Safe Interactions and Kinesthetic Feedback in High Performance Earth-To-Moon Teleoperation

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***Abstract*—The international space agencies plan to implement orbiting space stations around celestial bodies as moon or Mars in the near future. Autonomous robots will be assigned with exploration tasks and the building of structures as habitats. A teleoperator interface will be available in the orbiter to assure the possibility of direct control of the robots located on the celestial body as a fallback, in case an autonomous functionality fails. Communication links will be comparable to the ones between the International Space Station and earth, reaching from direct S-band communication, to communication via geostationary relay satellites in a Ku-Forward link. Since the planned Gateway orbiting the moon will not be manned throughout the year, further interfaces have to be established with which the robots can be controlled from earth. An available laser link to the moon provides a high-bandwidth communication with 2.6s roundtrip-delay, which currently allows for supervised control, for example via a tablet interface. Current advances in control theory can achieve stable and high performance kinesthetic feedback in bilateral telemanipulation at delays above 1s. This paper presents the first experimental analysis of the feasibility and human operator performance of telemanipulation with an Earth-to-Moon like delay of 3s. In light of the fact that several technologies such as visual augmentation and shared control can be integrated in addition, the results are highly promising.**

TABLE OF CONTENTS

1. INTRODUCTION

Teleoperation was initially developed for the atomic industry to replace humans in harsh environments. In future, this technology can also support astronauts during extra vehicular activities (EVA) with robotic manipulators. Besides this safety aspect [1], the telepresence technology can also reduce costs, since human traveling can be reduced exemplary through robotic maintenance of satellites or robotic avatars for exploration [2], [3]. International space exploration plans involve the implementation of a Gateway orbiting the moon as well as Mars missions in which astronauts will be located in an orbiting space station. Autonomous robots located on the celestial body would perform exploration tasks or build habitats. As a fallback scenario, the humans in the orbiter should be able to control these robots via teleoperation in case of difficult tasks or emergency. Depending on the orbit, a high communication delay needs to be handled. Analogously, delays of up to 600ms are observed for direct communication between the earth and geostationary satellites. In a Ku-Forward link from the International Space Station (ISS) to earth via relays satellites, roundtrip-delays of minimal 800ms or in practice around 1.2s can arise. In contrast, a direct-view S-band communication from earth to ISS can be realized at around 30ms roundtrip-delay. For the Lunar Laser Communication Demonstration (LLCD, [4]) a laser link from earth to a satellite at the moon was established which achieved a roundtrip-delay of 2.6s at a bandwidth of 20Mbps. In [5], bilateral control of a robot on a satellite via a communication of 7s roundtrip-delay was conducted. By deriving the stability conditions for a PD controller under delays of 6-7s, it was shown that direct bilateral teleoperation and force feedback proved to be useful to the operator even at such high delays.

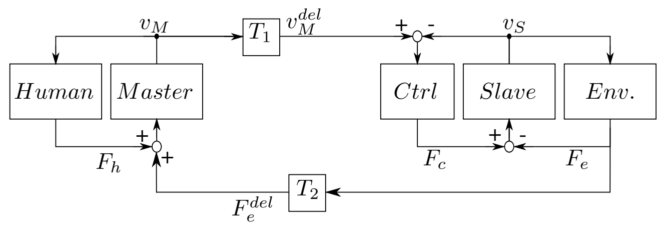

Figure 1: Signal Flow Diagram of a Bilateral Teleoperator with Measured Force Feedback

A lot of research has been conducted on a large variety of robotic space applications in recent years. In [6], [7], [8], the assembly of structures in space by robots has been proposed. Constructing rover teams for planetary exploration were investigated in [9]. Teleoperation experiments focused on the validation with space link communication on earth [10], robots in space on satellites [5] or on the International Space Station (ISS) [11]. Other research analyzed the human-robot cooperation in space environments [12].

The research platform ISS served several teleoperation experiments in the last decade. In the Rokviss project, a two

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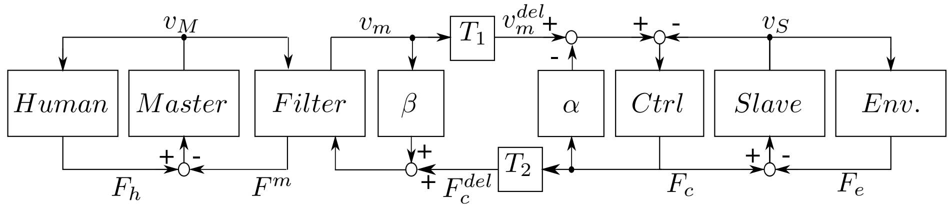

Figure 2: Signal Flow Diagram of a Bilateral Teleoperator with Computed Force Feedback and Standard TDPA

