Empirical Study of User Tele-operation of 5 DOF Manipulator

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Monica Palla
2018701008
monica.p@research.iiit.ac.in

International Institute of Information Technology
Hyderabad - 500 032, INDIA
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International Institute of Information Technology
Hyderabad, India

CERTIFICATE

It is certified that the work contained in this thesis, titled "**Empirical Study of User Tele-operation of 5 DOF Manipulator**" by **Monica Palla**, has been carried out under my supervision and is not submitted elsewhere for a degree.

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Date	Adviser: Prof. **Kamalakar Karlapalem**

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Abstract

Remote coordination between humans and robots has been of much interest over the past many years. In this thesis, we perform an empirical study regarding the comfort level of users in teleoperating a robotic manipulator to perform operations such as pick and place and stacking. We claim that such daily life operations while easy to perform by humans, are difficult to remotely operate using a manipulator due to their limited sensory perception. The problem is challenging because it requires optimum placement of cameras and an intuitive interface for the user to view and control the manipulator simultaneously. Hence, in our work, instead of limiting the control options, we give users the freedom to choose between controlling the manipulator using Cartesian Control and Joint Control, Joystick interface and also zoom in and out the various camera views for accurate visibility for pick and place and stacking tasks from a remote location.

We validate our results by conducting the user trials on users with age between 21 and 63 from multiple countries. We observe that 71% of the users prefer using Cartesian space as the reference control, 57% feel the need for additional viewpoints for better visibility in first experiment which reduced to 29% in third experiment with different positioning of the same cameras, and more than 90% do not require the data from a distance sensor for guidance.

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Chapter 1

Introduction

Robotic manipulators are used in various industries such as manufacturing, food, and health care to help perform day-to-day activities such as pick and place, and stocking [19] as well as precision tasks. While both automation and teleoperation are the most commonly used modes of operation, partial autonomy is gaining prominence due to human presence in the loop reducing error rate by the manipulator. Tasks such as robotic surgeries require high precision where partial automation is the preferred mode of operation [17].

In India, we wanted to test out if tele-operation can be successful with whatever network and system resources that we have. In that context we conducted within the lab, teleoperation experiments. We got a ready to assemble manipulator, which is generic, integrated and controlled with appropriate software, wrote our own modules for controlling the manipulator remotely to pick static objects and had also planned to extend it for dynamic objects. We also came up with a modified design to increase the DOF from 5 to 6 but then we proceeded with 5 DOF due to payload limit.

A console for Keyboard and Joystick Interface input was developed. In addition, tried Voice commands to instruct the manipulator.

Initially camera calibration techniques were performed to detect the object to be grasped. But in reality, not all the objects possess markers that could help estimate the distance of the object from the gripper, therefore we switched to Ultrasonic sensor for distance calculation to assist in Tele-Operation.

For the initial setup of the tele-operation system, we connected the PS3 cameras for video streaming and hosted this page on a server. For controlling the manipulator through commands, we tried to ssh to the system that is connected to the manipulator. This system was working with a lag of more than 7s from the time the instruction command was given, and the motion of the Robotic arm was executed.

Soon enough covid stuck and the hardware was taken and setup in home to continue the experiments. We had to explore and decide upon the experiment setup that could help us with real time tele-operation and so we experimented and found that zoom software was the best available solution to start with the experiments of teleoperation.

During this phase of Covid, we had to shift to a new city. With finalized hardware and software setup design for the experiments, we began our experiments by initially testing the system and ensured that tele-operation was successfully performed with ease in the new place. We ran several experiments in which we studied the performance using Joint and Cartesian controls and the combination of these for tasks of Pick and Place and Stacking. We noted the latency and other factors in relation to this tele-operation setup and took users feedback to improvise the Tele-Operation system and check which factor impacted the performance of the users. e.g., Camera positions, Ultrasonic Sensor measurement for distance etc.

For initial set of experiments, we could get around 8-9 users from which few resided in India, and few outside the country. They all ranged from age group of 21 to 44. The group consisted of students and working professionals. The second set of experiments was conducted with newer users and were all students and belonged to the age group ranging from 24 to 31. We included a Joystick interface in this experiment. And the third experiment consisted of setup that was improvised based on the feedback from experiment 1 which also included new users from different countries and a mix of students and working professionals.

While performing jobs such as waiting tables at restaurants and stocking in super markets it is intuitive to desire teleoperation and clear visibility as it involves human interaction and creating an aesthetic appeal to a workplace.

We implement a remote manipulator system to help perform such activities and reduce the error rate in this work. The manipulator detects the objects to be grasped and moves to a convenient position for the human to take over. Once the robot moves to the convenient position, the control is handed over to the human to perform precise movements. The semi autonomous architecture helps the manipulator move quickly to the desired location leaving smaller error margin for the human operator.

Though such a semi autonomous system looks very promising, a huge factor deciding the success of an operation is the user interface and the ability to convey the manipulator's view to a remote location. Significant amount of work has been done to improve the perception for the end user. Various views have been facilitated such as placing overhead cameras and generation of a first person view by placing a camera on the manipulator. Other works to improve the control are the use of virtual reality.[2]

To facilitate user control-ability, input formats such as keyboard, mouse, joystick, and haptics are most commonly used. Throughout this thesis we use the keystrokes obtained from the keyboard as user input. Studies have been conducted to observe the impact of camera placement and attaining optimal visibility for the user[12]. However, limited flexibility has been given to the users to select an interface for controlling.

In our study involving 410 grasping operations, we recorded and observed the following from users:

- User affinity towards Joint control and Cartesian control types.
- System visibility given a three camera setup.
- Value of sensor data feedback.

The rest of the thesis is organized as follows: Our results show the robotic manipulation and tele-operation process and the related work in Chapter 2. Next in chapter 3 we detailed about the available robotic manipulators in the market and the reasons behind our choice of manipulator. Followed by Chapter 4.1 we explain the user study conducted to observe control affinity, user reliance on sensor data and importance of camera placement for perfect grasping. In Chapter 4 we will validate our system by conducting user trials for pick and place, and stacking operations on a heterogeneous user group. Finally in Chapter 6 we will explain our findings and results obtained leading to Chapter 7 where we conclude and detail some areas for future work.

Chapter 2

Related Work

The performance of a person controlling a remote manipulator is hugely affected by factors such as: interface types, task types, and interface-task combinations [21]. The ability to properly control a robot also depends on the correlation between performance and satisfaction metrics[14]. The better the understanding of the robot, the easier it is to control it. Therefore, teleoperators draw the attention of many people who want robots that help accomplish daily life activities without disturbing them for instructions. In a study conducted by Neta Ezer Et al. [13], which included 117 older adults (aged 65-86) and 60 younger adults (aged 18-25) showed their willingness to have home robots perform infrequent tasks with minimal human-robot interaction followed by service tasks and least willing to have robots perform interactive tasks with them. For e.g., factor weight based on analysis in their study for infrequent task such as ”Warn me about a danger in my home” was 0.8, where as factor weight for service task such as ”Help me with housework” was 0.52. Teleoperators can act as a bridge between people and robots in these scenarios by taking over the disturbing human-robot interaction.

Our experiments observed users’ performance when using a basic keyboard and terminal interface, as detailed in following chapters. A three camera setup that displays all the views of the the manipulator and objects was used. A clear perception of the setup plays a prominent role according to V. Lumelsky [10]. Lumelsky finds that adequate input information such as fixed or moving TV monitors looking at the scene from different directions, force sensors, and a high quality master-slave system that allows translation of commands are necessary but not sufficient to accomplish a real-time teleoperation as the difficulties arise due to inadequate commands given by the operator.

