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NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Computer Science

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Accuracy of Markerless Motion Capture: A Comparative Study

Graduate thesis in Computer Engineering
Supervisor: Tomas Holt
May 2024

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Abstract

The need for markerless motion tracking systems in animation, sports, and health sectors is increasing. Traditional methods typically require markers placed on the human body or clothing. These systems require multicamera setups, consume time, and necessitate knowledge about marker placement. This reduces the recording efficiency, which can be crucial in various situations.

This thesis explores markerless motioncapture, utilizing OpenPose, an open-source project that uses machine learning to identify key points on the human body to construct a two-dimensional skeleton. By utilizing three cameras from different viewpoints, it is possible to triangulate the images, resulting in three-dimensional coordinates.

The thesis introduces five main contributions:

1. Methods for camera calibration.
2. A synchronization method for multiple cameras.
3. A framework for triangulation of two-dimensional points to three-dimensional coordinates.
4. A basis for comparing different models for key-point estimation.
5. A basis for comparing marker-based and markerless systems.

The calibration process utilized Zhang's method, resulting in a reprojection error of 4.2 pixels. Using ”weighted Direct Linear Transformation”, three-dimensional estimations of the joint centers were generated, showing a variance in accuracy across motion speed and direction. The markerless results were compared against Qualisys, which was used as the ground truth due to its well-established foundation for motion capture. The analysis showed that 88.58% of the data had an error margin of less than 40 mm.

Sammendrag

Behovet for markørløs bevegelsesfangst innen animasjon, idrettslære og helsefeltet er stort. Tradisjonelle metoder krever markører festet på hud eller klær. Disse systemene krever betydelig plass, flere kameraer og tidskrevende markørplassering, som igjen krever betydelig kompetanse. Dette begrenser mulighetene for rask tilpasning, noe som kan være kritisk innen helsevesenet.

Dette forskningsprosjektet utforsker markørløs bevegelsesfangst, ved bruk av OpenPose, et prosjekt med åpen kildekode som ved hjelp av maskinlæring identifiserer nøkkelpunkter på menneskekroppen for å konstruere et todimensjonalt skjelett. Ved bruk av tre kameraer fra ulike synsvinkler, trianguleres bildene for å generere tredimensjonale koordinater.

Denne forskningsrapporten presenterer fem hovedbidrag:

1. Metoder for kamerakalibrering.
2. En metode for synkronisering av flere kamera.
3. Et rammeverk for triangulering av todimensjonale koordinater for å oppnå tredimensjonale koordinater.
4. Et sammenligningsgrunnlag for ulike modeller for nøkkelpunktsgjenkjenning.
5. Et sammenligningsgrunnlag mellom et markørbasert og markørløst system.

Kamerakalibreringen benyttet Zhang's metode, som resulterte i en reprojeksjonsfeil på 4,2 piksler. Ved bruk av "weighted Direct Linear Transformation" ble tredimensjonale estimater av leddsentrene generert, med variabel nøyaktighet avhengig av bevegelsens hastighet og retning. Resultatene ble sammenlignet med Qualisys, et veletablert markørbasert system. Analysen viste at 88,58% av dataene hadde en feilmargin under 40 mm.

Preface

The choice behind this thesis was driven by the potential to work on a unique scientific research project with the possibility of publication. Based on this and the accessibility of the necessary equipment, the group decided to pursue this topic. Additionally, the decision was influenced by the expertise and experience of VizLab, which provided a strong foundation for the project's success. Our gratitude goes to Tomas Holt for his guidance and for providing access to the equipment at VizLab, NTNU.

Trondheim *May 18, 2024:*

Stian Lyng Stræte & Tomas Beranek

Assignment Details

Initially, the group planned to experiment with both marker-based and markerless solutions using the same camera setup. However, this changed when the group encountered challenges with the provided software. This led the group to find other solutions. Consequently, the project's premise changed to analyzing the potential of markerless solutions by comparing them to the ground truth from a marker-based system.

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Glossary

AlphaPose An open-source framework that detects human body keypoints and skeletal data.. 77

body-model Representation of the human body in Openpose, consisting of key points or joints.. viii, xix, xx, 31, 51, 52, 54, 66, 68, 76

Camera Manager Camera management suite by 3D Motion Technologies at NTNU.. 60

deepfake Manipulation technique combining deep learning and fake imagery or videos.. 81

GAIT Systematic study of human walking.. 81

GANTT A diagram that illustrates a project's schedule and dependencies between different tasks.. 60

IEEE The Institute of Electrical and Electronics Engineers (IEEE) is an association for electronics and electrical engineering.. i

image processing Processing of images using algorithms on a computer. 3

Mathworks A corporation that specializes in mathematical computing software.. i

Matlab A proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks.. 70

MediaPipe Open-source framework by Google that focuses on computer vision tasks like hand tracking and face detection.. 77

OpenCV real-time optimized Computer Vision library, tools, and hardware.. vi, 29, 62, 70

OpenPose Real-time multi-person keypoint detection library for body, face, hands, and foot estimation.. i, ii, vi, vii, ix, x, xvii, xviii, 1, 2, 29–33, 38, 41, 43–47, 49, 51, 54, 62–65, 68–71, 74, 76, 77, 79, 81

OptiTrack Motion capture and 3D tracking systems for video game design, animation, virtual reality, robotics, and movement sciences.. 80

pip Python package manager.. vii, 33

Pose2Sim Library for 3D markerless motion capture.. vi, 33

QTM QTM Qualisys Track Manager - Motion capture software.. 31, 39

Qualisys Qualisys is a provider of motion capture and 3D positioning tracking systems.. iv, vi, vii, ix, x, xii, xiii, xviii, 2, 23, 29–31, 35, 38–41, 43–47, 54, 59, 62–64, 67–69, 71, 76, 80

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Trackpoint Motion capture software by 3D Motion Technologies at NTNU.. 60

Acronyms

P_i	Image Coordinates.
p_u	Pixel Width.
p_v	Pixel Height.
P_w	Real World Point.
μs	Microseconds.
hz	Hertz.
1K	Camera with a pixel width of 1000 pixels.
2D	Two-dimensional.
3D	Three-dimensional.
4K	Camera with a pixel width of 4000 pixels.
8K	Camera with a pixel width of 8000 pixels.
AI	Artificial Intelligence.
AIM	Automatic Identification of Markers.
BSI	back-illuminated sensors.
CPU	central processing unit.
CSV	Comma-separated values.
Db	Decibel.
DLT	Direct Linear Transformation.
DSR	Design Science Research.
f	Focal Length.
fps	Frames Per Second.
GB	Giga Byte.
GPIO	General-Purpose Input/Output.
GPU	graphics processing unit.
GUI	Graphical User Interface.
HD	High Definition.
IR	infrared.
JSON	JavaScript Object Notation.
LOESS	locally estimated scatterplot smoothing.
MAE	Mean Absolute Error.
NSD	Norwegian Center for Research Data.
NTNU	Norwegian School of Science and Technology.
OS	Operating System.
PAF	Part Affinity Field.

PCT Point Clustering Technique.
qca Qualisys file format.
qtm Qualisys file format.
RAM random access memory.
RGB Red Grenn Blue.
SDK Software Development Kit.
TRC Trace Files.
TSV Tab-separated values.

1. Introduction

Traditionally, motion capture technology has primarily been used by larger health institutions and the entertainment industry. However, advancements in the field of machine learning and artificial intelligence have progressed significantly. Combined with the rapid increase in processing power in consumer-grade hardware, these technologies are becoming more accessible for various use cases that were previously impossible. In this research paper, the group explores the biomechanical field of motion capture, specifically markerless motion capture.

Existing motion capture systems present significant barriers, including high economic expenses, limited accessibility, the need for competence in marker placement, and the requirement of substantial space for capturing movements. The group investigates how using machine learning to detect key points on a subject's body, rather than relying on physical markers, could advance motion capture technologies.

1.1 Research Question

The research questions are outlined below:

- **RQ1:** Is it possible to achieve consistent accuracy of less than 40mm, using OpenPose as the markerless solution?
- **RQ2:** Is it possible to achieve consistent accuracy across different types of body movements?
- **RQ3:** What are the best practices for minimizing errors in markerless motion capture?
- **RQ4:** What are the different benefits and limitations of markerless and marker-based solutions?

1.2 Outline

The report follows a typical structure for a science-related research paper. The theory chapter serves as a foundational component, providing background knowledge for understanding the project and its outcomes. The chapter is structured into four parts, with the first being an explanation of the crucial aspects of camera technology and computer vision, followed by an examination of motion capture, data manipulation, and error estimation techniques. Subsequently, the third section looks at biomechanics and human movement, and finally, various research methods and methodologies are discussed.

In addition to the theoretical aspects, the group would like to highlight that a basic understanding of matrix projection and homogeneous matrices is expected. This is necessary in order to explain the theory thoroughly and accurately without omitting important information and understanding.

The method chapter first defines the group's chosen method and how they align with the overall goals of the thesis. The chapter further the explains the reasoning behind the selected methods. This detailed description ensures that the project and its results, can be reproduced.

The results are then sectioned into scientific, engineering, and administrative results, each providing insight into the different outcomes of the thesis. The scientific results contain evaluations of OpenPose, using Qualisys for validation, including aspects such as filtering, error correction, and the performance and accuracy of the markerless motion tracking. The engineering section outlines the results based on the goals set by the group in the early stages of the project. While the administrative section includes the administrative results regarding milestones, timesheets, and meetings.

The discussion chapter of the report analyzes the results based on the goals, assessing the project period and how the project met these goals and their unexpected complications.

The conclusion provides a summary of the key points of the findings and their importance. It also reflects on the project period as a whole and discusses future goals or research areas to expand on.

Finally, a part including the social impact of the solution is included. This chapter delves into the societal, ethical, economical, and health impacts of the possible solution. It also reflects on the ethical guidelines that the group followed.

2. Theory

The theory chapter will provide essential background for understanding the project and its results. The chapter is going to be divided into four main parts, where the first part will cover important knowledge of camera technology and computer vision. The second part will address motion capture, data manipulation, and error estimation. The third part will focus on biomechanics and human movement capture. The final part will discuss research methodologies. Dividing the chapter in this manner ensures that the reader gains an easy and thorough understanding of the important background needed for the rest of the project.

2.1 Computer Vision

”At its core, computer vision is the ability of computers to understand and analyze visual content in the same way humans do ” (UoSD, 2023). In simpler terms, the task of computer vision is to automate and replicate how humans see and characterize objects they observe in the world. Computer vision acquires these observations through different devices such as cameras and then uses image processing methods to categorize and analyze the data. ”The image is then sent to an interpreting device that uses pattern recognition to break the image down, compare the pattern in the image against its library of known patterns, and determine if any of the content in the image is a match” (‘What Is Computer Vision? | Microsoft Azure’, 2024). For this to work, the deep learning interpreting device needs a massive dataset with relevant visual data. To read more about deep learning and neural networks, see Appendix A.1.

2.2 Camera Calibration

Camera calibration, or camera resectioning, is the process of determining important Two-dimensional (2D) image parameters that can be created while operating on one or more cameras. ”These parameters can then be used to correct lens distortion, measure the size of an object in world units, determine the location of the camera in the scene, and other Three-dimensional (3D) computer vision tasks” (‘What Is Camera Calibration? - MATLAB & Simulink - MathWorks Nordic’, 2024). Camera calibration is performed on each individual camera separately before employing other calibration or computer vision techniques for multi-camera setups.

To preform camera calibration, one must first go through a process of finding important metrics that are both camera-specific and environment-specific. The following tasks outline the necessary steps for camera calibration:

- Camera Extrinsic (Section - 2.2.1)
- Camera Intrinsic (Section - 2.2.2)
- Undistort Camera (Section - 2.2.3)
- Direct Linear Transformation (Section - 2.2.5)
- Zhang's Method (Section - 2.2.6)
- Reprojection Error (Section - 2.2.9)

2.2.1 Camera Extrinsic

The extrinsic parameters of a camera are variables that depend on the camera's environment and placement. These parameters are crucial for transforming real-world coordinates (X_w, Y_w, Z_w) to the camera coordinate system. The transformation is accomplished through the utilization of a matrix known as the extrinsic matrix. If Real World Point (P_w) represents a point with real-world coordinates (X_w, Y_w, Z_w), determining the camera rotations for these three planes involves multiplying rotation matrices along each axis by the translation matrix. This process yields the resulting extrinsic matrix. Since the extrinsic matrix is placement-dependent, the extrinsic parameters needs to be recalculated when the camera location changes.
(Anwar, 2022)

Figure 2.1 describes how to calculate the rotation and translation for the extrinsic matrix. This is done based on the difference between the real-world axes (see bottom left corner of image) and the camera axes (see middle of image). The translation is calculated based on the offset of the camera location in the real-world axis system, determining how much the camera has moved in the x, y and z directions relative to the real world. This is done through the use of reference points on a known pattern (Theory - 2.2.6)

Figure 2.2 describes the homogeneous extrinsic matrix, simplifying subsequent calculations (Theory - 2.2.6).

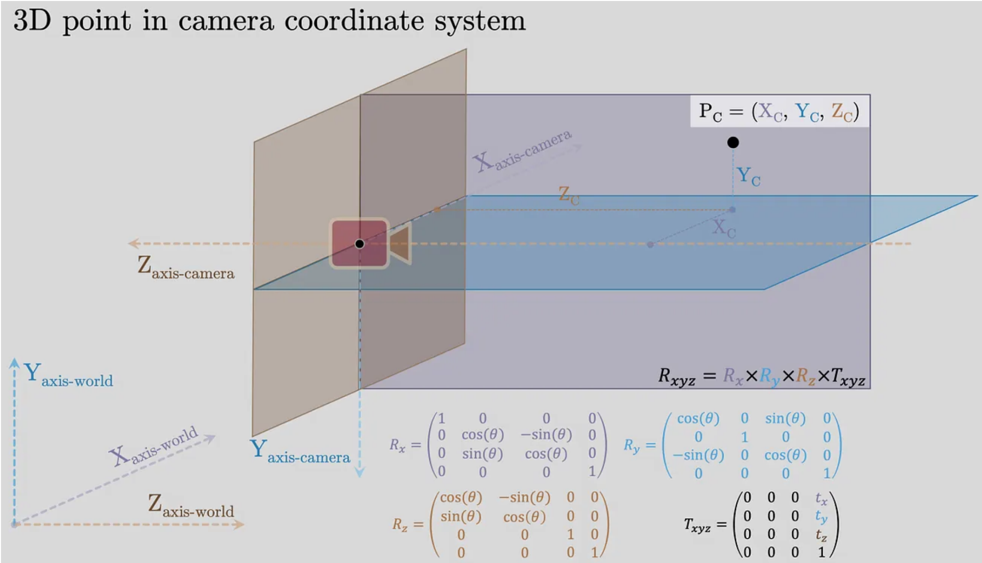


Figure 2.1: This image describes how to calculate the rotation and translation for the extrinsic matrix. This is done based on the real-world(bottom left of the image), and the camera axes(The middle of the image) **Source:** Anwar, 2022

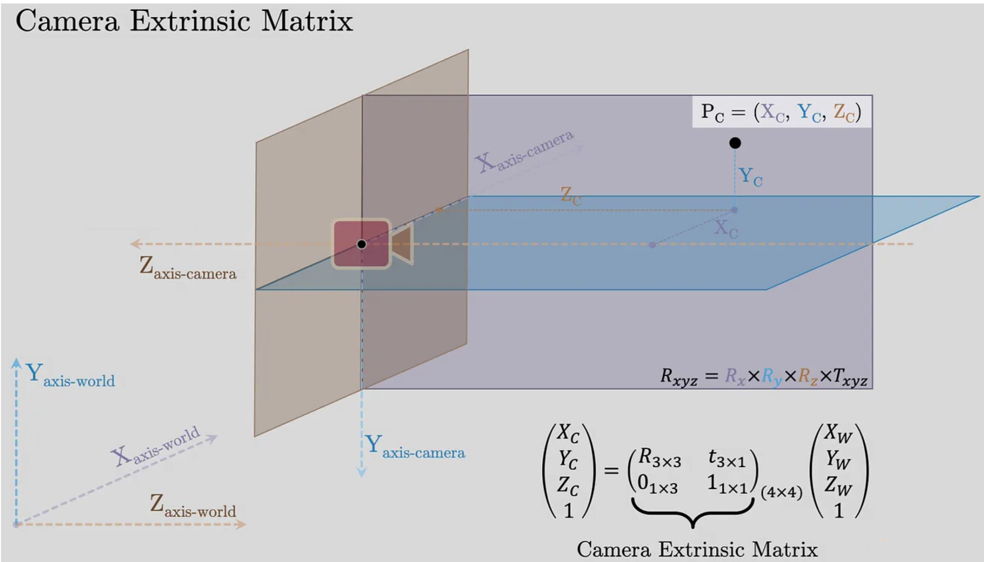


Figure 2.2: The extrinsic matrix is calculated by the matrix multiplication of the R and T matrices. **Source:** Anwar, 2022

To fully understand the images and how to calculate rotation and translation, it is suggested to read (Krishna, 2022a). These calculations and their understandings are out of the scope of this thesis and are therefore only referred to.

2.2.2 Camera Intrinsic

To correctly translate real-world 3D coordinates to 2D pixel coordinates, the intrinsic parameters of the camera must be taken into account. The camera's intrinsic parameters are camera-specific variables, such as the focal length and optical center of the lens. When calculating the intrinsic matrix, it is necessary to first translate the camera coordinates from the extrinsic matrix to image coordinates, and then to the pixel coordinate system. When translating the camera point coordinates from the extrinsic matrix, the points or rays pass through the center (optical center) and re-project onto a 2D plane that is normal to the real-world z-plane. The new coordinates are called Image Coordinates (P_i) or image points. The distance from the optical center to the image plane is equal to the camera's Focal Length (f). The coordinates of P_i (X_i and Y_i), can be found using the principle of similar triangles as depicted in figure 2.3 (Anwar, 2022). This method is often referred to as the pinhole method 2.2.4.

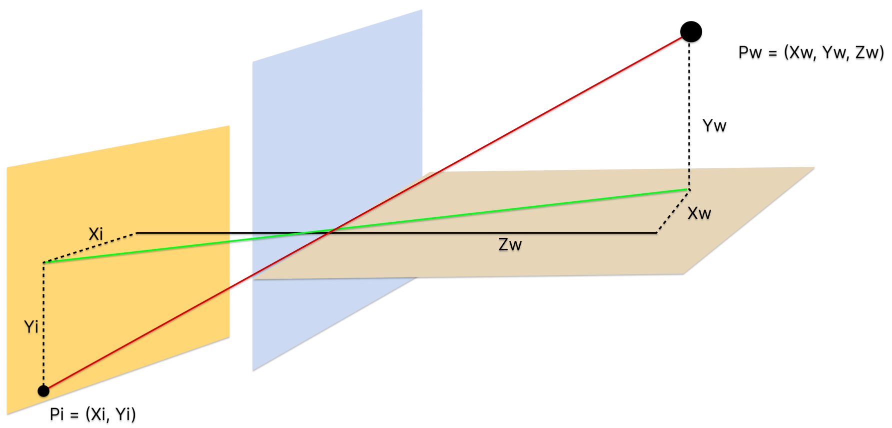


Figure 2.3: Figure illustrates the Principle of similar triangles. The z-axis is normal to the image plane. The Yi and Xi coordinates can be calculated using this equation: $X_i = f \cdot \frac{X_w}{Z_w}$ and $Y_i = f \cdot \frac{Y_w}{Z_w}$

The distance from the image center to the point on the image plane can then be simply calculated using the formula for finding the square diameter:

$$r = \sqrt{(X_i^2 + Y_i^2)}$$

After this initial part, the intrinsic matrix will have the format below:

$$\text{Intrinsic Matrix} = \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

(Anwar, 2022)

The next step is to calculate the pixel coordinates. This part needs the inclusion of an image pixel plane, which is a 2D plane that corresponds to the image plane from the earlier steps. The only difference is that the pixel image plane has a different origin point, which in this situation is the top left corner (not the center). It is therefore important to calculate for this new origin. The standard labeling for pixel coordinates is u,v for x,y, and the equations for calculating u and v are: (for further reference see figure 2.4):

$$u = 1/p_u * f * X_c/Z_c + c_y$$

$$v = 1/p_v * f * Y_c/Z_c + c_x$$

The equations above are based on the number of pixels in the image. Where the pixel width is p_u and its pixel height is p_v. Calculating the pixel coordinates results in changes to the intrinsic matrix:

$$\text{Intrinsic Matrix} = \begin{bmatrix} f/p_u & 0 & c_x \\ 0 & f/p_v & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

(Anwar, 2022)

Tangential Distortion for Camera Intrinsic

Sometimes, when the lens is not aligned with the image sensor, the image appears skewed, meaning the angle between the x- and y-axes is not 90 degrees. When this happens, another transformation is needed before transforming from image to pixel coordinates (Anwar, 2022; ‘OpenCV: Camera Calibration’, 2024). The transformation is depicted in figure 2.5

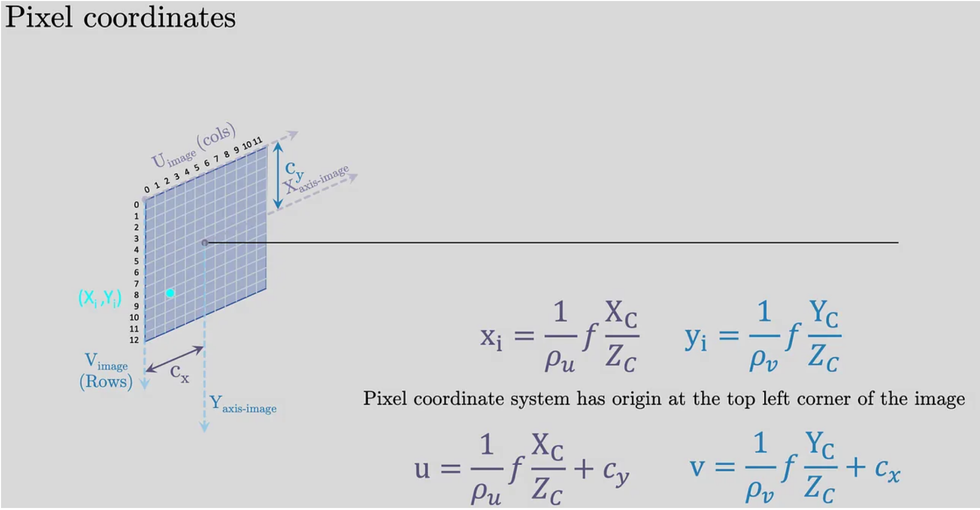


Figure 2.4: Figure illustrating a pixel-coordinate system and the calculation of u and v. The equation shows how to calculate u and v, representing the number of pixels in the image. These values are then used to calculate the intrinsic matrix.
Source: Anwar, 2022

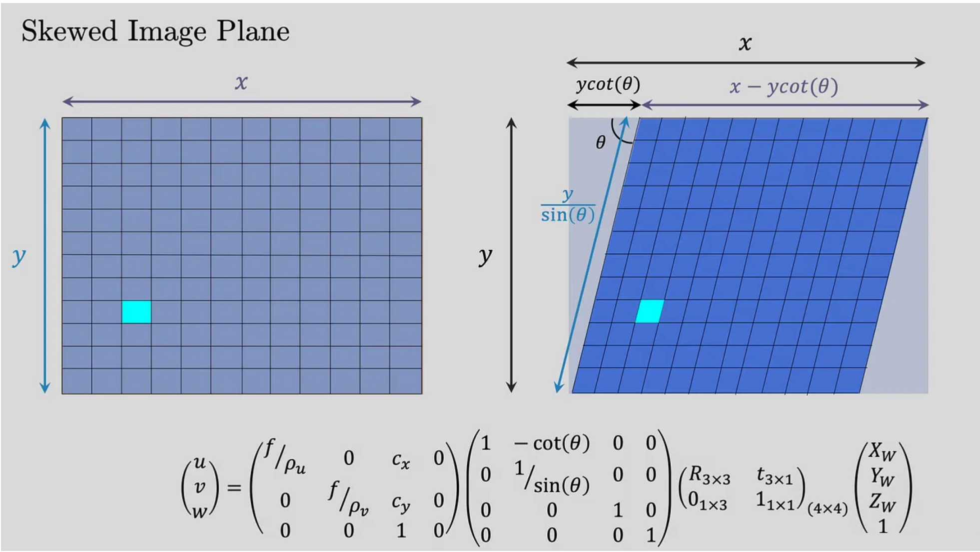


Figure 2.5: Figure illustrating the transformation when the image includes tangential distortion. Since the image-plane is skewed, the skew must be added to the calculation of the intrinsic matrix.
Source: Anwar, 2022

2.2.3 Camera Distortion

A human eye normally works as described in section 2.2.4, but once lenses are introduced, this method isn't sufficient. Since light enters the camera through a lens instead of the pinhole, the camera will suffer from distortion, and the distortion must be compensated for.

There are two major types of camera distortion effects ('Understanding Lens Distortion | LearnOpenCV #', 2021).

- **Radial distortion**, is a common distortion effect that causes straight lines to appear curved.
- **Tangential distortion**, which occurs when the lens is not aligned with the image sensor, causing the images to appear tilted or skewed ('OpenCV: Camera Calibration', 2024).

The tangential distortion is accounted for when calculating the intrinsic matrix, as described in section 2.2.2. However, correcting radial distortion requires a separate calculation. To achieve camera calibration without distortion, the intrinsic and extrinsic values are used in subsequent calculations. Let u, v be the ideal distortion-free pixel image coordinates, and m, n the corresponding real observed image coordinates (Zhang, 2000). Removing distortion involves calculating the distortion coefficients ($k1$ and $k2$) and applying them through the following equations:

$$\begin{bmatrix} (u-u_0)(x^2+y^2)/((u-u_0)^2+(v-v_0)^2) \\ (v-v_0)(x^2+y^2)/((u-u_0)^2+(v-v_0)^2) \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} = \begin{bmatrix} m-u \\ n-v \end{bmatrix}$$

To simplify, the equation appear as follows:

$$D * k = d$$

Finding the distortion coefficients k involves using simple matrix calculations

$$k = (D^T \cdot D)^{-1} \cdot D^T \cdot d$$

The distortion coefficients can then be used to undistort the image during the calibration process of the cameras (Zhang, 2000).

2.2.4 Pinhole Method

"The fundamental idea of image formation is to capture the rays that are reflected from an object onto a medium" (Krishna, 2022b). The rays from the object bounce back to the medium, but the problem is that the rays will overlap with each other and the point would be wrong. The solution is to place a pinhole (small hole) in front of the medium. This way, the world points will correspond one-to-one to the pixels in the medium. The medium or the image plane can then be used to find different matrices that can be used for calculating the relationship between the real-world coordinates and the corresponding pixel coordinates on the image plane, captured by the camera (Nielsen, 2020, Krishna, 2022b).

2.2.5 Direct Linear Transformation

Direct Linear Transformation (DLT) is a method used in computer vision to find a transformation between two sets of points. DLT works by creating linear equations for a specific problem and representing these equations in matrices in order to find the wanted unknown variables (Aktaş (2022)). Tasks such as image stitching, object recognition, or planar object detection often require establishing a linear equation of the form $Ah = 0$, where A includes the known values and h represents the unknown homography matrix. Constructing a matrix A based on all the coefficients from the equations, and a vector h based on the unknown coefficients of the homography matrix H, forms the foundation for the equation $Ah = 0$ to solve for the transformation matrix H (R. Hartley and Zisserman, 2004, p. 90).

If P_s represents a homogeneous 2D point in the source image, a homography matrix H and corresponding unknown points P_t in the target image are required.

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}$$

Establishing both the unknown and known points results in the matrix equation below:

$$\begin{bmatrix} X_t \\ Y_t \\ 1 \end{bmatrix} = H \cdot \begin{bmatrix} X_s \\ Y_s \\ 1 \end{bmatrix}$$

Since homogeneous coordinates represent a ratio, 2D to 2D corresponding coordinates, solving the equation for the 2D homogeneous image points results in two equations.

$$x_t = \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}}$$
$$y_t = \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}}$$

Further solving the equations yields these two equations:

$$x_t \cdot h_{31}x_s + x_t \cdot h_{32}y_s + x_t \cdot h_{33} = h_{11}x_s + h_{12}y_t + h_{13}$$
$$y_t \cdot h_{31}x_s + y_t \cdot h_{32}y_s + y_t \cdot h_{33} = h_{21}x_s + h_{22}y_t + h_{23}$$

Rearranging the equations in matrix form, $Ah = 0$, yields:

$$A = \begin{bmatrix} -x_{s1} & -y_{s1} & -1 & 0 & 0 & 0 & x_{s1}x_{t1} & y_{s1}x_{t1} & x_{t1} \\ 0 & 0 & 0 & -x_{s1} & -y_{s1} & -1 & x_{s1}y_{t1} & y_{s1}y_{t1} & y_{t1} \end{bmatrix}$$

$$h = \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix}$$

(Aktaş, 2022; Zhang, 2000)
Since there are not enough equations in the A matrix, more image points are needed to be able to solve for the unknown h matrix. It is therefore necessary to have at least five reference image points to fill up the A matrix with up to nine equations. The final matrix equation is listed below:

$$\begin{bmatrix} -x_{s1} & -y_{s1} & -1 & 0 & 0 & 0 & x_{s1}x_{t1} & y_{s1}x_{t1} & x_{t1} \\ 0 & 0 & 0 & -x_{s1} & -y_{s1} & -1 & x_{s1}y_{t1} & y_{s1}y_{t1} & y_{t1} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -x_{sn} & -y_{sn} & -1 & 0 & 0 & 0 & x_{sn}x_{tn} & y_{sn}x_{tn} & x_{tn} \\ 0 & 0 & 0 & -x_{sn} & -y_{sn} & -1 & x_{sn}y_{tn} & y_{sn}y_{tn} & y_{tn} \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix}$$

After finding the required matrices, the h values are solved using singular value decomposition. This is done by finding the smallest eigenvalue of $A^T A$. This eigenvalue will be in the 9x1 form and equal to the unknown h vector (Aktaş, 2022; Zhang, 2000).

2.2.6 Zhang's Method

Zhang's calibration method is one of the most popular calibration methods. The reason why it is so popular is that it simplifies the DLT 2.2.5, and is therefore easier and more applicable for solving the calibration problem. According to Aktaş, 2022, Zhang's calibration method utilizes, the 2D world frame points and their corresponding 2D image points. These 2D frame points are typically organized in a checkerboard pattern (2.2.7), where the dimensions of the squares are predetermined. Utilizing the inherent x and y axes of the checkerboard simplifies the DLT process by excluding the z-axis from consideration. By substituting the H-matrix with the camera re-projection matrix (the dot product between intrinsic and extrinsic matrices), the rotation and translation parameters can be estimated using DLT. Specifically, the rotations about the x-axis ($r1$) and the y-axis ($r2$) can be expressed as equations, where K represents the intrinsic matrix:

$$r1 = K^{-1} \cdot h1$$

$$r2 = K^{-1} \cdot h2$$

Since the rotation vectors are orthonormal to each other, two constraints are created:

$$r1^T \cdot r2 = 0$$

$$||r1|| = ||r2|| = 1$$

If $r1$ and $r2$ are replaced with their resulting values, the constraints are also changed:

$$h1^T \cdot K^{-T} K^{-1} \cdot h2 = 0$$

$$h1^T \cdot K^{-T} K^{-1} \cdot h1 - h2^T \cdot K^{-T} K^{-1} \cdot h2 = 0$$

(Zhang, 2000)
Solving the camera calibration problem starts with an analytical solution, then proceeds with a nonlinear optimization technique based on the maximum likelihood criterion. Finally, taking lens distortion into account provides both analytical and nonlinear solutions (Zhang, 2000).