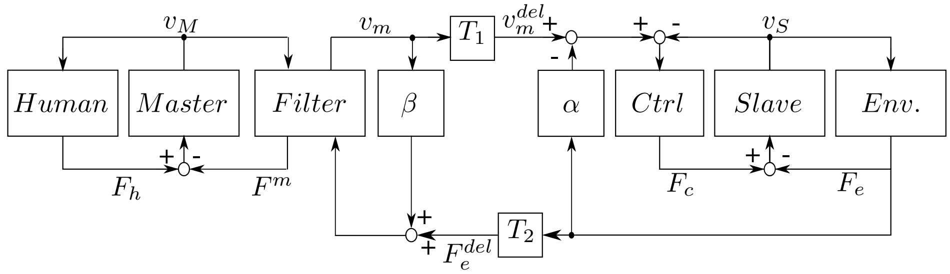

Figure 3: Signal Flow Diagram of a Bilateral Teleoperator with Measured Force Feedback and Proposed TDPA

joint impedance controlled robot was installed on the ISS and teleoperated from earth [11]. Recently, this setup was inversed in the Kontur-2 project to evaluate microgravity effects on the human operator's performance aboard the ISS [13] over S-band communication. Also the Meteron project served the evaluation of teleoperation from the ISS in a space exploration scenario. Supervised control of an autonomous robot [14], [15] as well as direct teleoperation and operator perception was analyzed in the 1-DoF setup of [16].

Several different teleoperation control principles and architectures have been proposed in the last decades. In [11], the wave variables concept [17] and the Time Domain Passivity Approach (TDPA, [18]) were applied for a position-force architecture. In [5], a constant controller parametrization was determined via Llewellyn criterion for a position-position architecture. The authors of [19] applied the TDPA for the teleoperation of a mobile robot at delays similar to the Ku-Forward link. Also in [20] and [21], the TDPA was utilized for standard teleoperation from the ISS and robotic collaboration with a cosmonaut on ISS respectively.

The TDPA gained high attention in the community since it provides an adaptive damping instead of constant conservative controller parametrization and is robust to variable delay, jitter and packet loss. Still, in the state-of-the-art Time Domain Passivity Approach (TDPA), the admittance type passivity controller (PC) has to dissipate a lot of energy (by variation of the velocity reference) at high delays which leads to enormous position drift. Position Drift compensation methods are not effective at very high delays since the energies that can be injected by the drift compensation are not high enough to compensate for the drift to a relevant degree. Furthermore, the drift compensation may further disturb the operator's perception of the control task which is anyways limited at high delay. The performance of the state-of-the-art TDPA might be insufficient for astronauts, since the task execution would take too long due to position drift and the resulting necessary iterative workspace indexing. It can be assumed that astronauts would prefer systems without force feedback requiring no passivity control to the state-of-the-art of closed loop control.

In this paper, we propose a solution that reduces the position drift in free motion while preserving a safe and stable interaction with the remote slave environment. Therefore, the admittance type PC dissipation is maintained during contact such that a force is only applied at the slave after the operator has haptically perceived the contact and authorized the interaction. This also leads to a safe interaction during unexpected collisions. The main contribution is a thorough experimental evaluation at a Earth-to-Moon like communication delay. The simulated delay was set to 3s such that an additional delay from a geostationary satellite at the moon to the robot on the moon surface is considered. Besides the teleoperation of robots on the moon surface, the presented approach can also be applied to robots in the Gateway that will not permanently be manned.

2. FUNDAMENTALS

Fig. 1 presents the signal flow diagram of a bilateral teleoperator with measured force feedback. A human operator uses a haptic input device (master M) to control a robotic manipulator (slave S) in its environment. The communication channel is represented by the forward T_1 and backward delay T_2. Depending on the sampling time T_s and the tuning of the coupling controller $Ctrl$ (generally stiffness K and damping B), instability can result already from low delay of few milliseconds.

The Time Domain Passivity Approach is based on energy observation and control. The standard implementation considers the power conjugated signals v_m and F_c

$$\text{CC}: \begin{cases} \langle\, F_c(k-T_2), v_m(k)\,\rangle & \text{at the master,} \\ \langle\, F_c(k), v_m(k-T_1)\,\rangle & \text{at the slave,} \end{cases}$$

to calculate the power $P(k) = v(k)F(k)$ exchanged in time step k through the communication channel. With the power sign, the power flow direction can be determined ($P^M(k) =$

