Intercontinental multimodal Tele-Cooperation using a Humanoid Robot

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***Abstract*— In multimodal tele-cooperation as considered in this paper two humans in distant locations jointly perform a task requiring multimodal including haptic feedback. One human operator teleoperates a remotely placed humanoid robot which is collocated with the human cooperator. Time delay in the communication channel as destabilizing factor is one of the multiple challenges associated with such a tele-cooperation setup. In this paper we employ a control architecture with force-position exchange accounting for the admittance type of the haptic input device and the telerobot, which both are position-based admittance controlled. Llewellyn's stability criteria are employed for the parameter tuning of the virtual impedances in the presence of time delay. The control strategy is successfully validated in an intercontinental tele-cooperation experiment with the humanoid telerobot HRP-2 located in Japan/Tsukuba and a multimodal human-system-interface located in Germany/Munich, see also the corresponding video submission. The proposed setup gives rise to a large number of exciting new research questions to be addressed in the future.**

I. Introduction

Telerobotic systems combine skills as human adaptability and decision-making ability with some advantages of robotic manipulation. While the former enables to operate in highly variable, unstructured, unknown or dynamic working environments, the latter allows to perform complex tasks in remote and inaccessible environments.

If a task is too difficult or complex for one person, humans typically multiply their output by sharing facilities and capabilities. In this work this ability is combined with a classical teleoperation system resulting in a multiple operator, single robot system (MOSR), see Fig. 1. Hereby multiple operators collaborate in order to perform a common task. Explained in more detail a human operator (H2) is assisted by a robot (TOP), which is controlled by a remotely located human operator (H1) via a human system interface (HSI). Hereby direct interactions with the teleoperator as well as interactions via an object (O) can be considered. Such an architecture is of interest when the task requires an expert which is not located at the remote site. In this case the expert can operate remotely assisted by a local human operator.

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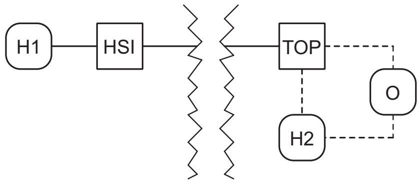

Fig. 1. Multiple operator, single robot teleoperation system

Challenges in telerobotics have lead to specific research efforts in the fields of bilateral teleoperation [1], Virtual Reality techniques for teleoperation, or teleoperation of humanoids [2]. Closely related to this paper, collaborative telemanipulation tasks have been performed [3] between the NASA's Robonaut and a human in order to evaluate the impact of force feedback on telemanipulation tasks. However, authors did not consider time delay, nor specifically addressed stability issues. The operated robot was ground-based, thus discarding the problem of balance during the collaborative task. Furthermore, even small time delay may destabilize the bilateral teleoperation system. Sophisticated stabilizing control methods developed in the past address this issue, see e.g. [4], [5], [6], [7] for constant delay and extensions to varying time delay, e.g. [8], [9]. For an overview refer to [1].

In this paper we present a multiple operator, single robot system used for haptic tele-cooperation between Germany and Japan. Hereby a human operator controls a free-flying humanoid robot, which collaborates with another human located at the remote site. The contribution of this work is the inclusion of a human operator collaborating with the robot, which gives rise to stability issues both from the teleoperation set-up and the dynamic stability of the humanoid robot. Sec. II discusses those control tuning and stability issues, Sec. III presents the integrated teleoperation system. Finally some experimental results showing the effectiveness of the approach are reported.

II. Control

Control architectures for bilateral teleoperation systems are commonly classified according to the number and kind of variables transmitted between the master and the slave device, see [10] for an overview. In the often employed two-channel force-position architecture position and forces are exchanged between master and slave; the master (slave) is under local force (position) control, see e.g. [11]. While for impedance type devices, which are characterized by very light-weight constructions with low inertia and friction, high performance force controllers can be implemented, for admittance type devices, force control can only be realized with a very poor performance [12]. This is mainly due to the high dynamic properties and friction effects of admittance type devices, which can only be compensated by using some kind of low level position controller. For further details on impedance and admittance type devices see [13]. On this account classical bilateral control architectures with local force/position control are usually not very appropriate for teleoperation systems using admittance type master and slave devices.

Commonly admittance type devices are controlled by using a so called position-based admittance control architecture, see [12]. Depending on the application, such an architecture can be either used to render desired impedances or to achieve a certain compliant behavior when being in contact with the environment. In view of the classical two-channel control architectures, position-based admittance controllers can be implemented for master as well as slave devices and combined into a teleoperation control architecture where positions and forces are exchanged. Thus basically a position-based admittance control with force-position (see Fig. 2) and position-force exchange (mirrored version) can be distinguished. Hereby x_m and x_s mean the actual master and slave position, x_m^d and x_s^d the corresponding desired positions, f_m and f_s the master as well as slave motor force commands, f_h the human force input and f_e the interaction force with the environment.

