2015 IEEE International Conference on Robotics and Automation (ICRA)
Washington State Convention Center
Seattle, Washington, May 26-30, 2015

On the Role Duality and Switching in Human-Robot Cooperation: An adaptive approach

Bryan Whitsell and Panagiotis Artemiadis*

Abstract— **As the expansion of the field of robotics has continued, the physical interaction between robots and humans has become an increasingly important area of study. Many of these physical interactions can be seen as a cooperative task conducted by both the robot and the human. Often, when two humans are interacting, one of them will act as the leader of some aspect of the task and the other will act as a follower. This cooperation may require the switching of roles between leader and follower. This can be further complicated by the fact that different participants may be the leaders of different aspects of the task. Previous research in human-robot cooperation focused on the switching of only a single role. In this paper, we investigate a novel method for the simultaneous switching of two roles between a robot and a human participant. This switching method was examined using both fixed and adaptive parameters that control role switching. Overall, human-robot cooperation was successful in the task 85% of the time when using a non-adaptive method and 95% when using an adaptive control method.**

I. INTRODUCTION

As robotics continues to advance into every aspect of human life, cooperative tasks between robots and humans becomes an increasingly important area of research. Robotic systems have traditionally been used in closed cell-work areas with the intent of minimizing the possibility of human interaction. As the field progresses, robots are increasingly being used and studied in applications where interaction with humans is an essential element. One category of this interaction is where a human and robot are physically interacting and cooperating to achieve a shared goal.

There are many different applications for this type of cooperative task. These types of task vary from construction industry placement of large objects [1], retraining humans to perform motions correctly as in rehabilitation robotics [2], and for assistive robotics designed to help people regain lost capabilities. In all of these examples, the robotic system and the human are working together toward a common goal. The cooperation between participants is an essential element of these tasks.

During cooperation between two humans, often one of them acts as a leader and the other acts as a follower. There may be several reasons for this type of interaction. One is that at different points of the cooperative task, one participant may have a better view of the task and can perform better at leading the task. Another reason, is that different participants often bring different skills and abilities to the task. In extending human-human cooperation to the human-robot case, there is a need for the ability for the robotics system to be either the leader or the follower of a task and for the ability to switch roles during the task.

A number of researchers have addressed the issue of different roles of humans and robots in cooperative tasks [3]–[7]. Often the role of the leader is assigned to the human and follower to the robot. While this is useful for researching methods for controlling a robot to follow a human lead, as an application it is limiting. Some of the most compelling applications for robotics in cooperation with humans are where the robots are contributing abilities that the human does not possess. For robotic systems to be fully utilized, they need to be able to be both a leader and a follower in the task. An additional complication is that the roles of leader and follower may need to be changed during the task. One way some researchers [8] have tried to address this is by creating a continuous function by rapidly switching between discrete models of leader and follower behavior. One observation made by the researchers was that the human subjects often believed they were the leader when the robotic system thought that it was acting as the leader. However, Endsley and others [9] in the Human Machine Interface (HMI) field have shown a problem with approaches that leave the human uncertain of their role. If the human believes that they are leading and the robotic system is following, they will not be able to correctly predict the robotic systems response to their actions. This can lead toward confusion, mistrust, and accidents related to the robotic system. The switching method between leader and follower needs to be one in which the human is certain of roles and can act and react appropriately.

Reed and Peshkins research on human-human interaction also has some very important implications [10]. They showed that within a larger cooperative task, individual humans may specialize and take on different roles. Often individual humans would, without verbal negotiation with their partner, take on the role of either the acceleration or deceleration of the motion of an object in a one dimensional task. This is an interesting result and could be viewed as one human as the leader of acceleration part of the task and the other human the leader of the deceleration part of the task. This was a one dimensional task so only motion along one rotational axis was allowed. For a task with multiple degrees of freedom (DOF), this concept would suggest the need for the ability for the participants to be leader of different elements of the overall task.

