2017 IEEE International Symposium on
Safety, Security and Rescue Robotics (SSRR)
Shanghai, China, October 11-13, 2017

Robotic teleoperation: mediated and supported by Virtual Testbeds

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***Abstract*— In disaster scenarios or search and rescue applications an efficient, constructive and safe mission needs more than just robotic hardware and control. One major element is the interface between operator and robot. In this contribution, we present the approach of VTB-mediated teleoperation. This comprises (i) using standardized interfaces to integrate existing knowledge and libraries of the robotics community, (ii) the modular integration of necessary functionalities into the VTB, (iii) data handling and visualization in 3D simulation, (iv) direct control and feedback possibilities of real and virtual robotic systems, and (v) an overall modularity in terms of input and output modalities, internal and external libraries, as well as real and virtual data. This results in a holistic system of operator, VTB, and robotic system for training, support, prediction, and analysis before, after, and also during the mission.**

keywords: 3D simulation, simulation-based support and user interfaces, force feedback, ROS, operator interface

I. INTRODUCTION AND MOTIVATION

In disaster scenarios or search and rescue applications we mostly have to cope with dynamic, unknown environments. Thus, 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. Instead, we will focus on the teleoperation approach to incorporate the experience and intuition of a human operator. The combination of the cognitive capabilities of the user with a highly mobile and dexterous teleoperated robot seams to be the most realistic choice. But we are convinced that the advantages of human teleoperation cannot be fully exploited yet because of inadequate user interfaces and insufficient training possibilities. Additionally, adequate data pre-processing and visualization, as well as answers to the often needed “What if...?” questions are of paramount importance during the mission.

In robotic field systems, 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 single hardware and software components or the system as a whole. Additionally, the 3D simulation can be used for external algorithms as a data source or sink enabling early integration steps. Finally, simulation can be used in the final mission, as well as an additional abstraction layer between the operator and the robotic field system. Generating new user interfaces, enhancing the immersion of the operator, plan and verify possible next actions in simulation first before executing them in reality, is the main intention of this research.

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II. RELATED WORK

To give a comprehensive overview of related work we discuss 3D simulation technology and the Virtual Testbed (VTB) approach, teleoperation, its use in disaster scenarios, operator interfaces and control.

A. 3D Simulation Technology

In our previous work we utilized 3D simulation and VTBs as integrated development and simulation platforms for so-called “digital twins” of the real system. The simulation then comprises system models as well as environment models and connects them with simulation methods and algorithms, e.g. for perception and control. 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. Using simulation in combination with mental models is motivated in [1] as an conceptual extension of VTBs towards simulation-based control and simulation-based support. This can also be used for early integration procedures and direct robotic control in joint robotic projects. The general concept of using these VTBs in search and rescue applications has been presented in [2] where we initiated the approach of “3D simulation based operator interfaces”. This paper is now the continuation of this conceptual idea, implemented and optimized to be used in a disaster response unit.

B. Teleoperated robots in disaster scenarios

Besides optimal robot hardware, challenges like the DRC or RoboCup Rescue, show the need for optimized human-robot interaction, especially intuitive user interfaces for teleoperating mobile robots. 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 on human-in-the-loop control schemes [3][4][5]. Fong et. al. [6] give an overview on the general history of teleoperation interfaces for mobile robots and vehicles and summarizes their central aspects: ”Teleoperation interfaces provide tools and displays to perceive the remote environment, to make decisions and to generate commands.” Additionally, a teleoperated system setup has to withstand and to recover from loss of communication to the robotic field system due to difficult environments, which is one major challenge in research today. Niemeyer et. al presented in [7] (and subsequent publications) the approach of *model-mediated telemanipulation*, demonstrated in a simple haptic telemanipulation setup. Thus, it is an abstraction from sensory data by a model transmitted to the master, where it is haptically rendered without lag, to cope with communication delays.