We find interest in applications such as cleaning windows, ceilings and walls, moving heavy things, and wiping surfaces. In a survey by Lorenzo Blasi Et al. [9] elderly people and professional caregivers wanted a robot to perform such tasks. With these applications in mind we explored the difficulties that arise in pick and place, and stacking operation when performed remotely and in real-time. We further discussed our approach and methodology in the next section.

2.1 Surveys on Comparison between Joint & Cartesian Control

In work by Majewicz [11], the authors sought to figure out the best teleoperation approach for non-holonomic systems. With the example case of steering needles used in clinical procedures, they conducted a study to understand the most preferred space of operation by users. In the study, a simulated clinical environment was presented to the users to control a surgical needle. The experiment was evaluated using following metrics,

1. The norm of the position error between needle and target, at the end of the trial.

2. The time to reach the target.

3. The normalized insertion length (needle path length divided by a straight line to the target.)

4. Standard deviation of needle speed, as a measure of the smoothness of the needle path.
   These metrics are task performance specific metrics. For Cartesian space teleoperation, two additional metrics were considered:

   (a) The average tracking error between the user and the needle during insertion, as a measure of the needle lag.

   (b) The trajectory correlation between the user trajectory and the needle path, as a comparison of needle shape to the user desired trajectory.
   Additionally, users were asked to qualitatively rate the difficulty of completing the task with each teleoperation algorithm from not difficult (1) to very difficult (5).

Their work compared teleoperations in Joint space control, Cartesian space control and Cartesian space control combined with force feedback. According to them, Cartesian control with force feedback gave the least error in terms of difference between the destination and final position of the needle. They have also mentioned that though Cartesian space control clearly improves several performance metrics for steering virtual needles, several users preferred joint space control due to a perception of increased needle control.

Thus, the question arises regarding the user's perceived level of control over system behaviours versus objective measures of performance in teleoperation control. We also have encountered these in our work, as elaborated in the results chapter.

In another user study conducted by Wang[23], the authors evaluated the teleoperation of surgical needles using three kinds of metrics based on physiological, kinematic and task specific metrics. They measured the physiological responses such as Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration by measuring various bodily responses like muscular activation's, heart rate, EEG and skin conductance levels. Their basic comparisons were made between four systems, namely the Cartesian, joint space, steering control and Cartesian with force feedback.

Whereas our performance evaluation metrics are:

1. Usability of the remote system. Successful real-time teleoperation using the keyboard interface.

2. Measures of average time and standard deviation of operations to compare the adaptability towards the interface and the control types for both pick and place, and stacking.

3. Comfort level of the user in various aspects like terminal interface, camera views, control type preference etc obtained from user feedback to compare users preference with actual performance metrics.

Our work is more related to picking and placing and stacking remote objects, which are service-based applications. In contrast, work presented by Majewicz[11] and Wang[23] are on insertion needles belonging to medical applications. Further, the differences in methodology, results and other factors are mentioned in the following table.

2.2 Suggested Literature Review

In [3] paper, their focus is on problems related to time-varying communication delay in force reflecting bilateral teleoperation. Our work varies with their focus of research as we were more concerned with the usability of the teleoperation setup we built and we used zoom software to deal with the communication aspect for input and visual feedback. Also, our experiments are not related to force reflecting bilateral teleoperation as there was no force related feedback that was shared with the users for teleoperation.

In [5] paper, a novel control scheme is proposed to guarantee position and force tracking in nonlinear teleoperation systems subject to varying communication delays. Stability and tracking performance of the teleoperation system are proved using a proposed Lyapunov–Krasovskii functional. Whereas in our work we are interested in the usability of the system with minimum requirements in performing teleoperations of pick and place and stacking and relatively less concerned with the stability and tracking performance for achieving the same. We assume that manipulator control, handels these issues.

In [6], they focus on the control theoretic approaches to address inherent control problems such as delays and information loss. As we outsourced the communication aspect to zoom platform, an external software, which deals with the delays and information loss, we could focus more on user performance and their feedback on the usability/interface of the system.

In this paper [4] addresses the problem of steady-state position and force tracking in bilateral teleoperation. Position drift due to data loss and offset of initial conditions is a well-known problem in these types of systems. In this paper, they introduce a new architecture, which builds upon the traditional passivity-based configuration by using additional position control on both the master and slave robots, to solve the steady-state position and force-tracking problem. Lyapunov stability methods are used to establish the range of the position control gains on the master and slave sides. Whereas in our work, the focus is completely on the usability of the system and performance of successful teleoperation on 5 dof manipulator. The focus is also made on user data and feedback on performance, ease of use during such teleoperations.

Their work [22] revolves around the stability of the system achieved through contraction theory and a simplified wave variable design. Whereas in our research, we are focusing on the interface types and their usability for teleoperation tasks and we collected users feedback for the same and analyzed their performance. It is comparatively more concerned with users performance over stabilizing the system using any particular theory or design. We assume that manipulator control, handles the stability issues.

This work [7] presents a solution to maintain stability in a force-reflecting bilateral teleoperator in the presence of substantial time delay. An adaptation law is employed locally to learn and compensate for uncertain parameters associated with the gravity loading vector of the master and slave manipulators. Lyapunov-Krasovskii functions are employed to derive stability and tracking properties of the position, velocity, and synchronizing error of the master and slave manipulator. Our work majorly varies as it does not involve a master and slave setup. In addition, no force feedback is provided to the operator and therefore no information regarding contact force is shared from slave to master.

This work [18] is about a filter being used for smooth approximation of the possible loss in a data communication channel thereby guaranteeing the stability of the system. As mentioned before, zoom was used for communication. Any operations such as handling data loss, filter application etc were handled internally within the zoom letting us focus on getting users to teleoperate and their feedback on basic setup. Also these experiments involved some tracking mechanism (force feedback like haptics etc) but we haven't used any such mechanism for sensing the force or tracking the manipulator/arm in our experiments. We kept our user system simple and the user end did not have haptic feedback.

This paper [15] describes experiments of Internet modeling and of Internet-based teleoperation aimed at developing control laws to overcome the variable time-delay and data losses typical of Internet communication. From a control perspective, the Internet is shown to be characterized by mean and jitter of the data packet delay, and by packet losses. The effects of packet delay jitter and losses on teleoperation performance are demonstrated using a 2-dof force feedback teleoperation master. In our work, since we are relying on zoom software, the data loss packet, the aspects of packet loss and the network are handled internally by this software and thereby letting us focus on other aspects such as interface, user feedback etc related to the experiment.

Their [16] software architecture supports tools for modeling the delay of the computer network that connects the master to the slave thereby designing a stable controller and simulating the performance of a telerobotic system and also testing the control algorithms using a force-reflecting input device. The delay parameters of an internet segment are identified by probing the network and these parameters are used in designing a controller. Our studies involve simple input devices like keyboard, and joystick unlike haptics as used in the above work which involves force feedback. In addition, as the zoom software is managing the communication between the master and the slave by handling the network time-delay and data-losses if any on its own thereby makes our work more user interface centric.

The above mentioned works of literature are related to or around improving the communication aspects in bilateral teleoperation. Since our current focus is on ensuring a working teleoperation system and evaluating users performance for basic operations of pick and place and stacking through control types and interfaces, we relied on an external software called zoom for communication between the teleoperator and the robotic manipulator. As zoom is handling the communication aspects and the network, we did not find the need to handle packet loss and network etc related to communication rather improve the system in terms of interface and collect the feedback from the users related to such teleoperation.

