Fast Handovers with a Robot Character: Small Sensorimotor Delays Improve Perceived Qualities

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***Abstract*— We present a system for fast and robust handovers with a robot character, together with a user study investigating the effect of robot speed and reaction time on perceived interaction quality. The system can match and exceed human speeds and confirms that users prefer human-level timing.**

The system has the appearance of a robot character, with a bear-like head and a soft anthropomorphic hand and uses Bézier curves to achieve smooth minimum-jerk motions. Fast timing is enabled by low latency motion capture and real-time trajectory generation: the robot initially moves towards an *expected handover location* and the trajectory is updated on-the-fly to converge smoothly to the actual handover location. A hybrid automaton provides robustness to failure and unexpected human actions.

In a 3x3 user study, we vary the speed of the robot and add variable sensorimotor delays. We evaluate the social perception of the robot using the Robot Social Attribute Scale (RoSAS). Inclusion of a *small* delay, mimicking the delay of the human sensorimotor system, leads to an improvement in perceived qualities over both *no delay* and *long delay* conditions. Specifically, with *no delay* the robot is perceived as more discomforting, and with a *long delay* it is perceived as less warm.

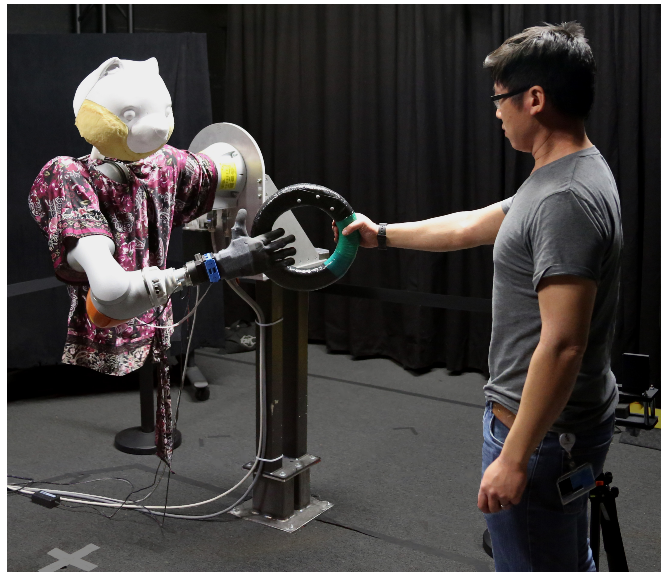

Fig. 1. The robotic character can perform both human-to-robot and robot-to-human handovers.

I. INTRODUCTION

Robots are starting to interact directly with humans and are gradually becoming more involved in our daily social interactions—as helpers, companions, and care-givers. This means that robots are not only required to be safe and functional, but should also act consistent with normal and expected human behaviors.

Handing over an object requires little conscious thought for a human, yet is filled with expectations and is seen against a lifetime of experiences. For robots, it presents a relevant example of a direct interaction with a human, and thus, handover interactions between humans and robots have been a topic of much study. We are particularly interested in endowing robots with handover behaviors that users perceive favorably and as natural, competent, and efficient.

In previous work [1], we studied handover interactions with a non-anthropomorphic robot and identified timing as the factor with the greatest effect on perceived qualities: faster behaviors were preferred over slower ones. We hypothesized that participants preferred interactions that were *more efficient*, i.e., required less time. However, all the studied interactions were significantly slower than typical human-human handovers.

To further explore this area, this work presents a system that is capable of executing fast and robust bidirectional (human-to-robot and robot-to-human) handovers. We believe matching and exceeding human timing more readily allows users to anthropomorphize and perceive the robot as part of a normal social interaction.

As part of an effort to encourage such perception, the robot has the appearance of the torso of a bear-like character and features a head and an anthropomorphic hand as seen in Fig. 1. Rounding out this compelling robotic character, the system uses adjusted minimum-jerk movements and is robust towards unexpected or uncooperative human behaviors.

