Kinematic Calibration of PhantomX Pincher Robot Arm

Project Report

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Contents

1 Introduction

Kinematic Calibration of Robots is a technique used to improve the repeatability and accuracy of a robotic manipulator. It is the fine tuning of a robot's mathematical model in order to match its real world behaviour. A robot's mathematical model is the relationship between a robot's joint configurations and the position and orientation of its end-effector.

Forward kinematics is the calculation of the end-effector's position and orientation given a set of joint configurations while inverse kinematics is the calculation of the joint angles required to reach a certain orientation and position in space.

However, after a certain period of time, the accuracy of the mathematical model is affected which in turn affects the repeatability and accuracy of the robotic manipulator. This is because the model is not only dependent upon the joint angles which are variables but also constants known as kinematic parameters which are based on the fixed geometry of the robot arm. Overtime, the values of these fixed kinematic parameters fluctuate which in turn affects the accuracy of the model.

The purpose of kinematic calibration is to use a set of points in space and the set of joint configurations corresponding to those points which can help determine the values of kinematic parameters that minimises the error due to the difference between the actual behaviour of the manipulator and the predictions made by the kinematic model.

Although there have been extensive studies on different methods of kinematic calibration, a comprehensive investigation to evaluate the most optimum method has not been conducted yet and the wider aim of our research is devoted towards that aspect. Our ultimate aim is to find out a most optimum approach in terms of accuracy and cost which can be incorporated in the Spring 2024 offering of this course.

2 Literature Review

2.1 Datasheet for the PhantomX Pincher

The datasheet for the PhantomX Pincher arm robot is a fundamental resource guiding our project. It provides an overview of the robot's technical specifications, including physical dimensions, joint arrangements, motor details, and movement range. By consulting the datasheet, we gain insights into the robot's kinematic structure, enabling accurate modelling and movement analysis. We can validate joint angle ranges, coordinate system conventions, and identify potential mechanical errors. This reference provides a strong foundation for our calibration work, ensuring precise and reliable robot movements within its operational range[1], [2].

Importance:

This source is important because it gives us the basic details about the PhantomX Pincher arm robot. The datasheet is like the first step in understanding how the robot's parts move, like its joints and how far it can go. Using it helps us make sure that when we change things, we do it right according to how the robot was designed.

2.2 ISO 9283-1998-1

ISO 9283-1998-1 is a global standard dedicated to fine-tuning industrial robots, especially their movement parameters. This standard provides clear methods for measuring and enhancing how the robot moves to ensure better accuracy and repetition. Its significance lies in its role as a recognized guide for calibration practices. Adhering to this standard aligns our calibration approach with industry norms, guaranteeing systematic and thorough calibration that leads to dependable robot performance. The standard addresses key aspects such as joint movement measurement, component length adjustment, and movement parameter optimization, directly relevant to our project's aim of enhancing the precision of the PhantomX Pincher arm's motion[3].

Importance:

This source is super important for our calibration work as ISO 9283-1998-1 is the standard everyone follows to make sure robots move accurately. It guarantees that our robot works consistently and well. If we follow the steps in the standard, we can use the suggested experiment methods and get the PhantomX Pincher arm robot calibrated correctly.

2.3 Course Material from Lab and Lecture of 'Introduction to Robotics'

The 'Introduction to Robotics' lecture and lab material such as lecture slides and lab handbook etc was crucial for building a foundational understanding of robotics, covering aspects like robot movement and kinematics. Since Zaryan and Asad have not taken the course 'Introduction to Robotics' yet, Dr. Basit gave them a few lectures to get acquainted with the course material and then bridge the theory with real-world practice by working on the project. By engaging with these materials, they developed the basic theoretical grounding in understanding robot movements and calibration processes. I have taken the course lecture and lab both and as we approached the calibration of the PhantomX Pincher arm, I was able to apply the theoretical knowledge gained in class to practical scenarios, ensuring that our calibration efforts are well-informed and based on the principles of robotics.

Importance:

The class materials give us a strong learning foundation for our project. They help us understand how robot movements work, why calibration is important, and we can also use what we learn from these materials to solve the problems we faced while calibrating effectively.

2.4 Research papers

We extensively reviewed calibration techniques for robotic manipulators, focusing on the PhantomX Pincher Robot Arm. We collected data from ten research papers and organized it using an Excel sheet with columns like

Paper Title, Link to the paper, Kinematic Model, Pose Measurement, Identification Method, and Experimental Results. Our analysis uncovered diverse calibration techniques employed by different researchers. This comprehensive study of various techniques helped us in selecting the approach for our research project. Some of the methods are discussed and summarized below.