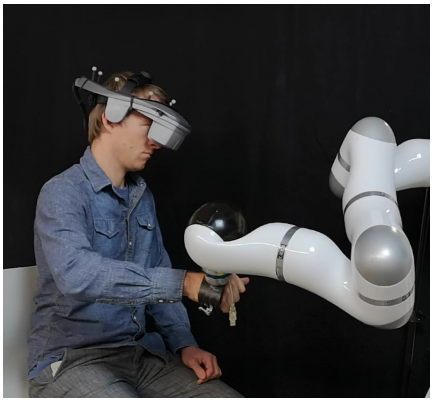

Figure 4: Human Machine Interface

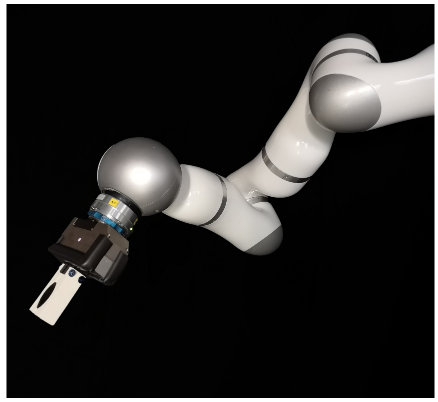

Figure 5: Slave Robot

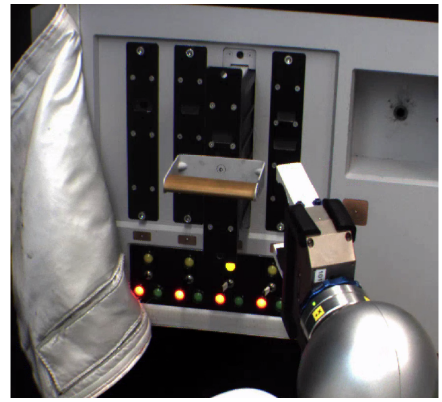

Figure 6: Operator's View through the Head-Mounted Display

$F_c(k-T_2)v_m(k)$):

$$P_{in}^M(k) = \begin{cases} 0, & \text{if } P^M(k) < 0, \\ P^M(k), & \text{if } P^M(k) > 0, \end{cases} \quad (1)$$

$$P_{out}^M(k) = \begin{cases} 0, & \text{if } P^M(k) > 0, \\ -P^M(k), & \text{if } P^M(k) < 0. \end{cases} \quad (2)$$

The slave side power input and output to the communication channel can be calculated analogously with $P^S(k) = F_c(k)v_m(k-T_1)$. Via integration over time, the respective energy can be calculated:

$$E^M(k) = T_s \sum_{j=0}^{k} P^M(j). \quad (3)$$

The passivity controllers $PC\ A$ and $PC\ B$ guarantee passivity by assuring

$$E_{out}^S(k) \leq E_{in}^M(k-T_1) \quad \text{and} \quad (4)$$

$$E_{out}^M(k) \leq E_{in}^S(k-T_2). \quad (5)$$

Therefore, the passivity controllers vary the output velocity $v_m(k-T_1)$ and force $F_c(k-T_2)$ with variable damping α and β:

$$F_c^{PC,out}(k) = F_c(k-T_2) + \beta(k)v_m(k), \quad (6)$$

$$v_m^{PC,out}(k) = v_m(k-T_1) - \alpha(k)F_c(k). \quad (7)$$

The variable damping α of $PC\ A$ is

$$\alpha(k) = \begin{cases} \frac{-W_{obs}^{PCA}(k)}{T_s F_c(k)^2} & \text{if } W_{obs}^{PCA}(k) < 0 \\ 0 & \text{if } W_{obs}^{PCA}(k) \geq 0, \end{cases} \quad (8)$$

and the variable damping β of $PC\ B$ is

$$\beta(k) = \begin{cases} \frac{-W_{obs}^{PCB}(k)}{T_s v_m(k)^2} & \text{if } W_{obs}^{PCB}(k) < 0 \\ 0 & \text{if } W_{obs}^{PCB}(k) \geq 0. \end{cases} \quad (9)$$

W_{obs}^{PCA} and W_{obs}^{PCB} are the energies that have to be dissipated by the passivity controllers:

$$W_{obs}^{PCA}(k) = E_{in}^M(k-T_1) - E_{out}^S(k) - E^{PCA}(k-1), \quad (10)$$

$$W_{obs}^{PCB}(k) = E_{in}^S(k-T_2) - E_{out}^M(k) - E^{PCB}(k-1), \quad (11)$$

with the energies E^{PCA} and E^{PCB} that have already been dissipated by the respective passivity controller.

With the integration of $v_m^{PC,out}$ over time, the position reference is calculated which is affected by a position drift due to the variation of the velocity reference. The impedance type PC leads to high frequency disturbances in the force signal. To smooth the force displayed at the master device, the authors of [22] introduced a passive filter. The TDPA structure with passive filter is presented in Fig. 2.

The state of the art extension of the computed force feedback architecture to measured force feedback with TDPA (according to publications on 3-Channel and 4-Channel implementations [23], [20]) considers the signals

$$PC\ A: \begin{cases} \langle\, F_c(k-T_2), v_m(k)\, \rangle & \text{at the master and} \\ \langle\, F_c(k), v_m(k-T_1)\, \rangle & \text{at the slave,} \end{cases}$$

and

$$PC\ B: \begin{cases} \langle\, F_e(k-T_2), v_m(k)\, \rangle & \text{at the master and} \\ \langle\, F_e(k), v_m(k-T_1)\, \rangle & \text{at the slave,} \end{cases}$$

such that $PC\ A$ considers the same signals as in the computed force case.

