Natural Robot-Human Handover Combining Force and Tactile Sensors

Norman Hendrich, Hannes Bistry, Johannes Liebrecht, Jianwei Zhang
Dept. of Informatics, University of Hamburg, Germany
{hendrich,bistry,8liebrec,zhang}@informatik.uni-hamburg.de

***Abstract*— Safe and efficient object handover between robot and human is a critical skill for a service-robot. Where humans employ a complex mixture of speech, gestures, arm motions, and tactile sensing to detect and indicate the phases of the handover, most robots today still lack sufficiently sensitive tactile sensing.**

In this paper we describe a multi-modal controller for object handover that combines force-sensing on the robot arm with tactile data from the robot gripper. The robot uses sounds and speech to indicate that it is ready, and releases the object when the user applies a force to the object. Our experiments indicate that force thresholds must be matched to the object weight to achieve interaction that feels natural to the users. We also present first experiments on handover operations triggered by the users while the robot arm is still moving.

I. Introduction

In this paper, we discuss a multi-modal architecture for object handover for low-cost indoor service robots. The interface has been implemented and tested on our *domestic robot*, a service robot designed to support elderly people in their homes. The robot forms part of the integrated ambient assisted living infrastructure currently under development in project Robot-Era [1].

The paper is structured as follows. First, section II introduces relevant related work on object handover, while section III presents an overview of the robot hardware with the available sensors and actuators and the low-level software. Section IV describes the sequencing of object handover for robot-to-human handovers and lists the multi-modal cues available on our robot. The experiment setup to test the efficiency and user-acceptance of different control strategies is presented in section V. The paper concludes with a summary and planned future work.

II. Related work

The importance of object handover has already been mentioned by [2], but the requirements for human safety were hard to fulfil with early industrial robot systems. While a lot of work concentrated on human-aware and predictable robot arm motion generation, a higher level evaluation of the handover process must also include subjective measures like user acceptability or mental strain [3], while [4] concentrated on the timing of the handover process. In this regard, multi-modal clues like gestures and gaze have been studied for joint action understanding [5] and best efficiency. A human-aware task planner was presented in [6], while a recent workshop on human-robot collaborative manipulation collected several interesting approaches to object handover [7] including the use of multi-modal interaction integrating natural speech, gesture, and legible robot motions. One study presented at the workshop made use of the Kinova Jaco arm [8] that is also used for some experiments reported in this paper. A human-inspired object handover controller based on force-measurements was presented recently in [9], while [10] focuses on natural interaction between human and robot. In the SAPHARI-project [11] the safe interaction between humans and robots is studied. This project bases on the recent progress achieved in the design of safe robot arms (e.g. the KuKa LWR series) and focuses on the sensor based detection of the user in a dynamic environment. With a set of internal and environmental sensors, the robot tracks the motion of the user and tries to predict his or her intention. Using multimodal communication methods including gestures, the human and the robot interact to perform collaborative tasks.

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III. System setup

This section sketches the robot hardware used for the experiments, that are performed on two completely different platforms (see figure 1):

- A mobile service robot designed for elderly care equipped with a Kinova Jaco manipulator.
- A work cell setup with a fixed Kuka LWR 4+ robot arm and a Schunk WSG 50 gripper.

While the service robot is intended for use-case studies with elderly users, the work cell setup is used for trying out new methods for object detection and manipulator control.

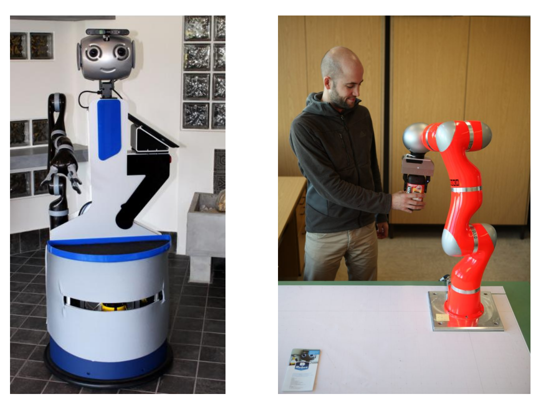

Fig. 1. The two robot systems used for the experiments: The mobile service robot (left) and an the work cell setup performing a robot-to-human handover task (right). Force-sensing is used to detect when to release the grasp.