We use this robot character handover system to conduct a 3x3 user study where we vary the speed of the robot motions and the system reaction time. To vary the reaction time, we include a variable sensorimotor delay. From our previous work [2], we know that closed-loop control with a small sensorimotor delay was preferred in human-robot handshaking. We thus hypothesize that the inclusion of a delay that mimics the latency of the human sensorimotor system will create a more compelling behavior. We consider three levels of sensorimotor reaction time: *no delay* (faster-than-human reaction), *short delay* (similar to human reaction time) and *long delay* (slower than human reaction time). For

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the speed, we consider three levels—*slow*, *moderate*, and *fast*—of which the *moderate* condition is similar to the speed of human arm motions.

Our study results show that the inclusion of the *short* sensorimotor delay improves the perceived qualities of the robot. With no delay added, the system is perceived as more discomforting—independently of the arm speed conditions tested. With a long delay, the robot is perceived as less warm.

In the following, we present the system as well as the user study followed by remarks discussing the work.

II. RELATED WORK

Handover interactions have received significant attention in the robotics literature. This includes both the characterization of human-human interactions to gain detailed models of different aspects of handover interactions [3, 4, 5, 6], as well as their implementation on robotic systems. The majority of these robotic implementations have focused on the robot-to-human handover direction [7, 8, 9, 5, 10], with some work considering human-to-robot handovers or bidirectional interactions [4, 11, 12, 13, 14]. Prior work has considered the robustness of handover systems to failure. In [15], a robot is fitted with an object acceleration sensing setup such that the robot can re-grasp a falling object during handover. In another stream of work, the role of gaze in handover interactions has been studied, showing that handover performance is improved if the robot uses its gaze as a cue to the user [16, 17].

While robotic handover systems frequently implement findings from human-human interactions, these systems are in general substantially slower than the human-human counterparts they emulate [18, 12]. Yet, timing in handover interactions has been posed as an important aspect by multiple works. Koene et al. [19] study the relative importance of spatial and temporal precision for handover interactions, and show that the temporal aspects are of greater importance. Hoffman [20] discusses the importance of using fluency as an evaluation metric for human-robot interactions. In our previous work, we found timings to play a significant role in the social perception of handover interactions [1]. Also relevant, Admoni et al. [21] study the effect of introducing delays to emphasize robot non-verbal communication such as gaze.

The social perception of robots in handovers and in other contexts has received some focused study in recent years: Aleotti et al. [22] argue for the importance of robots behaving in a social manner when interacting with humans. The Robot Social Attribute Scale (RoSAS) [23] has been presented recently as a psychometrically-validated scale for measuring the social perception of robots. This has been used to study robot appearance [24] as well as human-robot handover interactions [1].

III. SYSTEM FOR FAST AND ROBUST HANDOVER INTERACTIONS

A. Handover Task

This paper considers a bidirectional handover interaction. The human initiates by presenting the object. The robot reaches, grasps, and moves the object from the handover location to its resting position. It then returns the object to the same handover location. The handover sequence is depicted in Fig. 2.

The handovers are performed with a toroidal object of 30 cm diameter, depicted in Fig. 3. The toroidal shape of the object can readily be grasped by the robot from a range of approach angles. It also distances the human from the robot hand, eliminating potential interference and improving safety. An OptiTrack motion capture system uses a constellation of retroreflective markers on the toroid to track its position and orientation. Users do not wear markers or other instrumentation. During the user study, the object is initially placed in a cradle within reach of the human participant. The handover interaction starts when the object is removed from the cradle.

B. Robot Character

To aid the perception of the robot as a social entity, we create the appearance of an anthropomorphic bear-like character with torso, arm, and head. The system uses a KUKA LBR iiwa 7 R800 robot mounted horizontally to form the shoulders and right arm of the bear character as shown in Fig. 3. In this way, joint 6 of the robot becomes the elbow of the character, and joint 4 becomes the character's right shoulder. A cartoon bear head is attached to the second link and the "torso" is dressed in a shirt to reinforce the illusion of a character handover.

We use a Pisa/IIT SoftHand [25], which is a soft and underactuated hand with a single actuated degree of freedom. The hand has a five-fingered anthropomorphic design, which supports the character's appearance. Moreover, its softness allows the hand to robustly grasp in the presence of small locational variations of the object.