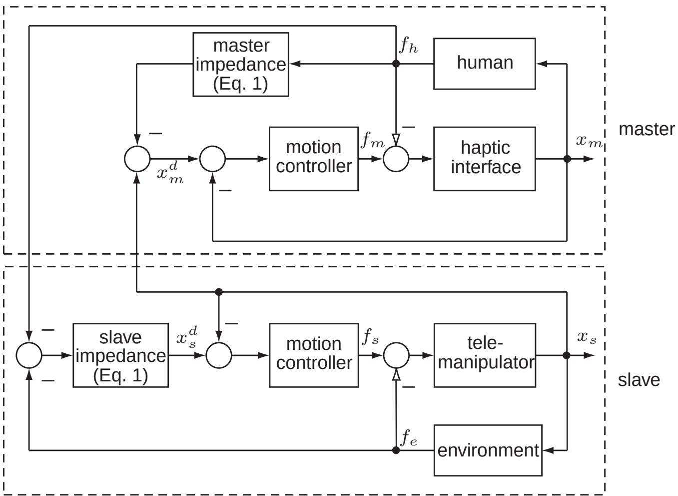

Fig. 2. Position based admittance control with force-position exchange for one degree of freedom

Observe that ideal transparency cannot any more be achieved by using these modified controllers, since transparency is affected by the desired master and slave impedances. In the context of this work these impedances are given by simple mass-spring-damper systems

$$\boldsymbol{f} = \boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{B}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x}, \tag{1}$$

whereby $\boldsymbol{x}$ are positions, $\boldsymbol{f}$ are forces and $\boldsymbol{M}$ means the mass, $\boldsymbol{B}$ the damping and $\boldsymbol{K}$ the stiffness matrix.

Assuming already well tuned low-level position controllers, the matrices $\boldsymbol{M}$, $\boldsymbol{D}$, and $\boldsymbol{K}$ have to be selected appropriately to guarantee stability of the overall teleoperation system in the presence of time delay. In the following a stability analysis is carried out to determine adequate parameters.

A. Stability analysis

In the standard teleoperation stability analysis passivity-based approaches are very common using the passivity argument for the environment and the human operator, see [10] for definition and overview. To the best knowledge of the authors there exist no results in the known literature on how to model human operators in cooperative tasks. In the lack of concise results in this direction we assume for the time that both, the human operator and the remotely located human collaborator, behave like a passive system and have bounded impedances. In consequence the stability of the overall teleoperation system can be analyzed using the concept of absolute stability. Further analysis concerning passivity in a cooperative telemanipulation task are subject of future research.

Definition: A linear two-port is said, it is absolutely stable if there exists no set of passive terminating one-port impedances for which the system is unstable. Otherwise the system is potentially unstable.

A necessary and sufficient condition for absolute stability is given by Llewellyn's absolute stability criteria [14]:

- h_{11} and h_{22} have no poles in the right half plane
- any poles of h_{11} and h_{22} on the imaginary axis are simple with real and positive residues
- for all real values of the frequency ω, the following conditions hold:

$$\mathrm{Re}\,[h_{11}] \geq 0, \quad \mathrm{Re}\,[h_{22}] \geq 0, \tag{2}$$

$$2\mathrm{Re}\,[h_{11}]\,\mathrm{Re}\,[h_{22}] - \mathrm{Re}\,[h_{12}h_{21}] - |h_{12}h_{21}| \geq 0, \tag{3}$$

whereby h_{ij} with $i, j = 1, 2$ are parameters of the hybrid matrix [15], which describes the linear two-port.

If this criteria is satisfied by the two-port network, then the teleoperation system is stable, if the two terminating impedances, namely the human operator interacting with the haptic interface as well as the remotely located collaborating human, act in a passive way. Note that absolute stability allows *arbitrary* passive terminating impedances, which results in a robust but rather conservative control design.

In the following absolute stability is tested for the two above presented control architectures and design guidelines for the selection of the parameters $\boldsymbol{M}$, $\boldsymbol{D}$, and $\boldsymbol{K}$ of master and slave devices are derived.

Assuming diagonal mass, damping and stiffness matrices the stability analysis of the overall system can be carried out for each degree of freedom separately. The hybrid matrices of the remaining one degree of freedom teleoperation system are given with:

$$\begin{bmatrix} F_h(s) \\ -V_s(s) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} V_m(s) \\ F_e(s) \end{bmatrix} \tag{4}$$

for the position-based admittance control with position-force exchange and

$$\begin{bmatrix} V_m(s) \\ F_e(s) \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} F_h(s) \\ -V_s(s) \end{bmatrix} \tag{5}$$

for the position-based admittance control with force-position exchange, where V_m, V_s, F_h, F_e are the Laplace transforms of $\dot{x}_m$, $\dot{x}_s$, f_h, and f_e, the master and slave velocity, the human input force and the interaction force with the environment, respectively.