Our main source from these papers was "A novel vision-based calibration framework for industrial robotics." This paper forms the core of our project and introduces a novel vision-based calibration method for industrial robots. It uses the Product of Exponential (POE) model to accurately describe the kinematic model and prevent singularities. Pose measurement is conducted using a single camera and Aruco Markers, arranged on a rhombicuboctahedron which is 3D-printed and attached on the robot's end-effector. Aruco Markers enable precise positioning measurement which enhances calibration accuracy. This approach combines the POE model and Aruco Marker-based pose measurement to refine kinematic parameters, demonstrating the potential of vision-based techniques in calibration and improving performance of industrial robotics[4].

In another paper, the method used was laser-based kinematic calibration using differential kinematics. The author employed the standard DH parameter model, adjusting the transformation matrix to accommodate physical errors in the DH parameters. For pose measurement, the structured laser module (SLM) and a camera are used. They set up a screen as the base frame and determine the homogeneous transformation for the two laser frames in relation to the base frame. The camera then measures the position of laser points on the screen. Utilizing geometry and the rotation matrix for the laser frame relative to the base frame, the theoretical position of the laser point on the screen is derived. The errors between the measured and theoretical laser beam positions are represented by the Jacobian matrix. To estimate the kinematic parameters of the model, the Extended Kalman filter is employed. This approach demonstrates the innovative use of lasers, cameras, and mathematical tools for precise kinematic calibration[5].

In a paper titled "Online Robot Calibration Based on Hybrid Sensors Using Kalman Filters," the authors applied DH parameters to model their robot's movements and measured the robot's pose using an IMU (Inertial Measurement Unit) and a position sensor. The IMU provided information about the end effector's orientation, while the position sensor gave the position details. With these measured poses, the Kalman Filter, a mathematical tool, was employed to estimate precise poses. This approach involves combining information from multiple sensors and using the Kalman Filter to refine and improve the accuracy of the robot's poses[6].

Another interesting approach was the use of drawstring displacement sensors to calibrate the robot. The authors use the modified DH parameters (MDH model), which helps calculate the theoretical end-effector position of the robot while the actual end-effector position is measured using four drawstring displacement sensors. Deviations are identified by comparing the desired position, the robot's error model, and actual measurements through a least-squares method. These deviations in kinematic parameters are then corrected using the Cartesian space compensation method to enhance the robot's absolute positioning accuracy. To validate the approach, the authors conducted experiments using a six-joint industrial robot. They pinpointed 50 locations within the workspace. The calibration process effectively reduced errors, leading to significantly improved accuracy in end-effector positioning[7].

In another research paper, the authors use an approach called "Autonomous Visual Measurement" for robot calibration. This method relies on cameras to calibrate the robot's movements. The camera is placed at the robot's tip and its intrinsic parameters are not identified. However, the authors tackle the problem of distortion in the camera's lens that could affect certain calculations. The authors suggest a way to control the robot's positions so that a specific point stays in the camera's view. They achieve this without needing to calibrate the camera itself by proposing a clever algorithm that improves how the robot's positions are automatically measured. This algorithm considers the robot's structure and how accurate the measurements need to be. They also use a method where the robot's movement is guided by what the camera sees which ensures that the robot's motion matches a target image, making the measurements very accurate. This approach simplifies calibration using visual cues and automatic adjustments[8].

The paper 'Kinematic Calibration and Geometrical Parameter Identification for Robots' presents an innovative way to calibrate robots. They use DH parameters and add an offset error d_i to improve accuracy and for measuring poses, the authors introduce a new method using a maximum likelihood approach to find errors. They set up a unique experiment to measure errors in the robot's end-effector position. The algorithm can detect both position and orientation errors in the measuring device[9].

In another paper, the authors applied a hybrid identification method for robot calibration using distance data. They used Modified DH parameters to construct the robot's kinematic model, emphasizing relationships between adjacent rotation joints through a homogeneous transformation matrix. For pose measurement, they delved into the connection between end effector motion and kinematic parameters. An error model based on the kinematic structure was developed, using displacement as a reference point. The authors removed redundant parameters through singular value decomposition (SVD). A hybrid approach combining an extended Kalman filter (EKF) and a regularized particle filter (RPF) was adopted to address noise-related problems. The EKF pre-identifies the linearized error model, while identification of kinematic parameters is done through the RPF[10].

Importance:

These research papers help us learn more about calibrating robots in general and showed us different ways that robot arms are calibrated. The papers gave us ideas for how to calibrate the PhantomX Pincher arm and what techniques to use. By using these ideas, we chose a suitable method to calibrate our robot arm.

In simple terms, by using these different sources—the datasheet, the ISO standard, research papers, and class materials—we get a complete way to fine-tune how the robot's parts move. Each source adds something special, like details about the robot, recognized rules, various ways to adjust it, and basic learning. All these sources work together to help us make sure the PhantomX Pincher arm moves exactly how we want it to.