First, define the matrix $B = K^{-T} \cdot K^{-1}$, where K is the intrinsic matrix of the camera. This matrix depends on unknown parameters such as the focal lengths (f_x, f_y), optical center (u_0, v_0), and skew (s). The matrix B can be expressed as:

$$B = K^{-T}K^{-1} \equiv \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{12} & B_{22} & B_{23} \\ B_{13} & B_{23} & B_{33} \end{bmatrix} = \begin{bmatrix} \frac{1}{f_x^2} & -\frac{s}{f_x^2 f_y} & \frac{sv_0 - u_0 f_y}{f_x^2 f_y} \\ -\frac{s}{f_x^2 f_y} & \frac{1}{f_y^2} + \frac{v_0^2}{f_x^2 f_y^2} & -\frac{s(v_0 s - u_0 f_y)}{f_y^2 f_x^2} - \frac{v_0}{f_y^2} \\ \frac{sv_0 - u_0 f_y}{f_x^2 f_y} & -\frac{s(v_0 s - u_0 f_y)}{f_y^2 f_x^2} - \frac{v_0}{f_y^2} & \frac{s(v_0 s - u_0 f_y)^2}{f_y^2 f_x^2} + \frac{v_0^2}{f_y^2} + 1 \end{bmatrix}$$

This results in a symmetric six-dimensional vector $b = [B11, B12, B22, B12, 23, B33]$. Since matrix B is symmetric there are only six unknown values. Considering the i^{th} column vector of H as h_i the relationship between the homography matrix and matrix B can be expressed as:

$$h_i^T \cdot B \cdot h_j = v_{ij}^T \cdot b$$

The equation, $v_{ij}^T \cdot b$ forms a linear equation with respect to the unknown vector b and the dot product of the column vectors from the homography matrix. This b matrix will represent the unknown homography matrix H in the DLT equation.

$$h_i^T \cdot Bh_j = v_{ij}^T \cdot b$$

The equations for rotations ($r1$, $r2$) from the preceding equations can now be expressed using B:

$$h1^T \cdot B \cdot h2 = 0$$

$$h1^T \cdot B \cdot h1 - h2^T \cdot B \cdot h2 = 0$$

Expanding the equation above yields multiple linear equations that relate the elements of the homography matrix H to the vector b. These linear equations can be expressed in terms of the homography matrix as:

$$\mathbf{v}_{ij} = \begin{bmatrix} h_{i1}h_{j1} \\ h_{i1}h_{j2} + h_{i2}h_{j1} \\ h_{i2}h_{j2} \\ h_{i3}h_{j1} + h_{i1}h_{j3} \\ h_{i3}h_{j2} + h_{i2}h_{j3} \\ h_{i3}h_{j3} \end{bmatrix}^T$$

The linear equations involving the vector b and the matrix v can be expressed as the A matrix described below:

$$\begin{bmatrix} v_{12}^T \\ (v_{11} - v22)^T \end{bmatrix} \cdot b = 0$$

The solution to $Ab = 0$ is the same as for DLT, the eigenvector $A^T \cdot A$ associated with the smallest eigenvalue. By solving the estimate of b, all camera intrinsic and extrinsic parameters can be computed from matrices K and B, as demonstrated in the equations for calculating these parameters below:

Intrinsic equation:

$$\begin{aligned}
v_0 &= (B_{12}B_{13} - B_{11}B_{23}) / \left(B_{11}B_{22} - B_{12}^2\right) \\
\lambda &= B_{33} - \left[B_{13}^2 + v_0\left(B_{12}B_{13} - B_{11}B_{23}\right)\right] / B_{11} \\
f_x &= \sqrt{\lambda / B_{11}} \\
f_y &= \sqrt{\lambda B_{11} / \left(B_{11}B_{22} - B_{12}^2\right)} \\
s &= -B_{12}(f_x)^2 f_y / \lambda \\
u_0 &= s v_0 / f_y - B_{13}(f_x)^2 / \lambda.
\end{aligned}$$

Extrinsic equation:

$$\begin{aligned}
\mathbf{r}_1 &= \lambda \mathbf{K}^{-1} \mathbf{h}_1 \\
\mathbf{r}_2 &= \lambda \mathbf{K}^{-1} \mathbf{h}_2 \\
\mathbf{r}_3 &= \mathbf{r}_1 \times \mathbf{r}_2 \\
\mathbf{t} &= \lambda \mathbf{K}^{-1} \mathbf{h}_3
\end{aligned}$$

2.2.7 Checkerboard Calibration

One of the most common practices for camera calibration is the use of a planar pattern with known dimensions, as described in Zhang, 2000. The specific reason for the usage of a checkerboard is that it doesn't change size or shape, and is therefore invariant to perspective and lens distortion. The checkerboard consists of small alternating black and white checkers with the same width and height ('Calibration Patterns - MATLAB & Simulink - MathWorks Nordic', 2024). For a better understanding and to view images describing the calibration methods, the group advises reading the method chapter.

2.2.8 Wand Calibration

Calibrating the cameras using a wand requires two calibration objects (Qualisys AB, 2011a). To define the origin and orientation of the coordinate system, an L-shaped (Appendix - D) bracket with markers at fixed lengths is used to establish the axes in the coordinate field. To determine the locations and orientations of the cameras, a wand (Appendix - D) with markers set at a fixed distance relative to each other is moved around in the measurement volume (often referred to as a ”wand dance”) (Pribani et al., 2007). ”In a computational sense, the goal of the wand dance is to refine the values of the initially computed camera parameters, enforcing the accurately known wand lengths.” (Pribanic et al., 2009). For a better understanding and to view images describing the calibration methods, the group advises reading the method chapter.

2.2.9 Re-projection error

The re-projection error is used to evaluate calibration accuracy. This error is estimated from the difference between the original image points and the resulting re-projected points from the 3D to 2D transformation. It is calculated as the arithmetic mean of all Euclidean distances between real-world coordinates and projected image points. The reason for calculating the re-projection error is to assess how well the camera calibration was performed. A high re-projection error indicates a poor calibration ('OpenCV: Camera Calibration', 2024).

2.2.10 Triangulation

One fundamental problem is determining the position of a point in three-dimensional space from multiple two-dimensional images with known position and orientation. This process involves finding the intersection of two rays, each projecting from the optical center of the image. In realistic scenarios, inaccuracies and measurement noise in the camera calibration or pose estimation process mean that the rays might not intersect perfectly (R. I. Hartley and Sturm, 1997). These inaccuracies necessitate methods to find the most probable point of intersection.

DLT

Triangulating a point from 2D to 3D can be performed using direct linear transformation to estimate the missing real-world coordinates when the camera projection matrix and the image point are known.

To acquire homogeneous linear equations, the operation $x \cdot PX = 0$ must be performed, resulting in a matrix that supports the possibility of DLT $AX = 0$. In this context, x represents the image point, P represents the camera projection matrix, and X represents the unknown real-world coordinates. For the final matrix, at least two 2D to 3D point correspondences are required, as it is logically impossible to determine depth from only one 2D image. Therefore, employing DLT, the homogeneous matrix equation can be formulated as follows (‘”Triangulation Carnegie Mellon University”’, n.d.):

$$\begin{bmatrix} yp_3^T - p_2^T \\ p_1^T - xp_3^T \\ y'p_3'^T - p_2'^T \\ p_1'^T - x'p_3'^T \end{bmatrix} \begin{bmatrix} X_w \\ Y_W \\ Z_w \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

2.3 Motion Capture

Motion capture is the technology of capturing an object’s movements using various kinds of capture techniques, such as cameras and markers. Capturing and analyzing an object’s movement has a wide variety of applications in game development, Virtual Reality, and the healthcare industry (Luvizon et al., 2023). But using these motion capture systems is quite expensive and time-consuming. As described in Nakano et al. (2020), there has therefore, in recent years, been a large attraction to the usage of markerless human pose estimation. ”A technique for human body kinematics estimation that does not require markers or fixtures placed on the body would greatly expand the applicability of human motion capture.” (Mndermann et al., 2006)

2.3.1 Marker-based motion capture

Marker-based motion capture is a method for digitally capturing an object's movement in a predefined and calibrated area. Motion capture relies on several reflective markers and a multi-camera setup. Tracking the markers can be done in various ways, but the most common is through the use of infrared cameras. These cameras work by emitting infrared light that is then reflected off the markers and sent back to each camera. This can then be translated to a two-dimensional image ('Infrared marker-based motion capture', 2022, 'Infrared radiation notice', 2022). These images are then triangulated to calculate the exact location of the markers in 3D space. The calibration process happens mostly as described in the section about camera calibration(Section - 2.2), with the exception of using wand calibration(Section - 2.2.8) instead of Zhang's method with a checkerboard.

To acquire a precise accuracy, additional sections need to be taken into account:

- Synchronization (Section - 2.3.2)
- Data filtering/smoothing (Section - 2.3.3)
- Active and Passive markers (Section - 2.3.4)

2.3.2 Synchronization

Synchronization is a fundamental concept that ensures operations or events are coordinated at the same time (Pikovsky et al., 2001, p. xvii). Figure 2.6 illustrates the timing of two asynchronous cameras.

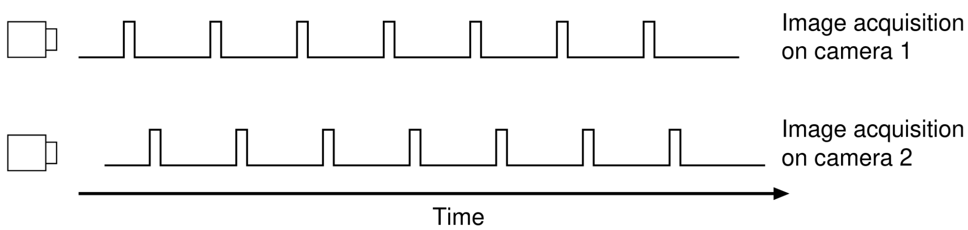


Figure 2.6: Frame generation across multiple cameras in regular capture mode is slightly asynchronous due to factors like varying individual camera timings and delays. **Source:** A. G., 2024

Trigger signal

A trigger signal initiates the frame generation process at the hardware level of the camera. Without the signal, the camera remains inactive and does not produce any frames. Triggering, however, is not related to storing or capturing the generated frames. For this, a record start signal is required ('FLIR Cameras', 2024).

Record Start Signal

A record starting signal starts the recording software, prompting it to begin capturing frames. When the camera operates in trigger mode, only the frames that are generated as a result of a trigger are outputted to the software (ensuring synchronization). However, in regular capture mode, where the frames are generated continuously, the frame generation across multiple cameras would be asynchronous and uncoordinated. This mode is useful in scenarios where precise start timing is less critical ('FLIR Cameras', 2024).

2.3.3 Filtering

A filter is defined as ”an operation that produces each sample of the output waveform *y* as a weighted sum of several samples of the input waveform *x*” (de Cheveigné and Nelken, 2019). During motion capture, the occurrence of noise is common. This can be due to camera quality, lighting, color mismatches, or other reasons (Skogstad et al., 2013). To remove unwanted noise from motion capture data, the use of data smoothing, or filtering, can be applied. The characteristics of different filters can be seen in Figure 2.7, where standard shapes show the magnitude transfer functions and impulse responses. There are multiple filtering algorithms, including the following:

Low-pass filter

Low-pass filters are used to allow the transmission of data below a specified highest level of acceptability, or low-frequency signals, while blocking the signals of higher frequency (Meyers, 2001, II.A, Nisbet et al., 2018).

High-pass filter

The high-pass filter acts in the opposite way, allowing the transmission of data above a specified lower level of acceptability, or high-frequency signals, while blocking the signals of lower frequency (Meyers, 2001, II.A, Nisbet et al., 2018, Ch. 4).

Band-pass filter

The band-pass filter is a combination of a low-pass and high-pass filter, with two cut-off frequencies instead of one. The data or signal between

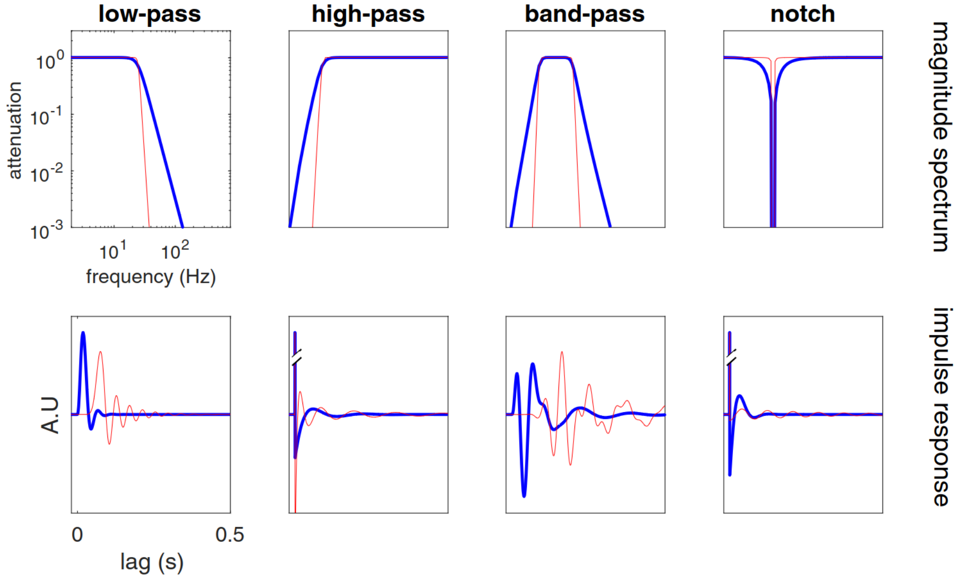


Figure 2.7: Standard shapes showing the magnitude transfer functions in the top row, and the impulse response in the bottom row. The blue curves represent the impulse responses with shallow frequency transitions. The red curves that depict impulse responses with steep frequency transitions. These curves show how the magnitude of a signal changes over time when passing through filters with different transition characteristics. **A.U** is an arbitrary unit. (de Cheveigné and Nelken, 2019).

these two cut-off frequencies is transmitted, while those on the outside are blocked (Nisbet et al., 2018, Ch. 4).

Butterworth

A butterworth filter is a type of signal processing filter that modifies the signal by selectively increasing or decreasing the amplitude of frequencies. Its primary objective is to provide a flat frequency response in the passband (Butterworth, 1930). The filter can be applied either to key points or to their speed of variation (Pagnon et al., 2022b).

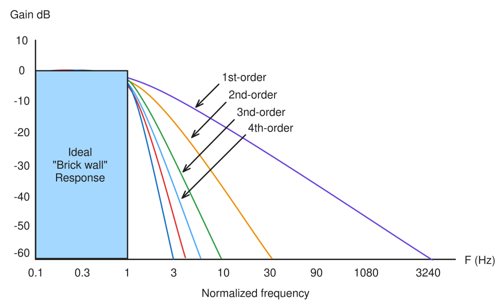


Figure 2.8: Frequency response characteristics of Butterworth filters of different orders compared to an ideal brick wall response. The graph illustrates the gain in decibels (dB) against normalized frequency (Hz) on the x-axis. This visualization highlights the deviation of different filter orders from the ideal response, emphasizing the trade-offs between filter order and attenuation performance.
Source: Kim, 2010

Order The order of the filter determines the steepness of its roll-off in the stopband (Kim, 2010). Figure 2.8 illustrates the frequency response characteristics of Butterworth filters of different orders.

Cutoff frequency Where in frequency space the cutoff frequency is located is measured in Hertz (hz). The cutoff frequency is the frequency at which the filter's response is reduced by half (-3 Decibel (Db)) from its passband value Kim, 2010.

Gaussian

A Gaussian filter is an image smoothing filter used for reducing noise and detail in images by applying blur to the image. It works by applying the Gaussian function to each pixel in the image:

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}}$$

The function performs a weighted average of the surrounding pixels, where x is the distance from the origin pixel, and σ is the standard deviation ('Gaussian Filtering', 2024, Jiang and Scott, 2020).

LOESS (Locally Estimated Scatterplot Smoothing)

LOESS is a statistical method used to create a smooth line through a scatter plot (Cleveland, 1979). LOESS builds on classical regression methods, such as linear and nonlinear least squares, by fitting simple models to localized data subsets ('4.1.4.4. LOESS (aka LOWESS)', 2024). This method estimates the underlying function in a point-wise manner, by using its neighboring points close to x. It assigns weights that decrease with the distance to x. For each weighted value of x, we estimate the value of $f(x)$ (Figueira, 2021).

More filtering methods

There exist even more data filtering methods than the ones mentioned in this section. Some of the more important filtering methods are therefore listed and described in Appendix A.2.

2.3.4 Active and Passive markers

There are different types of markers in motion capture systems. The two primary types are passive and active markers. Passive markers reflect infrared light for tracking, whereas active markers are battery-powered and emit their own light (‘Markers’, n.d.).

2.3.5 Markerless Motion Capture

Markerless motion capture is a technology used to track and record the movement of objects without the need for markers or other sensor technology. Instead of using markers, markerless motion capture relies on computer vision and other algorithms to accurately calculate the object’s movement. This is done through the use of artificial intelligence (see Appendix A.1). Using Artificial Intelligence (AI) to detect human movement can be used within the same domain as marker-based technology. The benefits of using markerless are the flexibility and efficiency, which often are the constrains of marker-based systems. As the accuracy of markerless technologies continues to improve and potentially reach the same level as marker-based systems, it could significantly impact multiple fields (Lam et al., 2023).

2.3.6 Part Affinity Fields

Part affinity fields are ”a set of 2D vector fields that encode the location and orientation of limbs over the image domain” (Cao et al., 2021). The Part Affinity Field (PAF) channels represent the connection between different parts of the human body. This is then used to find the magnitude and direction to each other (Cao et al., 2021).

2.3.7 Net-resolution

In markerless motion capture, ”net-resolution” refers to the dimension of the image. Increasing the net-resolution also increases the number of pixels in the image, resulting in an increase in computation time (Cao et al., 2019a).

2.4 Biomechanics of Capturing Human Movement

The most common technique for capturing human motion involves attaching reflective markers directly onto the skin, treating the data as a rigid body where the distance between any two points remains constant (Mndermann et al., 2006).

2.4.1 Calculation of Joint Angles in Marker-Based Systems

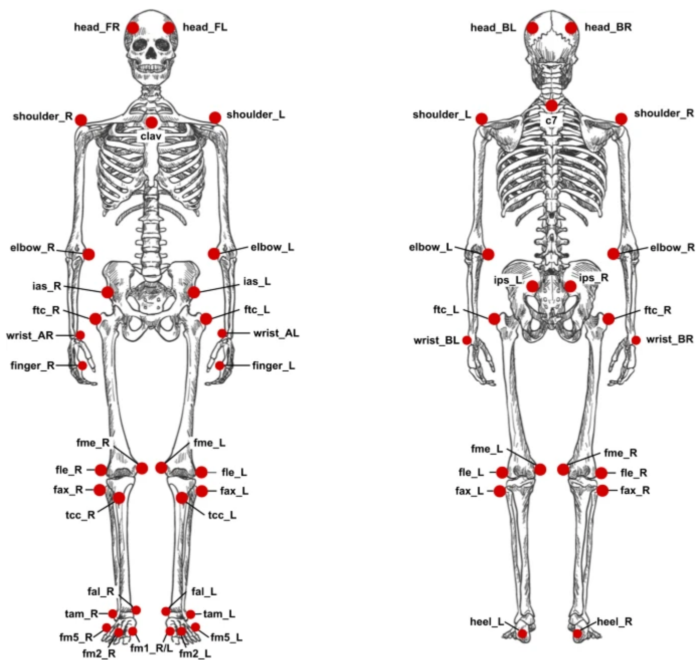


Figure 2.9: Reflective marker placements, based on known landmarks (Pellikaan et al., 2018)

In reality, joints can move in complex ways, involving motions such as sliding, gliding, or other types of motion (Boundless, 2024, Chapter 38.11). This, in conjunction with the motion of the skin in relation to the joints also creates inaccuracies in finding the correct angle positions (Choi et al., 2023).

Point Cluster Technique

Using a Point Clustering Technique (PCT) where a cluster of numerous points is placed in a specific way on the body segments, reduces the inaccuracies caused by the skin movement. An improvement to the original PCT introduces weighting among the markers, based on the rate of deformation (Alexander and Andriacchi, 2001). The PCT is calculated by first placing marker clusters around joints, as depicted in Figure 2.9. These are placed in specific ways to be able to correctly calculate the centers. The joint centers are then calculated using geometric reconstruction, which is based on the kinematic location of the mass center (based on the marker weighting) and the rotation (Alexander and Andriacchi, 2001). The detailed description of the algorithms and methods used by Qualisys for calculating joint angles can be found in the biomechanics section in the appendix A.3.

2.5 Scientific Research

In the proposed compendium, Anette Wrålsen (2017) describes science as ”a systematic approach to building new knowledge and gaining a better understanding of existing knowledge.” To participate in science, there needs to be chances to make clear observations and measurements, leading to an agreement on their accuracy. To do this in a credible and logical manner, science must be critical, relevant, validatable, and self-reflective. Achieving this requires adherence to various research methods. The most common approach involves utilizing qualitative, quantitative, and Design Science Research (DSR).

Qualitative Research Design

Qualitative research focuses on data that cannot be represented numerically (Anette Wrålsen, 2017).

Quantitative Research Design

Quantitative research focuses on data that, unlike qualitative data, can be collected numerically. This type of research method follows a more scientific structure involving testing and statistical analysis of the results (Anette Wrålsen, 2017).

DSR

”Design Science Research is a problem solving paradigm that seeks to enhance human knowledge via creation of innovative *artifact*” (Brocke et al. (2020)). The purpose of these artifacts is to improve the environment in which they are instantiated. In simpler terms, Design Science Research can be described as a research methodology based on creating and evaluating artifacts to identify and solve organizational problems. This approach is often used in IT domains because of its focus on problem-solving (Hevner et al., 2004).

DSR is divided into three, so-called, research cycles as visualized in Figure 2.10. Design, relevance, and Rigor cycle. The relevance cycle ensures the relevance of the artifact in the context of its real-world applicability. The design cycle focuses on development toward the desired solution. The rigor cycle is the foundation for the artifacts, using existing knowledge and engineering methods (Anette Wrålsen, 2017).

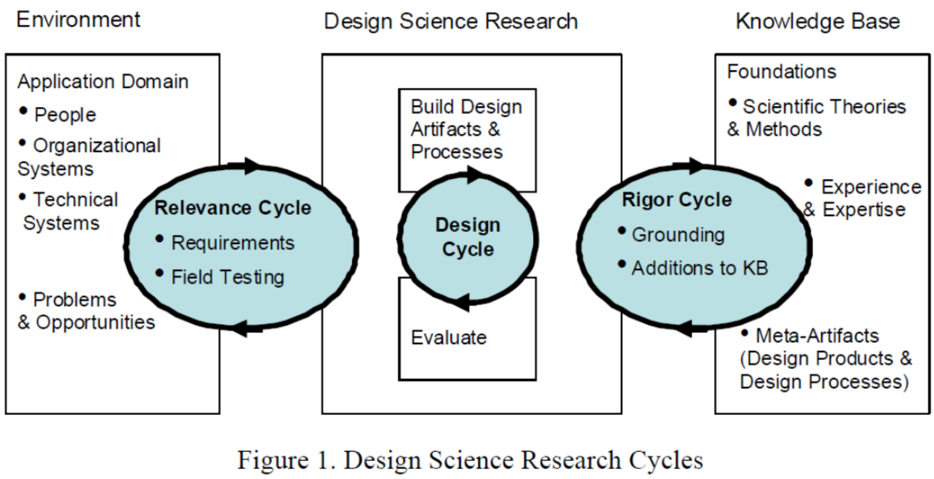


Figure 2.10: Design Science Research cycles
Source: Anette Wrålsen, 2017(p. 20)

3. Method

Research methods are procedures used in scientific research. These research methods are used to build credibility in a logical and thoughtful manner. Research methodologies serve as the foundation for researchers when examining data, drawing conclusions, and presenting findings in a reliable and consistent way (Anette Wrålsen, 2017). Research methods are therefore important when analyzing the quantitative and qualitative data for the project's thesis and its results. This chapter is going to first explain the bachelor group's chosen methods and technologies, and how they align with the overall goals of the thesis.

3.1 Researcher's Approach

During the course of this project, the project group conducted research based on the research framework from Oates (2006). The different steps were set prior to the start of the thesis research, and can be seen in Figure 3.1. The different steps are also described in the list below, and in more detail in the following section.

- **Experiences and motivations** refer to the use of prior experiences and current motivations to create a research question.
- **Research question** is needed to initiate the research. This question or questions are based on oneself (experience or motivation) or what others propose (literature review).
- **Experiment** is a research strategy for observing the effect of different variables and their correlation. It is used for testing the research question(s) in a controlled environment.
- **Observation data generation** refers to the means by which the data was generated, which in this case involves watching and observing.
- **Evaluation data generation** is used for collecting data to measure the effectiveness and performance of the particular problem.
- **Quantitative data analysis** refers to numerically measurable data (Theory - 2.5).

(Oates, 2006)

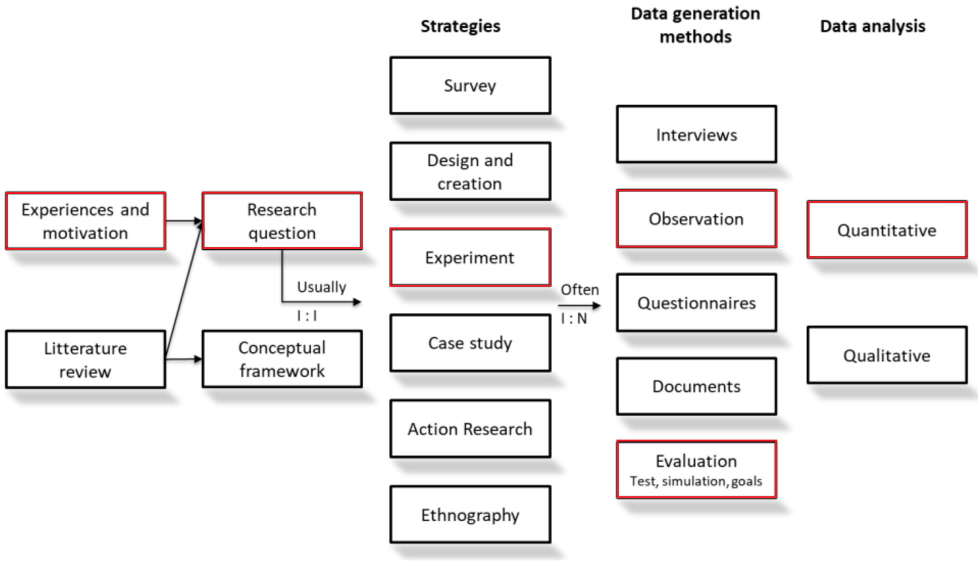


Figure 3.1: Groups main research's approach for the main bachelor thesis
Source: Anette Wrålsen, 2017

3.1.1 Experiences and motivations

A combination of research and previous experience with motion tracking led to the formulation of the problem domain. Building on these prior experiences, and motivated by Vizlab's need for research on markerless solutions, the main thesis was formulated.

3.1.2 Research question

To be able to answer the main research questions, three experiments were planned. The methodologies of the different experiments will be detailed in the experiment subsection:

- Camera synchronization
- Camera calibration
- Markerless & marker-based motion capture

3.1.3 Experiment

The camera setup was utilized in a more quantitative way, where the group used different articles and academic literature to test and experiment with different results. Firstly, the synchronization and calibration parts were conducted using different approaches, with the most promising approach being utilized. The results were based on the final re-projection error and the frame number length. This resulted in complete synchronization and an acceptable calibration.

The markerless motion capture was experimented with using the DSR approach. When utilizing DSR, multiple criteria are essential. The need for a functioning markerless solution led to the creation of a Python-based approach, satisfying criteria 1 and 2. The evaluation was based on previous articles, and the design of the solution was tested for its accuracy in markerless pose estimation and reliability of data loss. The main contribution will be the design artifact itself. Since the whole project will be published, the methods, experience, and results will contribute to the artifact's domain, thereby meeting criteria 7. For the main part of the research, the rigor-cycle was utilized as the main source of knowledge. When researching markerless solutions, the group often used supervisor-approved or other scientific articles as a clarification on what methods to use and what results to expect (fulfilling criteria 5 and 6).

The list of these criteria was found and followed based on (Hevner et al., 2004), and the complete list can be seen in figure 3.2 below:

Design-Science Research Guidelines

Guideline	Description
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Figure 3.2: The guidelines when following a design science research approach
Source: Hevner et al., 2004

The markerless solution followed a quantitative approach again, with already finished and quality-assured software. This solution led to the ground truth for the final thesis, and the accuracy was therefore important. Thus, the group used existing and scientifically accurate software, which would produce the desired results for this part of the process.

3.1.4 Observation and Evaluation

In the article Oates (2006) (p. 36), observation is described as, ”Watching and paying attention to what people actually do, rather than what they report they do. Often involves looking, but it can involve the other senses too: hearing, smelling, touching, and tasting.” This articulation doesn’t fully align with the project group’s data generation needs, and the group concluded to use observation as a data generation method for observing and testing the accuracy and performance of the data. This was done so that the group could connect all the parts from the experiment section and assess the results (see result section 4).

3.1.5 Quantitative

The resulting data was analyzed using a quantitative approach, in which the accuracy of each individual experiment was tested against the others. This was done through multiple statistical methods to determine how effectively the markerless solution aligned with the marker-based ground truth.

3.2 Selected Literature

The project drew its primary inspiration from an article provided by the supervisor, which had undergone peer review. This article served as a reference for the project and its methodologies. When additional sources of information were needed, Google Scholar was used to acquire relevant and scientifically valid literature. The group also used articles or papers created by relevant organizations such as Qualisys or OpenCV. While acknowledging the potential for bias in their materials, their credibility in the field and recognition by other scientists mitigated the concern of misinformation. Nonetheless, when the group used non-scientific articles, the methods or results were cross-referenced before being used. This way, the group aimed to maintain rigor when researching outside the scientific domain.

3.3 Hardware

This section introduces some of the hardware solutions used for this project.

3.3.1 Computer Hardware Specification

All programs and tests were run on a school-provided computer (Threadripper). The computer ran on Windows 11 with an RTX 2080 graphics card and 1024GB of random access memory (RAM).

3.3.2 FLIR Camera

For capturing the images for further processing in OpenPose, the group was provided a set of FLIR Blackfly S RGB cameras by Vizlab, NTNU. The cameras had a resolution of 1280x1024, CMOS global shutter, polarization, and high-sensitivity back-illuminated sensors (BSI). The cameras can be synchronized using either a software trigger, hardware trigger, or action command, which made it a suitable choice for our project's needs. The cameras were equipped with a *Computer A4Z2812CS-MPIR, 2.8mm-10mm, 1/2.7"*, CS mount Lens, which gave the group the possibility to experiment with different aperture levels during the experiment.

3.3.3 Raspberry Pi

To synchronize the FLIR cameras, the group implemented a custom sync trigger utilizing a Raspberry Pi 3, running Raspberry Pi OS Lite. The group developed a custom script that sent electrical triggers to the cameras via

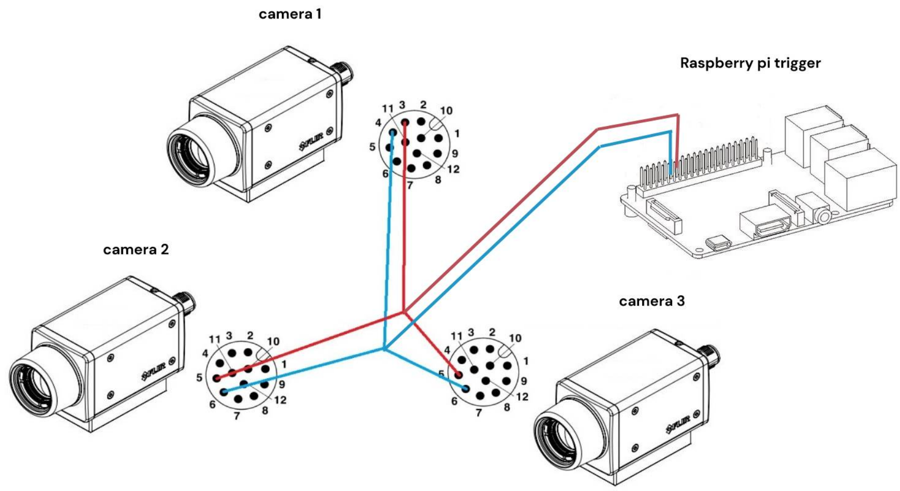


Figure 3.3: Created by the project group, based on illustrations from (A. G., 2024, 'Raspberry Pi Documentation', 2024)

three soldered GPIO wires connected to GPIO pin 16 and 17 on the circuit board of the Raspberry Pi (See Figure 3.3). The OS is configured to automatically log in and execute the trigger script after booting up. This means that the only required action from the user is powering on and off the device using the power cable.

