Towards a 3D simulation-based operator interface for teleoperated robots in disaster scenarios

Torben Cichon, Christian Schlette and Jürgen Roßmann[1]

***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 interface between operator and robot. In this contribution, we present the concept of utilizing 3D simulation as a central interface component for the operator to intuitively collaborate with teleoperated robots. Thus, means of 3D simulation are not only used during the development but also in the deployment of the final field system. Based on this notion, we will discuss operator interfaces with regards a) to direct interaction with the robot, b) communication between control station and real robot and c) the integration of already acquired knowledge and existing libraries in the robotics community.**

keywords: operator interface, virtual testbed, 3D simulation, force feedback, ROS

Fig. 1: Basic idea of the CENTAURO project – the joint hardware/software development of a teleoperated robotic field system for disaster-response.

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.

Based on the state-of-the-art today, the operation of autonomous mobile robots in such highly unpredictable scenarios is not feasible in terms of algorithmic robustness as well as skillfulness of autonomous mobility and manipulation. Thus, the most realistic choice currently is the combination of the cognitive capabilities of a human operator with a highly mobile and dexterous teleoperated robot. In such a robotic field system, 3D simulation can be utilized as a central component: Simulation can be used prior to the completion of the full system for the design, development and optimization of hardware and software components. Plus, simulation can be used in the final mission as well, as an additional interface between the operator and the robotic field system, e.g. to plan and verify next actions in simulation first before executing them in reality.

II. MOTIVATION

In todays mobile robots one main task is the optimization of direct control possibilities of the robot. As one could see at for example the DARPA Robotics Challenge (DRC) numerous operators were necessary each responsible for one single task, like hand movement, sensor data pre-processing, or leg movements for instance. Thus, new interfaces are needed to ensure an intuitive interaction of operator and robot with less manpower needed. We propose the use of only one main operator, responsible for all interaction tasks, and one support operator utilizing additional information of the robot's sensor data to assist the main operator. Special focus is put onto using 3D simulation in-the-loop of the final operator to ensure a stable, reliable, and easy to use man-robot interface.

In the CENTAURO project (see Fig. 1), we develop such specialized operator interface based on 3D simulation technologies.

III. RELATED WORK

To give a comprehensive overview of related work we discuss teleoperation, its use in disaster scenarios, 3D simulation technology, operator interfaces and force feedback We assume that the Robot Operating System (ROS) as the preferred communication platform in joint research projects in robotics is known (for further infomation see [1]).

A. *Teleoperated robots in disaster scenarios*

The ability to project the expertise of a given operator to another location and the ability to scale movements and other actions have already yielded many applications of teleoperation, ranging from robotic surgery to robot platforms for various environments, e.g. ground, underwater, or in the air. An overview of bilateral teleoperation is given in [2], where the two main goals of teleoperation are specified as "stability" in terms of system control and "telepresence" regarding the transparency of the robotic system, the environment and the operator. However, disaster scenarios such as Fukushima in 2011 newly underpinned the need for teleoperated robots to

[1]All authors are with the Institute for Man-Machine Interaction (MMI), RWTH Aachen University, 52074 Aachen, Germany
{cichon,schlette,rossmann}@mmi.rwth-aachen.de

safely act in highly hazardous and contagious environments. This demand forstered several highly funded challenges, in particular the DARPA Robotics Challenge (DRC), which focussed on the development of robot technologies for disaster-response tasks. In order to come up with stable system control, the most successful teams in the DRC concentrated not only on the development of reliable robot hardware but also of human-in-the-loop control schemes where the control stations are a few hundred of meters away from the robot on the course [3][4][5]. Besides, to overcome communication loss or instabilities is one major challenge in todays research in mobile rescue robotics, which are mainly related to the robotic hardware.

