Human-Robot Cooperation: Communication and Leader-Follower Dynamics

by

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ABSTRACT

As robotic systems are used in increasingly diverse applications, the interaction of humans and robots has become an important area of research. In many of the applications of physical human robot interaction (pHRI), the robot and the human can be seen as cooperating to complete a task with some object of interest. Often these applications are in unstructured environments where many paths can accomplish the goal. This creates a need for the ability to communicate a preferred direction of motion between both participants in order to move in coordinated way. This communication method should be bidirectional to be able to fully utilize both the robot and human capabilities. Moreover, often in cooperative tasks between two humans, one human will operate as the leader of the task and the other as the follower. These roles may switch during the task as needed. The need for communication extends into this area of leader-follower switching. Furthermore, not only is there a need to communicate the desire to switch roles but also to control this switching process. Impedance control has been used as a way of dealing with some of the complexities of pHRI. For this investigation, it was examined if impedance control can be utilized as a way of communicating a preferred direction between humans and robots. The first set of experiments tested to see if a human could detect a preferred direction of a robot by grasping and moving an object coupled to the robot. The second set tested the reverse case if the robot could detect the preferred direction of the human. The ability to detect the preferred direction was shown to be up to 99% effective. Using these results, a control method to allow a human and robot to switch leader and follower roles during a cooperative task was implemented and tested. This method proved successful 84% of the time. This control method was refined using adaptive control resulting in lower interaction forces and a success rate of 95%.

ACKNOWLEDGEMENTS

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INTRODUCTION

For most of their existence, robotic systems have been relegated to enclosed work cells in factories. These robots only operated by performing repetitive tasks that they could perform more efficiently than a human worker. These tasks typically were moving or manipulating a well defined object into a well defined location. In these applications the dynamics of the objects and the position of the items in the robotic cell are known and are accounted for in the programming of the system. While this type of application continues to be valuable, the field of robotics is being transformed.

Robotics are no longer confined only to the well defined environment, but are now progressing into the unstructured world. As the variety of robotic applications expands, so does the need for them to interact well with humans. The physical interaction of robotics and humans used to be something to be avoided. However, many current applications require physical interaction with a robotic system such as rehabilitation robotics, advanced prosthesis, and exoskeleton systems.

One of the challenges of the use of robotics in an unstructured environment has been how to deal with contact. In traditional robotics, the robot is programmed based off of position. When the robot was used in a work cell where the position of every item in the cell was well known, it could perform well. However, if it encountered an object that was not where the system expected it to be, it performed poorly. The system typically would exert maximum forces to try and force the robotic system to the programmed position. Additionally, if the object's weight, rotational inertia, or stiffness was not what was expected by the program there was no provision to deal with these variations.

To meet with these challenges, Hogan [13] showed that impedance control of the robotic system can be very effective. Impedance control allows the system to have a desired position but to also have a defined impedance relationship as to how to deal with disturbances to the desired position. For the simplest case of stiffness, this impedance creates a force toward the equilibrium position from the current position based on a spring constant. This is in the familiar equation $F_{imp} = k * x$. The spring constant is k. The distance from the equilibrium is x and F_{imp} is the force generated. For a positive k value this force is directed from the current position to the desired position, or equilibrium. Impedance control can be used as a way to control the position of the robotic system and to deal with disturbances through the impedance of the system.

One of the additional difficulties of physical human robot interaction (pHRI) is the the unpredictability of the human portion of the interaction. Humans have a control system and actuation system of their own. This allows them to change their interaction with the robotic system. This change can manifest itself through the human altering their impedance interaction with the robot. The human arm has been shown to be able to modulate its impedance [12, 29, 28]. This impedance can be characterized as an ellipsoid. This ellipsoid changes in shape and size through the co-contraction of opposing muscles of the arm. Through this capability, the impedance that the robot sees can change dramatically by changing the orientation of the arm as it interacts with the robotic system and the co-contraction of opposing muscles. This capability can cause both increased unknowns in the system but the human can also use this ability to better interact with the robotic system.

An important area of pHRI is the area concerning robot-human cooperation. In this area robots and humans are physically cooperating together to achieve a goal. This requires them to be either directly physically interacting or physically interacting through an object of interest. An example of this interaction is the manipulation and placement of objects larger than a human can perform alone, such as the installation of nonstructural exterior walls on buildings [19]. The goal for this cooperation is the efficient, effective and safe placement of a large object. In rehabilitation robotics, the cooperative goal of the robot and human is to train the human to move a particular part of the body through a specified motion or to a position [16]. The intent of this is to provide rehabilitation training to the patient and improve their capabilities outside of therapy. In exoskeleton systems, the human robot cooperative goal can be seen as moving the human body through a motion but with the added complexity of interacting with the outside world [31]. While these applications are very different, they also contain similarities. All of these cooperative tasks can be seen as moving an object of interest to a new end position. This object could either be the human body itself or a external item.

In order for two systems working together to cooperate, they need coordinated action. The ability to perform this coordinate action however relies on several factors. One of the main factors is establishing a **common goal**. To achieve a common goal some form of communication between the robotic system an the human must exist. With the advantages of using impedance as a control method for the robotic system, it would be beneficial if this could be extended to a method of communication between human and robot as a way of communicating a goal or a preferred direction of motion. Another major factor in cooperation is **role assignment** between the participants. Often in human-human cooperative tasks one human will act as a leader and the other as the follower. These roles can switch during the task. An example of this can be seen in moving a large object. When one person has a better view of an obstruction, they often act as the leader and the other person as the follower. This can change during the task as different people have different vantage points of obstacles. It would be useful to extend the communication of goals to also the switching of roles between leader and follower.

1.1 Motivation

The motivation for this work is to improve robot-human cooperation. Robot-human cooperation can have a significant impact on society. More specifically, this cooperation has a broad range of areas for applications such as industrial, construction, rehabilitation robotics, and service robotics for the elderly and disabled.

Moreover, improving the ability to communicate goals between the robot and human can have a significant effect. It can produce a better understanding of ways to switch leader-follower roles. Additionally, it can be used in the general sense of goal communication. This would allow a system to be designed so that when there is ambiguity in the determination of goals that it then seeks to refine those goal through communication. This means that the overall system would not have to anticipate all possible scenarios that it may encounter. Examining the ability to switch between leader and follower also has a potential for significant impact. Improved capability in this area would allow the use of either the human or the robot as the leader and dramatically improve the ability to fully utilize the robotic system.

1.2 Objective

There are three main objectives of this thesis. First, to investigate the use of impedance as a way of communicating a preferred direction between a robot and human. This communication between participants needs to be a two way method of communication. Secondly, to utilize insights gained from the previous objective to create a method to switch between leader to follower. Particularly, this is to develop a control method for a robotic system in switching from leader to follower and allowing the human to become the leader. The final objective is to refine the leader-follower controller to adapt to the human and reduce the interaction forces between the human and robot and to perform better at detecting when to switch these roles.

1.3 Overview

Chapter 2 reviews the previous work in this field. It begins with an examination of the use of impedance control in robotics. It then examines the use of communication and the importance of situation awareness. Additionally, it delves into the current research in leader-follower switching. Chapter 3 examines the methodology used in the experiments that were conducted. This includes two experiments in the ability for humans and robots to communicate a preferred direction utilizing impedance. Additionally, it examines the methodology for the leader-follower experiments. Chapter 4 examines the data analysis and results of the experiments. Chapter 5 contains the conclusions from this work and the future work to be done.

Chapter 2

BACKGROUND LITERATURE

2.1 Introduction

One of the challenges to human-robot cooperation is the variability of the dynamics involved. Even if the assumption is made that any external objects that the robot and human were manipulating were well defined, the dynamics of interacting with the human body can be very difficult to quantify prior to motion of the robotic system. They are significant differences in size, weight and densities of the human body and of its parts. Marrar and Kim found that there was a 37 lbs. standard deviation in the weight of industrial workers, but they also found differences between different anthropometric studies [20]. Additionally, an individual human can vary the dynamics of their interaction with a robot by slight difference of position of the human body or by modifying its stiffness through co-contraction of opposing muscles [16], [22]. Hogan showed in [13] that many of these variables can be dealt with by effectively utilizing impedance as a way of controlling the robot and its interactions both with the human and with external objects.

2.2 Impedance Control

Hogan[13] showed that the use of impedance control can be useful in overcoming the previously mentioned challenges of robot interaction. Hogan's overall purpose was to create an approach to control of a manipulated object that would be suitable for broad range of applications. Obviously, manipulation of an object requires physical interaction with the object of interest. Hogan classified the manipulation by the amount of mechanical work that was performed on the environment by the object. Historically, robotics used in industry often were used in a way in which the mechanical work that they imparted to the environment was minimal. However, in many potential industrial and non industrial applications the work is not insignificant.

In areas where there is work begin done on the environment by the object of interest, the control of the object can not be viewed in isolation of the environment. The control method must take into account this interaction. Hogan stated that focusing on only velocity, force or position, would not be sufficient. This is because these quantities do not individually control the work that is performed by the system on the environment. His solution to this was to control the force and either position or velocity of the system.

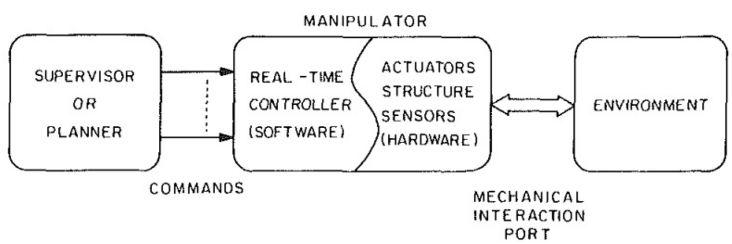

Figure 2.1: From [13]-Structure of Impedance Control for Robotics

Hogan's implementation of this is as a high level planner that sends commands to a low level controller that is directly controlling the robotic system. It is then the robotic system that interacts with the environment, as in Figure2.1 . The low level control is operating a feedback loop to control the robotic system as directed by the commands sent to it by the high level planner. Even though the high level planner has access to the data of the lower level system, it operates as if it is an open loop system. With this type of system, there are some important results. The first is that it becomes possible to control the input of work into the environment through two variables such as force and position. The second important result is that since the environment is not being controlled only one of these variables can be controlled by the system. An example of this is that if the system is to apply a force to a structure in the environment it can not also control the deflection of the structure. The reaction by the environment is beyond the control of the system. In this example the system can either control the deflection or the force applied but not both. If interacting with a linear system, either could be controlled to produce a similar result. However, if the environment that the system is interacting with is not a simple linear system, then the reaction of the environment to the control of one of these elements will be different than the control of the other.

The most commonly used terms for these elements are admittance and impedance. Admittance is where a force or some other effort is exerted and the output is some type motion. Impedance is the reverse of this. It is where some type of motion is input (position, velocity, etc) and it results in force or similar effort output. When systems interact in the environment they must represent opposite types of systems. If the object in the environment is acting as an admittance the robotic system that interacts with it must operate as an impedance. Hogan defines most of the environment that a robotic system would interact with as an admittance because a constrained rigid object can have a force applied to it but it does not necessarily move. Because of this, when a robotic system is interacting with the environment it should typically be controlled in an impedance mode. Additionally, because the appropriate impedance value varies for specific tasks, a robotic system that is to be utilized in a variety of applications should allow for the control of a range of values of impedance. Overall, impedance control of a robotic system can also be seen as position control with an additional disturbance response that is the impedance.

2.3 Communication and Situation Awareness

There are several challenges with robots and humans interacting to achieve a task. One of these difficulties is that while there are limitations and conditions imposed on each task for the movement of the object of interest, there are typically a large number of possible trajectories that could fulfill those imposed conditions. This can make the coordinated movement between the robot and human difficult to achieve. Many researchers have addressed this issue by using robotic systems only designed to follow or mimic the human [26, 21, 18, 27]. This method prevents the utilization of the robot as a leader in the cooperative task. The concept of a robot capable of communicating to the human a direction of motion is a very useful one. In the manipulation of a large object into or through a tight physical constraint the robotic partner at some point in the motion may have a better ability to sense the restrictions of motion. Additionally, robotic systems can have additional information or sensors systems beyond human capability, such as the work flow on the floor of a factory or the best path for the human arm to take to aid in rehabilitation. Similarly, the human may also have information that the robotic system does not have but needs for the cooperative team to successfully complete the task. In order to maximize the utilization of both the robotic system and the human engaged in a cooperative task, a two-way form of communication is necessary.

In general, audible and gesture based communication have been used by some researches as a way of establishing communication between the robot and human [23, 25, 30]. These methods have been shown to be useful for conveying limited communication such as communicating the higher level intent of the cooperative task. Audible communications are limited to environments that are not noisy and that other robotic systems with similar commands are not in close proximity. Additionally, they require hearing capability in the human subject. Gesture communication requires line of sight of the gesture with the camera sensor on the robot and may require the user to move their hands when not possible in a given task. Additionally, both of these communications methods would be cumbersome for the constant communication that would be needed to communicate the next direction of motion.

When examining human-robot interaction, it is useful to consider the significant work of Endsley [8, 7, 6, 4, 5] in human machine interfaces(HMI). Prior to Endsley's work, HMIs were primarily measured and the performance graded on human workload. Workload assessment focuses on the level of effort that a human has to engage in to accomplish a task. This can be a useful method of assessment and is still used. However, if the human utilizing the system has to make decisions about the overall actions to reach the goals, then an assessment of their ability to perform this is crucial to determining the effectiveness of the system. If the interface allows a user to do something easily but does not provide the information and understanding that is needed for the human to make decisions, it can have disastrous consequences. Endsley highlighted several airplane crashes where the pilots believed that the automated systems they were using would perform differently than they did. This potential hazard can also easily be seen in the field of robotics. If a robotic system does not perform in the way that is predictable to the human interacting with it, then it can be a source of significant problems. Endsley defined this overall concept as situation awareness.

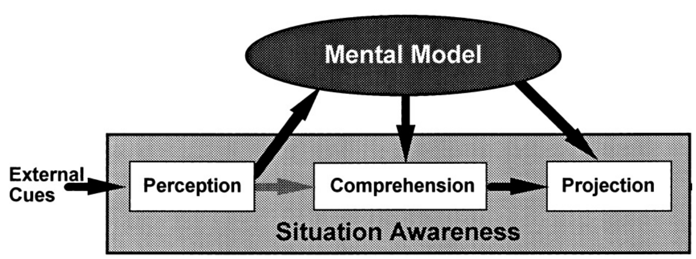

Figure 2.2: Adapted From [14]:Levels of Situation Awareness

Additionally, this was broken down to three levels. Each of these level builds on the previous levels. As in Figure 2.2, the first level is perception. This area examines if the human is able to perceive the basic information that is receiving. This can be data displayed on a screen or haptic input from the system. The human only has to be able to recognize the information to be successful at this level.