For the purpose of this paper, the service robot was used for initial feasibility studies, and the work cell setup for refinement of the handover strategies.
As both systems are controlled by ROS, most parts of the high-level software can be shared among them. In the following the two systems will be described in detail.

A. Common Software Architecture

Both the mobile service robot and the work cell share large parts of the software libraries. Most components are integrated within ROS [15] [16], while especially the mobile robot needs interfaces to other software subsystems. The software architecture uses four main abstraction layers [17] as shown in figure 2. The topmost layer consists of the user-interface (speech, tablet) and the PEIS ambient sensor network [18] which controls the robots and also all sensors in the ambient assisted living environment. The second level is formed by a set of carefully chosen *services* that encapsulate the robot skills for the elderly users.

The services in turn are implemented on the third layer by a large number of interacting ROS nodes. Perception relies on the PCL point-cloud library and a custom pipeline for SIFT-based [19] object recognition and 3D-pose estimation for a set of known objects. Object grasping and manipulation is provided by the MoveIt! framework, which interfaces to the perception nodes for collision-aware and self-filtered arm motion planning. Custom ROS nodes are used to control the Jaco hand and the Schunk gripper. A dedicated supervisor ROS node manages the scheduling of the ongoing services and provides feedback about task and subtask progress to the PEIS layer and the user-interface. The fourth level is made up of the different sensor and actuator drivers, which in turn interface to the actual hardware devices. Robot localization and navigation is performed by the Mira/Cognidrive software from Metralabs. A complete Gazebo simulation model with all sensors and actuators is also available for the robot.

B. The service robot

The domestic robot platform is designed in the Robot-Era project as a service robot platform for household tasks. Beside the feasibility for the tasks its design should meet the requirements of acceptability and safety for a user group of elderly people. The robot hardware integrates the proven Scitos mobile platform [12] with the Kinova Jaco manipulator [13] and a fairly standard set of sensors including laser-scanners, cameras, and the XtionPro RGBD camera (comparable to Microsoft Kinect). The Jaco robot arm was chosen for its combination of large reach, acceptable payload (1.5 kg), simple mechanical and electrical interface, and the versatile integrated three-finger hand. While the arm lacks tactile sensing, the joint torques can be estimated from the motor currents.

The robot arm is controlled by a modified ROS node [14]. The libraries interface to the Windows *.dll* files and provide the necessary functions needed for ROS and MoveIt! compatibility. For the purpose of these experiments the node was extended to read out and publish the joint efforts to the ROS message.

C. The work cell

The work cell described in this paragraph mainly consists of a desk with a rigidly mounted Kuka LWR4+ manipulator on it. The manipulator is equipped with a parallel gripper (Schunk WSG 50); all cables (power, Ethernet) are routed inside the manipulator. As sensory systems, one Microsoft Kinect and one high resolution webcam (Logitech C-910) are mounted on a table.

The robot arm is driven using the **F**ast **R**esearch **I**nterface from KuKa. For the communication between ROS/MoveIt! and FRI, a robot controller in the Robot Operating System (ROS) is needed. One popular LWR controller is contained in the lwr_fri package of the lwr_hardware stack, which was developed by Konrad Banachowicz of the University of Warsaw. For the purposes of this experiment the package has several disadvantages. It uses Orocos drivers, which makes it real time capable, but more difficult to integrate to new ROS distributions. Another point is that currently this package only contains a joint position controller, but for certain interaction tasks also Cartesian impedance control, joint impedance control and several other functionalities are needed.

