Combining an exoskeleton with 3D simulation in-the-loop

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***Abstract*—**

Beyond robot hardware and control, one major element for an efficient, constructive and safe mission of teleoperated robots in disaster scenarios such as Fukushima is the quality of the connection between operator and robot. In this contribution, we present the concept of using an exoskeleton and utilizing 3D simulation as a central interface component for the operator to intuitively collaborate with mobile teleoperated robots.

keywords: 3D simulation, exoskeleton, force feedback, operator interface

I. INTRODUCTION

Disaster scenarios such as at the Fukushima facility site clearly show that the capabilities of current disaster-response robot systems are hardly sufficient for providing the desperately needed support to reconnoiter and secure the situation – especially in the first critical hours.

The CENTAURO[3] project aims at the development of a novel teleoperated Centaur-like robot with whole-body telepresence of the human operator supported by 3D simulation in-the-loop, to allow for making elaborate decisions during the mission. Hence, the project will establish a safe cooperation where the operator is immersively present at the site of emergency, supported by situation-aware interpretations based on multi-modal information collected with the robot sensors as well as a-priori knowledge from other sources, e.g. 2D maps. The exoskeleton and a specialized exoskeleton simulator, used during the implementation, are developed at SSSA. At the MMI, a specialized force feedback interface for this exoskeleton based on 3D simulation technologies is developed.

The overall CENTAURO setup is shown in Figure 1. Based on prior knowledge in developing mobile robots, like the Momaro robot ((c), [1]), a holistic setup is developed consisting of a new Centaur-like robot, an exoskeleton for control (a), and 3D simulation for support (d). During the development process, special focus is put on the 3D simulation system and also an exoskeleton simulation (cf. (b)) to develop necessary interface structures used also in the final setup. The operator can use the information gathered from simulation and additionally switch seamlessly between real world interaction and its virtual counterpart. This feature will be used in risky situations to evaluate movements or actions in the virtual world first, before executing them in the real hazardous environment.

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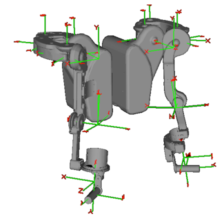
(a) Exoskeleton



(b) Exoskeleton simulation

(c) Real Centaur-like mobile robot[3]

(d) 3D simulation of robot and environment

Fig. 1: Using an exoskeleton with force feedback for robotic teleoperation, utilizing 3D simulation

II. RELATED WORK

A. *Exoskeleton*

The robotic interfaces for physical human-robot interaction represent an important aspect of tele-existence cockpits [2]. The exoskeleton represents the robotic system where the highest physical symbiosis with the human operator is achieved. Active exoskeleton systems are robotic devices that can be worn on the user's body, implying that they should satisfy requirements of safety and better compliance. Exoskeletons built for rehabilitation and human power augmentation make use of different actuation solutions, such as geared solutions, tendon drives, hybrid solutions (screw and cable actuators) or variable-impedance actuators [3], [4], [5], [6], [7], [8], [9]. Based on the adopted actuation, active exoskeletons can be classified as impedance based design (open-loop impedance control and impedance control with force feedback) or admittance-based design (admittance control with position feedback).

B. 3D Simulation Technology

Normally, simulation does not really plays a role in control schemes for teleoperated robotic field systems only in some rare and rather limited cases. It is mostly used for testing and validation of individual modules or algorithms during development. A more holistic approach to 3D simulation in robotics is provided by the *eRobotics* methodology [10][11][12][13] and so-called *Virtual Testbeds*. Complex technical systems and their interaction with prospective working environments are first designed, programmed, controlled and optimized in 3D simulation, before commissioning the real system. In our previous work we utilized 3D simulation already as integrated development and simulation platforms, which compromise system models as well as environment models and connect them with simulation methods and algorithms, e.g. for perception and control. Now, the simulation is used during the development process of robot and the exoskeleton, but more importantly will it also serve as the central system for providing the operator interface during field missions.

C. Force Feedback in 3D Simulation

Although, force feedback and corresponding devices are not new, their use in simulation is quite limited. Only specialized applications can be found where force feedback is used as one central compartment of simulation. Several force feedback devices are commercially available, in particular the 6 DoF *Geomagic Touch X*[4] (formerly Phantom Device) as the most common one. A general overview about history, complexity and benefits of haptic interfaces in simulation is given in [14]. From a technical point of view, the interface between simulation and (any) force feedback device should be the same and "can be viewed as computer extensions that apply physical forces and torques on the user." [15].