If further high-gain position controllers and the compensation of external forces are assumed, Fig. 2 can be simplified significantly and the hybrid matrix of the resulting two-port network is given as follows, see [7] for more details:

$$h_{11}^c = \left.\frac{F_h(s)}{V_m(s)}\right|_{F_e=0} = \frac{m_m s^2 + b_m s + k_m}{s}, \tag{6}$$

$$h_{12}^c = \left.\frac{F_h(s)}{F_e(s)}\right|_{V_m=0} = e^{-T_{sm}s}, \tag{7}$$

$$h_{21}^c = \left.\frac{-V_s(s)}{V_m(s)}\right|_{F_e=0} = -e^{-T_{ms}s}, \tag{8}$$

$$h_{22}^c = \left.\frac{-V_s(s)}{F_e(s)}\right|_{V_m=0} = \frac{s}{m_s s^2 + b_s s + k_s}, \tag{9}$$

where T_{ms} and T_{sm} represent the time delay from master to slave and slave to master, respectively. The time delay is assumed to be constant, an assumption which is justified by measurements, see Section III.

Testing absolute stability for this two-port network would give really conservative results, because infinite terminating impedances are considered. Taking into account that the human impedance is typically bounded and adapting the two-port model to incorporate this knowledge a much less conservative result can be obtained, see [16]. Hereby $Z_{h,max}$ and $Z_{e,max}$ mean the maximum impedances of human operator and remote environment. The modified two-port network with limited human and remote impedances is shown in Fig. 3. The corresponding parameters h_{ij} are:

$$h_{11}^m = \frac{Z_{h,max} h_{11}^c}{Z_{h,max} + h_{11}^c}, \tag{10}$$

$$h_{12}^m = \frac{Z_{h,max} h_{12}^c}{Z_{h,max} + h_{11}^c}, \tag{11}$$

$$h_{21}^m = \frac{Z_{h,max} h_{21}^c}{Z_{h,max} + h_{11}^c}, \tag{12}$$

$$h_{22}^m = h_{22}^c - \frac{h_{12}^c h_{21}^c}{Z_{h,max} + h_{11}^c} + \frac{1}{Z_{e,max}}. \tag{13}$$

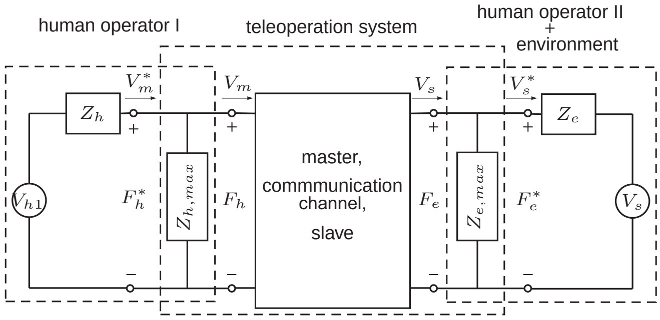

Fig. 3. Two-port network with limited human impedances

Analogously the coefficients g_{ij}^c for the position-based admittance control with force-position exchange are given with

$$g_{11}^c = \left.\frac{V_m(s)}{F_h(s)}\right|_{V_s=0} = \frac{s}{m_m s^2 + b_m s + k_m}, \tag{14}$$

$$g_{12}^c = \left.\frac{V_m(s)}{-V_s(s)}\right|_{F_h=0} = -e^{-T_{sm}s}, \tag{15}$$

$$g_{21}^c = \left.\frac{F_e(s)}{F_h(s)}\right|_{V_s=0} = e^{-T_{ms}s}, \tag{16}$$

$$g_{22}^c = \left.\frac{F_e(s)}{-V_s(s)}\right|_{F_h=0} = \frac{m_s s^2 + b_s s + k_s}{s}, \tag{17}$$

and the coefficients g_{ij}^m describing the modified two-port network can be obtained from (10) to (13) by simply exchanging h with g, $Z_{e,max}$ with $Z_{h,max}$, h_{11} with h_{22} as well as h_{12} with h_{21}.

Given these coefficients for the two before mentioned control architectures stability can be analyzed by evaluating Llewellyn's stability criteria.

B. Numerical stability test

For a cooperative telemanipulation task, as considered in this work, stability for two basic experimental conditions is required:

- stability when interacting with the remote collaborator
- stability when interacting with the remote environment

These two experimental conditions are represented by different upper bounds of the remote impedance $Z_{e,max}$. If the interaction with a human operator is considered $Z_{e,max}$ reflects an upper bound for the human arm impedance, which can be modelled as follows

$$Z_{e,max} = b_{h,max} + \frac{k_{h,max}}{s}. \tag{18}$$

Hereby $k_{h,max} = 40$N/m and $b_{h,max} = 6$Ns/m mean the maximum stiffness and damping the human operator can apply to the system. The corresponding parameters are taken from [17]. If stability for the interaction with stiff remote environments should be tested $Z_{e,max} = 10^4$N/m is assumed. Considering that human operator and remote environment impedance vary only in an interval from zero to the specified upper bound and the two operators act in a passive way, stability of the overall teleoperation system can be analyzed, without making further assumptions on the human operator and remote environment impedance.