The second level of situation awareness is comprehension of the current situation. This level of situation awareness deals with the processing of the incoming information and putting it into a context by the human's mental model of the system. If the human is successful at this level then they are able to correctly understand how the inputs of the system relate to and affect the current state of the system.

The third and highest level of situation awareness is the ability for the human to predict the future states of the system. This requires the human to utilize their mental model of the system to analyze the perceived data and the understanding of the current state to be able to predict what the system will do in the future. This can be what the system will do if the human does not perform any action, but also how the system will react to the user's input. This is a critical element for developing a high level of situation awareness. This final step can also be a particularly difficult step to achieve. First, all of the previous steps have to have been met. If there is a failure of either the ability to perceive the data or to understand what that data means in the current situation a greater level of prediction can not occur. Additionally the human has to have a compatible mental model that aids them in being able to predict the future states.

Achieving a high state of situation awareness can be particularly difficult when the human is interacting with a system that is highly automated. One of the main causes of this difficulty is what Endsley termed the"out of the loop syndrome". This can become a significant negative of the system both in general performance but also in safety of the system. This syndrome is caused primarily by tow main factors. The first is that the human is not sufficiently engaged in the current task. This can cause their attention to drift to other tasks. This causes a loss in situation awareness of all three levels because the user is no longer sufficiently focused on perceiving the necessary data to create either an understanding of the current situation or a prediction of the future states. Additionally, the "out of the loop syndrome" can be caused by the users lack of a mental model of how the system operates and results in an over reliance on the automation to perform correctly. Commonly this is often referred to as a description of how intuitive the system is to the user.

From Endsley's work some important elements can be drawn. One of the main issues is that the human needs the ability to project what the current goal of the system is. Endsley's work mainly focused on the human understanding and awareness. This however, can also be extended to the robotic system. For a robotic and human system to cooperate effectively then both systems need to be fully utilized and engaged. If a robotic system has an improved understanding of the goal of the human, the system can perform better. Two main ways it can do this is through selecting the same goal as the human and through being able to understand what the appropriate leader-follower roles are.

Researchers have investigated physical Human-Robot Interaction (pHRI) and intention estimation in cooperative tasks [3, 17, 2]. This previous research has focused on robotic systems estimating human intention and utilizing feedback to correct errors of intent to follow human movement. This research differs from the research done in this investigation in several key ways. First, the ability of both the robotic system and humans to predict the desired direction of motion of the other agent is examined and this does not limit the system to one agent as always the follower. Additionally, the ability of the agents to explicitly predict the desired direction of motion of the other agent is also examined. This required the desired direction to be cognitively determined in the humans (algorithmically determined in robotic case). This type of approach is significant because with further research it could be utilized as a way for a follower, human or robotic, to recognize when the intention of the leader may be incorrect or hazardous.

2.4 Cooperation and Leader-Follower Roles

In investigating cooperation between humans and robotic systems it is useful to look at how humans cooperate with each other and how other researchers have been able to duplicate this. Reed and Peshkin [24] conducted an experiment that examined different cases of cooperation. They performed three different experiments. In all of the experiments the subjects were performing a one degree of freedom task. This task was to turn a crank handle that rotated a disk until the angular position of the disk matched a goal position that was projected on the surface of the disk, as in Figure 2.3.

In the first experiment they performed the experiment on only human subjects. They had the subjects perform the task both as an individual and as a pair. When they had the subjects perform the task as a pair they doubled the rotational inertia to the disk as a way of normalizing the response of the pair of subjects to the single subject data.

They had several interesting results. First, the subjects performed faster as a pair than they did individually. As a pair they performed the task on average 8.5% faster than they performed individually. However, many of the subjects reported that the other person was a hindrance to their performance. This also suggests a potential difficulty with robot-human cooperation. The subjects quantifiably performed better, but they felt that their partner was a hindrance. This may mean that for robot-human

Figure 2.3: From[24]: Human-Human and Human-Robot Cooperation Test Setup

cooperation to be successfully implemented being quantifiable better is necessary but not sufficient. The increase in performance needs to be such that the humans involved recognize a significant advantage to using the robotic system, otherwise they may not adopt it.

One possible additional explanation as to the feeling of subjects that the other person was a hindrance was that, as the authors noted, the subjects took on different roles during the trials. There was a role specialization that occurred during the experimental process. Typically one subject would be apply more force to accelerate the disk to the target while the other subject in the pair would apply more force to decelerate the disk to stop at the goal. This specialization could also be looked at as a leader-follower behavior but with a different task. One subject could be considered the leader with regard to initial velocity and the other subject could be looked at as the leader for the deceleration phase.

Additionally the amount of specialization varied from different pairings. As in

Figure 2.4, some subjects showed a great deal of specialization while other subjects did not. This also suggests that for robot-human cooperation that there will need to be the ability of the system to adapt to the differences in the individual users. Also from this figure, it is noted that the duration that the subjects took to complete the task is not necessarily higher or lower depending on the degree of specialization.

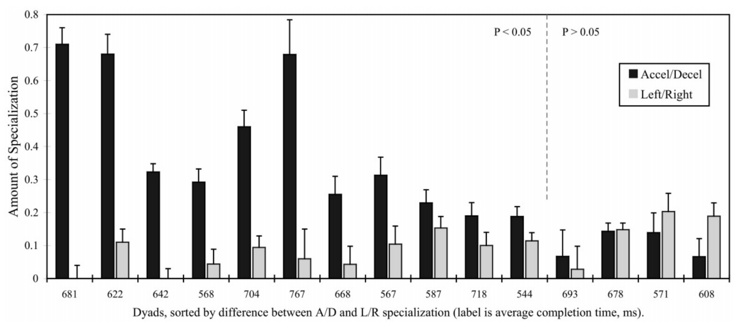

Figure 2.4: From[24]: Variation of Specialization

The second experiment conducted was to attempt to duplicate the human-human specialization with a robot-human pair. The same disk system was used in the second experiment. In this experiment however an electric motor was also engaged with the disk system. This allowed the experimenters to induce a torque into the disk in order to replicate the behavior of one of the human subjects. The acceleration force profile that was used was that of the subjects when they were operating the disk by themselves, except that they multiplied this acceleration force profile by 2.1. This was done to modify the trajectory to match the typical change between the operation of the disk by an individual and the change of how they operated the disk as a pair. Additionally, in half the trials the individual knew that they were working with a non human system. For the other half of the trials a person stood in the place where an additional partner would stand to give the subjects the appearance that they were working with a human partner. Of the 11 subjects that had a human standing in the correct position but were in fact interacting with a robotic system

10 of them believed that they were interacting with a human. Interestingly, when humans thought they were working with a human partner they performed about as well as when they worked alone (0.9 percent faster). When the subjects knew that they were working with a robotic partner they were 3.9 percent slower. During this experiment none of the subjects choose to specialize their motion even though this would have been possible. The robotic system applied sufficient torque to accelerate the disk and the human's arm toward the goal. The human could have chosen to have specialized in slowing down the forces but did not. There is potentially more research that needs to be done on the particular mechanics of role specialization in human-human interaction and reproduction of that in the human-robot case.

The third experiment that was conducted was examining the ability for perturbation rejection in the case of partners. When the human-human pairs had rotated the apparatus to where the system was in the target area a perturbation was applied by the robotic system. This procedure was also tested on single human subjects operating the system as before. The force applied was double for subject pairs(20 N) than for individuals (10 N). The results of the experiment found that pairs of subjects had a 12 percent greater displacement than that of the single subjects. This indicates that a pair of subjects are not able to reject twice the disturbance as a single subject. This is likely due to the difficulty of coordinating impedance across a short time period.

In dealing with leader-follower roles in human-robot cooperation, many researchers, such as [32], focus on assigning the roles for the experiment and do not deal with the possibility of switching of roles. However, some researchers [10, 9] have examined leader-follower roles as a continuous function instead of a discrete state. One way that researchers have performed this is by creating two models and switching continuously between them. In one model the robotic system is acting as a follower and is reacting to forces generated by the human leader. For the second model, the robot is the leader and the human is presumed to react to the forces of the leader. The system then creates a variation of these two models by constantly switching between the two models. This is an interesting concept, however it can cause confusion as to who is leading the task. In [10], the researchers noted that in the experiment there were several times that their avatar/robot system was acting as the leader but the subject did not interpret this as the case. This potentially can cause significant problems in an unstructured environment as the human thinks that the robotic system will react to his/her input, but the robotic system is employing a model that is opposite of this. While Endsley's previously mentioned work does not specifically examine leader follower switching, she documents aviation accidents directly related to the human's inability to predict the action of the automated system. In these accidents, one of the main causes was that the pilot thought that one of the aircraft's automatic system would respond differently than it did. The pilot was then not able to realize the error and correct in time to prevent the accident from occurring. If there is this conflict of understanding what the role is of the participants in robot-human cooperation, then when the two agents make different decisions on an intended path the result will be a conflict that could include a collision with the object itself.

Chapter 3

METHODOLOGY

3.1 Overview

The robotic system used for all experiments in this investigation was the KUKA Lightweight 4+ (KUKA LWR4+) robotic system. This system is made up of three main components. They are a 7 degree of freedom (DoF) robotic arm, a KUKA Robotic Controller (KRC), and a desktop computer. The KRC is connected directly to the 7-DoF robotic arm and performs the low level control of the arm. The KRC is also connected to the desktop computer. The desktop computer interfaces with the KRC utilizing KUKA's Fast Research Interface (FRI). This interface allows the computer to send control commands to the KRC controller. To program these commands on the computer, C/C++ programming language was used running on a Linux operating system. Additionally, on the KRC controller a program specific to the experiment was used. However, this program only specified the control method, command timing (5ms for all experiments) and the initial position of the robot. This program then established connection to the desktop for further commands.

The control method used for all of these methods was for impedance control of the robotic system in the Cartesian coordinate system based off of the location of the base of the robot arm. In impedance control the higher level control program can specify particular values to control the robot as desired. These values are the equilibrium position and orientation, Cartesian impedance values, Cartesian dampening values. Additionally, data can be received from the KRC system. The data received for these experiments were the current position and orientation of the end effector and the interaction forces with the end effector. These interaction forces are estimated internally in the KRC using the joint torques and kinematics of the current position.

From [1], the Cartesian impedance control for the robotic arm is governed by equation:

$$\tau_{cmd} = J^T(k_c(x_{equ} - x_{pos})) + D(d_c) + f_{dynamics}(q, \dot{q}, \ddot{q}) \tag{3.1}$$

In this equation, τ_{cmd} is the commanded joint torques of robotic arm. The desired position of the end effector is x_{equ} and the current position is x_{pos} . The spring constants are represented by k_c. The dampening coefficients are specified by d_c. The function $f_{dynamics}(q, \dot{q}, \ddot{q})$ takes into account the dynamics of the robotic system, and it is not changeable through the FRI. It is important to note that the values that are specified by the high level control in these experiments are the k_c, x_{equ} and d_c values.

Humans were used in all of the experiments conducted in this research. All human subjects gave informed consent to the experiment and the experiments were conducted in accordance with ASU IRB(Protocol# 1303008979).

3.2 Robot-Human Preferred Direction

In order to test if impedance can be used as a two way form of communication, two separate experiments were devised. The first of these experiments was to examine if a human can detect the preferred direction of the robotic system. In this experiment the robotic system would be utilizing a variable impedance field to convey a preferred direction to the human. In the second of the preferred direction experiments, the humans were to attempt to indicate to the robotic system a preferred direction of motion. This was then analyzed to see if this preferred direction of motion could be detected by the robotic system.

3.2.1 *Experimental Setup*

As discussed above, the robotic system utilized in these experiments was the KUKA LWR 4+ system. The system was programmed utilizing the FRI with the robotic system utilizing Cartesian impedance control. To prevent rotation of the fixture for both of the preferred direction experiments, the rotational spring constant was set at its maximum level (300 Nm/rad). Doing this minimized rotation of the test fixture so that the primary motion of the end effector of the robot was in translation. Additionally, these experiments were to take place in the horizontal plane. To facilitate that, a high impedance value was used in the y axis (vertical axis). This further limited the motion of the end effector to the horizontal (x-z) plane.

As in Figure3.1, a preferred direction board was created as a way of indicating to the human subjects what the possible choices of preferred direction were. A discrete set of preferred directions were used instead of a continuous set. The different preferred directions were at angles of $\frac{\pi}{7}, \frac{2\pi}{7}, \frac{3\pi}{7}, \frac{4\pi}{7}, \frac{5\pi}{7}$ and $\frac{6\pi}{7}$. This was done as a way of creating a simplified test setup and to indicate to the human the needed accuracy level of detection of the robots preferred direct. It also served as a way to give the human an easy to understand direction that they were to convey to the robotic system in the second experiment.

A fixture was designed to attach to the end of the robotic arm and to provide a place for the human to grip. The top and bottom sections of the fixture were made from clear plastic. This was done to allow the human the ability to look through the fixture and see the preferred direction board. The robotic arm was positioned so that the fixture was over the preferred direction board with the grip handle of the fixture directly above to origin of the preferred direction board.

The preferred direction board was placed on a movable table in the robotic

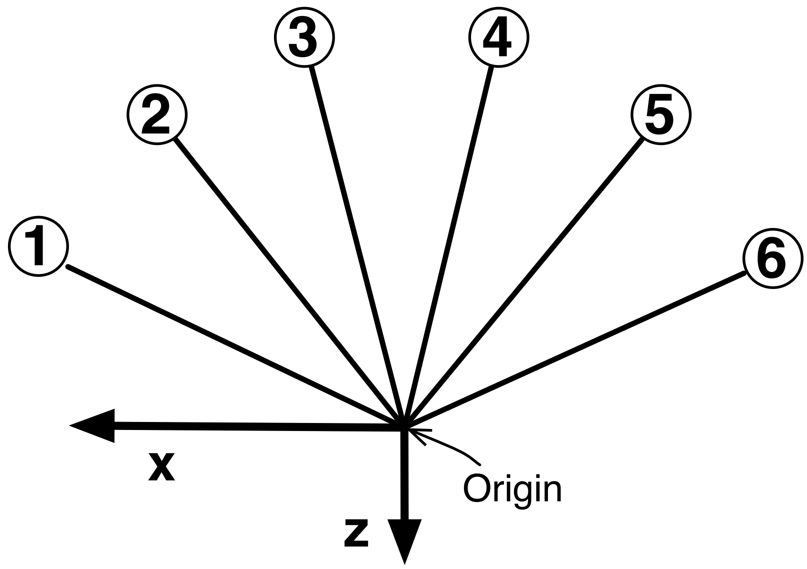

Figure 3.1: From[15]: Preferred Direction Board- x and z axis added for reference only

work space (Figure3.2). The position was chosen to allow for convenient manipulation of the test fixture by the human and to allow for an adequate range of motion for the robotic system. Since this table was movable, a calibration was performed at the beginning of each experiment. First, the robotic arm would move along the x axis. This allowed the matching of the x axis line on the preferred direction board to this motion. Then the robotic system was moved to each of the end target positions on the board. The position of these targets was recorded and used in the data analysis of the results. This ensured that the position value for the preferred direction in the analysis would match the position that the human viewed.