Then, $PC\ B$ varies the measured force feedback $F_e(k-T_2)$ according to $v_m(k)$ and $PC\ A$ varies the velocity $v_m(k-T_1)$ with respect to the computed force of the coupling controller $F_c(k)$:

$$F_e^{PC,out}(k) = F_e(k-T_2) + \beta(k)v_m(k), \quad (12)$$

$$v_m^{PC,out}(k) = v_m(k-T_1) - \alpha(k)F_c(k). \quad (13)$$

Since the coupling controller's spring is deflected during interaction and free motion, there is always a power flow and therefore a dissipation by $PC\ A$ (and thus position drift) when the master is leading the slave device (this is when power flows from master to slave).

This permanent position drift is resolved in the proposed method. Also, a safe interaction during initial impacts is achieved.

3. CONTROL APPROACH

As depicted in the signal flow diagram of Fig. 3, we propose to vary the delayed master velocity according to the measured force feedback. This changes the power conjugated signals considered for passivity control to:

$$\text{CC}: \begin{cases} \langle\, F_e(k-T_2), v_m(k)\,\rangle & \text{at the master,} \\ \langle\, F_e(k), v_m(k-T_1)\,\rangle & \text{at the slave,} \end{cases}$$

such that $P^M(k) = F_e(k-T_2)v_m(k)$ and $P^S(k) = F_e(k)v_m(k-T_1)$.

W_{obs}^{PCA} and W_{obs}^{PCB} that have to be dissipated by $PC\ A$ and $PC\ B$ are calculated again according to (10) and (11).

Then, $PC\ B$ varies the measured force feedback $F_e(k-T_2)$ according to $v_m(k)$ and $PC\ A$ varies the velocity $v_m(k-T_1)$ with respect to the measured force $F_e(k)$:

$$F_e^{PC,out}(k) = F_e(k-T_2) + \beta(k)v_m(k), \qquad (14)$$

$$v_m^{PC,out}(k) = v_m(k-T_1) - \alpha(k)F_e(k). \qquad (15)$$

Then, the variable damping α of $PC\ A$ is

$$\alpha(k) = \begin{cases} \frac{-W_{obs}^{PCA}(k)}{T_s F_e(k)^2} & \text{if } W_{obs}^{PCA}(k) < 0 \\ 0 & \text{if } W_{obs}^{PCA}(k) \geq 0. \end{cases} \qquad (16)$$

Then, in free motion, no force is sent to the master, such that also no power is flowing. That means that the passivity controllers don't have to dissipate energy. As a result, no position drift appears during free motion which is a crucial drawback of the state-of-the-art approach for teleoperation at high delays. Another benefit of the proposed concept is that the controller applies a force in the environment only after it was perceived by the operator.

It has to be noted that sensor noise and weights of carried objects can lead to position drift in free motion. Here, a deadband of the measured wrench is applied to avoid the negative effects of sensor noise. The compensation of the weight of carried objects in the measured wrench remains for future work.

4. EXPERIMENTS

All experiments where performed at a roundtrip-delay $T_{rt} = 3s$ and a corresponding visual feedback delay to the operator of about $1.5s$. One DLR light-weight robot (LWR) was used as an haptic input device (see Fig.4) and another LWR as the slave manipulator (see Fig. 5). The operator was equipped with a head-mounted display which provided a stereo view on the scene as depicted in Fig. 6. The stereo camera pair was fix with respect to the scene. Furthermore, a simulated robot was presented to the operator. In this view, the delayed slave robot pose (corresponding to the visual feedback of the real slave robot) and two more coordinate frames at the tool tip were visualized (see Fig. 7). The coordinate frame which is most distant from the LWR presents the estimated current desired slave pose and the coordinate frame in the middle represents the estimated current slave pose at the remote side. This estimation is possible since the delay is very high and constant within a relatively small margin such that the benefit is high despite inaccuracy of estimation. This pose augmentation informs the operator if the slave robot is already at the desired pose and which desired pose is currently set. This highly supportive information should be provided to the operator as an augmentation in the operator's view on the real scene in future work.