3.3.4 Qualisys

Qualisys is a provider of precision motion capture technology and is widely used in sports, animation, and health services ('Qualisys - About us', 2023). The group was granted access to the system at Vizlab NTNU, making it the preferred option for marker-based motion capture.

Infra Red Cameras

The group used a collection of eight Qualisys cameras (three - Oqus 310 and five - Oqus 500+). The cameras are designed to work with both passive and active markers (Theory - 2.3.4). For our project, using passive markers that reflect infrared light from the camera ensured minimal interference with the images, allowing them to be utilized with OpenPose. The cameras also had a low latency and supported frame rates up to 1660 fps. This gave the group the opportunity to better synchronize the two independent motion capture systems in post-production.

3.4 Software

The following text explains how and why the project group chose different software tools.

3.4.1 OpenPose

OpenPose, recommended by the group's supervisor, served as the main source for markerless motion capture data. OpenPose is a real-time multi-person system for detecting human body, hand, facial, and foot key points in images (Cao et al., 2019b). These key points, or pixel-coordinates, are then stored in a JSON file, which are then used to compute 3D body positions.

OpenPose offers a variety of body-models, with the default being ”BODY_25”. However, the group ended up using their experimental model ”BODY_25B”, which includes additional body key points and PAF channels (Theory - 2.3.6). The choice behind the selected body-model was based on the documentation from OpenPose (Cao et al., 2019a), stating that the increased number of PAF channels increases the complexity, but also the accuracy of the model.

3.4.2 Qualisys Track Manager

”Qualisys Track Manager(QTM) is a Windows-based data acquisition software with an interface that allows the user to perform 2D and 3D motion capture” (Qualisys AB, 2011b). Having an accurate reference point or ’ground truth’ to measure our findings against was an important part of the project. QTM offers an industry-standard solution with high accuracy and is therefore often used by medical and biomechanical engineers.

Skeleton Solving

To acquire the skeleton or joint center data, the usage of a skeleton solver was important. The skeleton solver is a functionality within Qualisys that calculates a human skeleton based on marker placement and therefore provides a ground truth for further analysis. This skeleton model is calculated using PCT (Theory - 2.4.1, Appendix - E), which is the medical standard and therefore ensured accuracy for the group's project.

Automatic Identification of Markers

Automatic Identification of Markers (AIM) is another functionality in Qualisys utilized by the group. The AIM model auto-labels markers, which can then be used to calculate the skeleton data. AIM was used together with self-labeling to be able to track a marker over the period of the recording, making it easier to analyze later on.

3.4.3 Spinnaker Software Development Kit

To ensure uniform settings across all cameras and manage the synchronization trigger, the group utilized the Spinnaker Software Development Kit (SDK). The SDK provided the group with a variety of visualization and debugging tools, a library of example code, and comprehensive documentation (‘Spinnaker SDK | Teledyne FLIR’, 2024).

SpinView Graphical User Interface

The SpinView interface provided the group with access to all essential camera controls. By using the demo application, the group was able to concentrate on tasks such as setting up the recording environment, performing calibration and triangulation, and testing how different variables affected the results in real time.

Hardware utilization in Spinnaker

Spinnaker adapts to available hardware, ensuring it runs seamlessly regardless of the system. When recording, the images are stored in a buffer in random access memory (RAM) while waiting for processing. This allows for capturing frames simultaneously from many cameras and with a high bit-rate. Spinnaker also uses the computer’s central processing unit (CPU) and graphics processing unit (GPU) for rendering the display (‘Spinnaker SDK | Teledyne FLIR’, 2024).

3.4.4 OpenSim

OpenSim is an free-to-use software used for creating dynamic simulations of movements (Delp et al., 2007). During the course of the project, having a tool for 3D visualization was important for multiple reasons. Firstly, it was used for visualization of data, enabling the creation of high-quality representations and images for the project poster and final report. Secondly, it played an important role in error checking, allowing for the identification of potential problems and providing a clear understanding of how various software tools represent data. This aided the group in resolving issues such as axis representations (addressed by modifying the axis - see Section 3.7.4) and the problem with negative y-axis values (transforming OpenPose y-axis - see Section 3.7.4).

3.4.5 Pose2Sim

Pose2Sim is an open-source Python library for calibration and triangulation purposes (Pagnon et al., 2022b, Pagnon et al., 2022a, Pagnon et al., 2021). The group modified their own version of Pose2Sim for its ability to deliver high-quality data. Its primary usage was for handling OpenPose JSON files, camera calibration and triangulation. Usually, Pose2Sim is installed using pip or other package managers. The group opted to clone the repository and modify the source code according to the requirements of the project. The decision to use Pose2Sim stemmed from the fact that it was developed over an extended period by a team of scientists, making it a preferred choice for achieving high accuracy (based on the project group's limited time frame).

3.4.6 Python

Python version 3.11.8 was used during development.

3.4.7 Project Files and Scripts

During the course of the project, the group had to develop multiple Python scripts. To get a full overview of the project, it is therefore encouraged to read through the chapters concerning the code documentation and the scripts in the appendix; however, this is not necessary for understanding the main report (See Appendix C and B).

3.5 Conventional Camera Setup

Calibrating the FLIR cameras involved using conventional instruments for calibration.

3.5.1 Camera Setup

The correct setup of each camera was important, including its settings and placement relative to the other cameras.

Camera Controls and Settings

The group chose SpinView GUI for controlling the camera settings due to its ability to quickly make changes and preview the results in real time with a multi-camera preview. When adjusting the camera settings, the trigger mode was set to software. Using the software trigger allowed for continuous frame generation. When all settings were set, the trigger mode

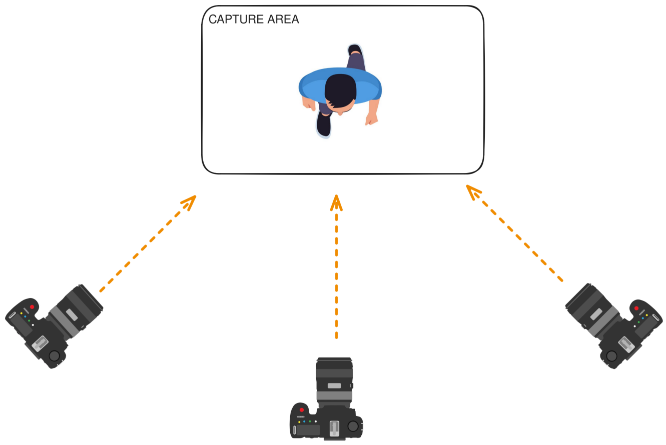


Figure 3.4: Illustration showing the positioning of the conventional cameras

was switched to hardware trigger mode (Line in), preparing the cameras for recording.

Trial cameras settings:

- **GPIO Setting**
  - Trigger mode: Line in
  - Trigger Source: Line 0
- **Settings**
  - Acquisition Mode: Off
  - Exposure Mode: Timed
  - Exposure Auto: Off
  - Exposure Time: 15000μs
  - Gain Auto: Off
  - Gain: 0Db
  - Gamma Enable: false

Positioning

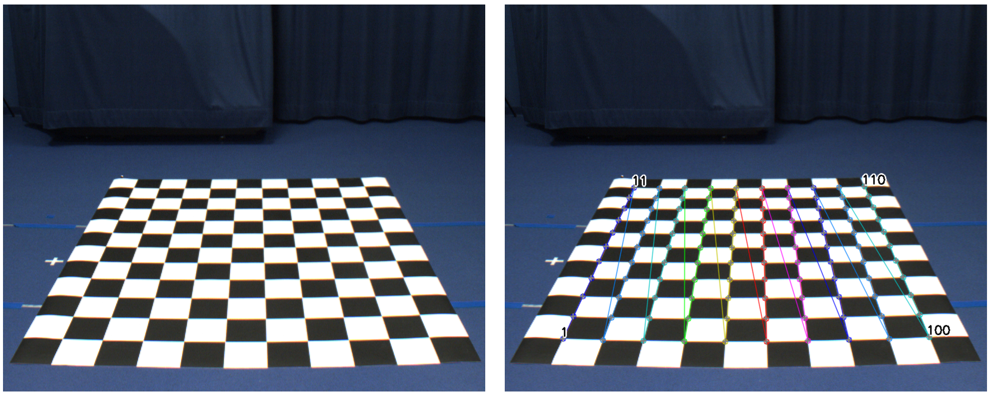
The cameras were elevated using a tripod at 160 cm above the ground. The cameras were named *cam_01*, *cam_02*, and *cam_03*, starting from the left. *Cam_02* was faced directly towards the participant, while the corner cameras were angled at around 45 degrees (see Figure 3.4). The group did not take measurements to ensure that these corner cameras followed a strict or specific angle.

3.5.2 Recordings

The capturing process was initiated by starting the recording in SpinView on the computer. As a result of the cameras being set in trigger mode, there was no image transmitted to the computer. The frames captured from each camera were to be stored in directories named *cam_01, cam_02*, and *cam_03*. To generate frames for storage, the trigger device had to begin sending pulses. Powering on the Raspberry Pi involved booting up the system and waiting for the synchronization script to begin.

After the signal was achieved, the recording process was ready to begin. At the beginning of the recording session, the extrinsic board (Method - 3.5.3) was laid on the ground with the participant out of view. Then the board was removed, and the participant moved around the frame with the intrinsic checkerboard (Method - 3.5.4), while making sure all angles were covered. After all the data for calibration was gathered, the participant walked to the capture area and positioned himself in the A-pose. Simultaneously, the group started the recording on the Qualisys system for capturing ground truth data. When the A-pose was held for a couple of seconds, the squat, walk, and throw motor tasks were performed (see Section 3.7.3). After all the tasks above were finished, the Raspberry Pi was powered off, and the Qualisys recording was ended.

3.5.3 Checkerboard for Extrinsic Calibration



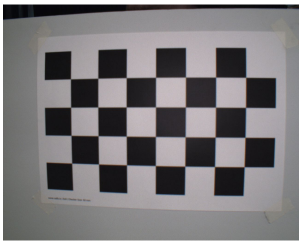
(a) Image for calculating extrinsic parameters

(b) Image illustrating the detected corners. Where 1 represents origo

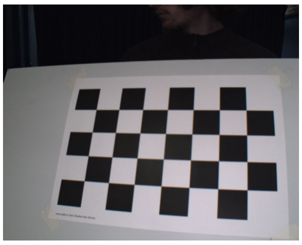
Figure 3.5: Illustrations showing the same image from cam_02

For calculating the camera extrinsic, an 11x12 checkerboard with a square size of 167 mm was laid on the floor. This checkerboard is bigger than the one used for intrinsic calibration and covers as much of the image as possible (See Figures 3.5).

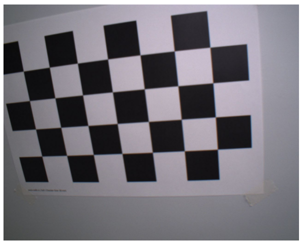
3.5.4 Checkerboard for Intrinsic Calibration



(a) Figure 1



(b) Figure 2



(c) Figure 3

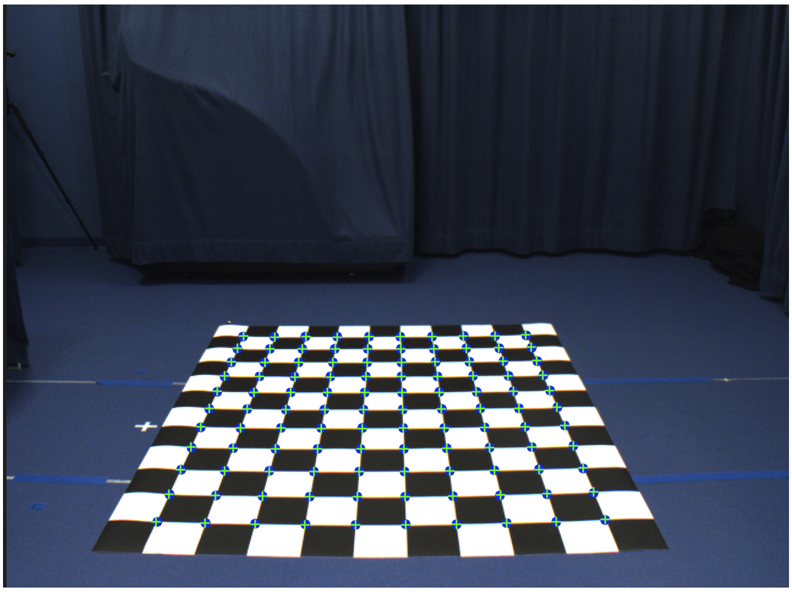
Figure 3.6: Example of three images captured for calculating the intrinsic parameters of *cam_02*

For calculating the intrinsic parameters, a 5x8 checkerboard with a square size of 50mm was moved around the frame of each individual camera (See Figures 3.6). The group made sure to capture 10 images per camera, ensuring that the entire field of view was covered. This process helped in removing radial distortion.

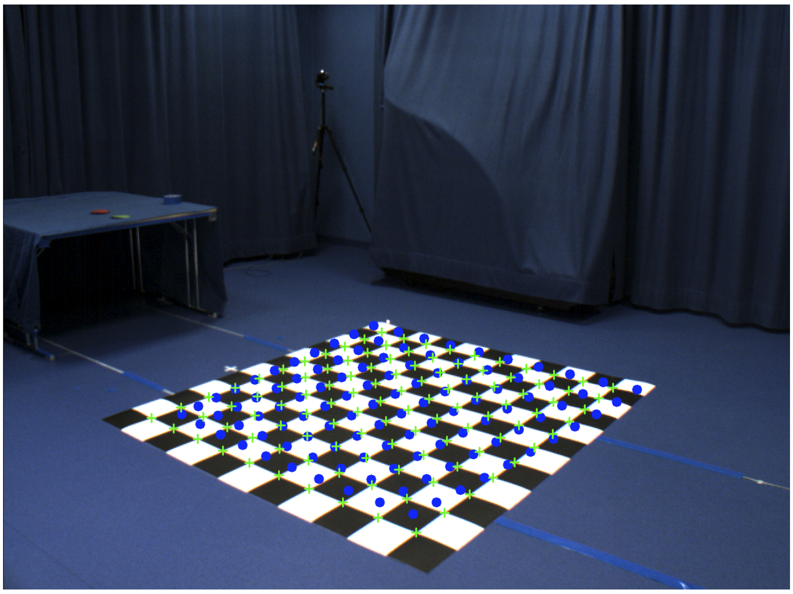
3.5.5 Re-projection error

The re-projection error was calculated after the intrinsic and extrinsic calculations (read theory 2.2.9, 2.2.2, 2.2.1 for further understanding). To get a low re-projection error, recordings with high quality were important (see subsection 3.5.2). The re-projection error was calculated every time the extrinsic or intrinsic values were changed. If this was not done, the re-projection would be based on incorrect values, and the triangulation would be inaccurate.

The details of how the recordings were taken can be found in section 3.5.4. The results from a well-executed recording, where a significant portion of the camera was covered with the checkerboard, led to the outcomes seen in Figure 3.7a, while a poorly executed recording resulted in the outcomes depicted in Figure 3.7b.



(a) Image with good re-projection and low error



(b) Image with bad re-projection and high error

Figure 3.7: Images represents the re-projection from two different calibrations processes. The blue dot represents the re-projection while the green "+" represents the real world location of the points

3.5.6 Calibration

The calibration part was handled using the Pose2Sim library. The group calibrated the cameras using Zhang's method (Zhang's method - Theory 2.2.6), with a checkerboard (Checkerboard - Method 3.5.4 - Theory 2.2.7) to identify 2D image points and determine the necessary variables using Direct Linear Transform (DLT - Theory 2.2.5). The first part of the calibration process was to estimate the intrinsic and extrinsic parameters, followed by image undistortion (Camera parameters - Theory 2.2). Finally, the re-projection error (Re-projection error - Method 3.5.5) was calculated and used to estimate the accuracy of the calibration (See Figure 3.7).

3.5.7 Triangulation

Triangulation was essential to acquire 3D real-world coordinates based on the 2D data from OpenPose. This was done using Pose2Sim, which utilizes weighted DLT for triangulation. The weighted DLT works similarly to conventional DLT and triangulation as described in theory(Section - 2.2.10). The main difference is the introduction of a confidence score.

This confidence score is provided by OpenPose, which self-estimates the accuracy of joint detections. The introduction of the confidence score introduced a problem for the group, by adding another threshold, making it harder to achieve recordings with high enough quality. Initially, meeting this threshold proved difficult, resulting in sub-optimal triangulation. However, as the team members gained experience and understanding of the recording requirements, this challenge became obsolete. The output of the triangulation process is a TRC file, which can then be compared to ground truth data from Qualisys.

3.6 Qualisys Setup

This section explains the usage of Qualisys and how to use it as a system for motion capture.

3.6.1 Camera Setup and Positioning

The camera setup and positioning is illustrated in Figure 3.9.

3.6.2 Recordings

The captured data is stored in a TSV file format, which contains the computed coordinates of the joint centers and the corresponding skeleton data. For the purpose of this project, the physical markers were disregarded, and only the joint centers were taken into calculations, as they are the primary points of interest.

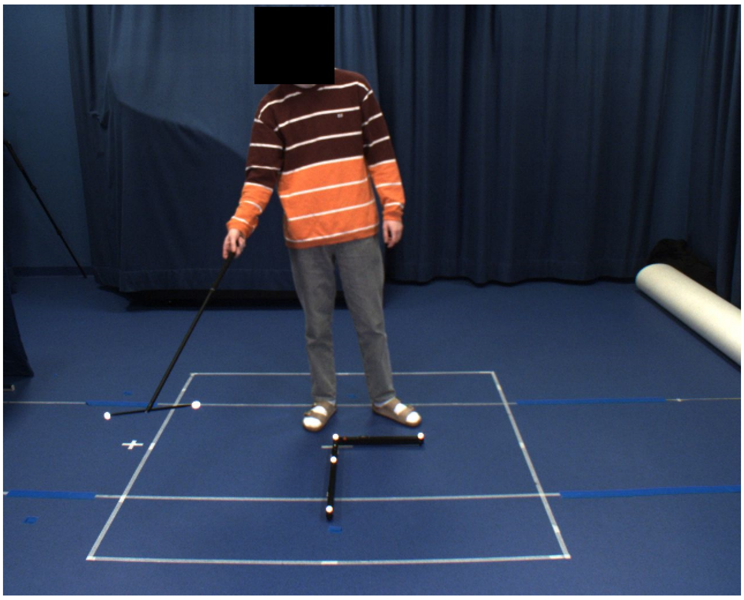


Figure 3.8: Calibration of Qualisys system using calibration wand and L-Frame. The subject in the image moved the wand around in different directions and rotations.

3.6.3 Instruments and Equipment

The group used spherical passive markers (Theory - 2.3.4) for capturing the key points. Detailed information on passive markers, calibration tools, and their utilization can be found in Appendix D.

3.6.4 Calibration

To calibrate the Qualisys system, the group first placed the L-frame on the floor. This was done to define the position of the camera extrinsics. The long arm of the frame defines the x-axis, the short arm defines the y-axis, while the corner defines the $origo$ point. These axes will later be used to define the position of the markers that are recorded within the measurement volume.

The distance between the spherical markers on the wand was then predefined in QTM before calibration. Before beginning the calibration process, the laboratory was prepared with blue tape and fabrics in order to remove all false markers that could be detected. The calibration recording time was set at 30 seconds at $100hz$ in QTM. After starting the recording, the wand was moved around continuously, performing the wand dance (Theory - 2.2.8). The performance of the wand dance can be seen in Figure 3.8. After the calibration process, the system automatically calculated the

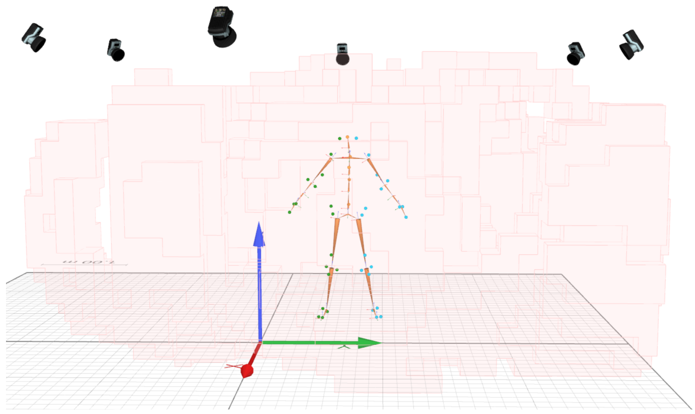


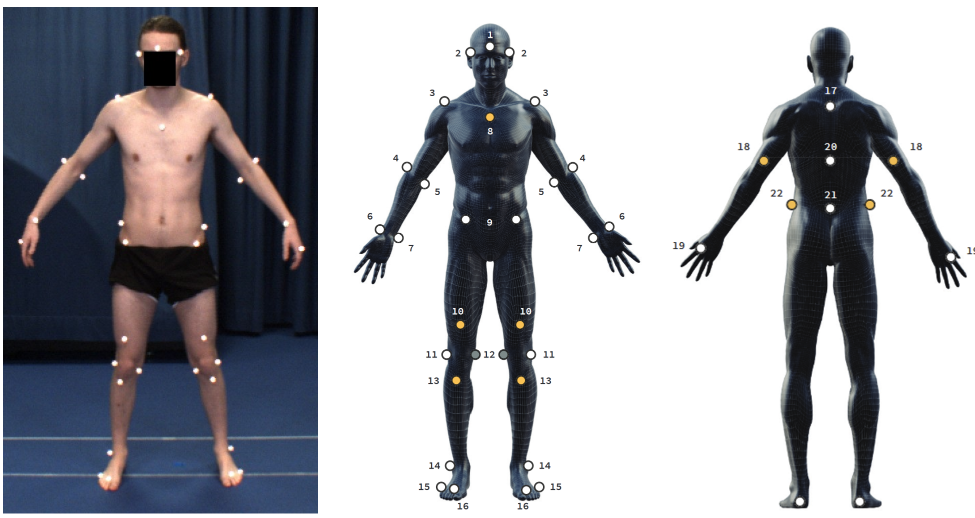
Figure 3.9: Illustration showing the calibrated area as pink coverage. This was the area of movement used when calculating the final results.

calibration and indicated whether it was successful or not. The calibration coverage area can be seen illustrated in Figure 3.9.

3.7 Bio-mechanics

The subsequent section are describing biomechanical methods and decisions.

3.7.1 Marker placement



(a) Marker placement on human body

(b) marker placement from front

(c) marker placement from back

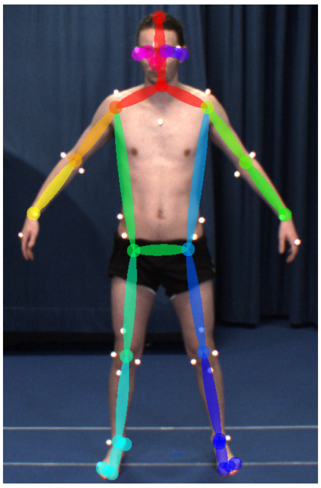
Figure 3.10: Illustrations showing marker-placement on human body in the A-Pose accordingly to how explained by Qualisys sport setup

Marker placement was based on the Qualisys sport marker set (see figure 3.10 for illustration and Appendix E for a detailed explanation), chosen for its suitability to the dynamic nature of the selected movements (see Section - 3.7.3). The sports marker setup had a more straightforward marker arrangement, making it convenient when new recordings were needed. The main reasoning behind the choice, however, is its similarity to the placement of markers when using PCT(Theory - 2.4.1).

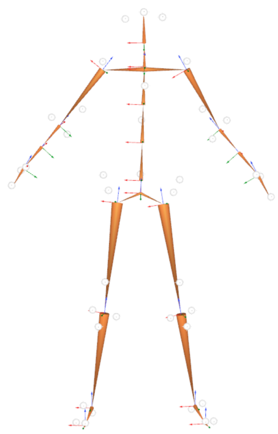
3.7.2 Marker Choice

Qualisys and OpenPose use different positions or keypoints to define their joint centers, making it difficult to compare and combine the data. Therefore, the group had to select a set of joints that were present in both OpenPose and Qualisys and shared consistent body placement. Ultimately, the group settled on 12 markers with these matching names (refer to Figure 3.11 for reference):

- Left & Right Shoulder
- Left & Right Elbow
- Left & Right Hand
- Left & Right Hip
- Left & Right Knee
- Left & Right Ankle



(a) OpenPose Body_25B Joints



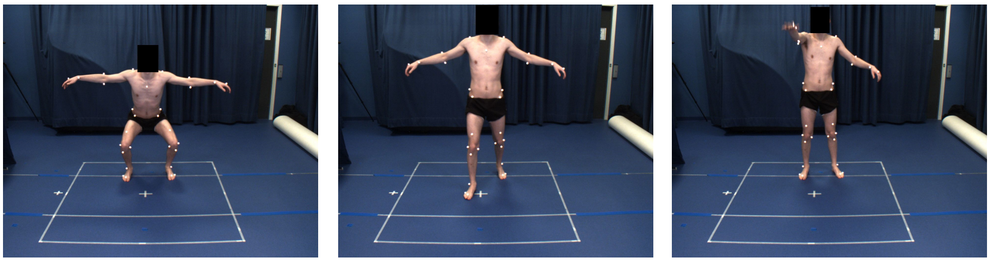
(b) Qualisys Skeleton Joints

(c) Chosen Joints By Group

Figure 3.11: Illustrations showing the differences in joint sets based on what was used for motion capture. The first is OpenPose, the second is Qualisys, and the last is the group's resulting joint set used for testing.

3.7.3 Chosen Motor Tasks

Three different motor tasks were chosen for this project: squatting, walking, and throwing. These movements were selected based on differences in muscle usage, movement velocity, and level of freedom. The purpose was to use both commonly performed movements and those that effectively test the accuracy of the marker-less solution. Walking is a very standard and slow 2D movement, while squatting and throwing are more dynamic 3D movements with different types of muscle usage. The motor tasks can be seen in more detail below in Figure 3.12.



(a) Squat **(b)** Walk **(c)** Throw

Figure 3.12: Images representing the three movements chosen by the group for the purpose of testing markerless motion-capture compared to markerbased

3.7.4 Data Processing

To produce high-quality and scientifically rigorous results, various data processing methods and techniques were applied to generate data suitable for analyzing the main thesis problem.

Filtering

A variety of filtering methods were utilized during experimentation. The choice of which filter to execute during the trial was defined in the configuration file located in the project's root directory. The methods used are listed below:

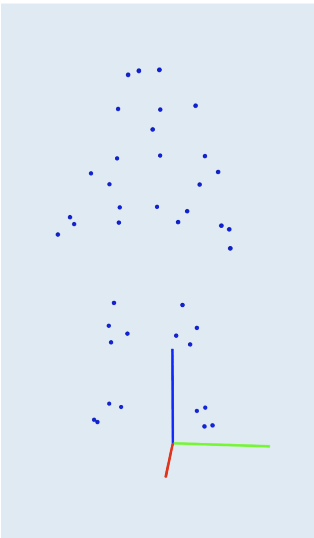
Butterworth Many different combinations of parameters were used to find the best combination possible. To control the roll-off of the filter, different *orders* were tried. After finding the correct order, different combinations of cutoff frequencies in hz were defined.

Gaussian The group only ran one trial using the Gaussian filter in Pose2Sim. The standard deviation of the Gaussian distribution (Theory - 2.3.3) used for controlling the amount of smoothing was set to 2 pixels.

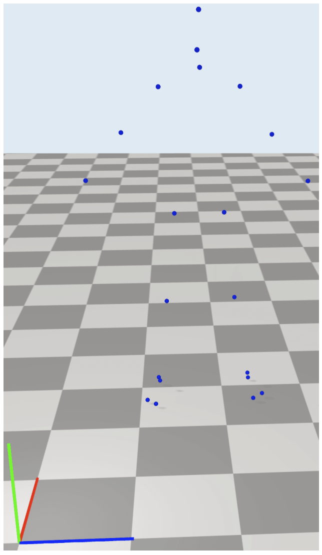
LOESS The group only ran one trial using the LOESS filter in Pose2Sim. The number of data points used for smoothing each point was set to 30 in the configuration file.

Changing the Axis

To be able to analyze the data collected from the different software tools (Qualisys and OpenPose), a necessary post-processing step was required. This step was necessary due to the distinct axis representations. OpenPose uses a convention similar to the pixel coordinate system where the image depth is represented by the z-axis, while the width and height are represented by the y- and x-axes, respectively. This axis representation is different from that of Qualisys, which uses a more traditional 3D space setup, with the z-axis as vertical, and the sagittal and frontal planes represented by the x- and y-axes. The difference in axis representations led to significant differences in their positioning, making it impossible to analyze the data in a logical manner (see Figure 3.13 for a more descriptive representation). It was therefore important to transform the data to follow the same axis representation to be able to further analyze the data.



(a) Axis from Qualisys



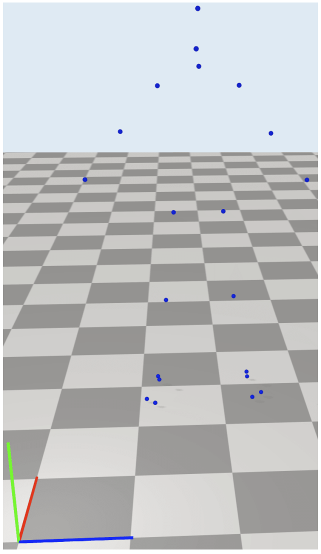
(b) Axis from OpenPose

Figure 3.13: Images representing the difference in axis between Qualisys and OpenPose. The green line is the y-axis, blue z-axis and red is x-axis

Transforming OpenPose y-values

Another problem that the group encountered was the orientation of the y-axis in OpenPose, where it corresponds to the negative sagittal axis of the image. This presents an issue as it assigns the ground as $origo$, and the image's height then hade negative values, resulting in the coordinates appearing flipped when simulated in OpenSim. To address this, the group implemented a solution within Pose2Sim, adjusting the coordinates by multiplying the flipped coordinate system by negative one (-1). Figure 3.14 illustrates the issue.

(a) Image illustrating the negative y problem



(b) Coordinates after transforming negative y

Figure 3.14: Images representing axis from Openpose before and after transforming the negative y-axis

Synchronizing OpenPose and Qualisys

Due to the use of two separate recording systems, the data was asynchronous and therefore needed to be synchronized. Calculating the time offset involved identifying the maximal y and x values of the elbow key point in each of the TRC files. This maximum value served as a common point in time, allowing for synchronization of the files.

Offset Calculation

To establish a common origin for the two systems, the difference between a defined set of key points had to be found. This process involved comparing the values of corresponding points and then applying the calculated offset to the main TRC file.

3.7.5 Data Analysis

When calculating the difference between data from Qualisys and the triangulated data fromOpenPose, the group used mean absolute error (MAE), calculating the difference between the predicted values from OpenPose and the actual values from Qualisys. This was done after data processing (subsection 3.7.4), and the Mean Absolute Error (MAE) was calculated based on the number of frames and the coordinates of the motion capture methods. The equation for MAE can be seen below, where n is the number of frames (time-space) and x_o and x_q are the measured values from OpenPose and Qualisys respectively.

$$MAE = \frac{1}{n} \cdot \sum |x_o - x_q|$$

It's important to emphasize that while the equation uses x as a representation of the unknown coordinates for conventional reasons, all three coordinates were calculated and analyzed, not just the x-coordinate. The results for the different motor tasks and the difference between the markerless and marker-based systems can be seen in the results Section 4.