In this paper, we used a task of a human and robot

*Corresponding author
All authors are with the Department of Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287, USA bwhitsel, panagiotis.artemiadis@asu.edu

transporting a ball balancing on a fixture to one of two bins. The robotic system is constrained to allow only motion in four DOF. Two of the DOF are for translation and the other two DOF are for rotation or maintaining the level of the fixture. Moreover, we examined the switching of roles of leader and follower during the human-robot cooperative task. In order to prevent confusion in the human subject, very distinct and easy discernible control strategies were used by the robotic system when it was acting as either the leader or follower. To switch between leader and follower, a threshold value was used based on the interaction forces between the robot and human. Using a set threshold value as well as an adaptive value was examined.

The significant novelty of this approach was for both the human and robot to be the leader of different elements in accomplishing the task and to examine the ability for the human and robot to simultaneously switch roles when demanded by the task. The four degrees of freedom for the task (2 rotations and 2 translations) allowed for an easy separation of the task into two different elements. One element was for the correct translation of the jointly manipulated fixture to the correct bin. The second element was maintaining the level of the fixture to keep the ball from rolling off of the fixture prematurely. This allows for each participant to be simultaneously a leader in one element and a follower in another element of the task.

The organization of the rest of the paper is as follows. In Section II, we discuss the details of the design of the experiment and the methods used to carry out the experiment. The results of both the experiments are reported and analyzed in Section III. Section IV contains our conclusions drawn from the experiments.

II. METHODS

A. Experimental Setup

The physical setup of the experiment can be seen in Fig.1. The robotic system used was a 7 DOF KUKA Lightweight 4+ robotic arm (LWR4+). This utilized the KUKA Robotic Controller (KRC) and interfaced with a computer utilizing KUKA's Fast Research Interface (FRI). Attached to the end-effector of the robotic arm was a fixture, as shown in Fig.1. This was designed to attach to the robotic arm on one side and to provide a handle on the other side for the human to grasp. Two pieces of clear plastic connect the handle to the plate that attaches to the robot A small rectangular lip was made on the bottom plastic cross piece and a foam ball was placed at the center of this rectangle. This ensured that the ball was in a similar location at the start of each trial and provided a small amount of resistance to rolling. A white board with a black path was placed below the fixture. The path was "T" shaped. A bin was placed at the end of each leg of the path, as shown in Fig.1.

The robotic system was controlled in Cartesian impedance mode. This allows the higher level controller to set different values for the stiffness in the Cartesian axes and to specify the equilibrium point for the stiffness. A high stiffness was used along the vertical (y) axis and for rotation about

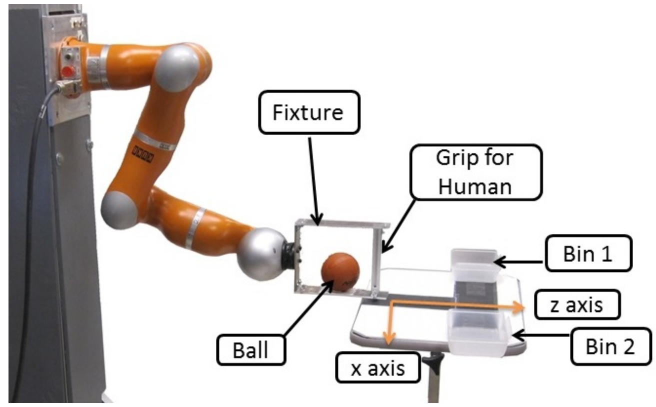

Fig. 1. Physical Setup for Leader/Follower Experiments

this axis ($k_{ty} = 5000N/m$ and $k_{ry} = 300Nm/rad$ respectively). This minimized the motion along the y axis both in translation and rotation. This constrained the task to translation along the horizontal $x-z$ plane and rotation about the z and x axes (4 DOF). The equations pertaining to the force generated by the robotic system can be seen below.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \mathbf{M}\ddot{\mathbf{x}} - \mathbf{B_t}\dot{\mathbf{x}} - \mathbf{K_t}\mathbf{x} \tag{1}$$