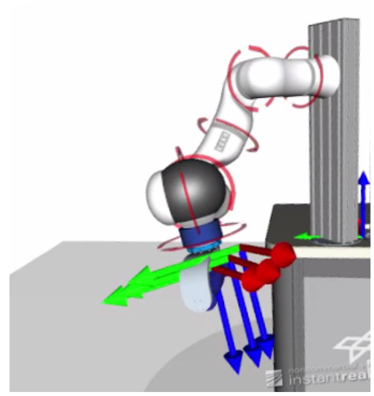

Figure 7: Robot Visualization

Slide and Plug-In Task

Fig. 8 presents a picture sequence of the first experiment which describes an abstract slide and plug-in task. The robot grasped a bar with square profile that had to be pressed against an object in horizontal and vertical direction such that it stayed in contact with the object during the whole procedure. Then, the bar had to slide down a slope and plugged into a hole and moved out and back again. Fig. 9a presents a 3D plot of the task motion. ${}^W H_S$ is the actual slave pose. Comparing the mater/mass pose ${}^W H_m$ and the desired slave pose ${}^W H_S^{ref}$, it is obvious that the coupling spring was always deflected which results in a force acting on the object. Despite the high delay and permanent contact forces, the position drift is relatively low. The wrench, depicted in Fig. 9b, presents the good wrench feedback quality despite passivity control. The wrench $w^M(k)$ displayed at the master device is very similar to the wrench $w_m^S(k-T_2)$ measured at the slave side. To avoid position drift during free motion due to sensor noise, a deadband has been set for the interaction wrench. In y-direction, the plug-in and -out procedure is visible at $t = [200s, 210s]$. Note that the plug-out and upwards motion at $t = [210s, 250s]$ is not visualized in the 3D plot. The energy plots of Fig. 9c and Fig. 9d provide the passivity confirmation of all degrees of freedom. This task would not be feasible without passivity control since too high forces might be applied to the object and oscillations would appear when the object is plugged in.

Maintenance Task

The second experiment describes a maintenance task. The respective picture sequence is depicted in Fig. 10. The robot moves to a handle which has to be grasped. Then, the attached module has to be pressed into its slot and the handle

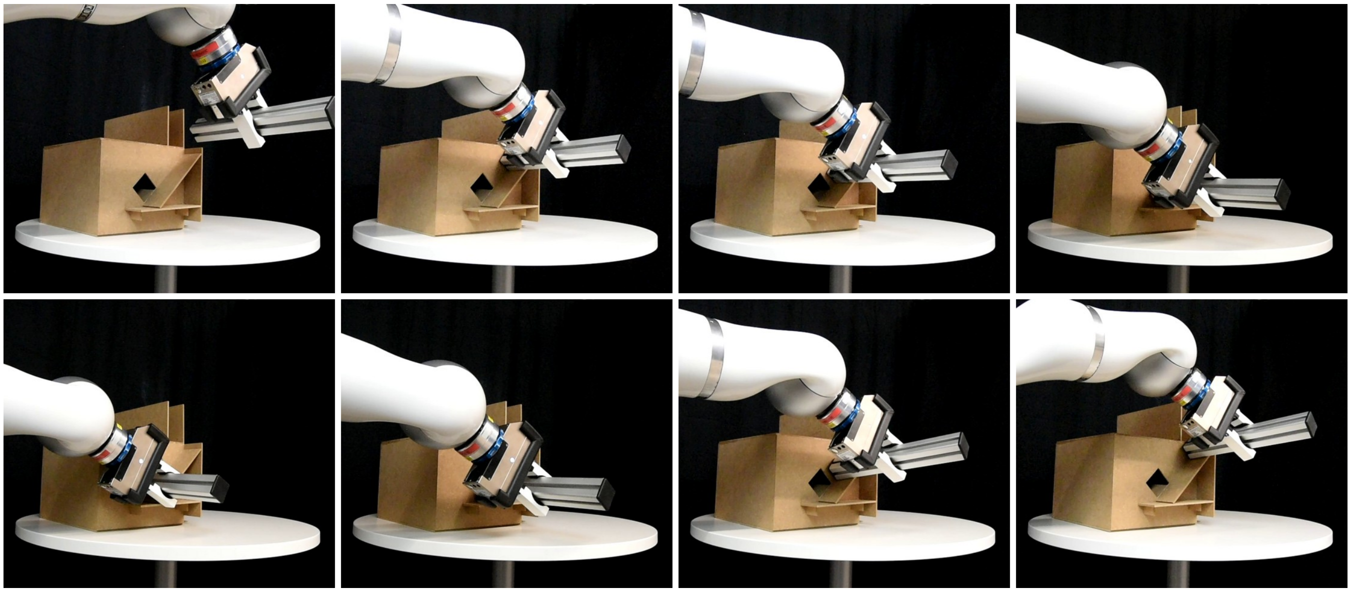

Figure 8: Picture Sequence of Slide and Plug-In Experiment at $T_{rt} = 3s$

has to be rotated by ninety degrees. Finally, a mechanical switch has to be switched to reactivate the module. Analyzing the position plot in Fig. 11a, it can be observed that the drift during free motion is negligible whereas the drift is increased during the insertion of the module. This is due to the fact that high forces had to be applied and due to a stepwise insertion which resulted from the low slipperiness of the module material. Again, the feedback wrench is of high quality despite passivity control. Note that the orientational DoFs of ${}^{W}H_m$ and ${}^{W}H_S^{ref}$ do not correspond to each other since the change of master orientation is integrated onto the initial slave orientation. Again, the energy plots of Fig. 11c and Fig. 11d provide the passivity confirmation of all degrees of freedom. Especially, the difficulty of the insertion task would have resulted in immense interaction forces without passivity control.

