2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Implementation of a Robot-Human Object Handover Controller on a Compliant Underactuated Hand Using Joint Position Error Measurements for Grip Force and Load Force Estimations*

Wesley P. Chan, Iori Kumagai, Shunichi Nozawa, Yohei Kakiuchi, Kei Okada, Masayuki Inaba

Abstract— **Object handover is a basic task in many human-robot interactive scenarios and therefore, it is important for assistive robots to be able to perform proper handovers. We previously designed a human-inspired grip-force-varying handover controller for a robot giver and showed on a Willow Garage PR2 robot that the controller yields human-like and human-preferred handovers. The PR2 robot had a non-compliant fully-actuated gripper. However, recently, compliant underactuated grippers have been gaining more popularity. Although compliant underactuated grippers can provide more flexibility in manipulation, it is generally difficult to accurately measure and control the amount of applied grip force. In this paper, we present an implementation of the human-inspired handover controller on a Kawada Industries HRP4R robot, which has compliant underactuated hands, using joint position error measurement for estimating the amount of applied grip force. Through an experiment, we show that we are able to achieve safe, smooth, and intuitive robot-human handovers despite the lack of accurate grip force control on our robot.**

I. INTRODUCTION

The development of assistive robots has seen a huge growth over the past decades. Unlike traditional robots which are built to work in isolated environments from humans, assistive robots are built with the intent of having them work alongside humans in various work places including factories, homes, and public facilities. Applications under development include intelligent factory assistants, homecare robots, hospital delivery robots, as well as astronaut robots [1]–[4].

Working in cooperation with humans, assistive robots will have many direct interactions with their users. One routine task requiring direct interaction between the robot and its users that will frequently arise in many occasions is object handover (Figure 1). For example, a mechanic may ask a factory assistant to hand over a screwdriver, waiter robots may need to hand over drinks to customers, and a delivery robot may need to hand over packages to the recipients.

Humans casually hand over various objects to each other numerous times in their daily lives. They rarely put in much thought when executing object handovers. Yet, without carefully planning for each handover, people in general complete each handover safely, efficiently, and smoothly. However, in contrast, most robots still have great difficulties handing over objects to people. Most robots require the user to follow specific procedures for object handover, and handovers between humans and robots still tend to be very mechanical. Since the ability to hand over objects is an essential skill for assistive robots and is crucial to enabling effective cooperation between humans and robots, there has been many efforts focusing on improving the human-robot interaction in object handovers.

*Research supported by the Ministry of Education, Culture, Sports, Science, and Technology in Japan.
The authors are with the Department of Information Science and Technology, University of Tokyo, Tokyo, Japan 113-8656 (phone: 3-5841-7416; fax: 3-3818-0835; email: wesleyc, iori, nozawa, youhei, k-okada, inaba @jsk.t.u-tokyo.ac.jp)

Figure 1. HRP4R handing over a bottled drink to a person.

II. RELATED WORKS

A. Robot-Human Handovers

Many existing studies have focused on various aspects of robot-human object handovers. Different methods have been proposed for indicating to the robot which object to hand over. Choi et al. proposed a method where motor-impaired patients use a laser pointer to identify the target object [5]. Ikai et al. proposed a method where users instruct the robot to handover an object using a predefined pointing hand gesture [6]. Others have studied how a robot should approach the person in preparation for a handover. Walters et al. found that when a person is seated, a frontal approach is disliked, since the robot may appear threatening, but is more acceptable when standing [7]. Shibata et al. and Huber et al. compared different reaching trajectories and they found that people prefer working with robots that use human-like (minimum-jerk) trajectories [8], [9]. Cakmak et al. and Aleotti et al. studied how a robot should orient the object when handing it over [10], [11]. They found that when a robot uses an orientation that takes object affordance into account, participants gave a higher rating in terms of appropriateness and safety.