C. Operator Interfaces and Human-Robot Interaction

Operator or user interfaces can be seen as the general system theoretical approach of what goes into the system and what comes out. On the one hand we have the visual (and audible) *output* from the system. Besides classical hardware, in current (state-of-the-art) 3D simulation tools we can divide these into "Virtual Reality" (VR), "Augmented Reality" (AR), and "Mixed Reality" (MR). These fields of visual output can be categorized by the associated hardware, primer purpose of use, or the amount of fusion from virtuality and reality. On the other hand, user interfaces cover the *input* (sometimes also combined with output) to the system. This can be categorized in terms of different input device technologies, like "controller-based" (CB), "sensor-based" (SB), or even "haptic" (H) devices. An introduction to operator interfaces utilizing AR and VR is given in [8], where they are applied in search-and-rescue applications.

D. IO Devices and Control

Using state-of-the-art technology as input devices for robotic control was already done in several fields of research. Gromov et al. showed in [9] the use of a gesture recognition bracelet (and thus a CB input device), namely *Thalmic Labs MYO*. The MYO was used control multiple mobile robots using speech, arm movement, and hand gestures to select, localize and communicate task requests and spatial information. Besides the *Microsoft Kinect*, which is widely in use to directly control robotic platforms like in [10], or for industrial gesture based human-robot interaction in [11], another optical sensor is the *LeapMotion Controller*. A general analysis (especially on accuraccy and robustness) of the LeapMotion can be found in [12]. Instead, [13] analyze the combination of Kinect and LeapMotion, whereas [14] base their research on enhancing more natural human-computer interactions with the main application in "Ambient Assistant Living" robotics. The use of force feedback (as one element of haptic feedback) devices for robotic control is still quite new but has shown first promising research. In [15] an overview of haptic interfaces in simulation is given, whereas in [16] an exoskeletal control of a teleoperated robot in simulation is presented.

As mentioned before we focus on applications where teleoperation is the method of choice. Nevertheless, during teleoperation single autonomous or supervised actions can be also a method of choice to reduce the workload of the operator. Using another view on the scene can also lead to new possibilities regarding control schemes. One example is the research of Petter Ögren, who e.g. shows in [17] the transfer from the standard "tank control" of unmanned ground vehicles to "free look control" to improve the overall mission performance.

III. APPLICATION SCENARIO AND REQUIREMENTS

The CENTAURO project aims at the development of a novel teleoperated Centaur-like robot with whole-body telepresence of the human operator to allow for making elaborate decisions during the mission, utilizing novel man-machine interfaces. There are specific requirements for the simulation framework to accomplish a safe cooperation of an immersively present operator, supported by situation-aware interpretations of current and a-priori data. First of all, the 3D simulation system itself has to fulfill to some degree real-time performance and a modularity in its core. Secondly, the operator needs to interact with the graphical user interface through a set of *input device*. These devices should enable an intuitive control, which is needed in time-critical decision making processes. Thus, besides a necessary keyboard/mouse control also state-of-the-art input devices should be possible to use. Thirdly, the *view* on the scene and on the data gathered by the robot is central for vision-based operators like humans. These views should also reduce complexity and workload of the operator by presenting all important information needed. Finally, the *data transfer* between the user and the robot has to be standardized. This data transfer should "stabilize" the communication link. In a more general sense the data storage and processing should be able to cope with a huge amount of data and even part-time connectivity or data loss.

IV. CONCEPT

To create a safe and constructive collaboration of operator and robot the main task is to create an intuitive interaction. To bridge this gap we propose one central interface, the 3D simulation. The 3D simulation itself then provides additional interfaces, e.g. to the hardware or algorithms. What is more, the 3D simulation can then be used as an input device, creating an additional abstraction layer for the user. As motivated in the previous sections, we aim for addressing these points based on a VTB in combination with commonly used state of the art input and output devices and ROS as the robotic middleware. The overall concept and communication structure can be seen in Fig. 1, where we present the operator station(s) as the system's client(s). The concept involves a modular 3D simulation system – resp. the VTB – as the central integration platform which integrates various modules for data processing and visualization. Additional interfaces are now on the one hand with an intuitive and immersive user interface, and on the other hand the direct interface via ROS to the hardware and external algorithms. This results in a three-layered structure of interfaces:

1) the user interface (I/O Controller),
2) integrated functionalities in the VTB,
3) and interfaces to other systems (CCC).

Generating a virtual representation of the robotic system (including actuators, sensors, and control) we can build a "digital twin". This digital twin behaves exactly like the real robotic system (cf. Fig. 2), can be actuated with the same commands, and sends simulated sensory output. With this concept we can then use the model for teleoperation. It allows us to connect, distinguish, or fuse virtual and real data, constructing worlds from the robot percepts or visualizing (external and internal) data.

