Haptic Tele-Assembly over the Internet

Sandra Hirche, Bartlomiej Stanczyk, and Martin Buss

Institute of Automatic Control Engineering, Technische Universität München
D-80290 München, Germany, `http://www.lsr.ei.tum.de`
`Sandra.Hirche@ei.tum.de` `Bartlomiej.Stanczyk@ei.tum.de` `Martin.Buss@ei.tum.de`

A multimodal telepresence system enables a human operator to perform tasks in a remote environment. The operator manipulates the human system interface (HSI) thereby commanding the executing robot (teleoperator). The multimodal sensor information from the remote environment is fed back and displayed to the operator. Data are transmitted over a communication network, as e.g. the Internet. Considering the visual and auditory feedback as state-of-the-art multimedia the focus of our research is on the haptic feedback system.

Telepresence and teleaction will be a key technology for rescue applications in hazardous environments. In addition to reconnaissance and transportation abilities, future rescuing robots need the possibility of physical interaction with the environment. An example of such a task is to put up scaffolding to support walls in a collapsed building. Aiming at the assembly application of haptic telepresence systems other researchers have performed standard peg-in-hole experiments [1, 2]. Issues regarding communication over packet switched networks and kinematical transformations though have not been addressed in the context of complex manipulation tasks.

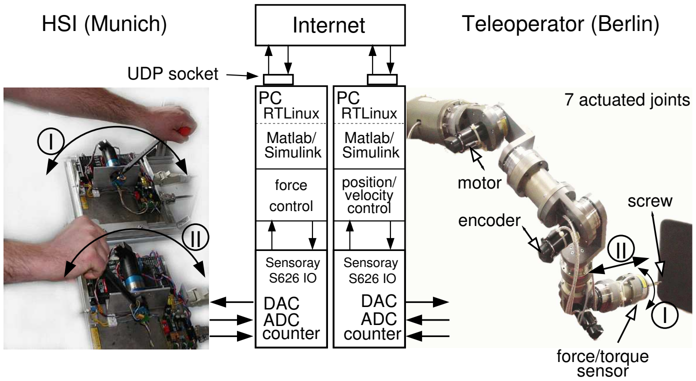

Fig. 1. Assembly experiment architecture.

As a first step towards an assembly application we consider the prototypic scenario of screwing a bolt into a wall. We propose a human arm like teleoperator with 7 degrees-of-freedom (DOF) [3], that provides due to is kinematic redundancy a high level of manipulability. However, to have an easier insight in the control, its movement is limited to 2 Cartesian directions at this stage. The HSI consists of two 1 DOF force feedback paddles, one of them controls the movement in the Cartesian y-direction, the other one controls the rotation around the y-axis, see Fig. 1. The experiment is conducted over the Internet between Munich, the operator site and Berlin, the teleoperator site. Main challenges are the network induced varying delay and packet loss as well as the different kinematics and work space of the HSI and the teleoperator. In the following passivity based control architectures are reviewed for there applicability in IP based communication networks, a control strategy coping with its packet oriented nature is derived. Furthermore, the design and local control architecture of the teleoperator is presented. Finally the results of the experimental evaluation validating the proposed approach are discussed.

Global Control Architecture

Without further control measures the network induced time delay destabilizes the global control loop. Passivity based arguments lead to the scattering transformation and the combined velocity/force control of teleoperator/HSI resulting in a stable system for arbitrary, but *constant* delay [4]. Increasing delay renders the communication two-port non-passive, in an extended approach time-varying gains shape the energy output of the communications in order to maintain passivity also for the *time-varying* delay case. Position tracking is improved by the position feedforward extension of the velocity/force architecture [6]. The feedforward gain I_p, see Fig. 2, is designed such that the excess passivity given by the damping of the teleoperator compensates the non-passivity of the mapping desired position $\dot{x}_t^d$ to the environment force f_e in contact. The cited approaches consider the continuous time case, they do not cover effects due to the packet switched nature of an IP based communication network, as e.g. packet loss.