For the analysis of the position-based admittance control with position-force exchange k_s is set to zero and $k_m = 600$ N/m. It should be noted that k_m represents a lower bound for displayable stiffnesses on the master side and thus it should be selected carefully. To reduce further parameters a constant mass m_m for the master impedance is selected. Perfect transparency would require the master mass to be set to zero. However in admittance control, this is not possible because the minimum target inertia is bounded by stability, see [18]. So a minimum mass m_m has been selected, which is able to stabilize the master system when operated alone.

Finally the remaining parameters m_s, b_s, and b_m are gridded and absolute stability is tested for each grid point. For the analysis a constant time-delay of $T_{sm} = T_{ms} = 150$ms is assumed. Figs. 4, 5 show the corresponding simulation results, whereby the area enclosed by the envelopes means control parameters, which stabilize the overall teleoperation system. As can be seen stability can only be guaranteed if a certain amount of master and slave damping is implemented. Moreover the number of stabilizing control parameters increases with increasing master mass m_m. It should be noted that due to actuator limitations a certain amount of m_s has to be implemented, which implies an appropriate selection of m_m. Summarizing it can be stated that for a position-based admittance control with position-force exchange stable behavior for the two conditions a) interaction with a remote collaborator and b) interaction with a stiff remote environment can be achieved if enough damping at master and slave side is provided.

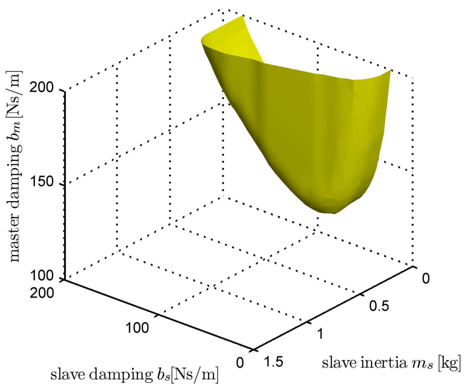

Fig. 4. Position-based admittance control with position-force exchange: absolute stability for a fixed master mass $m_m = 1$ kg

For the position-based admittance control with force-position exchange correspondingly $k_m = 0$ N/m and $k_s = 600$ N/m have been selected and the remaining parameters m_m, b_s, and b_m are gridded. A stability analysis with $k_{h,max} = 40$ N/m and $b_{h,max} = 6$ Ns/m and $Z_{e,max} = 10^4$ N/m showed, that absolute stability is always guaranteed when a minimal slave damping b_{ds} is implemented, see Fig. 6. Observe from the larger enclosed area that the force-position exchange architecture with local position-based admittance control allows a larger class of stabilizing controllers than the position-force exchange architecture.

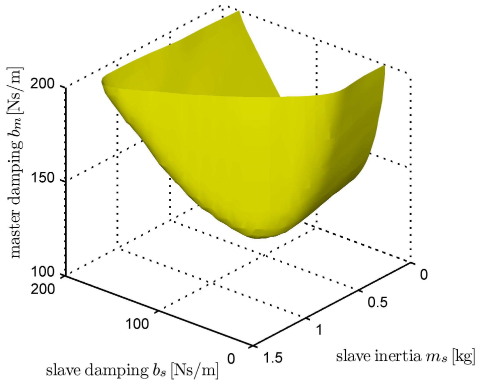

Fig. 5. Position-based admittance control with position-force exchange: absolute stability for a fixed master mass $m_m = 5$ kg

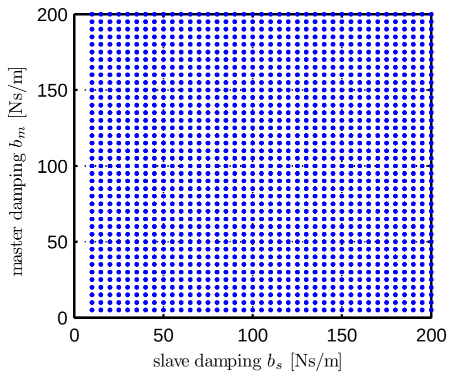

Fig. 6. Position-based admittance control with force-position exchange: absolute stability for a fixed slave mass $m_s = 5$ kg

III. Experimental Evaluation

One of the above presented control architectures has been tested in an intercontinental cooperative telemanipulation task, whereby the operator site is located in Munich, Germany and the teleoperator site in Tsukuba, Japan. As slave the humanoid robot HRP-2 and as master the haptic interface ViSHaRD7 is used. The experimental task is shown in Fig. 7. It consists in jointly grasping an object, moving it to a new position and finally releasing it. Hereby the task of the human collaborator was to follow the motion commanded by the human controlling the telerobot. In order to give the human operator a realistic impression of the remote environment visual, auditory, and haptic information has been exchanged over Internet, see Fig. 10. In the following the experimental setup is explained in more detail.