3.2.2 Experimental Protocol

Human Detection of Preferred Direction of Robot

In the experiment for the humans to detect the preferred direction of the robot, seven human subjects were used and conducted 48 trials per human (336 total trials).

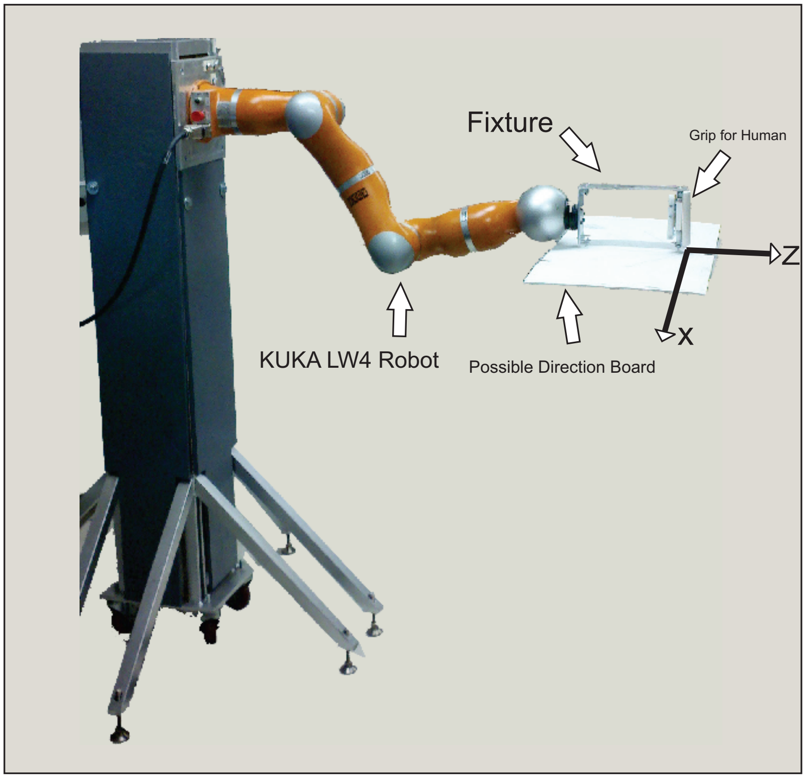

Figure 3.2: From[15]: Physical Setup for Preferred Direction Experiments

This was broken into two sessions of 24 trials with a short break, with additional instructions during the break.

Initially, the subjects were given very minimal instructions. This was to allow the subjects the freedom to approach the problem as they saw fit. They were told that the robot had a preferred direction of motion along one of the 6 lines marked on the board. They were instructed to slightly move the fixture in order to determine what the preferred direction of the robot was. This phase was 10 seconds long. A tone was played by the computer to mark the end of this phase and the beginning of the indication phase. In this phase the robot provided minimal resistance in the horizontal phase and the subjects were to move the grip end of the fixture to a position over the circle indicating the preferred direction of the robot. This indication phase was only for recording the choice of the human as to what the human thought the preferred direction of the robotic system was. They were given 5 seconds to perform this indication phase. After this they were to release the fixture and wait for the system to move back to the origin of the preferred direction board and wait to begin the next trial.

In each session of 24 trials, 4 trials were used for each of the preferred directions. The order of the trials was randomized so that neither the test subject nor the person conducting the test knew what the preferred direction was. This was done to minimize the possibility of the subject guessing the preferred direction based off of the reaction of the person conducting the experiment.

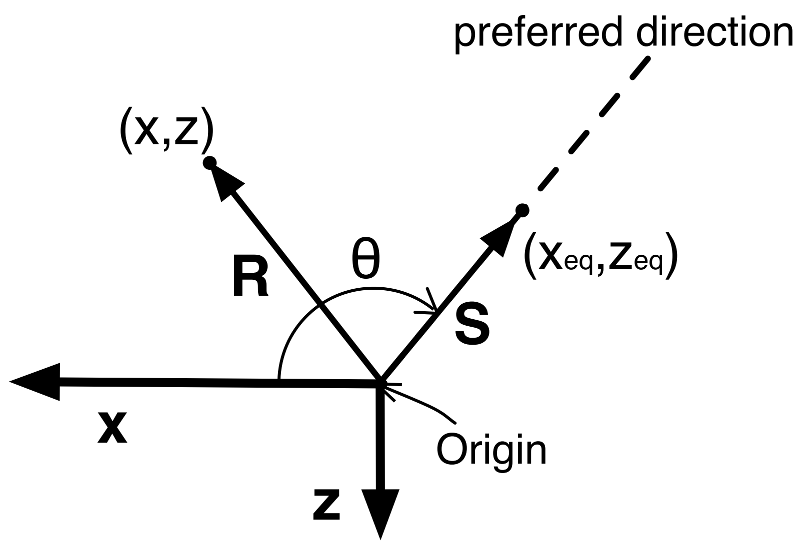

Figure 3.3: From[15]:Vector Diagram of Impedance Setup

For this first experiment, the robotic system needed to indicate the preferred direction of motion using a variable impedance field. To accomplish this, an algorithm was created to modify the forces felt by the human at a given position based on what the preferred direction was. To create the field the robot calculated how far away the human had moved the grip end of the fixture from the origin of the preferred direction board. This distance is represented as the R vector in Figure 3.3. To create the virtual equilibrium point, this R vector is rotated to match the preferred direction and then its magnitude is reduced to 90 percent of the magnitude of the original R vector. The 10 percent reduction of the magnitude was done as a way to prevent possible instability in the system. If there is noise or measurement error in the position of the fixture, using a 100 percent of the distance could represent in actuality an equilibrium greater than 100 percent and could potentially result in a continuously growing vector as the equilibrium point moves farther out along this vector. Therefore, if $\begin{bmatrix} x & z \end{bmatrix}^T$ is the current position of the fixture, then the force exerted by the robot arm to the human subject is given by:

$$\mathbf{F} = \begin{bmatrix} F_x \\ F_z \end{bmatrix} = \begin{bmatrix} K_x & 0 \\ 0 & K_z \end{bmatrix} \begin{bmatrix} x - x_{eq} \\ z - z_{eq} \end{bmatrix} \tag{3.2}$$

where $K_x = K_z = 300 {}^{N}\!/_{m}$ is the Cartesian stiffness, and $\begin{bmatrix} x_{eq} & z_{eq} \end{bmatrix}^T$ is the equilibrium point of the impedance field given by:

$$\begin{bmatrix} x_{eq} \\ z_{eq} \end{bmatrix} = \begin{bmatrix} 0.9\sqrt{x^2 + z^2}\cos(\theta) \\ -0.9\sqrt{x^2 + z^2}\sin(\theta) \end{bmatrix} \tag{3.3}$$

where θ is the angle of the preferred target, as shown in Fig. 3.3. Figure 3.4 represents what the impedance field would be if the preferred direction was along the negative z axis. The arrows on this figure represent the force vector that the system would impart to the fixture if located at that position.

This algorithm created an equilibrium point that was different from the current position of the fixture. This created a force that would drive the human toward the equilibrium point located on the preferred direction. This equilibrium point was updated every command cycle of the robotic system (every 5 ms). The human would move the fixture around as a way of detecting what the preferred direction was for the 10 second search phase. Then a tone was played for the beginning of the indication phase. The robotic system's impedance value was then set at 1 N/m in the x-z

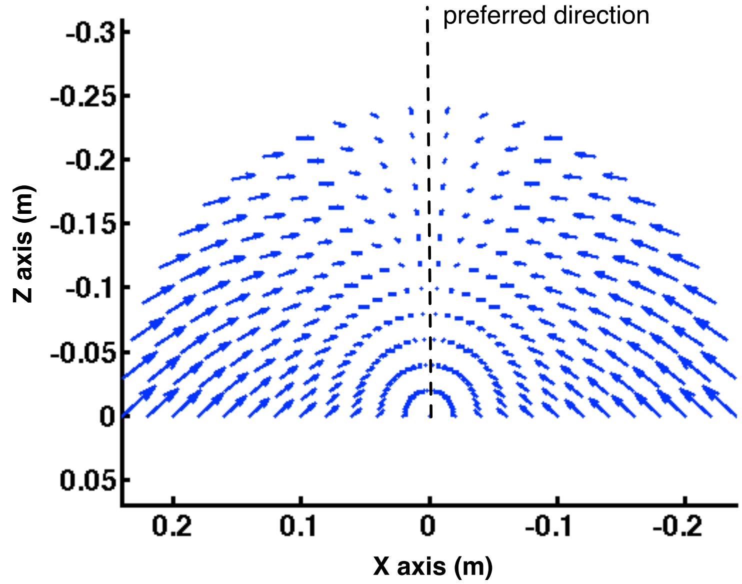

Figure 3.4: From[15]: Impedance Field

plane and each command cycle the current position of the fixture was set as the new equilibrium for the impedance system. This produced a very compliant system that did not indicate to the human if they were moving toward the correct preferred direction. In this phase the human positioned the handle over the target to indicate what they had determined the preferred direction to be. This was done as a way of allowing the human to indicate the perceived preferred direction of the robot.

After the first set of 24 trials, a ten minute break was given to the subjects. During the break additional instructions were given. The subject was informed that the robot was using impedance to indicate a preferred direction. Low impedance would be felt along the preferred direction and that higher impedance would be felt the further out they moved from this preferred direction. Additionally, the robotic system was setup to have a particular preferred direction and the subject was informed what the preferred direction was. The subject was then allowed to move the fixture around knowing what the correct preferred direction was. This was not counted as one of the experimental trials.

Robot Detection of Preferred Direction of Human

The purpose of the second experiment is to determine if a method could be determined for a robot to be able to discern the preferred direction of the human. In this experiment there were 5 human test subjects. All of them had participated in the previous experiment to identify the robot's preferred direction of motion. A total of 60 trials were performed for each of the human test subjects. This was done with 10 trials for each of the different preferred directions. During the experiment, three breaks of five minutes were given. This was done to prevent fatigue of the subjects. After the initial instructions were given, no additional instructions were given to the subjects. The order of the preferred directions was randomized.

During each of the trials, the robot would perform four search patterns to gather data that would be utilized to determine the preferred direction of motion. Each of these search patterns were conducted without a break between them. To the subject it appeared as a continuous attempt to determine the preferred direction but with a series of four techniques. At the end of each trial a short pause was given for the human to be told what the next preferred direction was and to prepare for the next trial.

The patterns used were conceptually similar to what was observed in the first experiment to have been used by humans in searching for the preferred direction. These patterns will be discussed in the results portion of the thesis, since they are related to the results of the previous experiment.

For this experiment, a varying impedance field was not used. The robotic system had an impedance of 3000 N/m for the x-z plane. The vertical y axis had an impedance value of 5000 N/m and the rotation axis's had a value of 300 Nm/rad. These were the same as the previous experiment. The equilibrium point of the robotic system was moved along different paths for the four different search patterns. The force generated by impedance of the system was the amount that the human resisted the movement of the robotic arm as the equilibrium point was moved. If no resistant force was applied by the test subject then the system would be at the equilibrium position or within the error and friction of the system.

3.3 Leader-Follower Switching

3.3.1 Introduction

A cooperative task was devised in order to test if a control method for switching between leader and follower roles created using the results from the previous experiment would be successful. The task needed to be one with an appropriate range of motion for both the human and the KUKA LWR4+ robotic system to be able to perform. Additionally, this task needed to be sufficiently difficult so that the follower in the task would be actively engaged. The reason for this is that if the follower is not actively engaged in the task then they are no longer cooperating in the task. Instead, they are being passively moved by the leader of the cooperative task. Additionally, Reed [24] found that in cooperative tasks there is often specialization of roles where the follower of the task takes on an additional responsibility. For this experiment the overall goal was for a human and robot to use a fixture to transport a ball along a path to a correct bin. The leader of the task was responsible for the translation motion of the fixture along the x-z plane. The follower of the task was responsible for moving with the leader and to maintain the level of the fixture so that the ball would not roll off during the task. This means that the follower was responsible for maintaining a level position in two axes of rotation (rotation about the x axis and rotation about the z axis). A small square lip was created to aid the follower in keeping the ball on the fixture. There were two possible bins that the ball could be put into. A correct bin was told to the follower (the human in this experiment). If the leader, the robotic system moved toward the incorrect bin the follower was instructed to guide the leader to the correct bin. This would test the ability of the leader-follower control method to be able to accurately switch roles from leader to follower while engaged in a cooperative task.