In addition, this experiments were conducted during covid time. In some cases internet was very good and in some cases, the internet was poor. Some people were working professionals and some were students and the usage of computer/system varied from one person to another. We had this natural mix. We didn't have time to do specific survey or have a common platform for selecting the end users as it was covid time leading to unavailability of user participation.

Chapter 3

Design of Tele-Operated 5 DOF Manipulator

3.1 Robotic Manipulator

Robotic manipulators are widely employed in industry and research because they can perform repetitive operations at high rates while maintaining high accuracy. Their precision is significantly superior than that of humans. Because they move in three spatial dimensions and three rotational dimensions, they are more sophisticated than mobile robots. Spot welding and painting are two examples of production processes where they are now commonly used. Manipulator hand (or end-effector) locations and velocities are digitally controlled to fulfil their functions properly and dependably.

The number of degrees of freedom (DOF) is used to classify robotic arms (degrees of freedom). The number of degrees of freedom is usually equal to the number of joints that move the robot arm's links. To allow the robot hand to attain an arbitrary pose (position and orientation) in three-dimensional space, it must have at least six degrees of freedom. Additional degrees of freedom allow the configuration of some arm links (e.g., elbow up/down) to be changed while the robot hand remains in the same pose. Kinematics is the study of body motion without taking into account the forces or moments that cause it. The analytical study of the motion of a robot manipulator is referred to as robot kinematics. For evaluating the behaviour of manipulators, developing appropriate kinematics models for a robot mechanism is critical.

The two central problems of manipulators are Forward kinematics, which asks where the end effector of the arm will be given the angles of rotation for the arm's joints, and Inverse kinematics, which asks what are the rotations of the joints given the end effector position. A rotation matrix whose entries are trigonometric functions of the angle of rotation is used to describe the rotation of a robotic manipulator. After determining the rotation matrix for a planar rotation, an overview of three-dimensional rotations is presented.
From the base frame to the end-effector, a manipulator is made up of serial links that are connected by revolute or prismatic or universal joints.

3.1.1 DH Parameters

The Denavit-Hartenberg technique, which employs four parameters a_{i-1}, α_{i-1}, d_i and θ_i, is the most prevalent way for expressing the robot kinematics model. They reflect the length, twist, offset, and junction angle of the links, respectively. To calculate DH parameters, each joint has a coordinate frame associated to it. The coordinate frame's Z_i axis points in the direction of the joints' rotating or sliding motion. The coordinate frame assignment for a general manipulator is shown in Figure **??**.

Table **??** and figure **??** shows how the DH parameters are assigned between two consecutive joints.

The general transformation matrix from frame i-1 to frame i denoted by ${}^{i-1}_{i}T$ is obtained using the above DH parameters as follows

${}^{i-1}_{i}T = R_x(\alpha_{i-1})D_x(a_{i-1})R_z(\theta_i)Q_i(d_i)$

$$= \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & -c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

[8]

Where R_x and R_z signify rotation around the X and Z axes, respectively, D_x and Q_i imply translation along the X and Z axes, and $c\theta_i$ and $s\theta_i$ are the short hands of $cos\theta_i$ and $sin\theta_i$, respectively. Multiplying all of the ${}^{i-1}_{i}T$ matrices yields the end-effector's forward kinematics with respect to the base frame.

$$ {}^{base}_{end-effector}T = {}^{0}_{1}T {}^{1}_{2}T ... {}^{n-1}_{n}T \quad (3.1)$$

3.1.2 Forward Kinematics

Calculating the position and orientation of the end-effector in terms of the joint variables of each joint is called as forward kinematics. The forward kinematics of the end-effector with respect to the base frame is determined by multiplying all of the ${}^{i-1}_{i}T$ matrices[8] as shown in the above equation 3.1. Consider a Manipulator with 6-DOF as illustrated in Figure **??**. The DH parameters corresponding to this manipulator are shown in Table **??**.

It is straightforward to compute each of the link transformation matrices using equation 3.1 and the final transformation matrix from base frame to end-effector is obtained as follows

$${}^{0}_{6}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where

$$r_{11} = -s\theta_6(c\theta_4 s\theta_1 + c\theta_1 c\theta_2 s\theta_4) - c\theta_6(c\theta_5(s\theta_1 s\theta_4 - c\theta_1 c\theta_2 c\theta_4) + c\theta_1 s\theta_2 s\theta_3)$$
$$r_{12} = s\theta_6(c\theta_5(s\theta_1 s\theta_4 - c\theta_1 c\theta_2 c\theta_4) + c\theta_1 s\theta_2 s\theta_3) - c\theta_6(c\theta_4 s\theta_1 + c\theta_1 c\theta_2 s\theta_4)$$
$$r_{13} = s\theta_5(s\theta_1 s\theta_4 - c\theta_1 c\theta_2 c\theta_4) - c\theta_1 c\theta_5 s\theta_2$$
$$r_{21} = s\theta_6(c\theta_1 c\theta_4 - c\theta_2 s\theta_1 s\theta_4) + c\theta_6(c\theta_5(c\theta_1 s\theta_4 + c\theta_2 c\theta_4 s\theta_1) - s\theta_1 s\theta_2 s\theta_5$$
$$r_{22} = c\theta_6(c\theta_1 c\theta_4 - c\theta_2 s\theta_1 s\theta_4) - s\theta_6(c\theta_5(c\theta_1 s\theta_4 + c\theta_2 c\theta_4 s\theta_1) - s\theta_1 s\theta_2 s\theta_5)$$
$$r_{23} = -s\theta_5(c\theta_1 s\theta_4 + c\theta_2 c\theta_4 s\theta_1) - c\theta_5 s\theta_1 s\theta_2$$
$$r_{31} = c\theta_6(c\theta_2 s\theta_5 + c\theta_4 c\theta_5 s\theta_2) - s\theta_2 s\theta_4 s\theta_6$$
$$r_{32} = -s\theta_6(c\theta_2 s\theta_3 + c\theta_4 c\theta_5 s\theta_2) - c\theta_6 s\theta_2 s\theta_4$$
$$r_{33} = c\theta_2 c\theta_5 - c\theta_4 s\theta_2 s\theta_5$$
$$p_x = d_2 s\theta_1 - d_3 c\theta_1 s\theta_2$$
$$p_y = -d_2 c\theta_1 - d_3 s\theta_1 s\theta_2$$
$$p_z = h_1 + d_3 c\theta_2$$

3.1.3 Inverse Kinematics

In order to control manipulators, inverse kinematics is required. In the real-time control of manipulators, solving the inverse kinematics is computationally intensive and takes a long time. A manipulator's tasks are accomplished in Cartesian space, whereas actuators work in joint space. The orientation matrix and position vector are included in Cartesian space. Joint angles, on the other hand, represent joint space. Inverse kinematics is the challenge of converting the location and orientation of a manipulator end-effector from Cartesian space to joint space. In order to derive the inverse kinematics solution, two methodologies are used: geometric and algebraic.

Few trigonometric equations used in the solution of inverse kinematics problem of the 6-DOF Manipulator in figure **??** are given in Table **??**.