A. Experimental setup

1) Teleoperator: Fig. 8 shows the HRP-2 humanoid robot when interacting with a human. HRP-2 has 30 degrees-of-freedoms (d.o.f.): six for each leg and arm, one for each gripper, two for the chest, and two for the head. In the experiment only the right arm and the head have been used, whereby the chest was allowed to rotate around the vertical axis to increase the manipulation area. HRP-2 has four cameras: one wide-angle and three narrow-angle cameras.

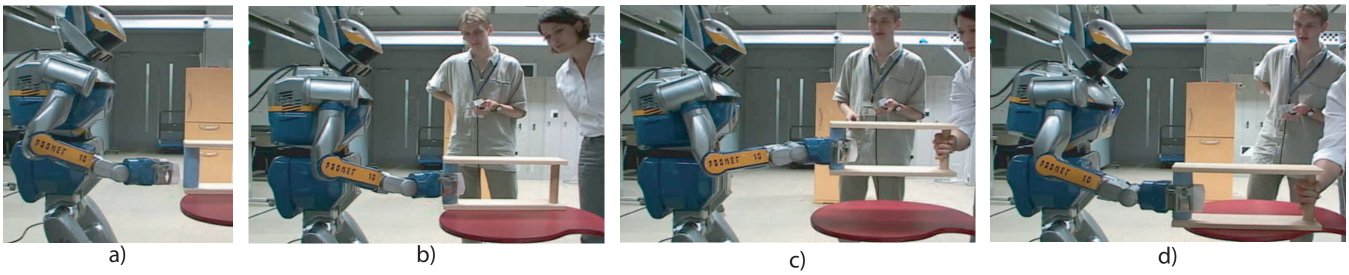

Fig. 7. Cooperative telemanipulation task: a) approach, b) grasp, c) lift, d) put down

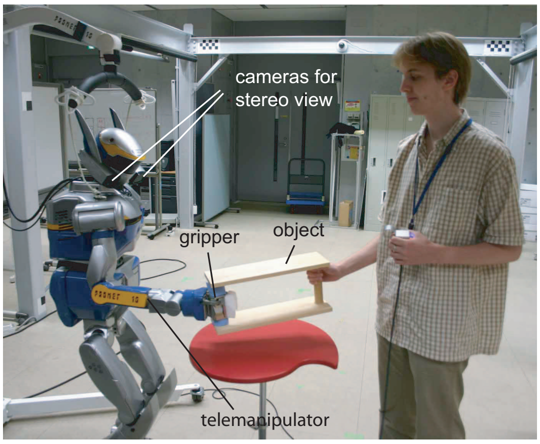

Fig. 8. Remote site: HRP-2 collaborating with a local human

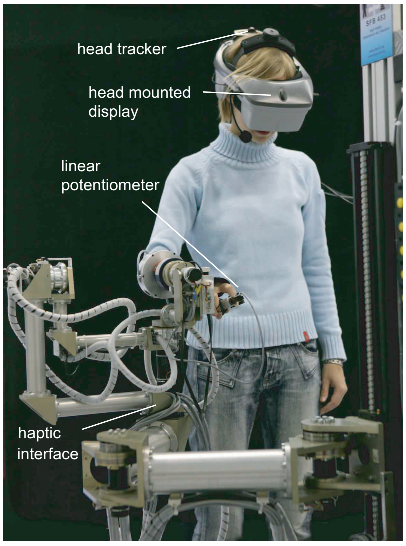

Fig. 9. Operator site: human operator and human-system-interface

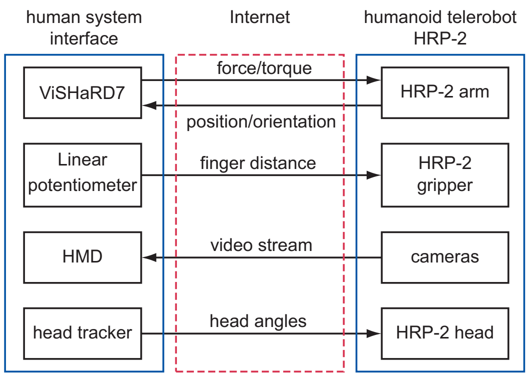

Fig. 10. Data exchange in the teleoperation experiment

For the teleoperation experiment the images of two narrow-angle cameras were used and send to the remotely located human operator. To provide force information HRP-2 is equipped with 6 d.o.f force/torque sensors located at the wrist of each hand. HRP-2 is controlled by using low-level high-gain joint PD controllers running at 1 kHz. The position reference signal is hereby provided by an outer control loop running at 200 Hz. More details about HRP-2 can be found in [19].