Therefore we created a simple ROS package called ros_fri, which currently provides most of the functionality of the FRI Library. In order to interface to the MoveIt! framework, ros_fri is also an action server, which executes joint trajectories of the type FollowJointTrajectory on request. According to FRI the LWR can operate with 1-100 ms cycling rate. We are working smoothly with ros_fri at a cycling rate of 10 ms. Operation with cycling rates below should be possible, but has not been tested yet.

IV. Multimodal Handover Controller

Currently two versions of the grasp-and-handover loop have been implemented. An overview of the main steps is shown in figure 3. Regarding the final object handover operation, we assume that the robot has already grasped an object and is close enough to the user. The robot to human object handover (without in-motion handover) operation then consists of the following main phases:

1) a free-space arm motion towards the user to the estimated handover position. Using the Kinect sensor and the ROS 3D-perception pipeline together with the robot self-filtering, real-time collision checks are performed during the motion to guarantee user safety,
2) the user grasps the object with one or both hands,
3) the robot detects that the user is ready,
4) the robot releases its grasp,
5) the user takes the object away from the robot,
6) the robot performs another collision-checked motion to retract its arm,
7) the robot is ready for the next task.

The control loop including in-motion handover differs from this handover strategy mainly in the point that during

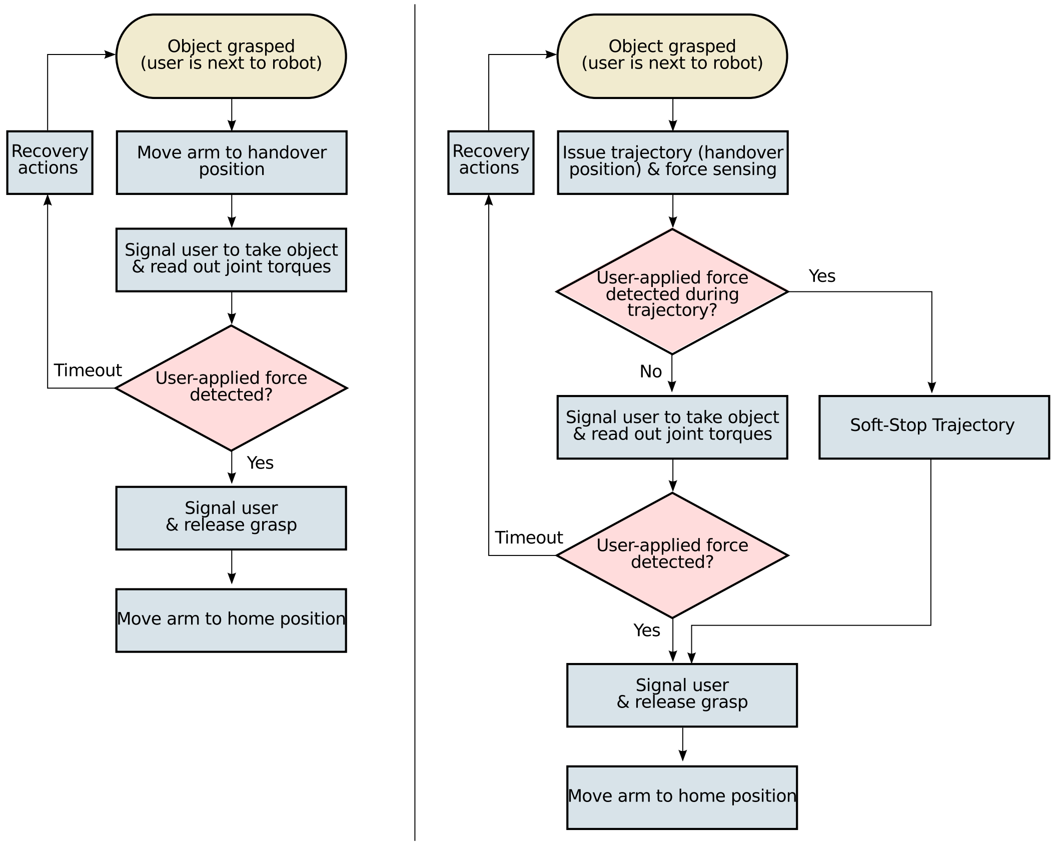

Fig. 3. Simplified state-machine diagram of the two handover controller modes. Left: the arm moves to the handover position and detects when the user applies force to the grasped object. Right: in this mode the force detection is already active during the trajectory execution. This operation mode required support in the ROS-node for trajectory control.