3.3.2 Experimental Setup

Physical Setup

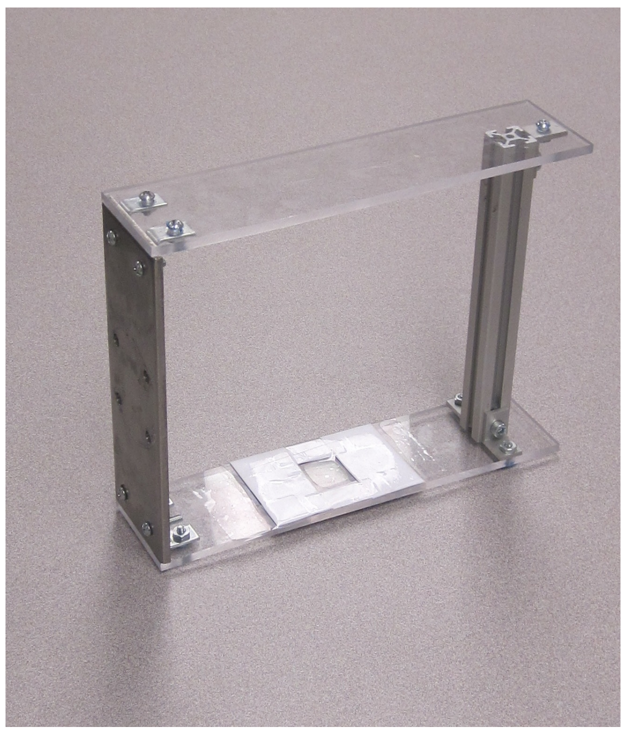

Figure 3.5: Fixture for Leader-Follower Experiments

A fixture similar to the one utilized in the earlier experiments was developed as seen in Figure 3.5. A small square lip was created on the surface of one of the clear cross pieces of the fixture. The fixture was attached to the robotic system similar to the previous experiment. A small foam ball was place in the square lip. The cooperative task was to move the fixture so as to transport the ball along a given path into one of two bins. A board, Figure 3.6 , was created to depict the path that the ball must take and two plastic bins were attached to the board. The board was placed on a movable table in the robotic work space. The location of the table was place so that it would be convenient for humans to interact with and so that there was sufficient travel for the robotic system to perform the task as seen in Figure 3.7.

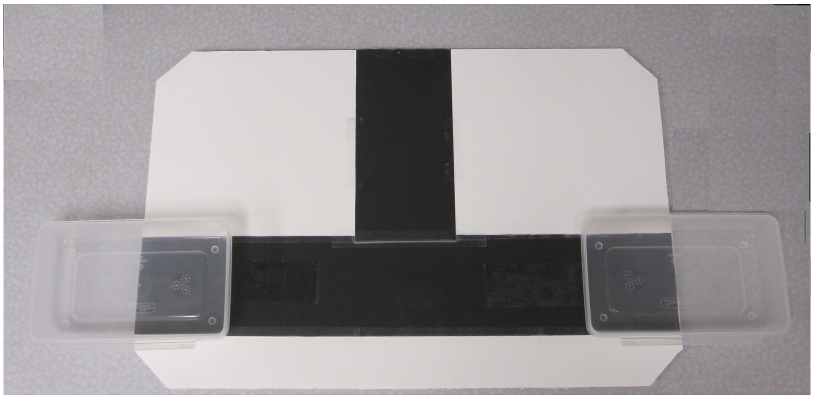

Figure 3.6: Board for Leader-Follower Experiments

Figure 3.7: Physical Setup for Leader-Follower Experiments

For this experiment, the robotic system would initially start as the leader of the task. Initially the fixture would be positioned 89 mm below where it was going to perform the task. The robotic system would be set with maximum impedance value in the y direction (5000 N/m). The rotational impedance values would also be set at maximum value of 300 N m/rad. The impedance for the x-z plane was set at 500 N/m to allow the subject to be able to move and influence the motion of the fixture. A tone was played by the computer at the start of the trial. The equilibrium point for the robotic system would move vertically 89 mm. The robotic system has high impedance in this direction so the system moved that direction with little influence from the human. Additionally, when it started to raise up the rotational stiffness was decreased in x and z axis to 1 N m/rad. This is to allow for rotation about x and rotation about z. The human has been instructed that as the follower they have to maintain the level of the fixture. The robotic system has a slight tendency to rotate during its motion. This requires the follower to actively level the fixture during the cooperative task. Once the system reaches the appropriate height, the cooperative task begins. If the robotic system stays as the leader during the task, then the robot proceeds to move in the positive z axis for 30 cm. Then it begins a 3 cm radius turn. It is important to note that the orientation of the fixture with respect to the y axis does not change but the translation motion of the fixture follows a curved path. This curve continues for 90 degrees. The curve is either toward the right of the subject or the left so that the fixture is moving either along the positive x axis or the negative x axis. The robotic system continues to move along the x axis a total of 20 cm. It then reaches the correct distance for dropping the ball in the bin. The robot stops the motion and a tone is played to let the human know that the motion has ended. This concludes the cooperative portion of the task. The robotic systems then rotates the fixture clockwise or counter clockwise depending on if it is on the positive or negative x axis. This rotation of the fixture about the z axis drops the ball into the bin correct if the cooperation was successful. The robotic system than returns to the original position to start the next trial. If during the task, the robotic system determines that the human wants to be the leader then it plays a distinctive tone and switches roles to become the follower. In this case the robotic system becomes compliant and allows the human to move the fixture in translation in the x-z plane. The robotic system also takes over the leveling function and increases the rotational impedance values to the maximum of 300 Nm/rad to ensure that the fixture is level. Once the human has moved the fixture to a position near either bin it plays a tone and then the robotic system again rotates to roll the ball into the bin.

Program and Control Method

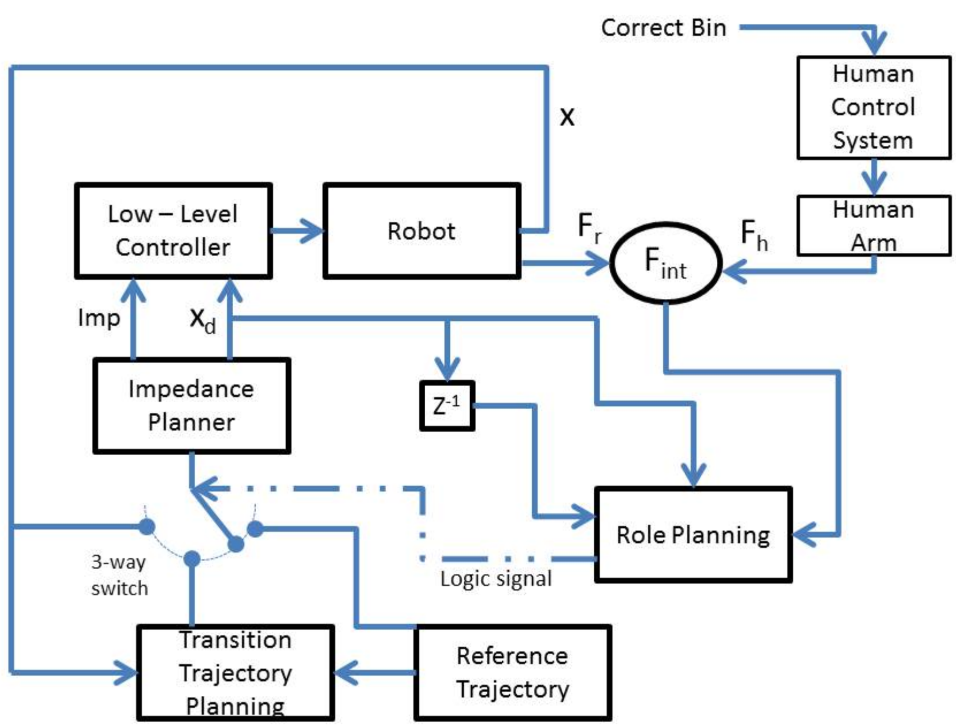

Figure 3.8: Control Diagram For Leader-Follower Control

In this initial leader-follower experiment a control method for switching from leader to follower for the robotic system was devised. This control method utilizes a key concept from the previous experiments. This concept is that one of the participants can communicate a preferred direction of motion using impedance. This is particularly important for the switching of leader-follower roles. If the current leader moves in a direction that is undesirable to the current follower, the follower can communicate this with high opposing forces. This means that when the leader moves in an incorrect direction they feel high opposing forces. This indicates that the follower has a different direction that they desire to move towards and that they should become the leader.

In order for the robotic system to switch modes from leader to follower a control method was developed as seen in Figure 3.8. As the human and robot cooperate, interaction forces are generated, F_{int}. These interaction forces and the current and previous value of the desired position of the system are input to the role planning function. This function determines if the human desired to become the leader in the cooperative task. If the human has desired to switch it also determines if the transition phase has been completed. The role planning function then switches the input into the impedance planner between one of three inputs. The first is the reference trajectory. The reference trajectory is the trajectory that the robotic system was originally following. This will be the input to the impedance planner as long as the robot remains the leader. If it is determined that the human desires to switch then the input to the impedance planner is switched to the transition trajectory planner. It remains at this function until the transition phase is complete (1 second). The transition trajectory planner creates a trajectory to transition from the current desired position (x_d) to the current position(x). After the transition is complete the impedance planner input is then the current position of the system.

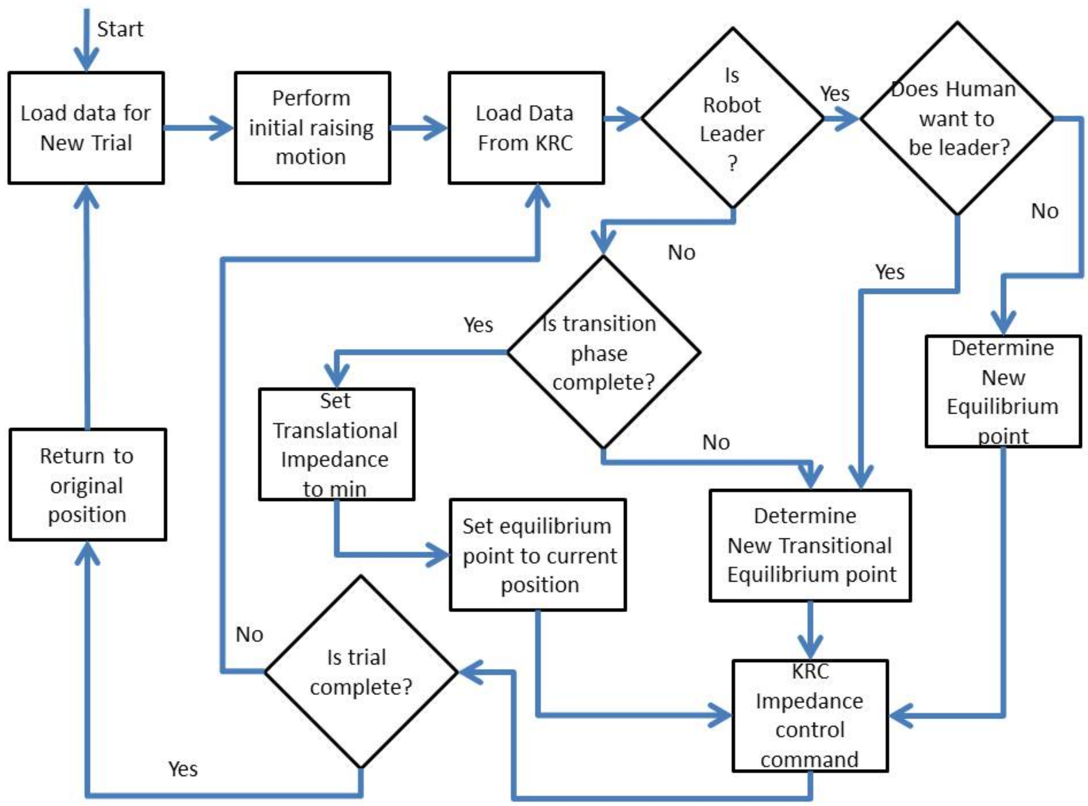

Figure 3.9: Flow Chart for Leader-Follower Program

To explain in detail how this control method is carried out in the computer system through the FRI interface a flow chart was constructed, Figure 3.9. At the start of a new trial, the system loads data for the individual trial into variables for the program. The data are the value of the leader-follower switching threshold and the data to create the reference trajectory. The reference trajectory is the path in the x-z plane that the robot is programmed to take. This path will be one of two paths ending at either the bin on the right or the bin on the left. After this data are loaded, the robot plays a tone and performs the initial raising motion. This raising motion is used as a time to decrease the rotation impedance so that the follower will begin maintaining the level of the fixture. Once this is complete the system loads the current data from the KRC. This is the output data from the robotic system. This includes the current position of the fixture and the interaction forces. The program then checks to see if the the robot is currently leader. If it is the leader, the program then checks if the human desires to be the leader. This process will be discussed in detail below. If the human does not want to be the leader then a next equilibrium point is determined from the reference trajectory. This new position along with the impedance levels are sent to the KRC impedance controller for the robotic system to execute. The program checks if the trial is complete by checking if the system has reached the area near one of the two bins. If the trial is complete the program performs the returning function. This includes the rotation motion to dump the ball into the bin and then returning to the original position to begin a new trial. If the trial is not complete the system returns to load new data from the KRC and begins the cycle again. If the program determines that the human wants to be the leader it sets the flag that the robot is now the follower and then a different equilibrium point is determined using a function to transition from leader to follower. This is discussed in detail below. If the robot is no longer the leader and the transition phase is complete then the translation x-z impedance values are set to min (1 N/m) and the new equilibrium position is set to the current position. This makes the robot very compliant in the horizontal plane. During the transition phase the robot also took over the responsibility of keeping the fixture level. To accomplish this the rotational impedance was gradually increase to the maximum of 300 Nm/rad during the transitional phase.