In addition to the robot's movement and posture, another important issue in object handover is how a robot, as the giver, can properly determine when to release the object during the actual transfer of the object to the receiver. Edsinger and Kemp used a simplistic approach where their robot releases the object one second after reaching its arm out [12]. However, their study shows that in certain situations, people will simply let the robot drop the object. Bohren et al. programed their robot to release the object when the receiver pulls hard enough to displace the robot's arm more than 1 cm [13]. This ensured that the robot does not drop the object accidentally, but required the receiver to pull very hard on the object [14]. To limit the amount of force required from the receiver, Choi et al. and Deyle et al. used a force/torque-based approach, where their robot releases when the force/torque at its fingers exceeded a threshold [2], [5]. While this approach ensures that the receiver can take the object without excessive force, it requires manual tuning of hardware-dependent thresholds (since finger lengths affect the resulting torque values) and makes it more susceptible to dropping the object due to unintentional collisions with the object or the arm.

B. *Human-Human Handovers*

To bridge the performance gap between robot-human handovers and human-human handovers, we previously conducted a user study to investigate and characterize the force interaction in human-to-human handovers [15]. We discovered that during the object transfer phase of a handover, as the object load is gradually transferred from the giver to the receiver, the giver gradually decreases the applied grip force in response to the changing load force, such that an approximately linear relationship between the grip force and load force is observed. Furthermore, in order to ensure that the object is safely transferred to the receiver, the giver does not completely release his/her grip until a slight pull from the receiver is detected through the object.

C. *Human-Inspired Handover Controller*

Following the human-human handover study, we designed a handover controller for a robot giver based on the discovered human grip force control strategy [16]. Our controller allows a robot giver to mimic a human's behavior by gradually decreasing its grip force in response to the decreasing load force during a handover. In a user study comparing our controller design with existing constant grip force controller design, we showed that our controller results in better performance in terms of handover smoothness and intuitiveness. Furthermore, results also showed that our controller yields human-like and human-preferred handovers.

D. *Compliant Underactuated Grippers*

In the previous implementation of our handover controller, we used a Willow Garage PR2 robot, which has a non-compliant fully-actuated gripper. While such type of grippers allows full control of each finger joint and the robot to more easily compute and predict the gripper configuration when interacting with the physical environment, it may be difficult to grasp irregularly shaped objects. Therefore, as an alternative, researchers have begun to consider the use of compliant underactuated grippers [17], [18]. Such grippers can yield better performance on grasping various irregularly shaped objects as they are capable of passively conforming to the object's shape. However, it is generally harder to control the applied grip force and the exact gripper configuration.

With complaint underactuated grippers becoming more common, it would be important to enable robots equipped with such gripper to perform handovers effectively as well. The ability to properly control grip force is very important in object manipulation and thus in handovers [19], [20]. However, one challenge with compliant underactuated grippers is the difficulty in accurately measuring and controlling the amount of applied grip force since there are usually multiple oblique contacting surfaces during grasping. In this paper, we demonstrate the feasibility of achieving smooth robot-human handovers on a compliant underactuated gripper with the use of the controller presented in [16], despite the lack of accurate grip force control. We use a Kawada Industries HRP4R robot as our hardware platform (Figure 1).

III. HANDOVER CONTROLLER DESIGN

A. *Grip Force Control Function*

The handover controller we proposed in [16] is based on the grip force control strategy used by humans [15]. Figure 2 shows the grip force control function of the handover controller. In the beginning of the handover, the robot supports the full load of the object, f_{Lo}, applying a grip force of f_{Go}. As the receiver begins to take the object from the robot and the load force, f_L, on the robot's hand decreases, the controller decrease the applied grip force, f_G, accordingly in a linear fashion. When the load force reaches zero, the controller continues to maintain a small non-zero amount of grip force, f_{ZLG}. Once the controller detects a slight pull from the receiver, and the load force reaches a small negative value, ε, the controller then releases the object completely. The zero-load-grip-force, f_{ZLG}, and the release-force-threshold, ε, are two tuneable parameters of the handover controller. In human-to-human handovers, f_{ZLG} and ε are found to be 2.3 N ± 1.7 N and 2.36% ± 4.16% of the object weight respectively [15]. Once the controller's f_{ZLG} and ε values have been chosen, the slope, m, of the grip force control function, $f_G(f_L)$, can be calculated as:

$$m = \frac{f_{Go} - f_{ZLG}}{f_{Lo}} \quad (1)$$

B. *Controller Flow Chart*

Figure 4 shows the flow chart for the handover controller. During a handover, the controller continually monitors the load force and computes the appropriate grip force according to $f_G(f_L)$. To prevent accidental drops due to collisions, the controller first checks to see if the acceleration of object is within a predetermined threshold, $\boldsymbol{a}$. If acceleration is within this threshold, the controller applies the computed f_G. Else, the controller will continue to hold on to