2) Human system interface: Fig. 9 shows a human operator interacting with the human system interface, which consists of devices for visual, auditory and haptic feedback. The redundant haptic interface VISHARD7 with 7 d.o.f. [20] is used to provide force-feedback information to the human operator and allows to control the remotely located telerobot. It is characterized by its relatively large workspace, high payload, as well as its redundancy to avoid kinematic singularities. In order to allow fine-manipulation the telemanipulator is additionally equipped with a two-finger gripper. To open and close this gripper, the distance of thumb and index finger is measured by a linear potentiometer. No finger-force feedback is provided.

The recorded video streams are transmitted to the operator site and then displayed on a head mounted display (HMD; NVIS nVisor SX, resolution 1280 x 1024) carried by the human operator. Efficient low-latency real-time video is made possible by the usage of a UDP-based, MPEG-4-compressed transmission approach using the XviD-codec (www.xvid.org). Requesting independently encoded frames in case of packet loss on the network ensures error resilience. The HMD is additionally equipped with an acoustic tracker (IS900), which is used for controlling of the camera head motion, so that the user can look around in the remote environment just by turning his/her own head.

3) Network: The packet rate, i.e. the network sampling rate, has been chosen to 50Hz. At this packet rate the packet loss probability was negligible ($< 1\%$) while undesired effects of sampling on performance still remained hidden as observed in preliminary experiments as well

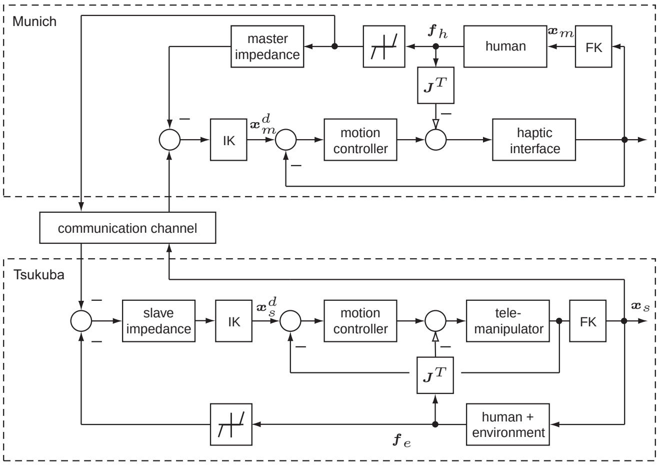

Fig. 11. Overall control architecture: position based admittance control with force-position exchange (HSI: human-system interface, TOP: teleoperator, FK: forward kinematics, IK: inverse kinematics)

as during the experiment itself. Similarily, the round trip time delay between Germany and Japan was measured to $T_{ms} + T_{sm} = 278 \pm 5\,\text{ms}$. Observe that the time delay variance over time of 5ms is below the sampling time interval of 20ms justifying the assumption of approximately constant delay.

4) Overall control architecture: Since position based admittance control with force-position exchange seems to have a greater variety of stabilizing controllers this architecture has been implemented for the presented teleoperation system. As shown in Fig. 11 admittance type controllers with low level joint-controllers are used for master as well as slave devices and connected by using a two-channel force-position architecture. Hereby forces are sent from master to slave and positions from slave to master. The stability analysis presented above allows only to distinguish between stable and non-stable regions, but gives no information about the transient behavior of the overall system. In order to guarantee a well damped behaviour the following parameters for the desired master and slave impedances have been found by experiment: $m_m = 1$ kg, $b_m = 200$ Ns/m, $k_m = 600$ N/m, $b_s = 200$ Ns/m, m_s =10 kg for the translational part and $m_m = 0.02$ kgm^2, $b_m = 2$ Nms/rad, $k_m = 20$ Nm/rad, $b_s = 1$ Nms/rad, $m_s = 0.2$ kgm^2 for the rotational part.

The relatively high mass and damping factor at slave side limits hereby the bandwidth of the system significantly and thus ensures stability of the overall teleoperation system despite of significant time delay in the communication channel.

In order to measure zero forces during free-space motion the end-effector masses have been compensated. Since the center of gravity of the end-effectors is only approximately known small deadzones are used. The small position errors introduced by these deadzones can be compensated by the human operator as she/he is provided visual feedback of the remote scene.

5) Details of HRP-2 control: Since HRP-2 is a humanoid robot advanced control strategies are needed for the usage in a teleoperation scenario. A very important issue hereby is the avoidance of singular configurations as well as collisions of the robot with itself. Since the human operator has only limited information about the remote environment adequate algorithms have to be implemented, which assist the human operator in avoiding forbidden areas. In the following some more details about the implemented control strategies for HRP-2 are given.

