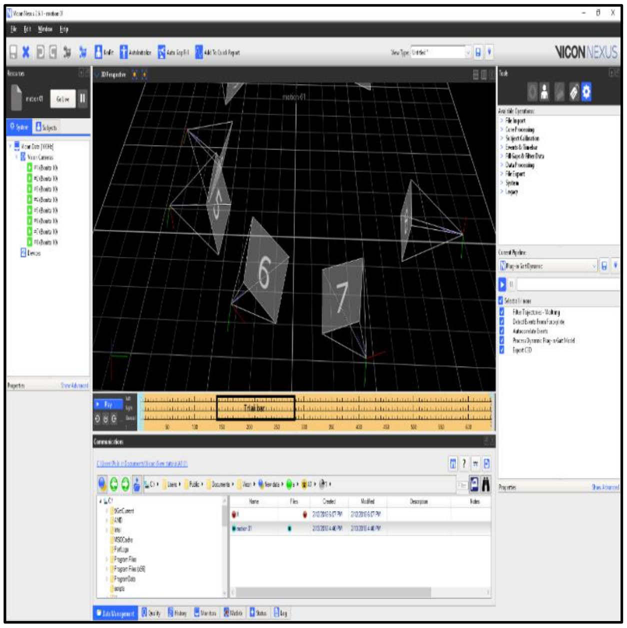


Figure 3.38. Trial bar

As Figure 3.37 shows and when the trail bar is in yellow, it means that the pipeline still has to be run on it. Once the pipeline has been applied on the trial, then the trial bar appears in white meaning that the excel output file of the captured data can be exported. To export the Excel file, the user has to go to the pipeline tab and then click on the arrow on the left hand side of the file export and then double click on ASCII option.

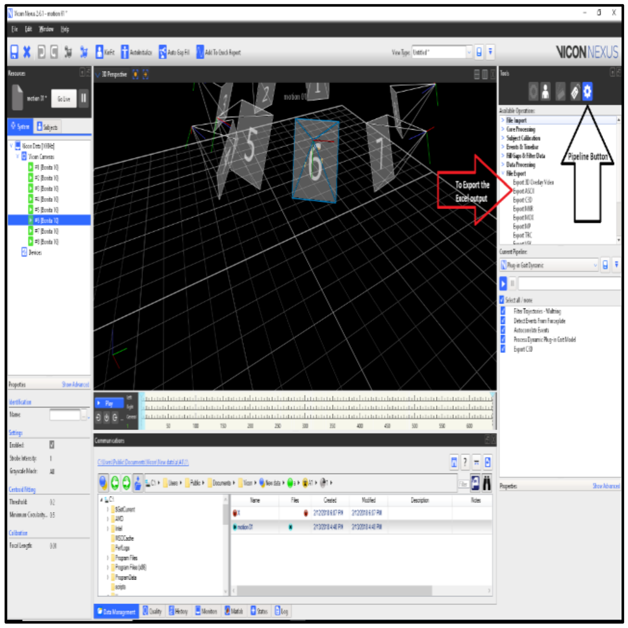


Figure 3.39. Pipeline button

Figure 3.38 shows where the pipeline tab is located and also shows where to export the excel output of the data. After double clicking on the export ASCII, the excel output is reachable with a click on the blue link which is located on top of communications tab.

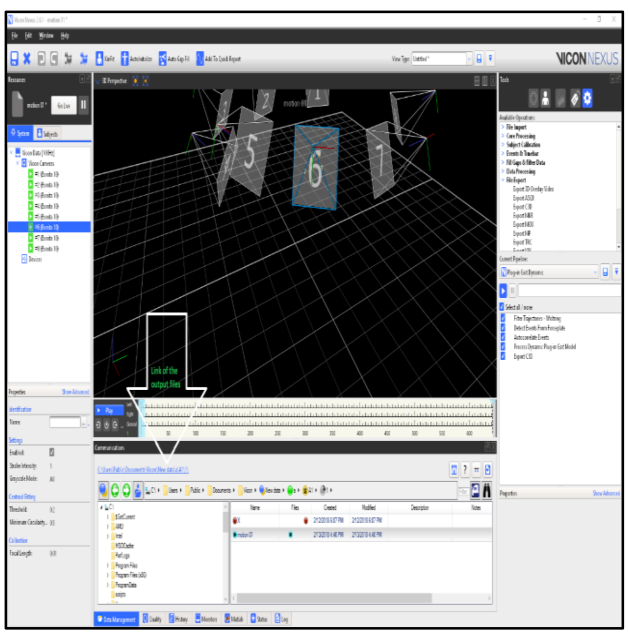


Figure 3.40. Link of the files

Figure 3.39 shows the link of the files that software saves the output files for captured trials.

In summary, the following steps should be taken so that software can give the permission to the user to start capturing: aim the cameras, mask the capture volume, calibrate the system, set up the capture volume origin, make a new template or labeling skeleton along with a new session for each round of capture and exporting data. These are the most significant steps to follow respectively.

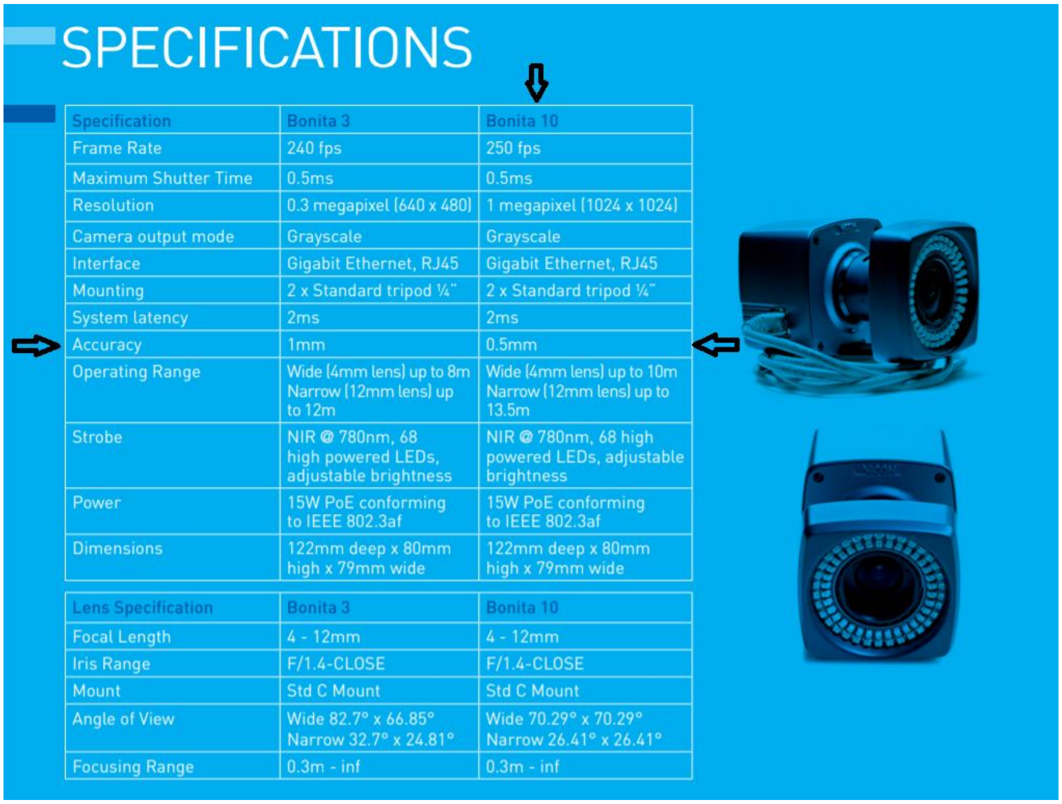
CHAPTER FOUR – EXPERIMENTAL WORK AND ELEMENTAL ERRORS VALUES

4.1 INTRODUCTION

In this study, the main focus is on the precision error and the accuracy of the system. Accuracy refers to how closely a measured value of a quantity corresponds to its true value. Precision express the degree of reproducibility or agreement between repeated measurements, therefore the more measurement we make and the better precision, the smaller the error will be [14]. Company catalogs have been used as the source for the accuracy error. To find out precision error, three different types of experiments were conducted at the Idaho State University motion capture laboratory by using hand-made mechanism to identify the elemental error components effecting the precision of the data. There are big advantages in identifying these elemental error components providing reliable and accurate results with negligible error.

4.2 ACCURACY ERROR

Regarding the accuracy of the system, the cameras that are used for motion capture were Bonita 10 and the specifications of this type of camera can be found in the following figure.



SPECIFICATIONS

Specification	Bonita 3	Bonita 10
Frame Rate	240 fps	250 fps
Maximum Shutter Time	0.5ms	0.5ms
Resolution	0.3 megapixel (640 x 480)	1 megapixel (1024 x 1024)
Camera output mode	Grayscale	Grayscale
Interface	Gigabit Ethernet, RJ45	Gigabit Ethernet, RJ45
Mounting	2 x Standard tripod ¼"	2 x Standard tripod ¼"
System latency	2ms	2ms
Accuracy	1mm	0.5mm
Operating Range	Wide (4mm lens) up to 8m Narrow (12mm lens) up to 12m	Wide (4mm lens) up to 10m Narrow (12mm lens) up to 13.5m
Strobe	NIR @ 780nm, 68 high powered LEDs, adjustable brightness	NIR @ 780nm, 68 high powered LEDs, adjustable brightness
Power	15W PoE conforming to IEEE 802.3af	15W PoE conforming to IEEE 802.3af
Dimensions	122mm deep x 80mm high x 79mm wide	122mm deep x 80mm high x 79mm wide

Lens Specification	Bonita 3	Bonita 10
Focal Length	4 - 12mm	4 - 12mm
Iris Range	F/1.4-CLOSE	F/1.4-CLOSE
Mount	Std C Mount	Std C Mount
Angle of View	Wide 82.7° x 66.85° Narrow 32.7° x 24.81°	Wide 70.29° x 70.29° Narrow 26.41° x 26.41°
Focusing Range	0.3m - inf	0.3m - inf

Figure 4.1. Bonita 10 specification

Figure 4.1 shows the accuracy of Bonita 10 is 0.5_{mm} which means that the captured point position by the cameras is 0.5_{mm} off from the actual position [15].

4.3 PRECISION ERROR

Speed of the motion, location of the subject in the capture volume and non-rigidity of human body are the elemental error components that effect the point positions in each frame or in the other words they effect the precision error.

Let p express the accepted position of point P in the space and e represent the error regarding the point position

$$p = \begin{Bmatrix} p_x \\ p_y \\ p_z \end{Bmatrix}$$ **Equation (2)**

$$e = \begin{Bmatrix} e_x \\ e_y \\ e_z \end{Bmatrix}$$ **Equation (3)**

Then, the accepted position of the point p expressed as:

$$P = p + e = \begin{Bmatrix} p_x + e_x \\ p_y + e_y \\ p_z + e_z \end{Bmatrix}$$ **Equation (4)**

where $e = \mathcal{E}_o + e_1 + e_2 + e_3$ and e_1, e_2, e_3 are the elemental components that cause this point position error[14] and p shows the true and absolute pint position. e_1 is the error due to the capture volume location, e_2 is error by the velocity of the motion, e_3 is the human body non rigidity error and $\mathcal{E}_o$ is the accuracy error by the cameras.

As a result,

$$P = p + \mathcal{E}_o + e_1 + e_2 + e_3 = \begin{Bmatrix} p_x + \mathcal{E}_o + e_{1x} + e_{2x} + e_{3x} \\ p_y + \mathcal{E}_o + e_{1y} + e_{2y} + e_{3y} \\ p_z + \mathcal{E}_o + e_{1z} + e_{2z} + e_{3z} \end{Bmatrix}$$ **Equation (5)**

It has been tried to identify these elemental errors and define a range for upper limit and lower limits of the error using some experimental methods. Since $\mathcal{E}_o$ is given[15], the absolute values of other three elemental errors need to be quantified in order to form a new version of the point position equation for Vicon Motion Capture System™.

4.4 EXPERIMENTAL WORK

4.4.1 TOOLS AND MECHANISMS

In order to figure out the effect of each elemental error, a mechanical model was constructed. The markers have been attached to the revolute joint and the motion of it has been captured in two different set of experiments separately to identify the effect of elemental error components and also the markers attached to the body to analyze the effect of the last elemental error in this study. Prior to starting the motion, the distances between markers have been measured physically by a digital caliper.

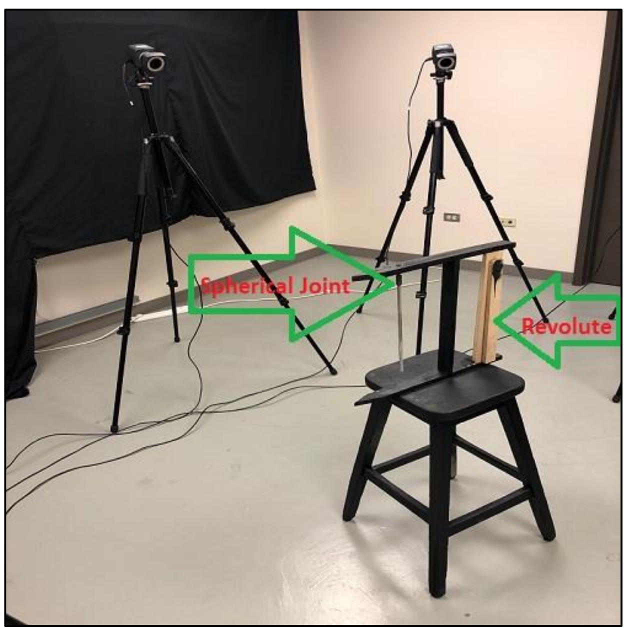


Figure 4.2. Mechanical Model

Figure 4.2 demonstrates the mechanical model along with the revolute joint. The revolute joint has been used to determine the error causing by the speed and capture volume location. The error varies by different speed rates and also in different areas of the capture volume.

Figure 4.3. Digital Caliper

Figure 4.3 shows the digital caliper by which the distance between the markers has been measured manually.

4.4.2 STEPS TO DO THE EXPERIMENT

In order to perform the experiment, some steps have been followed, listed as follows.

A. At first, the markers have been attached to a rigid plastic L-Frame. Figure 43 and 44 show the markers and the L-Frame before and after attaching the markers on it.

Figure 4.4. L-frames and markers

Figure 4.4 shows the rigid L-Frame and the markers that sit on it.

Figure 4.5. Markers attached to the L-Frame

Figure 4.5 shows the markers attached to the L-Frame using glue in the laboratory which is why the user needs to measure the distances between these markers since that distances varies each time the markers are attached to the L-Frame.

B. The distance between markers 1 and 2 has been measured by the digital caliper.

Figure 4.6. Distance between marker 1 and 2

Figure 4.6 shows the distance between marker 1 and 2 which is 22.44 mm.

C. The L-Frame has been attached to the revolute joint shown in figure 46.

Figure 4.7. Markers attached to the revolute joint

Figure 4.7 shows the markers attached to the revolute joint and at this point, all the steps for the experimental set up have been done and the mechanism is ready to use for the motion capture.

4.4.3 ERROR DUE TO THE CAPTURE VOLUME

In this section, the error due to the capture volume location is being studied. Having perfect aiming, masking and calibration is not practically possible which might be the sources of capture volume error. Therefore, it is hard to get the most tuned capture volume for each round of capture and it is possible that there are some points which can be impacted by these inhibitors, so they cause an area of error which called capture volume error.

A. ERROR DUE TO THE CAPTURE VOLUME AT FIRST LOCATION

The Position of the markers has been captured in three different motion to see the difference in fluctuation of the distance between markers. Since every type of measurement includes error, the manual measurement that has been done by the caliper includes error too. And the reason that this has been done is to prove that the value that physical measurement provides and the average value that system provides are almost the same and make sense. In other words, the basic source to find the error is the different value of the distance between markers that Vicon motion capture system provides in different frames. In order to make a good error analysis, all the data sets have been imported to MATLAB™.

Figure 4.8. Mechanism at first location

Figure 4.8 shows the position of the mechanism at first location.