To enhance the character behavior, joint 1 of the robot tilts the head to appear to look at the object. Joint 2 allows the character to lean forward with its right shoulder to reach towards a more distant handover location, i.e. beyond a specified radius of its right shoulder, or leans back if the location is too close.

An analytic inverse kinematics solver computes the remaining five joints to grasp the toroid. With two axes of symmetry around the major and minor radii, the toroid strictly requires only four degrees of freedom to achieve a grasp. We thus use the final degree of freedom to keep the elbow height as low as possible.

C. Online Trajectories for Fast and Smooth Motions

Human receivers often begin reaching for the object before it has reached its final handover location. To enable this behavior on the robot, we introduce the notion of an *expected handover location* x_{exp}. The position of this predefined

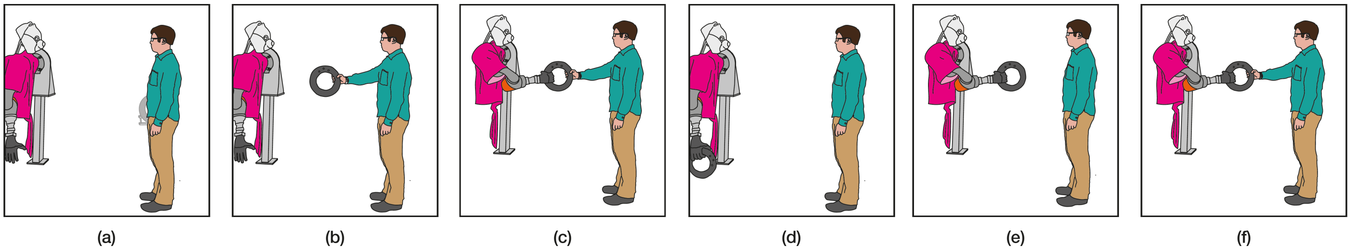

Fig. 2. Diagram of the handover sequence considered in this paper. (a) At the start, both the robot and human are in rest poses, with the object placed in a cradle close to human's right hand. (b) The human presents the object to the robot. (c) The robot reaches out and grasps the object. (d) The robot returns with the grasped object to the rest pose. (e) The robot presents the object to the human. (f) The human grasps the object. Finally, both parties return to their rest poses and the object is returned to the cradle. Note that in the implemented system, the robot does not wait for the object to reach the handover location before it starts moving, nor does the human.

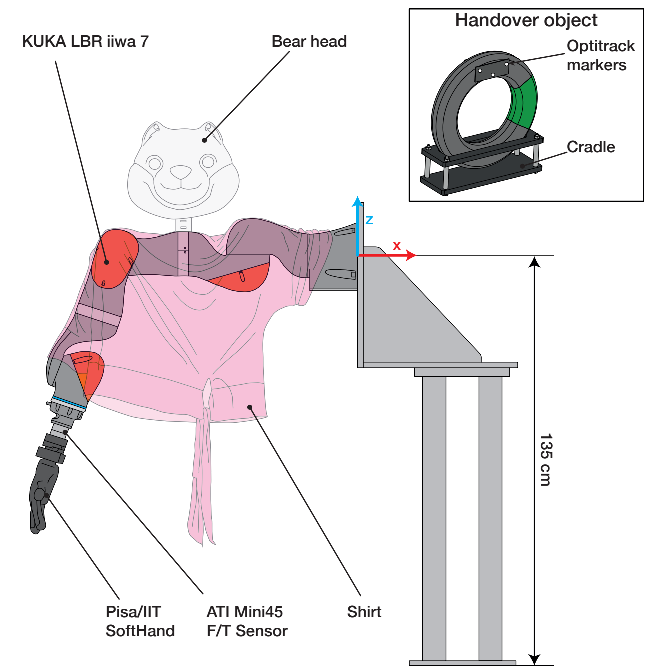

Fig. 3. The robot character and the handover object (inset) used in this study. The robot mechanism is mounted horizontally and dressed in a shirt, giving the appearance of the right arm and torso of an anthropomorphic robot character. A head is attached to the second link, allowing the first two joints to move the right shoulder forward or backwards, and to tilt the head up or down. The handover object (inset) is toroidal, outer diameter 30 cm, inner diameter 18 cm, thickness 4.5 cm, and has a set of motion capture markers attached. One part of the object is colored in green, indicating where the user should grasp the object.