Sample Pick and Place

Although the third experiment is the simplest in terms of interaction, it is of very high relevance for the focused Earth-to-Moon teleoperation scenario. The experiment presented in the picture sequence of Fig. 12 describes a sample pick and place task which is very typical in the field of space exploration. A highly unstructured environment cannot be handled by autonomous robots so far and has to be performed with a human operator in the loop. Also, a geologist requires haptic feedback for the analysis of relevant objects. The picture sequence presents the picking of two stones of different sizes which are then placed into a container for further analysis.

5. Conclusion

In this paper we presented the validation of a new control approach for kinesthetic coupling under extreme time delay in an Earth-to-Moon teleoperation scenario. An abstract experiment presented the successful conduct of a sliding and plug-in task. Additional validations were performed in a complex maintenance task. These are typical subtasks that a robot on the Gateway would have to do. In all cases safe interactions and passivity could be guaranteed. Despite high delay and passivity control, the kinesthetic force feedback was of high quality. The most important although not most complex contribution refers to a pick and place task of two stones which is a fundamental procedure in space exploration. In future work, visual augmentation and shared control concepts have to be integrated to further ease the manipulation task for the human operator.

Acknowledgments

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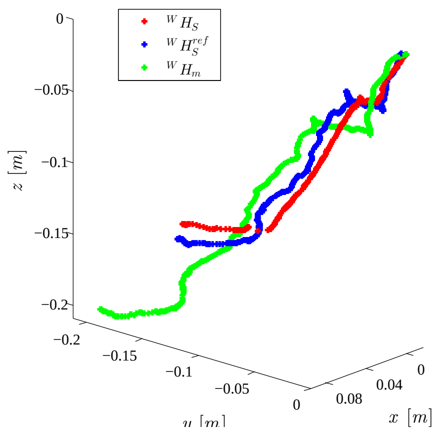
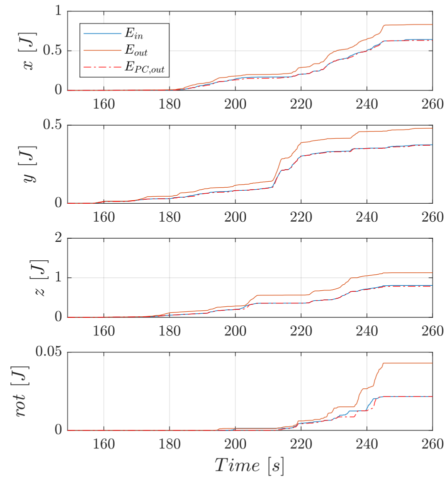
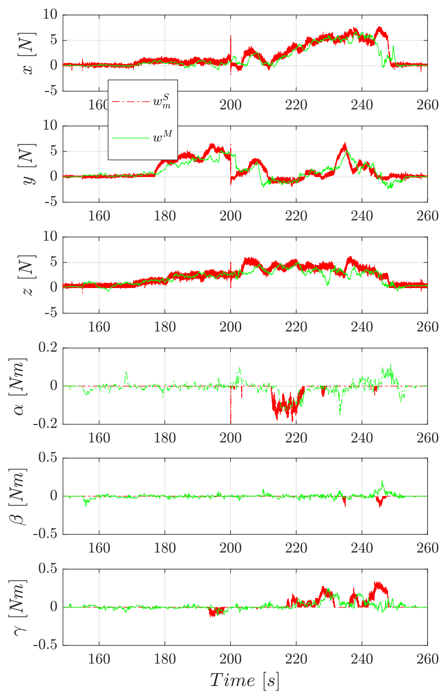


