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Connecting the Areas of eLearning, Virtual Training and Engineering in Multidisciplinary eRobotics Applications

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***Abstract*—The recent trend of Virtual Reality (VR) already found its way into entertainment and scientific applications. While current entertainment domains fully exploit the technical possibilities of modern graphics hardware and state of the art rendering approaches, many VR simulation system in scientific contexts put the focus on numerical results with rather functional representations. The objective of the novel research field of eRobotics is to effectively use electronic media to achieve the best possible advancements in the development of robotics-related applications. Corresponding eRobotics systems take the step from rather functional scientific simulations to attractive demonstrators using VR technologies, which can not only be applied in motivating eLearning scenarios but also in full-featured engineering applications in the context of virtual testbeds and cyber-physical systems. In this paper, we will introduce concepts and system structures that provide new opportunities for the development of a complex but comprehensive multidisciplinary development support tool. A broad range of practical applications in different domains will demonstrate the benefits of connecting the areas of eLearning, virtual training and engineering in a holistic eRobotics system.**

Keywords*—*Virtual Reality; eLearning; eRobotics

I. Introduction

Industrial production is getting increasingly complex due to globalization, product individualization, shorter product life cycles and volatile markets. The ever increasing complexity of corresponding technical and mechatronical systems demands highly optimized development processes. Due to the potential improvements with respect to cost and development time reduction, simulation systems became an indispensable part in research and in development. Cyber-physical systems (CPS) and the 4th industrial revolution (Industry 4.0) are two leading infrastructures for managing data and leaning toward more efficient production in current industry [1][2]. Key concepts of both infrastructures are sensing and communication to enable the system to gain self-awareness and self-predictiveness [3]. The same implies for corresponding software structures and simulation systems, which should be able to simulate corresponding technical systems and processes to support the development and commissioning process. These simulation systems have to simulate a large number of subsystems and their collaboration to simulate the system as a whole, particularly in robotic applications. This not only includes rendering and visualization capabilities but also the realistic simulation of various physical processes, e.g. the close-to-reality simulation of a broad range of sensors.

This contribution is motivated by the demand for a holistic and comprehensive multi-purpose tool for the application in a wide range of domains dealing with robotics. We present novel concepts for system and data structures that enable the realization of a unifying approach based on the ideas of the research field of eRobotics [4], a newly evolving branch of eSystems engineering. eRobotics applications are complex enough to be used as a full-featured engineering development tool on the one hand, and comprehensively to work with on the other hand; as a result, these systems are no longer just a domain for a small community of simulation experts. Even complex engineering applications can be coupled with an edutaining part, making the usage easy, enjoyable and suitable for attractive virtual training and eLearning scenarios. Fig. 1 shows a selection of current eRobotics applications in multiple domains using state of the art VR hardware, which range from interactive multi-screen stereo projections up to fully immersive CAVE environments.

Fig. 1. Examples of currently realized eRobotics applications in different domains using modern VR technologies.

These systems can be classified into the family of ”Multi-Domain VR Simulation Systems”; however, corresponding systems in scientific contexts mostly put the focus on numerical results with rather functional visualizations. In order to realize multidisciplinary VR simulation systems based upon the principles of eRobotics that bridge the gap between scientific simulators and aesthetic computer graphics, new concepts and system structures for the underlying software design were necessary. While eLearning applications obviously benefit from modern computer graphics with respect to user acceptance and motivation, a unifying approach offers new opportunities and chances to lift scientific multi-domain VR simulation systems to a new level. Simulation results are no longer solely represented in a functional way, they can interactively be explored in an intuitive, almost playful fashion in highly attractive virtual environments. By closely tailoring together simulation and rendering modules, arising synergy effects can further be used to apply advanced rendering techniques to directly support certain simulation tasks like optical sensor simulations. Newly developed robot systems and corresponding approaches can be experienced and further enhanced during a virtual test drive under realistic conditions before they are actually tested in real world testbeds. Similarly, these complex virtual testbeds can directly be presented to students or stakeholder to interactively demonstrate technical details, challenges or solutions. Last but not least, the vital role of high quality demonstrations of project ideas and results in attractive virtual worlds as a sales argument for possible follow-up projects must not be neglected.