In Figure 3.10, the process for determining if the human wants to become the leader is shown. The current equilibrium point is compared with the previous equilibrium point. This is used to calculate the change in the equilibrium point in the x and z plane from the previous command cycle of the robot. The direction of the angular direction of this motion is then calculated. The angular direction of the

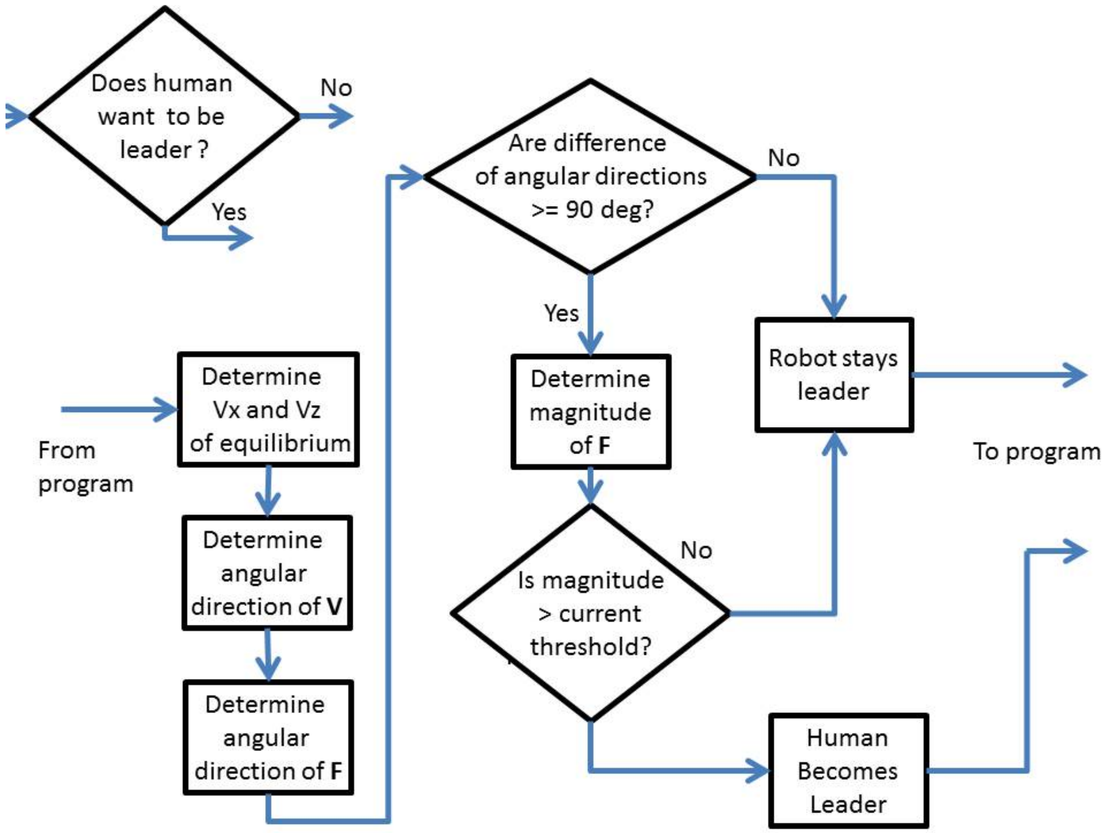

Figure 3.10: Flow Chart for Determining Leader or Follower

resultant force that the robot sensed in the x and z direction is then calculated. This is compared to the direction of the change in the equilibrium point. This compares the motion of the desired trajectory (change in the equilibrium point) and the direction of the forces from that motion. The actual position of the fixture could not be used for this instead of the position of the equilibrium point. This is because impedance control is being used and the position of the fixture is determined by the balance of the interaction forces and the impedance forces. This means that the even though the equilibrium point that is tracing the desired direction may be moving in one direction, the fixture may not be moving in this direction depending on the interaction forces that the system encounters. In comparing the angular direction of the interaction forces with the angular direction of motion of the equilibrium point, the program checks if the directions are different by at least 90 degrees. This verifies that the forces it is sensing are in substantially different direction than the current desired trajectory. The 90 degree value was used in this experiment because the other possible desired direction would be in the opposite direction of motion. However, this same process can be applied to a system with greater choices of possible trajectories by varying the size of the difference of angle needed to potential trigger a switch. The reason for using an angle requirement was to prevent the switching of roles if the follower was trying to move the system along the preferred direction faster that the current speed. This would result in a force along the desired trajectory. This requirement could be removed if it was desired to allow the follower to switch to the leader due to a desire to move faster along the current trajectory.

After verifying that the interaction forces are operating in a substantially different direction from the current trajectory, the program calculates the combined magnitude of the forces in the x and z direction. This value is then compared to a threshold value. If the forces are above the threshold value, then the system switches the robotic system to being the follower and the human to the leader. If not, then it keeps the robotic system as the leader.

While creating a control method for leader following switching, it became apparent early on that a way to transition from one mode to the other needed to be developed. When the robot is the leader and is trying to moving in the incorrect direction, the human opposes this motion. This creates higher interaction forces and through the impedance of the system a greater difference between the robot's current desired position and the current position of the fixture. If the system was switched without a transition phase so that the robot immediately became the follower, F_r would dramatically change. To demonstrate this a test was performed with a single subject and eight trials of switching from leader to follower without a transition phase.

The x-z interaction forces of four typical trials are plotted in Figure 3.11. For these tests a threshold of 15 N was used.

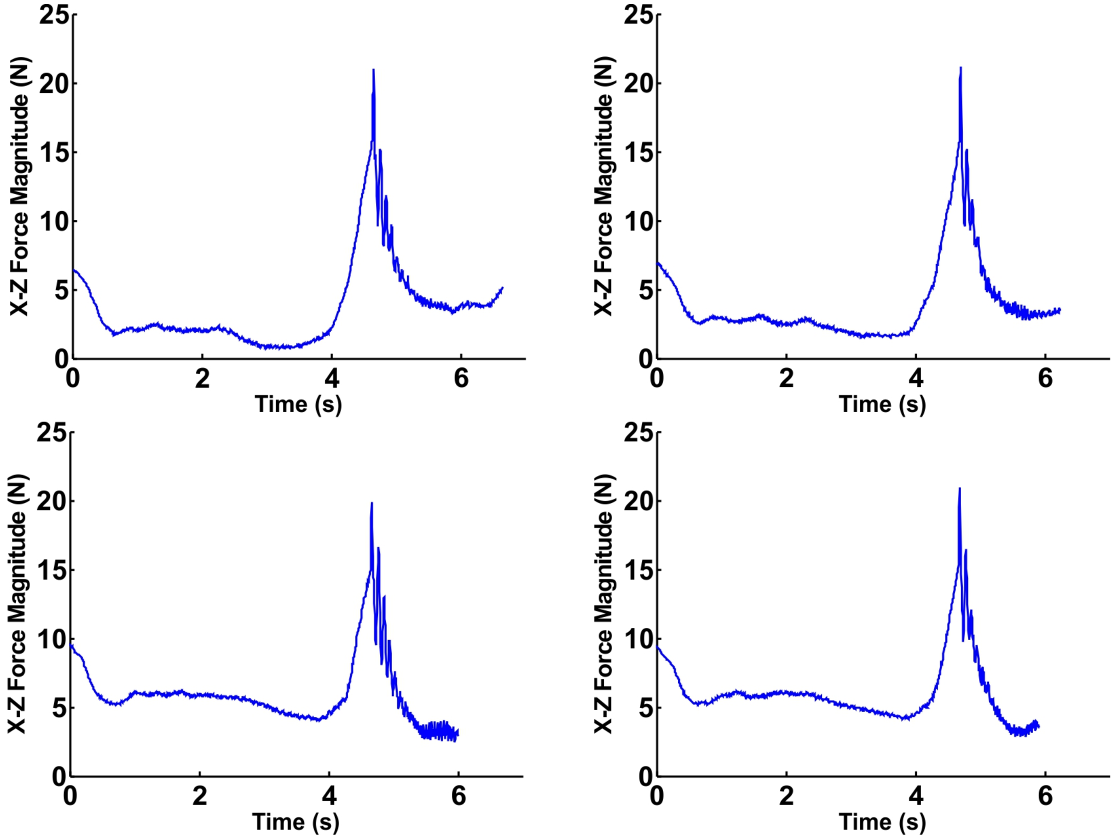

Figure 3.11: Interaction Forces without Transition Phase

Several rapid changes of force magnitudes are evident from when the system immediately switches to the follower. The rapidly changing force values suggest that an underlying problem of this immediate system is in jerk, or the rate of change of acceleration. Since $F = ma$, a fast rate of change of F (a large $\dot{F}$)would result in potentially a large $\dot{a}$ or jerk. The minimum jerk model developed by Flash and Hogan [11] concludes that when a human moves an object by themselves they tend to move the object in a trajectory that minimizes jerk. Drawing from this concept and utilizing the equation developed in the minimum jerk model , a fifth order equation was used to generate a transition trajectory. However, this trajectory is not necessarily of the actual motion of position but instead it is a trajectory designed to move the current equilibrium point to the current position of the fixture. The equations used to transition from leader to follower are:

$$x_{d(k+1)} = x_{d(k)} + (x_p - x_{d(k)})(10(c/n)^3 - 15(c/n)^4 + 6(c/n)^5) \tag{3.4}$$

$$z_{d(k+1)} = x_{d(k)} + (z_p - z_{d(k)})(10(c/n)^3 - 15(c/n)^4 + 6(c/n)^5) \tag{3.5}$$

These equations are in the same form as the minimum jerk model. The primary difference is in the particular variables used. In these equations, $x_{d(k+1)}$ and $z_{d(k+1)}$ represent the new equilibrium point. the current equilibrium point is represented by ($x_{d(k)}$,$z_{d(k)}$). The current x-z position is given by (x_p,z_p). The transition phase takes place over one second. From this, n is the number of command cycles in one second (200 cycles) and c is a counter that increase by one on each cycle. This counter, c, continues till it reaches n, or 200 cycles. This is very similar to the minimum jerk model. The main difference is that the minimum jerk model is describing the motion that a single person makes moving an object from an initial position to a final position.

This was done over a duration of one second. The time of one second was used because this would allow the human time to sense and react to the system transitioning to being the follower. The result of the addition of this transition can be seen in four typical trials plotted in Figure 3.12. This shows a significantly smoother transition from leader to follower by the robotic system.

3.3.3 Experimental Protocol

For the experiment to test the capability of the leader-follower control switching, four subjects were used. Each subject completed 42 trials for a total of 168 trials. The experiment was demonstrated for them 4 times prior to beginning. During two

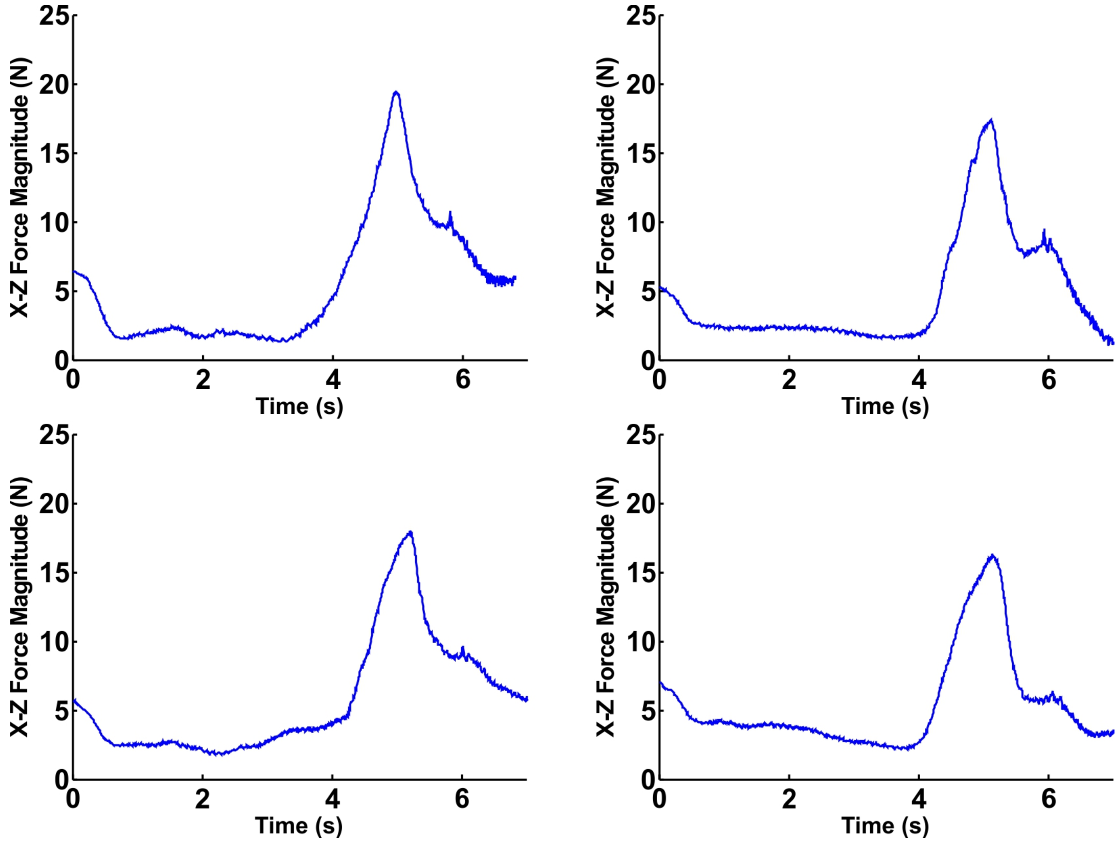

Figure 3.12: Interaction Forces with Transition Phase

of the demonstrations, the robot remained the leader and during the other two the robotic system became the follower. During the 42 trials, three different threshold values were used for switching between leader and follower. These values were 5, 15 and 25 N. These values were chosen based on observations of preliminary data of the interaction forces of the human with the robotic system. The trials were distributed evenly among the three threshold values for 14 trials per threshold per subject. Overall, half of the trials the robot was programmed to move toward the correct bin. Across all subjects this means that each of the three threshold values had 28 trials where the robot was programmed to move in the correct direction and 28 where the robot was programmed to move in the incorrect direction.

Chapter 4

RESULTS AND DISCUSSION

4.1 Preferred Direction Results

4.1.1 Human Detection of Preferred Direction

In the first experiment, the subjects were trying to discern the preferred direction of the robotic system. There were a total of 6 possible preferred directions that the robot could have. This equates to approximately 17 percent chance that the human would randomly guess the correct direction. Overall, the humans were able to correctly identify the robot's preferred direction 85 percent of the time. Additionally, if the goal is expanded to being correct or within one of the preferred direction (random guessing would be 50 percent) the humans were able to achieve this 98 percent of the time.

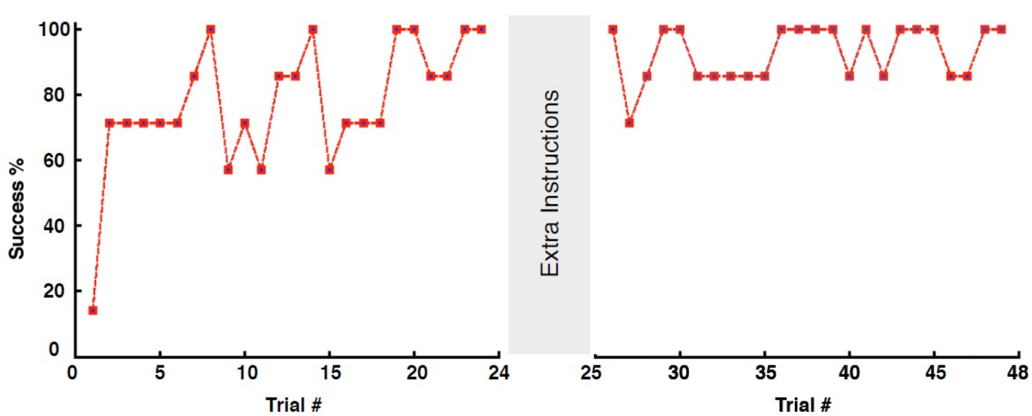

Figure 4.1: Preferred Direction Success by Trial Number

In Figure 4.1, the percentage of successfully determining the preferred direction is grouped by trial number. As can be seen in Figure 4.1, only one out of seven subjects were able to correctly determine the preferred direction of the robot on the first trial. This result is similar to what would be expected for random guessing. However, there accuracy rapidly improved and did not drop below 57 percent for the rest of the experiment. Additionally, in the last 20 trials the accuracy level did not drop below 85 percent. The break period that contained additional instructions between sets of 24 trials does not appear to have had a significant effect. The accuracy level does not significantly change between the trials immediately before and immediately after the break.