location was chosen based on prior work [13, 26]: it is approximately halfway between the robot and human, and slightly to the right-side of the robot. We precompute a smooth, minimum jerk trajectory to the joint configuration at this location based on Bézier curves. Execution begins with the appropriate trigger. During movement, the trajectory is updated on-the-fly as the object moves, such that the robot converges to the object location. This allows the robot to begin motion as soon as the human initiates the interaction.

Specifically, when the object is removed from the holding cradle at time t_0, we reset the relative time to $t = 0$s. After a specified delay T_d corresponding to the desired reaction time of the system (refer to Sec. IV), the robot initiates the precomputed trajectory $q_\mathrm{pre}(t)$ having a duration of T_f towards the joint configuration $q(x_\mathrm{exp})$. After another reaction time delay T_d following the start of the precomputed trajectory, a new target $q(x_\mathrm{obj}(t))$ is continually computed, applying the inverse kinematics to the current object location $x_\mathrm{obj}(t)$. A gradually increasing fraction of the equivalent shift is summed to the precomputed movement. This process of calculating the online joint trajectory $q(t)$ for $t \geq 0$ is mathematically represented in (1) and visually portrayed in Fig. 4.

$$q(t) = \begin{cases} q_\mathrm{pre}(0) & \text{if } t \leq T_\mathrm{d}, \\ q_\mathrm{pre}(t - T_\mathrm{d}) & \text{if } T_\mathrm{d} < t \leq 2T_\mathrm{d}, \\ q_\mathrm{pre}(t - T_\mathrm{d}) + \Delta q(t) & \text{if } 2T_\mathrm{d} < t \leq T_\mathrm{d} + T_\mathrm{f}, \\ q\big(x_\mathrm{obj}(T_\mathrm{d} + T_\mathrm{f})\big) & \text{otherwise.} \end{cases} \tag{1}$$

where

$$\Delta q(t) = \frac{t - 2T_\mathrm{d}}{T_\mathrm{f} - T_\mathrm{d}} \Big(q\big(x_\mathrm{obj}(t)\big) - q(x_\mathrm{exp}) \Big)$$

By the conclusion of the trajectory, the robot thus reaches the object. Overall, this accomplishes a smooth, natural-looking motion which appears both predictive (moving early) and responsive (watching the object's placement). It does so with two separate reactions: first reacting to the start of motion, and second adjusting to the observed object motion. All other motions also follow minimum jerk trajectories in joint space based on Bézier curves. The implementation of this handover system runs in real-time at 1 kHz.

D. Hybrid Automaton for Robustness

The handover interaction behavior of the robot is determined by a hybrid automaton, which enables the system to respond in a robust manner to unexpected or uncooperative human behaviors.

Fig. 5 shows the flowchart for the human-to-robot handover. For example, if the grasp fails as the object has moved to a short distance away, the robot will attempt to reach for the object again. When retreating from a successful grasp, the robot uses impedance control with low stiffness