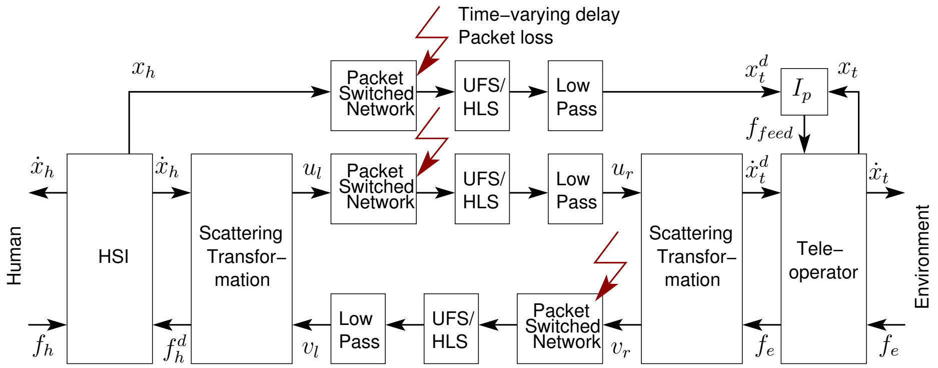

Fig. 2. Position feedforward architecture.

In a packet switched multipath network data packets are randomly delayed and possibly dropped due to congestion. Thus consecutive sent packets may arrive in switched order or may not arrive at all at the receiver side. Waiting for late packets, hence packet buffering and reordering is a packet processing strategy that introduces additional delay. The processing algorithm that is applied here uses the freshest sample (UFS) only and discards older packets, thus reduces the processing induced delay to zero at the cost of higher loss. Lost packets, either due to congestion or to the packet processing algorithm, result in empty sampling instances at the controller on the receiver side. A strategy that is successfully employed in networked control systems is to hold the last sample until new data is available (HLS). The passivity of the communication two-port, defined by the packet switched network itself and the packet processing algorithm, has to be verified in order to guarantee passivity of the overall system. The HLS algorithm though may inject additional energy to the communication two-port, hence does not preserve passivity [7]. Furthermore high frequency wave reflections may occur if HLS is applied, which decreases the transparency. We propose a simple solution to passify and to dampen the wave reflections by low pass filtering inside the communication two-port as shown in Fig. 2. The low pass is placed directly after the HLS algorithm. In simulations the passifying effect has been shown, further theoretical investigations are necessary. Here the low pass filter is designed heuristically.

Teleoperator Design and Control

To achieve transparent telepresence, the manipulator placed on the remote site has to be able to reproduce the manipulation properties of the human operator, both kinematics and dynamics. A kinematic analysis of human limbs reveals, that the minimum number of DOFs used for their modelling is 7. The resulting design consists of two spherical joints with three DOFs at the shoulder and the wrist, and one rotational joint at the elbow. In case of redundant manipulators, the inverse kinematics problem is solved usually on velocity level using the classical equation $\dot{q} = J^{\#}\dot{X}$, where q is the joint space vector, X - task space vector and J is the manipulator Jacobian. The Jacobian inverse $J^{\#}$ is chosen in a way that a scalar objective function of the joint variables is minimized. However, such a solution is sensitive to singularities [8], especially in teleoperation scenarios, when the user is liable to unintentionally drive the slave robot toward/through a singularity. That is why strategies are preferred, that do not involve Jacobian inversion neither for trajectory generation nor for dynamic control. The redundancy resolution presented here is based on the extension of the task space vector X using the orthogonal null space of the Jacobian is proposed. In this particular case, it has the following physical meaning: if the positions of the shoulder s, the wrist w and the end-effector d are fixed, the elbow e is free to swivel about the axis from the shoulder to the wrist, as shown in Fig. 3. The elbow position on the circle can be determined by specifying the angle θ between the plane spanned by the points s, e and w and the plane spanned by the line $s - w$ and the z_0 axis of the world coordinate system [9,10]. The IK function is defined then as a function of the hand position X and the elbow angle $q = IK(X, \theta)$. The X trajectory is generated by the user, while the θ trajectory is generated automatically by a planner optimizing an objective function $m(q) = m\big(IK(X, \theta)\big)$ dependent on θ. For the current 2 DOF experiment, the task space is defined as a vector consisting of the approach position and the screwing angle. The necessary kinematical transformations translate the task vector into the 6 DOF Cartesian workspace, scaling and limiting the movement to one axis perpendicular to the wall.