III. RESULTS

The following section describes the results in terms of combining an exoskeleton, force feedback and 3D simulation. On the one hand, the development of the exoskeleton and corresponding exoskeleton simulator is described. On the other hand, the required force feedback integration in 3D simulation and its interface to the exoskeleton (simulator) is presented.

A. Exoskeleton and Exoskeleton Simulator

The exoskeleton designed within the framework of the CENTAURO project (see Figure 2) is based on ALEx robot [5], a 12 DoFs (6 DoFs$\times$2 upper limbs) mechanically compliant exoskeleton for the human upper limb: 4 DoFs per arm are sensorized and actuated (shoulder abduction, rotation, and flexion; elbow flexion), and 2 DoFs per arm are sensorized and passive (forearm prono-supination and wrist flexion). However, the CENTAURO Master exoskeleton will substitute passive DoFs and will include additional DoFs for wrist and hand actuation to allow also the manipulation of objects through the teleoperated Centaur-like robot. More in detail, there will be 3 DoFs for each wrist and 17 underactuated DoFs (actually 5 DoFs) for each hand. The entire CENTAURO Master exoskeleton can reach about 90 % of the natural workspace of the human arm without singularities, covering an extended range of motion for each DoF. Moreover, the exoskeleton can be operated either in force mode, providing desired input forces to the EE or joint torques to each joint, or in compliant position mode, providing desired trajectories with the associated stiffness to the EE or to the joints.

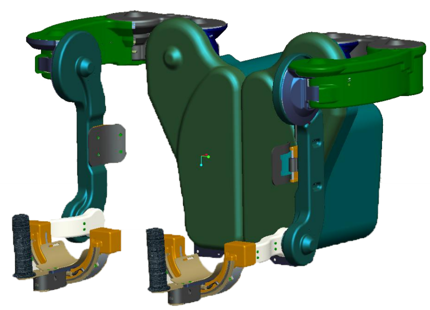


Fig. 2: The ALEx exoskeleton for upper limb.

A simulator of the CENTAURO Master exoskeleton has been designed for preliminary interaction with 3D simulation of the disaster scenario. The simulator includes the kinematic and dynamic models of the exoskeleton and relies on a physical model engine. The communication with the simulator is based on UDP/IP communication and integrates four channels: two for the device data (one for left and one for right arm) and two for the device command (one for left and one for right arm). The device data packet includes all the data related to the exoskeleton status, such as joint position, speed and torque, and end-effector position, speed and force. On the other hand, the device command packet includes several control strategies for piloting the exoskeleton, such as the desired end-effector force, the desired end-effector position, the desired joint torque, the desired joint pose or the desired joint impedance.

B. Using 3D simulation in-the-loop

The final Operation with a 3D simulation as a support system in parallel to the direct control of the real system which can be 'switched' seamlessly enhances the immersion into the teleoperated robot and its operability. Therefore, the force feedback has to be incorporated in the 3D simulation, too. Using a modular integrating approach, the underlying concept can be extended easily. First, the rigid body simulation within the 3D simulation is modified to enable a collision-based force feedback. Secondly, a simple force feedback device—the Geomagic Touch X [16] (formerly known as Phantom Device)—is used as an input device for simulation, testing and optimizing the force feedback capabilities. In the end, the full body exoskeleton can be used

[4]http://www.geomagic.com/en/products/phantom-desktop/overview

to interface a fully tested simulation environment including force feedback to the different joints.

C. Force Feedback Integration in 3D Simulation

The integration of force feedback in 3D simulation environments is not quite common in current research. Most commonly used as three-dimensional input devices for modeling, force feedback devices are only in some rare applications also used in specialized simulation environments, such as surgical simulations, where force feedback is then the main aspect of simulation. Integrating force feedback into a rigid body based simulation framework is therefore an advancement of the given technology.

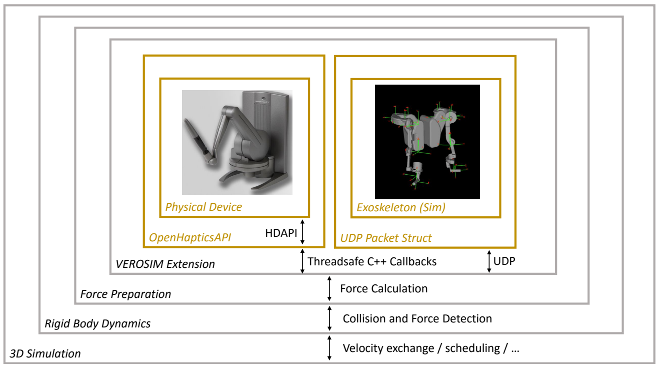


Fig. 3: Modular force feedback concept chart (chart idea based on [17]). Using a modular organization, the physical device and its API can be easily exchanged. The connection of simulation scheduling, rigid body dynamics, collision detection and force preparation is carried out in 3D simulation.