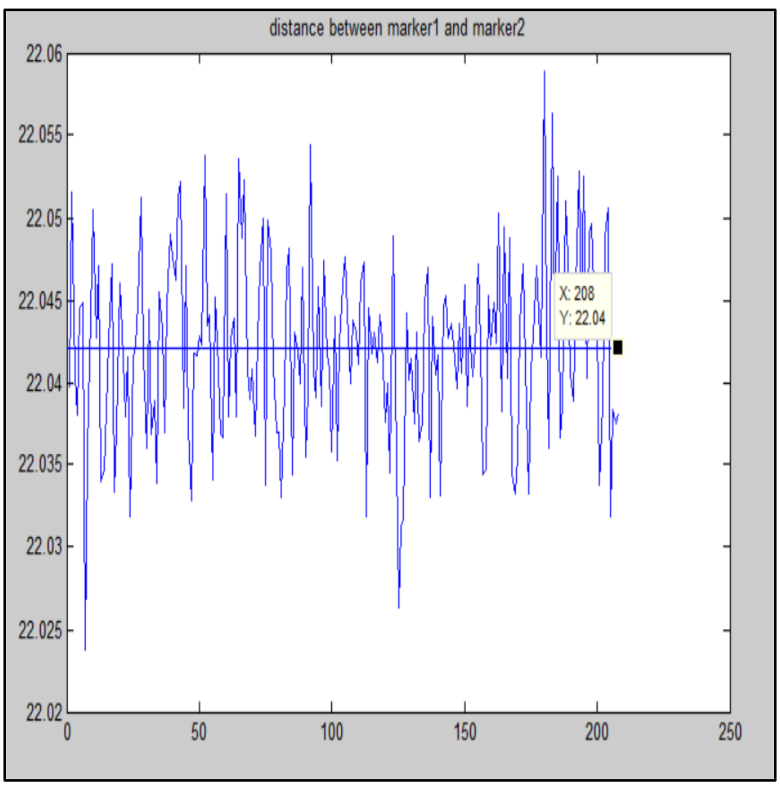


Figure 4.9. Distance between marker 1 and 2 at first location

The distance by the manual measurement is 22.44$_{mm}$ and the average of captured distances for 200 frames by Vicon Motion Capture System is about is 22.04$_{mm}$ (Figure 4.9) which makes sense. All these different values in different frames regarding the distances between markers have been deduced from the average values.

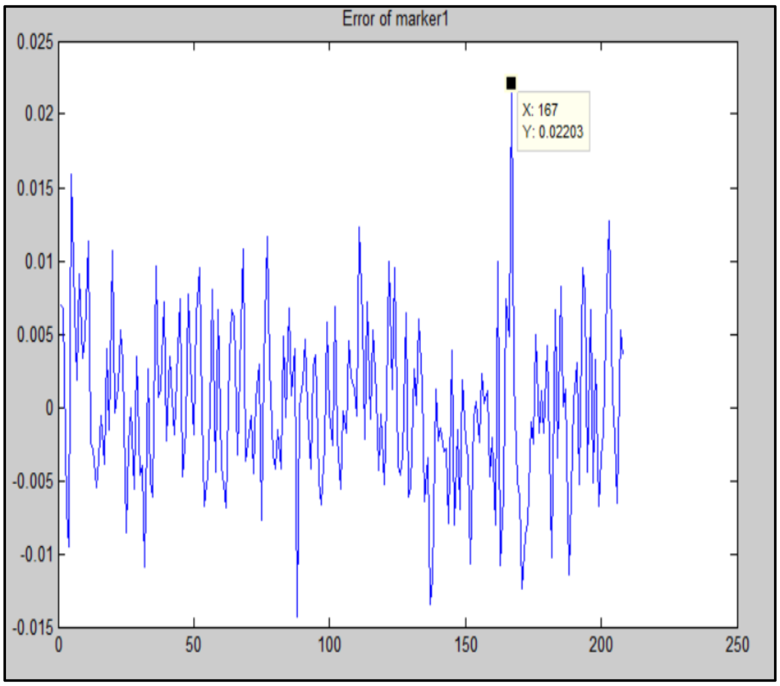


Figure 4.10. Error of marker 1 at first location

Figure 4.10 shows that the maximum value of error is about 0.02203$_{mm}$ and the range of error is between 0.01$_{mm}$ and 0.025$_{mm}$ at first location.

Prior to the second try the system has been switched off completely and all the steps including aiming, masking and calibrating to make the system ready to capture have been done again.

B. ERROR DUE TO THE CAPTURE VOLUME AT SECOND LOCATION

In the second try, the mechanism has been relocated and the distance between markers has been captured.

Figure 4.11. Mechanism at second location

Figure 4.11 shows that the mechanism has been relocated to second position.

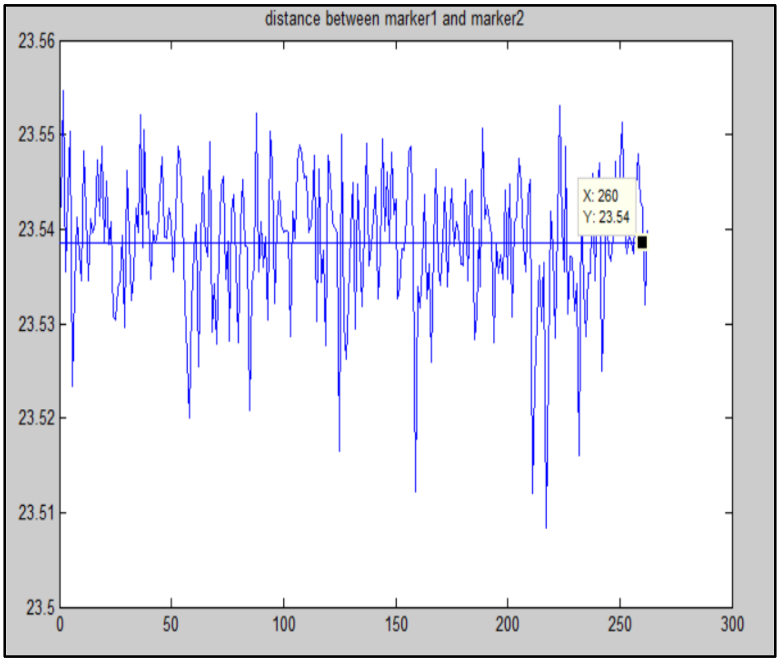


Figure 4.12. Distance between marker 1 and 2 at second location

Figure 4.12 shows the distance between markers 1 and 2 in about 280 frames and the average value is 23.54$_{mm}$. As it is obvious the distance between markers is not the same in the different frames.

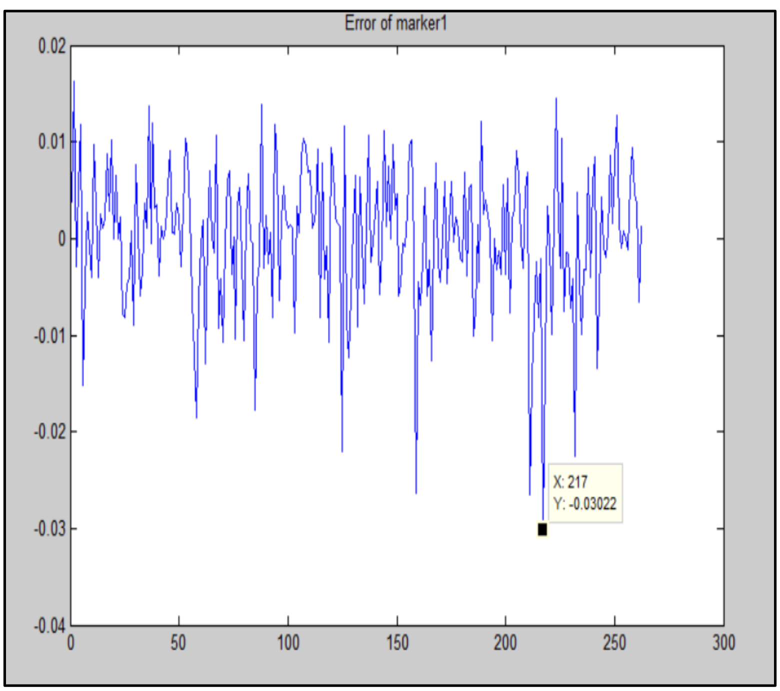


Figure 4.13. Error of marker 1 at second location

Figure 4.13 shows that the maximum value of error is 0.0.03022$_{mm}$ at the second location.

C. ERROR DUE TO THE CAPTURE VOLUME AT THIRD LOCATION

The mechanism has been relocated to the third location and the position of the markers has been captured with no motion and speed.

Figure 4.14. Mechanism at third location

Figure 4.14 shows the mechanism has been relocated to third position in the capture volume.

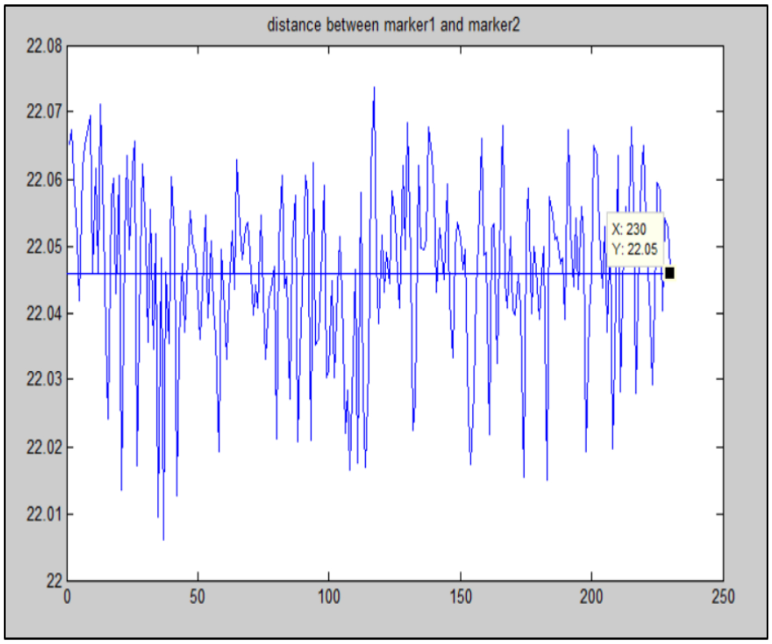


Figure 4.15. Distance between marker 1 and 2 at third location

Figure 4.15 shows that the average distance between markers is 22.05_{mm} and which is close to the physical measurements and seems reasonable.

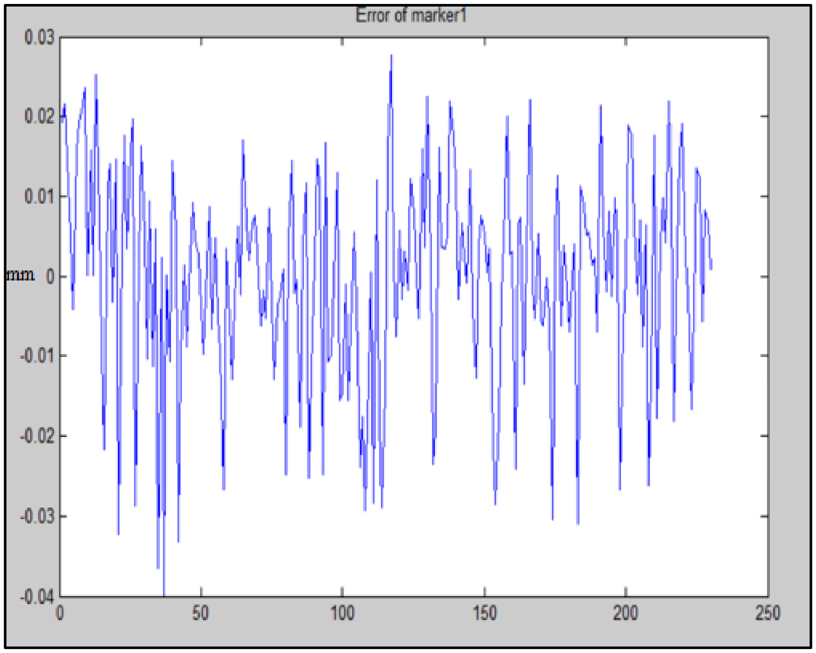


Figure 4.16. Error of marker 1 at third location

Figure 4.16 shows the error at third spot of the capture volume and the maximum value of error is 0.04_{mm}.

4.4.4 ERROR DUE TO THE VELOCITY

To prove that the speed of the motion causes error and it is one of the elemental error components, the motion of the revolute joint has been captured in three similar motions with different speed in the same exact capture volume location which has been tested before and provided the least amount of error so that it is possible to associate all the amount of error to speed of the motion.

A. ERROR DUE TO THE SPEED OF THE MOTION AT FIRST TRY

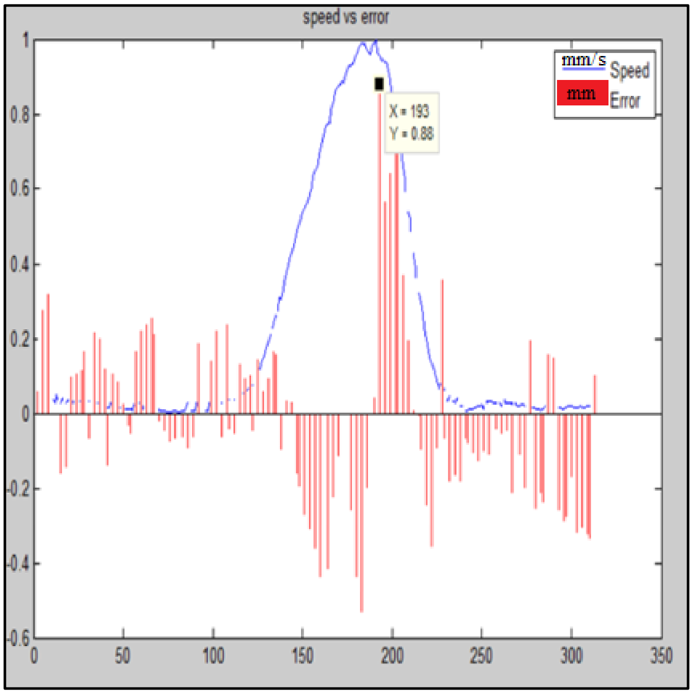


Figure 4.17. Velocity VS Error

Figure 4.17 shows that when pendulum which is connected to the revolute joint reaches the maximum speed that is $1000_{mm/s}$, the error also reaches the maximum value at 0.88_{mm}.

B. ERROR DUE TO THE SPEED OF THE MOTION AT SECOND TRY

During the second attempt, the error has been decreased with the decrease in speed.

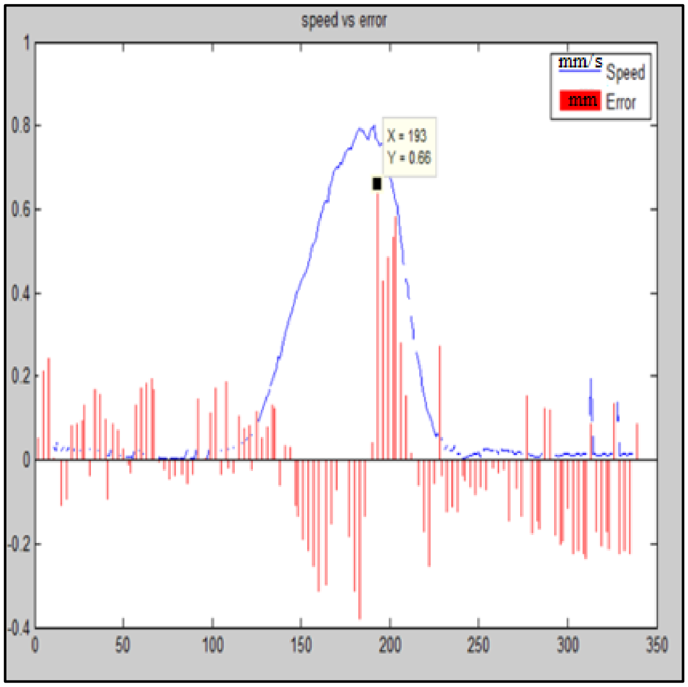


Figure 4.18. Velocity VS Error

Figure 4.18 shows the maximum speed is about $800_{mm/s}$ and the maximum value of error is 0.66_{mm}.

C. ERROR DUE TO THE SPEED OF THE MOTION AT THIRD TRY

In the last attempt also, the graph shows the same relation between speed and error. The slower the speed, the less the error.

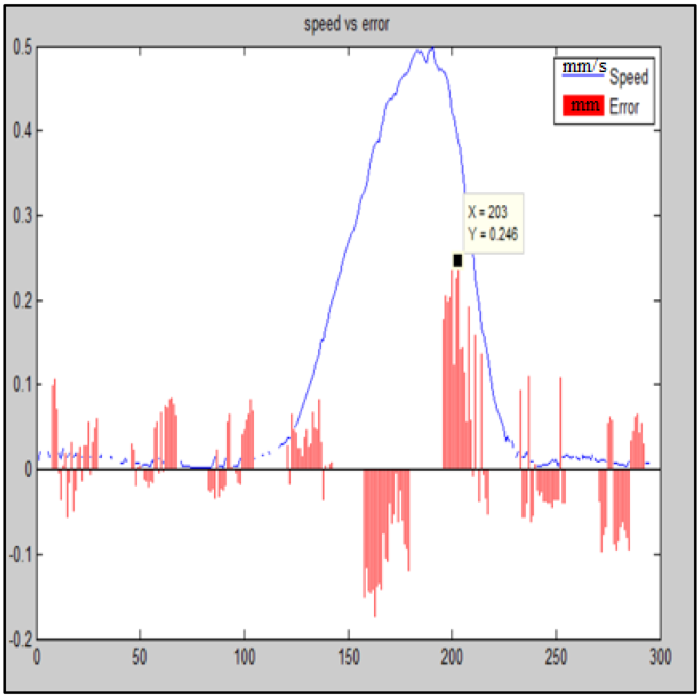


Figure 4.19. Velocity VS Error

Figure 4.19 shows the maximum speed of the pendulum is about $500_{mm/s}$ and the maximum value of error is 0.246_{mm}.