the trajectory execution towards the user the handover-sequence can be directly triggered. In that case the arm motion is instantly stopped and the gripper is opened. The main intention of implementing this strategy is to speed up the handover process and to support a more natural kind of handover. This mode is currently only supported on the work cell setup with the Kuka LWR manipulator and its precise force measurement.

As the process involves direct physical interaction during phases 2-4, visual collision-checks have to be disabled during this time. Safety is still guaranteed even for inexperienced or careless users, as:

- the mobile robot platform and arm are stationary during those phases, and the slow motions of the Jaco fingers cannot hurt the user.
- on the work cell the velocity of the manipulator is limited and a maximum force is specified in the controller

In order to test just the handover-phase, a third control strategy is implemented that just opens and closes the gripper without moving the manipulator. The criteria for robot-to-human-handover can be configured just like those for the other sequences mentioned above. The human-to-robot handover (particularly the closing of the gripper) is also triggered by force events, but will not be the focus of this paper.

V. Experiments - Scitos G5 with Jaco Arm

In a first set of experiments we started with an object already grasped in the Jaco-hand. The arm then moves to the handover position and the user has to apply force in the upwards direction to initiate the handover sequence. Figure 4 shows the recorded joint positions and joint torques for a typical handover sequence. The robot first moves to the planned handover position, and then waits for the user to reach for and touch the object. The most important phase here is (d), where the user begins to push the object to the side, as indicated by the changing torques on the shoulder jaw joint J1 (red). A torque difference of 3 Nm on J1 was set as the force threshold in this experiment (see arrow in the graph), to ensure that the user could reliably hold the object after the robot releases the grasp.

Using the joint J1 has the advantage that this joint is not affected by the weight force of the object and the parts of the arm. However, triggering the handover sequence is also possible by using the shoulder jaw joint J2. In that case the user needs to lift up the object. An experiment with this configuration is described in [20].

We are currently preparing a case-study, involving a group of elderly persons in the scenario sketched above. The robot gives an object to the user, using different handover positions and objects of different size and weights. Speech and LEDs

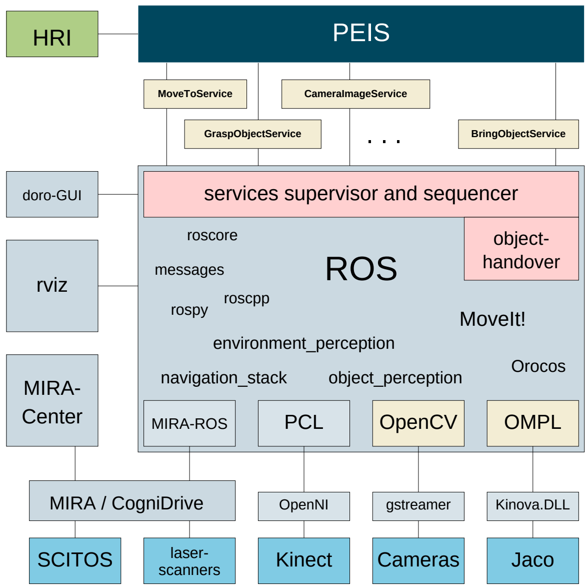

Fig. 2. The software architecture of the domestic robot platform and the planning components: The robot software is based on ROS and provides interfaces to the MIRA/Cognidrive navigation software and the PEIS ambient intelligence framework. The handover controller relies on MoveIt! and OMPL for motion planning, and OpenCV for perception.