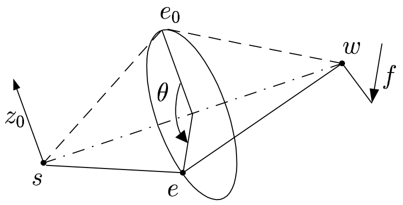

Fig. 3. The elbow angle θ definition

The signal coming out of the scattering transformation, thus the input to the teleoperator, is a desired velocity $\dot{x}_t^d$ in the task space, see Fig. 2. In order to obtain a valid position-based IK solution as described above, these velocity signals are integrated. The computed desired joint trajectories q^d are the input to a simple PD control in joint space. The controller gains are set relatively low to avoid oscillations while contacting the stiff environment. The forces and torques measured in the Cartesian y-direction and the rotational direction around the y-axis are fed back to the HSI, see Fig. 2.

Experimental Results

The goal of the experiment is to screw a bolt into a wall in Berlin by means of the two 1 DOF force feedback paddles located in Munich, visual and auditive feedback is supplied to the operator station. The right hand paddle controls the Cartesian y-direction, hence the approach of the bolt to the wall. The left hand paddle controls the turning around the y-axis. According to the proposed global control architecture the HSI is force controlled, the teleoperator is velocity/position controlled at a sampling rate of 500 Hz. The output of the scattering transformation, see Fig. 2 is sent over a UDP socket connection, with one UDP packet containing one sample, thus the sampling rate of the communication network is equal to the sampling rates of the local control loops. A first order low pass with a gain of one and a cut frequency of 17 Hz is placed after the HLS algorithm in the forward as well as in the backward path. The mean round trip delay is approximately 15 ms, its development over the time is shown in shown in Fig. 4(a). The regular pattern is likely to be a result of the routing policies of intermittent routers. The passivity analysis performed on the experimental data shows that the communication two-port is not passive without, but passive with low pass filtering. Both, the position and the force tracking of the approach is presented in Fig. 4(b) and (d), respectively. The force tracking shows very good results, further controller tuning at the teleoperator site is likely to further improve the position tracking. The screwing angle tracking is shown in Fig. 4(c), which is excellent. The experiment is also presented in the accompanying video, also available at http://www.lsr.ei.tum.de/movies.

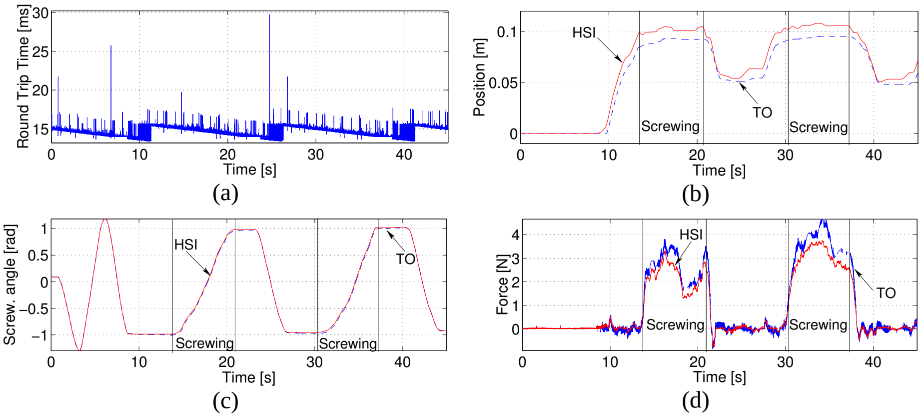

Fig. 4. Experimental results: Round trip time delay (a),y-position (b) and force (d) tracking and screw angle tracking (c)

Conclusion and Future Work

From known continuous time passivity based global control architectures we derived a control strategy for haptic telepresence over a packet switched network capable to cope with time-varying delay and packet loss. Main feature is the packet processing algorithm Use freshest/ Hold last sample (UFS/HLS) combined with low pass filtering. The control architecture is validated in a assembly experiment with two degrees-of-freedom over the Internet. Future work is to investigate complex assembly experiments with more degrees-of-freedom at the HSI.

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