The error drops down with decrease in speed of motion. Also, the graph shows that the maximum amount of error is when the pendulum reaches the maximum speed.

In order to find a reliable range of speed that results in a very small and negligible error, the motion of the pendulum has been captured 10 times at 10 different speed and the result has been presented in the following chart.

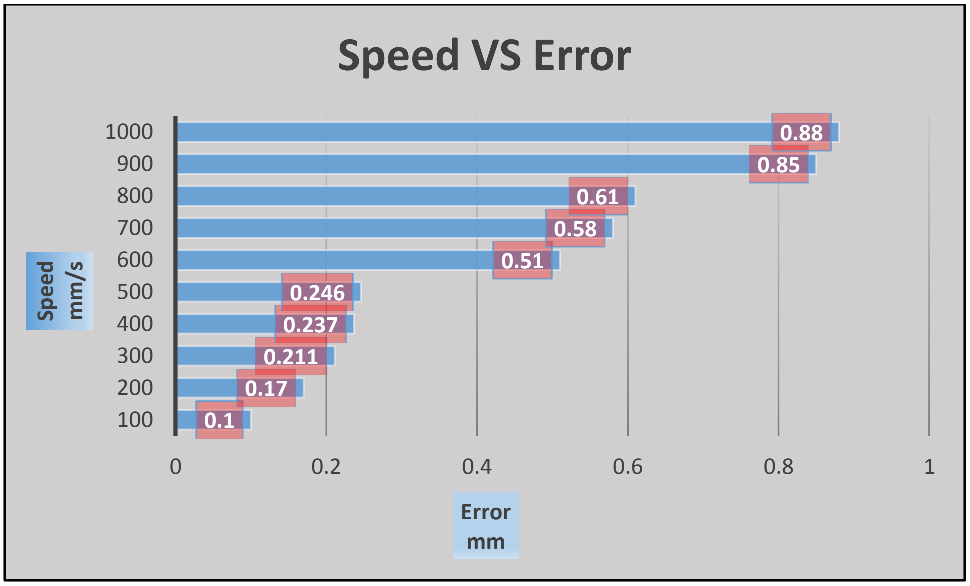


Figure 4.20. Maximum Values of Error VS Maximum Velocity

Figure 4.20 shows the result for 10 motions at 10 different speed and the maximum corresponding error value for each one. It is obvious that if the speed is less than $500_{mm/s}$, the error is lower than 0.3_{mm}.

4.4.5 ERROR DUE TO THE NON-RIGIDITY OF BODY

The other source of error that has a large effect on the precision of the data is the non-rigidity of body. Since it has been tried to capture the motion of the human joints and it is not possible to attach the markers on bones directly, movement of the muscles and skin causes the markers to be displaced from where they have been attached to the body and as a result add error to the marker positions in each frame. To make the effect of these non-rigidities obvious and analyze how big they effect the data, another experiment based on comparison has been done. At first, the markers attached on the L-frames and those L-frames attached to the skin and their motion has been captured. Next, the same motion has been captured by attaching the markers directly to the skin and the result has been compared.

A. ERROR DUE TO THE NON-RIGIDITY OF BODY AT FIRST TRY

Markers were placed on the Humerus [25] which is the long bone connecting the shoulder to the elbow.

Figure 4.21. Markers attached to L-frame on Humerus

Figure 4.21 shows the markers attached to the body by using the L-frame on the Humerus to see how big of a change in distance between markers this muscle causes. The motion of these markers has been captured and distance between markers has been graphed in MATLAB™ and analyzed.

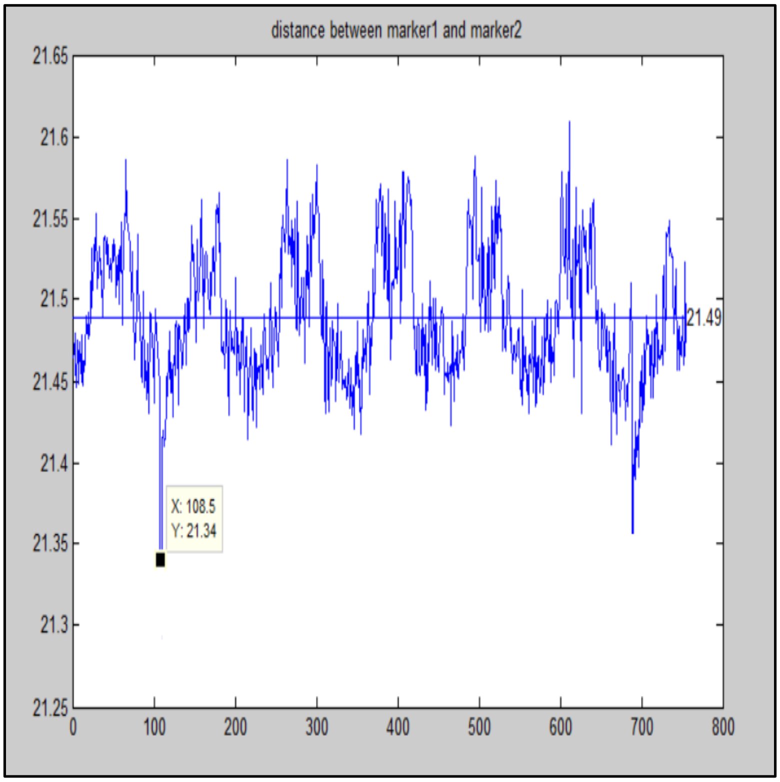


Figure 4.22. Fluctuation of distance between marker 1 and 2 attached to L-frame on Humerus

Figure 4.22 shows the distance between marker 1 and 2 is not the same even though the L-frame has been used to minimize the error of non-rigidity of the body. The average value is 21.49_{mm} and the greatest deviation is 21.34 which means the error is 0.15_{mm}.

Figure 4.23. Markers attchaed to Skin on Humerus

Figure 4.23 shows the markers have been attached to the skin without using the L-frame to see if the it increase or decrease the fluctuation of distance between markers.

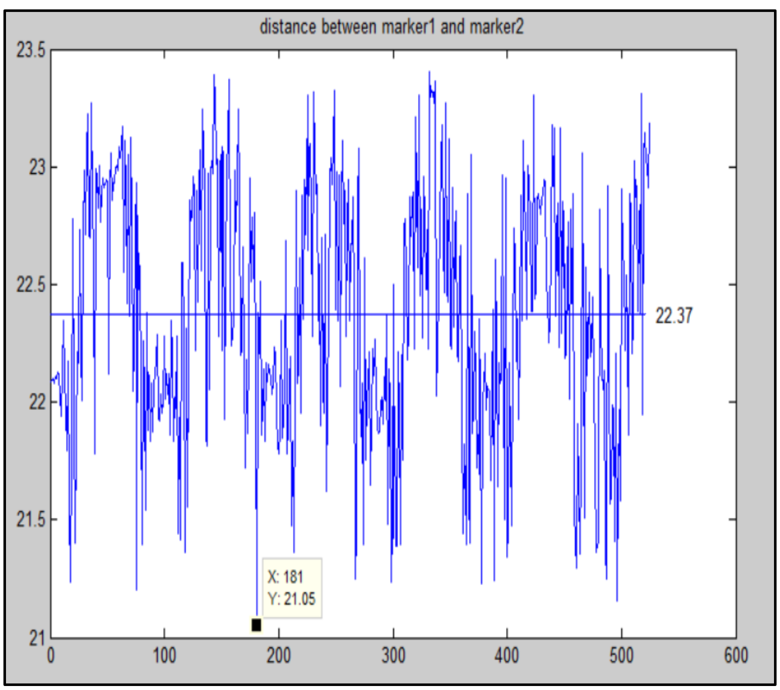


Figure 4.24. Fluctuation of distance between marker 1 and 2 attached to skin on Humerus

The graph in Figure 4.24 shows that the biggest distance between markers is 21.05_{mm} and the the average value is 22.37_{mm} and this gives the bigest value of error to be 1.32_{mm}.

B. ERROR DUE TO THE NON-RIGIDITY OF BODY AT SECOND TRY

The same process has been repeated for the area called Scapula[25] which is the bone that connects Humerus which is the upper arm bone with the Clavicle which is collar bone.

Figure 4.25. Markers attached to L-Frame on Scapula

Figure 4.25 shows that the markers attached to the L-frame on the Scapula.

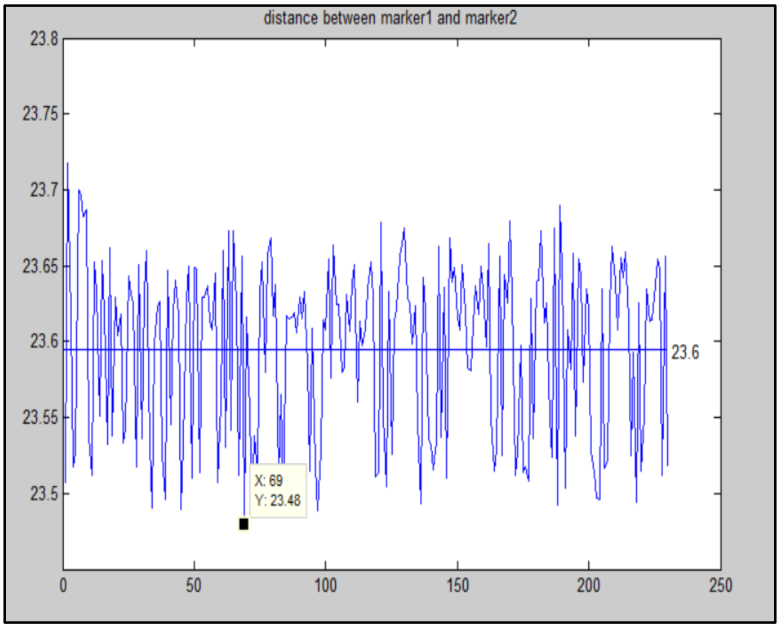


Figure 4.26. Fluctuation of distance between marker 1 and 2 attached to L-frame on Scapula

Figure 4.26 shows the distance between markers 1 and 2 on the Scapula in about 250 frames and the biggest value of error is 0.12_{mm} by use of L-Frame.

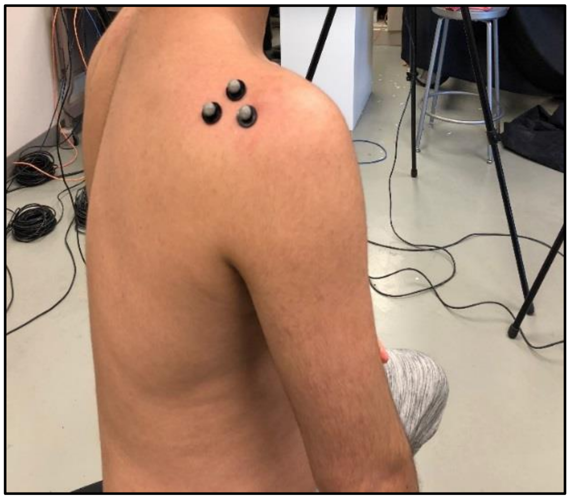


Figure 4.27. Markers attached to skin on Scapula

Figure 4.27 shows the markers attached to skin on the Scapula without using the L-frames.

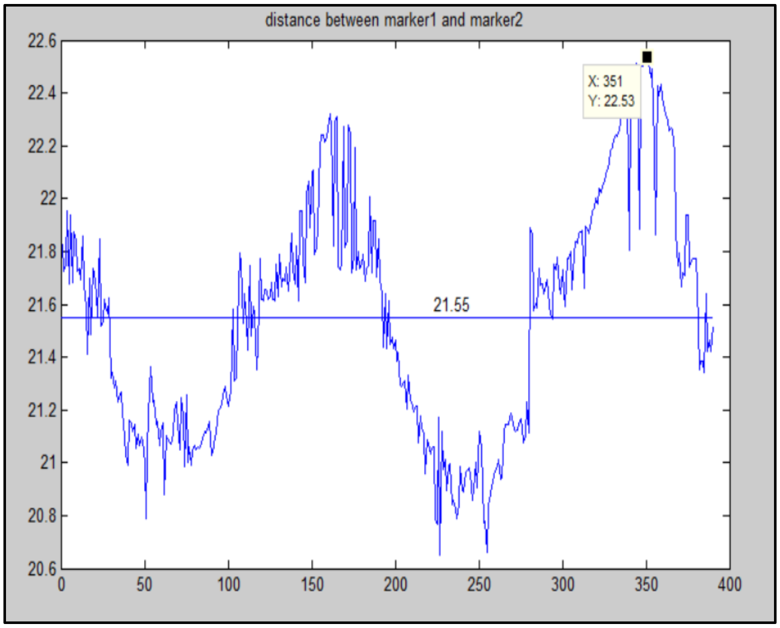


Figure 4.28. Fluctuation of distance between marker 1 and 2 attached to skin on Scapula

The Figure 4.28 shows the distance between markers changed very much without using L-Frame. The average value is 21.55_{mm} and the highest value is 22.53_{mm} which means the error is 0.98_{mm}.

C. ERROR DUE TO THE NON-RIGIDITY OF BODY AT THIRD TRY

The last motion is about the motion of the Sternum [25] which is the long flat bone located in the center of the chest which there is not much of muscles movement affects the motion and the bone itself does not have that large of a displacement either.

Figure 4.29. Markers attached to L-Frame on Sternum

Figure 4.29 shows the markers attached to the L-frame on Sturnem [25]. The motion of it has been captured and the result is as follow.

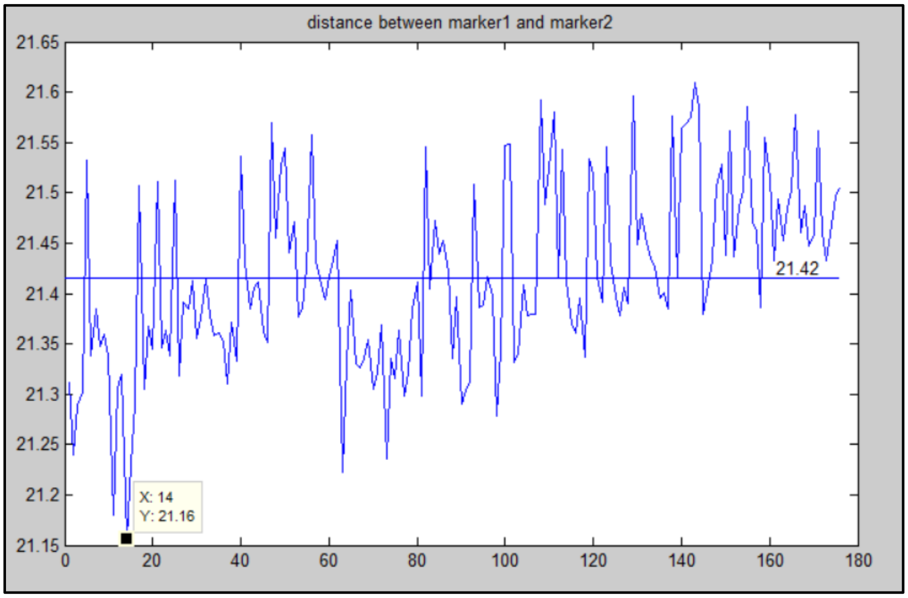


Figure 4.30. Fluctuation of distance between marker 1 and 2 attached to L-frame on Sternum

Figure 4.30 shows that the average distance between markers is 21.42 and the highest jump is 21.16 which means the biggest value of error can be 0.26_{mm}.

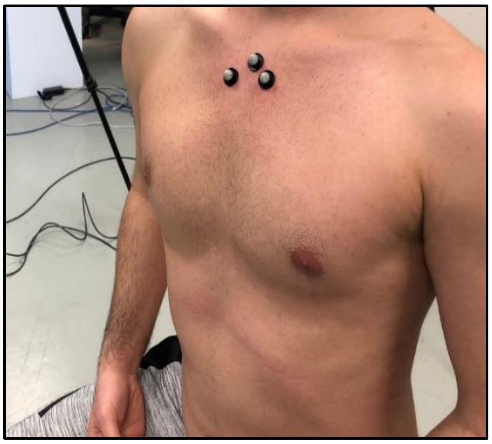


Figure 4.31. Markers attached to skin on Sternum

Figure 4.31 shows the markers has been attached to skin directly on sternum.