4. Results

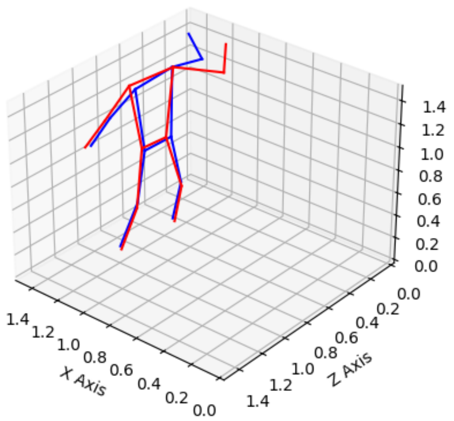
This chapter will present the project's results. The chapter is divided into three main parts. The first part covers the scientific results. The second part addresses the engineering results, and the last part addresses the administrative results.

4.1 Scientific Results

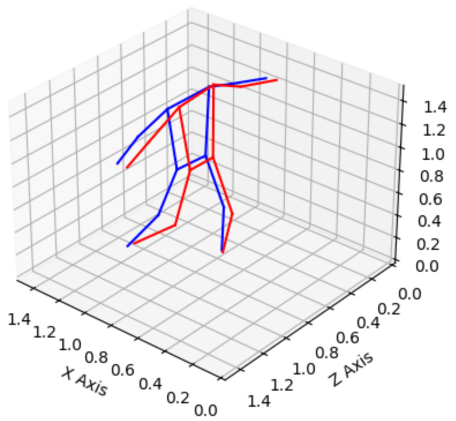
This section will go through the results from OpenPose and Qualisys, including different aspects such as filtering and loss errors.

4.1.1 OpenPose Body Estimation

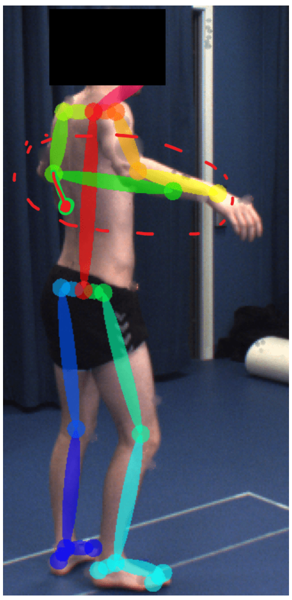
The evaluation of markerless and marker-based motion capture involved comparing the performance of OpenPose and Qualisys, taking into account various factors such as the number of cameras and their setup. OpenPose utilized three frontal cameras capturing at 30fps, while Qualisys used eight cameras with a 360-degree view at 100hz. These differences resulted in distinct views of the human body, sometimes leading the markerless model to wrongfully estimate the human body. This error was visible in the triangulation process and can be seen in the triangulation examples in Figures 4.1a and 4.1b, or directly in the prediction model OpenPose 4.1c and 4.1d. The Figure is also further described in Appendix F.



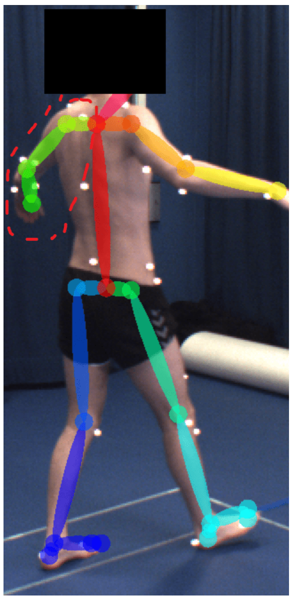
(a) OpenPose (blue) lags behind Qualisys (red) in a throwing motion



(b) OpenPose (blue) lags behind Qualisys (red) in a walking motion



(c) OpenPose wrongfully predicts left arm position



(d) Representation of how the left arm should be predicted in the previous image

Figure 4.1: Figure illustrates possible body estimation mistakes. In (a) and (b), a possible triangulation mistake is shown, where the body estimation lags behind the ground truth. In (c), OpenPose wrongly estimates the left arm, as can be seen in the correct version (d) where the hand is more outward and more down than the model predicts.

4.1.2 Motion Estimation using MAE

To evaluate the accuracy of markerless motion capture, MAE was used to calculate the difference between the real world and the predicted values. The evaluation focused on specific joints during various movements, comparing the MAE on a baseline model, Body_25B with 6th order Butterworth $2hz$. The results are listed in multiple graphs using millimeters over time as the measuring metrics.

A-pose

The A-pose resulted in an overall small error, with little to no lag or data loss. The A-pose was the starting position, resulting in the graphs depicted in Figure 4.2.

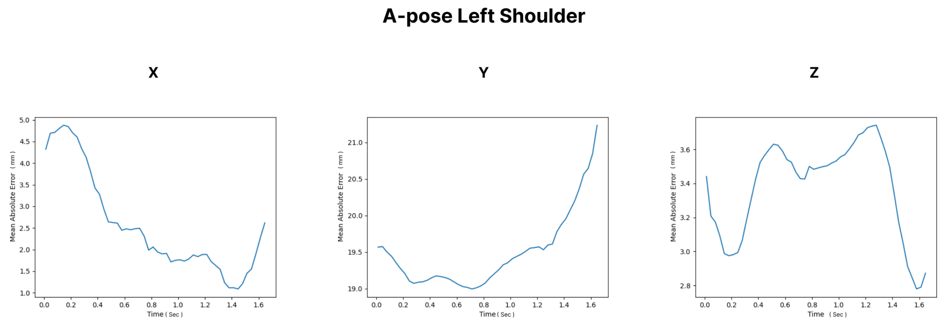


Figure 4.2: Image depicting the MAE of the left shoulder for the A-pose. The y-axis represents the MAE (millimeters), while the x-axis represents the timeframe (seconds) of the current movement. The peak of MAE for x-coordinates is 5 mm, for y-coordinates it is 21 mm, and for z-coordinates, it is 3.7 mm.

Squat

As a slower-paced 3D movement, the squat had a relatively low error. The joint used for estimating this error was the right knee, facing towards the camera. The MAE can be seen in Figure 4.3, illustrating the error of a 3D spaced movement.

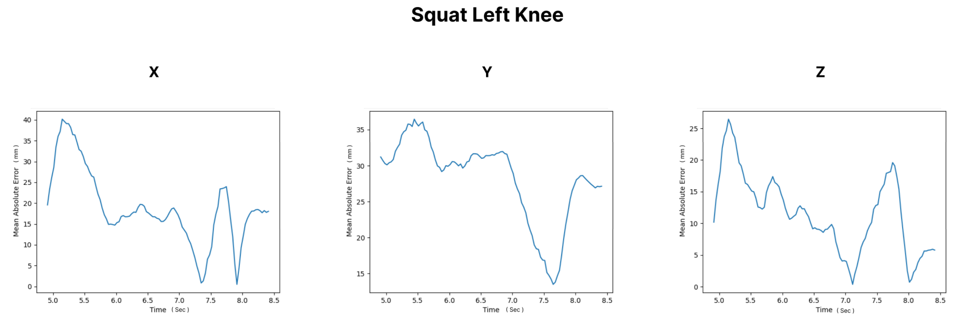


Figure 4.3: Image depicting the MAE for the Left knee during the Squat motion. The y-axis represents the MAE (millimeters), while the x-axis represents the time-frame (seconds) of the movement. The peak MAE for x-coordinates is 40 mm, for y-coordinates is 35 mm, and for z-coordinates is 25 mm.

Throw

Throwing is a high-speed 3D movement facing the cameras. This resulted in high data loss and wrongful triangulation as described in the section on body estimation (Section 4.1.1). The MAE can be seen with a rather large error spike on the detected joint of the throwing arm, which is the right elbow joint. The MAE can be seen in Figure 4.4.

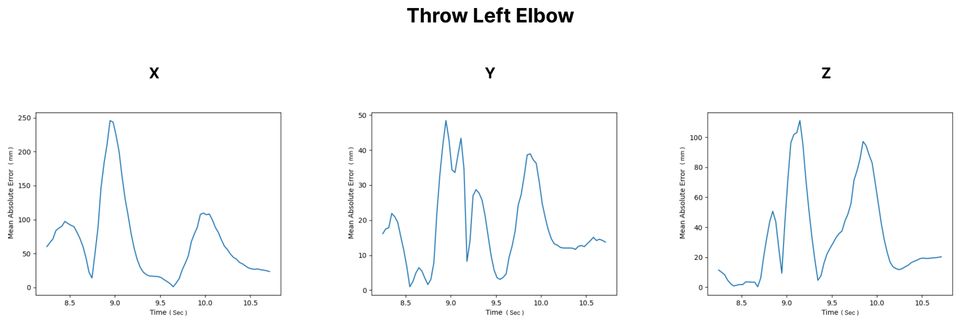


Figure 4.4: Image depicting the MAE for the Left Elbow during the Throw motion. The y-axis represents the MAE (millimeters), while the x-axis represents the time-frame (seconds) of the current movement. The peak of MAE for x-coordinates is 250 mm, for y-coordinates is 50 mm, and for z-coordinates is 100 mm.

Walk

When performing the walking motion towards the camera, the group observed visually and by analyzing the data, difficulties in finding the correct key points. After triangulation, the error or lag can be observed. This error can also be found by looking at the two-dimensional OpenPose results as well. The illustration of this problem is shown in Figures 4.1b and 4.5.

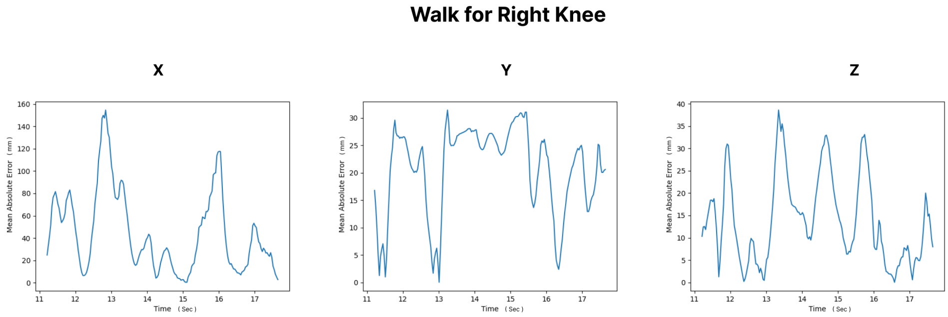


Figure 4.5: Image depicting the MAE for the Right Knee during the walking motion. The y-axis represents the MAE (millimeters), while the x-axis represents the timeframe (seconds) of the current movement. The peak MAE for x-coordinates is 160mm, for y-coordinates it is 30mm, and for z-coordinates it is 40mm.

Sideways Walk

After the observations in Subsection 4.1.2, the group added the sideways walk as a movement for comparison. The MAE is calculated on the same joint as for the walk motion and on the same baseline model. Figure 4.6 displays the MAE for the sideways walk.

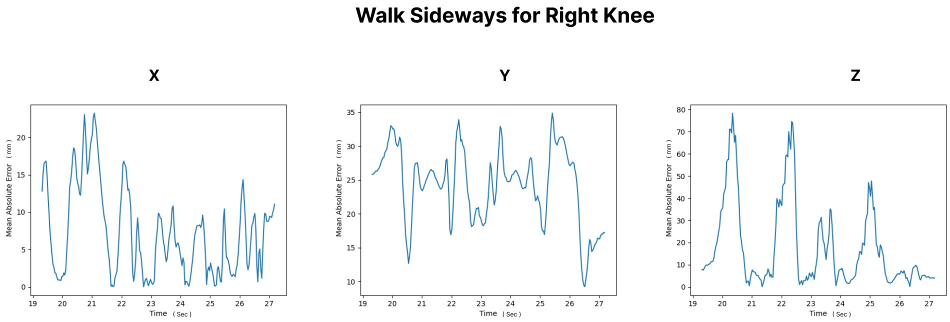


Figure 4.6: Image depicting the MAE for the Right Knee during the walking motion. The y-axis represents the MAE (millimeters), while the x-axis represents the timeframe (seconds) of the current movement. The peak MAE for x-coordinates is 30 mm, 35 mm for y-coordinates, and 80 mm for z-coordinates.

4.1.3 Body-models

The motion tracking was tested with two different body-models from OpenPose. The resulting difference between the two body-models was calculated based on their mean absolute errors on squat, throw, and sideways walking motion. Additionally, an average across all joints in the entire recording was computed. Based on the results, the conclusion is that the experimental Body_25B has a better accuracy. The results of the models can be seen in Figure 4.7, and the average MAE can be seen in Figure 4.8. The Figures are also further described in Appendix F.

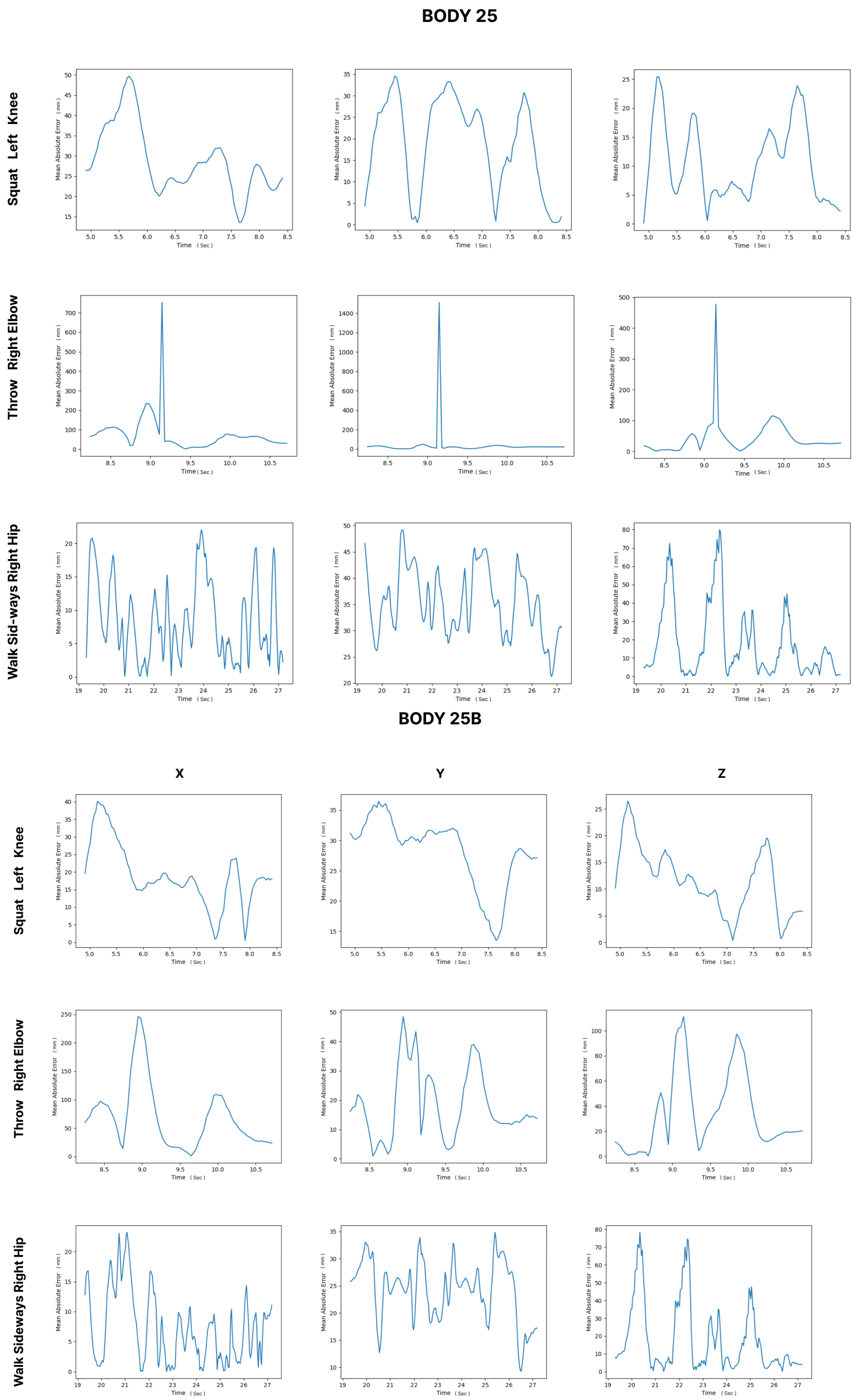
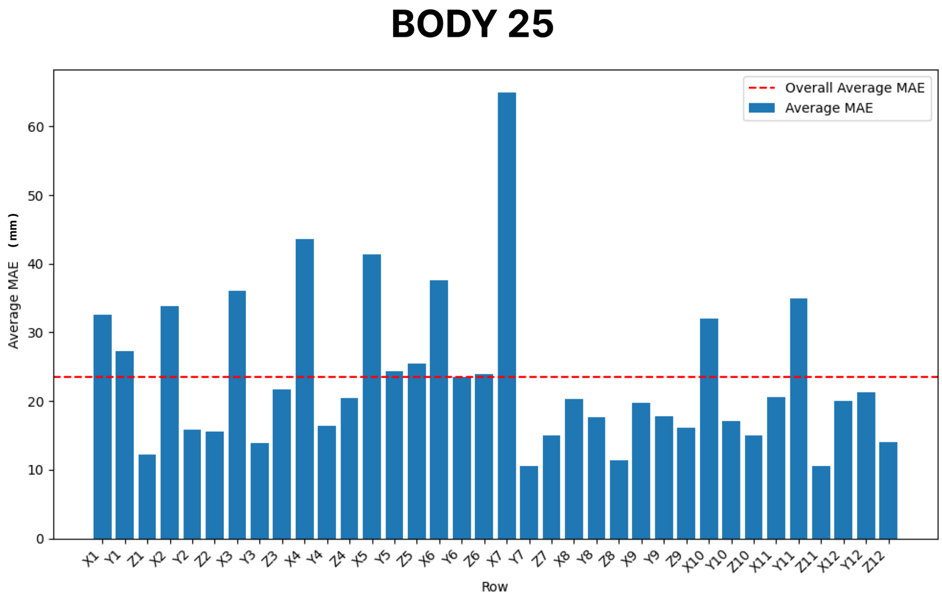


Figure 4.7: The two different graph sections show squat, throw, and sideways walk MAE for two body-models: ”Body 25” and ”BODY 25B”. The y-axis represents the MAE in millimeters, and the x-axis represents the timeframe in seconds.



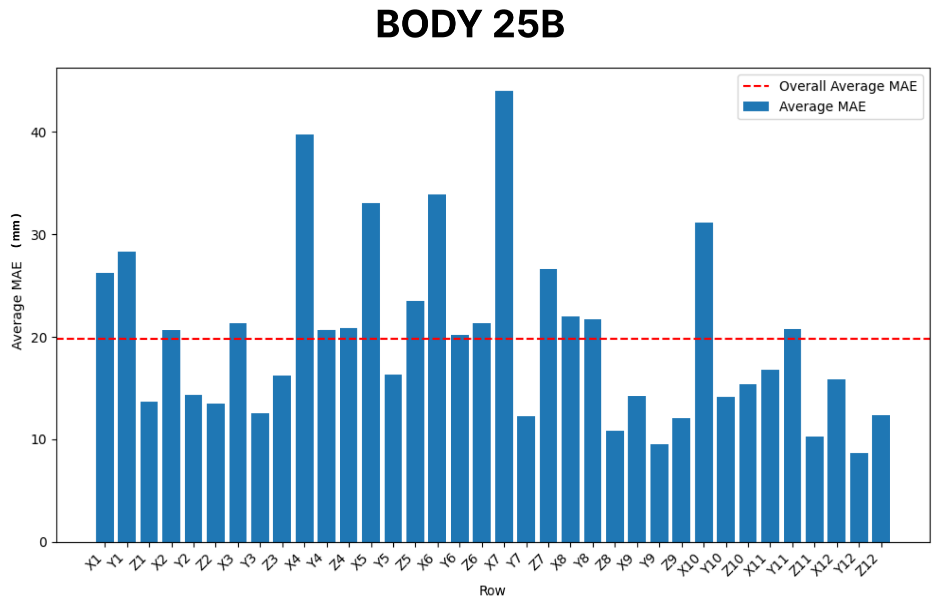


Figure 4.8: The two graphs show the Average MAE for each joint. The first represents Body_25, while the second represents Body_25B. As can be seen, the Body_25B models have an better average than Body_25. The individual x, y, and z columns represent the average MAE for a single joint. From the left end, the joints are: left shoulder, left elbow, left wrist, right shoulder, right elbow, right wrist, left hip, left knee, left ankle, right hip, right knee, right ankle.

4.1.4 Masked Markers

During recording, markers were present in both Qualisys and OpenPose. This was necessary because the recordings must be identical for both solutions when calculating the accuracy. Since markers are present in OpenPose, it is therefore important to examine the potential influence of markers on markerless body estimation. The markers were removed using a Python script (Appendix C), which masks markers utilizing the surrounding pixels. The results were then tested against the body-model Body_25. Figure 4.9 shows the MAE for the squat motion when masking markers, while Figure 4.10 depicts the average MAE of all joint coordinates for all motions. Based on the image of the average MAE, masking the markers seems to improve the performance of the body estimations.

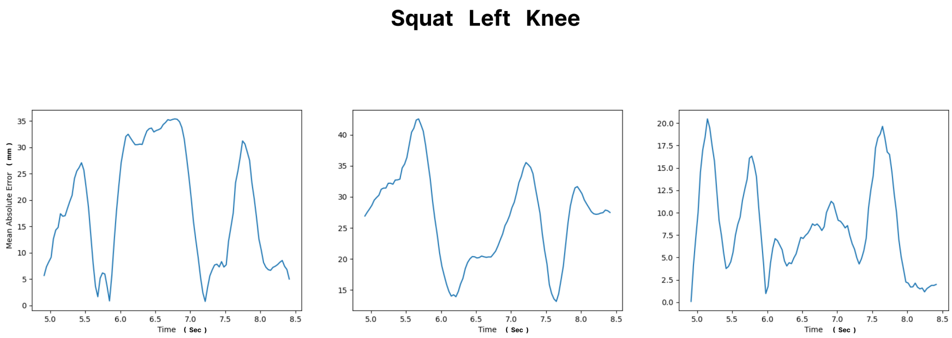


Figure 4.9: Image depicting the MAE for Right Knee for the squat motion. The y-axis is the MAE(millimeters), while the x-axis is the timeframe(seconds) of the current movement. The peak of MAE for x-coordinates is 35mm, 40mm for y-coordinates and 20mm for z-coordinates

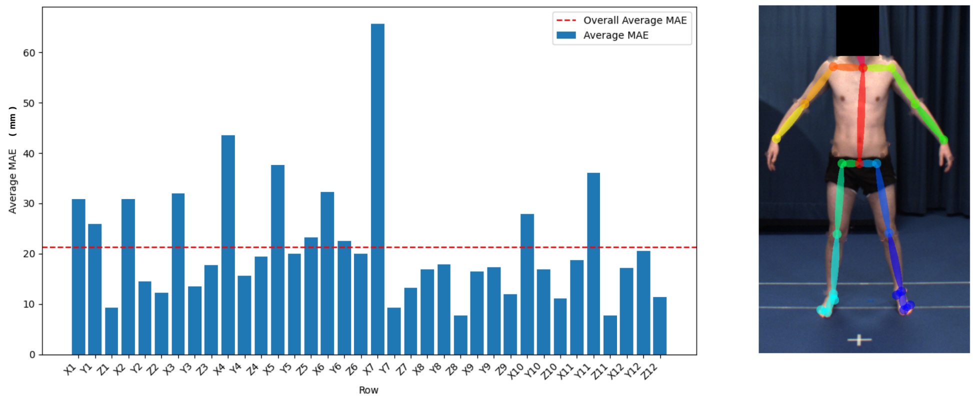


Figure 4.10: This image depicts the average of the BODY_25 model when removing markers from the image, as shown on the right body figure. Markers were removed using a Python script that utilizes KNN to match the surrounding pixels. The individual x, y, and z columns represent the average MAE for a single joint. From the left end, the joints are: left shoulder, left elbow, left wrist, right shoulder, right elbow, right wrist, left hip, left knee, left ankle, right hip, right knee, right ankle.

4.1.5 Filtering

Initially, the data was recorded without data filters (read more about filters in Theory - Section 2.3.3). Multiple filters were tested to find an optimal baseline for final testing.

No Filter

When using no filters, the data was less smooth, and the error tended to be slightly higher than when using filters. This can be seen in Figure 4.11.

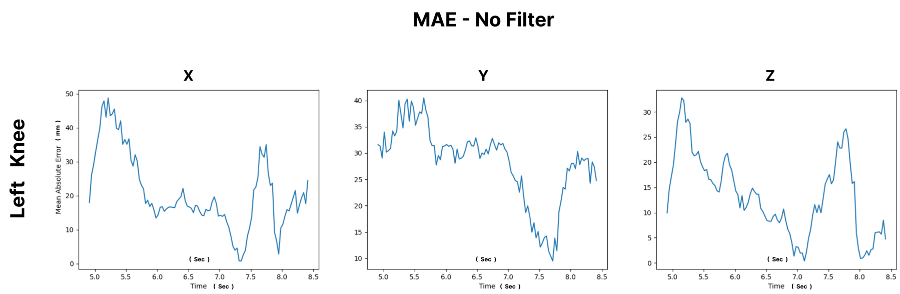


Figure 4.11: Image depicting the MAE with no data filter. The peak MAE for x-coordinates is 50 mm, 40 mm for y-coordinates, and 30 mm for z-coordinates. The y-axis of the graph is measured in millimeters, and the x-axis is measured in seconds.

Butterworth

To find the most optimal Butterworth filter, the group used a more experimental approach. The group evaluated various combinations of filter parameters such as order and cutoff frequencies by calculating the MAE. The best resulting combination ended up having a 6th order roll-off and $2hz$ cutoff frequency. This led to the resulting MAE having a smoother trajectory and a lower error than with no filter (See Figure 4.12).

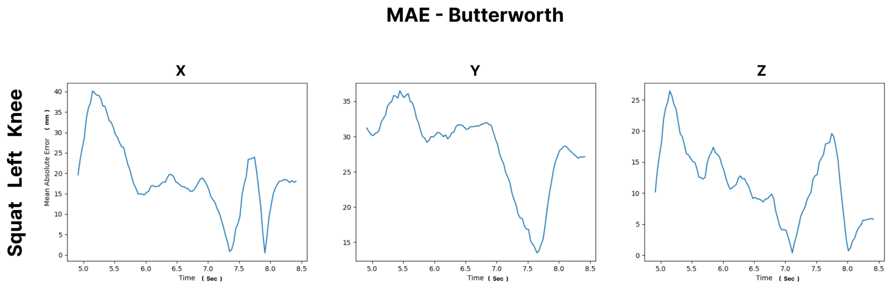


Figure 4.12: Image depicting the MAE with a Butterworth 6th order filter at 2 Hz. The peak of MAE for x-coordinates is 40 mm, 35 mm for y-coordinates, and 25 mm for z-coordinates. The y-axis of the graph is measured in millimeters, and the x-axis is measured in seconds.

Gaussian and LOESS

While the Gaussian filter had little to no difference from Butterworth, LOESS has a relatively better average MAE. The Gaussian filter was filtered with a 2px standard deviation, and LOESS was smoothed with 30 data points. LOESS ended up having a better MAE but seemed to be less smooth. This can be seen in the two graphs below (Gaussian - Figure 4.14, LOESS - Figure 4.13).

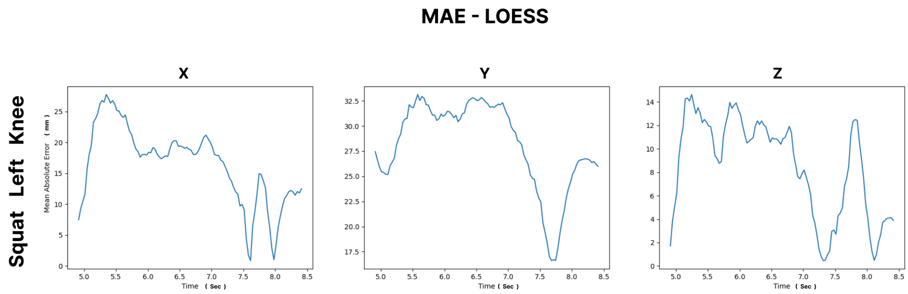


Figure 4.13: Image depicting the MAE using LOESS filter. The peak of MAE for x-coordinates is 27 mm, for y-coordinates is 32.5 mm, and for z-coordinates is 14 mm. The y-axis of the graph is measured in millimeters, and the x-axis is measured in seconds.

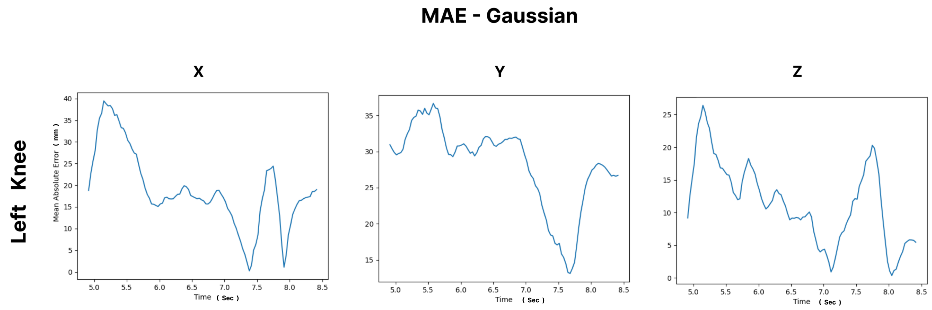


Figure 4.14: Image depicting the MAE using Gaussian filter. The peak of MAE for x-coordinates is 50 mm, 40 mm for y-coordinates, and 30 mm for z-coordinates. The y-axis of the graph is measured in millimeters, and the x-axis is measured in seconds.

4.1.6 Total Results

The overall assessment of the pose estimation accuracy was based on the Mean Absolute Error (MAE) values. This involved calculating the percentage of MAE values exceeding specific thresholds set at $40mm$, $30mm$, and $20mm$. The total results are detailed in Table 4.1. The process involved finding the number of values meeting each threshold, followed by calculating the overall percentage based on the total count. Results are categorized according to different movements, with all three coordinate axes (x, y, z) factored into the final calculation.

Movement	Over 40mm	Below 30mm	Below 20mm
Squat	14.58	76.94	61.25
Walk	19.23	72.32	56.22
Walking Sideways	11.56	81.45	63.80
Throw	37.58	54.08	40.19
Combined	11.42	80.69	64.23

Table 4.1: Table showing the percentage of MAE above 40mm, below 30mm, and 20mm. This was calculated for the different movements, and a total for the whole recording. The values were calculated using a simple method of counting the amount of values for the different thresholds, and then finding the percentage. The MAE values were calculated in Python, and the values were stored in a CSV file.

4.2 Engineering Results

The engineering results were based on the goals set by the group in the early stages of the project. Gaining more insight into the research domain resulted in more updated and relevant engineering goals. This section will, therefore, go through the result goals set by the group.

Technological Advancement

The group defined a goal of wanting to contribute to the technological advancement by producing a final report with a solid foundation for further application of markerless motion tracking. The group wanted to contribute to the ease of motion capturing for applications in animations, gaming, and healthcare services. The results show that the group has managed to create a solid foundation for further development, with room for improvement and scaling. The integration of fundamental concepts like synchronization, calibration, triangulation, and the use of the latest machine learning models proved valuable.

Perform Measurements using Synchronized Cameras

The first step for reducing the grounds for error is to make sure the cameras are fully synchronized. Utilizing the Raspberry Pi, as mentioned in section 3.3.3, proved to be an accurate method for synchronizing the cameras. Some recordings could contain around three thousand frames per camera, and each folder contained the exact same amount at the correct timestamp each time. This hardware-level synchronization approach eliminated any potential inaccuracies or synchronization errors, providing a solid foundation for analysis.

Perform Measurements using Calibrated Cameras

To ensure accurate measurement and reconstruction of the participant and the three-dimensional scene, the group employed methods such as Zhang's method mentioned in method 3.5.6. Calibration was conducted with variations in the distance of the checkerboard from the cameras. When the checkerboard was positioned nearer to the cameras, an intrinsic error of approximately 0.16 pixels was observed, whereas with the checkerboard placed further away, the intrinsic error increased to around 2.36 pixels.