B. 3D Simulation Technology

Simulation plays a role in control schemes for teleoperated robotic field systems only in some rare and rather limited cases. In teleoperation it is usually used for testing and validation of individual modules or algorithms during development. The simulation tools are mostly focussing on individual aspects or specific application areas, e.g. ROS Gazebo [6], which is also applied in the aforementioned DRC. A more holistic approach to 3D simulation in robotics is provided by the eRobotics methodology [7][8] and so-called Virtual Testbeds, where 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.

C. Operator Interfaces

An introduction to operator interfaces utilizing Augmented Reality and Virtual Reality is given in [9], where they are applied in search-and-rescue applications. Sheridan summarizes the state-of-the-art of human robot interaction in [10] by reviewing current challenges ranging from supervisory control of robots for routine industrial tasks to teleoperated vehicles and planes and human-robot social interaction. He concludes that, "[w]e need to revisit the discussions of where humans best fit into systems as compared with AI and computer control". As a central method in modern robot control Sheridan sees much potential in so-called mental models as "[...] built-in models of what is going on in the environment that are continually updated, much as what humans seem to do." Using simulation in combination with mental models is motivated in [11] as an conceptual extension of Virtual Testbeds towards simulation-based control and simulation-based support.

D. Force Feedback

Force feedback is one element of haptic feedback, which compromises force feedback, tactile feedback, and proprioceptive feedback [12]. Although teleoperation is mainly based on audio-visual feedback today, also force feedback starts to have more and more applications. Several force feedback devices are commercially available, in particular the 6 DOF *Geomagic Touch X* (formerly Phantom Device) A general overview about history, complexity and benefits of haptic interfaces in simulation is given in [13]. From a technical point of view, the interface between simulation and (any) force feedback device should be the same: "Force feedback interfaces can be viewed as computer extensions that apply physical forces and torques on the user." [12].

IV. CENTAURO PROJECT

In the context of the CENTAURO project, we develop novel operator interface for teleoperated robotic field systems in disaster scenarios by extending the existing approaches described in section III. We aim for enabling the operator to effectively combine the strengths of direct robot control in real-time with simulation-based support to develop elaborate decisions.

In our previous work we utilized Virtual Testbeds 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. Based on the concepts and findings in [11], we thus decide to utilize a Virtual Testbed to meet the aims and requirements of the operator interface in the CENTAURO project. They allow us to use the same input devices, control algorithms, sensor data processing etc. in 3D simulation as well as in reality and thus to interface with the simulated robot equivalently as to the real robot. It is then fit to safely test and verify actions in simulation first, before executing them in the real world with adequate guidance and support for the operator. This characteristic is often referred to as "digital twin" of the real system. Fig. 2 shows this (equivalent) simulated digital twin supervised by a support operator with a third-person view on the robot and its environment.

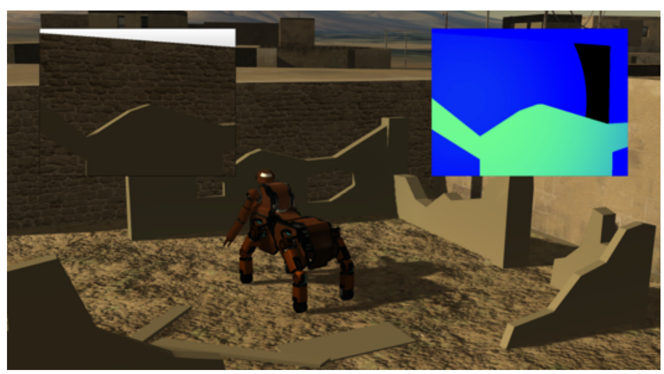


Fig. 2: Actual result – Third person view of the support operator based on 3D simulation.

There are specific requirements for the simulation framework to accomplish this behavior. Next to real-time performance, the central aspects are **integration** and **interfaces**: All necessary functionality for the simulation and simulation-based control of a robot in its environment has to be integrated ideally in a modular, complementary structure. Additional interfaces are needed to connect to the state-of-the-art in robot control software frameworks (here ROS) to incorporate developments by our project partners into the resulting robotic field system. The simulation-based operator interface then encompasses

- the direct control of the final robotic field system,
- the possibility to test and validate actions of the robot in a virtual environment, which is built from a-priori knowledge as well as real sensor data,
- the possibility to incorporate the state-of-the-art in terms of control algorithms etc., utilizing ROS as a commonly accepted communication link.