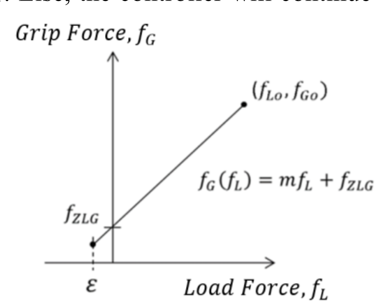

Figure 2. Grip force control function for a robot giver. During object transfer, the applied grip force, f_G, is regulated according to the experienced load force, f_L, in a linear fashion such that the grip force is gradually reduced as the load force decreases. The object is completely released after a slight upwards pulling force of $|\varepsilon|$ is sensed. (Figure from Chan et al. 2013 [16], axes relabeled for clarity.)

the object. Once the load force, f_L, drops below the release-force-threshold, ε, the controller then releases the object and the handover is completed.

IV. Previous Implementation

In a previous user study, we implemented our handover controller on a Willow Garage PR2 robot (Figure 3A) and verified that our controller produces smooth, safe, and human-preferred handovers [16]. Each arm of the PR2 robot is equipped with a two-fingered parallel gripper, and each fingertip is equipped with a force sensor array (Figure 3B). A 3-axis accelerometer is also embedded in each gripper. The rigid fully-actuated gripper allowed us to have precise control over the grasp configuration and control the applied grip force with reasonable accuracy and precision. Our user study showed that even when the achieved f_{ZLG} was around 4 N, and the $|\varepsilon|$ was around 10% of the object weight, our controller still produced handovers that are perceived as smooth and human-like.

The use of rigid fully-actuated grippers does however have some limitations. Using a simple parallel gripper, it is very difficult to grasp and hold irregularly shaped objects or objects that do not have a set of parallel surfaces (For example, a triangular prism). Furthermore, certain object geometries may also cause high pressure concentration at the contact points due to small contact surface area between the gripper and the object (e.g., an egg or a cylindrical mug). This kind of pressure concentration imposes a risk of breaking the object during grasping [20]. In certain situations, attempting to grasp an object when a rigid non-compliant gripper is misaligned with the object may also cause failure.

V. Implementation on a Compliant Underactuated Hand

In contrast to rigid fully-actuated grippers, compliant underactuated grippers do not allow full control of the gripper's configuration. It is also more difficult to control the applied grip force since there may be multiple oblique contacting surfaces with the object. However, compliant underactuated grippers can have better performance on grasping irregularly shaped objects since it can conform to the object's geometry. With more compliant and underactuated

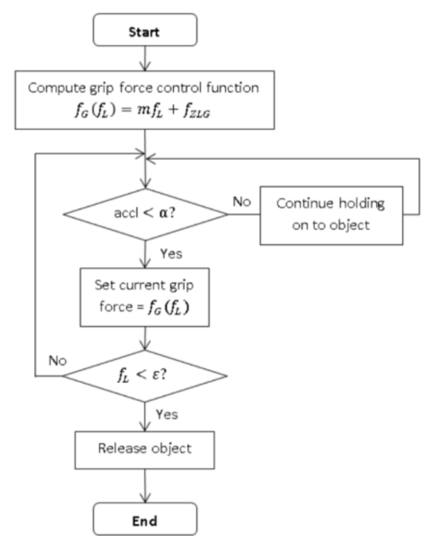

Figure 4. Handover controller flow chart. (Figure from Chan et al. 2013 [16].)