$$\begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} = \mathbf{J}\ddot{\theta} - \mathbf{B_r}\dot{\theta} - \mathbf{K_r}\theta \tag{2}$$

$$\mathbf{K_t} = \begin{bmatrix} k_{tx} & 0 & 0 \\ 0 & k_{ty} & 0 \\ 0 & 0 & k_{tz} \end{bmatrix} \qquad \mathbf{x} = \begin{bmatrix} x_p - x_e \\ y_p - y_e \\ z_p - z_e \end{bmatrix} \tag{3}$$

$$\mathbf{K_r} = \begin{bmatrix} k_{rx} & 0 & 0 \\ 0 & k_{ry} & 0 \\ 0 & 0 & k_{rz} \end{bmatrix} \qquad \theta = \begin{bmatrix} \alpha_p - \alpha_e \\ \beta_p - \beta_e \\ \gamma_p - \gamma_e \end{bmatrix} \tag{4}$$

In the above equations, F_x, F_y, and F_z represent the force generated by the robot along the x, y, and z axes respectively. T_x, T_y, and T_z are the torques generated by the robot along the x, y, and z axes respectively. The mass matrix, $\mathbf{M}$, and the rotational inertia matrix, $\mathbf{J}$, are computed by the robotic controller and are not modified during the experiment. The matrices $\mathbf{B_t}$ and $\mathbf{B_r}$ are the damping coefficients for translation and rotation, respectively. These damping coefficients are affected by the damping ratio that is set by the program (0.7 for these experiments). $\mathbf{K_t}$ is the translation spring constant matrix and $\mathbf{K_r}$ is the rotational spring constant matrix. These matrices are multiplied by displacement vectors to create a force generated from virtual springs. The elongation of the spring in translation is determined by the difference from the current position of the end-effector (x_p, y_p, z_p) and the equilibrium point (x_e, y_e, z_e). This equilibrium point is varied during the experiment by the program. Similarly, the elongation of the rotational spring is determined by the difference of the end-effector's current angular position (α_p, β_p, γ_p) and the equilibrium angular

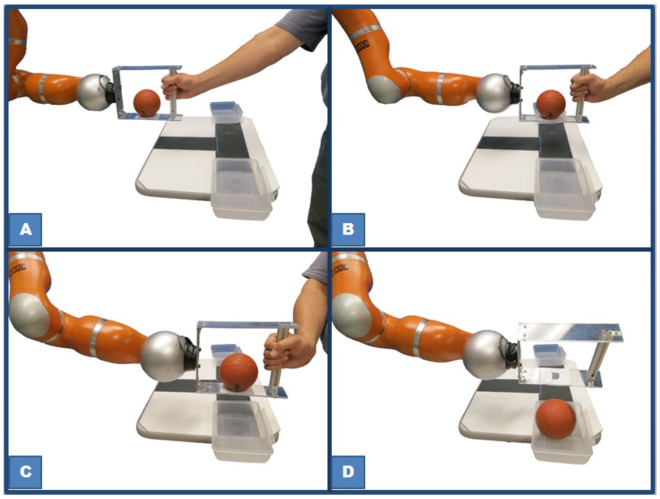

Fig. 2. Process of Trial:A) Initial start of trial, B)Beginning of lateral movement, C) End position at bin, D) Rotation by robot and ball drop into bin.

position (α_e, β_e, γ_e). The α, β,and γ variables represent the rotation about the x, y, and z axes respectively.

B. Program and Control Method

The motion of one trial can be seen in Fig. 2. At the beginning of each trial the robot starts as the leader of the translation task and as the follower of the leveling task. As a consequence of this, the human is the follower of the translation task and the leader of the rotational task. The human is informed of this during the initial instructions. The robotic system begins raising the fixture to the correct height for the trial. As it does this, it gradually adjusts the impedance values to equal the values that are used at the start of the trial. This initial phase was done to allow the subject time to adjust to the impedance values of the robot prior to the start of the cooperative task. This raising motion is also similar to the motion often seen in human-human cooperative transportation tasks. Once the robot reaches the correct height, the cooperative task begins.