The re-projection error was calculated with the checkerboard close to the cameras and resulted in a value of 2.9 pixels (which corresponds to approximately 6.1mm). As a result of using three cameras, one camera could be ignored during analysis on each image. The re-projection error resulted in *cam_01*, *cam_02*, and *cam_03* being excluded one percent of the time.

Basis for Comparing Marker-based and Markerless Tracking

In the preliminary project plan, the group aimed to have a clear basis for comparison between marker-based and markerless tracking upon completion of the project. Through the utilization of the various technologies outlined in this project, the group has established a comprehensive basis for comparing the two systems. Following the methodology as described in the method section of this paper will provide a framework for comparison between the marker-based and markerless system.

Accuracy

An initial goal was to analyze video with an accuracy within a margin of 2-4 cm, utilizing software provided by VizLab 3D Motion Technologies. This was later changed, and the group ended up using Qualisys as the ground truth. Not utilizing common methods for joint center estimation, such as PCT (Theory - 2.4.1), would lead to inaccurate results. Measuring the accuracy of the markerless system up against Qualisys resulted in most of the mean absolute errors between 20-40 mm, which was within the goals set in the preliminary stages.

Efficiency

One of the key objectives outlined in the preliminary project plan was to evaluate the efficiency of motion capture. An important factor in these use cases is the need for real-time analysis. This proved to be difficult to achieve with the same level of speed and accuracy found in marker-based systems. Our tests show that processing 30 seconds of footage, which accumulates to 900 frames at 30 frames per second, would take hours using the BODY_25B model. Using the default BODY_25 would yield results much faster, but with lower accuracy.

4.3 Administrative Results

The subsequent sections includes the administrative results regarding *Milestones*, *Timesheet*, and *Meetings*.

4.3.1 Milestones

The established milestones set by the group at the beginning of this semester included important deadlines for the bachelor thesis as a whole. These milestones were detailed in the preliminary project plan and vision document (Appendix - H and G). Subsequently, a GANTT diagram was created, including the same deadlines, in addition to some other self-imposed deadlines for the group to follow. Most of the deadlines were completed within their intended timeframe, with a few exceptions. Looking at GANTT (Appendix - I), the team was supposed to finish the software fixing phase on the 29th of January. This phase involved fixing important software provided by NTNU and was originally meant to be finished before the group started their thesis work. The software included a calibration and marker tracking tool (Trackpoint) and a multi-camera recording software (Camera Manager). However, instead of completing this phase by the specified date, the group decided to develop their own solution, ultimately finishing the task on April 8th. The group decided to create their own solution for two main reasons: firstly, to develop a deeper understanding of the theory behind the thesis work, and secondly, to address the numerous errors in the existing software. By doing so, the group aimed to have a more adaptable and controllable solution.

4.3.2 Timesheets

During the first four weeks of the project, the group maintained a consistent pace of ten to twenty hours each week. The first two weeks were spent on drafting the preliminary project plan and other administrative documents. The next three weeks were spent on trying to fix the school-provided software, self-education, and coding the final product. Weeks seven to nine were mostly spent on other school subjects, and little to no time was used on the thesis. Week twelve was spring break, and also the last week with no time spent on the thesis. After the spring break, the group focused on finishing the code so that they could start on the main report. After week fourteen, the main focus was on report writing. There were only a few hours splitting the group members, which was due to sickness, time spent on self-education, and exams. The group collectively met the targeted 500 hours with a variance of plus or minus 10%, with individual contributions totaling 502.7 and 502.2 hours.

4.3.3 Meetings

Based on the preliminary project plan, the group was supposed to have weekly group meetings and biweekly meetings with the supervisor. The group meetings were held as planned, with the group members convening to discuss weekly objectives and last week's work. However, the biweekly meetings with the supervisor sometimes occurred more frequently, especially at the beginning and end of the semester, and occasionally less frequently. There was a three-week gap on two occasions and a four-week gap on another occasion. Read about the reasons in the discussion section of this thesis 5.3.3.

The meetings were initiated by a meeting notice sent by one of the group members to the supervisor (the meeting notices can be seen in appendix I). In the meeting notice, the time and place of the meeting were included, together with meeting attendees and the agenda of the meeting. Participants who couldn't attend the meeting sent a notification regarding their absence. Meeting reports, summarizing the topics discussed, were written down post-meeting and can be found in the same appendix as the meeting notices.

5. Discussion

This chapter will discuss the various results and the decisions that led to the group's outcomes. The discussion is divided into several parts. The first part is about motion capture. The second and third parts are about the engineering and administrative results, respectively. The fourth part is about the group's teamwork. The last part directly addresses the research questions.

5.1 Motion Capture

This section delves into the selected methods and analyzes the scientific results.

5.1.1 Camera Setup

Initially, the group was supposed to test the markerless and marker-based solutions on the same camera setup, testing the accuracy and feasibility of usage with a limited number of cameras. Due to the circumstances mentioned in Section 5.3.1, the group needed to test the marker-based solution using another system. Given that Qualisys was already available in the lab where the group worked, it made sense to use Qualisys as the marker-based system. Therefore, the group divided the system into two components: OpenPose for the markerless solution and Qualisys for the marker-based solution.

Using Qualisys for ground truth had its benefits. The Qualisys system was really easy to use and had high data accuracy. However, due to the split setup, the group needed to synchronize the two setups according to each other (see Section 5.1.5).

5.1.2 Software

Initially, the group developed and used scripts from the ground up. These scripts were used for parsing, calibration, and triangulation of the Open-Pose JSON files, as described in Appendix C and B. They were developed utilizing calibration techniques based on the OpenCV library, Direct Linear Transformation (DLT), and stereo calibration methodologies.

Pose2Sim

Upon discovering Pose2Sim as a potential alternative, the group opted to transition to this solution. Pose2Sim uses a similar approach as the self-implemented calibration script, with the main difference being an all-in-one solution for calibration and triangulation, making it the preferred choice. In contrast to the group's own script, Pose2Sim was highly optimized for use with OpenPose.

While our own scripts used the commonly used DLT algorithm, Pose2Sim used a modified version, where the weighting given by OpenPose's confidence score was taken into account. Even though Pose2Sim had a lot of functionality directly related to our project, it was hard to implement with our own data. This was mostly due to the early stage of the Pose2Sim project, where the source code was actively maintained while the group was working on the project. This resulted in the group modifying the source code directly, adding desired functionality, and using only the relevant parts of the code for this project.

Spinnaker SDK

In order to utilize the FLIR cameras for recording, computer control was essential. These cameras lack built-in software, which necessitates control trough a computer. In the case of these cameras, that entailed using either the Spinnaker SDK or the pre-built software SpinView GUI. While in most cases it would be beneficial to utilize the SDK and develop a script with predefined parameters, it could be argued that using the GUI gave the group quick feedback on changes. Additionally, the ability to preview frames prior to capture was useful, and it further helped to separate the capture process from the data analysis.

5.1.3 Qualisys

To evaluate the markerless solution, it was crucial to use a marker-based ground truth as a reference. Even though marker-based systems have a small margin for error, inaccuracies can still occur.

For this project, the error was mainly due to the placement of markers. Despite the fact that Qualisys provides a quality-assured guide on how to place these markers, they were still placed by the group members and not by a biomechanical scientist. This introduces the possibility of wrongly placed markers. Since the evaluation is millimeter-based, even a small placement error could have a significant impact on results. Despite this limitation, the marker-based system is still recognized as the ground truth for the project, and no other solution with a smaller error margin would be possible (making this error inevitable).

Other sources of error include Qualisys itself. Even though Qualisys is well-established as a solution for marker-based motion tracking, it is not impossible for their systems to have marginal errors when estimating the joint center. Humans are differently built, and a general way of finding joint centers can therefore provide wrong values.

To minimize the potential for error, the group carefully and as accurately as possible placed the markers on the subjects' bodies. In addition, the group used the sport markerset (Appendix - E), which is provided to the users of Qualisys as the optimal markersetup for biomechanical and medical purposes. Using these approaches, the margin of error will be smaller but still affect the resulting data.

5.1.4 OpenPose

The implementation and usage of OpenPose were inspired by the article supplemented by the supervisor (The provided article - Nakano et al., 2020). This article guided some choices, such as the use of data filtering methods, and what aspects to analyze to get valid results. Even though the group took inspiration from the provided article, it differs in the most fundamental ways. This can be seen in the different accuracy results, and the overall baseline used for comparison.

Camera Parameters

The performance of OpenPose can be affected by parameters such as focal length, field of view, position, and angle of the camera. As mentioned in the method section, the FLIR cameras have a resolution of 1280x1024 and a *2.8mm-10mm, 1/2.7"* lens. The cameras were placed at a height of around 160cm above the ground which is a typical height to take pictures. The reasoning behind these decisions is that these parameters are quite normal and commonly used for images online and most likely used in the dataset.

Body Estimation Error

Analyzing the results, significant variance in the different MAE values was observed. While the majority of MAE values ranged from 0mm to 40mm, certain values exceeded 40mm. The highest observed MAE value for the baseline model reached approximately 200mm. There are several reasons behind these errors and why they occurred.

Firstly, the error could have occurred due to the 2D tracking error made by OpenPose (see section 4.1.1 for illustration). This body estimation error occurs either when a body segment is out of the frame of a camera or when it is hard for the AI model to determine the depth of the image (leading to errors in triangulation, giving the illusion of lag; see Result - Figure 4.1c). A possible solution for these errors could be the addition of more cameras. Adding more cameras from different points of view would possibly remove the error of limbs disappearing or being wrongly estimated. In addition, more cameras would also increase the performance of the weighted DLT and therefore the triangulation process as a whole. Getting more data and image points from different positions would potentially lead to better accuracy of the 3D estimation (due to the DLT working on OpenPose prediction score).

Another potential source of tracking error during 3D pose estimation was the exclusion of certain cameras from the process. Cameras failing to meet a triangulation threshold were excluded from the calculation, reducing the overall camera count and diminishing accuracy. Such exclusions increase performance issues and contribute to body segment disappearance; consequently increasing the MAE to extreme values (as observed in the Body_25 model during throw motion, Section 4.1.3). A similar strategy of camera addition could eliminate this problem as well. The addition of more cameras can actively help with performance if a camera gets excluded.

Body Models

Processing computational data using BODY_25B model on the used camera-setup proved to be computationally intensive. This led to the group preparing captured data during the day and computing the body estimate at night. A possible solution for cutting down the computation time was to use the BODY_25 model with lower net-resolution and image scale (see Theory - 2.3.7). Combining lower net-resolution with a model with fewer PAF channels (see Theory - 2.3.6) could lead to lower processing time. However, it would also lead to significantly lower accuracy for the body estimations. Since marker-based systems have the possibility of real-time data capture with high accuracy, BODY_25B model's computational demands must be weighed against the project's goal of exploring markerless motion tracking as a possible solution. Purely scientifically, BODY_25B is the better solution and better for testing the system's potential accuracy. However, as a potential replacement for marker-based systems, which can achieve better results even with fewer cameras, it is important to find an efficient solution with sufficient accuracy. One potential solution to manage the computation time for BODY_25B is mentioned in section 5.2.4.

Marker Masking

Masking the markers out of the frame resulted in an increase in performance in terms of accuracy. The tests were conducted using the BODY_25 body-model, due to BODY25_B's computation time which the team could not afford towards the end of the project period.

As can be seen in results section 4.1.4, masking the markers improved the overall model performance. This improvement is observed not only when performing individual motor tasks but also when considering the average of all motions. Masking the markers could have improved the accuracy due to the possibility that the markers introduced noise into the image. This noise might have misled the markerless model or caused it to misinterpret the data. Since most of the data used to train the model probably does not include reflective markers attached to the human body, removing the markers from the images led to an improvement in performance.

Filtering

Utilizing a filter was crucial for stabilizing the data and minimizing body estimation errors. Without a filter, the recorded data flickered, increasing accuracy errors. Using a data filter smoothed out the data, reducing jitter when analyzing. The squat movement was chosen for analyzing various filtering methods due to its stability, facilitating the observation of differences when optimizing filter variables.

In the research, the group used the Butterworth filter as a benchmark for comparison with other markerless methods and science papers. The reason being that Butterworth is a very common data filtering method. This allowed the group to evaluate the performance of the method in relation to other findings. Although LOESS showed better results in accuracy, Butterworth was chosen due to its widespread usage and high flexibility. Additionally, Butterworth filtering was selected because of its usage in the supervisor-provided article. This decision enabled the group to analyze their findings with those presented in the article and use its results as a reference point.

Filters played a critical part in removing noise and outliers from the result data. This was crucial because these outliers can affect the data analysis; however, these outliers can also be valuable to find important errors. For instance, the results from the BODY_25 model showed how fast movements towards the camera can impact the accuracy. Some values were so high that they met a threshold, leading to the joint disappearing or being set to null. By identifying these outliers, the group was able to adjust the filters to remove some of the errors. Once the filters were optimal, the data became more consistent, and the tracking became more stable. Adjusting the filters therefore contributed to the overall accuracy and the group's results.

Total Results

To summarize the results, the group created a table showcasing the percentages of the MAE values relative to various thresholds. This table can be seen in Table 4.1.6. Utilizing this approach allowed the group to evaluate how well the estimation model performed. Furthermore, certain factors that did not directly impact the results were considered important by the group to mention and reflect on.

Firstly, presenting the results in a true manner was crucial to demonstrate how the project was carried out and to maintain a scientific approach while interpreting the data. Therefore, the group decided to include overall results for the entire recording as well as results for each specific movement. This was important because the recording starts with an A-pose, which is not an actual movement and would improve the final result by minimizing joint estimation error.

Secondly, the group calculated the results for specific movements using only the affected joints. For example, in a throwing motion, only the MAE for the right arm was used in the calculation; including, for example, legs would minimize the estimation error. Another key decision was to base the MAE on all coordinate directions (x, y, and z). This impacts the results since the movements might be inaccurate in one direction while being spot-on in another. This can be seen in the throwing motion, where movement that occurred in the x-direction had a high MAE, whereas the MAE in the y-direction was closer to a desired value.

Analyzing the group's results in comparison to those from the provided article, the group's MAE values are generally higher. This can be due to several factors. Firstly, the scientists in the article used five 4K cameras, while this project employed only three 1K cameras. As discussed in section 5.1.4, the addition of more higher-quality cameras would probably increase the accuracy. Another factor is the solution used for collecting marker-based data. While the project group used Qualisys with eight cameras, the article describes their own method for calculating the joint centers using sixteen 200hz cameras.

These differences in system setups could lead to different accuracy and synchronization between markerless and marker-based motion capture. Therefore, it is important not to directly compare the two articles but rather to find common factors and potential improvements from both. Although the group did not achieve better results, the difference between the two projects may be due to the methods chosen or advancements in technology (such as the use of body-model Body_25B).

The descriptions and considerations above were important for the group to affirm academic reliability and to potentially contribute to the research domain.

Pose Variation

The quality and comprehensiveness of the training data are crucial factors for determining the performance of a machine learning model. The datasets used for training OpenPose might not cover the full spectrum of poses and movements. Keeping this in mind, the group opted for using known and well-documented poses and movements. The reason behind this choice was mainly to have a comparison ground to other articles, mainly the article mentioned in Section 5.1.4.

Biases

As a result of the scope of the project, the group did not have the time to validate the results of OpenPose to uncover specific biases such as body types, ethnicity, or clothing. Consequently, the group primarily conducted trials mostly unclothed on the upper and lower body to minimize inaccuracies stemming from the clothing's motion.

5.1.5 Data Offset

Synchronizing the Qualisys data with OpenPose data created new grounds for error. Using blinking lights or other methods for synchronization proved to be difficult when capturing the markers with the Qualisys IR cameras. Since the recorded data generated from Qualisys is in a text format and not in video or images such as conventional cameras, no visual cues could be used to slice the time. Using a marker that blinks could have been a reliable solution; however, the group decided not to add any complexity to the 30-second recording. In the end, the decision was made, and the group opted for taking the images for OpenPose at a 30-frame-per-second rate, while the Qualisys system at $100hz$. Keeping the OpenPose cameras on a limited frame rate meant the group could keep the computational load and storage low. The data acquired by the Qualisys system was, as mentioned, in a text-based format and needed little to no computation. This resulted in capturing the markers at a rate greater than the OpenPose system for minimizing the gap between the frames from OpenPose and Qualisys. Having a recording captured at approximately three times higher framerate gave the possibility of getting closer to the real-world timestamp of the lower framerate system.

In order to synchronize the systems, a script (*sync_trc_files.py*) was developed (see Appendix - C). It begins by converting the exported Qualisys data to a TRC format, then it finds the maximal y value of a given joint in the TRC files, and finally synchronizes them based on the timestamps of the maximal values.

5.2 Engineering

This section will look at the engineering results and discuss these results according to the group's experiences.

5.2.1 Technological advancements

Given the numerous applications and use cases for motion capture technology, we focused on establishing a foundational framework that integrates fundamental motion capture concepts with machine learning models for keypoint detection. Our results demonstrate the potential value of markerless motion tracking in various domains. However, the group recognized that further research and improvements are necessary when measuring its effectiveness on an individual basis. The group decided to develop a broad foundational framework rather than fine-tuning for specific use cases. A narrowly tailored framework might perform exceptionally well in a single context but would lack the versatility required for broader applications. For example, in animation and gaming, the ease of capturing human motion is most likely more important than having dead accurate data. In the health sector, however, it is more important to have accurate data in favor of ease of use. By adopting a holistic approach, we ensure that the framework is adaptable and can be fine-tuned for various specific applications as needed. This adaptability allows the technology to cater to a wider range of use, providing a broad basis for technological advancement.

5.2.2 Synchronization

Time synchronization of the cameras could have been done in many ways. Since the group had access to equipment and cameras with hardware functionality for trigger-based synchronization, the group opted for completely removing this as a source for error. A hardware solution for multi-camera synchronization was preferred over a software solution based on the fact that a software solution can lead to mismatch due to processing delays. Utilizing hardware trigger minimizes the possibility of this error. For that reason, the group experienced less need for manipulating the data, which includes the manipulation of the TRC files in post-recording.

5.2.3 Calibration

The group decided to use checkerboard instead of a wand as the instrument for calibration. Deciding to use the checkerboard technique was mostly due to the abundance of theory and documentation found about the subject. Another factor for using it is the fact that both OpenCV and Matlab have integrated solutions with high accuracy for testing and validating. However, during recording, the group experienced some cases where the ease of use during recording was limited. The distance from the camera, angle, and tilt of the checkerboard were crucial for good results (Results - 4.2, Method - 3.5.6). There was also the factor of having the correct exposure in the photo to ensure the white squares did not 'bleed' into the black ones. The group also discovered that maximizing the checkerboard's coverage within the captured frame resulted in the lowest re-projection error.

In early trials, we used an A3 sheet of paper with 11x12 checkers and stood around three meters away from the cameras. This resulted in images where the checkerboard itself occupied only a small portion of the entire image size, as one might expect. The group tried capturing the required number of frames (< 500) for filling the entire area; however, this was ineffective as one would need both tilt and rotation in the entire area. After learning that the coverage of the captured frame was important, we needed only ten frames per camera with different tilts and rotations while making sure the checkerboard covered as big a portion of the image as possible.

5.2.4 Goals for Accuracy

While OpenPose seemed to perform well in most scenarios, its accuracy varied based on a variety of factors. The trials were conducted in a controlled environment, where the lighting is consistent. Since OpenPose processes each frame independently, it struggled with fast-moving or complex movements, producing jitter and inconsistencies (as said in previous sections). This is because it does not consider previous or future frames when estimating poses.

5.2.5 Goals for Efficiency

Having to process the data from three cameras that capture 30 frames a second produces a total of 5400 frames per minute. Real-time processing of only a single camera using the BODY_25B model proved to be computationally intensive using our hardware. During trials, the group prepared all the captured data during the daytime for later computing during the night. A possible solution for the model's long computation time is therefore to run the computations overnight and record during the day. This removes the AI model's long computation time but could alter the workflow if used commercially. An addition to the solution is that using OpenPose minimizes the time needed for motion capture by removing markers. This, together with the fact that the processing can happen during the night, decreases the problem with the long computation time.

5.3 Administrative

The administrative part of this project was mostly based on templates provided by the school and was performed accordingly. However, due to the nature of the thesis choice, some deviations happened, leading to project-specific outcomes.

5.3.1 Milestones

In the results section, the milestones for this project were determined using a GANTT chart created by the group after consulting the supervisor. The group and the supervisor agreed on a simple GANTT chart. Due to the scientific nature of this project, the GANTT chart focused on high-level goals such as code completion, deadlines, and other mandatory tasks. A deeper level of overview would be hard to create since the group members lack experience in scientific research, which is more trial and error rather than constant progress in software development.

One notable deviation from the project plan was the software fixing. As described in results 4.3.1, the software needed for this project was supposed to be given to the project group at the start of the project. Due to multiple code errors, the project group ended up creating their own solutions. This caused the restructuring of the thesis work, consuming a lot of time. The time consumption can be seen in the timesheet (Appendix - I). Initially, the group was supposed to test markerless and marker-based motion capture on the same camera setup, testing the accuracy and possibility of usage on a limited amount of cameras. However, the new solutions led to the group testing the marker-based using Qualisys, introducing new problems with synchronization. Consequently, the thesis focused more on retesting existing solutions and exploring potential directions for future research.

As an alternative to the GANTT chart, the group could create a milestone table, which might have been more suitable for scientific projects. Estimating time usage in scientific projects is often challenging, so a table of milestones outlining wanted accomplishments rather than strict timelines might have made it easier to estimate the result of the project. This is because the table could be in deeper detail, including milestones not possible to incorporate into a GANTT chart.

5.3.2 Timesheet

The timesheet was used to track each group member's time spent on the project and on which tasks they spent their time. The template used for the timesheet was provided by NTNU and was updated by each individual group member at the end of their workday. This helped to further distribute work on tasks that were deprioritized in the previous weeks. As said in the subsection above, the first weeks of the bachelor were mostly spent on other courses, administrative work, and software fixing. This prioritization in the first weeks led to the next weeks being more about self-education where the group focused on gaining knowledge around the bachelor as a whole. After the exam in week 10, the group's main focus was on finishing the code and on gathering result data.

After the spring break in week 12, the group's focus was mainly on gathering results for analysis and on starting writing the main report. Due to the prioritization of other courses and because of the spring break, the group needed to start focusing on writing the bachelor thesis. This focus shift, which happened in week 15, led to the group meeting the mandatory 500 hours (plus or minus 10%).

5.3.3 Meeting

The weekly group meeting and the biweekly supervisor meetings both played a crucial role in the progress of the project. As written in results 4.3.3, the frequency of the meeting was dependent on project progression. When the group managed to make progress, the need for a meeting was naturally more appealing. However, on a few occasions, the group did not meet their criteria for biweekly meetings.

The first two instance occurred when the group's focus changed from the bachelor thesis to a mandatory course, which ran concurrently with the bachelor work. The second instance was right after the midway presentation when the group didn't have much new progress due to the spring break and the presentation just before the break.

Between the weeks without official meetings, the groups continued to meet internally, updating each other on their progress. Even though official meetings weren't held, the group still met up with the supervisor for unofficial meetings at VizLab. These meetings served to exchange updates between the group and the supervisor and provided an opportunity to ask any questions that arose. Although official meeting notices were not sent out, meeting reports were written. These reports, along with the other reports and notices, are available in the appendix (Appendix - I).

As the project neared its end, the main focus changed back to the bachelor thesis, leading to more frequent meetings. These meetings were important to achieve consistent feedback on the important parts of the thesis.

5.4 Teamwork

The collaboration involved in completing the bachelor thesis provided a valuable opportunity to apply academic knowledge in real scientific experimentation. Through effective teamwork, the group achieved both its collective and individual goals for the thesis.

To build a strong foundation for the thesis, both group members regularly read up on relevant theory, sharing their findings with one another. This encouraged a deeper understanding and facilitated a better collaborative environment.

As the group members had different experiences in the fields, the tasks were divided in a meaningful manner to ensure that each member could contribute with their unique strengths. For example, one member's experience with cameras and motion tracking made them primarily responsible for camera recording tasks. Despite this division of work, both members contributed equally in terms of working hours, including writing the report and coding.

The group's work ethic and shared desire to achieve a high grade led to the group fulfilling both collective and thesis objectives. Throughout the project, utilizing rigorous scientific methodology was central to the quality and credibility of the group's findings. By following a scientific approach, the group members hope that their results can be used for further research in the field.

5.5 Research Questions

This section will summarize the research questions outlined in the introduction.

RQ1: Is it possible to achieve consistent accuracy of less than 40mm using OpenPose as the markerless solution?

Across all body movements, the Mean Absolute Error (MAE) is less than 40mm 88.58 percent of the time. However, the accuracy varies with different movements. For instance, in cases like squatting and sideways walking, the MAE falls below 40mm 86.93 percent of the time. Conversely, for faster and more complex movements such as throwing, the accuracy degrades significantly, with the MAE exceeding 40mm 37.58 percent of the time. This is mainly due to body estimation errors and the number of 2D image points captured from various cameras. More cameras capturing a 2D point contribute to increased data on the joint, enhancing the model's accuracy when estimating the 3D position.

Based on the results, the groups goal of achieving an accuracy of 40mm and below is possible; however, it falls short of the desired consistency.

RQ2: Is it possible to achieve consistent accuracy across different types of body movements?

Consistent accuracy across different movements has proved to be a challenge. As observed in **RQ1**, the accuracy varies significantly depending on the type and speed of the movement. Simple and slower movements tend to have lower errors, while faster movements exhibit higher errors and data loss. Moreover, the complexity of movements directed towards the cameras increases these errors, primarily due to body estimation.

Due to the variation in accuracy across different movements, the group's results indicate that achieving consistent outcomes poses a considerable challenge.

RQ3: What are the best practices for minimizing errors in markerless motion capture?

Minimizing errors involves implementing several best practices that enhance the accuracy and reliability of the captured data. The following strategies have been utilized during the trials:

- **Multiple cameras:** Using three or more cameras reduces occlusion during body movements where one part of the body hides another from the camera's view. It improves the triangulation process by increasing the data points for the weighted Direct Linear Transformation (DLT) and filtering algorithms.

- **Applying data filters:** Smoothing the data by using filters such as Butterworth or LOESS results in cleaner and more accurate motion trajectories.
- **Masking markers:** To prevent markers from influencing the markerless model with visible markers that might interfere with the accuracy of the motion capture.
- **Choosing the optimal body model:** Selecting the appropriate machine learning model is crucial for motion capture accuracy and computational efficiency. Different models, such as BODY_25 and BODY_25B, offer varying levels of precision and computational demands. Choosing the most suitable body model based on the specific requirements of the motion capture trial can yield more accurate and efficient results.

RQ4: What are the different benefits and limitations of markerless and marker-based solutions?

Marker-based solutions involve attaching physical markers to the subject, a process that can be invasive, time-consuming, and uncomfortable. In contrast, markerless solutions do not require physical markers, thus eliminating these limitations. However, markerless solutions are generally less accurate, more prone to biases, and require more computational power. The primary advantage of markerless solutions lies in their cost-effectiveness and accessibility, as they can utilize any camera without necessitating specialized equipment.

Both marker-based and markerless solutions offer distinct benefits and limitations, where the choice of solution is based on the specific requirements.

6. Conclusion and Future Work

In conclusion, the evaluation of markerless and marker-based motion capture systems demonstrates both the potentials and limitations of using markerless systems as a solution. OpenPose, as a markerless system, shows promising results, being an open-source and user-friendly option for motion tracking. Nonetheless, further analysis reveals that OpenPose performs better with slower and more controlled movements, yet struggles with higher error margins for dynamic movements. For instance, the results showed that the accuracy for squatting remained within a 30mm range 76.94% of the time, while accuracy for throwing stayed within the range 54.08% of the time. Challenges with body estimation, particularly during high-speed movements, indicate the need for more robust data processing. Since the accuracy of OpenPose relies on recording quality, adding more cameras would potentially enhance the accuracy by increasing the number of triangulation points. Additionally, changing to the Body_25B body-model would further lead to an increase in accuracy (especially with the combination of a larger net resolution). However, the addition of more cameras and changing the body-model would increase the complexity of the solution, further decreasing the overall computational efficiency of OpenPose.

Eliminating markers and employing more affordable, user-friendly tools not only promises significant time savings in the lab but also underscores OpenPose's efficiency potential compared to systems like Qualisys. This efficiency can be enhanced by increasing the frequency of recordings and processing the data overnight, mitigating the issue of OpenPose's lengthy computation time.

Masking out markers improved the performance and accuracy of the body estimation, suggesting that reflective markers introduce noise to the image. This interference makes it hard for the AI model to accurately estimate the joint centers. Additionally, filtering plays an essential part in enhancing accuracy, with multiple filters, such as Butterworth and LOESS, demonstrating promising results.

Overall, OpenPose shows potential as a future solution for human body and motion tracking. However, further experimentation and advancements in the AI model are necessary for it to be a solution over the already high-accuracy marker-based systems. While the potential for markerless solutions is higher for domains where accuracy isn't as necessary, such as film and gaming industries, it's not yet viable for medical use where the error margin of 30mm is extremely crucial.

6.1 Further Work

This project utilized OpenPose as the AI model for the markerless system. Therefore, it would be interesting to test the accuracy of other AI models such as MediaPipe or AlphaPose, which have recently gained traction as possible alternatives to OpenPose. Testing different models could potentially improve overall accuracy and help identify solutions to existing problems. The group thus encourages exploring different models as part of the overall solution. Additionally, while these models mainly work for human body detection, testing the models on animal bodies could also provide scientific insights into the usage of motion tracking.

Further experimentation with different camera numbers is encouraged by the group. As described in the discussion Chapter 5, increasing the number of cameras has the potential to reduce errors and improve the performance of the model. Therefore, it would be interesting to measure how much adding or removing one camera would affect the accuracy of body estimation.

Camera quality would also be an interesting topic for further work. This has already been experimented with, as the group tested the model on images with higher net resolution, which increased accuracy. Therefore, experimenting with higher-quality cameras such as 8K Ultra HD cameras, which offer more pixels per image, could have a beneficial effect.

Another matter that could be interesting to explore is the bias of the AI model. As can be read in Ethical Considerations 7.5, the OpenPose model shows significant sensitivity to its own dataset. Future work could therefore include having multiple test subjects perform different motor tasks. When having test subjects, it's crucial to ensure data security during this process. Additionally, obtaining approval from Norwegian Center for Research Data (NSD) would be crucial for the group to protect participants' privacy and to follow ethical standards. These individuals should vary in age, height, ethnicity, and gender. Testing the subjects, together with different clothing variations (color and contrast), could reveal more about the model's error margins and provide insight into the extent of potential biases in the dataset.

Further development in the model's dataset could focus on creating a more varied dataset by increasing the sample size and including individuals of different genders and skin complexions. This approach could potentially improve the model's performance.

Implementing robust measures to ensure the quality and reliability of data, such as employing a separate system to detect outliers and statistical anomalies, could be highly beneficial, particularly in medical contexts where accuracy is important. For example, such a system could define predetermined thresholds for movements or motions deemed impossible. If the captured data displays such anomalies, it should be flagged as invalid.

7. Societal Impact

7.1 Environmental Impact

The environmental impacts of AI and machine learning is getting more attention. One major concern with AI is its high water usage and carbon emissions, largely stemming from the need to cool extensive computer systems. The term ”red AI” refers to AI models that prioritize accuracy over efficiency, leading to higher computational costs and consequently, increased water usage and carbon footprint (Dhar, 2020). For instance, in an article addressing Chat-GPT’s water consumption, it is noted that ”GPT-3, an AI model developed by OpenAI, reportedly consumed approximately 700,000 liters of water during its training phase” (George et al., 2023). Furthermore, the substantial increase in computational costs results in a significant amount of energy consumption.

The group utilized BODY_25B for its accuracy when analyzing the model’s potential. By utilizing BODY_25B in OpenPose, the computational cost exponentially increases, which in turn negatively impacts the carbon footprint. Nonetheless, it’s crucial to consider factors like implementing a centralized system for data analysis, reducing the necessity for purchasing new and costly motion capture equipment, and transportation costs due to high inaccessibility. These considerations play a vital role in determining the overall carbon impact.