3 Research Methodology

3.1 Phase I:

The initial phase of the research journey began with an extensive literature review of the already existing methods of kinematic calibrations such as vision-based, IMU and drawstring displacement methods and evaluating their accuracy weighed against one another. This phase also consisted of a series of fast-paced lectures on Robot Kinematics to instill the necessary knowledge required to undertake the research for cohort members who had not yet enrolled in the 'Introduction to Robotics' course. Cohort members also visited the Power Lab to familiarize themselves with the functioning of the Phantom X Robot Pincher Arm. Additional skills pertaining to computer vision such as working with the OpenCV library in python were also acquired in this period.

3.2 Phase II:

After a comprehensive literature review, two potential methods of kinematic calibration were shortlisted considering the feasibility of developing the experimental set up needed to conduct them and the time span within which we had to produce results. The experimental set up did not prove to be a very complex endeavour due to the availability of the already mounted Intel RealSense camera in the power lab. Necessary libraries were installed on our computers such as the PyrealSense library on Python to capture frames through the external camera. Pandas, Numpy and OpenCV were other necessary libraries that were installed as well. Modification to the structure of the Robot Arm was also required in order to install the 3D structure with markers intact. This was done by dismantling the gripper at the last joint of the robot arm and developing a slit-like structure that could be attached on it with screws. The 3-D structure was also printed as such that it had a mechanism that allowed it to slide into the slit which made it easily detachable. A grid was printed with 10 mm boxes for reference which covered the entire workspace and origins corresponding to both the co-ordinate system of the camera and the robot were marked on the grid.

3.3 Phase III:

In this stage, the task primarily entailed developing the code for the pipeline. This pipeline is responsible for obtaining measurements from the experimental arrangement and applying the designated identification algorithm to gauge the parameters of the kinematic model. The implementation is planned to be carried out using MATLAB and is a pending task up until the writing of this portion of the research report. The criteria for the selection of points was employed from a standard of instructions named ISO at the discretion of the supervisor. [11]

4 Design Details

The research design aimed at calibrating the PhantomX pincher robot arm, therefore the positional and orientation data of the end effector was to be measured accurately. After comparison between different measurement techniques covered in the literature review, a computer vision method was selected. With the IntelRealSense SR-305 installed along with the robotic arm, computer vision was a relatively easier, accurate and precise method.

Adopting the techniques used in one of the papers[4] fiducial markers were used to detect the position of the end effector. The fiducial markers used were the Aruco Markers, which are 2D-encoded fiducial markers. Using OpenCV [12] the position and the pose of the marker was detected.

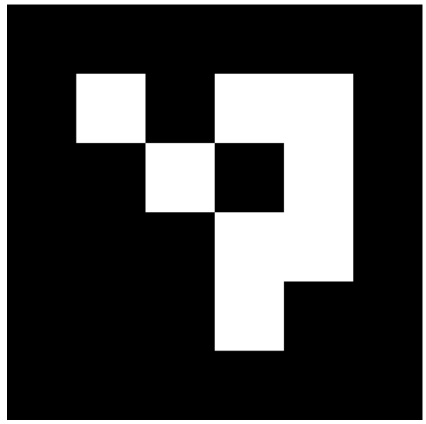

Figure 1: ID 0 Marker

The algorithm used to detect and estimate the pose of the aruco marker was written in Python. Using PyrealSense library the frames from the IntelRealSense depth camera were captured. For the scope of our project, the IR camera frames were not required therefore it was set off. The RGB frames captured were converted to grayscale for further processing. The markers were detected from the frame.

4.1 Marker Detection

The grayframe image is analysed to identify square shape patterns in the image. The image is segmented using the adaptive thresholding. The contours are extracted from the thresholded image and the contours that do not approximate to a square size or are not convex are discarded. The results are further refined by removing contours that are too small or too big, or contours that are too close to each other.

In order to verify that they are markers, the inner codification of the detected squares was analysed. For this the marker bits of each of the markers were extracted. In order to do it, perspective transformation is applied to get the marker in its canonical form. The canonical image is thresholded using the Otsu's Method, white and black bits are separated. In accordance with the size of the border and the markers, the image is divided into several cells. Then, to establish if a cell contains a white or a black bit, the number of black or white pixels in each cell is tallied. The bits are finally examined to establish whether the marker belongs to the particular dictionary. Techniques for correcting errors are used as necessary.

This procedure was applied using the OpenCV library in Python[13].

4.2 Pose Estimation

For the pose estimation, the camera has to be calibrated and it's parameters should be known. IntelRealSense SR-305 is already calibrated and therefore the camera parameters can be extracted using IntelRealSense SDK 2.0. Using this library, the extrinsic and intrinsic parameters of the camera were determined through a Matlab wrapper. The parameters determined were focal length, principal point and the distortion coefficients. These parameters are used in the form of a 3x3 camera matrix and 5x1 distortion coeffient vector.