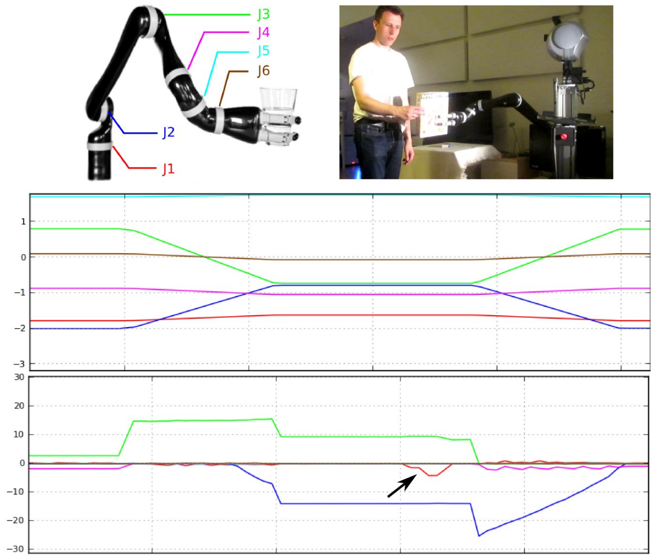

Fig. 4. Force controller handover with the Kinova Jaco arm. The robot arm and its joints (J1..J6) (top-left), a photo during handover-operation (top-right), measured arm joint-trajectory $[rad]$ (middle) and joint-efforts $[N]$ (bottom) during handover operation. In this experiment, handover was triggered by a force threshold on J1 (red line), the arrow marks the force that triggers release.

are used to indicate that the robot is ready, while different force thresholds will be used to detect whether the users have grasped the objects.

The initial results with the Kinova Jaco Arm show that multi-modal control of human-to-robot handovers is possible on simple robot arms without advanced tactile- or force-sensing. The controller guarantees that the user has grasped the object before releasing the robot grasp, improving usability and stability.

The torque sensors of the Kinova Jaco arm are quite inaccurate and have a high backlash. Therefore, small forces applied to the end-effector are not easily recognized, potentially limiting the user-acceptability of the process. In addition, the update rate of the force-information is quite low and this causes a significant delay in the handover process.

VI. Experiments - KuKa LWR 4+

Due to its unique set of features, the Kuka LWR robot arm has established itself as the de-facto standard for research on physical human-robot interaction. The arm combines low weight with high payload (7 kg), integrates torque-sensors on each of its 7 joints, and its real-time controller includes friction models to provide joint-level or Cartesian forces applied to the end-effector.

The experiments described in this paper cannot be regarded as a clinical study. They can be seen as a preparation of a clinical study with end-users that will be performed from Q4/2014 on within the Robot-Era project. As a clinical study involves a huge effort, it is important to prepare it as thoroughly as possible. The main purpose of this informal testing series, conducted with technical and non-technical staff, is to:

- reveale and improve **obvious weak spots** of the system, like system crashes, huge delays and other malfunctions
- determine criteria for user questioners
- figure out some possible alternative strategies for every task, with the intention of letting the users vote for the most convenient one (or even more generating strategies based on user feedback)

Our early experiments indicated that humans were quite sensitive regarding the efficiency of robot-to-human handover operations; even slight delays of the robot or wrong force thresholds were immediately noticed by our test persons. The experiments described in the following are designed to achieve a natural object handover that "feels right" to the test persons. A control cycle of 10 ms was used for the experiments in this section, with collision-aware trajectories generated by the ROS MoveIt! planner and real-time control by the FRIlib library.

A. First Experiment on Kuka Setup

In the first test a light medium sized object was used for the handover experiment. The object was grasped by the manipulator and then the manipulator moved to the handover position. The user had to apply force perpendicular to the fingers of the gripper. The system announced the release of the gripper via text-to-speech and after speech output opened the gripper. The handover worked in 98 % of all cases. Once there was a delay in the system; the gripper opened a couple of seconds late when the user already thought that the software had crashed.