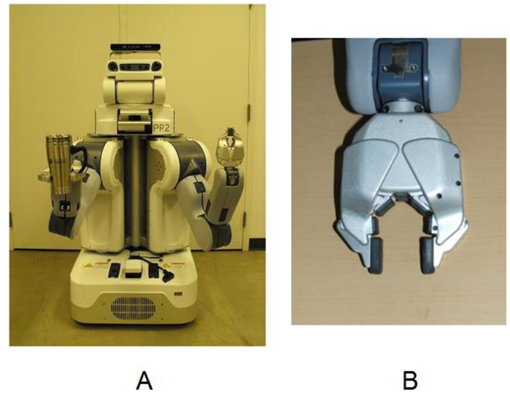

Figure 3. A - The PR2 robot used for our previous implementation of the handover controller (Figure from Chan et al. 2013 [15]). B - Parallel gripper of the PR2 robot. Each fingertip is equipped with an array of force sensors.

grippers being developed, we can expect to see more assistive robots being equipped with such grippers. Therefore, it is important for such compliant underactuated grippers to be able to perform handovers effectively. In this section, we present the implementation of the controller described in Section III on a humanoid equipped with compliant underactuated hands, in the absence of grip force sensors.

A. Hardware

Our hardware platform is a Kawada Industries HRP4R robot (Figure 1). The HRP4R is equipped with a two-degree-of-freedom hand on each arm. Figure 5A shows the hand in the opened position, with red dashed-lines indicating the joint axes. The thumb is composed of one rigid link and is actuated by one motor (joint_0), while the rest of the fingers are actuated together by another motor (joint_1). The fingers actuated by joint_1 are tendon driven. Each of these fingers is composed of three rigid links, and is compliant and underactuated. Figure 5B shows the hand in the closed position. To prevent grasped objects from easily slipping due to the smooth surface on HRP4R's fingers, we attached rubber pads to the fingers to increase the surface friction of the hand. One major challenge is that HRP4R is not equipped with any force sensors on its arms and hands. It only provides encoder readings and estimated motor torque values based on current measurements for each joint.

B. Load Force Estimation

In our previous implementation on the PR2 robot [16], we used the estimated wrist torque for calculating the load force on the gripper. We modeled the PR2's gripper and forearm as a simple two-link mechanism. By orienting the

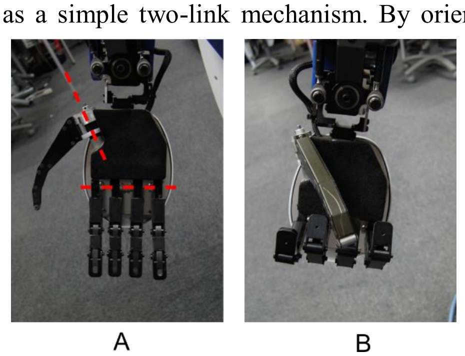

Figure 5. HRP4R's hand. **A** shows the hand in the opened configuration, with red dashed-lines showing the joint axes. **B** shows the hand in the closed configuration.

gripper parallel to the ground, the load force, f_L, can be calculated using the definition of torque with the equation:

$$f_L = \frac{\tau - \tau_o}{L_T} \qquad (2)$$

where τ is the measured torque value, τ_o is an offset, and L_T the distance from the wrist joint to the gripper tool center.

For our current implementation on the HRP4R robot, we used the joint error measurement, $\Delta\theta$, instead to estimate the load force. The joint error measurement is defined as the difference between the commanded joint position and the actual position. Torque estimations based on current measurements tend to be noisy since they are affected by various undesirable characteristics of the motors (For example, gear friction). Joint positions, on the other hand, are measured by encodes and have much smoother measurements. As a result, the joint error measurement from HRP4R gives us a much more stable estimation of the load force.

HRP4R uses PD control where joint torque output, τ_{ref}, is calculated as:

$$\tau_{ref} = P\Delta\theta + D\dot{\theta} \qquad (3)$$

where $\dot{\theta}$ is the angular speed, and P and D are constants. Assuming that the robot's joint has a sufficiently short response time, and that the handover is quasi-static, such that the actual joint torque is equal to τ_{ref}, and $\dot{\theta}$ is near zero, the joint torque becomes approximately linear with respect to $\Delta\theta$. Thus, combining Equation (3) with Equation (2) and regrouping the constants, the load force on HRP4R's hand can be estimated as:

$$f_L = \frac{\Delta\theta - \Delta\theta_{offset}}{K} \qquad (4)$$

where $\Delta\theta_{offset}$ is an offset, and K is a constant with units rad/N, acting as a conversion factor. To determine K, we placed an object weighing approximately 5 N in HRP4R's hand, let it grasp onto the object, and recorded the resulting joint error measurement. We then set K to be the measured joint error divided by 5 N.

