Optimal Interaction Forces for Natural Robot-Human Handover

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***Abstract*— Safe and efficient object handover between robot and human is a critical skill for personal robot interaction [1], [2], [3]. While humans also use a complex mix of speech, gaze, and gestures to indicate the phases of the handover, the actual object transfer relies heavily on tactile and force sensing.**

In this paper we describe a handover controller that uses force-measurements from the robot arm and hand to trigger the grasp release (robot to human handover) or grasp capture (human to robot). The algorithm was implemented and tested both on a mobile service robot with the Kinova Jaco robot and a stationary workcell with the KuKA LBR4+ robot.

Our case study indicates that interaction force thresholds must be matched to the object weight to achieve interaction that feels natural to the users. In fact, users prefer surprisingly low interaction forces, which in turn implies the use of sensitive and well-calibrated robot sensors.

I. Introduction

In this paper, we describe a multi-modal algorithm for object handover that integrates force data from the robot arm with tactile sensing from the robot fingers to trigger the handover (opening or closing the hand or gripper) reliably.

We present results from a user study that relates perceived handover quality (usability and acceptability) to object weight, gripper orientation, and robot motion. The results demonstrate clearly that acceptable force thresholds strongly correlate with perceived object weight, while gripper orientation or robot compliance are less important.

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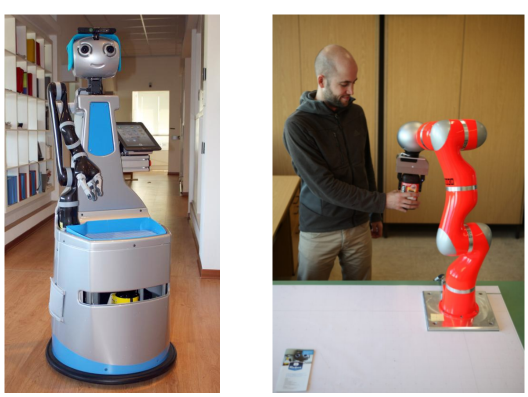

Fig. 1. The two robot systems used for the experiments: The *Domestic Robot* service robot designed for elderly care uses the Kinova Jaco arm (left). Our work cell setup with the KuKA LBR-4 in a robot-to-human handover task, shown with vertical gripper orientation (right). Our algorithm uses force and tactile sensor data to detect when to release the grasp.

II. Setup and Handover Controller

The setup for our experimental study consists of two different robots, see figure 1. The *Domestic Robot* is a mobile indoor service robot desigend for elderly care scenarios. The robot integrates a differential drive platform and the Kinova Jaco robot arm with its three finger hand [4]. The robot has been tested in two large scale user-studies with elderly users as part of European research project *Robot-Era* [5].

Our second platform is a stationary robot workcell that combines the KuKA LBR 4+ light-weight robot and the Weiss-Schunk WSG-50 two-finger gripper with integrated tactile matrix sensors.

For the experiments reported here, text-to-speech was used to indicate that the robot was ready, and force/tactile sensing from the robot arm and gripper was used to detect that the user had grasped the object, see figure 2. The handover is then triggered as soon as the estimated external force applied by the user exceeds a previously set threshold.

This force threshold must be selected carefully, because too low a force threshold can be triggered accidentally, increasing the risk that the object is dropped. On the other hand, large force thresholds imply that the user has to wrestle the object away from the robot. As the Jaco arm lacks dedicated torque sensors, motor current measurements are used to estimate applied forces. The LBR 4+ robot provides both joint torques and estimated Cartesian external forces.

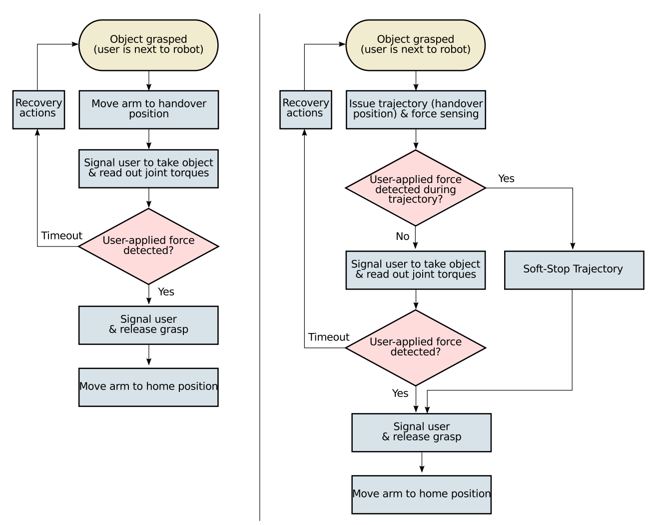

Fig. 2. (below) Flowchart of the handover controller (left): stationary robot arm, (right) in-motion handover. Here, the robot is switched to a soft-stop trajectory as soon as user interaction is detected.

