SIMULATION-BASED USER INTERFACES FOR DIGITAL TWINS: PRE-, IN-, OR POST-OPERATIONAL ANALYSIS AND EXPLORATION OF VIRTUAL TESTBEDS

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KEYWORDS

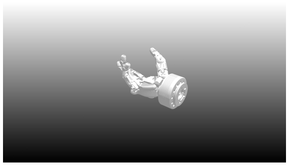
3D Simulation, Multi-Body Dynamics, Robotics, Teleoperation, User Interfaces, VR/AR/MR

ABSTRACT

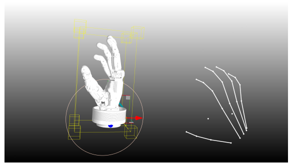
There is a need for a more natural interaction with complex systems in terms of usability, safety, and collaboration potential. No matter if it's the development and operation of a teleoperated robot, supervision of autonomous actions, planning or optimization of industrial processes, an intuitive and direct control possibility by observing all essential information is the key for an optimal man-machine-interaction. In our case, such UI then comprise (a) an experimentable digital twin of the real asset, (b) intuitive control by means of new UI hardware, (c) the virtual exploration of the evaluated process, (d) the preparation and visualization of sensor data, and (e) the process evaluation before, during or after the execution of a task. This holistic approach puts VTBs in between the user and the real system during the development, the execution, and the evaluation phase. This should enable the user to intuitively and safely interact with complex systems utilizing 3D simulation.

MOTIVATION

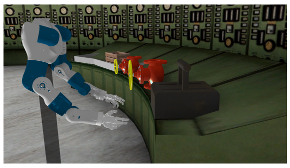
New developments in Virtual Reality (VR) and everything accompanied led to a rising interest in this kind of technology regarding 3D software and Input/Output (I/O) hardware. But still, in research not only an appealing visualization is important but also the physical plausibility is fundamental. The applications of VR are momentarily mainly based on consumer electronics and computer games but seams to strive more and more into the scientific research. Additionally, the interaction, cooperation, or even collaboration of man and machine represent key characteristics of next generation robotics. Working without cages and sharing the same work space humans can safely interact with robots physically, in application fields like industry, ambient assisted living, or search and rescue to name a few. Mainly, this research tries to enhance the symbiosis of the human leading and the technology enabling on the one hand, and on the other hand decreasing risks of failure and enhancing safety of operator and system. Combining technology, knowledge, and research in these applications with the use of 3D simulation software and current VR hardware seams to be a promising way of reducing the complexity of the underlying system, enhancing the safety, and bridging the gap between developer, user, and the overall system and process.



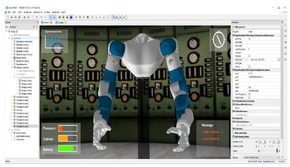
(a) Digital Twin of the *Schunk Five Finger Hand*



(b) Direct control using *LeapMotion Controller*



(c) Grasping scenario planning and execution in Virtual Reality



(d) "Online" parameter visualization, mirroring the real robotic system

Figure 1: From development to in-process monitoring: Using Virtual Testbeds and the *LeapMotion Controller* for intuitive manipulation tasks.

INTRODUCTION

We want to motivate our approach by exemplary show manipulation processes (cf. Fig. 1) with the help of such simulation-based user interfaces (UIs).
Intelligent and soft robotic systems are in the focus of today's research with regards to man-machine interaction and man-robot collaboration. Due to the dexterity and the usability of human-like tools this kind of man-robot cooperation uses hand-like end effectors, for example the *SCHUNK 5-Finger-Hand*, first introduced in Liu et al. (2008). Virtual Testbeds (VTBs) can then be used for