The inverse kinematics problem can be decoupled into inverse position and orientation kinematics. The inboard joint variables (first three joints) can be solved using the position vectors of both sides in equation 3.2.

$$\left[{}^0_1T\,{}^1_2T\right]^{-1}\,{}^0_6T = {}^2_3T\,{}^3_4T\,{}^4_5T\,{}^5_6T \tag{3.2}$$

$$\begin{bmatrix} . & . & . & c\theta_2(c\theta_2 p_x + s\theta_1 p_y) + s\theta_2(p_z - h_1) \\ . & . & . & -s\theta_2(c\theta_1 p_x + s\theta_1 p_y) + c\theta_2(p_z - h_1) \\ . & . & . & s\theta_1 p_x - c\theta_1 p_y - d_2) \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} . & . & . & 0 \\ . & . & . & d_3 \\ . & . & . & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The revolute joint variable θ_1 is obtained by equating (3,4) elements of each side in equation 3.2 similarly θ_2 by equating (1,4) elements and using the first and second trigonometric equations in Table **??**, respectively.

$$\theta_1 = -A\tan 2(p_x, -p_y) \pm A\tan 2(\sqrt{p_x^2 + p_y^2 - d_2^2}, d_2)$$

$$\theta_2 = \pm A\tan 2(c\theta_1 p_x + s\theta_1 p_y, -p_x + h_1)$$

The prismatic joint variable d_3 is extracted from (2,4) elements of each side from the same equation 3.2 as follows.

$$d_3 = -s\theta_2(c\theta_1 p_x + s\theta_1 p_y) + c\theta_2(p_z - h_1)$$

Last three joint variables are found using the elements of rotation matrices of each side of equation 3.2. The rotation matrices are given by

$$\begin{bmatrix} . & . & r_{33}s\theta_2 + r_{13}c\theta_1 c\theta_2 + r_{23}c\theta_2 s\theta_1 & . \\ d & e & r_{33}c\theta_2 - r_{13}c\theta_1 s\theta_2 - r_{23}s\theta_1 s\theta_2 & . \\ . & . & r_{13}s\theta_1 - r_{23}c\theta_1 & . \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} . & . & -c\theta_4 s\theta_5 & . \\ c\theta_6 s\theta_5 & -s\theta_5 s\theta_6 & c\theta_5 & . \\ . & . & s\theta_4 s\theta_5 & . \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $d = r_{31}c\theta_2 - r_{11}c\theta_1 s\theta_2 - r_{21}s\theta_1 s\theta_2$ and $e = r_{32}c\theta_2 - r_{12}c\theta_1 s\theta_2 - r_{22}s\theta_1 s\theta_2$.

The revolute joint variables θ_5 is determined equating the (2,3) elements of both sides in equation 3.2 and using the fourth trigonometric equation in Table **??**, as follows.

$$\theta_5 = A\tan 2(\pm\sqrt{1 - (r_{33}c\theta_2 - r_{33}c\theta_1 s\theta_2 - r_{23}s\theta_1 s\theta_2)^2}, r_{33}c\theta_2 - r_{13}c\theta_1 s\theta_2 - r_{23}s\theta_1 s\theta_2)$$

Extracting $cos\theta_4$ and $sin\theta_4$ from (1,3) and (3,3), $cos\theta_6$ and $sin\theta_6$ from (2,1) and (2,2) elements of each side in equation 3.2 and using the third trigonometric equation in Table **??**, θ_4 and θ_6 revolute joint variables can be computed, respectively.

$$\theta_4 = A\tan 2(\frac{r_{13}s\theta_1 - r_{23}c\theta_1}{s\theta_5}, -\frac{r_{33}s\theta_2 + r_{13}c\theta_1 c\theta_2 + r_{23}c\theta_2 s\theta_1}{s\theta_5})$$

$$\theta_6 = A\tan 2(-\frac{r_{32}c\theta_2 - r_{12}c\theta_1 s\theta_2 - r_{22}s\theta_1 s\theta_2}{s\theta_5}, -\frac{r_{31}c\theta_2 - r_{11}c\theta_1 s\theta_2 - r_{21}s\theta_1 s\theta_2}{s\theta_5})$$

3.2 Design Requirement

The requirement was a robotic arm which could support precise operations like driving a screw in addition to not so precise operations like picking a solid object. We also wanted a robotic arm that could be modular and therefore support extensibility when required.

Various factors were considered to decide upon the suitable model for our applications. These factors mainly included DOF, reach-ability, payload capacity, cost. The role/relevance of each of these factors along with the reasons in choosing the arm is explained below:

1. **DOF** - To be able to grab and tilt/rotate an object for applications like pouring water from a glass/bottle.

2. **Reach-ability** - For grasping small/big objects within the work-space.

3. **Payload** - Should be able to lift objects like small bottles, screw driver etc.

4. **Cost** - Feasible to purchase supporting and spare parts.

Table **??** shows various robotic manipulators for industrial and research purposes. All of these models that are industrial were expensive mainly because of the payload capacity, DOF and the repeatability/precision that they offered. We can see clearly that Dobot M1 and OpenManipulator-X has 4 DOF excluding the gripper and therefore they are relatively less in cost.

3.3 OpenManipulator-X

Open Source Manipulator, OpenManipulator-X had the best design that was feasible and suited our application requirement such as screw driving, object picking etc well. With the repeatability < 0.2mm it was cost effective and supported customizations like vacuum gripper, pen holder etc. The gripper is 3D printed and therefore could be customized/modified as per our requirements. OpenManipulator-X was not only customizable and extensible but also supports change in DOF. We can also increase the DOF to rotate the grasped object.

We calculated the modified DH Parameters which is used for calculating the Forward and Inverse Kinematics of this robotic arm if shown in table **??**

Hardware specifications of OpenManipulator-X are shown in Table **??** in which the Actuator used is Dynamixel XM series for good torque. Dynamixel XL series are light in weight but do not support enough torque and Dynamixel XH series have almost the same torque as XM but consume less power and are costlier than Dynamixel XM.

3.4 Hardware Connection

Figure **??** shows the hardware connection between PC/Computer which has ROS and is connected to OpenCR. This OpenCR in turn receives the input from the system and gives the output to OpenManipulator-X. OpenCR acts as a communication board between ROS Packages of PC and Dynamixel's of OpenManipulator-X. OpenCR is Open-source Control Module for ROS and it can be configured using the Arduino IDE. The power to Dynamixels is also drawn indirectly through OpenCR board avoiding direct supply from power source.

Chapter 4

Teleoperation Environment

4.1 Introduction

The experimental study was done on the 5 DOF OpenManipulator-X robotic arm which is Open-Source and is Robot Operating System(ROS) [20] enabled.

The robotic arm is operated using the OpenCR board and ROS. The OpenCR board is connected to the computer from which it takes input and the output is given to the robotic arm. The computer which can directly control the arm is also used for capturing and sharing the real-time video feed of the robotic arm and it's work-space thus help perform tele-operation from various locations via internet. The flow of control is briefly illustrated in Figure **??** , which is further explained in the experiment section.The arm is fixed on top of a table ensuring a safe work-space. Objects for pick and place, and stacking were placed on one side of the work-space. Three cameras with a distance of not more than $1m$ from the manipulator, facing the manipulator and the objects were installed to view them closely and clearly. Two or more views of the same scene from different perspective helps with the challenge of viewing 3D world in a 2D image by providing an intuition of the depth to a greater extent thereby ensuring better control. But three cameras were chosen to ensure that users are not confused with multiple views. In addition, an ultrasonic sensor that measures the distance of an object along the vertical axis was also installed on top of the gripper as shown in figure **??**.

Various number of cameras were used to conduct the experiments. Initially 4 cameras were positioned at different angles to view the setup of manipulator and the objects. Then the experiment was conducted with 3 cameras based on various positions that captured the setup. And based on the feedback from users of different experiment, we found the following

1. From experiment-1 with cameras positioned at front, front-diagonal and rear-diagonal users asked for more camera views.

2. From experiment-2 with cameras positioned at side, rear and front-diagonal, users mostly relied only on 2 cameras (side and rear) during most of the times. Position of cameras was found to be very essential to avoid redundant views and yet get users to perform required tasks.