At the start of the trial, the stiffness for the $x-z$ plane (k_{tx} and k_{tz}) was set at $500N/m$ to allow the subject to be able to move and influence the motion of the fixture and the rotational stiffness was set to $1Nm/rad$ for rotation about the x and z axis (k_{rx} and k_{rz}). The robotic system begins leading the translation task by changing the x_e and z_e to a new point (x_j,z_j) along a programmed reference trajectory. If the robotic system leads the human toward the incorrect bin, the human is to take over as leader of the translation task and lead the robotic system to the correct bin. When this occurs, the robot becomes the leader of the leveling task and maintains the level of the fixture to prevent the ball from rolling.

If the robotic system remains as the leader of the translation element during the trial, then the robot moves in the positive z axis for 30 cm. It then begins a 3 cm radius curve for 90 degrees. During this turn, the orientation of the fixture about the y axis does not change. The turn only affects the translation of the fixture. This curve is either toward the positive x direction or the negative x direction. The robot continues to lead the translation task an additional 17 cm along the x axis continuing to one of the bins. Then it reaches the correct position for dropping the ball into one of the bins. At this point a tone is played to let the subject know that it is at the end position. Then all of the stiffness values are increased to the maximum value and the robot performs a rotation along the z axis. This rotation is designed to drop the ball into the bin if the ball has remained on the fixture during the task. This is done as a way to score the cooperative task.

If the robotic system determines that the human wants to become the leader of the translation task, then the system plays a distinctive tone and the roles are switched. For the robotic system to follow the human's lead in translation, it lowers the stiffness in the $x-z$ plane to $1N/m$ (k_{tx} and k_{tz}) and resets the equilibrium for the impedance to be at the current location (x_p=x_e and z_p=z_e). This makes the robotic system very compliant in translation. When the robotic system takes over the lead of the rotational element, it increases the rotation impedance to $300Nm/rad$ along all axes. It uses the original orientation for its angular set point. This ensures that the fixture is level. Once the human moves the test fixture to the appropriate distance along the positive or negative axis, then the system plays tone and the trial ends. The robotic system performs the same rotation motion as noted previously. If the human has maneuvered the fixture to the correct position, then the ball will fall into the correct bin.

For the purpose of these experiments, only a desire to switch to become the leader of the translation element was examined, in future work this method will be applied to multiple tasks. For the initial leader-follower experiment a control method for the switching from leader to follower for the robotic system was devised. The concept behind the developed control scheme is based on the changing of the impedance of the follower. If the current leader begins to proceed in an incorrect direction, then the follower will naturally increases their impedance level, offering an increasing level of resistance. This results in an increase in interaction forces in a direction different that the current direction of motion. This indicates that the follower of the task desires to become the leader of the task.

$$\phi_e = ArcTan2(z_{e(k)} - z_{e(k-1)}, x_{e(k)} - x_{e(k-1)}) \quad (5)$$

$$\phi_f = ArcTan2(F_{int(z)}, F_{int(x)}) \quad (6)$$

$$\|\mathbf{F_{int}}\| = \sqrt{F^2_{int(x)} + F^2_{int(z)}} \quad (7)$$

$$\phi_{\mathbf{d}} = |\phi_e - \phi_f| \quad (8)$$

$$s = \begin{cases} 1, & \text{if } \phi_d \geq 90^\circ \text{ and } \|\mathbf{F_{int}}\| \geq F_{th} \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

The above equations describe the method for the robotic system to determine when to switch roles. In the above equations the previous equilibrium point is $x_{e(k-1)}$,$z_{e(k-1)}$. The current equilibrium point is $x_{e(k)}$,$z_{e(k)}$. These equations