After the determination of the camera parameters, the pose is estimated using the Perspective-n-Point algorithm. Using this algorithm, the pose is computed using the known correspondence between the 3D-points and their 2D projections on the image plane. The figure below shows this correspondence.

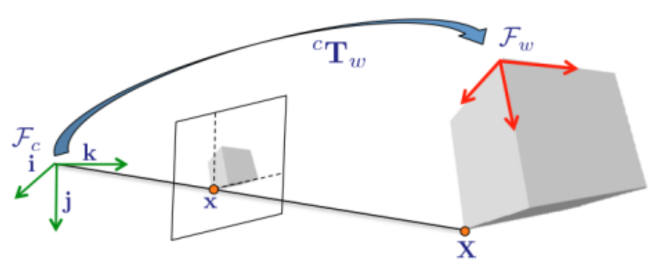

Figure 2: Rigid transformation ${}^{\mathrm{C}}\mathrm{T}_{\mathrm{W}}$ between world frame F_w and camera frame F_c and perspective projection.[14]

F_c is the camera frame and F_w is the world frame. x are the coordinates of the projected point pixels on the image plane. X is the 3D-point in the world frame.${}^{\mathrm{C}}\mathrm{T}_{\mathrm{W}}$ is the homogeneous transformation between the world frame and the camera frame with respect to the camera frame. A homogeneous transformation is a 4x4 matrix representing the rotation and translation required to align the world frame with the camera frame.

The main interest is then to find out this homogeneous transformation matrix to extract the rotation matrix and translation vector in order to compute the pose of the marker. Mathematically, it is achieved through the solution of an inverse problem. The following equation expresses the point x expressed in pixels, the projection of the 3D point${}^{\mathrm{W}}\mathrm{X}$ expressed in the world frame in the image plane.

$$x = K \prod {}^{\mathrm{C}}\mathrm{T}_{\mathrm{W}} \, {}^{\mathrm{W}}\mathrm{X}. \tag{1}$$

In the above equation, K is the camera's intrinsic parameters obtained through the camera calibration output as mentioned above. K is a 3x3 matrix and has four parameters. These four paramters include horizontal and vertical focal lenghts, co-ordinates of the principal point. The matrix representing K is given below

$$K = \begin{bmatrix} \mathrm{f}_x & 0 & \mathrm{c}_x \\ 0 & \mathrm{f}_y & \mathrm{c}_y \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

In the above matrix, f_x and f_y are the horizontal and vertical focal length respectively.c_x and c_y are the principal point co-ordinates expressed in pixels. $\prod$ is the projection matrix for the perspective projection model and is given by the following matrix

$$\prod = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{3}$$

${}^{\mathrm{C}}\mathrm{T}_{\mathrm{W}}$ is the homogeneous transformation between the camera and world frame with respect to the camera frame.

Using N points, a set of equations is formed from the above mentioned equation, and the system of equation is solved for the ${}^{\mathrm{C}}\mathrm{T}_{\mathrm{W}}$. Then using this result the rotation matrix and the translation vector is extracted and used for the pose estimation[14].

4.3 End Effector Design

The IntelRealSense camera is mounted directly above the robotic arm. Due to the small size of the end effector and the constraint to be visible to the camera for every pose, the marker could not be pasted on the arm. To cater this difficulty, a 3D-structure, rhombicuboctahedron, was printed and mounted on to the end effector. The structure is shown below

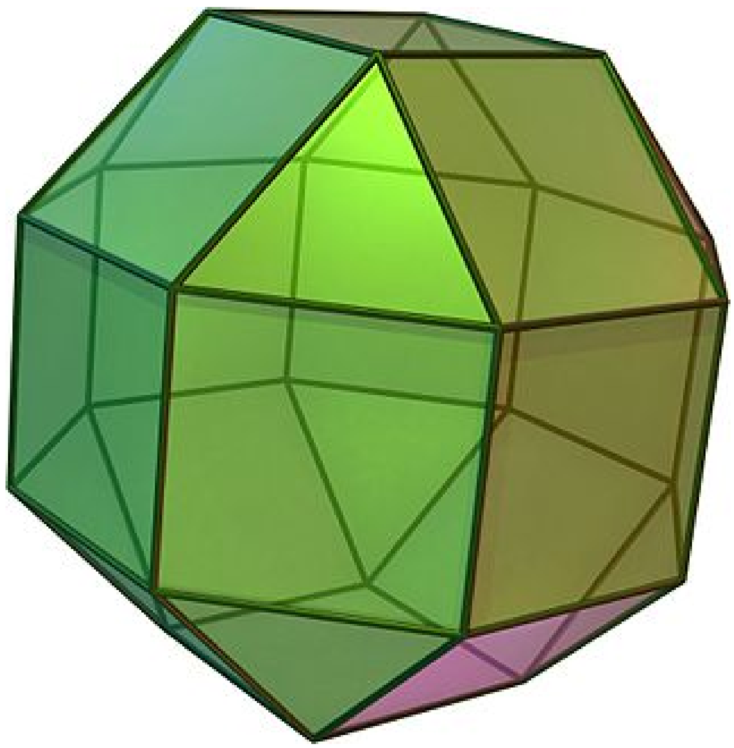

Figure 3: Rhombicuboctahedron, a shape with 18 squares and 8 isosceles triangles[15].