Initially, we attempted to use HRP4R's wrist joint error measurement for estimating the load force. However, HRP4R's wrist joint has very high friction and the joint error measurement does not really reflect the change in load force at the hand. Therefore, we used the elbow joint error measurement instead. This gives a larger moment arm and allows us to detect load force changes more easily. Thus, we re-write Equation (4) as:

$$f_L(\Delta\theta_{El}) = \frac{\Delta\theta_{El} - \Delta\theta_{El\_offset}}{K} \qquad (5)$$

where $\Delta\theta_{El}$ is the elbow joint error, and $\Delta\theta_{El\_offset}$ is the elbow joint error offset. Note that if the hand pose were changed, f_L can still be calculated by taking into account the Jacobian and wrist joint states. For consistency, the hand pose was kept constant in our experiment, and thus f_L simplifies to Equation (5).

C. Grip Force Estimation

For grasping the object, we fix the position of hand joint_0 at a near-closed position, and we control the amount of applied grip force by commanding the position of joint_1. To estimate the amount of applied grip force, we use the joint angle error measured at joint_1. When grasping the object in preparation for handover, we first place the object in HRP4R's opened hand, and we gradually increase the commanded joint_1 position, while monitoring the joint error, $\Delta\theta_{J1}$. When $\Delta\theta_{J1}$ exceeds a first threshold, $\Delta\theta_{contact\_threshold}$, we store the current joint angle as the contact angle, $\theta_{contact}$. The value of $\Delta\theta_{contact\_threshold}$ was manually selected to be as small as possible while remaining above the encoder noise, so that we do not detect false positives of object contact. We then continue to increase the commanded joint_1 position, until $\Delta\theta_{J1}$ reaches a second threshold, $\Delta\theta_{grasp\_threshold}$. The value of $\Delta\theta_{grasp\_threshold}$ was manually selected based on the object's weight and coefficient of friction such that the robot applies a grasp force slightly above the slip threshold. Once $\Delta\theta_{grasp\_threshold}$ is reached, we store the current joint angle as the initial angle, θ_{J1_o}, and grasping is completed.

We regulate the amount of applied grip force, f_G, through controlling the commanded joint_1 position, θ_{J1}. We assumed a linear mapping between f_G and θ_{J1}. During handover, the θ_{J1} command is computed from the desired grip force, f_G, according to:

$$\theta_{J1}(f_G) = \frac{\theta_{J1\_o} - \theta_{J1\_zgf}}{f_{Go}} f_G + \theta_{J1\_zgf} \qquad (6)$$

where θ_{J1_zgf} is the estimated joint_1 position at the zero grip force and is computed as:

$$\theta_{J1\_zgf} = \theta_{contact} - \theta_{J1\_offset} \qquad (7)$$

and f_{Go} is the initial grip force applied when the joint angle is at θ_{J1_o}. We set the offset, θ_{J1_offset}, arbitrarily to be 1 degree and we estimated f_{Go} to be 10 N. The value for f_{Go} was estimated based on the theoretical minimum grip force required to prevent the object from slipping. While in reality, f_G may depend on higher powers and derivatives of θ_{J1}, our experiment will show that the approximation given by Equation (6) is sufficient for producing smooth handovers.

D. Modified Handover Controller

In our implementation on the HRP4R robot, we estimate the load force, f_L, using the elbow joint error, $\Delta\theta_{El}$, and we control the grip force, f_G, through commanding the finger joint angle, θ_{J1}. In other words, we are essentially controlling θ_{J1} according to $\Delta\theta_{El}$ (i.e., $\theta_{J1} = \theta_{J1}(\Delta\theta_{El})$). By substituting Equations (1), (5) and (6) in to the grip force control function $f_G(f_L)$ shown in Figure 2, we obtain:

$$\theta_{J1}(\Delta\theta_{El}) = \left(\frac{\theta_{J1_o} - \theta_{J1_{zgf}}}{f_{Go}}\right)\left(\frac{f_{Go} - f_{ZLG}}{f_{Lo}}\right)\left(\frac{\Delta\theta_{El} - \Delta\theta_{El_{offset}}}{K}\right) + f_{ZLG} + \theta_{J1\_zgf} \qquad (8)$$

which is a linear function in $\Delta\theta_{El}$. This shows that in this implementation, the controller is actually varying the position of the finger joint, θ_{J1}, according to the elbow joint error, $\Delta\theta_{El}$, following a linear relationship. This means that while the resulting grip-force-to-load-force relation may not necessarily be linear, it should still be a monotonic one, assuming that the relationship between θ_{J1} and f_G, and the relationship between $\Delta\theta_{El}$ and f_L are monotonic.