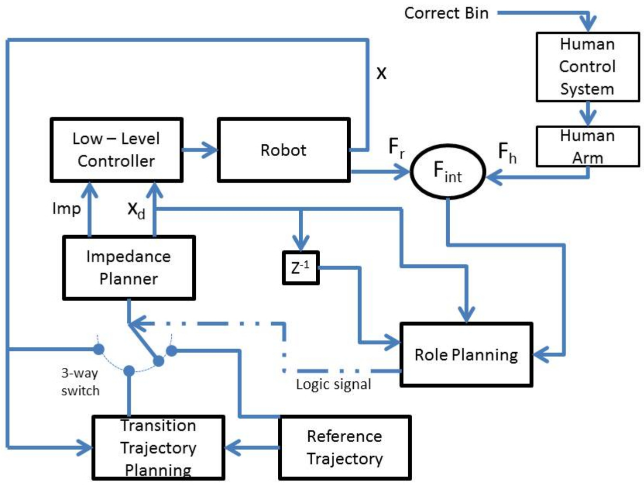

Fig. 3. Control Diagram For Leader/Follower Control

test if F_{int} is at least 90° from the direction of the planned path and that $\|\mathbf{F_{int}}\|$ is greater that the threshold, F_{th}. If true, then the system determines that the human desires to change roles, $s = 1$.

In order to simultaneously exchange roles, a short one-second transition phase was instituted to allow the human time to realize and react to the robot responding to the human's desire to change roles. If the human decides the robot is leading in the incorrect direction, the motion of the robot is opposed by the human. This creates a greater interaction force in a direction different from the desired trajectory. As a consequence of this, there is a larger difference between the current position of the robot and the equilibrium point. However, when the robot acts as a follower in translation it sets the current position as the desired position to minimize resistance to the human's leadership. To transition between the two states a smooth transition from the current equilibrium to the current position needs to be made. To perform this transition, the following fifth order equations were used.

$$x_{tr} = x_{e(k)} + (x_p - x_{e(k)})(10(c/n)^3 - 15(c/n)^4 + 6(c/n)^5) \quad (10)$$

$$z_{tr} = x_{e(k)} + (z_p - z_{e(k)})(10(c/n)^3 - 15(c/n)^4 + 6(c/n)^5) \quad (11)$$

$$k_m = 300(c/n)Nm/rad \qquad m = \begin{cases} 1, & \text{if } c = 200 \\ 0, & \text{otherwise} \end{cases} \quad (12)$$

In these equations, x_{tr} and z_{tr} represent the new equilibrium point. The current equilibrium point is represented by $(x_{e(k)}, z_{e(k)})$. 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 increases by one on each cycle. This counter, c, continues till it reaches n. The completion of the transition phase is indicated by $m = 1$.

Based on this, a control method incorporating this switching method was developed as in Fig. 3. It should be noted that for simplicity this diagram only shows the translation control elements. When the human and robot interact during a cooperative task, interaction forces are generated, F_{int}. The interaction forces along with the current and previous value of the desired position of the robot are sent to the role planning function as inputs. The function determines if the human desires to take control of the translation task. Initially this switch is set to send the reference trajectory into the impedance planner. The reference trajectory is the initial trajectory plan for the robot to follow. If a change of roles was determined as needing to be made by the role planning function, then this is switched to the transition phase. Once the transition is complete then the input to the impedance planner is the current position and the translation impedance values are lowered. This makes the robotic system compliant in the horizontal plane and it passively follows the humans motion. The changes of the system that are made by the operation of this three way switch are described by the following equations. If $s = 0$ and $m = 0$ (initial setup) then,

$$\begin{bmatrix} x_{e(k+1)} \\ z_{e(k+1)} \end{bmatrix} = \begin{bmatrix} x_j \\ z_j \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} k_{tx} \\ k_{ty} \\ k_{tz} \end{bmatrix} = \begin{bmatrix} 500N/m \\ 5000N/m \\ 500N/m \end{bmatrix} \qquad \begin{bmatrix} k_{rx} \\ k_{ry} \\ k_{rz} \end{bmatrix} = \begin{bmatrix} 1Nm/rad \\ 300Nm/rad \\ 1Nm/rad \end{bmatrix} \quad (14)$$