The structure was printed using a 3D-printer and designed such that the square and isosceles triangles have a dimension of 25mm. The size constraint was placed due to the maximum mass limit of 250g for the servo motors in the robot arm[2].

The gripper of the PhantomX Pincher Robot Arm underwent disassembly, with the subsequent attachment of the above structure in it's place using screws. This adjustment in robot's structure was prompted by the specific intent of ensuring that, for any given pose of the robot, a minimum of four squares remains within the camera's field of view. This configuration facilitates the detection of markers and the accurate estimation of camera poses for every conceivable configuration[4].

5 Results and Findings

5.1 Phase I

The Phase 1 was aimed towards developing a Computer Vision method of finding the pose of the end effector. For this purpose, we developed and tested Aruco-Marker detection and pose estimation algorithm. During the initial testing of the algorithm we detected aruco markers of various sizes and compared their results with external measurements made using metre rule and IntelRealSense Depth Measurement Tool.

The following figure shows the positional data results achieved for various marker sizes.

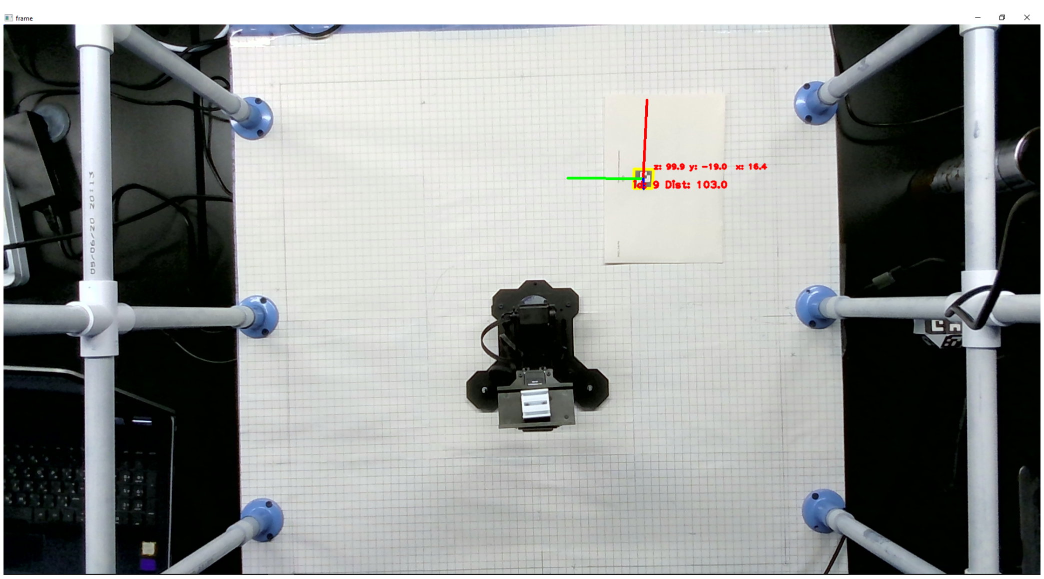

Figure 4: 25mm Marker size

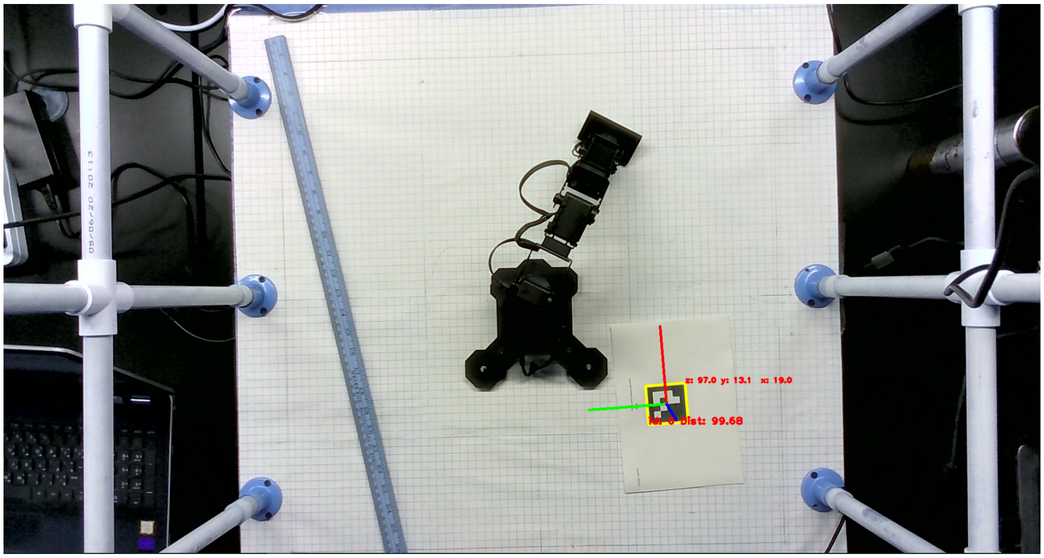

Figure 5: 50mm Marker size

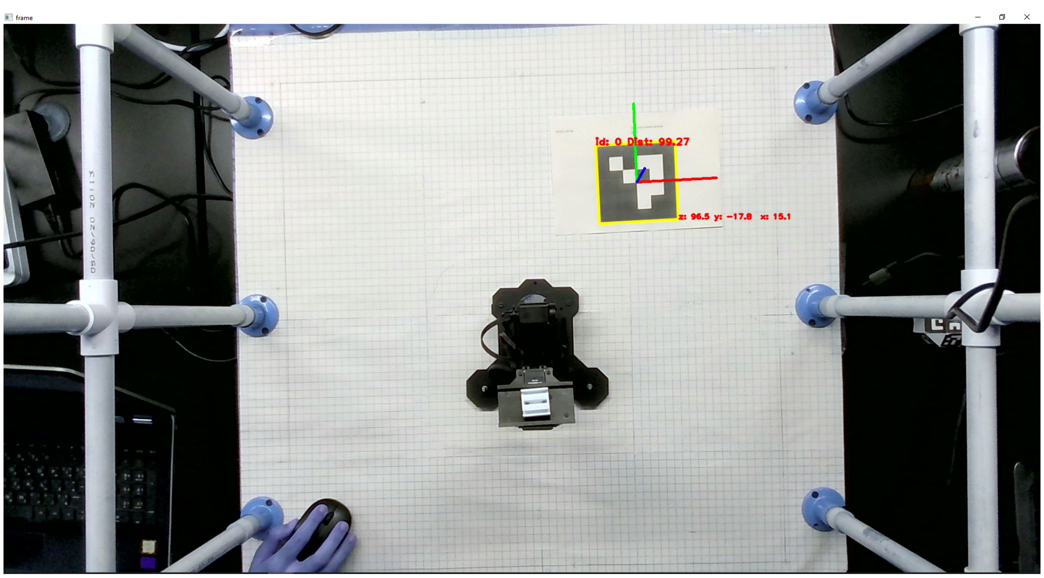

Figure 6: 100mm Marker size

Figure 7: Depth Measurement using the IntelRealSense Viewer

The measurements were compared with the depth measurements from IntelRealSense viewer and metre rule measurements made from the center of the camera projected on the grid. The 25mm marker gave the most precise and accurate depth measurement which aligned with our constraint on the size of the rhombicuoctahedron as mentioned in the End Effector Design section.

5.2 Phase 2

During the phase 2. the end effector structure was developed to be mounted in the place of the gripper. As a result we came up with the structure mentioned in the End Effector Design. The aruco markers of lenght 25mm were pasted on the square sides of the rhombicuboctahedron. The computer vision algorithm gave us the pose of the aruco marker with respect to the camera frame.