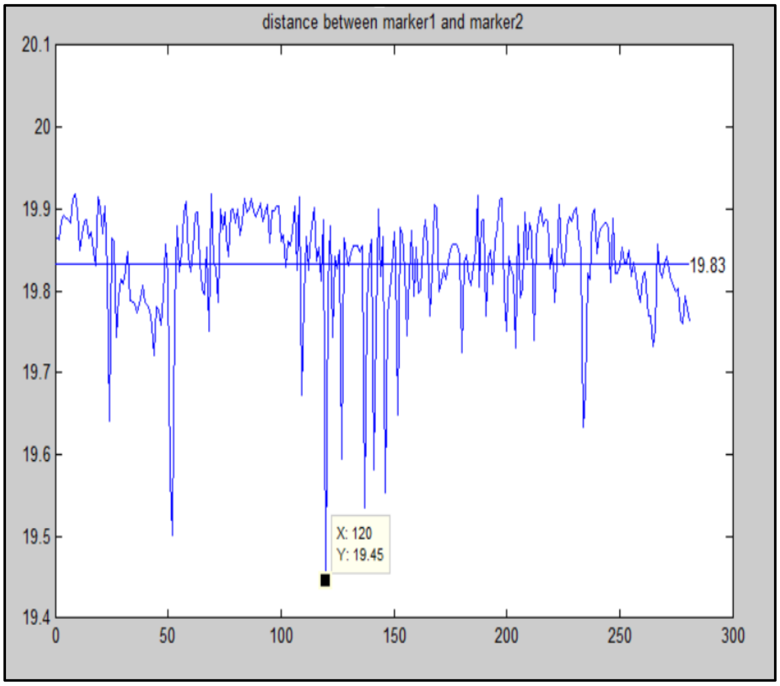


Figure 4.32. Fluctuation of distance between marker 1 and 2 attached to skin on Sternum

Figure 4.32 shows that the average distance between marker 1 and 2 is 19.83_{mm} and the highest deviation is 19.45_{mm} which means that then biggest value of error is 0.38_{mm}.

In a word, with this experimental wok, we have found the value for each elemental error component.

CHAPTER FIVE – SUMMARY AND RESULT

5.1 SUMMARY

The purpose of this study was to become familiar to use the Vicon Motion Capture System™ and evaluate the behavior of this system and to figure out the precision error of data that has been obtained from it under different experimental setup. Based on the literature review, there is no information on the error due to the velocity of the motions, non-rigidity of human body and error due to the capture volume location with eight cameras. In this study, the result of 12 different experiments have been presented and compared. The value of each elemental error components has been found and all the values have been combined to define an upper limit and lower limit for three different areas of the body.

5.2 RESULTS

This chapter presents the results of this investigation. The results are divided into three different parts. First, it has been proven that there is an absolute error value in obtained data from the Vicon Motion Capture System™. Second, the absolute value of each elemental error based on the experimental work at Idaho State University Motion Capture laboratory has been presented. Eventually the elemental errors have been combined to compute the absolute value of error.

5.3 PROOF OF ERROR IN DATA

To prove that there is error in the data, it has been hypothesized that the position of marker number 1 attached to the L-Frame is the center of a sphere whose radius is the distance between marker 1 and 2 and if the position of marker 2 meet with the surface of the sphere, it means there is no error. On the other hand, if the marker position passes over the surface of the sphere, it means that there is an error in point positions given by the Vicon Motion Capture System™.

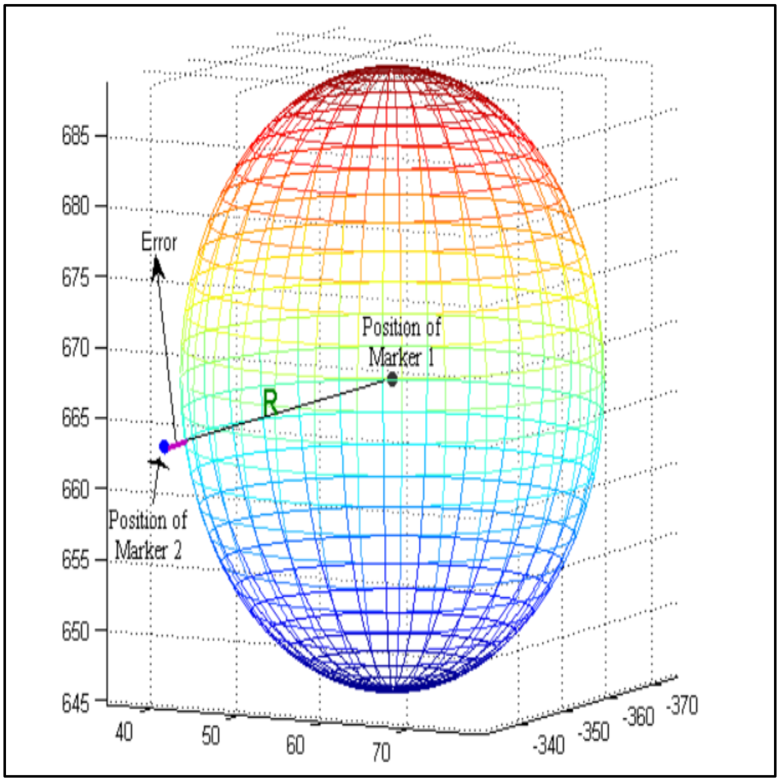


Figure 5.1. Proof of the precision error

Figure 5.1 demonstrates the precision error where the black dot is position of marker 1 and it is assumed as the center of the sphere; R is the radius of the sphere which is the distance between marker 1 and 2. As Figure 5.1 shows, the blue dot is the position of marker 2 which is not well fitted on the surface of the sphere and it passed over the surface meaning that the distance between marker 1 and 2 is more than the radius of sphere. The purple line that shows the small distance between marker 2 and the surface of the sphere is representing the precision error. The absolute value of this purple line or precision error varies each frame based on the type of the elemental error components which affected the precision of data.

5.4 ABSOLUTE VALUE OF EACH ELEMENTAL ERROR

In this section, the result of all experiments and error relationship with elemental error components which are due to the capture volume location, velocity and the non-rigidity of human body has been presented.

A. CAPTURE VOLUME LOCATION

The results about error due to the capture volume location from three experiments are presented in the following table:

Table 5.1 Capture volume location VS Error

Capture Volume location	Error of marker 1
1^{st} Location	0.02203_{mm}
2^{nd} Location	0.03022_{mm}
3^{rd} Location	0.04_{mm}

In the first experiment, where the location of the mechanism was close to the cameras number 2 and 3, the error is 0.02203_{mm}. In the second experiment, where the mechanism was close to cameras number 5 and 6, the error is 0.03022_{mm}. In the last experiment where the mechanism was in front of cameras 7 and 8, the error is 0.04_{mm}.

Based on the data presented in Table 5.1, it is obvious that different areas of the capture volume may cause different value of error. However, the calculated error associated with capture volume location in these three experiments are small indicating that two other elemental error components have bigger role.

B. VELOCITY

The results about error caused by velocity of markers displacement in three experiments are presented in the following table:

Table 5.2 Velocity VS Error

Experiment	Error
V_1=1000$_{mm/s}$	e_{21}=0.88$_{mm/s}$
V_2=800$_{mm/s}$	e_{22}=0.66$_{mm/s}$
V_3=500$_{mm/s}$	e_{23}=0.246$_{mm/s}$

In the first experiment when velocity is 1000$_{mm/s}$, the error is 0.88$_{mm/s}$. In the second try, the velocity is 800$_{mm/s}$ and the error is 0.66$_{mm/s}$. In the last experiment, the velocity is 500$_{mm/s}$ and the error is 0.246$_{mm/s}$.

Based on the data presented in Table 5.2, clearly faster displacement of markers add more error to the obtained data.

C. ERROR DUE THE NON-RIGIDITY OF BODY

The result about error due to the non-rigidity of human body has been presented in the following table:

Table 5.3 Non-rigidity of human body VS Error

Markers position on Body	**With L-frame**	**Without L-Frame**
Humerus	0.15_{mm}	1.32_{mm}
Scapula	0.12_{mm}	0.98_{mm}
Sternum	0.26_{mm}	0.38_{mm}

In the first experiment, the motion of Humerus has been captured in two different motion. In the first motion, L-Frame has been used to attach the markers on the bone and the error is 0.15_{mm}. In the second motion, the markers attached to the body without L-Frame and the error is 1.32_{mm}.

In the second experiment, the motion of Scapula has been captured in two separate motion. At first, L-Frame has been used and the error is 0.12_{mm}. Next motion captured without using L-Frame and error is 0.98_{mm}.

In the third experiment, the motion of the Sternum has been captured and the error in the motion that L-frame has been used is 0.26_{mm} and the motion that was without L-Frame gives the error of 0.38_{mm}.

Based on the data presented in the Table 5.3, the value of error goes up if the markers attach to the skin directly. L-Frame reduces the error in all three experiments meaning that the error due to the non-rigidity of body can be reduced, but it cannot diminish completely. Another significant point about the error due to the non-rigidity of body is that if the area of the body and bones that have less muscles movement around them provides less error. It is obvious that the Humerus which is surrounded by the arm muscles adds the biggest value of error to data and the Sternum that has less muscles movement around adds the least value of error to data.

5.5: COMBINING ELEMENTAL ERRORS

When we make measurement in laboratory, every measurement we make should also have some uncertainty which add or deduce an amount to the value we measured. If the amount of uncertainties is in the same unit with the value that has been measured, it is absolute uncertainty. Each elemental error combines with other areas of errors that increases the uncertainty of the measurement. A measurement of x which is subjected to have k elements of error, then the uncertainty caused by k elemental errors in the measurement of u_x can be calculated by the RSS method [14]:

$$u_x = \pm\sqrt{(e_1)^2 + (e_2)^2 + \cdots (ek)^2}$$ **Equation (6)**

Since we have three different elemental error components that are in the same unit as the value we measured in the laboratory, their average relationship over too many unknown possibilities is given by:

$$\delta = \sqrt{(\mathcal{E}_o)^2 + (e_1)^2 + (e_2)^2 + (e_3)^2}$$ **Equation (7)** [14]

Where δ represent the absolute uncertainties in data, $\mathcal{E}_o$ is the accuracy error by the cameras and e_1, e_2 and e_3 are the errors due to the capture volume location, velocity and non-rigidity of the body respectively.

The result based on Equation (7) has been presented in the following table. It should be noted that the result has been computed under two different criteria so that it makes it possible to define a lower and upper limit for the error.

Table 5.4 Upper limit and lower limit of error without accuracy error

Limit	Calculations	Absolute Value
Upper limit error for Humerus	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.88)^2 + (1.32)^2}$	1.67mm
Upper limit error for Scapula	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.88)^2 + (0.98)^2}$	1.41mm
Upper limit error for Sternum	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.88)^2 + (0.38)^2}$	1.08mm
Lower limit error for Humerus	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.246)^2 + (0.15)^2}$	0.58mm
Lower limit error for Scapula	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.246)^2 + (0.12)^2}$	0.57mm
Lower limit error for Sturnem	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.246)^2 + (0.26)^2}$	0.62mm

In Table 5.4, the upper limit errors have been computed with error due to the maximum velocity and error due to the non-rigidity of body without using L-Frame while lower limit errors have been computed with lowest error due to the velocity and non-rigidity of body error obtained with L-Frame. It is obvious that with lower velocity and by the use of L-Frame the error is almost 1mm lower.

There is one more scenario in finding the absolute value of error. Since the accuracy error is already included in the precision errors values, it seems reasonable to obtain the error by subtracting the accuracy error from the elemental error components and then compute the error. The result has been presented in the following table:

Table 5.5 Upper limit and lower limit of error including accuracy error

Limit	Calculations	Absolute Value
Upper limit error for Humerus	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.88 - 0.5)^2 + (1.32 - 0.5)^2}$	1.1mm
Upper limit error for Scapula	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.88 - 0.5)^2 + (0.98 - 0.5)^2}$	0.63mm
Upper limit error for Sturnem	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.88 - 0.5)^2 + (0.38 - 0.5)^2}$	0.41mm
Lower limit error for Humerus	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.246 - 0.5)^2 + (0.15 - 0.5)^2}$	0.44mm
Lower limit error for Scapula	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.246 - 0.5)^2 + (0.12 - 0.5)^2}$	0.46mm
Lower limit error for Sturnem	$\delta = \sqrt{(0.5)^2 + (0.04)^2 + (0.246 - 0.5)^2 + (0.26 - 0.5)^2}$	0.37mm

Table 5.5 demonstrates the result for the upper limit and lower limit of the error with respect to the subtraction of the accuracy error from the elemental error components values.

With respect to the result that has been found, the new form of Equation (6) for three different areas of the body which are Humerus, Scapula and Sternum has been presented in the following table:

Table 5.6 New form of equation (6)

Humerus	Scapula	Sternum
$P=p+1.67_{mm}$	$P=p+1.41_{mm}$	$P=p+1.08_{mm}$

Since this result presents the error in the measurement, ideally and from the mathematical point of view, we considered the biggest value of the error to form the new version of Equation (6) for these areas of the body where p represent the initial position and P represents the final position after error.

CHAPTER SIX - CONCLUSION AND FUTURE SCOPE

This chapter present conclusion along with the future scope of this research.

6.1 CONCLUSION

Velocity of the motion, Non-rigidity of the body and capture volume location are important parameters in terms of data precision in Vicon Motion Capture System. Error due to the velocity can increase to 0.88_{mm} in the worst case scenario. Depending on the velocity of the motion, the error in the data obtained from motion of Humerus can increase to 1.32_{mm} which can be decreased to 1.1_{mm} by using L-Frames in lower velocity range. The results in the other two areas of the body which are the Scapula and Sternum reach the same conclusion. Using L-Frame reduced the error from 1.41_{mm} to 0.57_{mm} and from 1.087 to 0.62_{mm} for the data obtained from Scapula and Sternum motions respectively.

Based on this research, reducing the velocity of the motion and use of the rigid L-Frames are effective methods to obtain more precise data from Vicon Motion Capture System™.

To sum up, the attempt to investigate the areas of errors regarding Vicon Motion Capture Data System™ and identify the absolute values of error followed by a handy explanation of the software and the system has been achieved.

6.2 FUTURE SCOPE

Error analysis is a vast area of research. In the research the impact of three elemental error components on data have been studied. The other areas of error that can be focused on are: distance of markers from each other, the distance of marker from the center of capture volume, number of markers in each segment [6], size of the markers, number of the cameras, system calibration, system aiming and system masking. Also, the biggest elemental error components which are non-rigidity of the body and velocity can be studied under these situations. Error due to the non-rigidity is different for each part of the body and can be a good area of research to focus and quantify the impact of it on precision of data. Since the velocity of motion impacts the precision of data as well, it is good to evaluate the effect of non-rigidity error in different velocities. This is a good method both to quantify the values of each error and define a range for the error associated with all parts of the body.

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APPENDIX A

EXCEL DATA SHEETS FOR ALL EXPERIMENTS:

Humerus1X	Humerus1Y	Humerus1Z	Humerus2X	Humerus2Y	Humerus2Z	Humerus3X	Humerus3Y	Humerus3Z
-109.673	127.033	543.077	-91.0384	132.768	554.442	-96.4704	110.59	536.759
-109.679	127.098	543.279	-91.0263	132.82	554.642	-96.4801	110.643	536.961
-110.019	127.583	543.55	-91.0371	132.843	554.838	-96.4946	110.693	537.145
-110.024	127.614	543.766	-91.0482	132.884	555.059	-95.8923	110.979	537.343
-109.993	127.647	543.995	-91.0699	132.947	555.301	-96.5349	110.811	537.594
-109.772	127.294	544.285	-91.0818	133.006	555.583	-96.5761	110.896	537.869
-110.08	127.764	544.676	-91.0881	133.07	555.871	-96.5933	110.962	538.141
-110.093	127.821	544.93	-91.0935	133.113	556.148	-96.0816	111.22	538.396
-110.056	127.752	545.19	-91.0877	133.163	556.425	-96.6373	111.075	538.676
-110.047	127.897	545.537	-91.0873	133.241	556.722	-96.6363	111.15	538.99
-109.826	127.697	545.893	-91.0747	133.365	557.061	-96.6398	111.271	539.338
-109.867	128.168	546.3	-91.0383	133.468	557.435	-96.6611	111.382	539.713
-109.844	127.985	546.689	-91.0221	133.587	557.803	-96.197	111.624	540.12
-110.064	128.608	547.192	-90.9945	133.668	558.181	-96.6629	111.527	540.51
-109.807	128.434	547.549	-90.9557	133.744	558.585	-96.6632	111.593	540.908
-109.831	128.461	548.019	-90.9006	133.807	559.013	-96.6371	111.69	541.342
-109.98	128.801	548.544	-90.8533	133.843	559.48	-96.5981	111.747	541.772
-109.722	128.629	548.982	-90.8164	133.909	559.956	-96.586	111.832	542.252
-109.726	128.659	549.468	-90.7724	133.964	560.413	-96.586	111.901	542.713
-109.91	128.956	549.972	-90.7683	133.982	560.849	-96.5796	111.95	543.113
-109.875	129.025	550.356	-90.7051	134.005	561.23	-96.5465	111.972	543.483
-109.647	128.726	550.692	-90.6345	133.994	561.587	-96.5084	111.994	543.847
-109.779	129.04	551.08	-90.6068	134.013	561.955	-96.4525	112.007	544.201
-109.744	129.111	551.487	-90.5466	134.086	562.32	-96.4339	112.103	544.56
-109.735	129.159	551.856	-90.503	134.159	562.692	-96.3824	112.142	544.953
-109.513	128.955	552.207	-90.4525	134.239	563.029	-96.343	112.196	545.306
-109.615	129.288	552.558	-90.3854	134.25	563.347	-96.3238	112.243	545.627
-109.576	129.277	552.898	-90.3117	134.285	563.652	-96.2678	112.267	545.933
-109.517	129.311	553.187	-90.2346	134.335	563.933	-96.2042	112.304	546.256
-109.428	129.418	553.491	-90.1609	134.415	564.253	-96.1608	112.383	546.564
-109.204	129.261	553.856	-90.1054	134.534	564.562	-95.6418	112.62	546.93
-109.368	129.617	554.244	-90.0153	134.626	564.866	-96.0493	112.551	547.235
-109.324	129.697	554.522	-89.9725	134.715	565.169	-96.0198	112.612	547.548
-109.255	129.75	554.809	-89.9165	134.803	565.453	-95.9788	112.692	547.837
-109.176	129.829	555.051	-89.8749	134.849	565.73	-95.9572	112.765	548.099
-108.965	129.62	555.357	-89.8379	134.893	565.983	-95.9228	112.818	548.359
-109.155	129.944	555.639	-89.7754	134.924	566.227	-95.8768	112.872	548.583
-109.128	129.983	555.875	-89.7514	134.972	566.459	-95.8438	112.935	548.815
-109.05	130.077	556.094	-89.7189	135.058	566.702	-95.8357	113.007	549.061
-109.01	130.135	556.331	-89.6894	135.129	566.947	-95.823	113.082	549.318
-108.795	129.915	556.593	-89.6702	135.183	567.189	-95.7934	113.144	549.564