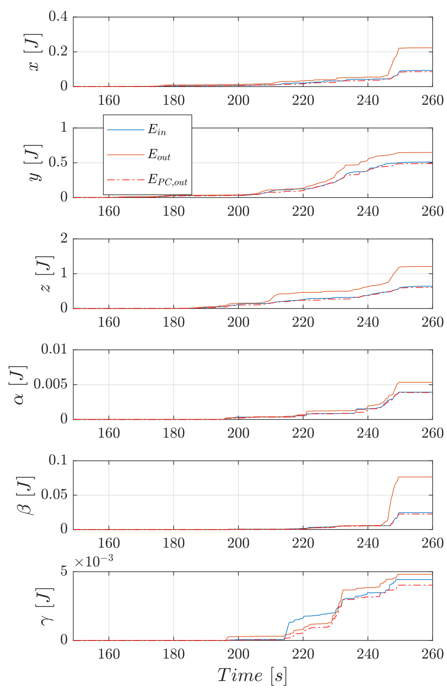
(a) 3D Pose



(c) Passivity Confirmation PC A



(b) Wrench



(d) Passivity Confirmation PC B

Figure 9: Slide and Plug-In Experiment

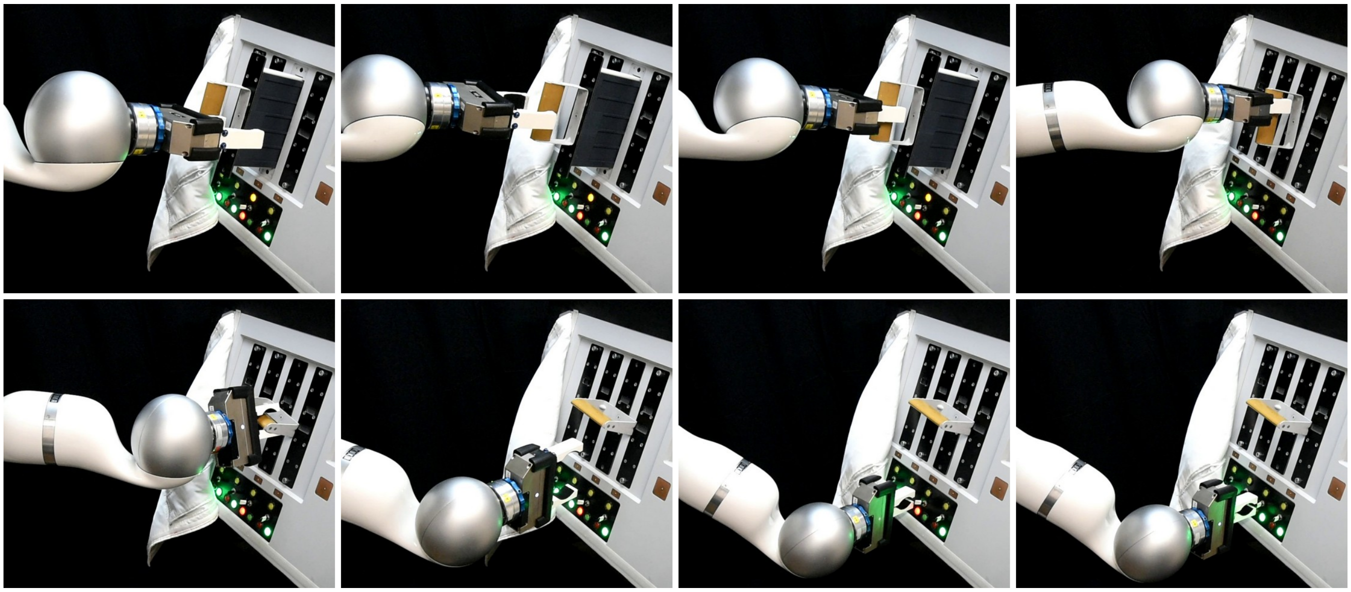


Figure 10: Picture Sequence of Maintenance Experiment at $T_{rt} = 3s$

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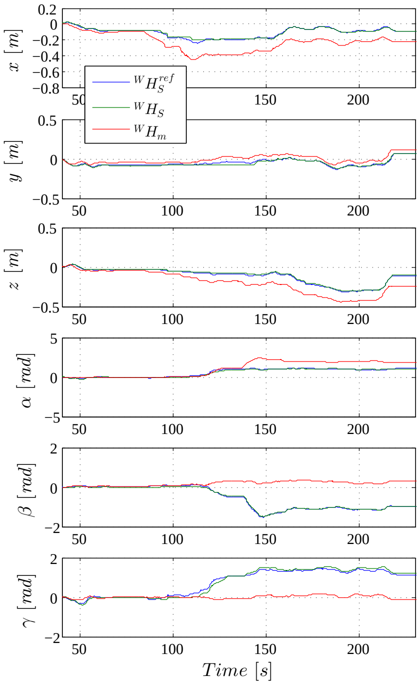
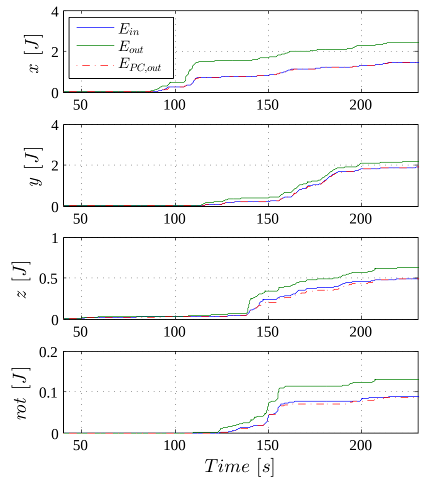
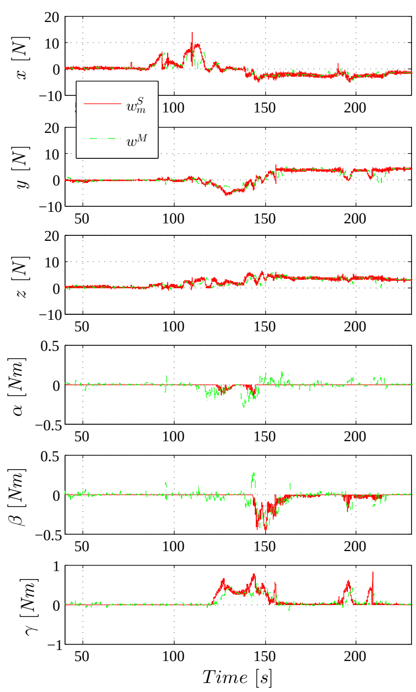


