Beyond Classical Teleoperation: Assistance, Cooperation, Data Reduction, and Spatial Audio

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Abstract— **In this video we present a teleoperation system which is capable of solving complex tasks in human-sized wide area environments. The system consists of two mobile teleoperators controlled by two operators, and offers haptic, visual, and auditory feedback. The task examined here, consists of repairing a robot by removing a computer and replacing a defective hard-drive. To cope with the complexity of such a task, we go beyond classical teleoperation by integrating several advanced software algorithms into the system.**

I. INTRODUCTION

Teleoperation has been a field of active research for many decades [1]. Today, actuators, sensors, and computers exist which offer unprecedented performance and allow system designers to develop highly integrated systems suitable for complex tasks. In this video, we show that the integration of advanced software algorithms into an existing teleoperation system can improve versatility and performance. Thereby, complex tasks become feasible.

II. SYSTEM

The hardware setup used here is identical to the setup presented in [2]. Thus, only a short overview is given, and the reader is referred to our previous publication for details and related references. The system consists of teleoperators controlled by two operators. Each teleoperator consists of two seven Degrees of Freedom (DoF) anthropomorphic arms equipped with one DoF grippers mounted on an omnidirectional, non-holonomic mobile base. In addition, two cameras are mounted on a three DoF neck. Microphones for sound localization are mounted at the shoulders.

One of the operators interacts with a stationary human-system interface, consisting of two ten DoF haptic devices, two data gloves to measure finger positions, a three DoF pedal to control base motion, a head-mounted display offering stereo-vision which is tracked by a magnetic tracking system, and earphones.

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The second operator interacts with a mobile human-system interface, consisting of two seven DoF haptic devices mounted on a mobile base to allow for natural, wide-area teleoperation. The operator's body and head are tracked by an acoustic tracking system. This data is used to control the mobile base and the neck of the teleoperator. A head-mounted display provides stereo-vision and earphones are used for auditory feedback.

III. SCENARIO

In this video we consider a futuristic scenario in which robots are utilized in many households. If one of these robots has a technical problem, instead of sending service staff to the broken robot it would be beneficial to teleoperate nearby robots to perform the necessary maintenance work. This scenario represents many challenges which are addressed by different advanced software algorithms.

The first phase of the task consists of removing a computer from the back end of the robot. As the computer is relatively heavy, the two teleoperators perform this task cooperatively. A damper-based virtual coupling is used to cope with closed kinematic chains and to stabilize the system (see Sec. IV-A). Furthermore, spatial auditory feedback results in natural communication between the operators (see Sec. IV-D).

After the computer has been placed on a table, one teleoperator is used to replace a defective hard-drive. During this phase, an intention recognition algorithm is used to determine the current task. Using this information appropriate assistance functions are activated which improve task performance and reduce the necessary amount of effort (see Sec. IV-B). Furthermore, haptic data reduction is used during this phase to reduce the amount of data transmitted over the communication channels (see Sec. IV-C). Finally, the computer is reinserted into the robot. This step is omitted in the video as it is very similar to the first phase, where the computer is removed.

IV. ALGORITHMS

In the following section some advanced control algorithms for haptic teleoperation which are integrated in this system are presented. Furthermore, the approach used for spatial audio feedback is outlined.

A. Multi-user teleoperation

When multiple manipulators simultaneously interact with the same stiff object instabilities due to closed kinematic chains may occur. One way of coping with this problem is to use an internal force controller [3]. Instead, we use a damper-based virtual coupling, which produces compensating forces from velocity errors. This approach has the advantage, of easy integration into our admittance-controlled system, while offering intuitive parameter tuning due to the physical interpretability of damping. The virtual damping, which is active between all currently closed grippers results in a force counteracting all non-synchronized movement. This approach was introduced in [4] for two DoF and extended to six DoF here.

B. Assistance functions and intention recognition

A computer-assisted teleoperation system is used for repairing the broken hard drive, consisting in removing the hard drive and replacing it with a new one. A stochastic task classification algorithm is used to recognize the currently performed task [5] and to select an appropriate assistance function. By adapting the assistance suitable for the currently performed task, the operator is optimally supported and task performance can be enhanced.

While this idea has already been investigated in literature, see e.g. [6], known approaches consider free space tasks only. We extend this concept in terms of classifier capabilities, complexity of tasks, and class of haptic guidance schemes. In contrast to state-of-the-art approaches, our implementation can deal with complex 6 DoF manipulation tasks including free space as well as contact. Special attention was also paid to the influence of the assistance on the task classification.

For haptic assistance, we use a variable impedance control approach for removing, inserting and positioning the hard drive in the rack. A velocity scaling from master to slave decreases time to task completion for free space movements, and a force scaling facilitates fine manipulations during positioning, see [7] for further details.

C. Haptic data reduction

In order to keep the network delay at a minimum, haptic samples are usually immediately transmitted upon their availability. In packet-switched networks, such as the Internet, this results in high packet rates up to the sampling rate (here 1000 Hz) and congests the network. Perception-based haptic data reduction approaches successfully address this challenge by reducing the packet rate by up to 90% while keeping introduced coding distortion imperceivable [8]. An extension for haptic signals with multiple degrees-of-freedom which introduces ellipsoid *"perceptual deadzones"* is discussed in [9] and employed here. This technique achieves an additional improvement in packet rate reduction of 30%. Furthermore, an optimization-based reconstruction strategy guarantees stability and preserves the high fidelity of the haptic interaction. For a review of the challenges in haptic data compression and communication in teleoperation systems, see [10].

D. Spatial Audio

The teleoperators are equipped with microphones that localize sound sources around them by using a GCC-PHAT localization algorithm that is computationally fast and robust in echoic environments [11].

The localized sound sources are then virtually synthesized according to their position relative to the teleoperator, using a set of Head-Related Transfer Functions (HRTFs). HRTFs describe spectral changes of sound waves on their way to the ear canal, due to reflexions and diffractions at the head, shoulders, torso and ears. As these geometric features differ from person to person, HRTFs are unique for each individual. Additionally, the reflexions of the human body are different for each source direction, and therefore HRTFs can be regarded as direction dependent filters [12]. Headphones are used to present the 3D-sound to the operator. Furthermore, the communication between different operators is HRTF-synthesized according to the relative position of the corresponding teleoperators [13], which improves comprehensibility of communication and orientation.

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