In Fig. 3 the seamless switch of operating the real robot or its digital twin is shown, supported by a second operator utilizing the 3D simulation. To overcome the complexity of the robotic system, giving all necessary data to the user and leading to a complete system of interoperable robots, we propose the 3D simulation-based interface for the operator. Thus, the simulation serves as an interface to combine a defined degree of robotic automation with software-based mental models. This extends semi-autonomous robots with the decision possibilities of a human operator "present" in the scene.

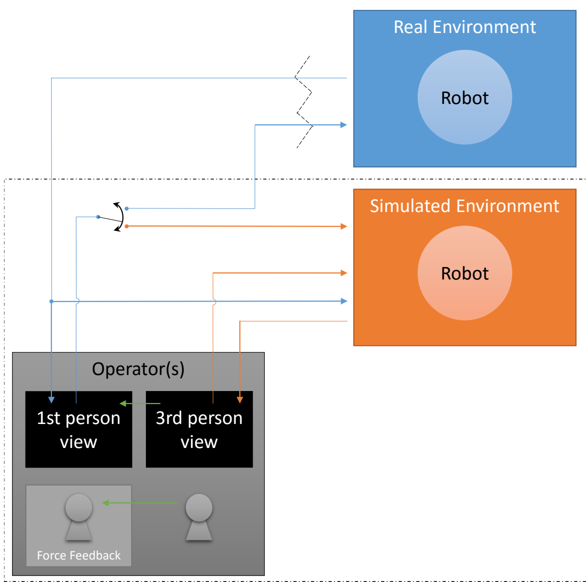


Fig. 3: Teleoperated robot setup enhanced with 3D simulation-based support of additional operators. Additionally, the second operator can give hints or send visual AR overlays to the main operator.

V. REQUIREMENTS

The application of teleoperated robots in disaster scenarios leads to the following requirements for the operator interface, it should

- reduce the complexity of teleoperation,
- overcome the lack of mobility and manipulation skills of robots,
- "stabilize" the communication link between robot and operator station,
- transfer huge amounts of sensor data from and to the robot (data storage, data preprocessing),
- reduce enormous workload for the operator(s) to reduce the risk of hazardous decisions.

Therefore, besides robust but dexterous and versatile robot hardware, a comprehensive operating system allows for intuitively controlling a highly complex teleoperated robot as well as for representing resp. visualizing the necessary data for the operator to achieve an immersive control and supervision of the robot. As described in section IV, we aim for addressing these points based on a Virtual Testbed in combination with commonly used (haptic) input devices and ROS. Additionally, simulation could be "used" to stabilize the communication link: In case of communication loss, the real robot would rest in a predefined state, while the operator could already plan the next steps in simulation. Such unstable communication areas could also be indicated in simulation, so that the operator could consider this knowledge in path planning.

VI. CONCEPT

Regarding our concept, the key aspect is the availability of a rigid body based physics simulation of the robot and its environment throughout the development process as well as during field operation. A human operator will control the robot intuitively using a full-body telepresence suit including force feedback. He will be supported by a second operator from a third-person perspective. Control tasks are mainly executed by the main operator, whereas the support operator can use the simulation in parallel to give hints and push visual assistance in the focus of the first operator. The simulation itself serves as an additional interface to the operator, so the complexity of robot hardware is hidden and the workload of the operator is reduced. As a result, the concept of the operator interface comprises the holistic interface between user and robotic field system.