Generally, all users expressed approval of the implemented handover strategy. But especially in the first experiment, there were a couple of points users criticised concerning this

	Experiment	Object	Weight	Criteria	Threshold	Notification	Users	$p_{success}$
1	Complete Loop	box	70 g	Force x-direction	2 N	Speech (delay)	5	98 %
2	Complete Loop	small cube	20 g	Force all-directions	2 N	Speech	5	98 %
3	2-way handover	pen	18 g	Touch + Force	0.5 N	Speech	3	100 %
4	2-way handover	steel-disc	800 g	Touch + Force	0.5 N	Speech	3	100 %
5	2-way handover	various	*	Touch + Force	adaptive	Speech	3	100 %
6	In-Motion-Handover	box	70 g	Touch	fixed	Speech	3	100 %

Fig. 5. Table of conducted experiments and success rate of object handover. Different objects and interaction cues have been used during the experiment. Per user 10 interaction trials were performed. A dropped object was counted as failure.

Experiments

Value	Explanation
Grasp-Loop	The robot system detects and grasps an object, moves the arm to the handover position and releases the grasp on a special criterion.
2-way handover	The user hands over an object to the robot by applying force to the gripper. The robot releases the grasp on a special criterion.
In-motion handover	The robot system detects and grasps an object, moves the arm to the handover position, monitors force during motion and will immediately initiate handover if the user tries to take the object.

Handover Criteria

Force X-direction	The force to the endeffector measured by the KuKa LWR robot arm. Only force in one direction is evaluated.
Force all directions	The force to the endeffector measured by the KuKa LWR robot arm. If the length of the force vector exceeds the threshold, the criterion is met.
Torque one joint	The torque of one joint is measured.

Fig. 6. These tables explain some of the different properties of the conducted experiments (comp. figure 5).

experiment:

Delayed release: The system released the grasp only after it finished speech output. This way, the user had to hold the object for a couple of seconds, while it was still grasped by the robot.

Unergonomic force direction: Some users expressed, that the system should release the grasp just based on the magnitude of the force and not by its direction. This was respected in the later experiments.

Slow operation: This was a general feedback about the operation of the manipulator. There were two main reasons for this. First, due to safety reasons the manipulator is operated at 40 % of its maximum speed, and second, the time needed for collision-free motion planning was quite significant. The latter issue will not be addressed within this paper, but will be investigated. Using a more powerful dedicated computer for arm control should solve this problem.

B. Second Experiment on Kuka Setup

In the second experiment, some user criticisms regarding the first experiment were addressed. Now forces in arbitrary directions are considered as the release criteria. In addition to that, the manipulator can release the grasp before the output of the speech has finished. The test users reported that the handover is now more convenient and comfortable.

Too high force threshold for small objects: For the small wooden cube used for the second experiment, the users reported that the force threshold was too high, one user described it as if the robot was unwilling to hand over the object. The users also stated that the release force was acceptable for the larger object from the first experiment.

C. Experiment 3 & 4: Handover with fixed threshold

Based on the feedback of the last experiment, the force threshold was reduced to 0.5 N. In experiment number 3, the force threshold was reported to be comfortable for the type of object. The experiment was repeated with a heavier object (4) and the users expressed the wish that the gripper should not release the object so easily, therefore the finding of this test is:

Fixed force threshold is unsuitable for different objects: For heavier objects the users usually expect the interaction partners to support the object until they perform a really stable grasp. For lightweight objects lower threshold values feel more comfortable.

D. Experiment 5: Handover with adaptive threshold

In order to improve the handover comfort an adaptive threshold was implemented. Therefore the weight of the object is estimated using the Cartesian force measurement of the robot arm. After the object is grasped, the arm is kept in an idle position for a while and the forces are sampled. After that the threshold values are set to $F_{th} = F_g + 1N$, where F_g is the weight force. This threshold calculation has been defined intuitively and may be refined in later experiments. An evaluation of the experiments is shown in figure 7.