7.2 Health Implications

Markerless motion capture technology has the potential to positively impact the healthcare system by enabling more accessible and noninvasive motion tracking solutions. This aligns with the United Nations’ Sustainable Development Goal 3.8, which focuses on ensuring that all people have access to quality healthcare, regardless of their geographical location or financial situation (‘God helse og livskvalitet’, 15.09.2023). By facilitating improved monitoring of physical health, this technology can contribute to injury prevention, particularly in sports and among aging populations. The simple deployment of the system broadens the reach of motion analysis to smaller clinics, fitness centers, tennis courses, and private facilities.

However, it is important to note that while the benefits are great, there are some concerns. For instance, the quality and reliability of the data, especially when used in a medical setting. Ensuring the validity of individual trials is crucial. Additionally, implementing a separate system to detect outliers and statistical anomalies might be a relevant endeavor.

7.3 Societal Implications

"By 2030, it is imperative to ensure the empowerment and advancement of social, economic, and political inclusion for all individuals, regardless of age, gender, disability, race, ethnicity, nationality, religion, or socioeconomic status" ('FN.no: FNs bærekraftsmål – Mindre ulikhet', 2023). This represents one of the sub-goals established by the United Nations to address inequality.

By introducing an easily accessible and medically qualified markerless solution for motion tracking, it could potentially lessen the inequalities for individuals facing health complications, thereby promoting more equal living conditions. Such a markerless solution could give better access to necessary medical care, helping individuals toward recovery from injuries or illnesses.

Moreover, adoption of markerless motion capture would enhance accessibility, democratizing the process and opening doors for smaller actors, particularly in the healthcare sector. This advancement can notably reduce the necessity of transporting patients from rural areas to larger institutions for analysis.

7.4 Economic Perspective

Current solutions such as Qualisys, OptiTrack, and others are proprietary systems with a high cost. The cameras are mostly single-use, meaning that they only work within their own ecosystem. The sheer complexity of the system, and its proprietary nature, also means there is a high operational cost. Having access to support and software often comes with a yearly fee that the customer has no control over in the years to come. Developing an open-source alternative that utilizes any camera will provide a good and economical alternative for smaller actors. Giving the customer the ability to decide on the camera quality and which computer model to run also provides great possibilities for defining a system that fits their budget and needs.

7.5 Ethical Considerations

Ethical Perspective

There are multiple potential ethical complications with the use of markerless systems and with motion capture. Lachance's study (LaChance et al., 2023) highlights that technologies like OpenPose demonstrate notable sensitivity to the datasets used for training the model. Lachance found significant biases for ages 18 to 30 and significant discrimination against individuals with darker skin complexions. Additionally, Lachance found higher performance for males compared to females. These problems could be managed or resolved by looking at the suggestions outlined in section 6.1.

Another example is the study of GAIT. Analyzing the GAIT of individuals without consent could create grounds for using the data with malicious intent. Analysis of the GAIT of public personas or people in general might be used for deepfake or other malicious activity. The research can also be used to capture movements, providing a basis for decision-making . What decisions are being made is up to speculation; however, historical data shows that computers making decisions sometimes come with a great cost, either economical, such as when a trading bot lost a company 440 million dollars in 45 minutes (Popper, 2012). Another example is when Paula Bower was forced to pay the Dutch authorities a hefty fine after being falsely accused of fraud by an AI algorithm (Gnther and Hagerup, 2024). One of the worst cases or scenarios is usage by the military, when GAIT analysis could predict the intentions of the subject in front of the camera.

Ethical and Methodological Reflection

The choice of scientific methodology was important for testing and investigating the research question. The project group found that the systematic approach helped ensure the consistency and validity of the project. As a scientific thesis, the choice of quantitative analysis, based on careful observation and evaluation, enabled the group to draw conclusions about their results. This was possible due to the comprehensive research and experimentation conducted within the chosen methodology. However, there are some errors that are difficult to account for. Since the group only used one person for testing and evaluation, it may have introduced bias, as noted in earlier chapters. Another possible limitation of the chosen methodology is that the group sometimes changed multiple variables between tests of the markerless system. A more rigorous scientific approach would involve changing only one variable at a time.

Since the group didn't have any participants outside the project group, the group didn't feel the need for written consent or approval from a research department, such as Sikt. However, the guidelines for handling sensitive data were followed. The recordings of the group member were only used for analysis, and the data was deleted as soon as it was extracted. These video recordings were stored on a password-protected hard drive, with restricted access, accessible only by the group and the supervisor. Based on these measures, the group concluded that the data was handled securely according to professional ethics.

The group's decision not to use any external participants was reflected on and suggested as a topic for further work. For scientific rigor, adding some variation to the test data would, however, be beneficial.

As the group has no conflict of interest regarding the research results, the possibility of bias is limited. Although the group members aim for a high grade, the scientific results and methods used have limited influence on the final grade. Therefore, the group has been as transparent as possible about the methods used and results found. When describing the total results in the discussion chapter, the group attempted to explain how the data should be interpreted. This was done to reduce the risk of wrongfully representing the data.

Based on the information above, ethical considerations can be drawn. The project group stated in their thesis that the results and methods used have been analyzed against existing research in the field. Although the results showed a slightly higher error margin compared to the supplemented article, the project used fewer cameras. This indicates that the methods and results might be of interest for future research. Following the suggestions for future work could further explore the potential advancements in this study, and possibly the field.

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A. Additional Theory

This appendix contain additional theory to get full understanding of the science domain. It not necessary for the understanding of the project, but can be interesting for people that want to have a deeper knowledge of discussed theory.

A.1 Deep learning

Deep learning is a class of machine learning that uses layers, so called neural networks (Theory - A.1.1), to learn representation and classification about data it has not seen on beforehand. ”In other words, a deep learning algorithm automatically extracts the low-and high-level features necessary for classification” (Lauzon, n.d.). High level features is often referred to as features that depends on other features. ”In the context of computer vision, this implies that a deep learning algorithm will learn its own low level representations from a raw image (such as edge detection, gabor filters, etc...), then build representations that depend on those low level representations (such as a linear combination of those low-level representations), and successively repeat the same process for higher levels” (Lauzon, n.d.).

A.1.1 Neural Network

A neural network is an system of nodes that represent how an human neuron system works and operates. The nodes are interconnected to each other in a layered structure with different weights and node number, as can be seen in figure A.1.

Based on the articles from IEEE and Mathworks (Lauzon (n.d.) and ‘What Is a Neural Network?’ (2024)), neural networks can be described as such

> *A neural network can learn from data, so it can be trained to recognize patterns, classify data, and forecast future events. A neural network breaks down the input into layers of abstraction. It can be trained using many examples to recognize patterns in speech or images just as the human brain does. The neural network behavior is defined by the way its individual elements are connected and by the strength, or weights, of those connections. These weights are automatically adjusted during training*

according to a specified learning rule until the artificial neural network performs the desired task correctly.

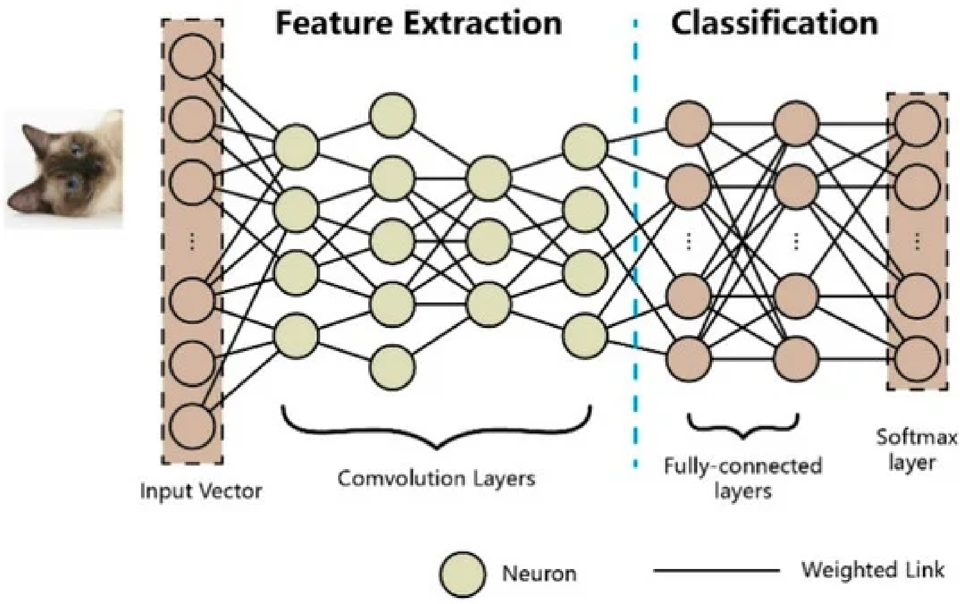


Figure A.1: Image representing how neural networks look like, and how they work. The small circles are the neurons, while the connection between the circles are the weighted links. The choices for how the data is handled, or interpreted, is based on how the neurons handle the data before sending it to the further. **Source:** Ruan and Dai, 2018

A.2 Additional Data Filters

These are additional data filtering methods that can be valuable to read through to get full understanding of the science domain.

Kalman filter

A Kalman filter is a algorithm that recursively estimates the state of a linear dynamic system over time, particularly when the measurements are noisy or inaccurate. (Kalman et al., 1960) ”it supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modeled system is unknown” (Welch and Bishop, 2006).

Extended Kalman filter (EKF)

Tries to estimate the state of a non-linear system by utilizing Taylor series to linearize the non-linear system models about the current mean and covariance (Welch and Bishop, 2006).

Median

A median filter is a nonlinear filter that works by replacing each pixel value with the median value of neighboring pixels. Median filters are known to preserve details such as and lines edges in digital images (Davies, 2005). The filter uses ”windows” that define the level of detail preservation. ”For example, 3 × 3 median filters remove lines 1 pixel wide, and 5 × 5 median filters remove lines 2 pixels wide” (Davies, 2005).

A.3 Biomechanics

The two sections below are from Qualisys Technical Notes. As these are direct quotes, the citations from the quotes are not listed. But they can be found in the quoted note.

A.3.1 Joint Angles

This Section is about the joint angel, and how to calculate them.

> *The joint angles are calculated using an extended Kalman filter algorithm. This algorithm is chosen because of its ability to deal with gaps in trajectories and give smoothed joint angles while keeping a good accuracy (Fohanno et al., 2014). The basic idea is to use the forward kinematic function to drive the biomechanical model minimizing the distance between the recorded markers and the model-based markers. For the first frame, the pose of the biomechanical model is initiated with a global optimization algorithm (Fohanno et al., 2014). This algorithm minimizes the same objective function defined previously but in a least-square sense. This algorithm is not used for the remaining instants because, contrarily to the extended Kalman filter algorithm, the computational time and the noise in the trajectories would have been larger. After this first frame, the number of used degrees of freedom is decreased for some joints (Table 2). The value of the unused degrees of freedom are kept fixed during the running trial and determined using the static trial. The position of the model-based markers are stored and they will be used for the next calculations to be sure that no gaps are present in the trajectories, contrarily to the recorded markers.*

('Qualisys Biomechanics Engine', 2024)

A.3.2 Joint centers

Qualisys uses different sources for their joint center calculations. The quote below describes this in more detail.

> *The hip joint center (HIP) is calculated from the R_ASIS, L_ASIS and SACR markers using the predictive equation provided by Bell et al., 1989 and information found in Tranberg, 2010. The knee joint center (KNEE) is calculated using the first running trial and a functional method called SCoRE Ehrig et al., 2007. The SCoRE method uses the markers located on the thigh and the*

> *shank. Once the axis of rotation is found, the KNEE joint center is located at a predicted distance from the FLE marker using the work of Drillis et al., 1964 and Mukhopadhyay et al. (2010). The HIP joint center is calculated and used as virtual marker for the calculation of the KNEE joint center. The ankle joint center (ANKLE) is calculated from the FLE, FAL and TTC markers using a predictive equation based on the work of Tranberg, 2010 and Gardner and Chief (1969). A local coordinate system is defined using the R_ASIS, L_ASIS, SME and TV2 markers. The shoulder joint center (SHOULDER) is then calculated as an offset from the SAE marker defined in this local coordinate system. The elbow joint center (ELBOW) is defined as the midpoint between the HLE and HME markers. The wrist joint center (WRIST) is defined as the midpoint the RSP and USP markers.*

('Qualisys Biomechanics Engine', 2024)

B. Code Documentation

The group worked on two projects during the experiments. First, we wrote the entire codebase containing all the essential algorithms needed for detecting markers, calibrating the cameras, and triangulating the exported markers. In the next phase, the group based the code on the work done on the Pose2Sim project, as stated in the method section (3.4.5). The code for this project is submitted as a zip file named `project_files.zip`. Below is an explanation of the contents inside the zip file:

B.1 Project Files

project_1:
This directory contains the project the group first started experimenting with. It includes a script for calibrating the camera using chessboard corners, converting images to grayscale, detecting markers, and storing the marker positions in a JSON file. Finally, triangulation is performed by loading the 2D coordinates from the JSON file. The scripts in this project are heavily influenced by and based on the documentation from OpenCV, as stated in the comments of the script.

project_2:
This directory contains the project that the group used during the final trial, which ended up being the basis for our results. As mentioned in the method section (3.4.5), the group cloned and created a modified version of Pose2Sim. The Pose2Sim directory contains a mix of scripts, including our own scripts in both the root folder and the utilities folder. Some of the most important scripts for this project are described in further detail in Appendix C.

qualisys_project:
This directory contains the Qualisys project files. It includes the raw recordings (identified by their qtm file extension). Additionally, you will find AIM models, as discussed in the 3.4 section, along with calibration files for the Qualisys cameras (identified by their qca file extension). Finally, the `FinalExport` directory contains the exported skeleton and keypoint data.

raspberry_pi:
This directory contains the bash script that sends electrical pulses through the GPIO pins on the Raspberry Pi.

B.2 Project Setup

To replicate our results or test out the codebase, getting started with the project is quite easy. Start by opening the `project_2` directory in your chosen IDE and installing the pip requirements. Having OpenPose installed on the computer is a requirement for this to work. Inside the root directory is the config.toml file. This file, in conjunction with the `main.py` file, is where the specific parameters of the project are set.

B.2.1 Calibration

You have two ways of calibrating the cameras: either calculate or convert. Convert is used if you have specific RGB cameras from Qualisys or Optitrack and want to use the calibration exports from these. These exports should be placed in the `S00_Calibration` folder. If the cameras used are regular RGB cameras such as the FLIR cameras used in this project, select `calculate`. The specific parameters of the recordings should be defined in the toml file under the calibration section. When the calibration is completed, the parameters are exported as toml files inside the `S00_Calibration` folder. Changing the `calculate_extrinsics` and the `overwrite_intrinsics` parameters to false in the config files makes it triangulate using the files instead.

Extrinsics

Select `board` in the extrinsic section and place one image from each camera inside the `S00_Calibration/extrinsics/ext_cam0X_img` directories. These images should contain a checkerboard that fills a large area of the image. Define the number of corners in the checkerboard and the size of the squares.

Intrinsics

Place the intrinsic images with the smaller checkerboard inside of the directory `S00_Calibration/intrinsics/int_cam0X_img` directories.

B.2.2 Triangulation

The parameters for triangulation are placed inside the triangulation section of the config file. There, the filters and parameters can be altered and experimented with.

B.2.3 Running the Project

Go over the config file, and make sure all the parameters are set correctly. If any new images for extrinsic, intrinsic calibration, or if OpenPose files need to be processed, make sure to change the preprocessing parameters to true, and ensure that all the required paths are defined in the `main.py` script. Finally run the `main.py` script and, and find the exported TRC file in the `pose-3d` directory.

C. Scripts and Packages

These are some of the most relevant scripts and packages used by the project group to achieve their results during the final trial.

marker_detection.py: This script is for detecting and processing markers in an image. To find the markers, the images are converted to greyscale, then it isolates white markers using thresholding, followed by finding the contours of the thresholded image. The script formats the detected keypoints into a JSON structure similar to OpenPose. This results in JSON files that can be processed by pose2sim.

sync_trc_files.py: This script finds the maximal y value of a given joint in TRC files and synchronizes them based on the timestamp of the maximal value.

set_offset_manually.py: This script allows you to set the delta of x and z manually.

fix_offset_trc_files.py: This script finds the x, y, and z coordinates of a specific joint in two TRC files, finds the offset, and applies it to a new file, making the files align.

offset_and_sync_trc_files.py: This script combines the functionality of `fix_offset_trc_files.py` and `sync_trc_files.py` into one script.

marker_removal.py: This script removes the reflective markers from the trial participant by swapping out the pixels of the reflective markers with their nearest neighbors. This ensures that the markers have minimal impact on the OpenPose results.

trigger: This script is a shell script with Python code that deals with sending out pulses on the GPIO pins of the Raspberry Pi. The script is configured to send a pulse at a rate of 30 pulses per second, which corresponds to 30 frames per second.

tsv2trc.py: The script is a custom implementation that converts TSV file outputs from Qualisys to TRC files, which are compatible with OpenSim for simulating marker movement. The script is project-specific to match the group's requirements, allowing for data comparison between OpenPose and Qualisys.

file_handler.py: This script handles various file operations needed for quickly experimenting with new data. It has methods for listing files in a folder, deleting files in a folder, copying images to a destination folder, copying every nth picture from a source directory to a target directory, and running OpenPose on a set of images.

calculate_mae.py: Calculate_mae is a script that was created for the purpose of analysis. It is a very project specific code and can therefore look unorganized. The code first calculates the MAE for each row, for each column in the OpenPose TRC file based on the closes timestamp in the Qualisys TRC file. It is Then used to plot different graph and values.

Packages:

anytree: Manages tree structures in Python.

contourpy 1.2.0: Creates contour plots for 3D data.

cycler 0.12.1: Cycles through colors in plots.

filterpy 1.4.5: Works with filters for signal processing and robotics.

fonttools 4.49.0: Manipulates font files.

kiwisolver 1.4.5: Solves sparse nonlinear optimization problems.

lxml 5.1.0: Processes XML and HTML documents.

matplotlib 3.8.3: Plots data and visualizations.

mpl_interactions 0.24.1: Creates interactive Matplotlib plots.

numpy 1.26.4: Handles large arrays and mathematical functions.

opencv-python 4.9.0.80: Analyzes images and videos.

packaging 23.2: Manages Python packages and distributions.

pandas 2.2.0: Manipulates structured data.

patsy 0.5.6: Describes statistical models.

Pillow 10.2.0: Processes images.

pyparsing 3.1.1: Parses text and grammars.

PyQt5 5.15.10: Builds cross-platform GUIs.

PySide2 5.13.2: Provides Qt bindings for Python.

python-dateutil 2.8.2: Manipulates dates and times.

pytz 2024.1: Handles timezones.

scipy 1.12.0: Provides scientific computing tools.

statsmodels 0.14.1: Performs statistical modeling.

toml 0.10.2: Parses TOML configuration files.

tqdm 4.66.2: Displays progress bars.

tzdata 2024.1: Manages time zone information.

D. Instruments and Equipment

During the recording sessions, a variety of instruments were used, including the standard equipment for the Qualisys system as shown below.

D.1 Reflective markers

12.5 mm Qualisys Super Spherical Passive markers(Figure D.1) was placed on the participants skin using double-sided adhesive tape. The markers are designed to have a thin and light-weight base making the ideal for attaching to moving objects or skin ('Super-spherical markers', 2024).

Figure D.1: Passive marker

D.2 Calibration Kit

For calibrating the intrinsic parameters the group used a 600mm calibration wand, with spherical markers made of carbon fiber, which makes it resistant to bending and expansion due to heat. For the extrinsic parameters an L-frame with a reference control length of 300.81 mm, and a nominal reference length of 300.83 mm. The calibration tools can be seen in figure D.2.

(a) Calibration L-frame

(b) Calibration Wand

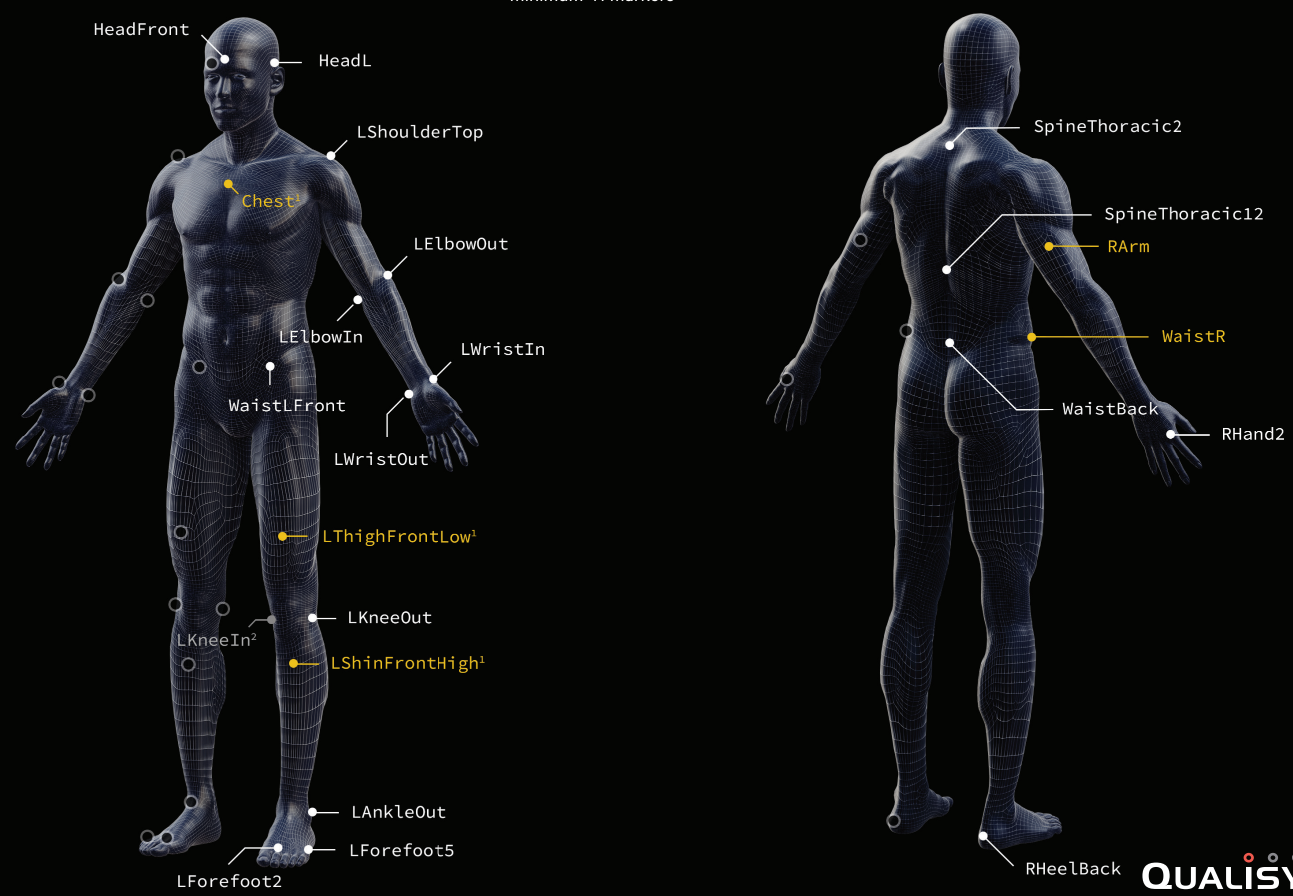
Figure D.2: The Qualisys Calibration kit 'Carbon fiber calibration kit', 2024

E. Sport Marker-set

This is the official pdf form Qualisys on how and where to place the markers on the subject body. The grey markers are static, meaning that they should be on for the static trail. (‘Qualisys Documentation’, n.d.)

Qualisys Sports Marker Set

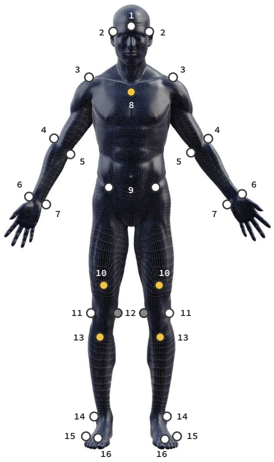
Minimum 41 markers

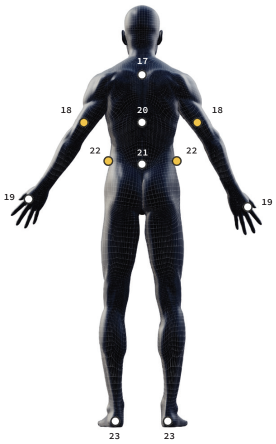


[1] Movable marker
[2] Static marker

QUALISYS

Detailed marker description





	Display name	Location	Ref[1]	Movable
1	HeadFront	Forehead, above the nose.	SGL	-
2	HeadL, HeadR	Just above the ear centre.	-	-
3	LShoulderTop, RShoulderTop	On top of the shoulder (bony prominence).	SAJ	-
4	LElbowOut, RElbowOut	On the outside of the elbow (bony prominence).	HLE	-
5	LElbowIn, RElbowIn	On the inside of the elbow (bony prominence).	HME	-
6	LWristIn, RWristIn	On the inside of the wrist (bony prominence on the thumb side).	RSP	-
7	LWristOut, RWristOut	On the outside of the wrist (bony prominence on the pinky side).	USP	-
8	Chest	Upper part of the sternum.	MSN	On the sternum
9	WaistLFront, WaistRFront	On the front of the pelvis (bony prominence).	IAS	-
10	LThighFrontLow, RThighFrontLow	Above the kneecap.	PAS	On the thigh
11	LKneeOut, RKneeOut	On the outside of the knee (bony prominence).	FLE	-
12	LKneeIn, RKneeIn STATIC	On the inside of the knee (bony prominence).	FME	-
13	LShinFrontHigh, RShinFrontHigh	Front of the shin.	TTC	On the shin
14	LAnkleOut, RAnkleOut	On the outside of the ankle.	FAL	-
15	LForefoot5, RForefoot5	On the base of the fifth toe.	FT5	-
16	LForefoot2, RForefoot2	On the base of the second toe.	FT2	-
17	SpineThoracic2	On the 2nd prominence below the biggest prominence on the top of the spine.	TV2	-
18	LArm, RArm	On the back of the upper arm.	HUM	On the upper arm
19	LHand2, RHand2	On the back of the hand at the base of the index finger.	HD2	-
20	SpineThoracic12	A few cm below the midpoint of the lower tip of the shoulder blades.	TV12	
21	WaistBack	On the midpoint between the two prominences on the back of the pelvis.	SACR	On the pelvis
22	WaistL, WaistR	On the sides of the pelvis (bony prominence).	ICT	-
23	LHeelBack, RHeelBack	Back of the heel.	FCC	-

FRONT

BACK

[1] Sint Jan, S. Van (2007). Color Atlas of Skeletal Landmark Definitions. Guidelines for Reproducible Manual and Virtual Palpations. Edinburgh : Churchill Livingstone

Additional information

STATIC MARKERS

The static markers should only be used when recording the static file in order to create the skeleton. They should be removed before making dynamic recordings or real-time performances.

EXTRA MARKERS

Extra markers can be placed on the subject to improve the tracking of the segments of the skeleton.

QTM automatically assigns any extra marker to the most appropriate segment of the skeleton. However, if needed, each extra marker can be manually assigned to the segment of the user's choice. To do so, the marker label should include the segment name just after the underscore (case-sensitive) used to separate the skeleton name from the marker name (i.e. `VF_RightHandExtra`). The available segment names are:

> `Hips`, `RightUpLeg`, `LeftUpLeg`, `RightLeg`, `LeftLeg`, `RightFoot`, `LeftFoot`, `RightToeBase`, `LeftToeBase`, `Spine`, `Spine1`, `Spine2`, `Neck`, `Head`, `RightShoulder`, `LeftShoulder`, `RightArm`, `LeftArm`, `RightForeArm`, `LeftForeArm`, `RightHand` and `LeftHand`.

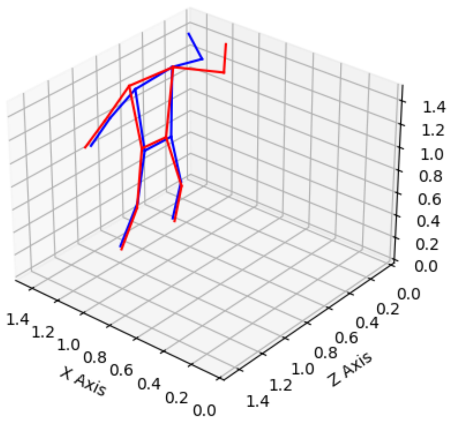
The RightToeBase, LeftToeBase, Spine1, Spine2 and Head are locked meaning that these segments do not have any degrees of freedom.

F. Figures from Results

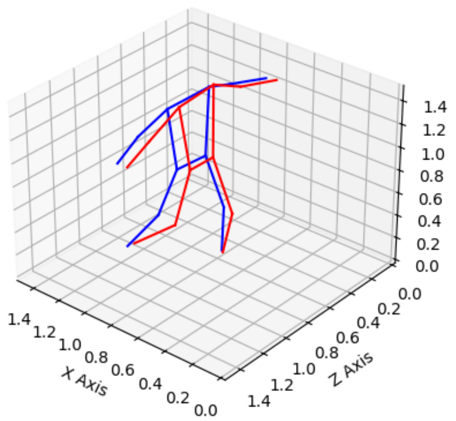
This chapter holds figures that can be on further interest to the reader.

F.1 Body estimation error

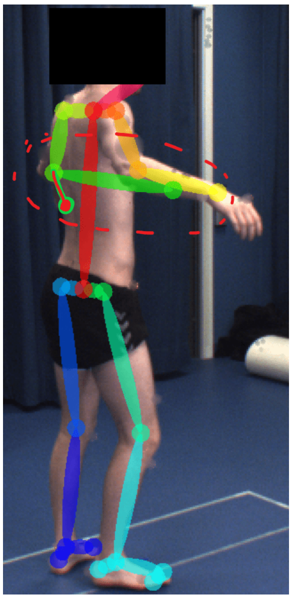
These images display two different kinds of body estimation errors. One error is due to jitter and lag, while the other is caused by incorrect body estimation made by .



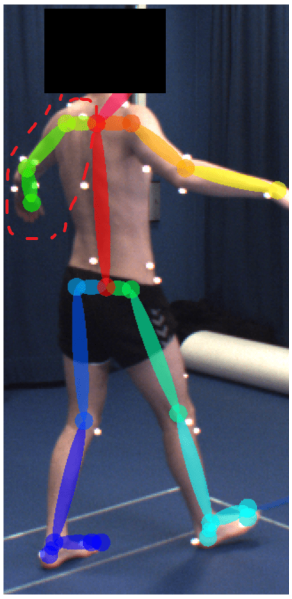
(a) OpenPose (blue) lags behind Qualisys (red) in a throwing motion



(b) OpenPose (blue) lags behind Qualisys (red) in a walking motion



(c) OpenPose wrongfully predicts left arm position



(d) Representation of how the left arm should be predicted in the previous image

Figure F.1: Figure illustrates possible body estimation mistakes. In (a) and (b), a possible triangulation mistake is shown, where the body estimation lags behind the ground truth. In (c), OpenPose wrongly estimates the left arm, as can be seen in the correct version (d) where the hand is more outward and more down than the model predicts.

F.2 MAE between two body-models

These two figures illustrate the difference between Body_25B and Body_25. As discussed in the Results and Discussion section, Body_25B exhibited superior performance. The first figure displays the Mean Absolute Error (MAE) between three different movements (squat, throw, and sideways walk). The x-axis of the plots represents time measured in seconds, while the y-axis represents mean absolute error measured in millimeters.

The second figure illustrates the average Mean Absolute Error (MAE) for all estimated joints and coordinates (x, y, z). The overall average is represented by the red line, indicating the overall mean error.