Within this experiment, subjects used different strategies to attempt to identify the preferred direction of motion of the robot with varying levels of success. These patterns were broken down into four basic patterns and a fifth group of unknown or multiple patterns. Subjects were not given any instruction as to how to find the preferred direction. The search patterns they used were of the ones that naturally occurred to them. Additionally, the subjects were not informed if they were correct in determining the preferred direction. Due to this, changes that the subjects made in search patterns were due only to the subject's perception as to how accurate or confident they were in the preferred direction.

The four patterns that were identified were small movements about the origin, moving the fixture along each of the possible preferred direction, using a sweeping or circular pattern, and a method that I call the minimization method. Of these four methods, the last method was the most successful.

The search pattern of small motions about the origin can be seen in Figure 4.2. This was the least used and least successful pattern. Out of the 336 trials, this pattern was used 8 times. It was typically used as one of the first patterns and then quickly discarded by the test subjects. The initial use of the pattern may have been a result of the initial instructions that instructed the subjects to slightly move the

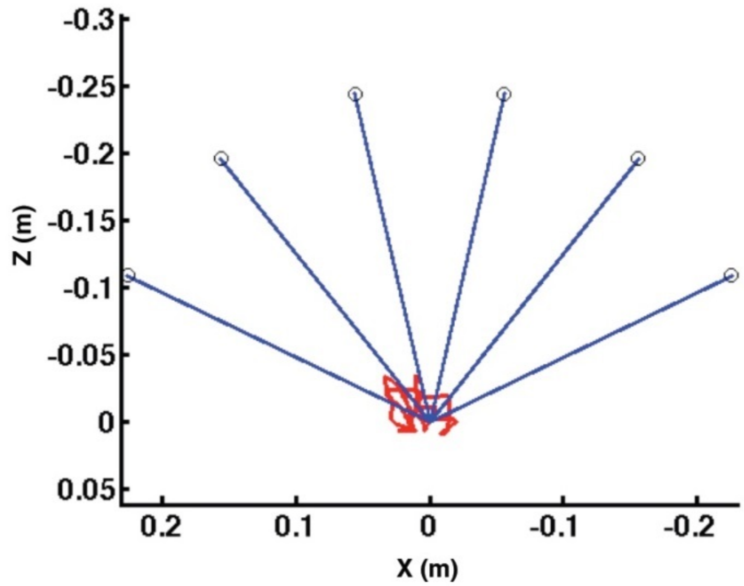

Figure 4.2: Small Motions by Human Subjects

fixture. However, no actual distance specification or demonstration was given. The interpretation of the instructions was left up to the test subjects. Due to the small motions of this pattern, smaller forces were generated during the search phase. This may account for its poor performance.

A typical tracing motion pattern can be seen in Figure 4.3 . This pattern was utilized 28 times during the testing. As can be seen in Figure 4.3 , the subject is not exactly tracing the pattern of the underlying preferred directions. This inaccuracy is due to the robot applying a force to them as previously described toward the preferred direction. This modifies the actual position of the fixture. Overall the subjects were correct when performing this search pattern 39 percent of the time (11 out of 28).

The sweeping or circular motion pattern can be seen in Figure 4.4. During this pattern the subject performed a sweeping or circular pattern of motion in order to determine the preferred direction of motion. Some subjects performed a circular or figure eight motion during this pattern. This technique was used 86 times during

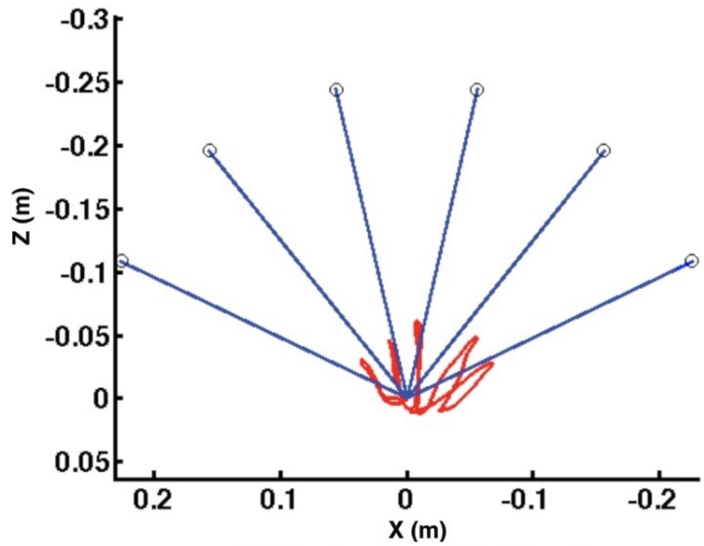

Figure 4.3: From[15]:Tracing Motion by Human Subjects

the testing. Overall, the human was able to correctly identify the preferred direction 76 percent (65 out of 86) of the time using this technique.

A typical example of a minimizing method can be seen in Figure 4.5 . This was the most used and most successful of the patterns. It was used 179 times during the testing. This is 53 percent of the total of all trials. For this method the human subject was able to correctly identify the preferred direction 99 percent (177 out of 178) of the time. In his method the subject pushes the fixture out from the origin and then appears to react radially to the force that is generated by the change in position of the fixture. This can be viewed in polar coordinates as increasing in the length of the radius and allowing */theta* to change based on the interaction forces. Essentially, the subject is minimizing the perpendicular force to the position vector. Subjects utilizing this method quickly identified the correct preferred direction. Then their behavior varied. Some subjects would stop moving and wait for the tone to play to signal the end of the search phase. Other subjects would go ahead and move the fixture to the position it needed to be in for the indication phase. Some subjects

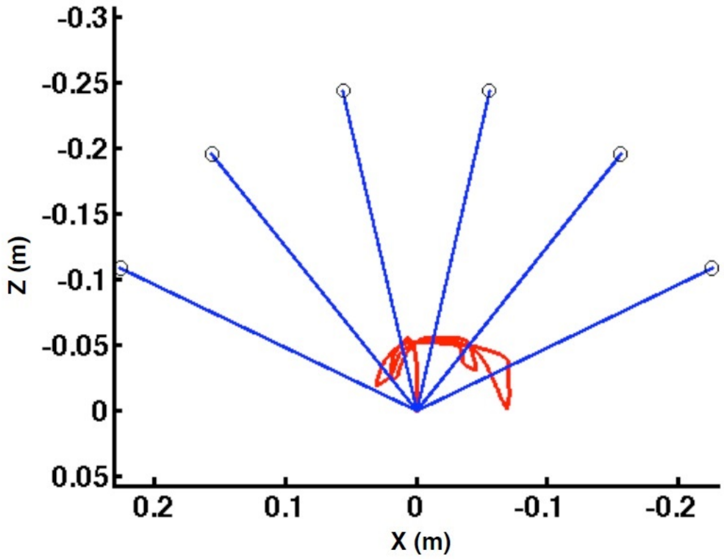

Figure 4.4: From[15]:Sweep Motion by Human Subjects

would engage in what appeared to be an action to test the accuracy of their results by oscillating between the preferred directions on either side of the identified preferred direction.

Overall, there were 35 trials where it was difficult to identify a single pattern that was used in the trial. These trials were successful 89 percent of the time (31 out of 35).

Table 4.1: Human Detection of Preferred Direction of Robot

Strategies	Small Motion	Trace	Sweep	Minimize	Other
Number of attempts	8	28	86	179	35
Number correct	2 (25%)	11(39%)	65(76%)	177(99%)	31(89%)
Number correct or within one	6(75%)	26(93%)	85(99%)	179(100%)	34(97%)

In Table 4.1 , the overall results are shown. One of the interesting notes is that subjects selected successful patterns more often than unsuccessful patterns. This

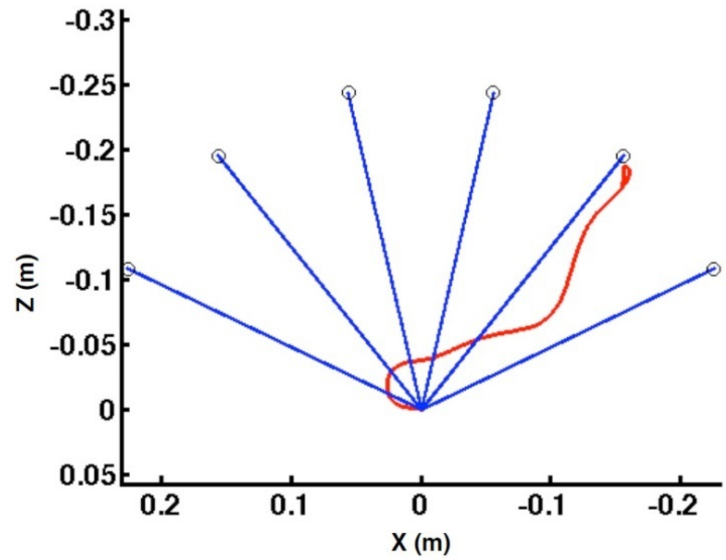

Figure 4.5: Minimizing Motion by Human Subjects

shows that subjects had a sense as to how confident they were in their response.

4.1.2 Robot Detection of Preferred Direction

The goal of the second experiment was to investigate if a robotic system could identify the preferred direction of motion of a human subject. In this experiment four search patterns were used. These search patterns were not exact replicas of the patterns used by the humans in the previous experiment. But, they were conceptually similar and inspired by the previous experiment. Five subjects participated in this experiment. All of the subjects had previously participated in the first experiment. For each of the subjects, 60 trials were performed with a randomized order that resulted in 10 trials per preferred direction. This amounts to 300 total trials across all subjects and all directions.

The first pattern used by the robotic system was small motions near the origin. The robot was programmed to move the equilibrium point along eight lines each 8mm long. These lines were spaced at 45 degree intervals. The order of this motion was randomized but the same order was used throughout the trials. Figure 4.6 shows a graph of the equilibrium position of the robot.

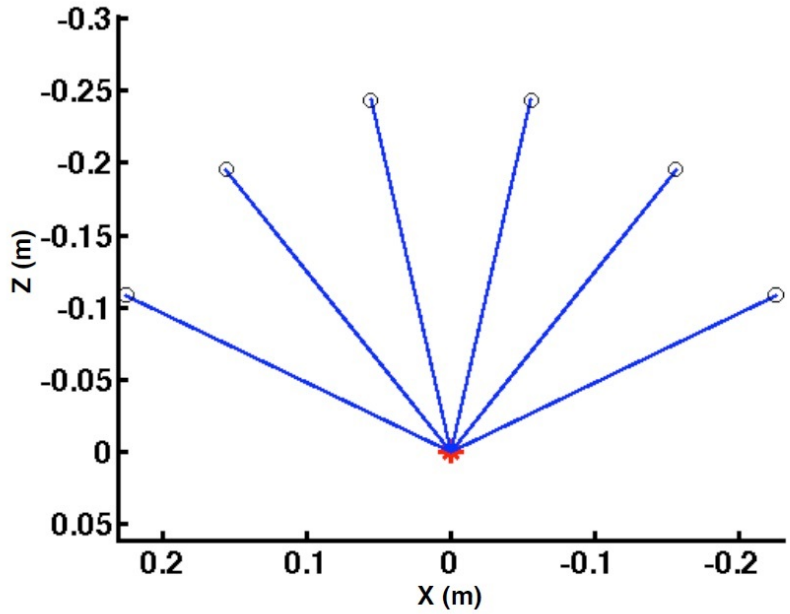

Figure 4.6: Small Motions by Robot

This search pattern was analyzed by summing all of the force vectors that were measure during the motion of the robot and to analysis the direction of the resultant force. These force vectors were calculated from the impedance force created by the distance of the actual position of the fixture from the equilibrium position of the robot as described in Equation 4.1 . This force vector is put into polar coordinates and the angle theta is matched with the closest angle of the different possible preferred direction. The closest preferred direction to the angle of the resultant force was the correct preferred direction 52 percent of the time (156 out of 300). Additionally, for 92 percent of the time (275 out of 300) the direction was either the correct direction or within one of the correct direction.

$$\mathbf{F_r} = \sum \mathbf{F_{im}} \tag{4.1}$$

$$\theta_r = \angle \mathbf{F_r}. \tag{4.2}$$

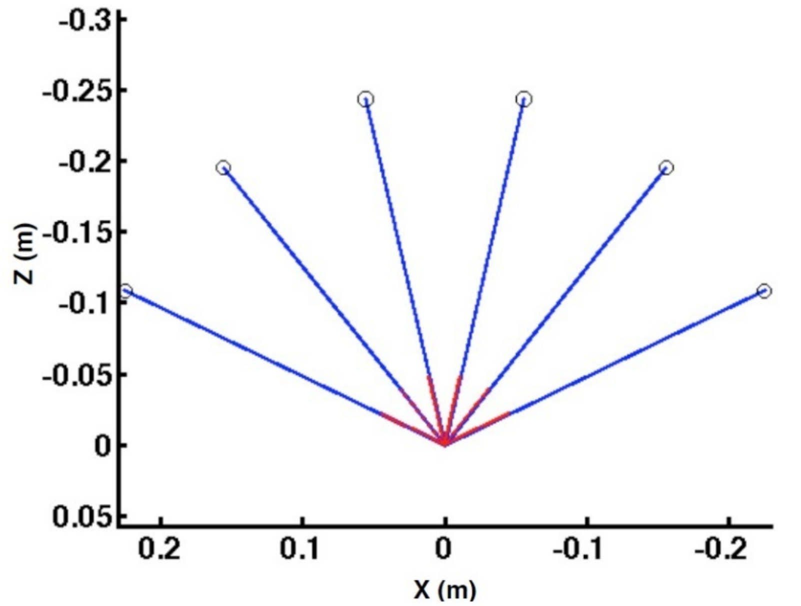

Figure 4.7: From[15]:Trace Motion by Robot

The second pattern used to detect preferred direction of the human was to move the equilibrium along each of the possible preferred direction. This was done on each leg a distance of 5 cm, as in Figure 4.3. This method was analyzed using Equation 4.3.

$$t_i = \sum_{a}^{b} |\|\mathbf{F_{im}}\| \sin(\angle\mathbf{R} - \angle\mathbf{F_{im}})| \tag{4.3}$$

In this equation, t_i(where i is from 1 to 6) is a value for each of six possible directions of the robot. The force vector $\mathbf{F_{im}}$ is created by the impedance of the robot and the difference between the robot's equilibrium point and the actual position of the robot. The position vector, $\mathbf{R}$, is the position vector form the origin to the the equilibrium point of the robot. The beginning and ending values of the summation, a and b, are the beginning and ending data points for the portion of the trial where the equilibrium point is tracing one of the 6 preferred directions. This is essentially adding up the value of the force components that are perpendicular to the equilibrium position vector. Then the possible direction that has the minimum value is evaluated as the preferred direction. This method was correct 57 percent of the time (173 out of 300).