3. In experiment-3, based on the feedback from experiment-1, position of the cameras was changed. And the new positions were side, rear and top. The performance and feedback from users on new camera positions and their reliability was drawn and compared with experiment-1 which was impressive and relatively better.

4.2 Participants and Their Background

4.2.1 Pre Experiment Survey

Users who participated in the experiments were members of family and friends. The background of users was collected using google forms. Details such as student or employee, age, location, experience with robotic interaction if any, number of hours they spend in front of the system per day etc were collected before beginning the experiment. This **form** was the used to collect pre-experiment details. The pre-experiment form contained questions like:

- **How familiar are the users with the operation of a computer?**
- **How familiar are the users with the operation of a terminal?**
- **How familiar are the users with the functioning of Zoom video platform?**
- **How familiar are the users with the operation of a robotic arm?**

These questions were directed towards the users to primarily understand their familiarity with using a computer, the terminal/console, video communication platforms like zoom and their general interactions and observations with a robotic arm. Other details such as their location and internet speed were collected to understand if the internet communication quality could affect the tele-operation of a robot.

Since, not many works previously conducted studies of tele-operation over the internet, we feel these factors give crucial feedback for the design of an ideal teleoperation approach. The appendix section shows the response of each user to questions in google form.

4.2.2 Post Experiment Survey

After the experiment, the participants were again **surveyed** for the feedback related to comfort level using the control types, video feed of the work-space from various directions, reliability on sensor data for distance, etc. The response or feedback of the users is present in the appendix section. The post-experiment form contained these questions:

- **Was there a need of additional camera viewpoints for tele-operation?**
- **Which type of control did users prefer during stacking?**
- **Which type of control did users prefer during pick and place?**

- **Was the experiment setup easy to navigate?**
- **Did the users experience discomfort in operation due to internet lag?**

While the pre-experiment survey tried to gauge the user expectations from the study, the post-experiment survey mainly asked questions regarding the practical experience of the users in terms of navigation of the arm, identification of objects and goals, amount of control the users felt they had during the experiment remotely. They were also asked their preferred method of control space for the arm in performing pick and place and stacking tasks. Though, we could understand and measure user performance using other metrics to evaluate the experiment like time, we asked users their feedback on the experiment through post-experiment surveys and explained in great detail in the results chapter.

4.3 Experiments

Three set of experiments were conducted. Please see table **??** for clear distinction between these experiments with respect to tasks performed, control type used for the mentioned task, variation of the camera positions and the step size for corresponding control type.

Figure **??** shows the top view of the placement of objects in these set of experiments and the number of participants included for that particular experimental setup. In experiment 1 and 3 objects are placed in similar position as that of experiment 3 but the number of participants for experiment 1 and 3 are 8 and 7 respectively. Because of hardware limitations and limitation in number of participants encountered due to covid, only 22 participants were recruited in total.

The first set of experiments had **eight** users perform pick and place task on one day followed by stacking on second day. Figure **??** shows the interaction page which has the three camera views and the console for taking input from the remote Users. Enlarged picture of this console is shown in figure **??**. The functions of different keys displayed on this console are briefly explained in the following chapter. Camera 1 shows the front view and cameras 2, 3 provide diagonal view of the manipulator from front and rear respectively.

In the second set of experiments we had **seven** users perform only pick and place task but using two different interfaces, keyboard and joystick/game-pad. For this experiment, we made use of combination of both control types. i.e., along with Cartesian control type, we gave the liberty to use one Joint control mainly the first joint, to rotate the arm either left or right for navigating purposes. This change was incorporated based on observations and feedback obtained from users in first set of experiments. The position of cameras was also changed. For viewing the feed from these new camera positions see figure **??** which is the interaction page for second set of experiments. Figure **??** and **??** show the console for Keyboard and Joystick interfaces respectively. The commands are explained in detail in the following chapter. In this remote users interaction page, camera 1 shows the front diagonal view and cameras 2, 3 provide top and rear view of the manipulator in action respectively.

In the third set of experiments, we had **seven** users perform pick and place on one day followed by stacking on another day, similar to first set of experiments. So we ensured to maintain the setup similar to first set of experiments but the camera positions were changed. Figure **??** shows the interaction page where the views of the work-space is similar to second set of experiments, Whereas the console used is same as that of the first set of experiments see **??**. As similar to second set of experiments, camera 1 provides front diagonal view and cameras 2, 3 provide top and rear view of the manipulator.

4.4 Autonomous motion

The manipulator is initially in rest position. To reach a location closer to the objects, a convenient position was chosen based on the location of the objects. Users were free to choose between reaching the predefined convenient position autonomously through a single keystroke which is key 3 as shown in the console in figure **??** or manually control the manipulator to help gripper reach any position of their choice. This choice was provided to analyse the usage of autonomous motion which reduces the time taken to perform tasks by the users.

4.5 Teleoperation

The console was used as an interface to take inputs from the remote user performing tele-operation. These inputs were taken using keystrokes from their keyboard and joystick/game-pad as well for second set of experiments. For first and third set of experiments, the users were provided with the option of tele-operating using two reference frames: Joint space for controlling the rotation of individual joints Vs Cartesian space for controlling the gripper/end-effector coordinates as shown in figure **??**. For the second set of experiments, the Cartesian control was used along with the combination of first joint control for rotating in left or right direction. See figure **??** and table **??** for locating the joints of the robotic arm starting from base joint which is the first joint. X, Y and Z direction provide motion of the gripper along a Cartesian reference frame which is fixed.

Chapter 5

Experimental Setup

5.1 Introduction

The real-time video feed from the three cameras is streamed and hosted on a local server of the system to which the robot and cameras are connected. To extend this control of the arm to remote users and to facilitate tele-operation, Zoom video communication platform was used. With the screen sharing and remote control access facilities available in Zoom software, users were able to view the real-time video being streamed in the local host of the system connected to the manipulator and also simultaneously control the manipulator using the console. The block diagram in Figure **??** visualizes the control flow and the application of Zoom software interface for controlling the manipulator remotely.

Initially, the video stream was hosted on a server and shared with the user to view the setup. SSH was used for controlling the manipulator remotely using terminal commands but a lag of nearly 7s between the instruction and execution time was experienced. It was not seamless as in comparison with zoom.

Zoom turned to be the best and stable option as the screen that was being shared contained all the videos being streamed and lag of this screen share was ranging between 100-200 milliseconds. It provided reliable communication and any significant multi-tasking and synchronizing across multiple screens and the console interface was handed by zoom.

Zoom screen sharing and remote control feature was used to view and execute the commands respectively. Remote control was done on the same screen that was being shared so both video streaming and motion commands used same channel.

The tele-operator's screen and their control inputs can be seen in the video shared at **User Experiment Playlist**.

5.2 Console and Interfaces

5.2.1 Keyboard

Experiment set one and three share the same console displayed in figure **??**. This console clearly displays two control options available for the users to make use of and complete the tasks given to them. The first control type involves the Cartesian/Gripper control, which has six keys. Figure **??** shows the control options and their respective keystrokes. Table **??** provides a detailed description of the functions of each keystroke used in Cartesian/Gripper control.

The second control type which involves control of individual joints, has 8 keys as shown in table **??**. The first row of this table shows the keys that rotate the respective joints in clock wise sense where as the second row displays the keys for counter-clock wise rotation of the same joints. The keys were chosen in a manner which would help users use it with ease. See figure **??** where keys ”y”, ”u”, ”i” and ”o” are present in one row, one beside the other on a keyboard. They rotate the joints $1, 2, 3$ and 4 by 5 degrees clockwise respectively. Similarly keys ”h”, ”j”, ”k” and ”l” are present one row below enabling the rotation of joints $1, 2, 3$ and 4 by 5 degrees counter-clockwise respectively. The rotation angle of all the joints was configured to 5 degrees per keystroke for first and third set of experiments as the objects were placed close to each other. In second set of experiments where objects were placed relatively far from each other and therefore the angle of rotation was changed to 10 see fig **??** for difference in position of these objects.