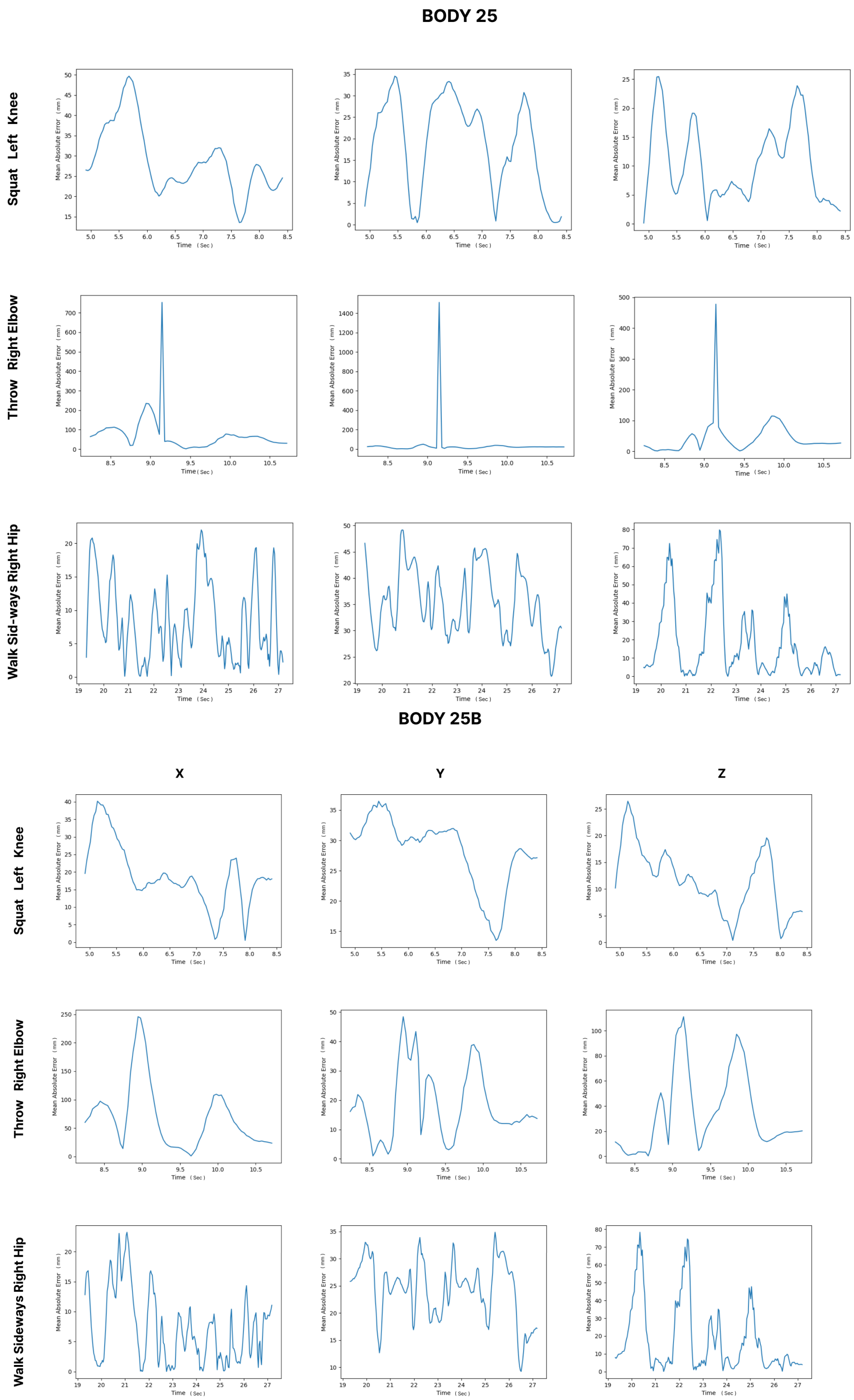


Figure F.2: The two different graph sections show squat, throw, and sideways walk MAE for two body-models: ”Body 25” and ”BODY 25B”. The y-axis represents the MAE in millimeters, and the x-axis represents the timeframe in seconds.

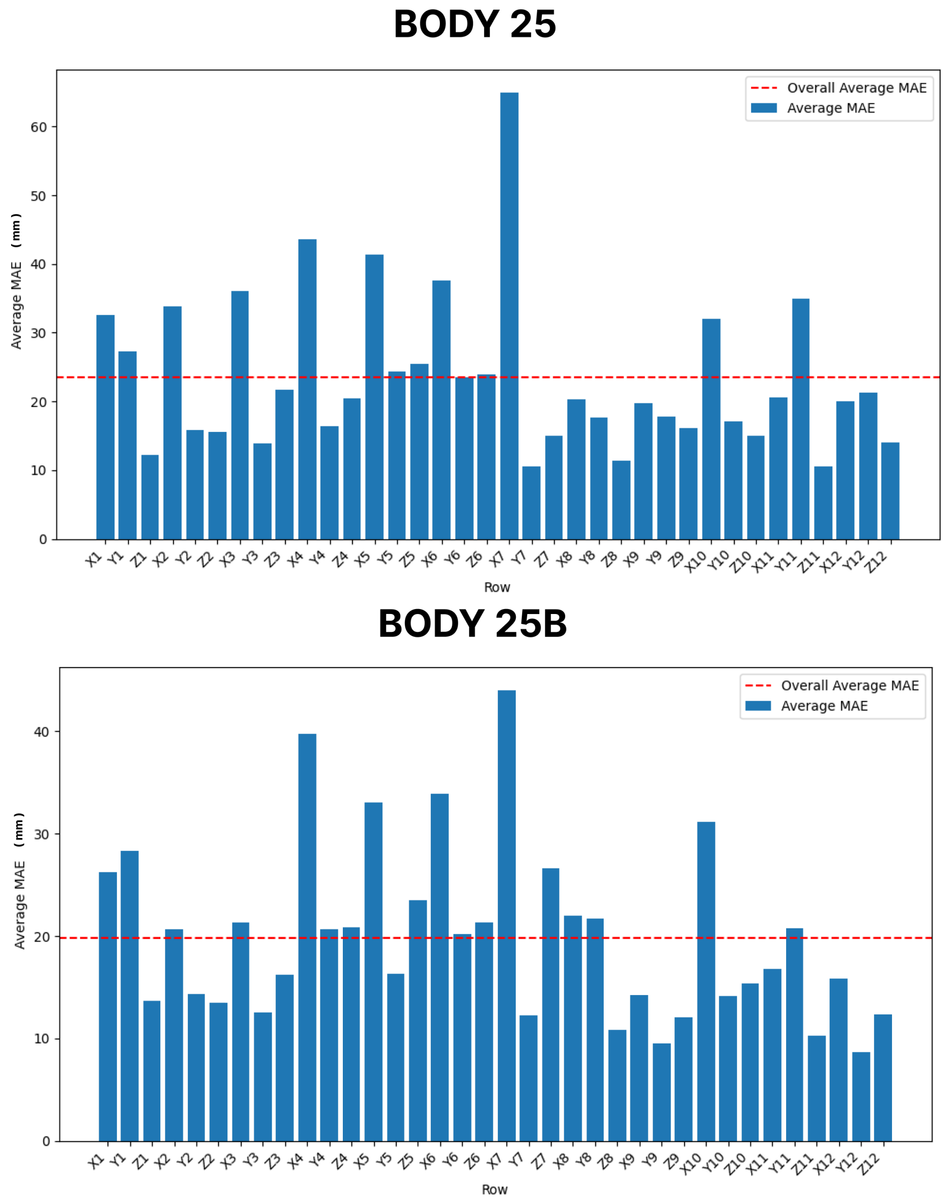


Figure F.3: The two graphs show the Average MAE for each joint. The first represents Body_25, while the second represents Body_25B. As can be seen, the Body_25B models have an better average than Body_25. The individual x, y, and z columns represent the average MAE for a single joint. From the left end, the joints are: left shoulder, left elbow, left wrist, right shoulder, right elbow, right wrist, left hip, left knee, left ankle, right hip, right knee, right ankle.

G. Preliminary project plan

The purpose of this document is to describe the plan for the execution of the bachelor thesis. The document contain task descriptions, schedule, goals, and risk assessments.

Bachelorgruppe 50

Accuracy of Markerless Motion Capture: A Comparative Study

Versjon <2.0>

Bachelorgruppe 50

Revisjonshistorie

Dato	Versjon	Beskrivelse	Forfatter
<dd/mmm/yy>	<x.x>	<detaljer>	<navn>
08.01.24	1.1	Leste gjennom, og skrev ned notater og tanker basert på de forskjellige underkapitlene	Tomas Beranek Stian Lyng Stræte
10.01.24	1.2	Skrevet ut nøkkelordene fra sist. Venter på godkjenning fra veileder.	Stian Lyng Stræte Tomas Beranek
11.01.24	1.3	siste endringer før møte med veileder	Tomas Beranek
24.01	1.4	små endringer på punkt 1. og 2.	Tomas Beranek Stian Lyng Stræte
25.01	1.5	endringer etter tilbakemelding fra veileder	Tomas Beranek Stian Lyng Stræte
18.05	2.0	Nytt Navn på oppgaven	Tomas Beranek

Bachelorgruppe 50

Introduksjon

Formålet med dette dokumentet er å beskrive planen for gjennomføringen av bacheloroppgaven nr 050. Dokumentet går gjennom oppgavebeskrivelser, tidsplan, mål og risikovurderinger. Forprosjektplanen inneholder også nødvendige vedlegg som ble etterspurt i malen.

Innholdsfortegnelse

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5. Risikovurdering 9
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    6.2 Adresseliste 10
    6.3 Avtaledokumenter 10
    6.3.1 Arbeidskontrakt for bachelor-gruppen 10
    6.3.2 3-partsavtale 10

1. Mål og rammer

1.1. Orientering

Oppgaven var delt ut som en av flere mulige valgbare oppgaver presentert av NTNU. Grunnlaget bak valget av oppgaven er det flere av. En av grunnene var å utforske en ny del av fagområdet som ikke har vært like muliggjort som for eksempel systemutvikling. Gruppen var også mer interessert i å jobbe med noe mer forskningsrelatert og uvitende enn noe fullt av premisser og faste mønster. Ved å velge dette prosjektet kunne gruppen derfor utforske noe nytt og spennende som enda ikke har blitt gjort gjennom studieløpet. Gjennom prosjektet ønsker gruppen videre å analysere, og potensielt fremheve, markørløs bevegelsefangst som en potensielt kandidat til flere sannfunsnyttige oppgaver.

1.2. Problemstilling / prosjektbeskrivelse og resultatmål

Oppgavebeskivlese:

Hensikten med dette prosjektet er å legge et grunnlag for fremtidig forskning innenfor markørløs bevegelsesangst for å oppnå en økt nøyaktighet med et kamera. Ved å legge frem eventuelle endringer og feilmarginer ønsker vi å skape et potensial for teknologisk fremskritt.

Hovedmålet med prosjektet er å måle nøyaktigheten av markørløs bevegelsesfangst ved bruk av OpenPose. Oppgavens formål er å sammenligne resultatene med markørbasert bevegelsesfangst, og utforske om målingene med markørløse systemer kan få en feilmargin mindre enn 2 - 4 cm. Til dette vil det bli brukt flere synkroniserte og kalibrerte kamera, og prosjektet vil bli utført i samarbeid med NTNU og 3D Motions Technologies(VizLab)

Første utkast til problemstilling:

Hvordan kan nøyaktigheten av markørløs bevegelsesfangst ved bruk av OpenPose sammenlignes og potensielt forbedres i forhold til tradisjonelle markørbaserte systemer, gitt den synkroniserte flerkamera teknologien? Videre, kan eksisterende algoritmer for markørløs bevegelsesangst forbedres gjennom målinger av feilmarginer og optimaliseringer?

Resultatmål:

Få en bra endelig karakter: Begge medlemmene på teamet ønsker å oppnå den høyeste karakteren mulig, A, og skal arbeide jevnt og trutt for å oppnå målet.

Framstille målinger ved bruk av synkroniserte kamera: Forsøkene som ble gjort skal ha blitt gjennomført med synkroniserte kamera ved hjelp av tilgjengelig utstyr på Vizlab.

Økt nøyaktighet: Vi ønsker ved sluttføring av prosjektet å ha et tydelig sammenligningsgrunnlag mellom markør og markørløs tracking. En målsetning vil være å kunne analysere video med en feilmargin under 2 cm i forhold til VizLab 3D Motion Technologies.

Framstilling av et akademisk papir: Basert på prosjektets funn skal det være framstilt og levert en bacheloroppgave som går grundig gjennom gruppens resultater og diskuterer disse på en faglig og akademisk måte.

1.3 Effektmål

Bidra til teknologisk framdrift innenfor spill og rehabilitering: Sluttrapporten skal potensielt skape et solid grunnlag for videre anvendelse av markørløs tracking som kan forbedre kvaliteten på animasjoner, spillopplevelser og på rehabiliteringsprosessen. Med markørløs tracking åpnes mulighetene for enklere diagnostisering og analyse i tilfeller hvor subjektet ikke har mulighet til fysisk oppmøte i laboratorium.

Forbedre nøyaktighet innenfor markørløs bevegelsesfangst: Analysere(og forbedre) nøyaktigheten i målingene utført med OpenPose ved å utnytte en bedre synkronisering og kalibrering av flere kamera, med mål om å redusere feilmargin i bevegelsesfangsten.

Bidra til et sunt arbeidsmiljø og et godt samarbeid: En av målene til teamet er å ha en trygg arbeidsplass, der alle føler seg velkomne og inkludert. For å få til dette må begge teammedlemmer jobbe med verdier innenfor teamarbeid og kommunikasjon. Dette går ut på verdier som, hjelpe hverandre, snakke sammen om problemene og planene fremover, teambuilding aktiviteter og definere regler som skal hjelpe ved tilfeller der teamet møter et problem.

1.4 Rammer

I forhold til forskningsprosjektet er det identifisert flere nødvendige ressurser for å sikre en vellykket gjennomføring.

Viktigst er tilgang til VizLab (NTNU) og 3D Motion Technologies' system, som kombinerer synkroniserte kamera med markørbasert tracking for å samle inn data. Eksperiment og opptak vil være nødt til å valideres med det markørbaserte systemet i Vizlab, noe som resulterer i at tilgang til rommet er essensielt for gjennomføring av prosjektet.

Opp til 5 videokameraer med god framerate og oppløsning er nødvendig for å sikre opptak med god kvalitet og med så lite feilmargin som mulig.

Videre vil det kunne være behov for tilstrekkelig datakraft slik som GPU, for å kunne gjøre de målingene og analysene vi ser som nødvendig. Dette kan bli tilgjengeliggjort ved bruk av NTNU IDUN, som gir elever tilgang til datamaskin med sterke GPU-er.

2. Organisering

Bachelorgruppe medlemmer:

- Tomas Beranek
- Stian Stræte Lyng

Veileder:

- Tomas Holt

Selskap:

- 3D Motion Technologies (NTNU)

3. Gjennomføring

3.1. Hovedaktiviteter.

Arbeidskontrakt

Etablerer de grunnleggende reglene og retningslinjene for gjennomføringen av prosjektet. Med hensikt å sikre en felles forståelse for arbeidsmetodikk, reaksjon og tilnærming til arbeidet som skal utføres. Dokumentet utarbeidet av alle involverte parter ved prosjektet før prosjektet ble påbegynt.

Visjonsdokument

Gruppens visjon skrives felles og deretter går vi gjennom og godkjenner. Dokumentet vil være en tilpasset versjon av IDIs mal, tilpasset fordi prosjektet hovedsakelig fokuserer på forskning fremfor systemutvikling. Dokumentet vil utarbeides tidlig i prosjektperioden og formålet er å ha en felles tanke om hvor vi skal og veien videre med prosjektet.

Forprosjektplan

Med formål å beskrive planen for prosjektet med milepæler, risikovurdering, implementasjon, veiledning. Dokumentet danner som grunnlaget for videre arbeid i prosjektet, og vil derfor fungere som en guide for å nå ønsket mål.

Poster og presentasjon

Utarbeide en poster med informasjon og bilder av produktet vi har til nå. Det må være detaljert og interessant slik at det kan være med på å vise andre hva gruppen holder på med. Presentasjonen skal være skrevet i fellesskap, der arbeidet fordeles likt. Posteren skal vise andre grupper hvor langt vi har kommet, og det er derfor nødvendig å ha hatt en progresjon for ha noe å vise frem. Selve formålet med poster og presentasjon er å inspirere andre grupper, men også oss selv, for å potensielt forbedre arbeidet videre. Presentasjonen av poster skjer i mars mellom 18 og 23 mars.

Utvikling

Utvikle et produkt som oppnår våre ønskede mål. Analyser resultatene og videre forbedre. Prøve flere teknikker for å få det fungerende. Alle på gruppen stiller til å hjelpe til med kunnskap innen AI, ML, OpenPose og tracking skjer gjennom hele prosjektperioden. Bruk av resultatene til å skrive rapport.

Rapport

Utarbeide en rapport basert på prosjektet og de oppnådde resultatene. Videre vil rapporten diskutere, og vurdere disse resultatene i detalj. Underveis i arbeidet vil det jobbes mye teori og metode parallelt med annet arbeid for å sikre fremdrift og god forståelse. Rapporten skal være på 50-70 sider pluss vedlegg. Det forventes at alle på gruppen bidrar i like stor grad i skrivingen.

Presentasjon

Presentasjon av bacheloroppgavene, hvor vi viser hva vi har jobbet med og hvordan vi utførte arbeidet. Henvise til resultater, og valg vi har tatt, samt hvorfor vi har valgt dette. Gjøres og fordeles likt innad i gruppen. Dette skal gjøres mellom 21-25 mai.

3.2. Milepæler.

Ettersom dette ikke vil være en utviklingsoppgave vil en del av dette være flytende ut ifra det gruppen trenger å gjøre. Gruppen har mye forskjellig forkunnskap og vil trenge personrettet grunnarbeid.

08.01.2024: **Første møte etter jul**

26.01.2024: **Innlevering av Forprosjektplan og Arbeidskontrakt**

29.01.2024: **Sette sammen forskjellige systemer for å kunne ta synkroniserte opptak**

15.02.2024: **Research**

14.04.2024: **Ferdig med potensiell kode og utvikling**

18.03.2024: ***Innlevering av Poster og Presentasjon***

21.05.2024: ***Innlevering rapport og eksterne vedlegg***

24.05.2024: ***Presentasjon av bacheloroppgave***

4. Oppfølging og kvalitetssikring

4.1 Kvalitetssikring.

Kvaliteten på arbeidet sikres med kontinuerlige møter med veileder underveis. Vi vil også legge høyt fokus på god kildehenvisning, og grundig valg av sikre kilder. Vi ønsker å publisere forskningsdata og råmateriale åpent slik at våre resultater kan etterprøves av andre. Vi planlegger også å ha ukentlige evalueringsmøter hvor vi diskuterer antagelser.

Utviklingsmessig er det viktig å ha en felles standard som er forståelig, og anvendelig for oss og andre. Koden skal følge reglene for kobling og cohesion. Kode burde være dokumentert, og skrevet på en oversiktlig måte. Komplekse kodebiter må dokumenters. Medlemmene av prosjektet må være flinke til å gi hverandre tilbakemeldinger på arbeidet utført, både det som er bra og det som er dårlig. Dette vil forebygge uenigheter, og en dårlig kodestandard, som ofte kan føre til dårlig kvalitet.

4.2 Rapportering.

Rapportering skjer via veileder. Vi ønsker kontinuerlig møter med veilederen, på ukentlig basis. Det vil imidlertid være vanskelig å planlegge faste dager da prosjektet ikke har en strømlinjeformet fremdrift. Dersom en av partene ikke har mulighet for statusmøte den ene uken, blir en ny dato valgt slik at den passer begge partene og slik at den ikke hindrer videre utvikling.

5. Risikovurdering

Hendelse	**Sannsynlighet (0 - 10)**	**Signifikans (0 - 10)**	**Konsekvens**	**Tiltak**
Problematikk med SDK til kamera	7	10	Tid brukt på noe som ikke har betydning for hva vi ønsker å forske på.	Prøver først å løse problematikken selv. Eventuelt gå over til en gammel og fungerende versjon.
Problematikk med kamera til prosjektet	2	3	Får ikke tatt opptak med et av kameraene.	Bytte til annet kamera, eller bruke 4 kamera istedenfor 5.
Sykdom	5	2	Gruppen må fordele arbeidet på nytt, slik at den syke personen får tid og mulighet til å bli frisk så fort som mulig	Dersom noen blir syk vil de bli tildelt arbeidsoppgaver som passer personens tilstand.
Uenighet i Gruppen	2	4	Arbeidet kan bli satt på pause helt til problemet er løst	Dersom medlemmene ikke kommer til en felles avgjørelse innen en kort tidsramme, vil veilederen bli kontaktet og en felles løsning utarbeidet.
Dataintegritet	5	10	Data blir korrupt, eller mistet.	Gode rutiner for sikker lagring og backup

6. Vedlegg

6.1 Tidsplan

6.2 Adresseliste

Navn	Firma	Tlf	E-Postadresse
Tomas Holt	NTNU	+47 930 57 750	tomas.holt@ntnu.no
Stian Lyng Stræte	None	+47 920 55 335	stials@stud.ntnu.no
Tomas Beranek	None	+47 941 99 891	tomaber@stud.ntnu.no

6.3 Avtaledokumenter

6.3.1 Arbeidskontrakt for bachelor-gruppen

Arbeidskontrakt for Bachelorgruppe 50.

Medlemmer: Tomas Beranek, Stian Lyng Stræte

Innledende tekst

Denne arbeidskontrakten er utarbeidet i henhold til rollene som skal fylles av de ulike partene i prosjektet. Prosjektet fokuserer på å analysere nøyaktigheten innenfor markørløs bevegelsesfangst ved bruk av OpenPose. Kontrakten tar for seg mål, arbeidsoppgaver og retningslinjer for prosjektperioden.

Prosjektets Mål

Effektmål

Bidra til teknologisk framdrift innenfor spill og rehabilitering: Sluttrapporten skal potensielt skape et solid grunnlag for videre anvendelse av markørløs tracking som kan forbedre kvaliteten på animasjoner, spillopplevelser og på rehabiliteringsprosessen. Med markørløs tracking åpnes mulighetene for enklere diagnostisering og analyse i tilfeller hvor subjektet ikke har mulighet til fysisk oppmøte i laboratorium.

Forbedre nøyaktighet innenfor markørløs bevegelsesfangst: Analysere(og forbedre) nøyaktigheten i målingene utført med OpenPose ved å utnytte en bedre synkronisering og kalibrering av flere kamera, med mål om å redusere feilmargin i bevegelsesfangsten.

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Få en bra endelig karakter: Begge medlemmene på teamet ønsker å oppnå den høyeste karakteren mulig, A, og skal arbeide jevnt og trutt for å oppnå målet.

Framstille målinger ved bruk av synkroniserte kamera: Forsøkene som ble gjort skal ha blitt gjennomført med synkroniserte kamera ved hjelp av tilgjengelig utstyr på Vizlab.

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Roller og oppgavefordeling

A. *Teamledelse*

Som følge av oppgavens natur og størrelsen på teamet vil det bli en flat lederstruktur hvor begge parter blir enige om valgene som tas.

B. *Dokumentansvarlig og Innleveringsansvarlig*

Dokumentansvarlig skal passe på at alle notater og dokumenter er plassert på riktig sted innenfor gruppens mappestruktur. Innenfor mappen blir dette gjort basert på dato og relevans. Gjennom prosjektet blir det brukt disse plattformer: Google Drive og Gitlab.

dokumentansvarlig - Tomas Beranek

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Vi ønsker å tilrettelegge for mestringsfølelse hos de involverte. For å kunne gjøre dette legger vi stort fokus på åpen og hurtig kommunikasjon. Sitter man fast i en problemstilling, involveres den andre. Slik vil man oppleve bedre samarbeid og videre en større grad av mestring. Ingen ideer eller spørsmål bør avkastes. Videre er det viktig at partene forsøker å forstå hverandre før man trekker videre konklusjoner.

D. *Uenighet, avtalebrudd*

Her er det spesielt viktig med stor takhøyde for å ta tak i uenigheter og eventuelle konflikter så fort som mulig. Det skal være åpenhet for ærlige tilbakemeldinger. Dersom man møter uenigheter, brudd og konflikter som ikke lar seg løse, vil andre aktører involveres.

Underskrifter

....

Tomas Beranek

....

Stian Lyng Stræte

6.3.2 3-partsavtale

Ettersom vi ikke gjennomfører forskningen for en tredjepart vil en 3-partsavtale ikke være nødvendig for denne gruppen.

H. Vision Document

The vision document describes the ideas and overall requirements for the Bachelor’s thesis.

Bachelorgruppe 50

Accuracy of Markerless Motion Capture: A Comparative Study

Visjonsdokument

Versjon <1.2>

Dokumentet er laget av Tore Berg Hansen.

Revisjonshistorie

Dato	Versjon	Beskrivelse	Forfatter
<dd/mmm/yy>	<x.x>	<detaljer>	<navn>
11.01.24	1.1	nøkkelord, og små avsnitt innført	Tomas Beranek
12.01.24	1.2	småendringer siste del av dokumentet	Tomas Beranek
18.05	2.0	Endring av Navn på Oppgave	Tomas Beranek

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2. Sammendrag problem og produkt 4
   2.1 Problemsammendrag 4
   2.2 Produktsammendrag 4
3. Overordnet beskrivelse av interessenter og brukere 4
   3.1 Oppsummering interessenter 4
   3.2 Oppsummering brukere 4
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   3.5 Alternativer til vårt produkt 5
4. Produktoversikt 5
   4.1 Produktets rolle i brukermiljøet 5
   4.2 Forutsetninger og avhengigheter 5
5. Produktets funksjonelle egenskaper 5
6. Ikke-funksjonelle egenskaper og andre krav 5

1. Innledning

Det du har behov for å si om hensikten med dokumentet og innledningsvis om. prosjektet

Dette dokumentet beskriver ideene og overordnede krav til Bacheloroppgaven. Vår visjon er å gjennom dette prosjektet analysere potensialet til markørløs bevegelsesfangst(med openpose), og potensielt forbedre nøyaktigheten og anvendelsen for markørløse system. Bacheloroppgaven foregår gjennom hele vårsemesteret 2024, og det vil bli utført av to elever, Tomas Beranek og Stian Lyng Stræte.

1.1 Referanser

2. Sammendrag problem og produkt

2.1 Problemsammendrag

Problem med	*Løsningen for dagens system er for unøyaktig til og kunne bli brukt i praktisk bruk utenfor det teoretiske.*
berører	*Oppgavegiveren er NTNU, men det er et bredt potensial av berørte, dersom prosjektet blir godt gjennomført.*
som resultatet av dette	*Ettersom systemene ikke er nøyaktige nok, er det behov for manuelt arbeid i arbeidsområder som tar i bruk markørløs bevegelsefangst.*
en vellykket løsning vil	*Potensielt gi muligheten til å videreutvikle en automatisert bruk av markørløs bevegelsesfangt.*

2.2 Produktsammendrag

For	*NTNU/vitenskap*
som	*har behov for forskning og analyse av markørløs bevegelsesfangst*
produktet	*være et akademisk papir*
som	*gir kunden muligheten til å potensielt anvende våre resultater beskrevet i bacheloroppgaven.*
I motsetning til	*dagens system som bruker markører for bevegelsesfangst.*
Har vårt produkt	*en potensiell stor mulighet til å forenkle arbeidet til flere aktører, som med våre resultater og metoder kan utarbeide en bedre løsning enn den de bruker per dags dato.*

3. Overordnet beskrivelse av interessenter og brukere

3.1 Oppsummering interessenter

NTNU/IDI *3D Motion Technologies*	*Veileder og klient*	*Vil gjennom semesteret gi oss konstruktiv tilbakemelding på arbeidet utført, og gjennom dette gi en pekepinne på hvordan vi burde gå videre for å nå ønskede resultater.*

3.2 Alternativer til vårt produkt

Dagen alternativ går ut på å bruke markørbasert systemer som til tider kan være dyre og vanskelige å sette opp.

4. Ikke-funksjonelle egenskaper og andre krav

Ikke-funksjonelle produktegenskaper og andre krav til produktet, som krav til standarder etc. Sjekk ut FURPS+ og kvalitetsattributter.

- Dokumentasjon på materiell som gjør det enkelt for andre å forstå..
- Målet er å redusere unøyaktighet, basert på artikkelen oppgitt i oppgaveforslaget.
- Det skal være mulig å fange og registrere bevegelser basert på video fra flere kamera
- Kameraene skal være synkronisert og nøyaktig for å fange et helhetlig bilde av bevegelsen
- Videoer skal være mulig å analysere i ettertid av opptaket
- Målingene skal foregå på både markørløs og markørbasert opptak

I. Project handbook

The project handbook serves as a reference document on how the project was managed and executed. The document contains the contract between the group members, progress plan, meeting notice templates, and time sheets with status reports. The meeting notices and summaries can be found in Appendix I.

Prosjekthåndbok

Innhold

Innhold

Arbeidskontrakt ***1***

Framdriftsplan – Gantt-diagram ***2***

Møteinnkalling, eksempel ***3***

Møtereferat, eksempel ***4***

Timelister m/statusrapporter ***5***

Arbeidskontrakt

Arbeidskontrakt for Bachelorgruppe 50.

Medlemmer: Tomas Beranek, Stian Lyng Stræte

Innledende tekst

Denne arbeidskontrakten er utarbeidet i henhold til rollene som skal fylles av de ulike partene i prosjektet. Prosjektet fokuserer på å analysere nøyaktigheten innenfor markørløs bevegelsesfangst ved bruk av OpenPose. Kontrakten tar for seg mål, arbeidsoppgaver og retningslinjer for prosjektperioden.

Prosjektets Mål

Effektmål

Bidra til teknologisk framdrift innenfor spill og rehabilitering: Sluttrapporten skal potensielt skape et solid grunnlag for videre anvendelse av markørløs tracking som kan forbedre kvaliteten på animasjoner, spillopplevelser og på rehabiliteringsprosessen. Med markørløs tracking åpnes mulighetene for enklere diagnostisering og analyse i tilfeller hvor subjektet ikke har mulighet til fysisk oppmøte i laboratorium.

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dokumentansvarlig - Tomas Beranek

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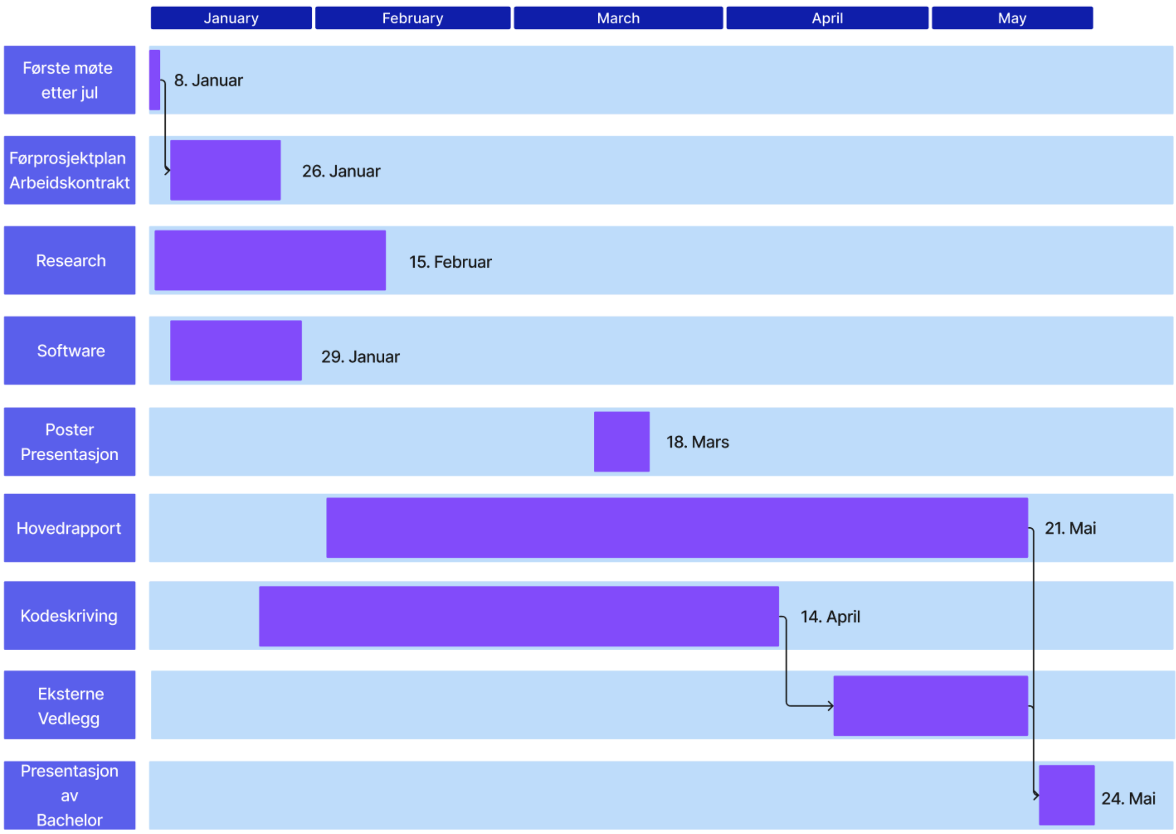
Underskrifter

....
Tomas Beranek

....
Stian Lyng Stræte

Framdriftsplan – Gantt-diagram

Dato	Versjon	Besrkivese	Forfatter
13.01.2024	1.0	Førsteutkast	Tomas Beranek Stian Strætte Lyng
18.01.2024	1.1	Endinger etter veileder møte	Tomas Beranek



Møteinnkalling og Møtereferat

Innkalling til møte: Bacheloroppgave 50.