If $s = 1$ and $m = 0$ (begin of transition)then,

$$\begin{bmatrix} x_{e(k+1)} \\ z_{e(k+1)} \end{bmatrix} = \begin{bmatrix} x_{tr} \\ z_{tr} \end{bmatrix} \quad (15)$$

$$\begin{bmatrix} k_{rx} \\ k_{ry} \\ k_{rz} \end{bmatrix} = \begin{bmatrix} k_m \\ 300Nm/rad \\ k_m \end{bmatrix} \quad (16)$$

If $s = 1$ and $m = 1$ then (completion of transition),

$$\begin{bmatrix} x_{e(k+1)} \\ z_{e(k+1)} \end{bmatrix} = \begin{bmatrix} x_p \\ z_p \end{bmatrix} \quad (17)$$

$$\begin{bmatrix} k_{tx} \\ k_{ty} \\ k_{tz} \end{bmatrix} = \begin{bmatrix} 1N/m \\ 5000N/m \\ 1N/m \end{bmatrix} \qquad \begin{bmatrix} k_{rx} \\ k_{ry} \\ k_{rz} \end{bmatrix} = \begin{bmatrix} 300Nm/rad \\ 300Nm/rad \\ 300Nm/rad \end{bmatrix} \quad (18)$$

Using information gained from the first set of experiments an adaptive control method was created. The only change to the control method (Fig. 3) was that the role planner was changed to an adaptive element. Moreover, the function of the role planner largely remains the same. The only part that changes is the threshold used for switching the leader-follower roles, which adapts based on the interactions of the human and robotic system.

Based off of the previous experiment, the initial threshold value for the role planner is 15 N. At the end of the trial the system checks to see if the robot remained the leader of the translation task during the trial. If the robot and human did not exchange roles, then the program analyzes whether or not to decrease the threshold value. If the maximum interaction force measured during the trial was less than the current threshold value minus a buffer value, then the threshold was decreased by the decrement value, d. The buffer value, B_f, used was 3 N. Initially, the decrement value used was 1 N ($d = 1$).

If during the trial the human took over as the leader of the translation task, the system checks to verify that this was not a false positive. It would classify it as a false positive if the human lead the task to the same bin that the robot was planning to ($E_r = E_h$). If this occurred, the decrement value was changed to 0.5 N ($d = 0.5$). This means that the next time that the robot lead to the correct bin, the most that the threshold could be decreased was 0.5 N. Additionally, when the false positive was detected, the threshold value F_{th} was increased by 2 N. This made it less likely for a false positive in future trials. If there wasn't a false positive detected, then all the values remained the same. The above are described by the following equations:
If $s = 1$ and $E_r = E_h$ then,

$$d = 0.5 \tag{19}$$

$$F_{th(k+1)} = F_{th(k)} + 2N \tag{20}$$

If $s = 0$ and $F_m < F_{th(k)} + B_f$ then,

$$F_{th(k+1)} = F_{th(k)} - d \tag{21}$$

C. Experimental Protocol

Four subjects were used for the first experiment. A total of 168 trials were conducted (42 trials per subject). Initially, the experiment was demonstrated to the subjects four times. During two of the demonstrations the robot moved to the correct bin and the roles were not exchanged. In the other two demonstrations, the robot moved toward the incorrect bin and the experimenter performing the demonstration exchanged roles with the robot and led the robot toward the correct bin.

Three different switching thresholds were used during the 42 trials for each subject. These threshold values were 5, 15 and 25 N. There were 14 trials for each threshold. In half of these, the robot was programmed to move toward the incorrect bin. The order of the trials was randomized so that the subject did not know what threshold was being used and was not aware of which bin that the robot would lead the fixture towards.