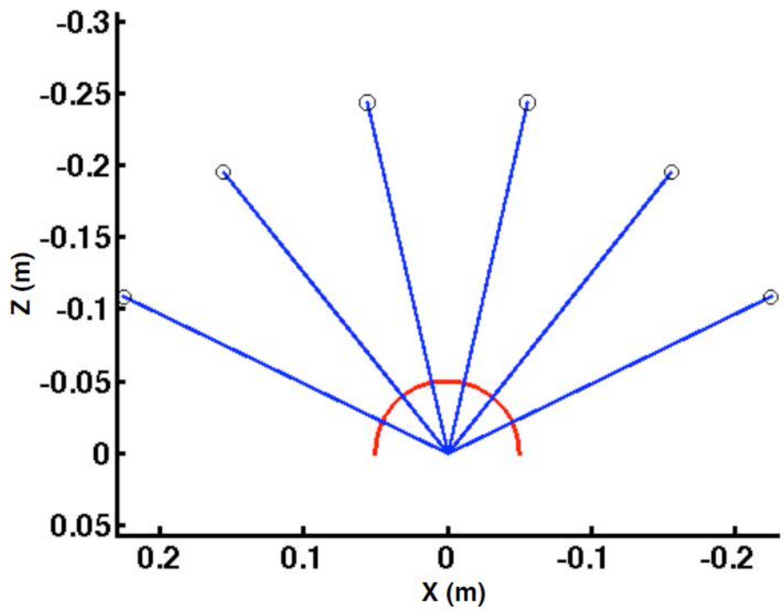

Figure 4.8: From[15]:Sweep Motion by Robot

A sweeping motion was used for the third method. In this method the robot equilibrium point was moved along a semi circular of radius 5cm, see figure4.8. To analyze this pattern, a very similar method to the previous one was used. This pattern was also evaluated with equation 4.3. The difference was that the values used for the beginning and ending of the summation, a and b, were based off of when the equilibrium point for the robot was closest to a possible preferred direction. Again, the t_i was created for each of the possible directions and the minimum value was evaluated as the preferred direction. This was successful at identifying the correct preferred direction 41 percent of the time (123 out of 300).

The final method used was a reactive method that tried to imitate the method that was most successful in the first experiment. The robot increased the distance

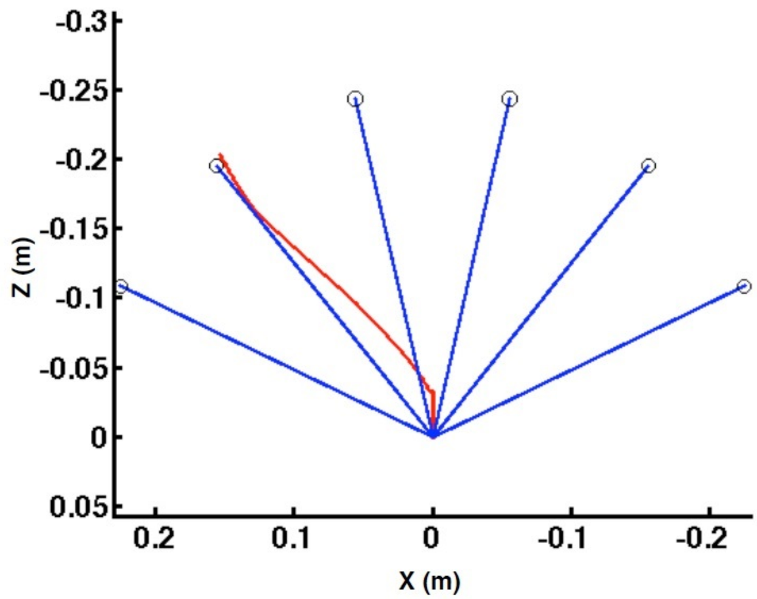

Figure 4.9: Minimizing Motion by Robot

from the origin and tried to minimize the forces perpendicular to the position vector form the origin to its current position. The robot stopped when it reached 25 cm. The closest potential preferred direction to the final position was used to determine the desired direction. Out of the 300 trials it was successful 297 times (99 percent). Because this method reacts to the subject each trial is different. However, Figure 4.9 represents a typical trial.

In Table 4.2 , the overall results are shown. One of the interesting notes is that the robotic system was much more successful at using small motions to determine the preferred direction than humans were.

4.1.3 Comparison to Human-Human

The experiments on the ability for robots and humans to communicate a preferred direction produced intriguing results. However, in order to put these results in context, they need to be compared to results that two human subjects have engaging

Table 4.2: Robot Detection of Preferred Direction of Human

Strategy	Small Motion	Trace	Sweep	Minimize
Number of attempts	300	300	300	300
Number correct	156(52%)	173(58%)	123(41%)	297(99%)
Number correct or within one	275(92%)	240(80%)	220(73%)	300(100%)

in a similar experiment. Dr. Santello and the Neural Control of Movement Laboratory conducted a similar experiment[15] that can be used to compare results between the case of robot-human and human-human.

The physical setup was very similar. In Figure 4.10, the preferred direction board is turned 90 degrees from its previous orientation. Two grip sensors are added to the previously used fixture. The robotic system is used in this experiment only as a way of restricting the motion of the fixture to the horizontal plane. The human participants each grasp one of the sensors. The leader is shown a number of the preferred direction. Then a signal is played for the trial to begin. The follower subject then tries to move the fixture to sense the preferred direction. The follower wrote down the preferred direction at the end of the experiment. The subjects are told to keep the center of the fixture within a 10 cm radius of the origin on the preferred direction board. This prevents a subject from knowing what the preferred direction is by use of position feedback instead of impedance.

In this experiment, ten subjects were used(5 pairs). Before starting the experiment, pairs of subjects engaged in 30 trial experiments in order to familiarize them selves with the experiment. After this, they conducted 60 trials per pair of subjects. For each pair, one subject was designated as the leader the other as the follower and this remained unchanged throughout the experiment.

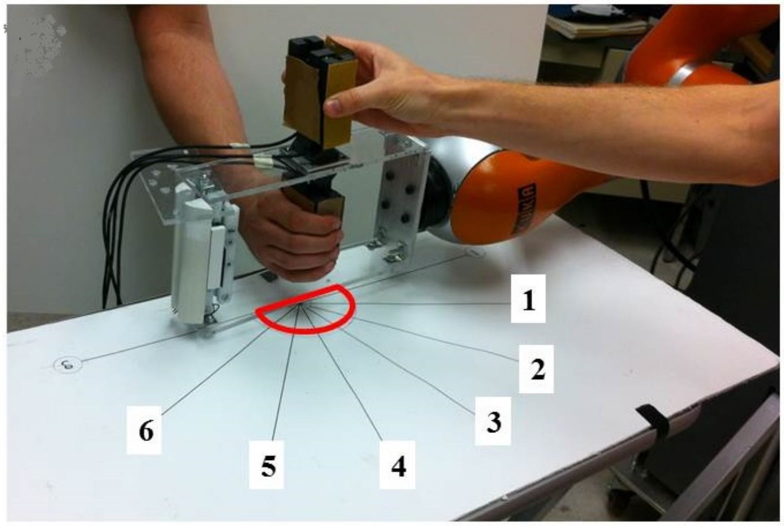

Figure 4.10: Adapted from [15]: Setup for Human-Human Experiment

To compare the data from the different experiments, the data from the robot-human experiments that represented the sweep and circular patterns were used. Given the motion restrictions of the human-human experiment the minimizing method was not performed in the human-human experiment. Additionally, the small movements about the origin were rarely used by humans in the robot-human experiments. Due to the reaction times of two humans coupled together the small movements about the origin method in the robot-human case would also be substantially different.

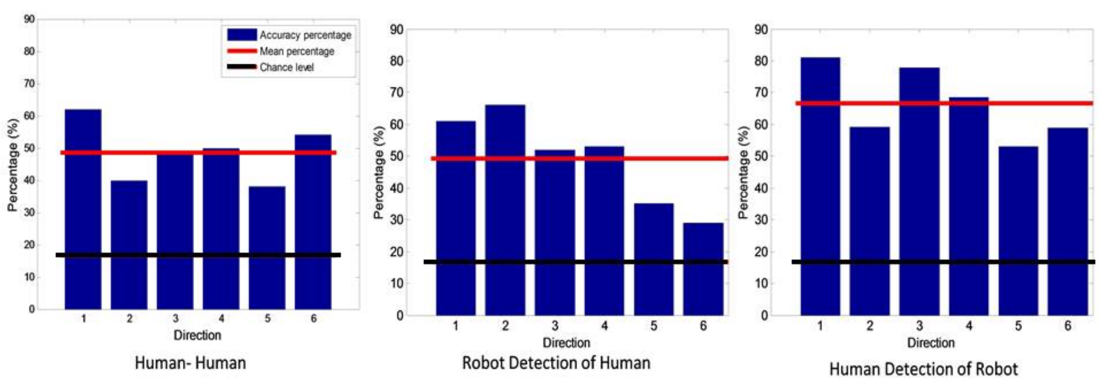

Figure 4.11: Adapted from [15]: Comparison of Success in Preferred Direction Experiments

As seen in Figure 4.11 , the overall accuracy in the preferred direction experiments are shown with accuracy of each of the directions listed. The higher levels of performance along the first and sixth preferred direction for the human-human experiment might be caused by their only being one other direction adjacent to it. The first preferred direction can not be confused with a direction to the left of it nor can the sixth direction be confused with a direction to the right of it. Also, in Figure 4.12, the error of the preferred direction is shown. While there are some differences, theses results are similar. It would additionally be expected for the robotic system to perform better at both creating a variable impedance field and in accuracy of sensing a similar interaction from the human. This explains why the robot-human performance would be slightly better than either the human-human or human robot case, but also provides evidence that the use of variable impedance as a means of communicating between robotic systems and humans performs similarly to human-human performance.

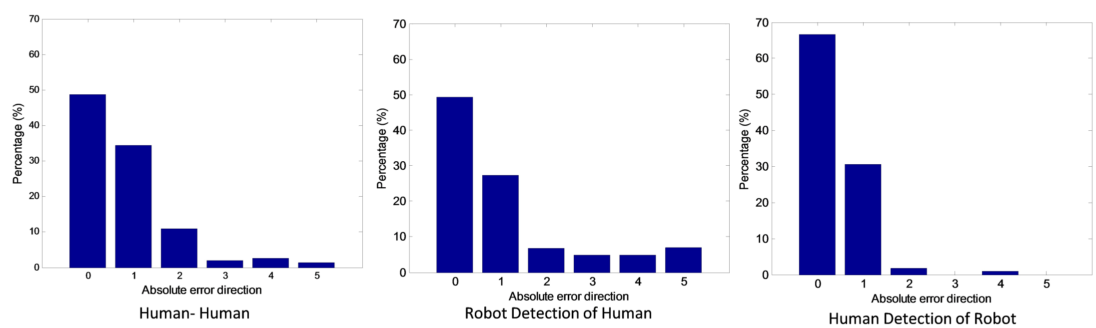

Figure 4.12: Adapted from [15]: Comparison of Error in Preferred Direction Experiments

4.2 Leader-Follower Control

In this initial leader-follower experiment a control method for switching from leader to follower for the robotic system was devised. This control method utilizes a key concept from the previous work. This concept is that the one of the participants can communicate a preferred direction of motion using impedance. This is particularly important for the switching of leader-follower roles. If the current leader moves in a direction that is undesirable to the current follower, the follower can communicate this with high opposing forces. This means that when the leader moves in an incorrect direction they feel high opposing forces. This indicates that the follower has a different direction that they desire to move towards and that they should become the leader.

In this experiment, three different threshold values were used. These values were 5, 15 and 25 N. These values were randomly distributed across 42 trials (14 for each threshold). In these trials, half the time the robotic system would have the correct trajectory. The other half of the time the robotic system would turn the incorrect way. This amounts to 7 correct trajectories and 7 incorrect trajectories for each of the thresholds per subject. For the four subjects this means that there were a total of 28 correct and incorrect trajectories for each of the three thresholds.

One of the key elements to examine in this experiment is the performance of the switching between leader and follower. For this analysis, a false positive is defined as when the robot system switches to follower but the human moved the fixture to the same location as was planned by the robotic trajectory. A false negative is where the human was trying to get the robot system to switch to being a follower but was unable. The results of this experiment can be seen in Table 4.3. The lowest threshold (5 N) produced a number of false positives, or switching when unnecessary. Out of the total number of trials at 5 N where the system should not have switched this amounts to 54% (15 out of 28). For the total number trials where the robot trajectory was correct this would equate to 18% (15 out of 84). For the highest trajectory (25 N), three of the four subjects had one occurrence where they were unable to get the robot system to switch and it moved the fixture and the human to the incorrect target. This was likely due to the high threshold value and that the humans were trying to also to maintain the level of the fixture to prevent the ball from falling off.

Table 4.3: Leader-Follower Results

	False Positives	False Negatives	Dropped Balls	Successful
Subject 1	3	1	5	36
Subject 2	5	1	8	33
Subject 3	3	1	3	38
Subject 4	4	0	7	35
Mean	3.75	0.75	5.75	35.5
Std. Dev.	0.96	0.50	2.22	2.08

During the successful trials where the robot remained the leader and the human remained the follower, the force exerted by the human varied between test subjects and between trials. This shows that while a threshold value of 15 N would be valuable, in the long term it would be better if this value adapted to the user. Additionally, this test was performing a single task with the same fixture and object of interest (ball). If this experiment was performed with objects of different weight or humans in different positions a different threshold may be required. Due to this, a better control method would be for the system to learn from the human's interaction and alter the threshold to this interaction.