-108.765	129.985	556.831	-89.6345	135.212	567.44	-95.7552	113.186	549.796
-108.736	130.016	557.087	-89.5568	135.255	567.648	-95.7274	113.207	550.021
-108.883	130.34	557.338	-89.5029	135.28	567.858	-95.6874	113.256	550.229
-108.819	130.395	557.551	-89.4538	135.332	568.088	-95.66	113.322	550.457
-108.766	130.47	557.751	-89.4008	135.433	568.291	-95.6119	113.376	550.708
-108.741	130.587	558.017	-89.3621	135.545	568.511	-95.5674	113.472	550.939
-108.533	130.388	558.25	-89.3021	135.681	568.727	-95.544	113.583	551.178
-108.523	130.483	558.497	-89.24	135.79	568.938	-95.5055	113.678	551.396
-108.489	130.588	558.709	-89.1928	135.878	569.139	-95.4896	113.756	551.626
-108.449	130.661	558.882	-89.1646	135.945	569.314	-95.4821	113.814	551.823
-108.411	130.708	559.028	-89.1408	135.975	569.462	-95.4472	113.858	551.957
-108.384	130.772	559.179	-89.1087	136.031	569.604	-95.4266	113.918	552.111
-108.364	130.841	559.347	-89.0838	136.088	569.748	-95.4167	113.995	552.255
-108.363	130.901	559.489	-89.0696	136.166	569.877	-95.4173	114.057	552.394
-108.363	130.952	559.586	-89.0731	136.215	569.975	-95.4286	114.098	552.495
-108.537	131.267	559.631	-89.0779	136.246	570.044	-95.4335	114.131	552.558
-108.567	131.292	559.727	-89.0877	136.288	570.113	-95.4439	114.179	552.631
-108.4	131.071	559.808	-89.0932	136.358	570.189	-95.4424	114.237	552.711
-108.641	131.428	559.938	-89.1094	136.424	570.257	-95.4587	114.283	552.79
-108.453	131.153	559.95	-89.1274	136.444	570.299	-95.4962	114.289	552.841
-108.694	131.382	560.018	-89.1523	136.396	570.332	-95.5165	114.255	552.856
-108.706	131.325	560.034	-89.171	136.299	570.373	-95.5436	114.213	552.852
-108.739	131.276	560.094	-89.1972	136.268	570.442	-95.5504	114.195	552.893
-108.746	131.338	560.201	-89.201	136.333	570.546	-95.5622	114.245	553.025
-108.761	131.467	560.32	-89.2236	136.442	570.668	-95.5922	114.324	553.193
-108.778	131.601	560.446	-89.2405	136.531	570.778	-95.6354	114.38	553.367
-108.797	131.677	560.541	-89.2664	136.606	570.889	-95.6594	114.421	553.493
-108.824	131.739	560.625	-89.2736	136.638	570.967	-95.6871	114.455	553.591
-108.6	131.374	560.746	-89.2644	136.668	571.052	-95.676	114.485	553.669
-108.579	131.427	560.83	-89.2682	136.727	571.133	-95.6736	114.533	553.751
-108.586	131.471	560.927	-89.243	136.79	571.198	-95.6815	114.587	553.845
-108.586	131.523	561.022	-89.2577	136.858	571.295	-95.688	114.645	553.966
-108.605	131.557	561.115	-89.2618	136.892	571.365	-95.7006	114.666	554.05
-108.614	131.567	561.177	-89.2952	136.89	571.441	-95.7136	114.682	554.103
-108.636	131.565	561.212	-89.3174	136.884	571.483	-95.7399	114.68	554.136
-108.658	131.564	561.245	-89.3272	136.875	571.522	-95.7637	114.691	554.153
-108.66	131.608	561.272	-89.3323	136.907	571.551	-95.7788	114.728	554.189
-108.663	131.679	561.313	-89.3431	136.984	571.599	-95.7844	114.785	554.24
-108.683	131.745	561.379	-89.3524	137.048	571.654	-95.7958	114.861	554.298
-108.698	131.8	561.414	-89.3652	137.094	571.686	-95.8038	114.923	554.326
-108.714	131.829	561.434	-89.3871	137.12	571.714	-95.8225	114.961	554.332
-108.728	131.893	561.419	-89.4016	137.165	571.713	-95.8482	115.013	554.323

-108.762	131.958	561.417	-89.434	137.228	571.701	-95.8829	115.084	554.309
-108.785	132.049	561.408	-89.4575	137.326	571.701	-95.9074	115.195	554.291
-108.793	132.211	561.395	-89.4753	137.462	571.689	-95.9311	115.312	554.297
-108.993	132.652	561.437	-89.4775	137.616	571.673	-95.9504	115.432	554.303
-108.799	132.495	561.394	-89.4685	137.769	571.655	-95.9454	115.557	554.309
-108.795	132.595	561.348	-89.4524	137.869	571.611	-95.9561	115.643	554.268
-108.796	132.667	561.276	-89.4726	137.914	571.585	-95.9437	115.715	554.2
-108.794	132.727	561.213	-89.4652	137.969	571.53	-95.9298	115.806	554.104
-109.009	133.126	561.212	-89.4611	138.065	571.494	-95.908	115.91	554.039
-108.985	133.295	561.155	-89.4466	138.234	571.484	-95.9173	116.083	554.04
-108.794	133.191	561.13	-89.4259	138.424	571.452	-95.9351	116.276	554.038
-108.794	133.343	561.103	-89.426	138.574	571.408	-95.9553	116.394	554.018
-108.815	133.451	561.057	-89.45	138.687	571.355	-95.9841	116.498	553.972
-108.843	133.539	560.997	-89.492	138.757	571.299	-96.0317	116.578	553.925
-108.88	133.628	560.946	-89.53	138.853	571.237	-96.0695	116.649	553.877
-109.101	134.009	560.889	-89.5822	138.957	571.178	-96.1201	116.727	553.855
-109.162	134.072	560.822	-89.6274	139.027	571.094	-96.1888	116.776	553.782
-109.244	134.06	560.687	-89.6976	139.004	570.978	-96.2581	116.773	553.662
-109.319	134.022	560.534	-89.758	138.933	570.836	-96.3121	116.73	553.478
-109.41	133.965	560.368	-89.8299	138.872	570.682	-96.3491	116.701	553.262
-109.459	134.002	560.215	-89.8791	138.889	570.502	-96.3779	116.707	553.09
-109.247	133.702	559.962	-89.9177	138.943	570.267	-96.417	116.707	552.917
-109.403	133.993	559.665	-89.9552	138.93	570.016	-96.4287	116.701	552.677
-109.492	133.958	559.371	-89.9622	138.891	569.707	-96.4611	116.665	552.355
-109.542	133.883	559.041	-89.9976	138.85	569.367	-96.496	116.623	552
-109.353	133.585	558.632	-90.0535	138.834	569.007	-96.529	116.59	551.651
-109.572	133.889	558.21	-90.1132	138.817	568.619	-96.5718	116.557	551.293
-109.693	133.829	557.833	-90.1516	138.768	568.184	-96.6153	116.524	550.841
-109.516	133.467	557.284	-90.2352	138.696	567.692	-96.6755	116.448	550.363
-109.753	133.647	556.725	-90.3244	138.565	567.198	-96.729	116.359	549.807
-109.824	133.502	556.176	-90.3709	138.463	566.606	-96.7549	116.234	549.22
-109.817	133.453	555.485	-90.4156	138.376	565.997	-96.8011	116.137	548.606
-109.922	133.363	554.907	-90.4817	138.301	565.361	-96.8479	116.051	547.985
-109.753	133.033	554.131	-90.5274	138.248	564.662	-96.8868	115.96	547.279
-110.003	133.19	553.336	-90.653	138.099	563.913	-96.9398	115.857	546.523
-109.93	132.732	552.466	-90.7377	137.932	563.081	-97.0359	115.696	545.656
-110.003	132.556	551.495	-90.8495	137.708	562.156	-97.1207	115.513	544.695
-110.288	132.615	550.468	-90.9906	137.46	561.179	-97.2129	115.3	543.654
-110.22	132.082	549.339	-91.103	137.218	560.099	-97.3056	115.056	542.535
-110.539	132.126	548.163	-91.2174	136.976	558.932	-97.3862	114.841	541.327
-110.621	131.902	546.807	-91.36	136.72	557.645	-97.4781	114.625	540
-110.746	131.668	545.288	-91.5248	136.445	556.205	-97.596	114.378	538.545

-110.865	131.313	543.601	-91.7226	136.091	554.606	-97.7373	114.027	536.908
-111.032	130.955	541.727	-91.9159	135.662	552.807	-97.8836	113.642	535.054
-111.227	130.456	539.66	-92.1593	135.166	550.795	-98.0691	113.161	532.993
-111.446	129.903	537.324	-92.3905	134.592	548.553	-98.2404	112.623	530.697
-111.668	129.374	534.723	-92.6525	133.975	546.081	-97.9657	112.258	528.124
-111.869	128.85	531.888	-92.9299	133.352	543.355	-98.6302	111.449	525.416
-112.106	128.174	528.846	-93.226	132.749	540.392	-98.4374	111.022	522.449
-112.434	127.54	525.519	-93.5801	132.13	537.198	-99.1335	110.213	519.307
-112.745	126.919	521.95	-93.967	131.442	533.729	-99.0638	109.617	515.886
-113.104	126.063	518.079	-94.4286	130.627	529.998	-99.3931	108.827	512.158
-113.546	125.208	513.938	-94.8787	129.731	525.976	-99.5249	108.136	507.858
-113.832	124.079	509.512	-95.3518	128.703	521.673	-99.852	107.032	503.601
-113.842	122.405	504.715	-95.7876	127.547	517.132	-100.109	105.824	499.073
-114.368	121.331	499.82	-96.2594	126.217	512.363	-100.423	104.435	494.342
-114.681	119.816	494.578	-96.7016	124.78	507.259	-100.668	102.907	489.319
-115.009	118.029	489.053	-97.1579	123.066	501.908	-100.941	101.119	484.029
-115.257	115.957	483.178	-97.56	121.142	496.19	-101.144	99.0383	478.411
-115.495	113.7	477.043	-97.9826	118.934	490.269	-101.247	96.7979	472.479
-115.655	111.291	470.707	-98.3129	116.608	484.13	-101.264	94.3994	466.411
-115.65	108.748	464.087	-98.5841	114.401	477.681	-101.167	91.8448	460.195
-115.271	105.671	457.304	-98.5905	111.693	471.093	-100.916	89.0711	453.793
-115.001	102.566	450.311	-98.5097	108.812	464.253	-100.522	85.9828	447.168
-114.57	99.0572	443.057	-98.3676	105.498	457.224	-99.9947	82.5363	440.285
-114.044	95.2013	435.639	-98.1382	101.767	450.05	-99.303	78.7532	433.173
-113.429	90.9866	428.093	-97.8056	97.7539	442.73	-98.5018	74.6521	425.936
-112.669	86.5589	420.423	-97.3851	93.4507	435.327	-97.6216	70.2955	418.633
-111.794	81.8518	412.755	-96.8202	88.9394	427.869	-96.5783	65.7275	411.262
-110.698	76.963	404.998	-96.0696	84.2727	420.348	-95.3786	60.9298	403.896
-109.402	71.8408	397.279	-95.0735	79.4017	412.773	-93.9574	55.892	396.556
-107.798	66.3801	389.44	-93.7788	74.2962	405.001	-92.2845	50.4958	389.17
-105.923	60.4658	381.563	-92.2463	68.6543	397.255	-90.2382	44.7125	381.7
-103.769	54.0656	373.562	-90.4837	62.533	389.479	-87.9266	38.4914	374.198
-101.408	47.2249	365.676	-88.6312	55.9606	381.804	-85.3944	31.8917	366.761
-98.934	40.1078	357.834	-86.5675	49.1888	374.155	-82.7552	25.022	359.406
-96.2814	32.6022	350.076	-84.3266	42.0244	366.457	-79.9753	17.7009	352.046
-93.3236	24.5922	342.118	-81.9103	34.3312	358.698	-76.9391	9.9237	344.627
-90.1204	16.1055	334.149	-79.1827	26.1576	350.868	-73.629	1.67051	337.15
-86.5536	7.2028	326.181	-76.1738	17.495	343.053	-69.9922	-6.99357	329.64
-82.7899	-2.04511	318.342	-72.8686	8.62426	335.317	-65.9772	-15.8379	322.375
-78.5109	-11.325	310.646	-69.2067	-0.307713	327.753	-61.6828	-24.8385	315.342
-73.908	-20.7147	303.233	-65.0262	-9.31104	320.298	-56.9315	-33.9697	308.482
-68.6529	-30.5366	295.826	-60.3755	-18.659	312.989	-51.634	-43.3783	301.732

-62.9023	-40.6797	288.67	-55.1446	-28.4576	305.783	-45.6565	-53.123	295.004
-56.5708	-51.2037	281.616	-49.5061	-38.6244	298.763	-39.1657	-63.167	288.433
-49.9568	-61.9726	274.799	-43.394	-48.959	291.942	-32.3756	-73.4183	282.087
-42.8989	-72.7499	268.227	-37.0245	-59.3999	285.318	-25.1451	-83.9884	275.958
-35.5906	-83.5923	261.935	-30.3102	-69.8528	278.93	-17.838	-94.2389	270.315
-27.7331	-94.4428	255.896	-23.2006	-80.263	272.832	-10.1567	-104.623	265.032
-19.6446	-105.369	250.461	-15.6471	-90.8251	267.118	-2.05673	-115.132	260.141
-10.9517	-116.509	245.346	-7.65405	-101.541	261.847	6.53548	-125.78	255.743
-1.7801	-127.814	240.839	0.815813	-112.484	257.068	15.594	-136.561	251.837
7.85615	-139.097	236.891	9.73115	-123.446	252.859	25.1474	-147.294	248.525
17.8344	-150.347	233.627	19.0445	-134.292	249.242	34.9588	-157.999	245.89
28.1206	-161.566	231.051	28.7062	-145.116	246.237	45.0565	-168.623	243.922
38.7221	-172.843	229.058	38.606	-156.03	243.8	55.4156	-179.317	242.561
49.6577	-184.262	227.672	48.8719	-167.075	241.942	66.1165	-190.088	241.749
60.9498	-195.725	226.9	59.3921	-178.245	240.748	77.1509	-200.901	241.568
72.5183	-207.135	226.913	70.2363	-189.358	240.216	88.5158	-211.565	242.073
84.2486	-218.539	227.577	81.2707	-200.328	240.474	100.082	-221.993	243.226
96.361	-229.32	228.824	92.6111	-210.989	241.334	111.795	-232.177	245.163
108.243	-240.244	231.395	104.008	-221.37	242.819	123.627	-241.993	247.662
120.583	-250.303	233.924	115.614	-231.255	244.869	135.414	-251.31	250.829
132.734	-260.083	237.372	127.207	-240.725	247.448	147.13	-260.286	254.599
145.057	-269.382	241.137	138.883	-249.949	250.651	158.8	-269.016	259.027
157.439	-278.795	246.087	150.683	-259.036	254.652	170.712	-277.47	264.07
169.932	-287.845	251.597	162.436	-268.061	259.462	182.717	-285.658	269.811
182.498	-296.705	257.704	174.176	-276.684	264.93	194.663	-293.479	276.195
194.53	-304.778	264.309	185.646	-284.734	271.027	206.284	-300.812	283.09
206.336	-312.368	271.499	196.905	-292.437	277.424	217.528	-307.619	290.523
217.817	-319.495	279.264	208.072	-299.474	284.249	228.516	-314.023	298.355
229.357	-326.105	287.497	218.939	-306.266	291.688	239.471	-319.788	306.355
240.561	-332.434	296.236	229.68	-312.647	299.616	250.091	-325.602	315.279
251.505	-338.377	305.382	240.053	-318.825	308.122	260.727	-330.652	324.147
262.07	-343.874	314.829	250.179	-324.493	316.87	270.901	-335.451	333.479
272.093	-348.889	324.368	259.768	-329.668	325.746	280.328	-340.077	343.308
281.616	-353.066	333.6	268.811	-334.323	334.629	289.376	-343.807	352.569
290.422	-357.232	343.413	277.452	-338.409	343.533	297.918	-347.082	361.727
298.93	-360.706	353.046	285.665	-342.064	352.516	305.914	-350.147	371.394
307.155	-363.502	362.474	293.484	-345.341	361.63	313.785	-352.477	380.619
314.766	-366.134	372.077	300.759	-348.257	370.716	320.984	-354.665	390.152
321.729	-368.358	381.292	307.475	-350.772	379.458	327.691	-356.374	399.137
328.04	-370.236	390.044	313.546	-353.009	387.712	333.832	-357.599	407.455
333.644	-372.063	398.471	319.125	-354.727	395.428	338.948	-359.076	415.914
338.909	-373.079	405.983	324.241	-356.149	402.722	344.115	-359.73	423.006