Admittance control: For the right arm admittance control as shown in Fig. 11 has been implemented by using the before mentioned impedance parameters. Hereby, the damping value for the yaw axis has been set to a higher value than for the roll and pitch axis, because motions around the yaw axis require large movements of the elbow and thus might result in collisions with the upper body of the telerobot. Finally the output of the admittance, the desired hand displacement and rotation, are sent to the full-body controller.

Full-body controller: HRP-2 is controlled by using the full-body controller developed in [21]. The algorithm allows to specify the position and orientation of the feet, the hand, the waist, the head, and the center of gravity. To keep the balance of the robot, the center of gravity is kept at a fixed position. In addition the stabilizer presented in [22] is used to compensate for deformations introduced by the flexibility of the feets. *Gripper control:* Since the human operator has no finger force feedback the maximum gripping force is saturated.

Head control: The head of HRP-2 can be moved around the yaw and pitch axis. The corresponding reference angles are applied as quaternions to the full-body controller.

Protection control: In order to protect HRP-2 against dangerous unpredictable motions a speed limitation is implemented. On this account all motions are slowed down by a certain factor. In addition an algorithm for joint limitation avoidance and collision avoidance has been implemented (based on V-clip, [23]). If a limit is reached motions are frozen until a desired configuration is commanded, which lies outside the forbidden area. Recently also some more advanced methods, limiting only the motion of certain joints, have been proposed by [24], [25].

B. Experimental results

Fig. 12 shows a typical example for position and force tracking during the experiment. Basically an approaching and grasping (1), moving (2), and releasing phase (3) can be distinguished. In the approaching phase the human operator approaches and grasps the object, in the moving phase the humans move the object from the starting to the target position and finally in the releasing phase the object is released after being in contact with the remote environment. During *free space motion* (phase 1) the position tracking is very good. While in this phase at slave site no forces can be measured, some forces at master site are necessary to change the position of the device. This is mainly due to the implemented impedances in the master and slave controllers. In the *contact phase* (phase 3), the force tracking is good and the positions slightly deviate from each other. This can be explained by the compliant behavior introduced by the admittance controller implemented at master site. As

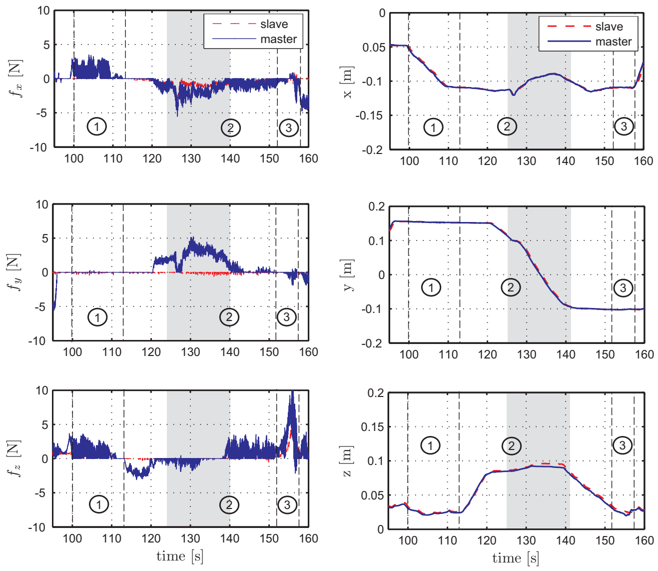

Fig. 12. Force and position tracking during experiment. 1: approaching phase, 2: moving phase, 3: releasing phase, shaded area: human located at the remote site applies forces to the object

a consequence also the perception of the remote impedance is altered. In y-direction, the remote collaborator behaves as a task follower, because the shape of the manipulated object makes it difficult to apply forces in these directions. On the contrary, the shaded area in phase 2 indicates a region, where the human collaborator located at the remote site applies forces in positive x-direction onto the carried object. This results in small deviations of master and slave position. Finally it should be mentioned that a stable behavior during all experimental phases can be oberved.

IV. Conclusion

A long distance collaborative task between two human operators is achieved by using the HRP-2 humanoid controlled as well as an advanced human-system-interface. The task was simply to lift and transport an object, collaboratively, from a position to another without requiring locomotion of humans. This preliminary set-up and experiment allowed assessing several problems to be solved. One of the major issues is the modeling of human behavior in cooperative tasks and the corresponding energy exchange for the use in stability analysis and control synthesis. Further future work consist in extending this experiment to a more complex scenario where the human operator will perform a collaborative teleoperation task with a more complex object and using locomotion of the humans and the humanoid.

References

[1] P. F. Hokayem and M. W. Spong, “Bilateral teleoperation: An historical survey,” *Automatica*, vol. 42, pp. 2035–2057, 2006.

[2] A. Kheddar, E.-S. Neo, R. Tadakuma, and K. Yokoi, *Advances in Telerobotics*. Springer, 2007, ch. Enhanced Teleoperation Through Virtual Reality Techniques, pp. 139–159.