This paper is organized as follows: Section II addresses related work regarding the aspects of eLearning in engineering domains and VR simulation systems in robotic domains. In Section III, the concepts of eRobotics systems and matching system and data structures are detailed. Section IV shows a broad range of currently realized eRobotics applications in multiple domains that emphasize on the successful combination of eLearning, virtual training and engineering in a holistic system structure. Finally, Section V concludes this contribution and suggests future work.

II. Related Work

A. eLearning in Engineering Domains

In CPS and in Industry 4.0, virtual training and eLearning applications become more and more important due to the wider range of responsibilities of workers in an extended problem domain. An example for an adaptive learning assistance systems in smart factories was presented by Gorecky et.al. [5]. Considering eLearning scenarios in the university environment, the concepts of Gamification are a popular trend to address the attention of students. The term ”Gamification” was coined by N. Pelling in 2003 and has risen as a trend around 2010. Today, it is used in various areas from business to education to give instant feedback and to boost productivity and motivation. A study of G. Barata et al. showed that gamification as motivation for engineering students showed clear benefits over non-gamified courses [6]. A systematic literature review that addresses gamification in the context of engineering education is given by Morelock [7]. M. Wardaszko noted that the most interesting thing would be using a combination of simulation and gamified courses [8].

B. VR Simulation Systems in Robotic Domains

In the field of mobile robot simulations, well known systems are USARSim [9], Player/Stage/Gazebo [10], ROAMS [11] or WeBots [12], which are applied in a broad range of research and development projects. In addition to physics simulations and rigid body dynamics, they also feature the simulation of various sensors, which are essential for mobile robotics applications; however, the virtual environments used for testing and evaluation are usually purely functional. They are limited to a single scenario like an indoor environment with several rooms, an alleyway with several houses or a small outdoor environment, as illustrated in Fig. 2. Only a few published works try to realize more realistic environments [13] [14] and state of the art rendering techniques are rarely applied. An in-depth comparison of these systems is given by Staranowicz and Mariottini [15].

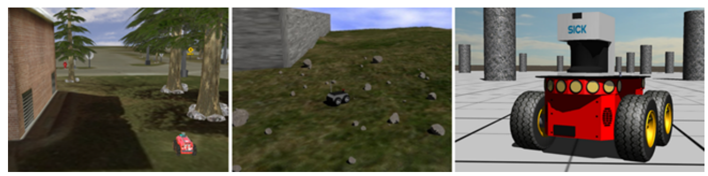

Fig. 2. Screenshots of current mobile robot simulators, which demonstrate typical testing environments. Left: USARSim, middle: Gazebo, right: Webots. Images taken from the developers’ websites.

III. Concepts and Implementation of eRobotics Systems

The novel research field of eRobotics has been established recently [4]. Its objective is to effectively use electronic media to support and enhance processes in the development of advanced robotics applications. This also incorporates state of the art rendering techniques and the use of modern VR technologies to efficiently represent and make available the inherent capabilities of a robotic system to experts and people not familiar with the specific area of expertise. As illustrated in Figure 3, eRobotics applications cover all aspects of VR. Attractive virtual environments not only support eLearning scenarios by helping to understand complex mechanisms and correlations in an intuitive manner, such systems are also complex enough to be used as a full-featured engineering tool to support the development process or act as a decision support system (DSS) in an early concept phase [16] [17]. Which kinds of sensors are best suited to fulfill the requirements of the developed system? What level of measurement errors is acceptable to achieve satisfactory results? What error rate can be tolerated before the results start to worsen? Which approaches can be implemented in order to make the developed system more robust? eRobotics applications should provide engineers with a software tool to answer these questions right from the beginning of the development process.