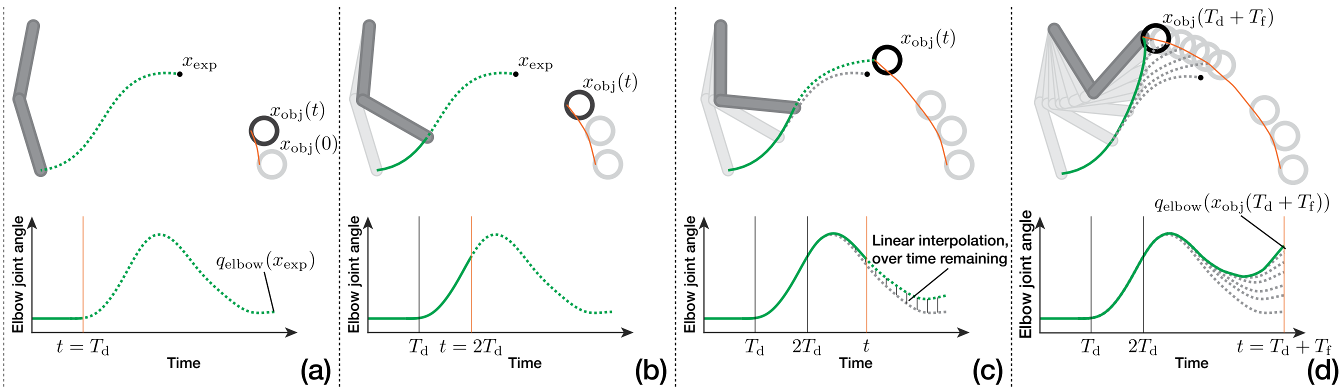

Fig. 4. An illustration of the interactive tracking method. (a) The robot is stationary for period $t \leq T_{\mathrm{d}}$ as the object begins to move to the handover location. (b) At $t = T_{\mathrm{d}}$, the robot begins moving along a precomputed trajectory towards an *expected handover location* x_{exp}, until $t = 2T_{\mathrm{d}}$. (c) For $t > 2T_{\mathrm{d}}$ (i.e., following another delay of T_{d}), a new target $q(x_{\mathrm{obj}}(t))$ representing the current object location $x_{\mathrm{obj}}(t)$ in joint space is computed. The algorithm then shifts the precomputed trajectory proportional to the remaining time. (d) The trajectory is continuously updated in real time, as the object moves through the workspace. This ensures that the robot smoothly reaches the object position $x_{\mathrm{obj}}(T_{\mathrm{d}} + T_{\mathrm{f}})$.

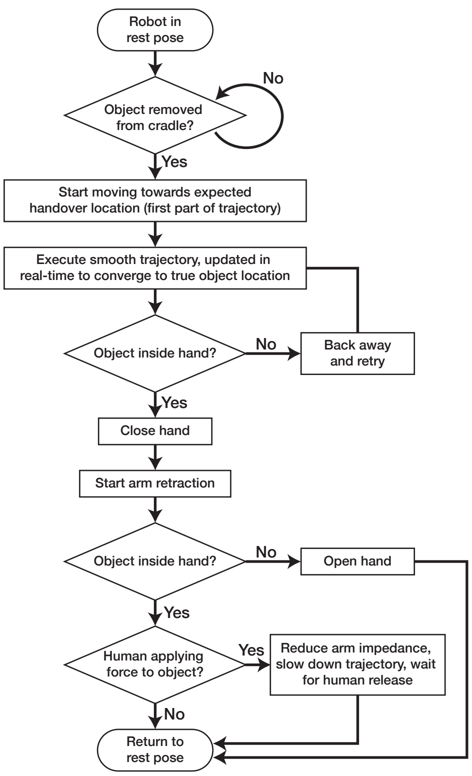

Fig. 5. Flowchart, human-to-robot handover.

to accommodate any human forces. The robot fully return to the rest pose only when the user releases the object.

For the robot-to-human handover, the object is released when the human force exceeds an appropriate threshold. The hybrid automaton for the robot-to-human handover is shown in Fig. 6.

The resulting behaviors are best seen in the supporting video, where both the speed and robustness of the handover interactions can be observed.

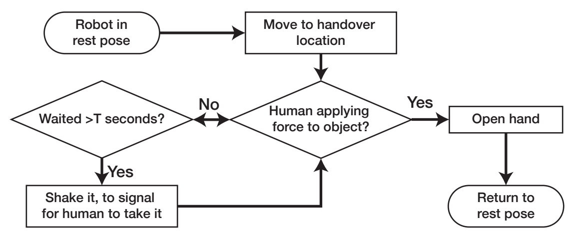

Fig. 6. Flowchart, robot-to-human handover.