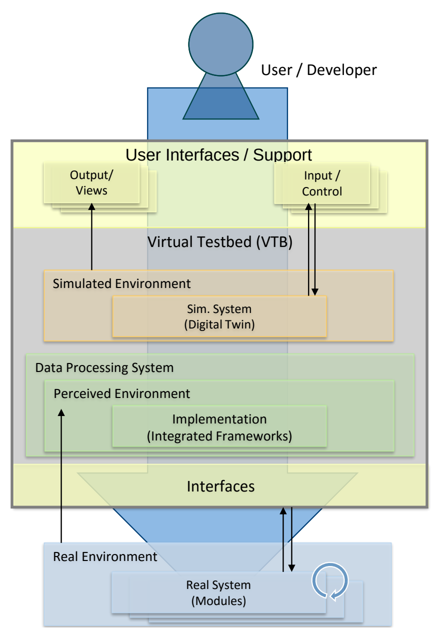


Fig. 4: Concept of the 3D simulation-based operator interface utilizing a Virtual Testbed.

As depicted in Fig. 4, our concept involves a modular 3D simulation system – resp. the Virtual Testbed (VTB) – as the central integration platform which integrates various modules for data processing and visualization. Additional interfaces are now on the one hand the final operator interface for the user with an immersive force feedback interface, and on the other hand the direct interface to ROS. This results in a (simplified) three-layered structure of interfaces: the user interface, integrated functionalities in the VTB, and interfaces to other systems. This structure is what we then call **3D simulation-based operator interface**, which allows operators as well as developers to easily and directly connect to the real robotic field system.

This concept defines the necessary background to develop, test and optimize a virtual setup of a real robot in different virtual environments. Furthermore, it enables the operator in field missions to use the simulation in the loop for testing and evaluating proposed tasks and to effectively evaluate sensor data from the robot.

VII. SYSTEM IMPLEMENTATION

The following section describes the implementation of the proposed concept. In terms of feasibility one has to distinguish between integration and interfaces: While the integration of functionalities in a holistic simulation environment is often favorable in terms of real time requirements and interoperability, it might also be reasonable in other cases to establish interfaces to commonly used and accepted other software (frameworks). Thus, we use a Virtual Testbed as a basis for integrative developments as well as extended interoperability with other frameworks to create an overall system of robot hardware, software, simulation and most importantly the operator.

A. Modular 3D Simulation System

In CENTAURO we develop a Virtual Testbed which comprises the relevant system components and enables early integration, testing and evaluation of system modules from our project partners. Core aspect is the development of a physical simulation of the robot in interaction with its environment as well as establishing a Central World Model (CWM), which can be updated from the percepts and actions of the robot. A predictive model for the robot-environment interaction will support the operators by enabling them to estimate the future behavior of the robot in order to evaluate alternative actions during missions.

For our approach we use the *VEROSIM* system which we co-develop at MMI. The modularity of *VEROSIM* enables us to easily integrate additional functionality, as interfaces to and from *VEROSIM* have to be established to communicate with other (given) frameworks and assimilate available prior developments, knowledge or modules.

B. Data Processing and Visualization

We have seen in section III that although system development in robotics often focuses on robot hardware and control software, the operator interface is of paramount importance to enable modes of teleoperation and telepresence. In particular the visualization of the sensor data collected from optical and other sensors has to be pre-processed and made available in an intuitively and understandable manner.

Due to the fact that one person will not be capable of supervising the robot alone, we propose the introduction of one or more support operators who provide additional, necessary information for the pilot. For the two types of operators, we accomplish two different views on the scene, 1) an immersive first person view using a head mounted stereoscopic display (here the *Oculus Rift*), and 2) a third person view onto the whole scene in simulation. For this development we need sufficient data processing for visualizing the input from various sensors. This data processing and visualization is based on the internal sensor framework (see [14] for further information) at first, but can be modularly extended or replaced by external libraries, particularly ROS sensors and ROS-based data processing algorithms.