Similarly in case of Cartesian control, keys ”w” and ”s” as are present one below the other, and are therefore chosen to move the gripper forward and backward on y-axis. Keys ”a” and ”d” are chosen to move the gripper on negative and positive directions of x-axis which move the gripper to the left and right respectively. The step size for each keystroke for gripper control type is 2cm for both first and third set of experiments.

Table **??** shows the common control keys which can be used in both control types.

In the second set of experiments, based on the feedback from users in first set of experiments, the following changes were made for the keyboard interface.

1. The keys ”*z*” and ”*x*” were replaced with ”*UP*” and ”*DOWN*” arrows.
2. Keys ”*y*” and ”*h*” were replaced with ”*LEFT*” and ”*RIGHT*” respectively.
3. Keys ”*f*” and ”*g*” were replaced with ”*z*” and ”*x*”.

Figure **??** displays these new keys ”Up”,”Down”,”Left” and ”Right” as replacement for keys ”z”, ”x”, ”y” and ”h” respectively.

In other words, the control of the first Joint (q1) was combined with Cartesian/Gripper control for second set of experiments which included only pick and place task. Figure **??** is the keyboard console for second set of experiments with all these changes of keystroke commands incorporated in it. Table **??** shows the keys for 1st set of experiment in one column and 2nd in another column.

5.2.2 Joystick

The Joystick control has the buttons "*UP*", "*DOWN*", "*LEFT*", "*RIGHT*" for performing the same function as keys "*w*","*s*","*a*" and "*d*" respectively. "*YELLOW*" and "*GREEN*" buttons were chosen for motion of the gripper in positive and negative "*z*" direction. "*RED*" and "*BLUE*" were used for controlling the rotation of first joint in clockwise and counter-clockwise sense. "*RB*" and "*LB*" were chosen for opening and closing the gripper.

Figure **??** displays the Joystick buttons whose functions are described in table **??**.

The console for joystick interface is displayed in figure **??**.

5.3 Autonomous Control and Teleoperation

A Virtual Cylindrical Object (VCO) is assumed to illustrate the autonomous control which is performed before tele-operator takes over the control of the robotic arm. The VCO has diameter of 5.5 cm while it's height varies with it's distance from the manipulator. This variation in height is due to the work-space of the 5 DOF manipulator. The VCO ensures that any object enclosed in it whose height and width are within its dimensions, can be grasped by the manipulator. Figure **??** shows a blue colored virtual cylindrical object covering the object that the gripper is trying to reach.

By definition, either the height of the object coincides with the height of the VCO or is smaller than VCO thereby ensuring that the object perfectly fits inside. Let the center of the upper surface of the object be enclosed within the VCO at (a_1, b_1, c_1). Using the Inverse Kinematics (IK) solution whose mathematics is explained in great detail in chapter 3, the 5 DOF robotic arm positions its gripper autonomously on top of the surface of the object at (a_2, b_2, c_2). Where a_1 and b_1 are close to a_2 and b_2 respectively.

Once the Gripper reaches (a_2, b_2, c_2) autonomously, the control of this semi-autonomous robot is passed on to the tele-operator to accomplish the task of grasping the desired object precisely with the use of the ultrasonic sensor and the vision feedback obtained from the multiple camera streams. The user tries to grasp the object with the help of feedback from the camera stream and the ultrasonic sensor which gives the distance between the gripper and the object that is $c_2 - c_1$ when the gripper is exactly on top of the object (i.e,. $a_1 = a_2$ and $b_1 = b_2$). Thereby letting the user know how far the gripper is from the object in the z-axis direction and assisting the user in grasping the object without fail.

In order to get the joint angles of the robotic arm for positioning the gripper at (a_2, b_2, c_2) the inverse kinematics solution is obtained using the DH Parameters shown in table **??**.

5.4 Pick and place

Picking an object and placing it in the desired location forms the crux of tele-operating a manipulator. We hence observed the users' performance when picking an object and placing it in a basket. The User is first directed to perform pick and place operation using the direct Gripper Control and then Individual Joints Control in the first set of experiments and for third set of experiments, the order of controls which was assigned was random and altered. The second set of experiments involved combination of both controls. Five small bottles of diameter 3.5 cm and height $7 - 15$ cm, and a basket with diameter of 20 cm have been used as the test objects for the pick and place operation. The bottles are placed $7 - 10$ cm apart in the work-space which was closer to all the cameras while the basket was placed on the other side of the work-space as shown in Figure **??**. The user was asked to pick objects in the order of their choice for first set of experiments. In next set of experiments, based on observations from first set of experiments, users were asked to pick the objects which were closer to the robotic arm first to avoid knocking of the objects closer to the robotic arm while trying to reach the farther objects. During the operation if the target object or other object was knocked down while reaching target object, the user was instructed to pick the next object or the ones that are not disturbed. The fallen object was replaced in position by the research associates only when the user is performing the place operation far away from the picking location. The time for each pick and place operation execution was noted and has been analyzed.

5.5 Stacking

Once the user completed the pick and place operation, a gap of one day was given before performing the stacking operation as we wanted to analyze how well the user performed given a rest period of $24hrs$. The stacking operation involved four steel glasses of diameter $5cm$ and height $10cm$ each. The fifth glass was placed as reference to stack onto. Similar to the pick and place operation, first users performed stacking using the Gripper Control and then moved on to the Joint Control. Stacking involved 4 operations with each control type totalling 8 stacking operations per user. To observe effect of the camera view and obstruction in visibility while picking objects if any, the user was directed to pick objects closest to the manipulator first for stacking operation. Again the time to pick each object and stack them was noted for each user.

Chapter 6

Experimental Results

6.1 Introduction

A task of picking one object and placing it in a box/container or stacking an inverted glass on fixed inverted glass is called one operation. So a total of 290 pick and place operations were performed, out of which 35 operations were of Joystick. In addition, stacking included 120 operations. The users belonging to age group ranging from 21 - 63 participated in these experiments. The users were located in different countries across the globe like India, USA and Norway. The following results were obtained based on the real-time performance of each user in all the operations.

This chapter is further divided into individual sections where results related to each set of experiment, comparison between them and feedback of the users individually and collectively are being presented.

6.1.1 Experiment - 1

The total time taken by each user in performing 10 operations of pick and place using each control type i.e., 5 operations by Cartesian control and 5 operations by Joint control have been listed in table **??**. Similarly for the stacking task which includes 8 stacking operations in total of which 4 operations use Cartesian control and 4 operations use Joint control have also been listed in the same table. In addition to showing the total time taken by each user to accomplish a particular task, this tables also have information such as location, internet speed at the user's end and latency encountered while sharing the screen with the users.

The results in tables **??**-**??** provide the analytic such as minimum, maximum, average time, and standard deviations of the user while performing a particular task i.e., pick and place, and stacking using both control types.