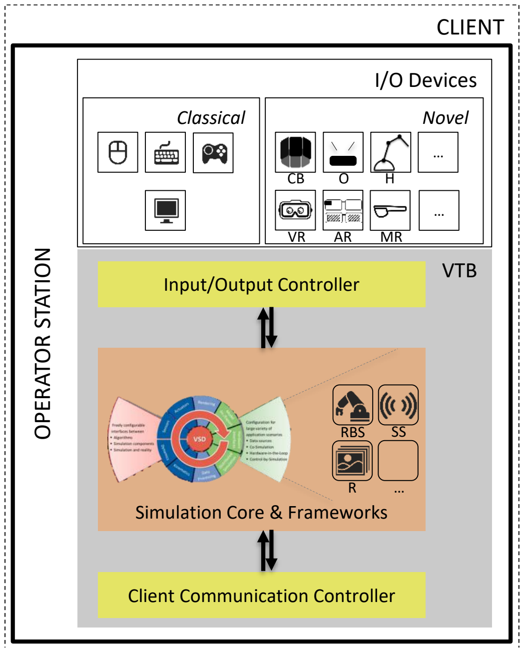


Fig. 1: Using VTBs in this scope requires the **Input/Output (I/O) Controller** to incorporate a set of I/O devices, **integrated frameworks** (besides the VSD core [18]) especially cooperating with the Rigid Body (RBS) or Sensor Simulation (SS) and the Rendering (R), as well as the **Client Communication Controller** (CCC) to interact with other modules.

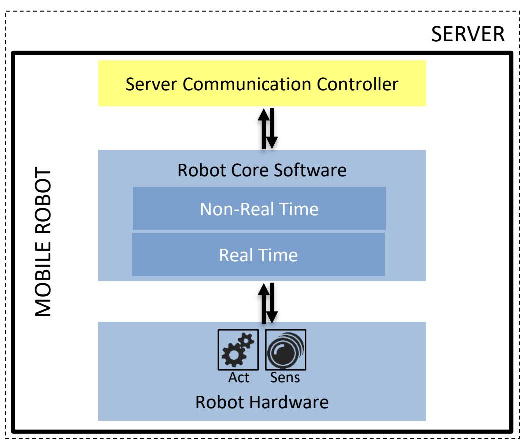


Fig. 2: The real robotic server and blueprint for the **digital twin**, providing the same interface (SCC)

This modularity is presented in Fig. 3 where we (i) establish multiple clients by choosing I/O devices and function of the operators, and (ii) connect these clients to (multiple) robotic servers, either to real systems or digital twins. Using direct control of the digital twin is very useful as long as the real system is not fabricated yet. In the final operation it is then even possible to mix and combine single or multiple real and virtual data servers to single or multiple operator clients.

Using this concept allows us to control a robotic system or its digital twin, assist the operator by means of data

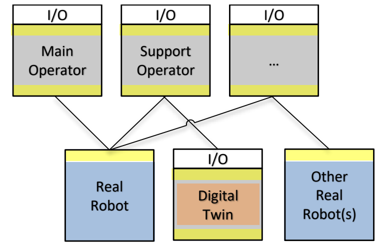


Fig. 3: **Modularity**: Multiple clients with combinations of I/O devices for different types of operators with the possibility to switch and connect to real or virtual robotic servers

processing, visualization, and immersion, and also test and predict robotic actions in simulation first before execution in reality. Of course, the design, development, optimization as well as the early virtual modular integration in simulation is also part of this idea. Thus, the simulation itself can be seen as the central interface between user and robotic system. It can 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, subsidized by information from the digital twin and simulation-based X methods (see e.g. also [19] or [1]). Additionally, there is a seamless switch between real and virtual interaction. What is more, the fusion of real and virtual data I/O is established, as well as the connectivity from ROS messages and internal framework utilities.

V. SYSTEM IMPLEMENTATION

The following section describes the implementation of the proposed concept. In terms of feasibility we will start with the interfaces first, before introducing the simulation system and the user interfaces.