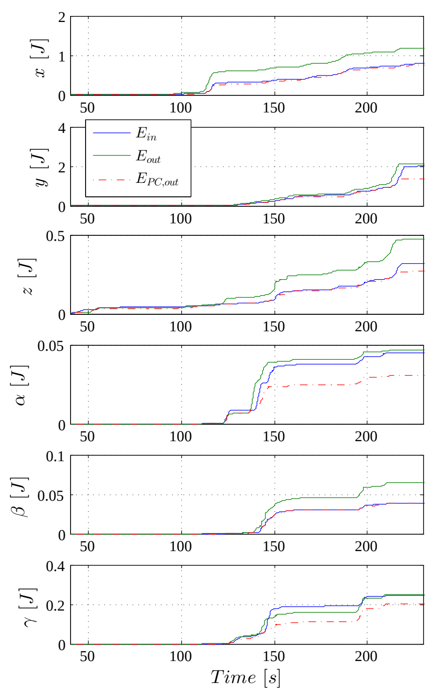
(a) Pose Tracking



(c) Passivity Confirmation PC A



(b) Wrench



(d) Passivity Confirmation PC B

Figure 11: Maintenance Experiment

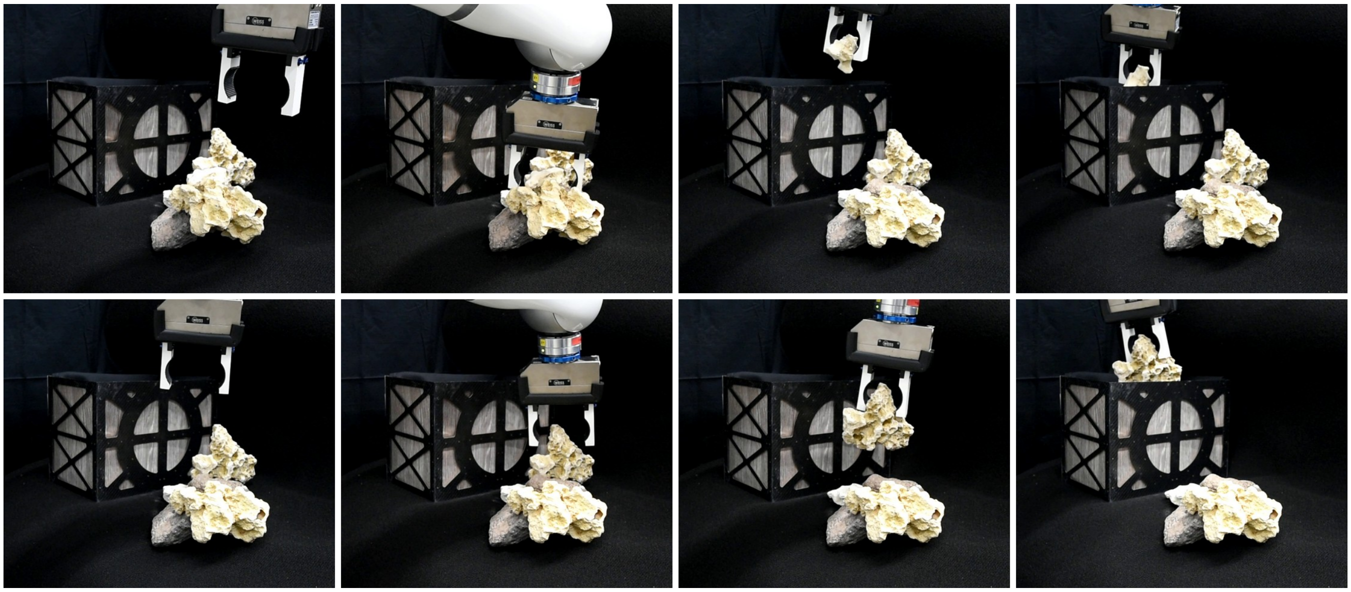


Figure 12: Picture Sequence of Sample Pick and Place Experiment at $T_{rt} = 3s$

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BIOGRAPHY

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Alin Albu-Schäffer *received his M.S. in electrical engineering from the Technical University of Timisoara, Romania in 1993 and his Ph.D. in automatic control from the Technical University of Munich in 2002. Since 2012 he is the head of the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR), which he joined in 1995 as a Ph.D. candidate. Moreover, he is a professor at the Technical University of Munich, holding the Chair for "Sensor Based Robotic Systems and Intelligent Assistance Systems" at the Computer Science Department. His personal research interests include robot design, modeling and control, nonlinear control, flexible joint and variable compliance robots, impedance and force control, physical human-robot interaction, bio-inspired robot design and control. He received several awards, including the IEEE King-Sun Fu Best Paper Award of the Transactions on Robotics in 2012 and 2014; several ICRA and IROS Best Paper Awards as well as the DLR Science Award. He was strongly involved in the development of the DLR light-weight robot and its commercialization through technology transfer to KUKA.*