VI. Experiment

A. Set Up and Procedure

To validate our implementation, we conducted an experiment where HRP4R performed object handovers with a person. In the experiment, HRP4R handed over a plastic drink bottle (a common everyday object) to a subject. To be able to measure the load force experienced by the person (receiver), we attached an FTSens 6-axis force/torque sensor to the bottom of the drink bottle, and another plastic drink bottle at the other side of the force/torque sensor to serve as a handle to the robot. The total weight of the apparatus is approximately 4 N. During the experiment, in the beginning of the handover, the robot (giver) holds onto the handle by grasping it with its right hand, and the receiver stands in front of the robot. The robot begins the handover by reaching its right arm forward. Once the robot has completed its reach, the receiver then reaches his right hand over and takes the object. After object transfer, the receiver retracts his right arm, and the handover is completed. The participant was a healthy 22-year-old male with no known sensory disorders.

In the experiment, we first allowed the subject to perform four practice handovers with the robot to become familiarize with the experimental procedure. The subject then performed another four handovers where we collected the data for analysis. We set the parameters of the handover controller to be f_{ZLG} = 2 N and ε = -0.4 N.

B. Data Analysis

From the measured receiver load force data, we extract the maximum excess receiver load force percentage, $MERL\%$, and object transfer time, $t_{transfer}$. The maximum excess receiver load force, $MERL$, is defined as the maximum amount of receiver load force measured minus the weight of the object, and $MERL\%$ is $MERL$ expressed as a percentage of the object weight. The $MERL\%$ measures how hard the receiver has to "pull" to take the object. The object transfer time is the total duration of the object transfer and is measured from when the receiver's load force first rose above a threshold δ_1, to when the receiver's load force first settles to the weight of the object within a threshold, δ_2. The thresholds δ_1 and δ_2 are set to be 0.7 N. This value was chosen manually to be a small constant sufficiently greater than the observed noise in the load force measurements. We compare the $MERL\%$ and the $t_{transfer}$ from the experiment with those measured in human-to-human handovers [15]. We also recorded the number successful handovers and the number failed handovers.

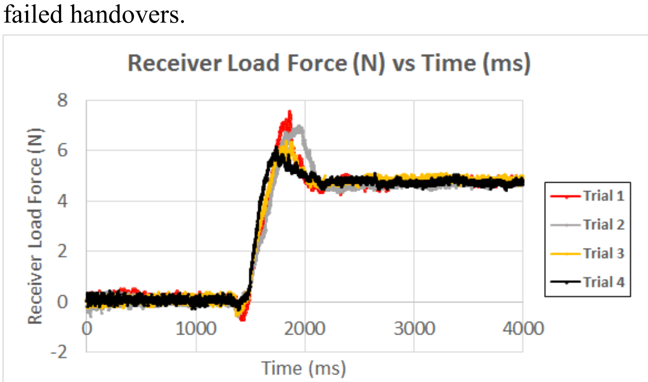

Figure 6. Receiver load force data measured in the handover experiment from all four trials.

C. Results

Results from all four handover trials are shown in Figure 6. The measured $MERL\%$ and $t_{transfer}$ are summarized in Table 1. The average $MERL\%$ was measured to be 42.3% ± 15.0%, and the average $t_{transfer}$ was measured to be 462.7 ms ± 95.7 ms. The robot and the subject completed all handovers successfully, and there were no failed handovers. In all four trials, the bottle was safely handed over from the robot to the receiver.

Table 1. Results from the handover experiment.

	$MERL\%$	$t_{transfer}$ (ms)
Trial 1	58.5	476.0
Trial 2	50.8	586.0
Trial 3	33.7	431.9
Trial 4	26.0	357.9
Average	42.3 ± 15.0	462.7 ± 95.7

D. Discussion

In our previous human-human handover study, we found that typical $t_{transfer}$ are in the order of 500 ms [15]. Comparing this with the value of 462.7 ms measured in our experiment, we see that our implementation on the HRP4R was able to achieve human-like object transfer times. Since object handover is a basic subtask that arises frequently in many higher-level tasks, it is important that robots are able to execute handovers promptly. If too much time is required to perform such basic subtasks, the efficiency of the higher-level task will be compromised. The results show that our implementation enables efficient robot-human handovers from an object transfer time standpoint.