A. *INTERFACES TO OTHER SYSTEMS*

We implemented a generic integration of ROS to use the full spectrum of ROS functionalities from within the 3D simulation utilizing all internal frameworks. In order to make use of the knowledge already available from prior ROS setups, we implemented the communication infrastructure to the message passing system and use the *Momaro* setup [20], a working robotic setup based on ROS. The developed ROS interface is now in use and covers all needed ROS standard message types. Additionally, we created not only the possibility to subscribe to external messages but also to publish message from the VTB. This enables an easy transformation from the client VTB to become the server VTB using the digital twin of the robot (like in Fig. 3). To add further ROS functionalities using the *roscpp* API we already have static and template-based conversions of ROS message types. Additionally, using the *rospy* API lead to first results to add and embed new message types at run time and using ROS also under Windows. What is more, we implemented an automated URDF file importer, which builds a dynamic model of the robot and thus the needed digital twin of the system automatically.

B. INTEGRATED FUNCTIONALITIES IN THE VTB

In this section the integrated components into the VTB are presented. This involves an embedding of these components into the given frameworks of the 3D simulation system, different simulation models as well as the data handling.

1) 3D Simulation System: Based on the concepts and findings in [1], we thus decide to utilize a VTB to meet the aims and requirements. 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.

For our approach we use the *VEROSIM* system which we co-develop at MMI. Its modularity enables us to easily integrate additional functionality, as interfaces have to be established to communicate with other (given) frameworks and assimilate available prior developments, knowledge or modules. Besides core components, mostly important in this context are the already developed rigid body [21], the sensor [22] and rendering [23] frameworks. Additionally, the internal connectivity with the central I/O board [24] can be used to intertwine different components (also during runtime).

2) Robot and environment models: For a modular approach of 3D simulation technology we need a set of different models. On the one hand, robot models which are mainly based on real robot developments but can also be a playground for roboticists to try out and test new prototypes of robots in simulation. On the other hand, environment models which reach from simple (almost empty) benchmark scenarios to holistic static or dynamic scenes.

We established already a set of multiple different robotic systems and environments, like one can see in Fig. 5. Robotic parts, like for example the robots body, a new sensor head or a set of hands, can easily be combined or exchanged to generate a holistic robot. This can then be tested in different scenarios of increasing complexity, with regards to different control schemes or strategies for example. Afterwards, the system can be used as a data source for external (ROS-based) algorithms of sensor data processing, planning, etc., or can be used as a data sink to directly control the robot's digital twin, or evaluating the output of the aforementioned algorithms.

3) Data Perception and Processing: Using ROS as the central communication middleware one can define a "Central World Model" (CWM). This CWM can be seen as a container of knowledge and is a construct including all data which is send and received via the ROS network. The simulation can then use the CWM, or parts of it, to reconstruct realistic worlds from the robot's percepts. Likewise, all other components, modules, or algorithms can use the CWM for their navigation planning, sensor pre-processing, etc.

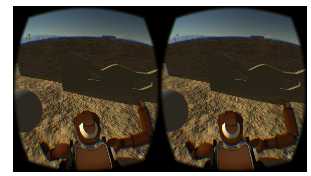
The CWM can also be used for in-line object generation. If there is an object recognized by the robots sensors this object can be inserted into the scene as a rigid body, which then can be picked up or even used by the digital twin in the perceived environment.

Data in general can either come out of the simulation itself, using for example the internal sensor framework or can be modularly extended or replaced by external libraries.Again, this is only possible by using a modular implementation scheme in addition to the ROS interface including VEROSIM/ROS data type conversions and connections via the IO-Board. In the end, we achieve a collaborative composition of internal functionalities and external frameworks with regards to hardware, data communication, data processing and data visualizations.

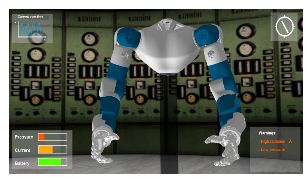
C. USER INTERFACE

The user interface can be divided into the visual output and the control in- and output. Regarding Visualization one can take a closer look at the visualization output and also the type and method of visualizing scientific data.