343.736	-374.032	413.353	329.104	-357.294	409.617	348.671	-360.448	430.222
348.21	-375.024	420.623	333.401	-358.254	416.387	352.984	-360.855	437.043
352.237	-375.354	426.951	337.28	-359.03	422.638	356.762	-361.295	443.576
355.806	-375.79	432.932	340.788	-359.66	428.382	360.18	-361.49	449.38
358.889	-376.359	438.536	343.812	-360.09	433.521	363.195	-361.574	454.635
361.753	-376.248	443.29	346.624	-360.325	438.202	365.876	-361.557	459.455
364.337	-376.281	447.929	349.187	-360.493	442.651	368.382	-361.4	463.943
366.727	-376.231	452.191	351.521	-360.589	446.744	370.797	-361.078	467.893
368.846	-376.216	456.076	353.515	-360.74	450.513	372.789	-360.999	471.782
370.656	-376.211	459.472	355.234	-360.919	453.813	374.557	-360.857	475.006
372.101	-376.261	462.374	356.743	-360.983	456.562	375.994	-360.748	477.836
373.343	-376.215	464.888	357.999	-360.991	458.923	377.13	-360.639	480.276
374.423	-376.066	467.088	359.098	-360.93	460.953	378.141	-360.5	482.416
375.409	-376	469.073	360.141	-360.853	462.777	379.085	-360.312	484.333
376.363	-375.869	470.86	361.054	-360.757	464.529	380.011	-360.112	486.059
377.147	-375.759	472.449	361.666	-360.653	466.214	380.75	-359.969	487.574
377.76	-375.719	473.731	362.204	-360.669	467.445	381.279	-359.898	488.81
378.19	-375.669	474.77	362.678	-360.611	468.458	381.73	-359.837	489.861
378.507	-375.825	475.997	363.115	-360.492	469.399	382.139	-359.666	490.809
379.053	-375.376	476.712	363.487	-360.397	470.343	382.57	-359.464	491.694
379.321	-375.528	477.786	363.81	-360.316	471.227	382.955	-359.297	492.513
379.688	-375.111	478.243	364.089	-360.212	471.862	383.259	-359.15	493.139
379.824	-375.051	478.748	364.272	-360.138	472.367	383.338	-359.082	493.685
379.855	-375.259	479.428	364.427	-360.046	472.715	383.426	-358.98	494.104
380.127	-374.813	479.63	364.607	-359.913	473.114	383.589	-358.817	494.52
380.27	-374.681	480.088	364.719	-359.811	473.581	383.723	-358.675	494.983
380.456	-374.599	480.528	364.877	-359.73	474.008	383.854	-358.55	495.375
380.475	-374.838	481.164	365.019	-359.669	474.341	384.04	-358.463	495.741
380.715	-374.473	481.195	365.165	-359.635	474.637	384.194	-358.396	495.995
380.891	-374.397	481.439	365.329	-359.558	474.874	384.389	-358.319	496.235
381.101	-374.312	481.657	365.317	-359.562	475.132	384.595	-358.206	496.425
381.25	-374.205	481.772	365.585	-359.394	475.256	384.754	-358.099	496.545
381.264	-374.109	481.816	365.644	-359.27	475.277	384.795	-358.014	496.58
381.233	-374.018	481.744	365.632	-359.156	475.2	384.778	-357.915	496.533
381.235	-373.911	481.64	365.652	-359.049	475.107	384.78	-357.823	496.443
381.3	-373.76	481.587	365.738	-358.87	475.06	384.937	-357.543	496.177
381.392	-373.588	481.508	365.807	-358.707	475.032	384.986	-357.472	496.257
381.469	-373.43	481.385	365.882	-358.546	474.918	385.047	-357.33	496.19
381.499	-373.267	481.16	365.881	-358.419	474.706	385.078	-357.206	495.971
381.467	-373.158	480.835	365.832	-358.309	474.384	385.042	-357.093	495.587
381.427	-373.087	480.503	365.85	-358.184	474.04	385.028	-357.005	495.264
381.423	-372.938	480.174	365.852	-358.019	473.729	385.046	-356.867	494.949

381.37	-373.043	480.079	365.881	-357.828	473.44	385.11	-356.716	494.65
381.457	-372.61	479.496	365.889	-357.665	473.125	385.134	-356.556	494.298
381.438	-372.425	479.055	365.847	-357.498	472.693	385.072	-356.419	493.866
381.315	-372.317	478.569	365.723	-357.366	472.211	384.944	-356.343	493.487
381.17	-372.221	478.061	365.632	-357.243	471.724	384.848	-356.245	492.944
381.091	-372.102	477.597	365.576	-357.114	471.266	384.757	-356.182	492.513
381.073	-371.99	477.166	365.516	-356.979	470.813	384.704	-356.076	492.074
380.96	-371.896	476.713	365.248	-356.953	470.424	384.66	-355.971	491.659
380.861	-371.768	476.265	365.31	-356.759	469.994	384.592	-355.867	491.212
380.769	-371.695	475.814	365.222	-356.651	469.538	384.542	-355.735	490.68
380.635	-371.883	475.56	365.122	-356.551	469.11	384.467	-355.707	490.266
380.599	-371.528	474.864	365.035	-356.451	468.695	384.376	-355.668	489.89
380.508	-371.415	474.44	364.973	-356.321	468.242	384.306	-355.576	489.447
380.453	-371.348	473.967	364.97	-356.27	467.726	384.248	-355.464	488.953
380.342	-371.268	473.547	364.882	-356.227	467.302	384.182	-355.416	488.537
380.219	-371.238	473.072	364.742	-356.195	466.865	384.069	-355.399	488.076
380.068	-371.463	472.816	364.634	-356.102	466.411	383.92	-355.397	487.635
380.027	-371.205	472.184	364.558	-356.077	465.988	383.828	-355.397	487.241
379.885	-371.186	471.845	364.502	-356.074	465.647	383.77	-355.381	486.894
379.808	-371.146	471.513	364.271	-356.082	465.342	383.714	-355.339	486.57
379.698	-371.097	471.207	364.258	-356.038	465.07	383.605	-355.328	486.258
379.563	-371.08	470.855	364.079	-356.013	464.748	383.443	-355.361	485.951
379.383	-371.126	470.496	363.884	-356.015	464.487	383.251	-355.396	485.671
379.172	-371.357	470.441	363.736	-356.017	464.227	383.092	-355.406	485.411
379.011	-371.357	470.26	363.585	-355.998	464.037	382.937	-355.451	485.279
378.884	-371.346	470.093	363.45	-356.003	463.865	382.818	-355.472	485.098
378.716	-371.157	469.713	363.307	-356.02	463.642	382.706	-355.476	484.858
378.507	-371.226	469.541	363.176	-356.045	463.416	382.509	-355.55	484.708
378.356	-371.321	469.406	363.017	-356.121	463.302	382.321	-355.628	484.586
378.228	-371.406	469.281	362.879	-356.17	463.204	382.175	-355.714	484.496
378.107	-371.477	469.205	362.776	-356.216	463.118	382.036	-355.8	484.408
377.969	-371.553	469.17	362.681	-356.287	463.034	381.94	-355.855	484.34
377.849	-371.612	469.144	362.551	-356.377	463	381.831	-355.92	484.286
377.719	-371.669	469.107	362.405	-356.454	463.025	381.738	-355.998	484.251
377.6	-371.949	469.238	362.263	-356.565	462.987	381.618	-356.083	484.203
377.447	-372.062	469.138	362.124	-356.638	462.896	381.471	-356.177	484.124
377.301	-372.153	469.014	361.974	-356.698	462.784	381.318	-356.257	484.018
377.139	-372.236	468.937	361.857	-356.737	462.681	381.182	-356.337	483.938
377.019	-372.288	468.864	361.771	-356.794	462.621	381.074	-356.388	483.864
376.876	-372.361	468.796	361.643	-356.832	462.555	380.962	-356.47	483.792
376.697	-372.432	468.677	361.504	-356.907	462.444	380.822	-356.548	483.687
376.51	-372.311	468.322	361.255	-356.988	462.325	380.612	-356.66	483.543

376.348	-372.4	468.133	361.043	-357.084	462.175	380.378	-356.769	483.391
376.162	-372.481	468.01	360.869	-357.18	462.044	380.185	-356.856	483.266
376.013	-372.534	467.932	360.733	-357.247	461.956	380.08	-356.928	483.162
375.841	-372.632	467.873	360.591	-357.3	461.914	379.973	-357.006	483.07
375.623	-372.745	467.776	360.402	-357.365	461.793	379.821	-357.089	482.937
375.362	-372.859	467.6	360.166	-357.432	461.612	379.559	-357.204	482.76
375.106	-372.925	467.389	359.939	-357.454	461.405	379.292	-357.303	482.582
374.848	-372.977	467.239	359.732	-357.508	461.249	379.071	-357.359	482.427
374.652	-373.02	467.095	359.5	-357.578	461.136	378.854	-357.43	482.305
374.451	-373.064	466.963	359.264	-357.682	461.039	378.645	-357.493	482.188
374.244	-373.134	466.844	359.033	-357.747	460.954	378.441	-357.556	482.064
374.03	-373.23	466.717	358.832	-357.797	460.821	378.22	-357.662	481.996
373.792	-373.315	466.56	358.651	-357.868	460.67	378.135	-357.592	481.613
373.58	-373.371	466.392	358.428	-357.897	460.508	377.837	-357.774	481.606
373.353	-373.388	466.27	358.252	-357.91	460.357	377.647	-357.821	481.462
373.185	-373.374	466.094	358.068	-357.911	460.207	377.465	-357.841	481.302
372.972	-373.404	465.903	357.908	-357.892	460.031	377.306	-357.844	481.111
372.731	-373.639	465.847	357.662	-357.888	459.783	377.083	-357.864	480.871
372.49	-373.645	465.55	357.414	-357.919	459.513	376.814	-357.924	480.622
372.219	-373.683	465.308	357.163	-357.944	459.289	376.582	-357.976	480.398

Following excel data sheets are

Speed Test 1, 2 ,3

Respectively.

Humerus1x	Humerus1Y	Humerus1Z	Humerus2X	Humerus2Y	Humerus2Z	Humerus3X	Humerus3Y	Humerus3Z
-106.673	130.033	546.077	-88.0384	135.768	557.442	-93.4704	113.59	539.759
-106.679	130.098	546.279	-88.0263	135.82	557.642	-93.4801	113.643	539.961
-107.019	130.583	546.55	-88.0371	135.843	557.838	-93.4946	113.693	540.145
-107.024	130.614	546.766	-88.0482	135.884	558.059	-92.8923	113.979	540.343
-106.993	130.647	546.995	-88.0699	135.947	558.301	-93.5349	113.811	540.594
-106.772	130.294	547.285	-88.0818	136.006	558.583	-93.5761	113.896	540.869
-107.08	130.764	547.676	-88.0881	136.07	558.871	-93.5933	113.962	541.141
-107.093	130.821	547.93	-88.0935	136.113	559.148	-93.0816	114.22	541.396
-107.056	130.752	548.19	-88.0877	136.163	559.425	-93.6373	114.075	541.676
-107.047	130.897	548.537	-88.0873	136.241	559.722	-93.6363	114.15	541.99
-106.826	130.697	548.893	-88.0747	136.365	560.061	-93.6398	114.271	542.338
-106.867	131.168	549.3	-88.0383	136.468	560.435	-93.6611	114.382	542.713
-106.844	130.985	549.689	-88.0221	136.587	560.803	-93.197	114.624	543.12
-107.064	131.608	550.192	-87.9945	136.668	561.181	-93.6629	114.527	543.51
-106.807	131.434	550.549	-87.9557	136.744	561.585	-93.6632	114.593	543.908
-106.831	131.461	551.019	-87.9006	136.807	562.013	-93.6371	114.69	544.342
-106.98	131.801	551.544	-87.8533	136.843	562.48	-93.5981	114.747	544.772
-106.722	131.629	551.982	-87.8164	136.909	562.956	-93.586	114.832	545.252
-106.726	131.659	552.468	-87.7724	136.964	563.413	-93.586	114.901	545.713
-106.91	131.956	552.972	-87.7683	136.982	563.849	-93.5796	114.95	546.113
-106.875	132.025	553.356	-87.7051	137.005	564.23	-93.5465	114.972	546.483
-106.647	131.726	553.692	-87.6345	136.994	564.587	-93.5084	114.994	546.847
-106.779	132.04	554.08	-87.6068	137.013	564.955	-93.4525	115.007	547.201
-106.744	132.111	554.487	-87.5466	137.086	565.32	-93.4339	115.103	547.56
-106.735	132.159	554.856	-87.503	137.159	565.692	-93.3824	115.142	547.953
-106.513	131.955	555.207	-87.4525	137.239	566.029	-93.343	115.196	548.306
-106.615	132.288	555.558	-87.3854	137.25	566.347	-93.3238	115.243	548.627
-106.576	132.277	555.898	-87.3117	137.285	566.652	-93.2678	115.267	548.933
-106.517	132.311	556.187	-87.2346	137.335	566.933	-93.2042	115.304	549.256
-106.428	132.418	556.491	-87.1609	137.415	567.253	-93.1608	115.383	549.564
-106.204	132.261	556.856	-87.1054	137.534	567.562	-92.6418	115.62	549.93
-106.368	132.617	557.244	-87.0153	137.626	567.866	-93.0493	115.551	550.235
-106.324	132.697	557.522	-86.9725	137.715	568.169	-93.0198	115.612	550.548
-106.255	132.75	557.809	-86.9165	137.803	568.453	-92.9788	115.692	550.837
-106.176	132.829	558.051	-86.8749	137.849	568.73	-92.9572	115.765	551.099
-105.965	132.62	558.357	-86.8379	137.893	568.983	-92.9228	115.818	551.359
-106.155	132.944	558.639	-86.7754	137.924	569.227	-92.8768	115.872	551.583
-106.128	132.983	558.875	-86.7514	137.972	569.459	-92.8438	115.935	551.815
-106.05	133.077	559.094	-86.7189	138.058	569.702	-92.8357	116.007	552.061
-106.01	133.135	559.331	-86.6894	138.129	569.947	-92.823	116.082	552.318
-105.795	132.915	559.593	-86.6702	138.183	570.189	-92.7934	116.144	552.564
-105.765	132.985	559.831	-86.6345	138.212	570.44	-92.7552	116.186	552.796