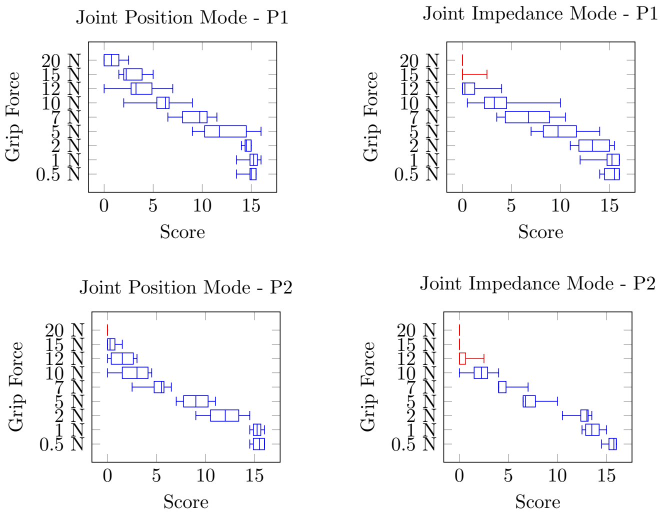

Fig. 3. User scores of handover force-threshold ("'grip force"') versus object weight in four different robot control modes. From top-left to bottom right: (a) stiff robot, horizontal gripper orientation, (b) compliant robot, horizontal gripper, (c) stiff robot, vertical gripper, (d) compliant robot, vertical gripper. While higher force thresholds ensure a more reliable operation, users clearly prefer low interaction forces.

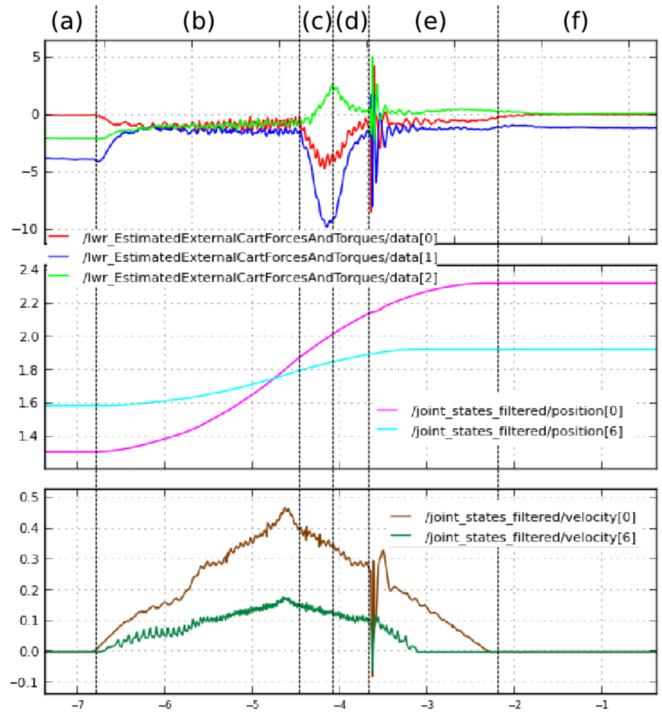

Fig. 4. In-motion object handover (LBR4+): (above) Measured external tool forces (F_x, F_y, F_z); (middle) robot joint positions (θ_0, θ_6); (lower) corresponding joint velocities. The annotation indicates the handover phases: (a): robot idle, (b): arm motion towards the user, (c): user touches and grasps the object, (d): gripper opens (and forces decrease), (e): arm stops, (f): robot stopped.

III. User Study

We designed a simple user study for stationary handover tasks (robot arm stopped) with objects of different weight and gripper orientation. For the KuKA LBR4+, we also tested different robot control modes, namely pure position control (stiff robot) and joint impedance control (compliant robot). In the latter case, the robot arm gives way a bit when the user touches the robot. For an object of given weight, different force thresholds were tested in a random sequence, and the user acceptability scores were recorded.

See figure 3 above for a summary of the results, with the overall user scores (range 0..15) plotted against the handover force threshold. Each boxplot indicates the user acceptabily of a given force threshold averaged over all users and all test objects, as well as the lower and upper limits. The overall trend is the same for all four scenarios tested, namely stiff and compliant robot with either horizontal (P1) or vertical (P2) gripper orientation. Interaction forces larger than 10 N were disliked by all test persons, and best results were achieved with force tresholds of 1 N or lower. A more detailed analysis (in preparation) indicates that users accept higher force thresholds for heavier objects.

In the above experiments, users would have to wait until the robot reached its end postion until handover was activated. This was critized by our users. Correspondingly, we changed the handover controller to also trigger handover while the robot was still moving. See figure 4 for example sensor values and the corresponding robot soft-stop trajectory. Note that the force/torque measurements from the robot arm are quite noisy while the robot moves. Only by combining force data from the robot arm with tactile data from the robot gripper (which is less sensitive to arm motions) was it possible to achieve in-motion handover that felt natural to our users.

IV. Summary

In the study reported here, interaction force thresholds were tested against object weight, gripper orientation, and robot stiffness. Our results indicate clearly that users prefer very low interaction forces, but will accept higher force thresholds with increasing object weight. Interestingly, our user scores are largely independent of gripper orientation, despite the higher risk of dropping the object in vertical robot gripper orientation.

Precise estimation of external forces applied to a moving robot requires both accurate sensing and a dynamic model of the robot. Our results therefore set lower limits regarding the needed force and tactile sensing capabilities for physical human robot interaction in future service robots.

References

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