IV. USER STUDY: THE EFFECT OF ROBOT SPEED AND REACTION TIME

Using the described system, a study was designed to investigate the effect of robot speed and reaction time on the perceived qualities of the interaction. We hypothesized that matching human characteristics would improve the experience and were curious whether excessive speed might be counter-productive.

A. Method

A 3x3 experimental design was implemented, to investigate the effects of robot speed and reaction time. For the robot's speed, three conditions of *slow*, *moderate* and *fast* were chosen by visually comparing the robot-to-human handover motions and adjusting parameters to obtain a speed similar to what a human would commonly use (*moderate*), as well as slower and faster conditions. The three speed conditions can be seen in the supporting video, and we also refer to the analysis below where we compare the speeds of the human and robot in the experiments.

To vary the reaction time of the system, we artificially induced delays in the robot's reactions to stimuli (e.g., motion capture and force data). As described in Sec. III, these delays are applied twice during the human-to-robot handover interaction: to delay the robot's movement along its precomputed trajectory to the expected handover location, and to postpone the start of the trajectory updates to accommodate movement of the handover object. In the robot-to-human handover, the delay is applied to the release of the handover object following detection of a minimum force. Three conditions of *no delay* (0.03 s latency), *short delay* (0.25 s latency) and *long delay* (0.75 s latency) were tested. The *no delay* condition enables a faster-than-human robot response and represents the fastest achievable reaction time of the system, whereas the *short delay* condition has a delay which is similar to that of the human sensorimotor system. The interval between the *long delay* and *short delay* conditions was exaggerated with respect to the *no delay/short delay* interval as we wanted to ensure that the *long delay* was significantly slower than human reaction time.

18 participants (9 female, 9 male) with ages ranging from 21–41 [*M*=29.83, *SD*=5.88], completed the study. All participants were employees of Walt Disney Imagineering and consented to both participation in this experiment and collection of video and motion capture data. No reward was given for participation in this study.

Participants were asked to stand in a designated area in front of the robot, with a distance of approximately 140 cm from the robot (as observed in human-human handover studies in [26]). The object was placed in the cradle located to the right of participants. At the start of a trial, the experimenter verbally signaled to the participant to pick up the object from the cradle and hand it over to the robot. The robot then retrieved the object, brought its arm back to the rest pose with the object in its hand for 0.5 seconds, and then proceeded to hand the object back to the participant at the same location where the human-to-robot handover took place. The participant retrieved the object and returned it to the cradle, concluding the trial. Each participant completed four trials per condition—each consisting of a human-to-robot and robot-to-human handover (a total 36 human-to-robot and 36 robot-to-human handovers per participant). The order of the conditions was counterbalanced using a Williams design Latin square to mitigate first-order carryover effects.

After each condition, participants were asked to complete the RoSAS questionnaire [23]—a set of 18 Likert scale questions pertaining to the three underlying factors of *warmth*, *competence*, and *discomfort*. We used 7-point Likert scales. Throughout the experiments, the pose of the robot (in both joint and Cartesian coordinates) and object, and times that the object was removed from and replaced back into the cradle were recorded for later analysis. The experiment lasted approximately 45 minutes per participant.

B. Results

1) RoSAS: A two-way repeated measures MANOVA was conducted to test the effects of robot end-effector speed and reaction time on the RoSAS attributes. MANOVA effect sizes are reported in terms of partial eta squared (η_p^2).[1] Post hoc pairwise comparisons were adjusted for multiple comparisons using the Bonferroni correction. Effect sizes for these pairwise comparisons are reported using Cohen's d (*d*).[2]

TABLE I
ROSAS ESTIMATED MARGINAL MEANS AND STANDARD ERRORS FOR ROBOT SPEED.

speed	warmth		competence		discomfort	
	mean	std. err.	mean	std. err.	mean	std. err.
slow	3.520	0.350	4.732	0.250	2.105	0.211
moderate	3.425	0.305	4.827	0.267	2.275	0.249
fast	3.310	0.274	4.742	0.255	2.529	0.225

TABLE II
ROSAS ESTIMATED MARGINAL MEANS AND STANDARD ERRORS FOR ROBOT REACTION TIME.