-105.736	133.016	560.087	-86.5568	138.255	570.648	-92.7274	116.207	553.021
-105.883	133.34	560.338	-86.5029	138.28	570.858	-92.6874	116.256	553.229
-105.819	133.395	560.551	-86.4538	138.332	571.088	-92.66	116.322	553.457
-105.766	133.47	560.751	-86.4008	138.433	571.291	-92.6119	116.376	553.708
-105.741	133.587	561.017	-86.3621	138.545	571.511	-92.5674	116.472	553.939
-105.533	133.388	561.25	-86.3021	138.681	571.727	-92.544	116.583	554.178
-105.523	133.483	561.497	-86.24	138.79	571.938	-92.5055	116.678	554.396
-105.489	133.588	561.709	-86.1928	138.878	572.139	-92.4896	116.756	554.626
-105.449	133.661	561.882	-86.1646	138.945	572.314	-92.4821	116.814	554.823
-105.411	133.708	562.028	-86.1408	138.975	572.462	-92.4472	116.858	554.957
-105.384	133.772	562.179	-86.1087	139.031	572.604	-92.4266	116.918	555.111
-105.364	133.841	562.347	-86.0838	139.088	572.748	-92.4167	116.995	555.255
-105.363	133.901	562.489	-86.0696	139.166	572.877	-92.4173	117.057	555.394
-105.363	133.952	562.586	-86.0731	139.215	572.975	-92.4286	117.098	555.495
-105.537	134.267	562.631	-86.0779	139.246	573.044	-92.4335	117.131	555.558
-105.567	134.292	562.727	-86.0877	139.288	573.113	-92.4439	117.179	555.631
-105.4	134.071	562.808	-86.0932	139.358	573.189	-92.4424	117.237	555.711
-105.641	134.428	562.938	-86.1094	139.424	573.257	-92.4587	117.283	555.79
-105.453	134.153	562.95	-86.1274	139.444	573.299	-92.4962	117.289	555.841
-105.694	134.382	563.018	-86.1523	139.396	573.332	-92.5165	117.255	555.856
-105.706	134.325	563.034	-86.171	139.299	573.373	-92.5436	117.213	555.852
-105.739	134.276	563.094	-86.1972	139.268	573.442	-92.5504	117.195	555.893
-105.746	134.338	563.201	-86.201	139.333	573.546	-92.5622	117.245	556.025
-105.761	134.467	563.32	-86.2236	139.442	573.668	-92.5922	117.324	556.193
-105.778	134.601	563.446	-86.2405	139.531	573.778	-92.6354	117.38	556.367
-105.797	134.677	563.541	-86.2664	139.606	573.889	-92.6594	117.421	556.493
-105.824	134.739	563.625	-86.2736	139.638	573.967	-92.6871	117.455	556.591
-105.6	134.374	563.746	-86.2644	139.668	574.052	-92.676	117.485	556.669
-105.579	134.427	563.83	-86.2682	139.727	574.133	-92.6736	117.533	556.751
-105.586	134.471	563.927	-86.243	139.79	574.198	-92.6815	117.587	556.845
-105.586	134.523	564.022	-86.2577	139.858	574.295	-92.688	117.645	556.966
-105.605	134.557	564.115	-86.2618	139.892	574.365	-92.7006	117.666	557.05
-105.614	134.567	564.177	-86.2952	139.89	574.441	-92.7136	117.682	557.103
-105.636	134.565	564.212	-86.3174	139.884	574.483	-92.7399	117.68	557.136
-105.658	134.564	564.245	-86.3272	139.875	574.522	-92.7637	117.691	557.153
-105.66	134.608	564.272	-86.3323	139.907	574.551	-92.7788	117.728	557.189
-105.663	134.679	564.313	-86.3431	139.984	574.599	-92.7844	117.785	557.24
-105.683	134.745	564.379	-86.3524	140.048	574.654	-92.7958	117.861	557.298
-105.698	134.8	564.414	-86.3652	140.094	574.686	-92.8038	117.923	557.326
-105.714	134.829	564.434	-86.3871	140.12	574.714	-92.8225	117.961	557.332
-105.728	134.893	564.419	-86.4016	140.165	574.713	-92.8482	118.013	557.323
-105.762	134.958	564.417	-86.434	140.228	574.701	-92.8829	118.084	557.309
-105.785	135.049	564.408	-86.4575	140.326	574.701	-92.9074	118.195	557.291

-105.793	135.211	564.395	-86.4753	140.462	574.689	-92.9311	118.312	557.297
-105.993	135.652	564.437	-86.4775	140.616	574.673	-92.9504	118.432	557.303
-105.799	135.495	564.394	-86.4685	140.769	574.655	-92.9454	118.557	557.309
-105.795	135.595	564.348	-86.4524	140.869	574.611	-92.9561	118.643	557.268
-105.796	135.667	564.276	-86.4726	140.914	574.585	-92.9437	118.715	557.2
-105.794	135.727	564.213	-86.4652	140.969	574.53	-92.9298	118.806	557.104
-106.009	136.126	564.212	-86.4611	141.065	574.494	-92.908	118.91	557.039
-105.985	136.295	564.155	-86.4466	141.234	574.484	-92.9173	119.083	557.04
-105.794	136.191	564.13	-86.4259	141.424	574.452	-92.9351	119.276	557.038
-105.794	136.343	564.103	-86.426	141.574	574.408	-92.9553	119.394	557.018
-105.815	136.451	564.057	-86.45	141.687	574.355	-92.9841	119.498	556.972
-105.843	136.539	563.997	-86.492	141.757	574.299	-93.0317	119.578	556.925
-105.88	136.628	563.946	-86.53	141.853	574.237	-93.0695	119.649	556.877
-106.101	137.009	563.889	-86.5822	141.957	574.178	-93.1201	119.727	556.855
-106.162	137.072	563.822	-86.6274	142.027	574.094	-93.1888	119.776	556.782
-106.244	137.06	563.687	-86.6976	142.004	573.978	-93.2581	119.773	556.662
-106.319	137.022	563.534	-86.758	141.933	573.836	-93.3121	119.73	556.478
-106.41	136.965	563.368	-86.8299	141.872	573.682	-93.3491	119.701	556.262
-106.459	137.002	563.215	-86.8791	141.889	573.502	-93.3779	119.707	556.09
-106.247	136.702	562.962	-86.9177	141.943	573.267	-93.417	119.707	555.917
-106.403	136.993	562.665	-86.9552	141.93	573.016	-93.4287	119.701	555.677
-106.492	136.958	562.371	-86.9622	141.891	572.707	-93.4611	119.665	555.355
-106.542	136.883	562.041	-86.9976	141.85	572.367	-93.496	119.623	555
-106.353	136.585	561.632	-87.0535	141.834	572.007	-93.529	119.59	554.651
-106.572	136.889	561.21	-87.1132	141.817	571.619	-93.5718	119.557	554.293
-106.693	136.829	560.833	-87.1516	141.768	571.184	-93.6153	119.524	553.841
-106.516	136.467	560.284	-87.2352	141.696	570.692	-93.6755	119.448	553.363
-106.753	136.647	559.725	-87.3244	141.565	570.198	-93.729	119.359	552.807
-106.824	136.502	559.176	-87.3709	141.463	569.606	-93.7549	119.234	552.22
-106.817	136.453	558.485	-87.4156	141.376	568.997	-93.8011	119.137	551.606
-106.922	136.363	557.907	-87.4817	141.301	568.361	-93.8479	119.051	550.985
-106.753	136.033	557.131	-87.5274	141.248	567.662	-93.8868	118.96	550.279
-107.003	136.19	556.336	-87.653	141.099	566.913	-93.9398	118.857	549.523
-106.93	135.732	555.466	-87.7377	140.932	566.081	-94.0359	118.696	548.656
-107.003	135.556	554.495	-87.8495	140.708	565.156	-94.1207	118.513	547.695
-107.288	135.615	553.468	-87.9906	140.46	564.179	-94.2129	118.3	546.654
-107.22	135.082	552.339	-88.103	140.218	563.099	-94.3056	118.056	545.535
-107.539	135.126	551.163	-88.2174	139.976	561.932	-94.3862	117.841	544.327
-107.621	134.902	549.807	-88.36	139.72	560.645	-94.4781	117.625	543
-107.746	134.668	548.288	-88.5248	139.445	559.205	-94.596	117.378	541.545
-107.865	134.313	546.601	-88.7226	139.091	557.606	-94.7373	117.027	539.908
-108.032	133.955	544.727	-88.9159	138.662	555.807	-94.8836	116.642	538.054
-108.227	133.456	542.66	-89.1593	138.166	553.795	-95.0691	116.161	535.993

-108.446	132.903	540.324	-89.3905	137.592	551.553	-95.2404	115.623	533.697
-108.668	132.374	537.723	-89.6525	136.975	549.081	-94.9657	115.258	531.124
-108.869	131.85	534.888	-89.9299	136.352	546.355	-95.6302	114.449	528.416
-109.106	131.174	531.846	-90.226	135.749	543.392	-95.4374	114.022	525.449
-109.434	130.54	528.519	-90.5801	135.13	540.198	-96.1335	113.213	522.307
-109.745	129.919	524.95	-90.967	134.442	536.729	-96.0638	112.617	518.886
-110.104	129.063	521.079	-91.4286	133.627	532.998	-96.3931	111.827	515.158
-110.546	128.208	516.938	-91.8787	132.731	528.976	-96.5249	111.136	510.858
-110.832	127.079	512.512	-92.3518	131.703	524.673	-96.852	110.032	506.601
-110.842	125.405	507.715	-92.7876	130.547	520.132	-97.109	108.824	502.073
-111.368	124.331	502.82	-93.2594	129.217	515.363	-97.423	107.435	497.342
-111.681	122.816	497.578	-93.7016	127.78	510.259	-97.668	105.907	492.319
-112.009	121.029	492.053	-94.1579	126.066	504.908	-97.941	104.119	487.029
-112.257	118.957	486.178	-94.56	124.142	499.19	-98.144	102.0383	481.411
-112.495	116.7	480.043	-94.9826	121.934	493.269	-98.247	99.7979	475.479
-112.655	114.291	473.707	-95.3129	119.608	487.13	-98.264	97.3994	469.411
-112.65	111.748	467.087	-95.5841	117.401	480.681	-98.167	94.8448	463.195
-112.271	108.671	460.304	-95.5905	114.693	474.093	-97.916	92.0711	456.793
-112.001	105.566	453.311	-95.5097	111.812	467.253	-97.522	88.9828	450.168
-111.57	102.0572	446.057	-95.3676	108.498	460.224	-96.9947	85.5363	443.285
-111.044	98.2013	438.639	-95.1382	104.767	453.05	-96.303	81.7532	436.173
-110.429	93.9866	431.093	-94.8056	100.7539	445.73	-95.5018	77.6521	428.936
-109.669	89.5589	423.423	-94.3851	96.4507	438.327	-94.6216	73.2955	421.633
-108.794	84.8518	415.755	-93.8202	91.9394	430.869	-93.5783	68.7275	414.262
-107.698	79.963	407.998	-93.0696	87.2727	423.348	-92.3786	63.9298	406.896
-106.402	74.8408	400.279	-92.0735	82.4017	415.773	-90.9574	58.892	399.556
-104.798	69.3801	392.44	-90.7788	77.2962	408.001	-89.2845	53.4958	392.17
-102.923	63.4658	384.563	-89.2463	71.6543	400.255	-87.2382	47.7125	384.7
-100.769	57.0656	376.562	-87.4837	65.533	392.479	-84.9266	41.4914	377.198
-98.408	50.2249	368.676	-85.6312	58.9606	384.804	-82.3944	34.8917	369.761
-95.934	43.1078	360.834	-83.5675	52.1888	377.155	-79.7552	28.022	362.406
-93.2814	35.6022	353.076	-81.3266	45.0244	369.457	-76.9753	20.7009	355.046
-90.3236	27.5922	345.118	-78.9103	37.3312	361.698	-73.9391	12.9237	347.627
-87.1204	19.1055	337.149	-76.1827	29.1576	353.868	-70.629	4.67051	340.15
-83.5536	10.2028	329.181	-73.1738	20.495	346.053	-66.9922	-3.99357	332.64
-79.7899	0.95489	321.342	-69.8686	11.62426	338.317	-62.9772	-12.8379	325.375
-75.5109	-8.325	313.646	-66.2067	2.692287	330.753	-58.6828	-21.8385	318.342
-70.908	-17.7147	306.233	-62.0262	-6.31104	323.298	-53.9315	-30.9697	311.482
-65.6529	-27.5366	298.826	-57.3755	-15.659	315.989	-48.634	-40.3783	304.732
-59.9023	-37.6797	291.67	-52.1446	-25.4576	308.783	-42.6565	-50.123	298.004
-53.5708	-48.2037	284.616	-46.5061	-35.6244	301.763	-36.1657	-60.167	291.433
-46.9568	-58.9726	277.799	-40.394	-45.959	294.942	-29.3756	-70.4183	285.087
-39.8989	-69.7499	271.227	-34.0245	-56.3999	288.318	-22.1451	-80.9884	278.958

-32.5906	-80.5923	264.935	-27.3102	-66.8528	281.93	-14.838	-91.2389	273.315
-24.7331	-91.4428	258.896	-20.2006	-77.263	275.832	-7.1567	-101.623	268.032
-16.6446	-102.369	253.461	-12.6471	-87.8251	270.118	0.94327	-112.132	263.141
-7.9517	-113.509	248.346	-4.65405	-98.541	264.847	9.53548	-122.78	258.743
1.2199	-124.814	243.839	3.815813	-109.484	260.068	18.594	-133.561	254.837
10.85615	-136.097	239.891	12.73115	-120.446	255.859	28.1474	-144.294	251.525
20.8344	-147.347	236.627	22.0445	-131.292	252.242	37.9588	-154.999	248.89
31.1206	-158.566	234.051	31.7062	-142.116	249.237	48.0565	-165.623	246.922
41.7221	-169.843	232.058	41.606	-153.03	246.8	58.4156	-176.317	245.561
52.6577	-181.262	230.672	51.8719	-164.075	244.942	69.1165	-187.088	244.749
63.9498	-192.725	229.9	62.3921	-175.245	243.748	80.1509	-197.901	244.568
75.5183	-204.135	229.913	73.2363	-186.358	243.216	91.5158	-208.565	245.073
87.2486	-215.539	230.577	84.2707	-197.328	243.474	103.082	-218.993	246.226
99.361	-226.32	231.824	95.6111	-207.989	244.334	114.795	-229.177	248.163
111.243	-237.244	234.395	107.008	-218.37	245.819	126.627	-238.993	250.662
123.583	-247.303	236.924	118.614	-228.255	247.869	138.414	-248.31	253.829
135.734	-257.083	240.372	130.207	-237.725	250.448	150.13	-257.286	257.599
148.057	-266.382	244.137	141.883	-246.949	253.651	161.8	-266.016	262.027
160.439	-275.795	249.087	153.683	-256.036	257.652	173.712	-274.47	267.07
172.932	-284.845	254.597	165.436	-265.061	262.462	185.717	-282.658	272.811
185.498	-293.705	260.704	177.176	-273.684	267.93	197.663	-290.479	279.195
197.53	-301.778	267.309	188.646	-281.734	274.027	209.284	-297.812	286.09
209.336	-309.368	274.499	199.905	-289.437	280.424	220.528	-304.619	293.523
220.817	-316.495	282.264	211.072	-296.474	287.249	231.516	-311.023	301.355
232.357	-323.105	290.497	221.939	-303.266	294.688	242.471	-316.788	309.355
243.561	-329.434	299.236	232.68	-309.647	302.616	253.091	-322.602	318.279
254.505	-335.377	308.382	243.053	-315.825	311.122	263.727	-327.652	327.147
265.07	-340.874	317.829	253.179	-321.493	319.87	273.901	-332.451	336.479
275.093	-345.889	327.368	262.768	-326.668	328.746	283.328	-337.077	346.308
284.616	-350.066	336.6	271.811	-331.323	337.629	292.376	-340.807	355.569
293.422	-354.232	346.413	280.452	-335.409	346.533	300.918	-344.082	364.727
301.93	-357.706	356.046	288.665	-339.064	355.516	308.914	-347.147	374.394
310.155	-360.502	365.474	296.484	-342.341	364.63	316.785	-349.477	383.619
317.766	-363.134	375.077	303.759	-345.257	373.716	323.984	-351.665	393.152
324.729	-365.358	384.292	310.475	-347.772	382.458	330.691	-353.374	402.137
331.04	-367.236	393.044	316.546	-350.009	390.712	336.832	-354.599	410.455
336.644	-369.063	401.471	322.125	-351.727	398.428	341.948	-356.076	418.914
341.909	-370.079	408.983	327.241	-353.149	405.722	347.115	-356.73	426.006
346.736	-371.032	416.353	332.104	-354.294	412.617	351.671	-357.448	433.222
351.21	-372.024	423.623	336.401	-355.254	419.387	355.984	-357.855	440.043
355.237	-372.354	429.951	340.28	-356.03	425.638	359.762	-358.295	446.576
358.806	-372.79	435.932	343.788	-356.66	431.382	363.18	-358.49	452.38
361.889	-373.359	441.536	346.812	-357.09	436.521	366.195	-358.574	457.635