The experiment protocol for the second experiment is similar to the first experiment. For the adaptive control experiment, four subjects were used. Each of the subjects performed 42 trials. The initial threshold value was 15 N and the threshold value was allowed to adapt during the experiment. Half of the 42 trials were trials where the robot was going to lead the task in the incorrect direction. Other than the adapting threshold, instead of three threshold values, there were not any additional deviations from the procedure of this experiment compared with the previous experiment.

III. Results

A. Leader Follower Control

Three thresholds(5, 15 and 25 N) were used for the first leader-follower experiment to determine if the human wanted to exchange roles. These thresholds were randomly distributed across the 42 trials per subject.

One of the key ways to examine the performance of this control method is to examine the accuracy that it switched the robotic system from the leader to the follower of the translation element. To score this performance, two categories were defined. The first category is the false positive category. This occurs when the system switches the roles with the human, but the human then leads the system to the bin that the robotic system was already going to move towards. False negatives are where the human desired to switch to become the leader but the robotic system continued leading the system to the incorrect bin. An additional element was tracked. This however did not measure the switching method. This additional element was if the ball was dropped during the trial and aids in measuring the overall successfulness of the trial.

During trials where the lowest threshold was used, a number of false positives occurred. Across all subjects 168 trials were conducted. Of those trials one third were at each of the thresholds and half of them the robot was programmed to move to the incorrect bin. For analyzing the false positive value, this means that 28 of the trials for each threshold value are trials that could have a false negative. For the lowest threshold (5 N), the percentage of false positives was 54%. All of the false positives occurred at the lowest threshold value. For the total experiment (across all subjects and thresholds), there equates to an 18% false positive rate.

At the other extreme, the false negative is where the human wanted to become the leader but the robotic system didn't change roles. This case occurred three times during the experiment. All of the occurrences were when the threshold value was at 25 N. This represents 11% rate of false negative. This false negative is likely caused by two factors. First, the subjects were trying to take over as leader of the translation element of the task but were still the leader of the rotational element. Because of this they had to balance their desire to switch with their desire to keep the ball on the fixture. This may have limited the amount of force they felt comfortable applying. Additionally, some subjects noted that the system didn't seem to respond to them during the trial. This perceived lack of response may have resulted in the subjects giving up on switching. Additional testing would be required to determine this precise cause due to the low number of occurrences of this during the current study.

The results of this experiment can be seen in Table I. A successful trial was defined as where the robot and human are able to cooperate to move the ball to the correct bin. Because of this, false positives were not counted as being unsuccessful. Essentially, a false positive is where it switched unnecessarily. While this decreases the efficiency of the system, it doesn't actually prevent the ball from being moved by the robot and human to the correct bin. However, a false negative or a dropped ball does affect the successfulness of the trial.

TABLE I

LEADER FOLLOWER RESULTS

	False +	False -	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

The data from this first experiment, suggests that the 15 N threshold provided the best overall performance. However only three different thresholds were used and the performance of the subjects varied. While 15 N provided the best results out of the three thresholds tested, this may not represent the best value for an individual subject. Additionally, this threshold value may not perform the best if the task was changed. Considering this, an adaptive threshold control method was developed and tested. Table II shows the results of the adaptive control experiment.

The adaptive control method showed improved results compared to the previous experiment. Across the entire experiment, all categories improved in the adaptive control method. The only area the previous experiment had better results was in the number of false positives in the 15 N threshold compared with the adaptive control. Although the adaptive control had 3 false positives the 15 N threshold had none. However, the interaction forces required by the user to switch from leader to follower were lower in the adaptive control system. Fig. 4A shows how the threshold for switching roles adapted to a lower value. This figure corresponds to a set of trials with one representative subject. The threshold values adapt lower until a false positive is encountered. The system reacts raising the threshold by 2 N and decreases the amount the threshold would decrease to 0.5 N. In the end the threshold value had decreased to 13 N. In Fig. 4B, the threshold values for the one subject that did not have a false positive are shown. In this case, the threshold decreased to a lower level (11 N) than the other 3 subjects. This shows the ability of the system to adapt to a level that is subject-dependent.