reaction	warmth		competence		discomfort	
	mean	std. err.	mean	std. err.	mean	std. err.
no delay	3.229	0.245	4.680	0.235	2.225	0.220
short delay	3.562	0.315	4.807	0.261	2.216	0.239
long delay	3.464	0.305	4.814	0.266	2.467	0.202

A significant main effect of speed on reports of discomfort was detected [F(2,32)=4.483, p=.019, η_p^2=.550]. Post hoc pairwise comparisons found that the average discomfort score for the *fast* speed [*M*=2.529, *SD*=0.928] is 0.425 points higher than the *slow* speed [*M*=2.105, *SD*=0.870] signifying a medium effect size [*d*=0.471].

Significant main effects of reaction time on warmth [F(2,32)=4.561, p=.018, η_p^2=.222] and discomfort [F(2,32)=4.369, p=.021, η_p^2=.215] were also found. Post hoc pairwise comparisons indicate that the average warmth score for the *short delay* reaction time is 0.333 points higher than the *long delay* reaction time [*p*=.020], representing a small effect size [*d*=0.286]. In terms of discomfort, the *no delay* reaction time scored higher than both the *short delay* and *long delay* reaction times by 0.252 [*d*=0.286, *p*=.044] and 0.242 [*d*=0.274, *p*=.023] points, respectively.

No other significant main or interaction effects were detected at the α=.05 level. Mean ratings are tabulated in Tab. I and Tab. II, and visualized along with significant effects in Fig. 7.

2) Comparison of Human and Robot Arm Speeds: Using the motion capture data, we computed the average speed of the object when being moved by the human, as well as the average speed of the object when being moved by the robot for the three different speed conditions. We also computed the mean peak velocity across all trials for both the human and the three robot speed conditions. See Tab. III.

Our obtained average speed for human participants is somewhat faster than the value of 0.55 m/s reported by Koene et al. [19]. It can be seen that the average speed for human participants in our experiments lies between the

[1]As a rule of thumb, Cohen indicates that partial eta square values of .0099, .0588, and .1379 may serve as benchmarks for small, medium, and large effect sizes [27].

[2]Cohen's d values of .2, .5, and .8 may be interpreted as small, medium, and large effect sizes respectively [27].

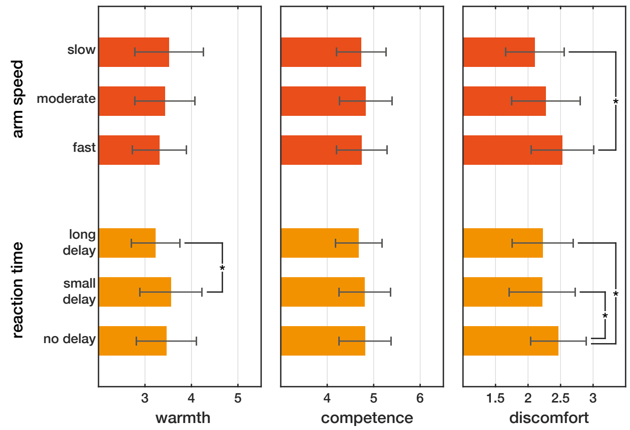

Fig. 7. Mean RoSAS ratings for the different conditions. Error bars show 95 % confidence intervals, and significant effects are indicated with *.

TABLE III
AVERAGE AND PEAK SPEEDS ACROSS HUMAN PARTICIPANTS AND FOR DIFFERENT ROBOT SPEED CONDITIONS.

	average speed (m/s)	standard deviation	peak speed (m/s)	standard deviation
Human	0.638	0.119	1.355	0.549
Robot (*slow*)	0.369	0.054	0.507	0.090
Robot (*moderate*)	0.573	0.054	0.882	0.101
Robot (*fast*)	0.694	0.069	1.149	0.123

moderate and *fast* conditions, while the *moderate* condition is close to the value reported in the literature [19].

One can also observe that the human motion has greater variability in speeds, i.e., a greater difference between the average speed and the peak speed than the robot conditions. This would be expected, due to the significantly smaller inertia of the human arm.