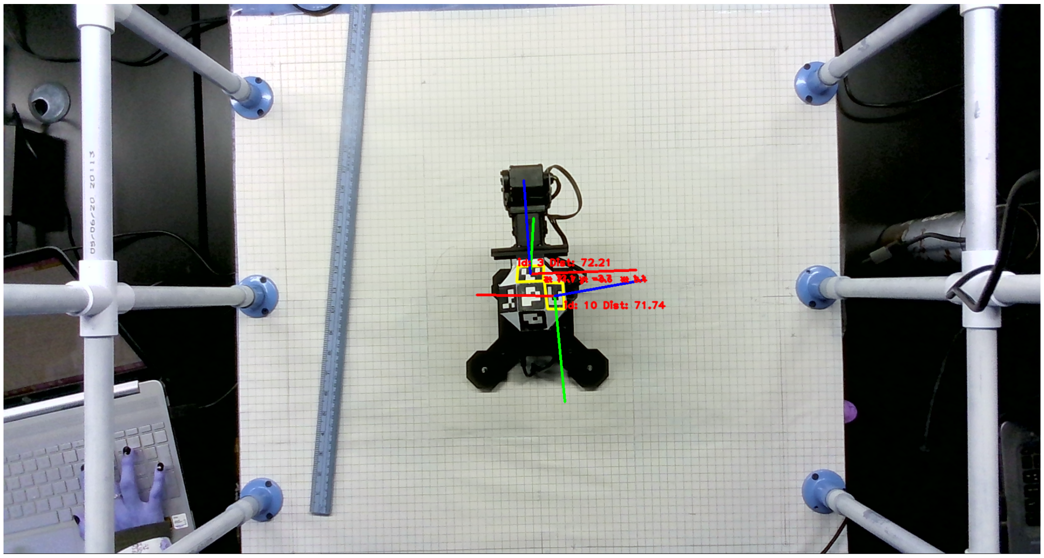

Figure 8: Pose 1

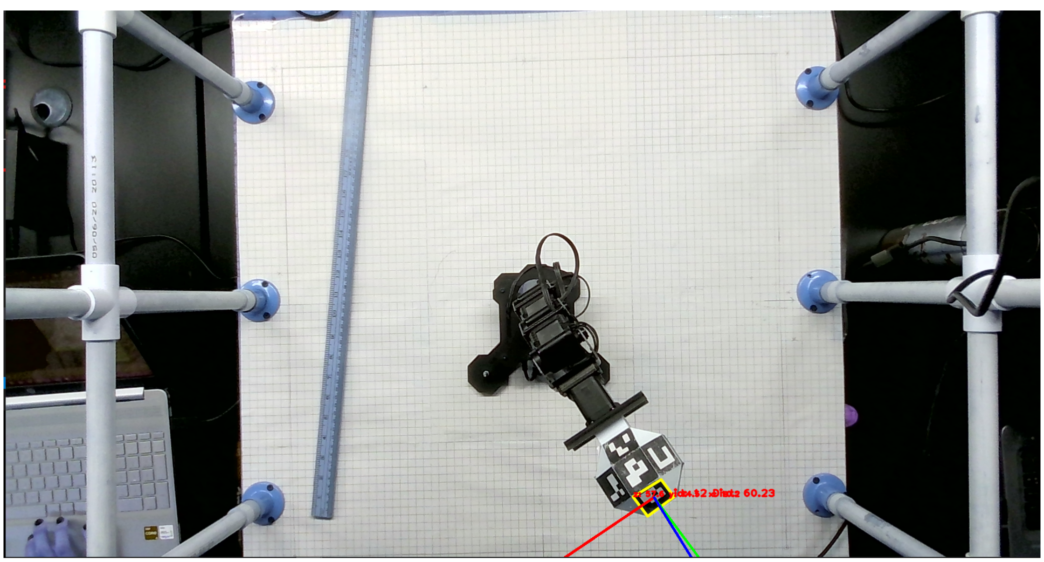

Figure 9: Pose 2

Using homogenous transformation, the co-ordinates of the center of the detected aruco marker was expessed with respect to the base frame. The aim is to get the position of the TCP(end effector center position) from the measured position of the aruco marker. It was to be achieved in Phase 3.

5.3 Phase 3

However, the experimental procedure encountered significant setbacks stemming from hardware challenges, conceptual intricacies, and unforeseen time delays arising from the 3D-printing process. Consequently, the intended timeline was disrupted, leading to a postponement in attaining the conclusive outcomes. As of now, the final results remain pending.

Upon the successful completion of the ongoing experiment, the essential dataset necessary for the optimization of kinematic parameters will become accessible. Subsequently, a meticulous comparative analysis will ensue, the performance of the robotic arm prior to and subsequent to the calibration procedure will be compared and reported as accuracy and precision metrics.

Ultimately, the culmination of this research endeavor will culminate in the integration of the final outcomes into the comprehensive report.

6 Conclusion

Choosing a rhombicuboctahedron, a convex polyhedral with thirteen squares and four isosceles triangles, as the shape used for the 3D structure to be mounted upon the end-effector of the robot was a clever choice as it allowed at least four ARUCO markers to be detected at any given pose of the robot arm. To ensure the stationary behaviour of the intel RealSense camera mounted on a PVC pipe structure above the robot arm, we procured Jubilee clips which solved our problem to an extent.

However, to stop the revolutionary movement around the PVC pipe, we had no other choice but to stick the ends of the camera to the pipe with the assistance of play dough. Expanding more upon limitations, I would like to highlight that the movement of the robot arm through MATLAB as well as calculation of inverse and forward kinematics and detection of markers through OpenCV on Python proved to be cumbersome and added some delay to the experimental procedure which although was not detrimental to the accuracy of the calibration procedure itself it did significantly extend the duration of the overall calibration process.

A better alternative would have been to code the script used to control the movement of the Robot in Python itself. However, the absence of the desired API meant that the entire process would have to be repeated in a different language which was not feasible due to the time constraint of the research project. Our current calibration procedure took solely positional accuracy into account. Although we embarked on incorporating orientational accuracy at a point, we were instructed to put a pin on that endeavour by the supervisor owing to the difficulty of working with Inertial Measurement Unit Sensors.