The handover procedure was now reported to feel comfortable and stable. Nevertheless smaller optimizations remain. Currently, in order to measure the weight, the gripper is kept idle for a while and the user is instructed by speech

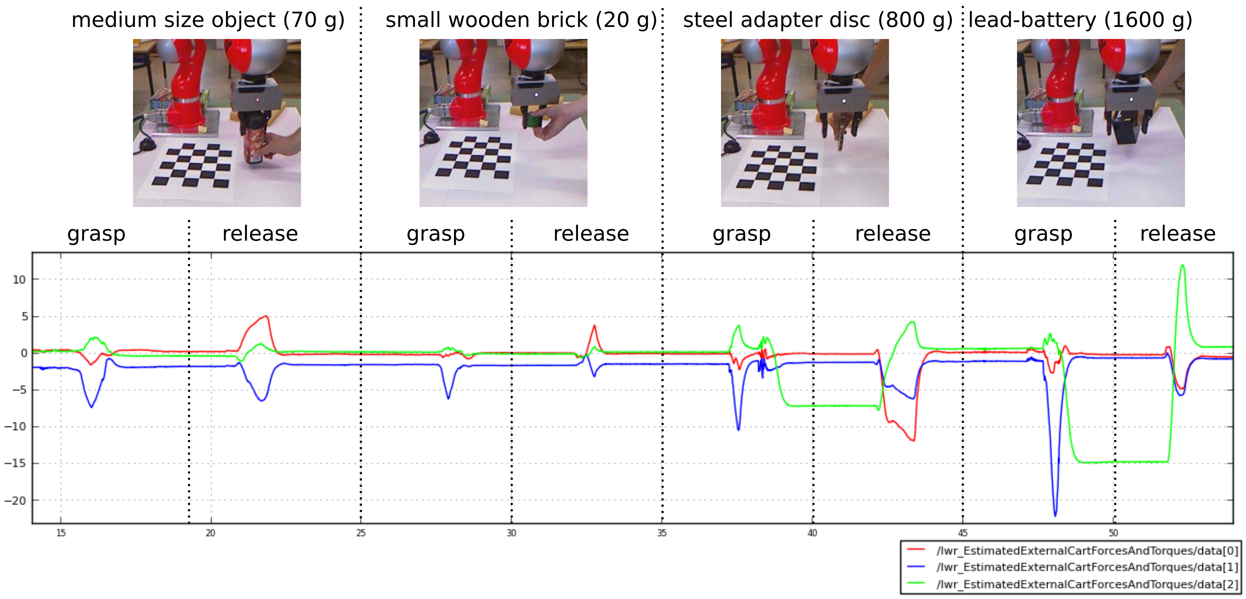

Fig. 7. In the experiment visualized here the human hands over different objects to the gripper. The robot arm measures the force and initiates the closing (grasp phase) and opening motion (release phase) of the gripper. The Cartesian forces in N are visualized by the red (x), blue (y) and green (z) lines. It can be seen that the forces that need to be applied depend on the weight of the object. The actual occurring forces also depend on the way the user grasps the object and the delay before the gripper opens. During the carry phase it can be seen that for the two heavier objects the z-force of the gripper matches the weight force of the objects quite accurately.

output when to start the handover procedure. In an earlier experiment the fixed idle time was too short, and the weight was sampled while the user still touched the object, leading to inaccurate measurements that caused the gripper to open immediately and drop the object. Therefore the idle time was increased. However, the extra delay in execution was criticized by some users.

Delay due to force measurement: Measuring the idle force is currently implemented by waiting a fixed timespan (2 seconds). A more sophisticated way would be to monitor the force values continuously and wait until they have settled. This future improvement is expected to lead to shorter delays, and more importantly, reduce the risk of dropping the object.