From table **??** we can infer that the performance of the task or operation of the individual user is not being affected by the latency they experience on their screen. For example, from table **??**, we see that 7 out of 8 users had sample latency within the range of 200-300 ms for stacking operations and the standard deviation was ranging only from 0:50 to 1:55. From the sample latency of user 5, 6 and 7 during pick and place, which were almost same, the standard deviation of user 5 was 10:05, and of user 6 and 7 was 1:08 and 1:56 respectively which shows that performance of the User is not affected by the latency but users themselves. Surprisingly, location of the users does not affect the performance of a user as can be seen from statistics of user 4 and 5 who are located in different countries but took almost same total time for pick and place operation. It is further elaborated in experiment-3 in the following sections of this chapter. Thus, we could infer that although latency plays a vital role in real time tele-operation, Users performance depended more on users themselves than on other external factors like latency, location, etc.

6.1.2 Experiment - 2

In this section, the table **??** contains the information related to Users who performed only pick and place operation of five objects using both Joystick and Keyboard interface each at a time.

It can be inferred from table **??** that 71% of the users finished the pick and place experiment, faster, using Joystick. Joystick therefore was more adaptable and usable for the users as it was better both in terms of time and ease of use when compared with keyboard interface. When users were enquired about the camera views, it was noted that more than 85% of them responded that they mostly used camera views from camera 2 and 3 and very rarely looked at the view from camera 1. See figure **??** for these camera views.

From table **??** and figure **??** it is clear that the experiment 2 and 3 varied significantly in three aspects, control type, step size, and in the position of the objects in the work-space. The camera position for both the experiments was same. The Keyboard interface results from table **??** reflect the drastic improvement of the performance time when compared with the results from table **??**. The total time taken for Pick and Place task in experiment 2 is collectively less than total time taken in experiment 3. Thus, the combination of both Cartesian and Joint Control, and the increase in step size results in faster completion of the experiments.

6.1.3 Experiment - 3

The following results include the measure of time taken for a total of 70 Pick and Place and 42 Stacking operations by all users. In this experiment unlike in first experiment, the users were randomly assigned the sequence of control type to be used. Users 1-4 in the following tables of this section performed operations using Joint control first followed by Cartesian control, Users 5-7 performed operations using Cartesian Control first followed by Joint Control similar to experiment 1.

Clearly we can see from table **??** that irrespective of the order in which the controls were used, operations with Joint control consumed more time than Cartesian control and 71% of the users consumed more time with Joint Control operations over Cartesian control. But in experiment-1 where all the users performed using Cartesian control first and Joint control second, the operations performed using Joint Control were executed faster for pick and place. This indicates the adaptability towards the control types.

Irrespective of the sequence of control type assigned, users were performing faster with experience/the usage of the system.

6.2 Perspective/Feedback Based Analysis

We surveyed each user using a feedback form after their participation in all the experiments of Pick and Place and Stacking. From feedback and time performance results in experiment-1, there is a trade-off between the comfort of the users and the time taken for accomplishing the pick and place task. 50% of the users felt comfortable with Cartesian control for Pick and Place contradicting the results obtained from the time performance analysis where they finished the experiments faster using Joint Control. Also, they felt comfortable with Cartesian control for stacking and finished it faster using the same. The reason being Cartesian control is more intuitive when the gripper is closer to the objects to be grasped and also while placing the grasped objects precisely at a particular point as in the case of stacking but the performance time for Cartesian control was more than Joint Control because users had to focus on both x and y direction for navigation in the case of Cartesian Control. Therefore they felt more comfortable in reaching to a desired location precisely although it took more time to navigate than compared to Joint control.

6.3 Time Performance Analysis

From table **??**, we can see that all users took longer using gripper control to perform pick and place operation and were able to accomplish the same task relatively faster using joint control. On the contrary, we see that 75% of the users were able to perform the stacking operation faster using gripper control than joint control. This shows adaptability towards Cartesian control was faster than joint control.

Table **??** shows the meaning of the labels used in figures **??**, **??** and **??**.

As mentioned before, in experiment 1, all the users were instructed to use Cartesian control first followed by Joint control for both the tasks. Figure **??** shows that the average and standard deviation of the Cartesian control for stacking task has decreased than pick and place. This is representing the adaptability towards the Cartesian control. Whereas for Joint control we can see that stacking tasks although performed after pick and place, standard deviation and the average has increased unlike for Cartesian control.

Figure **??** and **??** show the results of experiment 3, where users 1-4 had performed the experiments using Joint Control first followed by Cartesian control and users 5-7 performed the experiments using Cartesian Control followed by Joint control similar to experiment 1. From these figures, it's clear that irrespective of the order of the control type used for Pick and Place and Stacking, Joint Control took more time for completion than Cartesian Control. As stacking operation requires more precision than pick and place, the users found it difficult to do stacking with Joint control and which eventually resulted in longer completion time using Joint control.

6.4 Heat Maps of User Paths

6.4.1 Pick and Place

The figures in **??** represent the heat maps for Pick and Place operation in experiment-3. The figures on the first row displays the heat maps for the Cartesian control and on the second row represents Joint control. Clearly the heat maps on the first row show the path of the manipulator to be straight lines except for when the commands given were key stroke ”1” and ”3”. Similarly, the paths taken by manipulator in Joint control are curved. The first column of images show the isometric view of the paths traced by the manipulator, followed by side view and top view.

6.4.2 Stacking

The figures in **??** represent the heat maps for Stacking operation in experiment-3.

Similar to the images in the Pick and Place operation, in this section as well, the images on the first row represent stacking of the glasses using Cartesian control and on the second, represents stacking using Joint control. Stacking operation involved **four** objects where as Pick and Place Operation involved **five** objects, this is also visible in the images where the number of troughs represents the number of objects. Since Pick and Place operation had a box for dropping the picked objects, from the heat maps The Stacking operation had a static inverted glass placed on which rest of the glasses were to be stacked on to, this is visible in the heat map from the top view where the color is dense on the right corner where all the glasses were stacked unlike the images in the Pick and Place operation where the objects could be dropped anywhere within the boundaries of the box.

6.5 Significance of Camera positions

The effect of the position of the cameras on performance can be clearly analysed from drawing comparison between first and third set of experiments as one of the major difference between these two sets of experiments was the position of the cameras in addition to the control sequences which the users were requested to follow.

Table **??** shows the average time taken by the users of first set of experiment in column two and third set of experiments in column three. Clearly the time lapse in column three are less for both the tasks performed using both control types when compared with those in the column two. This proves that the position of cameras in third set of experiments is benefiting users by reducing the time taken to finish the tasks . This shows the significance of the position of cameras for viewing the remote environment and performing the tele-operation.

6.5.1 User Feedback of the Camera Views

For the first set of experiments when the users were surveyed regarding the need for an additional viewpoint apart from the current camera positions, 6 out of 8 users which is 75% of the users responded with the willingness to have more camera views preferably at top and 2nd joint etc. Please see Appendix A for the responses of the Users in relation to more number of camera views.

With consideration of these responses, when third set of experiments were conducted and when new users were surveyed if there was a need for additional cameras/camera views etc, 5 out of 7 which is approximately 71% percent of the users replied no. This indicates that most of the users felt comfortable with the position of the cameras as given in third set of experiments i.e,. Top, Rear and Front Diagonal, with faster completion time of the experiments.

6.6 Discussion

These experiments provide the information related to users' performance while teleoperating a manipulator. The impact of factors such as internet speed on the users end, users location, sensor data, camera positions, etc on the experiment were drawn and analysed.

The internet speed on the manipulator side had huge impact on the teleoperation than that of users end.

In conclusion, in these kind of teleoperations good internet connectivity is recommended on the manipulators side with decent network connectivity on the users' side. The lag of internet at manipulators end resulted in incorrect execution of the commands. This was sometimes frustrating to the users and often impacted their performance time.