[3] J. Glassmire, M. OMalley, W. Bluethmann, and R. Ambrose, “Cooperative manipulation between humans and teleoperated agents,” in *Proceedings of the 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS’04)*. Los Alamitos, CA, USA: IEEE Computer Society, 2004, pp. 114–120.

[4] R. Anderson and M. Spong, “Bilateral control of teleoperators with time delay,” *IEEE Trans. Robot. Automat.*, vol. 34, no. 5, pp. 494 – 501, 1989.

[5] G. Niemeyer and J.-J. Slotine, “Stable Adaptive Teleoperation,” *IEEE Journal of Oceanic Engineering*, vol. 16, no. 1, pp. 152–162, January 1991.

[6] D. Lawrence, “Stability and transparency in bilateral teleoperation,” *IEEE Trans. Robot. Automat.*, vol. 9, no. 5, pp. 624 – 637, 1993.

[7] H. C. Cho and J. H. Park, “Impedance control with variable damping for bilateral teleoperation under time delay,” *JSME International Journal*, vol. 48, no. 4, pp. 695–703, 2005.

[8] Y. Yokokohji, T. Imaida, and T. Yoshikawa, “Bilateral Control with Energy Balance Monitoring under Time-Varying Communication Delay,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, San Francisco (CA), US, 2000, pp. 2684–2689.

[9] R. Lozano, N. Chopra, and M. Spong, “Passivation of Force Reflecting Bilateral Teleoperators with Time Varying Delay,” in *Proceedings of the 8. Mechatronics Forum*, Enschede, Netherlands, 2002, pp. 954–962.

[10] S. Hirche, M. Ferre, J. Barrio, C. Melchiorri, and M. Buss, “Bilateral Control Architectures for Telerobotics,” in *Advances in Telerobotics*, M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer, Eds. Berlin: Springer STAR series, 2007.

[11] J. Kim, P. Chang, and H. Park, “Transparent teleoperation using two-channel control architectures,” in *IEEE/RSJ International Conference on Robots and Systems*, 2005, pp. 2824–2831.

[12] M. Ueberle and M. Buss, “Control of kinesthetic haptic interfaces,” in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, Workshop on Touch and Haptics*, 2004.

[13] C. Clover, G. Luecke, J. Troy, and W. McNeely, “Dynamic simulation of virtual mechanisms with haptic feedback using industrial robotics equipment,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Albuquerque, New Mexico, April 1997.

[14] F. Llewellyn, “Some fundamental properties of transmission systems,” in *Proceedings of IRE*, 1952, pp. 271–283.

[15] R. J. Adams and B. Hannaford, “Stable haptic interaction with virtual environments,” *IEEE Transactions on robotics and automation*, vol. 14, no. 3, pp. 465–474, 1999.

[16] K. Hashtrudi-Zaad and S. Salcudean, “Analysis of control architectures for teleoperation systems with impedance/admittance master and slave devices,” *The International Journal of Robotics Research*, vol. 20, no. 6, pp. 419–445, June 2001.

[17] D. Lawrence and J. Chapel, “Performance trade-offs for hand controller design,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, 1994, pp. 3211–3216.

[18] E. Colgate and N. Hogan, “An analysis of contact instability in terms of passive physical equivalents,” in *IEEE International Conference on Robotics and Automation*, 1989, pp. 404–409.

[19] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, K. Hirata, M. Akachi, and T. Isozumi, “Humanoid robot HRP-2,” in *Proceedings of the 2004 IEEE International Conference on Robotics and Automation*, 2004.

[20] A. Peer and M. Buss, “A new admittance type haptic interface for bimanual manipulations,” *IEEE/ASME Transactions on mechatronics*, 2008.

[21] E. S. Neo, K. Yokoi, S. Kajita, and K. Tanie, “Whole-body motion generation integrating operator’s intention and robot’s autonomy in controlling humanoid robots,” *IEEE Transactions on Robotics*, vol. 23, no. 4, pp. 763–775, August 2007.

[22] K. Yokoi, F. Kanehiro, K. Kaneko, K. Fujiwara, S. Kajita, and H. Hirukawa, “A honda humanoid robot controlled by aist software,” in *Proceedings of the 2001 IEEE-RAS International Conference on Humanoid Robots*, 2001.

[23] B. Mirtich, “V-Clip: fast and robust polyhedral collision detection,” *ACM Transactions on Graphics*, vol. 17, no. 3, pp. 177–208, 1998.

[24] O. Stasse, A. Escande, N. Mansard, S. Miossec, P. Evrard, and A. Kheddar, “Real-time (self)-collision avoidance task on a HRP-2 humanoid robot,” in *IEEE Int. Conf. on Robotics and Automation, ICRA-08*, Pasadena, California, May 2008.

[25] N. Mansard and O. Khatib, “Continuous control law from unilateral constraints,” in *IEEE Int. Conf. on Robotics and Automation, ICRA-08*, Pasadena, California, May 2008.