(a) Over-the-shoulder view

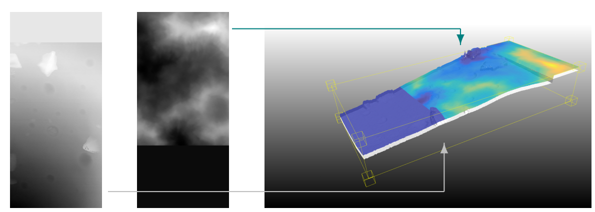


(b) Stereoscopic 1st person view



(c) Head Up Display (HUD)

(d) Projected billboards



(e) Rigid body 3D environment, generated via a ROS height map with a color overlay of a traversability cost map

Fig. 4: Rendering metaphors to enhance the operator's overview on the mission, robot state, and possible actions

1) Visualization: Instead of just using classical I/O devices, the visualization output of the VTB can also be achieved with commercially available VR, AR, or MR Hardware. In the context of teleoperation this is often done via fully immersive stereoscopic VR goggles, in our case the *Oculus Rift* or the *HTC Vive* are fully implemented and in use. Other AR technology is currently under implementation, like the *Vuzix M300* or the *Microsoft Hololens*, which are especially suitable for assisted search and rescue tasks or design and development processes in various research areas.

As presented in sec. II-D the *view* on the scene can have an enormous impact on the overview of the operator and the controllability of the robot. Using different views in 3D simulation this problem can easily be tackled. For example, manipulation tasks can be done in 1st person view, whereas autonomous driving can be monitored in 3rd person (over-the-shoulder) view, and exploration of the surrounding can be done with a free flying camera, whereas some mechanical raw data can be monitored in a terminal. One example of such views is shown in a virtual exploration scenario in simulation in Fig. 4a and 4b.

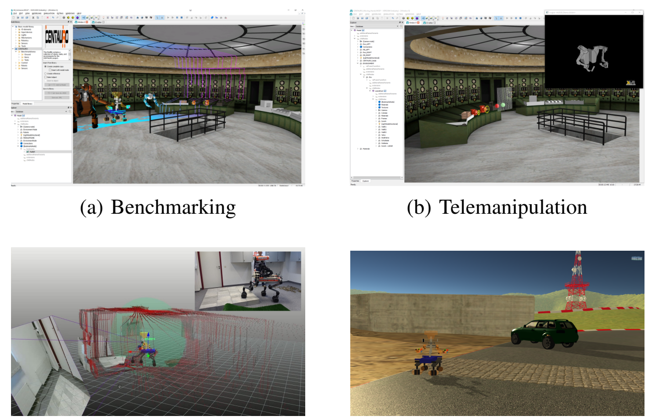
Intuitive visualization of any kind of data is often the key element to an enhancement of user experience. Thus, we extend frameworks to generate *overlays*, in particular Simulation-based User Interfaces (SbUI) [8], and widen the approach of projective VR [25]. As one can see in Fig. 4c one can generate a user- or application-oriented Head-up Display (HUD) to visualize internal or external data. This user interface can then be used in the final mission in an individual setup, based on the operator and the chosen I/O devices. Additionally, environment or object information can be projected into the 3D scene to visualize additional information. Such (ROS transmitted) detected object (detection, type, pose, additional information) can be rendered at the site of occurrence in the 3D environment (cf. Fig. 4d), using *billboards*. Besides billboards, such projection can be maps used for generating 3D environments, combined with traversability cost maps as an direct overlay on top of the 3D geometry (cf. Fig. 4e). Such SbUI can be associated with current AR/VR applications, car cockpits, visor or even the current operator status in computer games.

2) Control / IO Devices: The motivation of control of a 3D simulation and everything that is connected to it is very similar to the visualization. Again, the ease of use and the best suited device for a given application should be used. Often, this results in using a keyboard, mouse, and a simple monitor. But the opportunity to exchange these is also given in our approach, using an object oriented integration.

In AR/VR applications the human body or in particular the human hands are often meant to be the most natural and universal interface. Thus, we implemented an interface to the *MYO* and the *LeapMotion* controller. A modular, object-oriented implementation scheme leads to a layer of input devices that can be abstracted from the simulation system, but easily connected with any internal framework. Such controller-based (CB) or optical (O) input devices can additionally be utilized with gesture recognition to enhance the ease of use. In contrast to these, force feedback devices have to be additionally coupled to the rigid body simulation and fulfill hard real time requirements. Here, hard real time requirements can be achieved using not ROS but an UDP-based interface with defined command and data structs. Nevertheless, the modular object oriented implementation scheme connected via the IO Board (cf. Fig. 1) led already to use cases where we can easily exchange the different input devices (CB or O or H) suitable for the given application. We also combined the aforementioned gesture recognition with force feedback of haptic (H) input devices. This leads to further possibilities on guided movements supported by simulation, either for gestures or for direct control.