designing and testing the robotic hardware with a virtual model during its development phase (Fig. 1a). Additionally, a sophisticated rigid body simulation can be used to evaluate feasible grasping scenarios of the hand already in this early stage of developments. But with state of the art user interfaces for such systems it can be a time consuming, tedious process of applying the correct force/torque on the different motors of the phalanges. Thus, we use the *LeapMotion Controller*[1] as a **natural user interface**, which directly maps the joints of the human hand to the virtual robotic ones (Fig. 1b). Additionally, grasping is not limited to the hand itself, it is more an overall process of full-body movement interacting with the environment. Like picking up a coin from a table it is natural for humans to use multiple hands for swiping it to an edge or exploiting the environment to reduce the complexity of the task. Therefore, Virtual Testbeds can be used to push the manipulation process into its context, of for example grasping and turning a valve with a teleoperated mobile robotic system, like in a real scenario (see Fig. 1c).
Another central aspect of user interfaces is the visualization. Besides state of the art VR technology, like *Oculus Rift* and *HTC Vive* for VR, *Vuzix MR300* and *Google Glass* for AR, or *Microsoft Hololens* and *Acer Mixed Reality Headset* for MR, the pre-processing and visual preparation and presentation of external and internal information is of paramount importance. The user should directly and intuitively see all necessary information in his sight. Therefore, we want to use 3D simulation to generate highly customized user interfaces (like in Fig. 1d) to visualize for example the battery consumption or forces and torques of each joint motor, either of the real robotic system or its digital twin.
Thus, establishing Virtual Testbeds and their 3D simulation core as the **central interface** for the user to interact with complex systems is the main intention of this contribution. This comprises (a) new input devices for VTBs, (b) enhanced visual aids generated within the VTB, and (c) ensuring seamless connectivity to internal VTB modules and external hardware. Combining such new user interface constituents and then exploring VTBs is the pivotal use case of this paper. This exploration starts already in the design and development phase, where modeling becomes more natural. But it can also be used "online", mirroring a real system, or even afterwards for evaluating and optimizing processes. All in all, such new user interfaces should lead to a holistic system of a human user, the VTB as a mediator, and the real system.

RELATED WORK

In this chapter we will present the related work w.r.t the general use of digital twins and Virtual Testbeds, the interface between user and complex system, and finally the use of simulation technology as a mediator.

Virtual Testbeds Using Digital Twins

No matter in which application, simulation tools are almost used in every field of research. Mostly, these tools are focusing on individual aspects or specific application areas. A more holistic approach to 3D simulation, especially used in robotics, is provided by so-called Virtual Testbeds (VTBs), presented for example in Rossmann et al. (2013), 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.

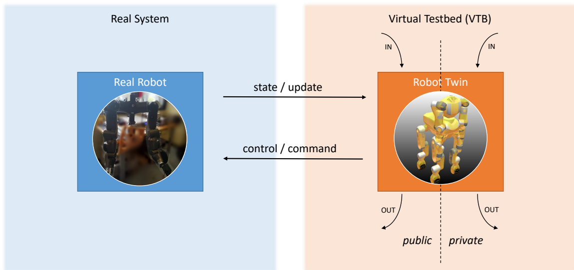


Figure 2: Digital Twin: Example of a digital twin including data exchange and privacy conditions

Within these VTBs we use **digital twins** of the real system. Exemplary shown in Fig. 2 we present the digital twin of a mobile robot (in its development stage), where we can use the virtual asset to test and develop the asset itself and also everything interacting with it. Additionally, the digital twin can be updated according to the current robot' state and could also control or send individual commands to its real counterpart. The privacy condition of the digital twin can be useful to separate externally retrievable and private data. But all in all, this whole system comes down to the simplified essential requirement of providing the **same in- and output** of the real asset and corresponding digital twin, as shown in Fig. 3.

Figure 3: Simplified equality of asset and digital twin

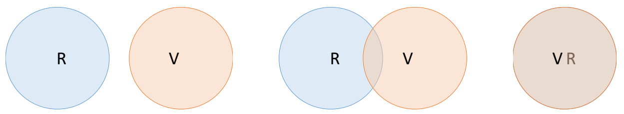
Interfacing Digital Twin and Real System

The User Interface (UI) is the layer where interactions between human users and the VTB occur. This inte-

[1] https://www.leapmotion.com

raction includes the **input** to and **output** from the system.

I/O Technologies
The input can be categorized in terms of different input device technologies, like "controller-based", "optical", or even "haptic" devices. Fong et al Fong and Thorpe (2001) already defined major interface types for (vehicle) teleoperation, where they named VR and haptic interfaces "Novel". Such a novel haptic feedback in 3D simulation is quite rare in current research and can mostly be found in rehabilitation applications. Regarding teleoperated robots, we already conducted this approach using a customized exoskeleton and VTBs in Cichon et al. (2016a).