In handovers among humans, the $MERL\%$, was found to be as low as around 2% [15]. In our previous implementation on the PR2 robot, we achieved a $MERL\%$ of 10.7% ± 11.4%, and according to the participants, the resulting handovers still felt smooth and human-like. The $MERL\%$ measured for the implementation on HRP4R was 42.3% ± 15.0%. While this value is quite higher, it still allowed all handovers to be completed successfully in the experiment. Our previous study showed that if a robot holds onto the object too long and the $MERL\%$ exceeds ~40%-50%, the handover becomes unintuitive to users, and the handover will fail [16]. Participants would not naturally pull harder than ~40%-50% object weight without explicit instructions from the experimenter, and once the load force reaches ~40%-50%, participants will simply continue to hold onto the object or abort the handover. It appears that the resulting $MERL\%$ of our HRP4R implementation is just below the unintuitive threshold and still within the subject's acceptance. Therefore, the resulting handovers were intuitive enough for the subject to successfully complete all handovers without any special instruction from the experimenter.

The resulted $MERL\%$ was quite higher than we intended. Two causes for this are 1) the lack of accurate load force measurements, and 2) the lack of accurate grip force control. Due to the lack of force sensors on the HRP4R, it was impossible to obtain accurate load force and grip force measurements. We estimated the load force using elbow joint angle error, and therefore, the error in this estimation is likely to have caused HRP4R to release the object later than it should have. Similarly, we were only able to estimate and regulate the applied grip force through measuring the finger joint angle error and commanding the finger joint position. The error in grip force control is also likely to have caused a delayed release of the object by HRP4R. These two hardware limitation related problems would be the cause of the high $MERL\%$ observed in the experiment. With more sophisticated and accurate models of $\theta_{J1}(f_G)$ and $f_L(\Delta\theta_{El})$, one should be able to reduce the resulting $MERL\%$.

Despite the hardware limitations, experiment results showed that our implementation was still able to yield handovers with transfer times similar to those of typical human-human handovers, and that the robot and the subject were able to safely and successfully complete all handovers. This shows that despite the lack of accurate load force sensing and grip force control on the compliant underactuated hand of HRP4R, we are still able to achieve time-efficient, safe, and intuitive handovers with our controller.

VII. CONCLUSION

We have presented an implementation of a robot-to-human object handover controller, which we developed previously, on a compliant underactuated hand. Two great challenges in this implementation are the lack of sensors for load force measurements, and the lack of a means for accurate grip force control. We used simple linear models for estimating the load force from elbow joint angle error measurements and for estimating the applied grip force from finger joint angle error and position. Our experimental results showed that using this method, we were able to allow a robot with compliant underactuated hands to hand over an object to a person safely, intuitively, and in a timely manner. In our future work, we wish to extend our studies to include more objects with different shape, size, and weight. We also plan on testing the use of our controller for robot-to-robot handovers. In this study, we tested our implementation with a human as the receiver, since humans are the target end users we had in mind. However, the receiver could also be a robot. In this use case, the controller would sever as an alternative means to setting up a network communication channel for coordinating object transfer between two independently controlled robots.

REFERENCES

[1] R. Wilcox, S. Nikolaidis, and J. Shah, "Optimization of Temporal Dynamics for Adaptive Human-Robot Interaction in Assembly Manufacturing," in *Proceedings of Robotics: Science and Systems Conference*, 2012.

[2] T. Deyle, H. Nguyen, M. S. Reynolds, and C. C. Kemp, "RFID-Guided Robots for Pervasive Automation," *IEEE Pervasive Comput.*, vol. 9, no. 2, pp. 37–45, Apr. 2010.

[3] W. Fung, Y. Leung, and M. Chow, "Development of a hospital service robot for transporting task," in *Proceedings of the International Conference on Robotics, Intelligent Systems and Signal Processing*, 2003, pp. 628–633.