The combination of accurate simulations and a modern rendering framework is a key feature of eRobotics systems. Modern software design patterns, as well as the concepts of semantic world models and graph databases provide new opportunities for the development of a new class of modern multi-domain VR simulation systems. In order to combine various data structures and components from different simulation

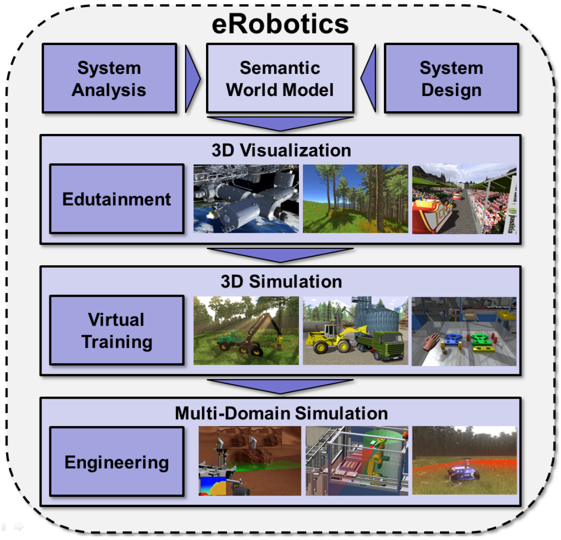

Fig. 3. eRobotics systems cover all aspects of VR. Model descriptions are based on semantic world modeling.

and rendering domains in an efficient manner, a flexible data description and system structure is vital.

A. *Semantic World Models as Basis for eRobotics Applications*

As illustrated in Fig. 4, the key idea of eRobotics systems is to base simulation and rendering components on a central semantic database. This approach grants the close interplay between all modules involved. Each module can define its own view to the database and integrate subgraphs to meet its specific data structure requirements. The semantic database also acts as connecting element between the simulation and rendering framework and grants the inter-communication between them. A multi-graph can be created by adding references to other elements, thus defining additional arbitrary sets of edges within the database.

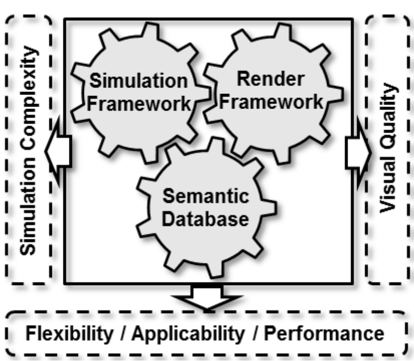

Fig. 4. Illustration of the interplay of the three major components of an eRobotics system.

Semantic world models provide a powerful basis to combine different data structures in a single system database. Corresponding models are stored in schema-aware graph databases that contain elementary facts and rules and allow a set of nodes with dynamic attributes to be arbitrary linked to other nodes through edges [18]. In contrast to predefined data structures like scene graphs, semantic world models can describe the environment much more detailed and are not limited to spatial relations or geometry. They can contain almost any kind of data. In order to make graph databases practical for software systems, they can be realized following the object-orientated paradigm. These kinds of databases are known as graph-oriented object databases (GOOD) [19].

The database concept presented so far is completely passive and must be polled to check for data modifications. In object-oriented systems, active data structures are usually implemented by using call-back functions; however, call-back functions create dependencies between the involved modules. A popular approach to realize interconnected software structures with minimal dependencies is the decoupled observer pattern realized through the signal and slots pattern as implemented by the Qt framework [20]. The signal slot pattern not only allows to react to state or data changes, it further allows to react to almost any event in a system. Signals can be sent when the object is created or destroyed, when a certain user interaction occurred or when a simulation task reaches a defined progress. By integrating this functionality directly into the database's basic instance, an active, graph-oriented object database can be realized that fully complies the requirements of the micro-kernel architecture. The difference to common, passive systems is illustrated in Fig. 5.