(a) VR (b) AR (c) MR

Figure 4: Distinction and fusion of virtuality (V) and reality (R) based on data source

The output of the system in state-of-the-art 3D simulation tools is mostly done on standard monitors but can also be extended to "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 like in Fig. 4.
Although it is not directly part if the user interface itself, to bridge the gap from user to real system, the interface between VTB and final hardware is of course also important. As the mostly used middleware in robotics we use the Robot Operating System (ROS). A first introduction about ROS is given in Quigley et al. (2009), whereas in Muratore et al. (2017) a real-time capable approach of mobile robotics is presented which can also be integrated in different 3D simulator software.

Using Simulation In-the-loop
Although the use of simulators in-the-loop or even as a mediator is quite limited, the general approach of using models for teleoperation is an ongoing research topic. Willaert et al. (2012) discussed the approach of model-mediated telemanipulation especially with the goal of stability assurance. Special focus is put on the model consistency (model adjustments versus discrete model jumps) where they underlined the power of using models for prediction. The approach of using so-called mental models for human robot interaction is motivated in Sheridan (2016) and brought to application in Cichon et al. (2016b) as an conceptual extension of VTBs towards simulation-based control and support.

UI Software
A general support operator setup during teleoperation of mobile robots can be found in Schwarz et al. (2017), where they also give a current view on the application site of mobile robotics utilizing ROS functionalities. Such visualization comprises different tools to visualize for example (a) live images, (b) 3D point clouds, (c) command line error log, (d) actuator diagnostics, (e) 2D height map, (f) network statistics, etc. An introduction to operator interfaces utilizing AR and VR is given in Roßmann et al. (2010), where special visualizations are applied in search-and-rescue applications.

UI Hardware
Using state-of-the-art technology as input devices for robotic control was already done in several fields of research. The evaluation and analysis of the devices themselves, comparing specifications, and their use in various fields of application are the main foci of research. Regarding the *LeapMotion* sensor Weichert et al. (2013) use an industrial robot to analyze the devices' accuracy and repeatability, whereas Guna et al. (2014) combine the technology with high-precision motion tracking to show the prospects and limits of *LeapMotion* as a professional tracking system. In the application field of ambient assisted living Bassily et al. (2014) use the *LeapMotion* for human-robot interaction for elderly or physically impaired people. Gromov et al. showed in Gromov et al. (2016) the use of a gesture recognition bracelet using IMU and EMG signals of the user's arm, namely *Thalmic Labs MYO*[1]. The *MYO* was used to control multiple mobile robots by speech, arm movement, and hand gestures to select, localize and communicate task requests and spatial information.

CONCEPT

Although the concept of simulation-based cognitive man-robot collaboration encompasses more, we will focus here on simulation-based UI and thus the in- and output of the VTB to develop, use, explore, and analyze digital twins in VTBs. Thus, we will present the four main compartments: Fusion of real and virtual data, natural and intuitive UI input, flexible and feasible UI output, as well as fast and simple data analysis throughout the whole life cycle of a system.
Combining real and virtual information can lead to a new approach on how to use and interact with complex systems. Diving into virtual worlds instead of just looking at (raw) data on a monitor can create a deeper sense of **immersion**. This immersion can then be enhanced by using the correct UI in terms of hardware and software.
Although keyboard and mouse are naturally not the most **intuitive input devices** on the market, long year

[1]`https://www.myo.com`

usage led to a widespread acceptance and intuition of the user and thus simple buttons and mouse movements can be the method of choice for intuitive UI. Going one step further, the most natural interface of a human operator is mostly his body and especially his hands. Thus, we want to include new UI hardware which support body/finger tracking and even force feedback.
Due to the human fixation on seeing and feeling things, audio- visual- and haptic- **feedback** are core elements of new user interfaces. Haptic feedback in Virtual Testbeds, applied on exoskeletal teleoperated mobile robots has already been presented in Cichon et al. (2016a), and will only be addressed briefly in the scope of this paper. Additional help by visual means will be addresses regarding rendering techniques, as well as feasible data representations. Although audio feedback is also helpful, we will address this (for now) just mediated by the real system directly and not via 3D audio simulation.
Within the scope of such new user interfaces we want to be able to **explore** the digital world. This comprises the exploration of the digital twin itself, but also in the direct sense of exploring environments with the help of VTBs. This can then be used prior to fabrication of the system by testing and optimization, as well as "online" during the use of the real system. Additionally, VTB functionalities, like logging presented in Atorf et al. (2015), can be used for a post-mission wrap-up and evaluation. Overall, generating such new user interfaces for VTBs enables us to predict possible outcomes and answer some "What if...?" questions ahead to their execution.