This analysis shows that the three speed conditions studied here are indeed similar to average human arm speeds.

V. DISCUSSION

Our study has shown that it is advantageous to mimic a human-like sensorimotor delay for human-robot handover interactions: with a longer delay the robot is perceived as less warm, and with no delay it is perceived as more discomforting. This aligns with our previous findings from the context of closed-loop handshaking control [2]. It would suggest that sensorimotor delays are generally beneficial, and could be applied to other interactive robotic systems and also digital characters. For example, one could apply such a delay to robot gaze control.

We also found that *fast* movements were perceived as more discomforting, while there was no observed difference between the *slow* and *moderate* conditions. Considering the values in Tab. III, this indicates that participants prefer the robot moving slower than, or perhaps at, their own speed. Discomfort to high speeds could be attributed to the appearance, larger size and/or inertia of the robot arm – however, this warrants further study.

It is worth noting that even the *slow* speed condition here is faster than the speeds considered in previous handover studies (e.g. [1]). In previous work, we found that faster and 'more efficient' handovers resulted in higher perceived competence for the robot. Although the current experimental setup is somewhat different, the fact that small effect sizes and non-significant effects on competence were observed here suggests that perhaps all conditions were sufficiently fast, or sufficiently close to human speeds. If desired, this could be tested by reducing the robot speed of the current setup further, which we expect to lead to lower ratings of competence.

As seen from the analysis on movement speeds, our robot handover system is able to match human handover speeds. We believe that this is highly relevant for being able to observe the effects seen here: as the system behavior is closer to human behavior, users are able to more readily apply human social expectations to interpret the robot behavior. The character-like appearance of the robot would be expected to further support this transfer of social expectations.

It would be interesting to study if the more responsive robot system can also change human handover behavior. If a system waits for the object to reach the handover location before initiating its motion (as in [1]), then the handover location is necessarily determined by the human. However, if both parties are moving simultaneously then it is reasonable to hypothesize that the handover location is negotiated by the two parties and reaches a consensus agreement. Backing up this notion, we observed in human-to-robot handovers that the human would frequently adjust the object position as the robot was about to grasp it.

With regards to the character appearance, our system is strongly stylized with a plain-color head lacking any distinctive facial features, and without a formed torso. While it seems reasonable to assume that a more character-like appearance would be capable of conducting more lifelike and realistic interactions, it is an open question how specific design changes would influence this. We leave this for further work. It is worth noting that depending on the direction taken, at some point the uncanny valley could be encountered and have a negative influence on perceived qualities.

Finally, we note the largest remaining difference in timing between human-robot and human-human handovers stemming from hand speed: the human hand is able to close significantly faster than the robot hand used here. One reason for this is that the human hand is able to exploit pre-shaping, i.e., starting to close the hand before the object is reached. We found that pre-closing the single degree of freedom hand unfortunately decreased grasp robustness as the actuator would pull in the finger tips too early. A faster soft robot hand would be a useful addition for future work.

VI. CONCLUSION

We have presented a fast and robust system for handovers with a robot character. Fast handovers are enabled by an online trajectory generator, allowing the robot to begin motion as soon as the human initiates a handover. The generator also smoothly adjusts its trajectory as the object moves and converges to the object location, giving the robot's reaction a natural and responsive feel. Robustness is enabled by a hybrid automaton which detects system failures such as the human being uncooperative, and responds accordingly. We also leverage a fast robot, motion capture system with minimal latency, soft hand, and the inviting appearance of a bear-like character to create a robot interaction that feels organic and character-like.

We studied the effect of robot speed and reaction time on the perceived qualities of a bidirectional handover. Our findings show that the addition of a small sensorimotor delay to the robot has a positive effect on perceived robot qualities: the *no delay* condition is perceived as more discomforting and the *long delay* condition is perceived as less warm. We also show that the perceived discomfort increases if the robot speed is higher than the human speed in a typical handover.

Although our findings have been demonstrated in this specific handover scenario, one would expect them to readily transfer to other areas of interactive robotics and systems. We look forward to giving all robots natural and socially acceptable behaviors and having people interact with them.

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