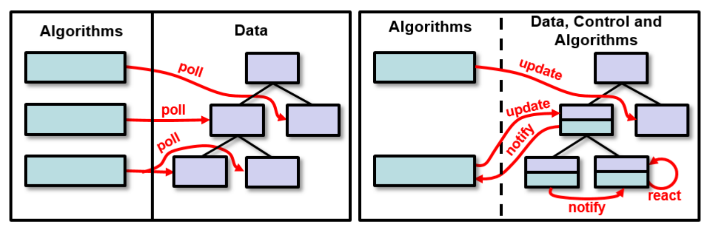

Fig. 5. Left: common, passive system structure. Plugins provide algorithms that poll data stored in the database. Right: system based on an active, event-driven database.

The system architecture needs to be as flexible as the database to face the challenges of changing conditions, which makes a modular architecture indispensable. The micro-kernel pattern is a very popular approach to address the complexity problem. Originally developed for operating systems and embedded systems [21], it can also be applied to software systems that have to be able to adapt to changing conditions. The main idea is to separate a minimal functional core from extended functionality and project-specific parts. As illustrated in Fig. 6, the microkernel defines the very basic structure of the framework and also serves as a socket for plugging in extensions and coordinating their collaboration. Regarding the presented eRobotics system, this micro-kernel is called the Versatile Simulation Database (VSD) [22]. Fully implemented in C++, the VSD further provides the central building blocks for data management, meta information, communication, persistence and user interaction. Plugins integrate new functionality and extend the database with the definition of new elements. For example, the 3D geometry renderer defines nodes required for rendering purposes (VSD3D). The VSD builds a powerful basis for the realization of a wide range of different applications. The main elements are nodes and extensions, which build the basis for varying data structures required for multidisciplinary applications. While nodes build the main element to construct the graph database, extensions can be attached to any element in order to add domain-specific information or mark the element for further handling by interested plugins.

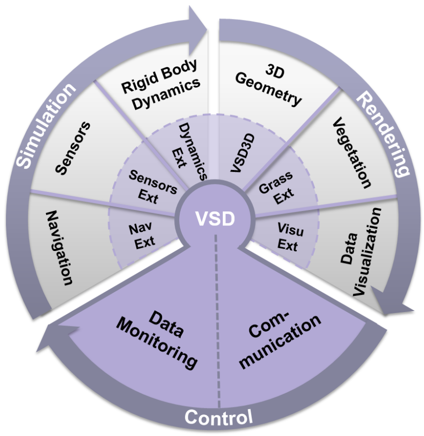

Fig. 6. The micro-kernel design pattern of the eRobotics system. Plugins can extend functionalities with new algorithms and self-defined database elements.

B. Efficient Rendering on Semantic Datasets

Real-time rendering frameworks are highly advanced and optimized software toolkits that rely on optimized data structures in order to perform best and to efficiently integrate state of the art rendering techniques. Semantic databases usually do not comply with these requirements; hence, it is still a challenge to combine both areas and similarly maintain the flexibility and description power of semantic databases as well as the rendering performance achieved with scene graph structures. To address this issue, Mendez et al. suggested to separate semantics from rendering in the scene graph by using semantic tags as attributes [23]. Recently, Tobler picked up this idea and suggested a more complete solution by fully separating semantics from rendering [24]. He introduced a split scene graph architecture containing a separate semantic and rendering scene graph as illustrated in Fig. 7