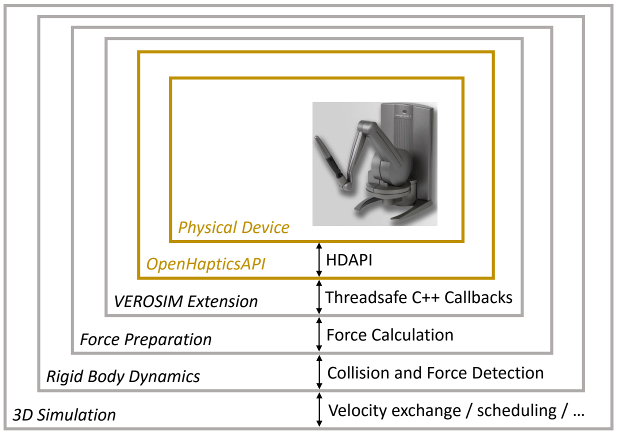
In addition, the *Oculus Rift* stereoscopic view has to be implemented in simulation. In the end, we achieve a collaborative composition of internal functionalities and external frameworks with regards to sensor hardware, sensor data communication, sensor data processing and sensor data visualizations.

C. Force Feedback Interface

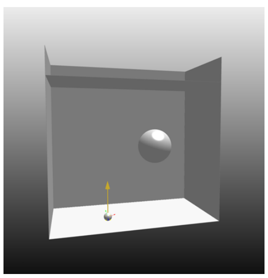
The integration of force feedback in 3D simulation environments is not quite common in current research. As stated before, force feedback devices such as the *Geomagic Touch X* depicted in Fig. 5 are most commonly used as three-dimensional input devices for modeling. Using the *Geomagic Touch X* as a sample force feedback input device, we developed a generic interface to couple rigid body dynamics based force generation, force reprocessing and specialized driver interfaces for each force feedback device 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, e.g. Phantom Device, which
    a) transmit the calculated force F_{FF}^{TouchX},
    b) and provide positional input p^{TouchX}.

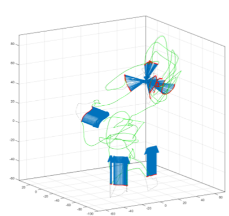
Starting with the *Geomagic Touch X*, we used the freely available *OpenHaptics API* [16] to implement the driver interface to the *Geomagic Touch X*, while the deeper layers were achieved in *VEROSIM*. The modularity of *VEROSIM*, and thus the associated independence of individual modules, requires a systemic management of force feedback in time, space and magnitude. As one can see in Fig. 5a, 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 between *VEROSIM* and the *OpenHaptics API*. On a higher level, the



(a) Modular force feedback concept chart (chart idea based on [15]). 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 *VEROSIM*.



(b) Force feedback from simulation in *VEROSIM*



(c) Force feedback analyzed in MATLAB

Fig. 5: The force feedback interface couples collision detection, spring-damper dynamics and the haptic device.

collision and force detection, calculation and scheduling is of paramount importance. We implemented and validated a collision-based determination of each force feedback event ($\rightarrow t_{FF}$). The setup can be seen in Fig. 5b) and Fig. 5c where a simple 3D model is used to test the collision detection in *VEROSIM* and the force vectors are analyzed in *Matlab*. Now, either a) the calculated force on interacting rigid bodies F_{RB} can be used as force feedback, b) the force of 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 [17][18]. In c), a variance analysis of current position and target position is used to calculate a (virtual) spring-damper based force (F_{SD}) (see Fig. 5c). 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*. This interface, using the *TouchX*, is implemented, coupled with the rigid body dynamics, and is already in practical use. Experiments, evaluation and optimization is still done with regards to feedback force calculation and preparation in general.

We assume either a direct positional input of a frame to move a given rigid body in time and space, or we use the transfered joint-angles directly. Also with respect to other input devices, like an exoskeleton, it will always be possible to transmit either end-effector position or a given set of joint angles or torques. Device specific characteristics can be managed independently of the generic interface in the manufacturer-specific driver interfaces resp. in specialized *VEROSIM* extensions.