4.3 Adaptive Leader-Follower Control

To improve on this control method and adaptive controller was created as seen in Figure 4.13. This control block diagram largely functions the same as the non-adaptive version. The difference is that the Role Planner is now adaptive and changes based on the robot's interaction with its environment. The overall program flow chart is shown in Figure 4.14 .

The difference is the inclusion of an adaptive Leader-Follower block. The

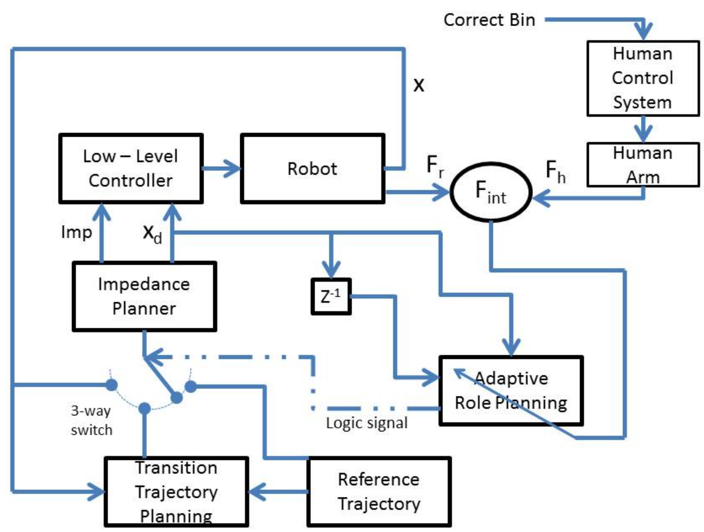

Figure 4.13: Leader-Follower Adaptive Control Diagram

process describing how this block operates is shown in Figure 4.15 . Initially the program checks to see if the robot remained the leader during the trial. If it did remain the leader, then it checks to see if the maximum interaction force measured was less than the current threshold value minus a buffer value. The buffer value used in this controller was 3 N. If it was lower, then the system decreases the threshold by the decrement value. This value is initial set at 1 N, but it is changed to 0.5 N if a false positive is detected. If the value measure was not less than the threshold minus the buffer, then the threshold stays the same. If the robot did not remain the leader, then the program checks to see if the human moved the fixture to the same position that it was already going to move it to. If this did occur, then this is a false positive. Then the decrement value is changed to 0.5 N and the threshold is increased by 2 N. If it was not a false positive the threshold remains the same.

For this experiment the control method would be modified to learn from the human's interaction with in to adapt both its switching of leader-follower roles and to adapt the robot's trajectory while it is the leader. Initially the robotic system begins

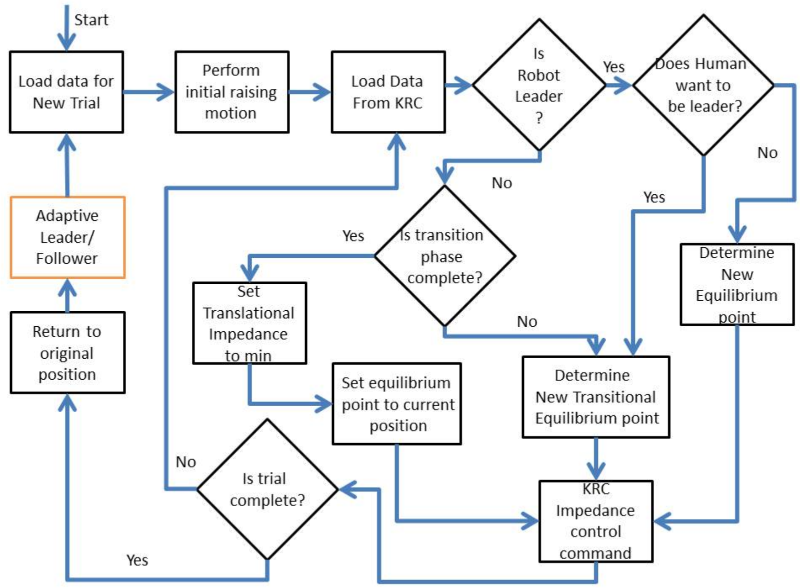

Figure 4.14: Leader-Follower Adaptive Flow Chart

with a threshold of 15 N. This was chosen based off of the initial testing performed in the previous experiment. For this experiment, four subjects were used performing 42 trials each as in the previous leader-follower experiment.

The results of the adaptive leader-follower experiment can be seen in the Table 4.4 .

Table 4.4: Adaptive Leader-Follower Results

	False Positives	False Negatives	Dropped Balls	Successful
Subject 1	1	0	3	39
Subject 2	1	0	3	39
Subject 3	0	0	1	41
Subject 4	1	0	2	40
Mean	0.75	0	2.25	39.75
Std. Dev.	0.50	0	0.96	0.96

The adaptive control improved the performance of the system. In Figure 4.16, the percentages of false positives are shown. The first bar is the the percentage of false

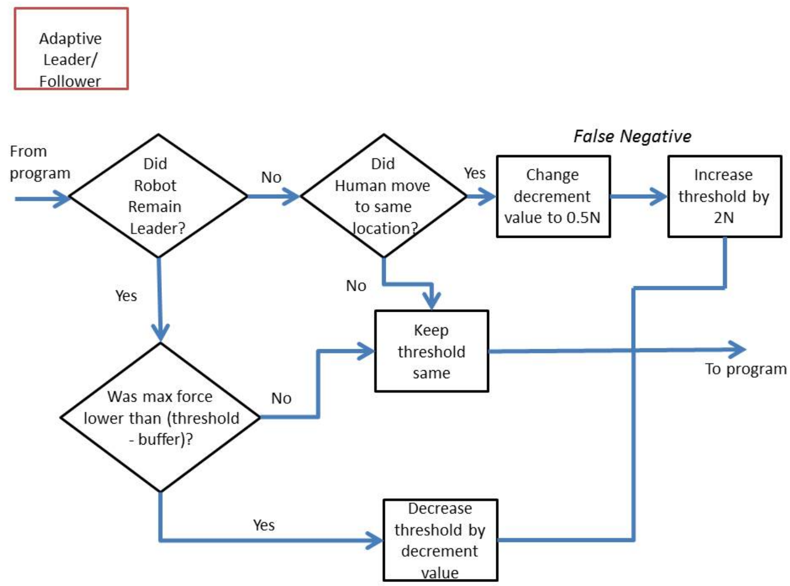

Figure 4.15: Leader-Follower Adaptive Process Flow Chart

positives out of the number of 5N threshold trials in the non-adaptive experiment. The second bar is the percentage of false positives for the entire number of trials for the non-adaptive experiment. The final bar is the percentage of false positves out of the entire adaptive experiment. The non-adaptive program had much higher percentages of false positives than the adaptive version. This shows that the adaptive element was able to improve the performance of the system.

Additionally, the adaptive version was able to adapt to different threshold needs for different subjects. Figure 4.17 shows the changes in the adaptive threshold over the 42 trials for one subject. The threshold adapted from an initial 15 N to a final 13 N. Figure 4.18 shows the changes in the adaptive threshold over the 42 trials for a different subject. The threshold adapted from an initial 15 N to a final 11 N. The threshold for all subjects adapted downwards from the initial 15 N. This shows that the adaptive controller also lowered the interaction forces needed to trigger a switch of roles.

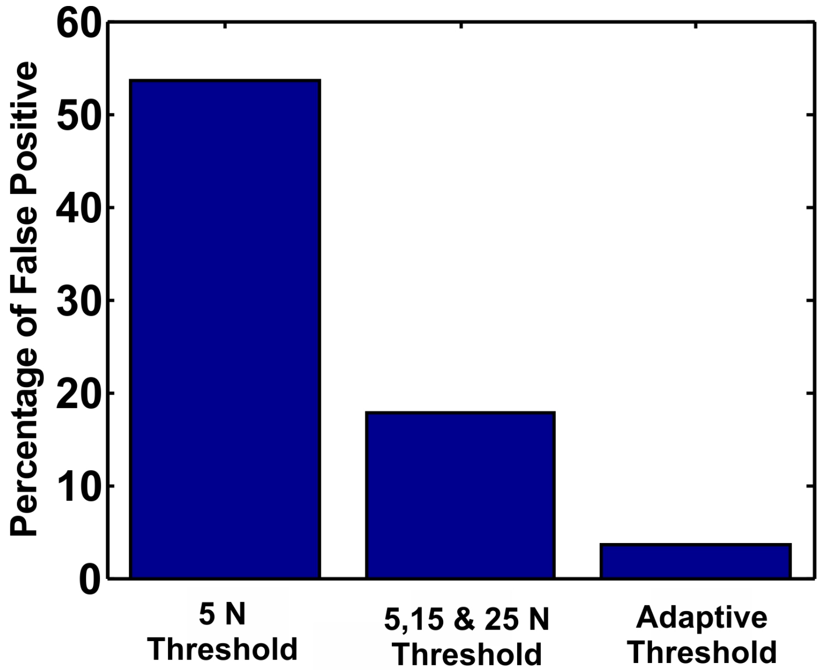

Figure 4.16: Leader-Follower False Positive Percentage

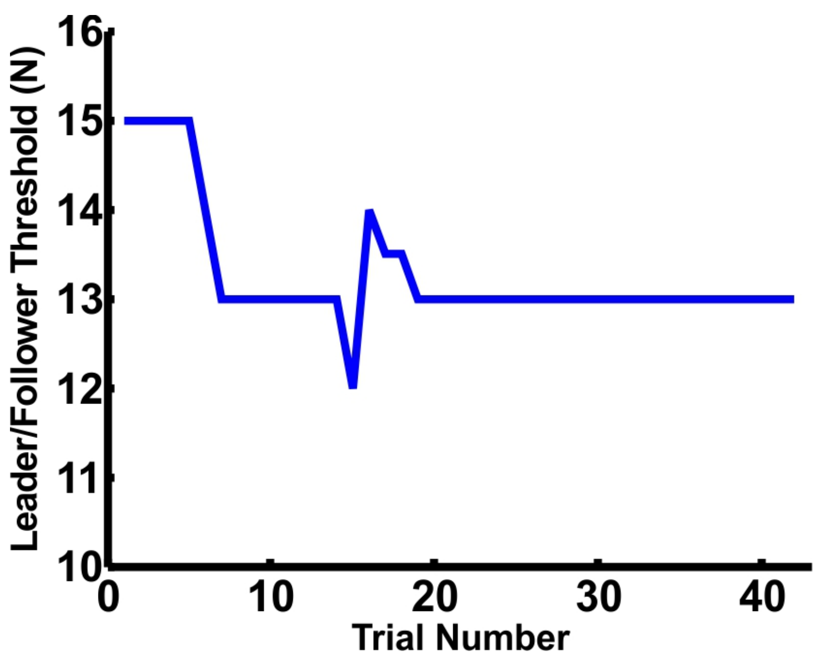

Figure 4.17: Leader-Follower Threshold for Subject One

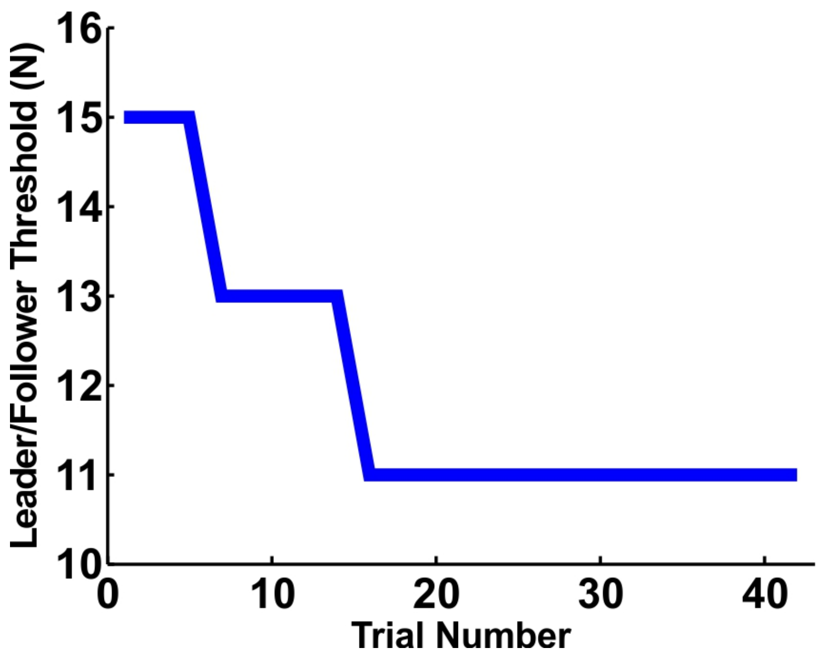

Figure 4.18: Leader-Follower Threshold for Subject Two

Chapter 5

CONCLUSION AND FUTURE RESEARCH

5.1 Conclusion

Several conclusions can be drawn from the research in this thesis. First, the ability of both humans and robotic systems to communicate to each other a preferred direction was shown. This ability to detect the preferred direction of either the human or robot was shown to be up to 99% effective, depending on the method used. This is valuable because it means that impedance can be an effective communication during a cooperative task. This also means a system does not have to have all possible scenarios programmed into it, as it can also rely on communicating with its human partner. Additionally this suggests a solution to leader-follower switching. This research also showed that a leader-follower switching controller based off of the previous communication concepts could be an effective way of dealing with this type of switching. This method proved successful 84% of the time. Finally, this control method was refined using adaptive control resulting in lower interaction forces and a success rate of 95%. This shows the capability of future development of adaptive control in human-robot cooperation.

5.2 Future Research

There are several areas for future research based off of this thesis. First is the extension of these methods to the 6-DoF case. All of these methods focused on moving in a horizontal plane. While there are many applications that are essentially planar movement, for full implementation in the widest array of applications these methods need to be expanded to the 6-DoF case. Additionally, leader-follower switching also needs to be extended for the case of the robot taking over as leader during the task. It is believed that a similar method would work for this case as the one used in these experiments, but this needs to be implemented and tested. Finally, adaptive control has shown itself to be useful in adapting to the variations of humans and tasks. This method of control deserves further development and implementation in areas of human-robot interaction. One possible area of adaptation is the buffer value used in leader-follower switching. In this research a value of 3 N was used. This value could be adapted based on the consistency of the human's interaction with the system. The more consistent the human interacts with the system the smaller the buffer value needs to be. Overall, adaptive control has the ability to simplify the information needed to develop a system that can interact with humans in an unstructured environment.

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