We developed a generic interface to couple rigid body dynamics based force generation, force reprocessing and specialized driver interfaces for each force feedback device. This interface is initialized with the *Touch X* and then extended towards a force feedback ready exoskeleton. As a result, the overall force feedback interface implements three layers:

1) Intertwining of dynamic simulation and events of force feedback calculation at time t_{FF},
2) Generic interface for force feedback devices, calculating a generic force feedback force F_{FF} at the time t_{FF},
3) Specialized driver interfaces for each haptic device,
   a) *Touch X* with *OpenHaptics API*
      - transmit the calculated force F_{FF}^{TouchX},
      - and provide positional input p^{TouchX} of the tool center point.
   b) Exoskeleton with UDP/IP connection
      - transmit an exoskeleton device command struct, either in 'force mode' (using joint torques τ_i^{exo} for each joint i) or 'compliant position mode' (using the end effector position p_{out}^{exo})
      - and provide an exoskeleton device data struct, with positional input of the end effector p_{in}^{exo}.

Starting with the *Touch X*, we used the freely available *OpenHaptics API* [18] to implement the driver interface, while the deeper layers were achieved in simulation. As one can see in Fig. 3, the *API* is just used for low level interfacing the physical hardware. Visible for the user in the 3D simulation is just an extension that manages a thread-safe communication channel. On a higher level, the collision and force detection, calculation and scheduling is of paramount importance. We implemented a collision-based determination of each force feedback event ($\rightarrow t_{FF}$). Now, either a) the calculated force on interacting rigid bodies (F_{RB}) can be used as force feedback, b) specific force torque sensors (F_{FT}) e.g. in the joints, or c) a more general approach, where the virtual coupling is based on a mass-spring-damper system as found in [19][20]. In c), a variance analysis of current position and target position is used to calculate a (virtual) spring-damper based force (F_{SD}). This procedure has the advantage of equal force dimensions, irrespective of the two colliding bodies. Otherwise the calculated collision force could become too high or too volatile for the force feedback device. As a result, we use c) for force direction and magnitude calculation, the integrated dynamic rigid body framework for collision detection, and a separate thread to safely collaborate with the *OpenHaptics API*.

Using this interface, it is also possible to exchange the *Touch X* with other force feedback devices, like the exoskeleton. During the development of the final exoskeleton an exoskeleton simulator is used as a substitute to define, develop, and use the exoskeleton interface in the 3D simulation. This exoskeleton simulator provides the exact same interface design as the final exoskeleton. Therefore, defined exchange information structs (encompassing endeffector position, joint angles, joint force and torques, etc.) can already be received by and send from simulation. Although the communication between simulation and *Touch X* is based on a specific API and thus completely different to the UDP- based connection of the exoskeleton, the infrastructure of the force feedback interface already provides all necessary pre-processing of forces. The low level interface layer of the UDP exoskeleton is then added on top of the force feedback fundament.

Using the exoskeleton simulator led to a defined interface concept for simulation and already shows first promising results in terms of the communication protocol and also realtime capable communication. More effort has to put on optimizing feasible force feedback generation from simulation for a direct and more intuitive sense of immersion.

IV. CONCLUSIONS

In the final operation of the CENTAURO project, this robot will be directly controlled by a first person operator, using an exoskeleton (with force feedback) for control and 3D simulation in-the-loop, supporting the operator. The use of a force feedback exoskeleton supports the operator in his mission by means of intuitive control and the positive effects of immersion, and hence being telepresent at the site of operation accompanied by simulation. The development of an exoskeleton for teleoperating mobile robots is continuously evolving and refined, accompanied by the exoskeleton simulator which is already of paramount importance in terms of interface definition and developments. We could already achieve first results in coupling dynamic simulation, force reprocessing, and interfacing multiple force feedback devices. The integration of force feedback in simulation in general also opens up prospect to a huge amount of applications to dive into virtual realities prior to the completion of the real setup or also in parallel to the real mission.

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