D. ROS Interface

We implemented a generic integration of ROS into *VEROSIM* to enable to use the full spectrum of ROS functionalities from within the 3D simulation and thus the operator interface. As we stated before, implementing an interface to the communication infrastructure of ROS aims at connecting the message passing system with *roscore* to open up many possibilities regarding other core components of ROS. In order to make use of the knowledge already available from prior ROS setups, we use the Momaro setup [4][19], a working robotic setup based on ROS. The milestone to achive was to be able to resemble the features in the Momaro setup to test and verify the developed interface.

The Momaro setup is mainly based on standard ROS data types. Thus, we started the implementation in *VEROSIM* with according standard message types as well as combined message types for the central input/output board (IO Board) [20] which then allows for dynamically connecting internal functionalities with the ROS framework. As a result, internal scheduling, rendering and the other frameworks can utilize the inputs and outputs of ROS nodes from within *VEROSIM*.

The following implementation scheme is used to continuously add ROS functionalities using the *roscpp* (and *rospy*):

1) Static data type conversions for *std_msg* types
2) Static data type conversions for combined *std_msg* and specialized types
3) Template-based conversions for arbitrary msg types
4) Completely dynamic (Python-based) embedding of ROS data types into *VEROSIM*

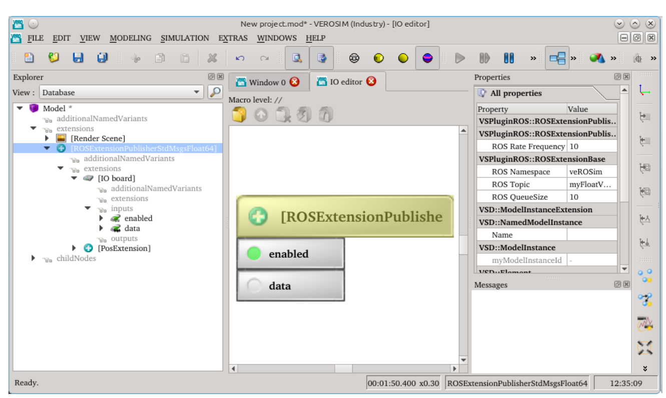


Fig. 6: ROS Interface to *VEROSIM*.

Step by step, this will lead to a continuous integration (and easy template based extensibility) of data types according to the requirement analysis. Finally, it will be possible to use a given set of ROS message types from within simulation (input and output).

Using this implementation scheme already led to first results. In Fig. 6 a ROS *std_msg float64* publisher and its corresponding subscriber are used to connect two instances of *VEROSIM*.

E. Complete System

Our concept intertwines integrated functionalities from a 3D simulation system with external libraries, mainly from the ROS context. This leads to a modular, flexible and robust overall setup, enabling an optimized 3D simulation-based operator interface. The overall setup includes an optimized operator interface for controlling robots in disaster scenarios by means of immersive and intuitive control from a first person perspective with the *Oculus Rift* and force feedback using the *Geomagic Touch X* device. Accompanied by a supporting third person view, overlays for sensor data visualization and a direct interface to ROS, the operator interface is able to effectively support the main operator in his decisions.

VIII. CONCLUSIONS

We presented the concept of a 3D simulation-based operator interface which comprises the development of the simulation technology necessary to setup a high fidelity operator interface consisting of simulatable models of the robot and its environment as well as means for intuitive interaction and visualization to safely operate and supervise the remote robot with multiple operators using various devices. In addition, the operator interface enables the direct access to the common ROS middleware. Thus, the interface is prepared for connecting the simulation with customized ROS nodes and the reuse of existing ROS modules. The use of force feedback devices 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 and supported by pre-processed data. The integration of force feedback in simulation in general opens up prospect to a huge amount of applications to dive into virtual realities prior to the real setup.

In summary, the 3D simulation-based operator interface for teleoperated robots in disaster scenarios applies 3D simulation to generate new integration and interface options, to establish an intuitive and effective combination of robotic field system, data exchange and processing algorithms and to the coordination of human control and supervision.

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