IMPLEMENTATION

The following section describes the implementation of the proposed concept. This covers the Input/Output hardware with an integration layer, the visualization of data, and the final setup of an ideal user interface for a given application utilizing real and virtual data.

Input/Output

We implemented a generic integration of different UI hardware to use the full spectrum of VTBs, utilizing all internal frameworks. 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 for example the Rigid Body Simulation (RBS), the Sensor Simulation (SS), the Rendering (R), or the ROS framework (see Fig. 5).
For now, we have implemented the *LeapMotion* sensor, *Thalmic Labs MYO* wristband, and even haptic input devices like the *Geomagic Touch X*. Due to the fact that all input devices are implemented following the same scheme we will present the **LeapMotion** sensor exemplary in the following in more detail.
From the user perspective the point of origin is one *Leap-*

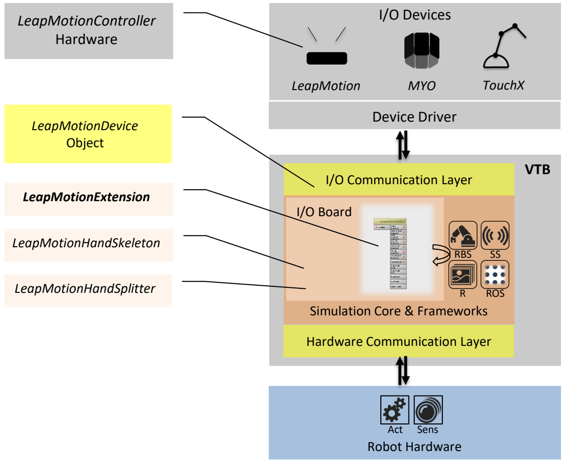


Figure 5: Implementation Scheme of a variety of I/O Devices, especially the *LeapMotion* Sensor

MotionExtension, which can be added to any 3D model in a VTB. This Extension holds an object *LeapMotionDevice* in the I/O communication layer. The *LeapMotionDevice* can then establish the communication to one *LeapMotion* sensor, with the *LeapMotion* SDK and the device driver. It polls the current data (frames, hand exoskeleton, ...) from the sensor, which are directly relayed to the Extension where the data types are converted and written to the I/O-board. With this scheme all hardware dependencies are encapsulated in one object which can also be transferred to a separate thread for example.
Using the I/O board of the VTB we can then access all data of the extension. Additionally, we can connect each property to another I/O board of the same type. To simplify these connections it is even possible to extend the I/O data types with a *LeapMotionHandSkeleton* which can be transmitted to a *LeapMotionHandSplitter* node handling the mapping. For example, we can use the hand frame of the *LeapMotion* to move the frame of the Schunk hand, and connect the phalanges position (via the splitter node) to rigid body based motors to move each finger according to the user's hand movement.
Additional information of the sensor, like raw data or an included gesture recognition, can then also easily be incorporated in the I/O framework. This leads to an infinite amount of possibilities to connect single or multiple gestures to all aspects of simulation. One example would be the direct control of the Schunk hand, only if the *MYO* wristband recognizes a "fist" gesture.

All in all, such "natural" UI hardware increases the so-called **embodiment** of the user. This embodiment is supported by visualizing the human body in VR (cp. Fig. 6), which is very important for an intuitive use.
As a further step, it is also possible to use the ROS inter-

face (presented in Cichon et al. (2016c)) to connect the VTB with ROS-compatible hardware. Thus, the UI hardware can directly be used to interact with real systems by connecting the I/O Board to the ROS framework. Consequently we can directly control ROS-capable hardware, like for example the real *Schunk Hand*, mediated via the VTB.