E. Experiment 6: In-motion handover

In this experiment the in-motion-handover described in section IV is tested. As a permanent issue in the user feedback was the slow operation of the manipulator system, this strategy may provide a solution for this issue. The handover sequence can be initiated anytime during the manipulation sequence by grasping the object. We need to mention that within this work we do not primarily focus on the aspect of safety. As mentioned in section II, there are many research projects dealing with these issues. The handover sequence during arm motion is triggered by the touch sensors in the grippers. Trials where the estimation of external forces was used sometimes did not work reliably, because during motion the force estimation was quite inaccurate, which calls for a high threshold. Nevertheless, in the example shown in figure 8 it would also have been possible to use the Cartesian force as a criterion, as the force applied by the user is higher than the force jitter occurring during motion. In addition to that, the dynamic forces due to the object weight would need to be considered in the force calculation.

VII. Summary

In this paper we have shown our work on implementing natural human-robot handover operations on robot systems. Force and touch sensor information can reliably be used to trigger the object handover in both directions (human to robot, robot to human). The test persons that used the systems expressed their opinion that using force sensing will benefit the work-flow of human-robot interaction tasks. In the tests it has been shown that the handover procedure is perceived as being most comfortable when the force threshold depends on the type of object. In our future work we will improve the handover strategies and tune the force thresholds in many ways. One option is to track the hand pose and the user pose and incorporate it in the handover process. In addition to that, different objects may need different grasping- and handover strategies in order to satisfy object affordances and constraints.

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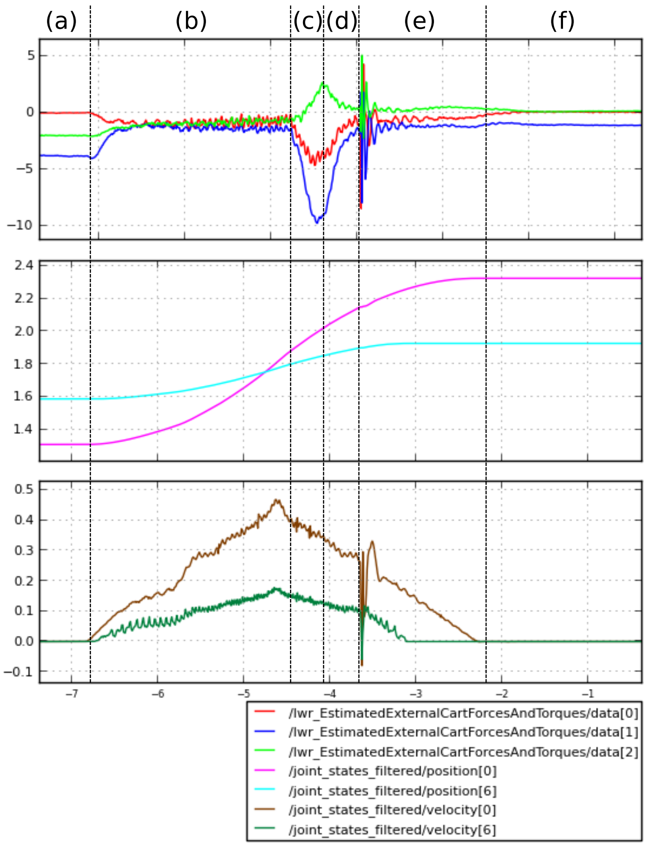

Fig. 8. In-motion-handover: The Cartesian end effector forces $[N]$ (top), the joint position $[rad]$ (middle) and joint velocity $[rad/s]$ during the handover procedure. The different phases of the handover process can be seen:
(a): idle (zero velocity, constant position and force values),
(b): moving towards user (noise in measured force values),
(c): user grasps object (visible in force values),
(d): threshold reached, gripper opens, therefore external forces decrease,
(e): arm controller stops the arm (a jerk occurs),
(f): the arm is idle.
It can be seen that the controller reacts delayed to the stop command. This issue has been criticised by the users and is under investigation as well as the occurring jerk.

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