VI. THE SYSTEM AT WORK

In Fig. 5 one can see the presented system at work. Whereas in (a) the model library is used to create a benchmarking scenario of manipulation tasks, in (b) a force feedback exoskeleton is used to interact with the simulation system. In (d) the simulation is used as a data source for ROS based terrain classification algorithms because in simulation we can produce sensor data of the different terrain types (street, cobble stone, grass, ...) very easily. In (c) the live visualization of real sensor data is shown, where the Momaro robot is performing navigation and stepping tasks and the simulation visualizes point cloud, image, or joint state data.

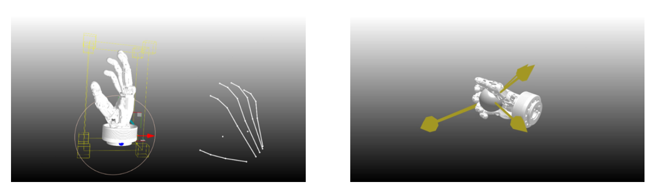


(a) Benchmarking (b) Telemanipulation

(c) Live data visualization (d) Terrain classification

Fig. 5: Holistic system evaluation, training, and in-the-loop operation of VTBs in disaster response tasks

Another more specific application is shown in 6a where a digital twin of the *Schunk Five Finger Hand* is controlled by means of the *LeapMotion* controller. Using the rigid body simulation one can even grasp something with the hand and analyze the arising forces as one can see in (b). Such manipulation experience will be enhanced in a next step by using a hand exoskeleton instead of the *LeapMotion* to allow more intuitive grasping, utilizing force feedback.



(a) LeapMotion control (b) Schunk Hand force analysis

Fig. 6: Control and evaluation of single components of tele-operated robots using novel user interface devices

The presented concept (and its use) intertwines integrated functionalities from a 3D simulation system with a set of useful input devices, specialized user interfaces, useful data visualization metaphors, and also connects to external libraries, mainly from the ROS context. This leads to a modular, flexible and robust overall setup, enabling an optimized

VTB-mediated teleoperation. Due to the modularity of real system or digital twin, the views and visualization types, the control devices and schemes, accompanied by the possibility to switch between or fuse virtual and real data seamlessly leads to an optimized human-robot team. Additionally, in case of communication loss the real robot could rest in a predefined state while the operator plans the next steps in simulation, "stabilizing" the communication link. Such unstable communication areas could also be indicated in simulation, so that the operator could consider this knowledge in path planning. Finally, the performance improvements of this system in search and rescue applications can be assessed in a quantitative metric based on the real and virtual benchmarks tasks.

VII. CONCLUSION / OUTLOOK

We presented the VTB-mediated teleoperation, which can be utilized pre, post, and even in mission. This includes the VTB as a central interface between the user and the robotic system. Different input devices, AR/VR output, optimized user interfaces, and useful data visualization metaphors let the user make educated decisions intuitively with all necessary information in his focus. Integrated functionalities, the use of already established frameworks, and connections to external libraries make a profound basis for using VTBs also in disaster scenarios. The connection from the simulation to ROS does not only allow the simulation to be a data sink, but can also utilize the VTB and the robot's digital twin as a source of necessary data during the development and during mission. This enables the user to switch easily between the real system and its digital counterpart, and create an optimal working environment. Using these features also online have to be evaluated in more detail, especially regarding the approximations that are made by the simulation engine regarding physics and rendering, to preserve a stable and performative process, but already showed prominent results.

In summary, robotic teleoperation mediated and supported by VTBs applies 3D simulation to generate new symbiotic relationships of reality and virtuality as well as the operator and the robotic system, to establish an intuitive and effective combination of human control and supervision.

ACKNOWLEDGEMENT

This project has received funding from the European Unions Horizon 2020 research and innovation program under grant agreement No 644839.

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