11.01.2024 kl 11:00 – 13.00, VizLab, U1, IT-bygget

Følgende personer innkalles:

Tomas Holt(veiledere)

Stian Lyng Stræte
Tomas Beranek

Agenda:

Sak 01 Spørre hva slags dokumentasjon skal skrives

Sak 02 Gå gjennom nødvendig utstyr

Sak 03 Gå gjennom nødvendig software

Møtet planlegges avsluttet kl. 13.00

Ta kontakt med undertegnede dersom du ikke har anledning til å komme

Mvh

Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

11.01.24 kl 11:00 - 13:00

VizLab, U1- IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt(veileder)

Frafall: Ingen

Møteleder: Tomas Beranek

Sak 1 Hvilket dokumentasjon trengs

Det som er nødvendig er arbeidskontrakt og forprosjektplan. I tillegg så skulle alle vedleggene være med, men kan utelatte delene som handler om systemutvikling. Gantt diagram skal også lages, men blir litt mindre detaljer enn i en systemutvikling bachelor.

Sak 2 Gå gjennom nødvendig utstyr

Veileder ga bachelorgruppen en gjennomgang i VizLab og hva slags utstyr som skal lages. Dette inneholdt alt som hadde med kamerautstyret og gjøre, og det som hadde med tracking å gjøre.

Sak 3 Gå gjennom nødvendig software

Software som skal brukes av gruppen skulle være tilgjengeliggjort av veileder, men softwaren fungerer ikke med oppdatert versjon av Windows. Veilederen skulle se nærmere på det og det skal være mulig å fikse problemet slik at gruppen kan begynne så fort som mulig.

11.01.2024, Tomas

Innkalling til møte: Bacheloroppgave 50.

18.01.2024 kl 11:25 – 12.00, VizLab, U1, IT-bygget

Følgende personer innkalles:

Tomas Holt (veiledere)

Stian Lyng Stræte

Tomas Beranek

Agenda:

Sak 01 Se gjennom dokumentasjonen som skal leveres i uke (Forprosjektplan Arbeidskontrakt)

Sak 02 Gå gjennom manglende software som fungerer

Sak 03 Eventuelt gå gjennom GANTT og Visjonsdokument om nødvendig

Møtet planlegges avsluttet kl. 12.00

Ta kontakt med undertegnede dersom du ikke har anledning til å komme

Mvh

Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

18.01.24 kl 11:30 - 12:00

VizLab, U1- IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt (veileder) Frafall: Ingen

Møteleder: Stian Lyng Stræte

Sak 1 Dokumentasjon

Arbeidskontrakten skulle ikke sjekkes av veileder, men forprosjektplanen ble etter avtale sendt til veileder; og skal bli tilbakesendt dersom endringer trengs.

Sak 2 Mangel på fungerende software

Medlemmene av Bachelorgruppen skulle få fungerende software av veileder som skulle brukes gjennom hele bacheloroppgaven. Her har det vært noe trøbbel med at software og programmet ikke fungerer og noe må fikses av gruppen selv (noe mangler enda å bli fikset). Dersom dette ikke ble ordnet i løpet av nærmeste tid ble gruppen anbefalt og enten bruke programmene separat, eller å finne en annen løsning på problemet.

Sak 3 Nødvendighet av Gantt og visjonsdokument

Gantt diagrammet var fint nok, noen endringer skal gjøres etter tilbakemelding fra veileder. Ettersom visjonsdokumentet ikke passer for en forskningsoppgave uten bruker og et forventet produkt, ble malen sendt til veileder som selv skulle endre på den slik at den passet til et forskningsprosjekt. Dette ble foreslått av veilederen selv

18.01.2024, Stian

Innkalling til møte: Bacheloroppgave 50

25.01.2024 kl 11:00 – 11.45, Møterom VizLab IT-bygget

Følgende personer innkalles:

Tomas Holt (veiledere)

Stian Lyng Stræte

Tomas Beranek

Agenda:

Sak 01 Gå gjennom Oblig. 1 og Gantt

Sak 02 Hvordan kan vi synkronisere kameraene

Sak 03 Eventuelt.

Møtet planlegges avsluttet ca kl. 11.45

Ta kontakt med undertegnede dersom du ikke har anledning til å komme

Mvh

Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

25.01.24 kl 11:00 - 11:30

VizLab, U1- IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt (veileder) Frafall: Ingen

Møteleder: Stian Lyng Stræte

Sak 1 Synkronisere Kamera

Vi fikk en fin forklaring på hvordan kameraene fungerer, og hvordan triggerimpulser skal sendes, og hvordan de blir sendt nå.

Sak 2 Gå gjennom Oblig 1.

Forprosjektsplanenen så fin ut, men vi burde endre litt på hva vi egentlig skal frem til, og hva vi forsker på. Visjonsdokumentet skal enten skrives inn i forprosjektsplanen, eller så skal det leveres som et enestående dokument, men blir ikke stort.

Sak 3 eventuelt

Vi fikk tilgang til fargekamera og kan nå prøve oss frem med det, ettersom openpose skal gi bedre resultater med fargekamera.

25.01.2024, Stian

Innkalling til møte: Bacheloroppgave 50

15.02.2024 kl 14:00 – 14.45, Møterom VizLab IT-bygget

Følgende personer innkalles:

Tomas Holt
(veiledere) Stian
Lyng Stræte

Tomas Beranek

Agenda:

Sak 01 *Koden til nå*

Sak 02 *Tanker om hva som skal gjøres videre*

Sak 03 *Eventuelt tema rundt arbeidet så langt, og fremtidsplanlegging*

Møtet planlegges avsluttet ca kl. 11.45

Ta kontakt med undertegnede dersom du ikke har anledning til å komme

Mvh

Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

15.02.24 kl 14:00 - 14:30

201, 2. etg. IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt (veileder) Frafall: Ingen

Møteleder: Stian

Sak *Koden til nå*

Koden skal docs, den skal være bra forklart, og fint strukturert. Veilederen sa teamet hadde kommet lengre med koden enn forventet. Koden kan til nå kalibrere, stereo

kalibrere og triangulere. Det neste som trengs er å fikse situasjonene og visualiseringen av punktene for validering.

Sak *Tanker om hva som skal gjøres videre*

Trikset videre er å sjekke med markere, og uten markere. Siden temaet må ta opptak med markers så må de maskeres ut ved hjelp av nearest neighbour. Blir det forskjellig med og uten nearest neighbour, og om det er påvirkning basert markers i bildet? Hvordan se på markerbased?

Sak *Eventuelt tema rundt arbeidet så langt, og fremtidsplanlegging*

Resultatet og rapporten er essensen i oppgaven. Koden skal gi disse resultatene, men det som står i rapporten som er det som skal være viktig.

15.02.2024, Stian

Referat fra uoffisielle møter på vizlab bacheloroppgave 50

26.02.24 til 01.03.2024

VizLab, U1. etg. IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt (veileder) Møteleder: Ingen

Grunnet jobbing med prosjektrapport og eksamen i INGT2300, samt arbeid med posterpresentasjon ble det i denne perioden litt mindre møteaktivitet med veileder. Vi hadde heldigvis flere uoffisielle møter på Vizlab.

Sak: Kalibreringsmetode

Vi hadde brukt stereo kalibrering, og lurte litt på hans tanker rundt dette. Lurte også på om dette ble brukt i Trackpoint. Snakket også en del om bruk av checkerboard vs wand for kalibrering.

Sak: Hjelp til Trackpoint

Vi fikk bidrag til hvordan feilsøke, hva som kan være feil. Fikk flere USB sticks med forskjellige versjoner av programvaren.

01.03.2024, Stian

Innkalling til møte: Bacheloroppgave 50

19.03.2024 kl 11:00 – 11.45, Møterom VizLab IT-bygget

Følgende personer innkalles:

Tomas Holt
(veiledere) Stian
Lyng Stræte

Tomas Beranek

Agenda:

Sak 01 Hvordan vi kan gå videre med marker based

Sak 02 Hvordan finne error mellom openpose og markers

Sak 03 Kalkulering av joint center, eller alternativ måte å finne det

på Sak 04 Eventuelle spørsmål som oppstår

Møtet planlegges avsluttet ca kl. 11.45

Ta kontakt med undertegnede dersom du ikke har anledning til å komme

Mvh

Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

19.03.24 kl 14:00 - 14:30

201, 2. etg. IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt
(veileder) Frafall: Ingen
Møteleder: Stian

Sak: Hvordan vi kan gå videre med marker based

Diskusjonen begynte med en gjennomgang av forskjellige tilnærminger til markørbaserte metoder og deres relevans for prosjektet.

Sak: Hvordan finne feil, eller differanse mellom openpose og markør baserte data

Teamet diskuterte ulike metoder for å kalkulere feilmargin mellom OpenPose og det markørbaserte systemet. Bruken av mean absolute error ble nevnt

Sak: Kalkulering av 'joint center', eller alternativ måte å finne det på

Det ble diskutert hvilke tilnærminger som brukes for å beregne 'joint center', og hvorvidt dette var inkludert i Trackpoint. Siden dette ikke var en funksjonalitet i Trackpoint, ble vi

enige om at vi kunne benytte oss av Qualisys som 'ground truth' dersom dette var nødvendig.

Sak: Eventuelle spørsmål som oppstår

Ingen ytterligere spørsmål ble reist.

Møtet ble avsluttet som planlagt kl. 11.45.

Mvh

Tomas Beranek og Stian Lyng Stræte

19.03.2024, Tomas

Innkalling til møte: Bacheloroppgave 50 24.04.2024 kl
12:30 – 13.00, Møterom VizLab IT-bygget ***Følgende personer innkalles:***

Tomas Holt

(veiledere) Stian Lyng

Stræte

Tomas Beranek

Agenda:

Sak 01 Tilbakemelding på teoridel i rapport, som sendes på tirsdag.

Møtet planlegges avsluttet ca kl. 13.00

Ta kontakt med undertegnede dersom tiden ikke passer

Mvh

Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

24.04.24 kl 12:30 - 13:00

201, 2. etg. IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt (veileder)

Frafall: Ingen

Møteleder: Stian

Sak: Tilbakemelding på teoridel

Holt ønsket et sammendrag, litt tidligere i prosessen. Det var en del teori Holt mente kunne flyttes til appendix(software, python bibliotek, machine learning teori). Lurte på hvor detaljert matematikken skulle være. Det sies på blackboard at en andreklassing skal forstå rapporten, i vårt tilfelle ble vi enige med veileder om at vi skal skrive i innledning at det forventes forkunnskap om homogene ligninger og projeksjons matriser Møtet ble avsluttet som planlagt kl. 13:00.

Mvh

Tomas Beranek og Stian Lyng Stræte

24.04.2024, Stian

Innkalling til møte: Bacheloroppgave 50

06.05.2024 kl 11:00 – 11.45, Møterom VizLab IT-bygget

Følgende personer innkalles:

Tomas Holt
(veiledere) Stian Lyng
Stræte

Tomas Beranek

Agenda:

Sak 01 Gjennomgang av metode

Sak 02 Se gjennom vitenskapelig metode.

Sak 2.1 Spørsmål ang. delkapittel om litteratur?

Sak 03 Hva som er skrevet på resultat, og hva som eventuelt mangler.
Dette gjelder særlig vitenskapelige resultater.

Sak 04 Hvordan strukturere diskusjon, og hva som burde nevnes

Møtet planlegges avsluttet ca kl. 11.45
Rapporten i sin nåværende tilstand er lagt til som vedlegg med mailen
Ta kontakt med undertegnede dersom du ikke har anledning til å
komme

Mvh
Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

06.05.24 kl 11:00 - 11:45

201, 2. etg. IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt (veileder)

Frafall: Ingen

Møteleder: Stian

Sak: Gjennomgang av metode:

Hadde en diskusjon rundt metodene som ble brukt. Så generelt bra ut. Samme som sist, legge ting i appendix. Dette hadde vi ikke fått tid til å gjøre enda.

Sak: Se gjennom vitenskapelig metode:

Den fikk vi godkjent og positive tilbakmeldinger på. Måten det var skrevet og redegjort på var ifølge Holt forståelig og relevant.

Sak: Spørsmål angående delkapittel om litteratur:

Vi lurte på hvor detaljert denne delen skal være, noen rapporter har en veldig detaljert beskrivelse, andre mindre. Han syntes vi traff godt i henhold til vår oppgave.

Sak: Gjennomgang av resultater og eventuelle mangler:

Holt mente vi burde sammenligne mer opp mot rapport fra oppgavebeskrivelsen. Vi snakket om hvorfor våre resultater var annerledes. Og hvorvidt de egentlig var dårligere eller bedre. Rapporten fra oppgavebeskrivelse hadde en prosentvis feilmargin fra 20mm til 30mm, og vi hadde fra 20mm til 40mm. Vi ble enige om å finne MAE på under 30mm istedet for 40mm slik at tallene bedre kunne sammenlignes.

Sak: Strukturering av diskusjon og relevante emner (Sak 04):

Temaet ble ikke diskutert da fremdriften var raskere enn forventet, og gruppen hadde ferdigstilt diskusjonsdel før møtet.

Møtet ble avsluttet litt etter planen, kl. 12:00.

Rapporten i sin nåværende tilstand ble sendt som vedlegg i forkant av møtet.

Mvh

Tomas Beranek og Stian Lyng Stræte

06.05.2024, Stian

Innkalling til møte: Bacheloroppgave 50

15.05.2024 kl 11:30 – 12:00, Møterom VizLab IT-bygget

Følgende personer innkalles:

Tomas Holt (veiledere)

Stian Lyng Stræte

Tomas Beranek

Agenda:

Sak 01 Innlevering av kode. Er det nødvendig?

Sak 02 Er bildene på side 5 og 8 i teoridelen forklart godt nok?

Sak 03 Våre forventinger til karakter, om hvorvidt de ser ut til å stemme

Sak 04 Skal vi ha resultater i sammendraget, av typen "approximately 47% were <20 mm, and 80% were <30 mm. However, 10% were >40 mm."

Sak 05 Er det fint å nevne en alternativ måte å utføre milsestones på. gjelder særlig diskusjonsdelen på side 68.

Sak 06 Overordnet om diskusjonsdel (Er det mulig at du tar en ekstra titt på den i sin helhet?)

Sak 07 Burde vi ha et eget delkapittel på diskusjon der vi ser på resultatene basert på forskningsspørsmålene, eller svarer vi greit på dette nå. (Vi skal være innom alt, men det er kanskje ikke så tydelig, siden det er strødd utover)

Møtet planlegges avsluttet ca kl. 12.00

Rapporten i sin nåværende tilstand er lagt til som vedlegg med mailen

Ta kontakt med undertegnede dersom du ikke har anledning til å komme

Mvh

Tomas Beranek og Stian Lyng Stræte

Referat fra prosjektmøte bacheloroppgave 50

15.05.2024 kl 11:30 – 12:00, Møterom IT-bygget

Tomas Beranek, Stian Lyng Stræte, Tomas Holt (veileder)
Frafall: Ingen
Møteleder: Stian Lyng Stræte

Saker:

Sak 01 Innlevering av kode. Er det nødvendig?

- Holt mente vi burde levere inn, men understreket at dette var forskning, og at kodekvalitet derfor ikke var avgjørende.

Sak 02 Er bildene på side 5 og 8 i teoridelen forklart godt nok?

- Holt mente det kunne være hensiktsmessig å flytte beskrivelsen av bildene til tekst over eller under. Eksempelvis: bildet under beskriver etc.…

Sak 03 Våre forventinger til karakter, om hvorvidt de ser ut til å stemme

- Syntes at prosjektet ser bra ut. Holt mener vi har gjort en god jobb.

Sak 04 skal vi ha resultater i sammendraget, av typen "approximately 47% were <20mm, and 80% were <30 mm". "However, 10% were >40 mm."

- Kanskje mer en teaser av typen “90% av tilfellene etc… ”

Sak 05 Er det fint å nevne en alternativ måte å utføre milestones på. gjelder særlig diskusjonsdelen på side 68.

- Ja, det er fint.

Sak 07 Burde vi ha et eget delkapittel på diskusjon der vi ser på resultatene basert på forskningsspørsmålene, eller svarer vi greit på dette nå. (Vi skal være innom alt, men det er kanskje ikke så tydelig, siden det er strødd utover)

- Svar på spørsmålene direkte, ved et kort og konsist svar på hvert enkelt spørsmål.

15.05.2024, Stian og Tomas

Timelister m/statusrapport

Timelistene er delt opp antall uker på bachelor, fra uke 1 til uke 20. Dette er antall uker som var på bachelor og stemmer dermed ikke med ukenummer, ettersom bachelor arbeidsstart i uke nummer 2.

Name - team-member	Activities	Categories
Tomas Beranek	Self-education	Documentation
Stian Lyng Stræte	Information search	Adminstration
	User testing	Quality assurance
	Prototyping	Wireframe
	Coding	MVP
	Testing of code	Final delivery
	Error correction	Utstyr veiledning
	Project reporting	Uncategorized
	Presentation including preparation	
	Team meetings	
	Team meetings with supervisor	
	Camera Management/Recording	
	Software fixing	
	Add your activities	

Summary of timesheets for project:

Week no	Tomas Beranek	Stian Lyng Stræte
Week 1	10,00	9,00
Week 2	12,0	12,0
Week 3	20,8	18,8
Week 4	30,0	25,0
Week 5	30,0	30,0
Week 6	28,0	28,5
Week 7	28,0	28,0
Week 8	5,6	5,6
Week 9	0,0	0,0
Week 10	8,0	8,0
Week 11	20,0	20,0
Week 12	0,0	0,0
Week 13	31,0	38,0
Week 14	36,0	36,0
Week 15	42,0	42,0
Week 16	43,0	43,0
Week 17	46,0	46,0
Week 18	50,0	50,0
Week 19	54,3	54,3
Week 20	8,0	8,0
Total sum hours pr person	**502,70**	**502,20**

Summary of hours by activity

Activity	Tomas Beranek	Stian Lyng Stræte	Total sum hours pr activity
Self-education	47,5	42	**89,5**
Information search	0	0	**0**
User testing	0	0	**0**
Prototyping	0	0	**0**
Coding	123,5	132	**255,5**
Testing of code	1	1	**2**
Error correction	0	0	**0**
Project reporting	253	249,5	**502,5**
Presentation including preparation	7	7	**14**
Team meetings	0	0	**0**
Team meetings with supervisor	9,2	9,2	**18,4**
Camera Management/Recording	24	24	**48**
Software fixing	37,5	37,5	**75**
Total sum hours	**502,7**	**502,2**	**1004,9**

Summary of hours by category

Category	Tomas Beranek	Stian Lyng Stræte	Total sum hours pr categori
Documentation	244,5	244,5	**489**
Adminstration	10,5	6	**16,5**
Quality assurance	0	0	**0**
Wireframe	0	0	**0**
MVP	0	0	**0**
Final delivery	147,5	155	**302,5**
Utstyr veiledning	3	3	**6**
Uncategorized	97,2	93,7	**190,9**
Total sum hours	**502,7**	**502,2**	**1004,9**

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Project reporting	Adminstration	4,5
Team meetings with supervisor	Utstyr veiledning	3,00
Project reporting	Adminstration	2,50
Week 1		**10,00**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Project reporting	Adminstration	3,5
Team meetings with supervisor	Utstyr veiledning	3,00
Project reporting	Adminstration	2,50
Week 1		**9,00**

Weekly Status Report

Initial meeting with supervisor. The group got an tour trough the lab and the equipment they are going to use(together with the software). The group started writing a preproject plan

Timesheet

Timesheet		Tomas Beranek	
Activity	**Category**	**Duration (hours)**	
Project reporting	Documentation	2,50	
Self-education	Documentation	2,00	
Software fixing	Uncategorized	5,00	
Self-education	Uncategorized	2,0	openpose
Team meetings with supervisor	Uncategorized	0,5	
Week 4		**12,0**	

Timesheet		Stian Lyng Stræte	
Activity	**Category**	**Duration (hours)**	
Project reporting	Documentation	2,50	
Self-education	Documentation	2,00	
Software fixing	Uncategorized	5,00	
Self-education	Uncategorized	2,0	Litteratur, og forskningsartikkel
Team meetings with supervisor	Uncategorized	0,5	
Week 4		**12,0**	

Weekly Status Report

The group started on self-education on openpose.Meeting with supervisor about software and administrative work. Started with software fixing on camera-maneger.

Timesheet

Timesheet		Tomas Beranek	
Activity	**Category**	**Duration (hours)**	
Software fixing	Uncategorized	6,0	
Software fixing	Uncategorized	3,5	
Software fixing	Uncategorized	6,0	
Team meetings with supervisor	Uncategorized	0,3	
Project reporting	Adminstration	1,0	
Project reporting	Adminstration	0,5	
Self-education	Uncategorized	3,5	openpose
Week 2		**20,8**	

Timesheet		Stian Lyng Stræte	
Activity	**Category**	**Duration (hours)**	
Software fixing	Uncategorized	6,0	
Software fixing	Uncategorized	4,5	
Software fixing	Uncategorized	6,0	
Team meetings with supervisor	Uncategorized	0,3	
Self-education	Uncategorized	2,0	Litteratur, og forskningsartikkel
Week 2		**18,8**	

Weekly Status Report

Finished pre-project plan, and other administrative documentaton, such as GANTT. The group wrote down imporatante theory in repport while reading up on it. Kept on with softwarefixing camera-manager. Meeting with supervisor was mostly to get validified administrative documentation, which it was (pre-project plan)

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Software fixing	Uncategorized	10,0
Software fixing	Uncategorized	7,0
Project reporting	Adminstration	2
Self-education	Uncategorized	3,0
Camera Management/Recording	Uncategorized	8,0
Week 3		**30,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Software fixing	Uncategorized	10,0
Software fixing	Uncategorized	7,0
Camera Management/Recording	Uncategorized	8,0
Week 3		**25,0**

Weekly Status Report

The group started with recording, trying SpinView as an alternativ to camera-manager. Still trying to fix software. Concidering to change to other working solution

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Self-education	Uncategorized	10,0
Self-education	Uncategorized	10,0
Self-education	Uncategorized	10,0
Week 4		**30,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Self-education	Uncategorized	10,0
Self-education	Uncategorized	10,0
Self-education	Uncategorized	10,0
Week 4		**30,0**

Weekly Status Report

Group started to read on camera theory. The group decided to switch from camera-manager to Spinnview. Started on developing calibration tool for multi camera usage

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	6,0
Self-education	Final delivery	3,0
Coding	Final delivery	7,5
Coding	Final delivery	6,0
Self-education	Final delivery	4,0
Testing of code	Final delivery	1,0
Team meetings with supervisor	Uncategorized	0,5
Week 5		**28,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	5,0
Self-education	Final delivery	3,0
Coding	Final delivery	8,0
Coding	Final delivery	8,0
Self-education	Final delivery	3,0
Testing of code	Final delivery	1,0
Team meetings with supervisor	Uncategorized	0,5
Week 5		**28,5**

Weekly Status Report

Contnuing on self-education and camera calibration code from previouse week. On suppervisor meeting the group talk about the change from camera manager to other software. Talked about a frame trigger made in rasberry pie

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	9,0
Coding	Final delivery	9,0
Coding	Final delivery	10,0
Week 6		**28,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	9,0
Coding	Final delivery	9,0
Coding	Final delivery	10,0
Week 6		**28,0**

Weekly Status Report

Group found pose2sim and opensim as two possible softwares for calibration triangulation and 3d visualization. The group tried to make it work with their needs. The group managed to make it work, and decided to use it as it utilizes the same methods as those the group made in previouse weeks.

Timesheet

Timesheet		Tomas Beranek	
Activity	**Category**	**Duration (hours)**	
Coding	Final delivery	5,0	
Team meetings with supervisor	Uncategorized	0,3	unofficial
Team meetings with supervisor	Uncategorized	0,3	unofficial
Week 7		**5,6**	

Timesheet		Stian Lyng Stræte	
Activity	**Category**	**Duration (hours)**	
Coding	Final delivery	5,0	
Team meetings with supervisor	Uncategorized	0,3	unofficial
Team meetings with supervisor	Uncategorized	0,3	unofficial
Week 7		**5,6**	

Weekly Status Report

Since the group finished their work with camera calibration in pose2sim. they started to contect it to openpose, and potenstialy trackpoint. There were little work this week due to INGT2300 repport and exsam reading. The group therefore hade unofficial meetings with suerpvisor to update on how often the meeting shoudl be held, and on what the groups should do next.

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Week 8		**0,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Week 8		**0,0**

Weekly Status Report

No work was done on thesis, due to other school subjects

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Presentation including preparation	Uncategorized	4,0
Coding	Final delivery	4,0
Week 8		**8,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Presentation including preparation	Uncategorized	4,0
Coding	Final delivery	4,0
Week 8		**8,0**

Weekly Status Report

Group finished school subject INGT2300, and could no focus on thesis until spring break. The group started and finished poster presentation for next week. Kept on coding and looking for solution for markerbased motion capture.

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	8,0
Camera Management/Recording	Final delivery	8,0
Presentation including preparation	Uncategorized	3,0
Team meetings with supervisor	Uncategorized	1,0
Week 9		**20,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	8,0
Camera Management/Recording	Final delivery	8,0
Presentation including preparation	Uncategorized	3,0
Team meetings with supervisor	Uncategorized	1,0
Week 9		**20,0**

Weekly Status Report

During the meeting with supervisor the group got access to Qualisys and chose that as their solution for marker-based system. The group started on recording to get a feel of the program and the markerplacement. The group finished the presentation

Timesheet

Timesheet		Tomas Beranek
Activity	Category	Duration (hours)
Week 10		0,0

Timesheet		Stian Lyng Stræte
Activity	Category	Duration (hours)
Week 10		0,0

Weekly Status Report

No work was done on thesis, due to spring break

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	7,0
Coding	Final delivery	8,0
Camera Management/Recording	Final delivery	8,0
Coding	Final delivery	8,0
Week 10		**31,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	7,0
Coding	Final delivery	8,0
Camera Management/Recording	Final delivery	8,0
Coding	Final delivery	8,0
Coding	Final delivery	7,0
Week 10		**38,0**

Weekly Status Report

The group finished their recordings, and started to connect all part together, OpenPose Qualisys and pose2sim/opensim.

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	7,0
Coding	Final delivery	7,0
Coding	Final delivery	8,0
Coding	Final delivery	7,0
Coding	Final delivery	7,0
Week 10		**36,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Coding	Final delivery	7,0
Coding	Final delivery	7,0
Coding	Final delivery	8,0
Coding	Final delivery	7,0
Coding	Final delivery	7,0
Week 10		**36,0**

Weekly Status Report

The group only need to fix problems with qualisys and openpose not aligning in axes and coordinate rotations. The group managed to connect both openpose and qualisys to pose2sim and opensim. At the end of the week the group managed to connect all and finished the code.

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	7,0
Project reporting	Documentation	7,0
Project reporting	Documentation	8,0
Project reporting	Documentation	10,0
Project reporting	Documentation	10,0
Week 10		**42,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	7,0
Project reporting	Documentation	7,0
Project reporting	Documentation	8,0
Project reporting	Documentation	10,0
Project reporting	Documentation	10,0
Week 10		**42,0**

Weekly Status Report

The starten on the theory chapter of the thesis, while still

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	9,0
Project reporting	Documentation	9,0
Project reporting	Documentation	7,5
Project reporting	Documentation	8,0
Project reporting	Documentation	8,0
Team meetings with supervisor	Uncategorized	1,5
Week 10		**43,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	9,0
Project reporting	Documentation	9,0
Project reporting	Documentation	7,5
Project reporting	Documentation	9,0
Project reporting	Documentation	7,0
Team meetings with supervisor	Uncategorized	1,5
Week 10		**43,0**

Weekly Status Report

The group sent their finished theory to supervisor for evaluation, and showed the results from the analysis. The group started on methods chapter.

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	9,0
Project reporting	Documentation	8,0
Project reporting	Documentation	10,0
Project reporting	Documentation	9,0
Project reporting	Documentation	5,0
Project reporting	Documentation	5,0
Week 10		**46,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	9,0
Project reporting	Documentation	8,0
Project reporting	Documentation	10,0
Project reporting	Documentation	9,0
Project reporting	Documentation	5,0
Project reporting	Documentation	5,0
Week 10		**46,0**

Weekly Status Report

The group finished the method chapter, and chanegd the theory chapter based on the suggestions from sueprvisor. The group started on resultchapter and discussion

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	8,0
Project reporting	Documentation	8,0
Project reporting	Documentation	9,0
Project reporting	Documentation	9,0
Project reporting	Documentation	8,0
Project reporting	Documentation	7,0
Team meetings with supervisor	Uncategorized	1,0
Week 10		**50,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	8,0
Project reporting	Documentation	8,0
Project reporting	Documentation	9,0
Project reporting	Documentation	9,0
Project reporting	Documentation	8,0
Project reporting	Documentation	7,0
Team meetings with supervisor	Uncategorized	1,0
Week 10		**50,0**

Weekly Status Report

The group finsihed result and discussion chapter, and started on conclusion and social impacts. The group sent their updated thesis to supervisor for review. Changes were made acording to what was said during the meeting.

Timesheet

Timesheet		Tomas Beranek	
Activity	**Category**	**Duration (hours)**	
Project reporting	Documentation	7,5	
Project reporting	Documentation	8,0	
Project reporting	Documentation	7,0	
Project reporting	Documentation	8,0	
Project reporting	Documentation	8,0	
Project reporting	Documentation	8,0	
Project reporting	Documentation	7,0	
Team meetings with supervisor	Uncategorized	0,5	
Team meetings with supervisor	Uncategorized	0,3	unofficial
Week 10		**54,3**	

Timesheet		Stian Lyng Stræte	
Activity	**Category**	**Duration (hours)**	
Project reporting	Documentation	7,5	
Project reporting	Documentation	8,0	
Project reporting	Documentation	7,0	
Project reporting	Documentation	8,0	
Project reporting	Documentation	8,0	
Project reporting	Documentation	8,0	
Project reporting	Documentation	7,0	
Team meetings with supervisor	Uncategorized	0,5	
Team meetings with supervisor	Uncategorized	0,3	unofficial
Week 10		**54,3**	

Weekly Status Report

The grup finsihed their first draft and send it to the supervisor. The group finished neccesary attachments for the thesis. Changes were maed on thesis according to the feedback from supervisor. The thesis was finished, and the group started to reading through for spellingerrors and propper grammer. Often with the use of chatGPT

Timesheet

Timesheet		Tomas Beranek
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	8,0
Week 10		**8,0**

Timesheet		Stian Lyng Stræte
Activity	**Category**	**Duration (hours)**
Project reporting	Documentation	8,0
Week 10		**8,0**

Weekly Status Report

The group wrote the self-reflection and read through the main report one final time. The group finished the project and a thesis work.

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