[4] M. Diftler, J. Mehling, and M. Abdallah, "Robonaut 2 - the first humanoid robot in space," in *Proceedings of the International Conference on Robotics and Automation*, 2011, pp. 2178–2183.

[5] Y. S. Choi, T. Chen, A. Jain, C. Anderson, J. D. Glass, and C. C. Kemp, "Hand It Over or Set It Down: A User Study of Object Delivery with an Assistive Mobile Manipulator," in *Proceedings of the International Symposium on Robot and Human Interactive Communication*, 2009, pp. 736–743.

[6] T. Ikai, S. Kamitani, and M. Ohka, "Vision and Tactile Based Robot-to-Human Object Handover," in *The 31th Annual Conference on Robotics Society of Japan*, 2013, pp. 1G3–04.

[7] M. L. Walters, K. Dautenhahn, S. N. Woods, and K. L. Koay, "Robotic Etiquette: Results from User Studies Involving a Fetch and Carry Task," in *Proceedings of the International Conference on Human-Robot Interaction*, 2007, pp. 317–324.

[8] S. Shibata, B. M. Sahbi, K. Tanaka, and A. Shimizu, "An Analysis of the Process of Handing Over an Object and its Application to Robot Motions," in *Proceedings of the International Conference on Systems, Man, and Cybernetics*, 1997, pp. 64–69.

[9] M. Huber, M. Rickert, A. Knoll, T. Brandt, and S. Glasauer, "Human-Robot Interaction in Handing-Over Tasks," in *Proceedings of the International Symposium on Robot and Human Interactive Communication*, 2008, pp. 107–112.

[10] M. Cakmak, S. S. Srinivasa, M. K. Lee, J. Forlizzi, and S. Kiesler, "Human Preferences for Robot-Human Hand-over Configurations," in *Proceedings of the International Conference on Intelligent Robots and Systems*, 2011, pp. 1986–1993.

[11] J. Aleotti, V. Micelli, and S. Caselli, "Comfortable Robot to Human Object Hand-Over," pp. 771–776, 2012.

[12] A. Edsinger and C. C. Kemp, "Human-Robot Interaction for Cooperative Manipulation: Handing Objects to One Another," in *Proceedings of the International Symposium on Robot and Human Interactive Communication*, 2007, pp. 1167–1172.

[13] J. Bohren, R. B. Rusu, E. G. Jones, E. Marder-Eppstein, C. Pantofaru, M. Wise, M. Lorenz, W. Meeussen, and S. Holzer, "Towards Autonomous Robotic Butlers: Lessons Learned with the PR2," in *Proceedings of the International Conference on Robotics and Automation*, 2011, pp. 5568 – 5575.

[14] Willow Garage, "Beer Me, Robot," 2010. [Online]. Available: http://www.willowgarage.com/blog/2010/07/06/beer-me-robot. [Accessed: 13-Jul-2012].

[15] W. P. Chan, C. A. C. Parker, H. F. M. Van der Loos, and E. A. Croft, "Grip Forces and Load Forces in Handovers: Implications for Designing Human-Robot Handover Controllers," in *Proceedings of the 7th ACM/IEEE International Conference on Human-Robot Interaction*, 2012, pp. 9–16.

[16] W. P. Chan, C. A. C. Parker, H. F. M. Van der Loos, and E. A. Croft, "A Human-Inspired Object Handover Controller," *Int. J. Rob. Res.*, vol. 32, no. 8, pp. 971–983, 2013.

[17] Willow Garage, "Willow Garage 2G Velo Gripper." [Online]. Available: http://www.willowgarage.com/velo2g. [Accessed: 15-Sep-2013].

[18] J. Schuurmans, R. Q. van der Linde, D. H. Plettenburg, and F. C. van der Helm, "Grasp force optimization in the design of an underactuated robotic hand," *IEEE 10th Int. Conf. Rehabil. Robot.*, pp. 776–782, 2007.

[19] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks.," *Nat. Rev. Neurosci.*, vol. 10, no. 5, pp. 345–59, May 2009.

[20] J. M. Romano, S. Member, and K. Hsiao, "Human-Inspired Robotic Grasp Control With Tactile Sensing," *Trans. Robot.*, vol. 27, no. 6, pp. 1067–1079, 2011.