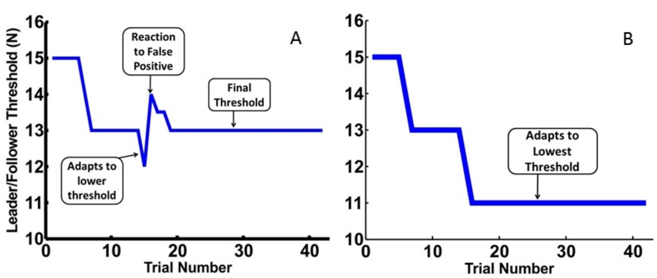

Fig. 4. Leader/Follower Threshold for Two Subjects

TABLE II

ADAPTIVE LEADER FOLLOWER RESULTS

	False +	False -	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

IV. CONCLUSIONS

In this paper, we examined a novel approach to role exchange in human-robot cooperative tasks that required dual roles. The simultaneous switching of two different tasks was explored both using a set threshold values and an adaptive mechanism. Overall, subjects were able to successfully cooperate to move a ball to the correct bin 85% of the time when using threshold switching values that varied between 5, 15 and 25 N. Using the adaptive mechanism, the subjects were able to successfully cooperate with the robot 95% of the time. The proposed adaptive approach provides additional benefits to the human in that it can lower the interaction forces required to switch based on how the user interacts with the system. Additionally, the adaptive nature of the switching mechanism may make it more suitable for a greater variety of tasks but this requires additional testing to establish.

REFERENCES

[1] S. Y. Lee, K. Y. Lee, S. H. Lee, J. W. Kim, and C. S. Han, "Human-robot cooperation control for installing heavy construction materials," *Autonomous Robots*, vol. 22, no. 3, pp. 305–319, 2007.

[2] H. I. Krebs, J. J. Palazzolo, L. Dipietro, M. Ferraro, J. Kroz, K. Rannekleiv, B. T. Volpe, and N. Hogan, "Rehabilitation robotics: Performance-based progressive robot-assisted therapy," *Autonomous Robots, Kluwer Academics*, vol. 15, pp. 7–20, 2003.

[3] A. De Santis, B. Siciliano, A. De Luca, and A. Bicchi, "An atlas of physical human–robot interaction," *Mechanism and Machine Theory*, vol. 43, no. 3, pp. 253–270, 2008.

[4] S. A. Setiawan, J. Yamaguchi, S. H. Hyon, and A. Takanishi, "Physical interaction between human and a bipedal humanoid robot-realization of human-follow walking," in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, vol. 1. IEEE, 1999, pp. 361–367.

[5] K. Morioka, J.-H. Lee, and H. Hashimoto, "Human-following mobile robot in a distributed intelligent sensor network," *Industrial Electronics, IEEE Transactions on*, vol. 51, no. 1, pp. 229–237, 2004.

[6] H. Lee, B. Lee, W. Kim, M. Gil, J. Han, and C. Han, "Human-robot cooperative control based on phri (physical human-robot interaction) of exoskeleton robot for a human upper extremity," *International Journal of Precision Engineering and Manufacturing*, vol. 13, no. 6, pp. 985–992, 2012.

[7] J. Stuckler and S. Behnke, "Following human guidance to cooperatively carry a large object," in *Humanoid Robots (Humanoids), 2011 11th IEEE-RAS International Conference on*. IEEE, 2011, pp. 218–223.

[8] P. Evrard and A. Kheddar, "Homotopy switching model for dyad haptic interaction in physical collaborative tasks," in *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*. IEEE, 2009, pp. 45–50.

[9] M. R. Endsley, *Designing for situation awareness: An approach to user-centered design*. CRC Press, 2012.

[10] K. B. Reed and M. A. Peshkin, "Physical collaboration of human-human and human-robot teams," *Haptics, IEEE Transactions on*, vol. 1, no. 2, pp. 108–120, 2008.