Data Visualization

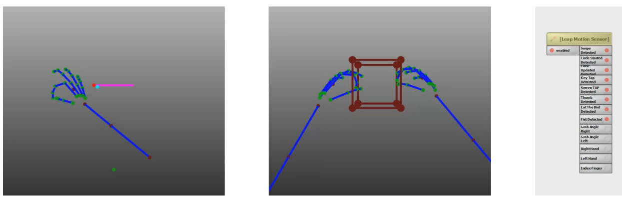
We extended the scope of the visualization framework and expanded its capabilities to support stereoscopic VR goggles. This led to the possibility to define customized head-up-displays for monitor or VR views and project costmaps or occupancy grids into the 3D scene. Additional immersion could be achieved by using a live ROS audio stream, directly transmitted to the user. With respect to the aforementioned state of the art in teleoperation and visualization and the GUI of Schwarz et al. (2017) we can incorporate parts of it within the VTB and also push selected information into the view of a first person operator with a stereoscopic headset.

Fusion of Reality and Virtuality

Utilizing the aforementioned Input/Output and visualizations it is now possible to design a customized user experience for a given application. This includes the choice of an adequate input hardware selection (which can also be a combination of multiple hardware devices), and a customized visual head-up-display.
Combining visualization and input devices with gesture recognition we can even move and place user interfaces in the 3D scene. One prominent example is using the 'bloom' gesture to show an interface which then can be used to edit some properties.
Due to the used implementation and the underlying VTB it is now also possible to choose which data source to use, virtual or real.

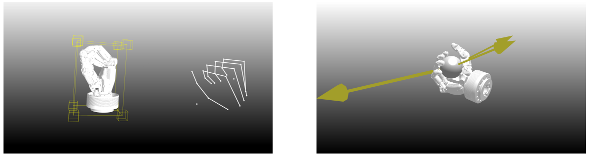
APPLICATIONS

Applications for using simulation-based user interfaces for digital twins range from single aspect to whole processes and systems in their development, assessment, or in use. Of course, the first aspect of using such new input devices is to model something in the 3D world. This comprises simple geometric modeling of boxes (see Fig. 6b) but also virtual interactions like buttons or sliders (see Fig. 6a).



(a) Interaction: Slider (b) Modeling (c) I/O Board

Figure 6: Leap Motion Extension used for modeling



(a) Movement and Grasping Types (b) Force Mangnitude and Contact Evaluation

Figure 7: Manipulation Force Analysis

The aforementioned manipulation and grasping scenario is one aspect of the CENTAURO project[1]. Thus, before an exoskeleton is manufactured or the real *Schunk Hand* is not at hand, it is possible to use the *LeapMotion* with the digital twin to evaluate grasping forces in simulation first (see Fig. 7).
The overall goal of the CENTAURO project is to develop a human centered teleoperated mobile robotic system for disaster scenarios. Besides a robust and dexterous robot, one main focus is on the UI to reduce the workload of the operator. Using the simulation-based UI, the operator should be able to inspect all necessary information as he needed visualized in a VR goggle. Additionally, he should be able to switch from the direct control of the real system to its digital twin in the VTB which uses the real sensor input to generate an environment model in the rigid body simulation. Switching into VR then allows to test possible actions safely first, before execution in reality.

Such new user interfaces can also be used in industrial application. One example is the monitoring of assembly processes. Here, the VTB can be used to visualize internal critical parameters prior to failure, or can be used in AR to show possible alternative processes.

CONCLUSION AND OUTLOOK

Taking everything into consideration, we have presented a holistic UI framework which is already in use for a set of UI hardware visualized on VR hardware. It comprises multiple input devices using the same implementation scheme and interface layer no matter if controller based (*MYO*), optical (*LeapMotion*), or even haptic (*Touch X*). It enables feasible data visualizations even for stereoscopic or dynamic user interfaces. Finally, a modular integration into the VTB allows access to all other frameworks incorporated into the 3D simulation system, independent of the application. Combined with a ROS hardware interface for a direct connection and feedback loop this is already in everyday use. The coinciding pos-

[1] `https://www.centauro-project.eu`

sibilities and the modularity of the overall implementation leads a more immersive and embodied experience interfacing complex systems. It becomes more natural to evaluate systems and explore their use and the virtual world itself in VTBs, enabling the user to analyze the system pre-, in-, and post operation.

Besides various other prospects, we already initiated developments of using these UIs and VTBs in AR or MR hardware in industrial applications, which seems to be very promising. Using the developed UI framework in the *Microsoft Hololens* or the *Vuzix M300* could lead to a good collaboration of industrial robots and humans, working side by side. Assembly processes, workplace optimizations, or worker guidance with the help of VTBs are just some examples of the possible applications.

ACKNOWLEDGEMENTS

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