364.753	-373.248	446.29	349.624	-357.325	441.202	368.876	-358.557	462.455
367.337	-373.281	450.929	352.187	-357.493	445.651	371.382	-358.4	466.943
369.727	-373.231	455.191	354.521	-357.589	449.744	373.797	-358.078	470.893
371.846	-373.216	459.076	356.515	-357.74	453.513	375.789	-357.999	474.782
373.656	-373.211	462.472	358.234	-357.919	456.813	377.557	-357.857	478.006
375.101	-373.261	465.374	359.743	-357.983	459.562	378.994	-357.748	480.836
376.343	-373.215	467.888	360.999	-357.991	461.923	380.13	-357.639	483.276
377.423	-373.066	470.088	362.098	-357.93	463.953	381.141	-357.5	485.416
378.409	-373	472.073	363.141	-357.853	465.777	382.085	-357.312	487.333
379.363	-372.869	473.86	364.054	-357.757	467.529	383.011	-357.112	489.059
380.147	-372.759	475.449	364.666	-357.653	469.214	383.75	-356.969	490.574
380.76	-372.719	476.731	365.204	-357.669	470.445	384.279	-356.898	491.81
381.19	-372.669	477.77	365.678	-357.611	471.458	384.73	-356.837	492.861
381.507	-372.825	478.997	366.115	-357.492	472.399	385.139	-356.666	493.809
382.053	-372.376	479.712	366.487	-357.397	473.343	385.57	-356.464	494.694
382.321	-372.528	480.786	366.81	-357.316	474.227	385.955	-356.297	495.513
382.688	-372.111	481.243	367.089	-357.212	474.862	386.259	-356.15	496.139
382.824	-372.051	481.748	367.272	-357.138	475.367	386.338	-356.082	496.685
382.855	-372.259	482.428	367.427	-357.046	475.715	386.426	-355.98	497.104
383.127	-371.813	482.63	367.607	-356.913	476.114	386.589	-355.817	497.52
383.27	-371.681	483.088	367.719	-356.811	476.581	386.723	-355.675	497.983
383.456	-371.599	483.528	367.877	-356.73	477.008	386.854	-355.55	498.375
383.475	-371.838	484.164	368.019	-356.669	477.341	387.04	-355.463	498.741
383.715	-371.473	484.195	368.165	-356.635	477.637	387.194	-355.396	498.995
383.891	-371.397	484.439	368.329	-356.558	477.874	387.389	-355.319	499.235
384.101	-371.312	484.657	368.317	-356.562	478.132	387.595	-355.206	499.425
384.25	-371.205	484.772	368.585	-356.394	478.256	387.754	-355.099	499.545
384.264	-371.109	484.816	368.644	-356.27	478.277	387.795	-355.014	499.58
384.233	-371.018	484.744	368.632	-356.156	478.2	387.778	-354.915	499.533
384.235	-370.911	484.64	368.652	-356.049	478.107	387.78	-354.823	499.443
384.3	-370.76	484.587	368.738	-355.87	478.06	387.937	-354.543	499.177
384.392	-370.588	484.508	368.807	-355.707	478.032	387.986	-354.472	499.257
384.469	-370.43	484.385	368.882	-355.546	477.918	388.047	-354.33	499.19
384.499	-370.267	484.16	368.881	-355.419	477.706	388.078	-354.206	498.971
384.467	-370.158	483.835	368.832	-355.309	477.384	388.042	-354.093	498.587
384.427	-370.087	483.503	368.85	-355.184	477.04	388.028	-354.005	498.264
384.423	-369.938	483.174	368.852	-355.019	476.729	388.046	-353.867	497.949
384.37	-370.043	483.079	368.881	-354.828	476.44	388.11	-353.716	497.65
384.457	-369.61	482.496	368.889	-354.665	476.125	388.134	-353.556	497.298
384.438	-369.425	482.055	368.847	-354.498	475.693	388.072	-353.419	496.866
384.315	-369.317	481.569	368.723	-354.366	475.211	387.944	-353.343	496.487
384.17	-369.221	481.061	368.632	-354.243	474.724	387.848	-353.245	495.944
384.091	-369.102	480.597	368.576	-354.114	474.266	387.757	-353.182	495.513

384.073	-368.99	480.166	368.516	-353.979	473.813	387.704	-353.076	495.074
383.96	-368.896	479.713	368.248	-353.953	473.424	387.66	-352.971	494.659
383.861	-368.768	479.265	368.31	-353.759	472.994	387.592	-352.867	494.212
383.769	-368.695	478.814	368.222	-353.651	472.538	387.542	-352.735	493.68
383.635	-368.883	478.56	368.122	-353.551	472.11	387.467	-352.707	493.266
383.599	-368.528	477.864	368.035	-353.451	471.695	387.376	-352.668	492.89
383.508	-368.415	477.44	367.973	-353.321	471.242	387.306	-352.576	492.447
383.453	-368.348	476.967	367.97	-353.27	470.726	387.248	-352.464	491.953
383.342	-368.268	476.547	367.882	-353.227	470.302	387.182	-352.416	491.537
383.219	-368.238	476.072	367.742	-353.195	469.865	387.069	-352.399	491.076
383.068	-368.463	475.816	367.634	-353.102	469.411	386.92	-352.397	490.635
383.027	-368.205	475.184	367.558	-353.077	468.988	386.828	-352.397	490.241
382.885	-368.186	474.845	367.502	-353.074	468.647	386.77	-352.381	489.894
382.808	-368.146	474.513	367.271	-353.082	468.342	386.714	-352.339	489.57
382.698	-368.097	474.207	367.258	-353.038	468.07	386.605	-352.328	489.258
382.563	-368.08	473.855	367.079	-353.013	467.748	386.443	-352.361	488.951
382.383	-368.126	473.496	366.884	-353.015	467.487	386.251	-352.396	488.671
382.172	-368.357	473.441	366.736	-353.017	467.227	386.092	-352.406	488.411
382.011	-368.357	473.26	366.585	-352.998	467.037	385.937	-352.451	488.279
381.884	-368.346	473.093	366.45	-353.003	466.865	385.818	-352.472	488.098
381.716	-368.157	472.713	366.307	-353.02	466.642	385.706	-352.476	487.858
381.507	-368.226	472.541	366.176	-353.045	466.416	385.509	-352.55	487.708
381.356	-368.321	472.406	366.017	-353.121	466.302	385.321	-352.628	487.586
381.228	-368.406	472.281	365.879	-353.17	466.204	385.175	-352.714	487.496
381.107	-368.477	472.205	365.776	-353.216	466.118	385.036	-352.8	487.408
380.969	-368.553	472.17	365.681	-353.287	466.034	384.94	-352.855	487.34
380.849	-368.612	472.144	365.551	-353.377	466	384.831	-352.92	487.286
380.719	-368.669	472.107	365.405	-353.454	466.025	384.738	-352.998	487.251
380.6	-368.949	472.238	365.263	-353.565	465.987	384.618	-353.083	487.203
380.447	-369.062	472.138	365.124	-353.638	465.896	384.471	-353.177	487.124
380.301	-369.153	472.014	364.974	-353.698	465.784	384.318	-353.257	487.018
380.139	-369.236	471.937	364.857	-353.737	465.681	384.182	-353.337	486.938
380.019	-369.288	471.864	364.771	-353.794	465.621	384.074	-353.388	486.864
379.876	-369.361	471.796	364.643	-353.832	465.555	383.962	-353.47	486.792
379.697	-369.432	471.677	364.504	-353.907	465.444	383.822	-353.548	486.687
379.51	-369.311	471.322	364.255	-353.988	465.325	383.612	-353.66	486.543
379.348	-369.4	471.133	364.043	-354.084	465.175	383.378	-353.769	486.391
379.162	-369.481	471.01	363.869	-354.18	465.044	383.185	-353.856	486.266
379.013	-369.534	470.932	363.733	-354.247	464.956	383.08	-353.928	486.162
378.841	-369.632	470.873	363.591	-354.3	464.914	382.973	-354.006	486.07
378.623	-369.745	470.776	363.402	-354.365	464.793	382.821	-354.089	485.937
378.362	-369.859	470.6	363.166	-354.432	464.612	382.559	-354.204	485.76
378.106	-369.925	470.389	362.939	-354.454	464.405	382.292	-354.303	485.582

377.848	-369.977	470.239	362.732	-354.508	464.249	382.071	-354.359	485.427
377.652	-370.02	470.095	362.5	-354.578	464.136	381.854	-354.43	485.305
377.451	-370.064	469.963	362.264	-354.682	464.039	381.645	-354.493	485.188
377.244	-370.134	469.844	362.033	-354.747	463.954	381.441	-354.556	485.064
377.03	-370.23	469.717	361.832	-354.797	463.821	381.22	-354.662	484.996
376.792	-370.315	469.56	361.651	-354.868	463.67	381.135	-354.592	484.613
376.58	-370.371	469.392	361.428	-354.897	463.508	380.837	-354.774	484.606
376.353	-370.388	469.27	361.252	-354.91	463.357	380.647	-354.821	484.462
376.185	-370.374	469.094	361.068	-354.911	463.207	380.465	-354.841	484.302
375.972	-370.404	468.903	360.908	-354.892	463.031	380.306	-354.844	484.111
375.731	-370.639	468.847	360.662	-354.888	462.783	380.083	-354.864	483.871
375.49	-370.645	468.55	360.414	-354.919	462.513	379.814	-354.924	483.622
375.219	-370.683	468.308	360.163	-354.944	462.289	379.582	-354.976	483.398
378.362	-369.859	470.6	363.166	-354.432	464.612	382.559	-354.204	485.76
378.106	-369.925	470.389	362.939	-354.454	464.405	382.292	-354.303	485.582
377.848	-369.977	470.239	362.732	-354.508	464.249	382.071	-354.359	485.427
377.652	-370.02	470.095	362.5	-354.578	464.136	381.854	-354.43	485.305
377.451	-370.064	469.963	362.264	-354.682	464.039	381.645	-354.493	485.188
377.244	-370.134	469.844	362.033	-354.747	463.954	381.441	-354.556	485.064
377.03	-370.23	469.717	361.832	-354.797	463.821	381.22	-354.662	484.996
376.792	-370.315	469.56	361.651	-354.868	463.67	381.135	-354.592	484.613
376.58	-370.371	469.392	361.428	-354.897	463.508	380.837	-354.774	484.606
376.353	-370.388	469.27	361.252	-354.91	463.357	380.647	-354.821	484.462
376.185	-370.374	469.094	361.068	-354.911	463.207	380.465	-354.841	484.302
375.972	-370.404	468.903	360.908	-354.892	463.031	380.306	-354.844	484.111
375.731	-370.639	468.847	360.662	-354.888	462.783	380.083	-354.864	483.871
375.49	-370.645	468.55	360.414	-354.919	462.513	379.814	-354.924	483.622
375.219	-370.683	468.308	360.163	-354.944	462.289	379.582	-354.976	483.398
377.451	-370.064	469.963	362.264	-354.682	464.039	381.645	-354.493	485.188
377.244	-370.134	469.844	362.033	-354.747	463.954	381.441	-354.556	485.064
377.03	-370.23	469.717	361.832	-354.797	463.821	381.22	-354.662	484.996
376.792	-370.315	469.56	361.651	-354.868	463.67	381.135	-354.592	484.613
376.58	-370.371	469.392	361.428	-354.897	463.508	380.837	-354.774	484.606
376.353	-370.388	469.27	361.252	-354.91	463.357	380.647	-354.821	484.462
376.185	-370.374	469.094	361.068	-354.911	463.207	380.465	-354.841	484.302
375.972	-370.404	468.903	360.908	-354.892	463.031	380.306	-354.844	484.111
375.731	-370.639	468.847	360.662	-354.888	462.783	380.083	-354.864	483.871
375.49	-370.645	468.55	360.414	-354.919	462.513	379.814	-354.924	483.622
375.219	-370.683	468.308	360.163	-354.944	462.289	379.582	-354.976	483.398

APPENDIX B

MATLAB™ CODES:

The following codes have been used to graph and plot data spreadsheets in order to analyze them.

```
clear; close all; clc;

%% Distance - still
% measure the distances between markers
% capture the data of the L-frame for 1000 frames in a still
postion (no motion)
S = csvread('Speedtest1.csv');
[nF, nC] = size(S);

Humeres_Marker1_Still = S(:,10:12); % 19:21
Humeres_Marker2_Still = S(:,13:15); % 22:24
Humeres_Marker3_Still = S(:,16:18); % 25:27

% distances
for i = 1:nF
    Distance12_Still(i) = norm(Humeres_Marker1_Still(i,:) -
Humeres_Marker2_Still(i,:));
    Distance13_Still(i) = norm(Humeres_Marker1_Still(i,:) -
Humeres_Marker3_Still(i,:));
    Distance23_Still(i) = norm(Humeres_Marker2_Still(i,:) -
Humeres_Marker3_Still(i,:));
end;
% assume these are real measured distances
D12 = mean(Distance12_Still);
D13 = mean(Distance13_Still);
D23 = mean(Distance23_Still);

%% Distance - normal motion
M = csvread('Speedtest1.csv');
[numberFrame, numberColumn] = size(M);

Humeres_Marker1 = M(:,10:12);
Humeres_Marker2 = M(:,13:15);
Humeres_Marker3 = M(:,16:18);

% distances
for i = 1:numberFrame
    Distance12(i) = norm(Humeres_Marker1(i,:) -
Humeres_Marker2(i,:));
```

```
    Distance13(i) = norm(Humeres_Marker1(i,:) -
Humeres_Marker3(i,:));
    Distance23(i) = norm(Humeres_Marker2(i,:) -
Humeres_Marker3(i,:));
end;
fig_d12 = figure;
plot(Distance12); hold on; plot([0, numberFrame],[D12, D12]);
title('distance between marker1 and marker2')
fig_d13 = figure;
plot(Distance13); hold on; plot([0, numberFrame],[D13, D13])
title('distance between marker1 and marker3')
fig_d23 = figure;
plot(Distance23); hold on; plot([0, numberFrame],[D23, D23])
title('distance between marker2 and marker3')

% error
figure;
Error12 = Distance12 - D12; plot (Error12); title('Error of
marker1')
figure;
Error13 = Distance13 - D13; plot(Error13); title('Error of
marker3')
figure;
Error23 = Distance23 - D23; plot(Error23); title('Error of
marker2')

%% Projection

for i=1:numberFrame
    H12 = Humeres_Marker2(i,:)-Humeres_Marker1(i,:);
    Humeres_Marker2_Projected(i,:) = H12/norm(H12)*D12 +
Humeres_Marker1(i,:);
    H13 = Humeres_Marker3(i,:)-Humeres_Marker1(i,:);
    Humeres_Marker3_Projected(i,:) = H13/norm(H13)*D13 +
Humeres_Marker1(i,:);
end;

%% Sphere
% sphere with marker1 in the center
frame = 176;

Xc = Humeres_Marker1(frame, 1);
Yc = Humeres_Marker1(frame, 2);
Zc = Humeres_Marker1(frame, 3);
R1 = D12;

figure
```

```
[xs,ys,zs] = sphere(30);
mesh(xs*R1+Xc, ys*R1+Yc, zs*R1+Zc); alpha(0.2); axis equal; hold
on;
scatter3(Xc, Yc, Zc, 'filled', 'black'); hold on

scatter3(Humeres_Marker2(frame, 1), Humeres_Marker2(frame, 2),
Humeres_Marker2(frame, 3), 'filled', 'red')
scatter3(Humeres_Marker2_Projected(frame, 1),
Humeres_Marker2_Projected(frame, 2),
Humeres_Marker2_Projected(frame, 3), 'filled', 'blue')

%% Distances - for projected points
for i = 1:numberFrame
    Distance12_Projected(i) = norm(Humeres_Marker1(i,:) -
Humeres_Marker2_Projected(i,:));
    Distance13_Projected(i) = norm(Humeres_Marker1(i,:) -
Humeres_Marker3_Projected(i,:));
end;
figure(fig_d12);
hold on; plot(Distance12_Projected);
title('distance between marker1 and marker2')
figure(fig_d13);
hold on; plot(Distance13_Projected);
title('distance between marker1 and marker3')


%% velocity

for i=1:nF-1

    Humeres_Marker1_Vel(i,:) = (Humeres_Marker1(i+1,:) -
Humeres_Marker1(i,:))/0.01;
    Humeres_Marker1_Vel_Norm(i,:) =
norm(Humeres_Marker1_Vel(i,:));

    Humeres_Marker2_Vel(i,:) = (Humeres_Marker2(i+1,:) -
Humeres_Marker2(i,:))/0.01;
    Humeres_Marker2_Vel_Norm(i,:) =
norm(Humeres_Marker2_Vel(i,:));

    Humeres_Marker3_Vel(i,:) = (Humeres_Marker3(i+1,:) -
Humeres_Marker3(i,:))/0.01;
    Humeres_Marker3_Vel_Norm(i,:) =
norm(Humeres_Marker3_Vel(i,:));
end;
figure;
plot(Humeres_Marker1_Vel_Norm, 'color', 'cyan')
```

```
title('velocity of marker1 vs time frames, mm/s')
figure;
plot(Humeres_Marker2_Vel_Norm, 'color', 'cyan')
title('velocity of marker2 vs time frames, mm/s')
figure;
plot(Humeres_Marker3_Vel_Norm, 'color', 'cyan')
title('velocity of marker3 vs time frames, mm/s')

%% velocity vs error
figure
plot(Humeres_Marker1_Vel_Norm/max(Humeres_Marker1_Vel_Norm) );
hold on
plot(Error12/max(Error12), 'color', 'red' )
title('speed vs error')
```