The camera positions in experiment 1 where Camera 2,3 were displaying the iso-metric view of the environment often created deceiving views as the information of the depth in 2D images is not possible. When users tried to pick the farther(far from the manipulator) objects, they frequently knocked the closer objects because of the fore mentioned deceiving views. This issue was rectified to a greater extent when top view was made possible instead of one of the isometric view.

Overall, despite the above mentioned issues in the control of the manipulators remotely, the users were successfully able to control the manipulator and finish the stacking and pick-place tasks assigned to them.

Chapter 7

Conclusion and Future work

Robotic manipulators are utilised in a variety of industries, including manufacturing, food, and health care, to assist with day-to-day chores such as pick and place, stocking, and precision jobs. While automation and teleoperation are the most prevalent modes of operation, partial autonomy is gaining popularity since the presence of a human in the loop reduces the manipulator's error rate.

Our work is more related to picking and placing and stacking remote objects, which are service based applications. In contrast, work presented by Majewicz[11] and Wang[23] are on insertion needles belonging to medical applications. Moreover, our study was conducted in real time on manipulator and not simulated.

For performing the fore mentioned tasks, the requirement was a robotic arm which could support precise operations like driving a screw in addition to not so precise operations like picking a solid object. A robotic arm was chosen such that it could be modular and therefore support extensibility when required. Various factors such as DOF, reach-ability, payload capacity, cost led to the choice of Open Source Manipulator, OpenManipulator-X that was feasible and suited our application requirement.

Teleoperation using keyboard and joystick/gamepad of 5 DOF Openmanipulator was made possible in real time. Participants recruited belonged to age group ranging from 21 to 63, which included a set of students and working individuals who were located at various cities and countries across the globe. And results were drawn based on users performance in addition to their feedback related to the experiments.

We made use of zoom as the communication platform for performing the real time teleoperation. The experimental setup was viewed using the real time video feed from three cameras positioned at different locations as mentioned in the chapter 4. The instructions were given in the console and the experimental setup was visualized using these cameras.

It was observed that the performance of the Users was dependent upon the individual as to how comfortable they are and how intuitive the interface is for them. The results clearly show that the performance of the user was mostly impacted by the interface and camera views of the environment over their location, latency and internet speed. Also, they were getting adapted to the interface over time and with number of operations. This has been elaborated in the results section with statistical analysis. Our results over three experiments conducted with twenty two users were based on time statistics and user feedback showed that

1. In the first experiment preference to Cartesian control even though it was faster using joint control.
2. In the second experiment experiments were accomplished faster using Joystick interface than Keyboard.
3. In the third experiment both preferences and performance favoured Cartesian control.
4. Adaptability towards Cartesian control was faster than Joint control.
5. The ability of the user to tele-operate had bigger impact on their performance than latency.
6. The camera views were sufficient and placement of cameras has a role in time taken for the tasks, and users were not relying on the sensor data for the task.
7. The overall user feedback on tele-operation of 5 DOF manipulator was positive.

As part of future work, one can study

1. Impact of other interfaces including augmented reality for tele-operation.
2. A training program for users to expertly perform tele-operation of manipulators.
3. Tele-operation with tools such as screwdrivers, pliers, and hammers.
4. Picking up fast moving objects on a conveyor belt.

One of the major limitations of the experiment are number of participants. We could only recruit total of 22 participants due to covid and also due to hardware setup issues which arose because of covid. Internet speed at the manipulator end plays a key role in users teleoperation. When at times the internet was down, the keyboard commands were not executing as per the users expectations and thereby resulting to their frustration which in turn effected their performance.

Appendix A

appendix

Name	Age	Internet download speed (Mbps)	User location	Operated a robotic manipulator before?	Number of hours spent on a computer/day.	Familiar with video communication platforms (Scale: 1 - 5)	Familiar with terminal
Experiment 1, User 1	24	42.51	Navi Mumbai, India	No	8	3	Yes
Experiment 1, User 2	23	1.34	Kothagudem, India	Both	8	5	Yes
Experiment 1, User 3	23	10.58	Chennai, India	Operated	12	5	Yes
Experiment 1, User 4	23	19.71	Kota, Rajasthan, India	No	8	4	Yes
Experiment 1, User 5	41	200	Naperville, IL, USA	No	8	4	No
Experiment 1, User 6	23	24.2	Hyderabad, India	No	8	1	Yes
Experiment 1, User 7	23	17.58	Pune, India	Worked on	10	4	Yes
Experiment 1, User 8	23	24.36	Palamaner, India	No	10	5	Yes
Experiment 3, User 1	41	128	Alpharata, USA	No	8	5	Yes
Experiment 3, User 2	27	83.17	Mumbai, India	No	10	4	Yes

Table A.1 continued from previous page

Name	Age	Internet download speed (Mbps)	User location	Operated a robotic manipulator before?	Number of hours spent on a computer/day.	Familiar with video communication platforms (Scale: 1 - 5)	Familiar with terminal
Experiment 3, User 3	27	7.5	Hyderabad, India	No	8	4	Partially
Experiment 3, User 4	63	46.78	Mumbai, India	No	6	4	No
Experiment 3, User 5	27	296.08	Oslo, Norway	No	10	4	Yes
Experiment 3, User 6	26	3.1	Aurangabad, India	No	10	5	No
Experiment 3, User 7	21	22.2	Mumbai, India	Operated	7	4	Yes

Table A.1: Pre-survey questions

A.0.1 Post Experiment Survey

User	1) Did you enjoy performing the experiments?	2) How comfortable was the user interface to work with?	3) How comfortable did you feel when controlling the Robotic Arm?	4) How good was the visibility of the system given the 3 views? (Scale: 1-5)	5) How reliable was the zoom-in option in the video stream ?
User 1	Yes	4	3	3	4
User 2	Yes	5	4	5	5
User 3	Yes	3	3	2	4
User 4	Yes	3	4	5	3
User 5	Yes	5	4	4	5
User 6	Yes	5	4	4	3
User 7	Yes	4	4	3	3
User 8	Yes	5	5	5	4

Table A.3: Post experiment 1 survey details P-1

User	**1) Did you enjoy performing the experiments?**	**2) How comfortable was the user interface to work with? (Scale: 1-5)**	**3) How comfortable did you feel when controlling the Robotic Arm? (Scale: 1-5)**	**4) Comfortable in viewing all the objects and their positions, how good was the visibility of the system given the 3 views? (Scale: 1-5)**	**5) How reliable was the zoom-in option in the video stream ? (Scale: 1-5)**
User 1	Yes	4	5	5	5
User 2	No	4	4	5	5
User 3	Yes	4	4	4	3
User 4	Yes	4	4	4	3
User 5	Yes	4	4	4	4
User 6	Yes	5	4	5	3
User 7	Yes	4	5	4	3

Table A.8: Post experiment survey details P-1

User	6) Did you feel any need for an additional viewpoint apart from the current camera positions?	If you replied yes to the above question, how many additional cameras and at what positions would you suggest?	7) Which control type do you prefer for Pick and Place?	8) Which control type do you prefer for Stacking?	9) How comfortable did you feel while grasping/grabbing an object? (Scale: 1-5)	10)How well did you like performing the pick and place operation? (Scale: 1-5)
User 1	No		Gripper control	Gripper	5	4
User 2	No		Gripper control	Gripper	4	4
User 3	Yes	Adjacent to the dropbox.	Joint control	Gripper	4	4
User 4	No		Gripper control	Gripper	5	5
User 5	No		Gripper control	Joint control	4	4
User 6	No		Gripper control	Gripper	4	4
User 7	Yes	Lateral front view, longitudinal side view	Gripper control	Joint control	4	5

Table A.9: Post experiment survey details P-2

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