However, we do understand that orientational data is crucial for a complete understanding of robotic systems and their control. Hence, the long term aim of our project is to address and resolve the issues associated with the mounting and functioning of IMU sensors and develop a more comprehensive calibration approach that integrates orientational accuracy along with positional accuracy through an effective way of measuring and calibrating orientational parameters. This aligns with our aim of refining the calibration process to minimize the deviation between the predicted and actual behaviour of robotic systems.

7 Group Member Reflections

7.1 Asad Muhammad

For me this research was a tremendous opportunity to expand my array of skills through learning the necessary to conduct different experiments. The most crucial skill was Computer Vision for which I preferred working with Python as I was already familiar with the language due to my background in Computer Science.

Through this hands-on experience, I not only refined my programming prowess but also cultivated a profound understanding of the underlying principles governing Computer Vision. I grappled with challenges such as image preprocessing, object detection, and image classification, which demanded both theoretical acumen and practical finesse.

A real challenge I encountered was when I had to utilise python's pyrealsense library to capture the video stream from the external camera. This was due to compatibility issues between the Intel RealSense camera and the OpenCV library. Converting the script to capture the video stream through a new library seemed to be a daunting task at first but I was able to achieve this through the problem-solving skills inculcated in me as a Computer Science student.

Apart from that, learning about Robot Kinematics at the beginning of the research was a great opportunity for me to determine the extent of my interest in robotics and help me decide if Introduction to Robotics is a course I should be looking forward to enroll in the future.

7.2 Syeda Manahil Wasti

Firstly, the cool thing about STRP was that we all had to take mandatory CITI program courses which in my opinion was a good thing because it provided a lot of insight and background knowledge of researching, especially human-subject research.

It was fascinating to learn about the different researches/experiments as well. Also, it was nice to learn about making good research posters and the project also helped me in getting acquainted with noting meeting minutes.

Our project was to develop a cost-friendly and effective kinematic calibration setup for Phantom X Pincher arm, to be utilized in the Introduction to Robotics course lab at Habib University and as I had already taken the lecture and lab before this project, it was interesting and fun to work on it and apply all the theory and skills we learned in the course itself.

However, learning about the ISO standards and different ways of kinematic calibration was new to me as it is not covered in the course material.

During the project I worked mainly on MATLAB and did a lot of debugging which increased my experience and knowledge about the arm and its built-in functions included in the MATLAB toolbox.

The project itself was demanding and we faced a lot of errors especially during the 3D printing part due to the printer not working mostly. But getting results after spending hours solving an error was quite a rewarding experience as well. Overall it was a nice experience spending my summer on this project. Hopefully the robot arm can be calibrated so that students in the next offering of the course do not face issues regarding accuracy when performing lab tasks.

7.3 Zaryan Ahmed Siddiqui

The concept of research used to feel overwhelming and complex to me, but my perspective underwent a profound transformation during my involvement with STRP. This experience illuminated the true essence of research, revealing that it demands more than just the ability to comprehend diverse concepts – it necessitates unwavering perseverance and patience.

My engagement revolved around a hobby robotic arm, which presented a unique challenge as there were no existing research papers available for its calibration. Amidst the array of techniques for pose estimation – such as CMMs, theodolites, and laser trackers – elaborated and implemented in various research papers focusing on the kinematic calibration of industrial manipulators, I discovered that these methods were not only expensive but also unsuitable for the scope of our project.

As a result, I was compelled to explore other alternatives. Computer vision, which was uncharted territory, emerged as the novel and feasible approach for pose measurement. It was difficult for me as I lacked any previous experience with it, and efforts were required to learn the basics of it.

In addition to delving into computer vision, I embarked on a sensor fusion approach incorporating the Inertial Measurement Unit (IMU). The IMU, a 6-DOF system, comprises a trio of axes encompassing gyroscope and accelerometer measurements. The concept of sensor fusion entailed amalgamating data from both the gyroscope and accelerometer, harnessed through a Kalman Filter, to derive yaw, pitch, and roll values for the end effector.

While the Kalman Filter adeptly mitigated noise in the dataset, a pivotal challenge surfaced concerning the optimal mounting of the sensor onto the end effector. Regrettably, due to time constraints, the pursuit of this method was curtailed, leading to a redirection of efforts toward the advancement of computer vision methodologies.

Yet, these trials and the immersive research journey bestowed upon me invaluable competencies. I delved deeper into the realms of Computer Vision and Image Processing techniques, developing hands-on proficiency. Furthermore, I garnered a proficiency in Arduino Programming, fostering a newfound comfort with microcontrollers integral to IMU sensor manipulation.

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