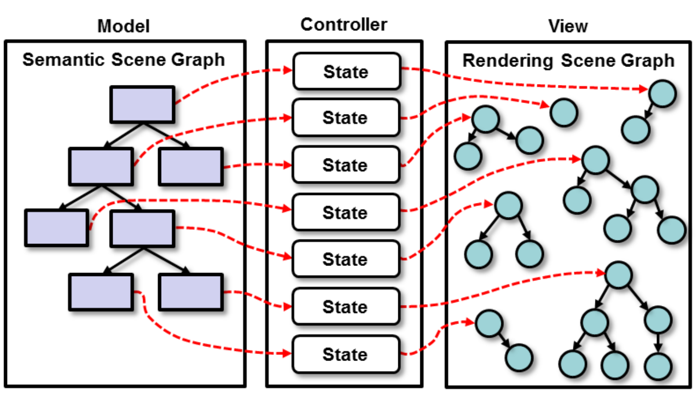

Fig. 7. Illustration of the split scene graph approach to separate semantic from rendering data, following the Model-View-Controller (MVC) design pattern.

As illustrated in Fig. 8, the semantic eRobotics database can be seen as the model regarding the MVC design pattern. This model doesn't imply system-specific requirements and only describes the content of the scene in some way, e.g. like the user has modeled it or like it was imported from an external data source. As demanded by the MVC design pattern, the model has to be uncoupled from system-specific implementations as far as possible. In order to do so, plugins not only extend the database with new elements, they further provide a set of rules that allow to transform these elements into system-specific views, optimized for a specific graphics API like OpenGL. For example, the 3D geometry plugin defines a set of semantic nodes (VSD3D), which contain basic nodes such as geometric elements, texture nodes or material nodes that can be used to model the scene in a "natural" fashion. A set of rules (controller) is also defined by the VSD3D that transform the semantic nodes into a rendering-optimized data structure (view) automatically, using the data monitoring possibilities provided by the VSD. The used models are completely decoupled from system-specific requirements. This technique enables ease modelling and the efficient integration of modern rendering techniques, ranging from realistic ground vegetation over weather effects up to advanced data visualization techniques [25].

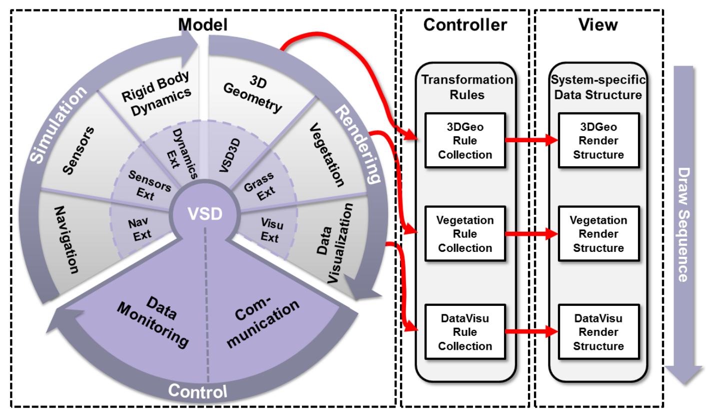

Fig. 8. Illustration of the system's micro-kernel architecture in combination with the MVC design pattern. Plugins can extend functionalities with new algorithms and self-defined database elements. Defined rules transform the semantic graph into system-specific data structures for efficient rendering.

C. Rendering-Supported Optical Sensor Simulations

The developed simulation system features a sensor framework that enabled the convenient development of applications with sensor support [26]. The presented rendering framework can actively support the simulation processes. Considering the simulation of optical sensors, the arising advantages are twofold. First, a realistic looking virtual environment directly enhances realism when using the rendered images as input for digital camera simulations. Second, advanced rendering techniques can be applied to simulate other optical sensors, such as time-of-fight (ToF) cameras or laser range scanners (LiDAR) with high accuracy. As illustrated in Figure 9, an application can request a sensor data stream through a sensor abstraction layer, which triggers a simulated or a real world sensor and provides the acquired data to the application for further processing. In an ideal case, the application performs similarly with the simulated and the real world data. The general simulation process consists of a simulation plugin, which applies rendering techniques and data provided by the rendering framework to support accurate real-time sensor simulations.

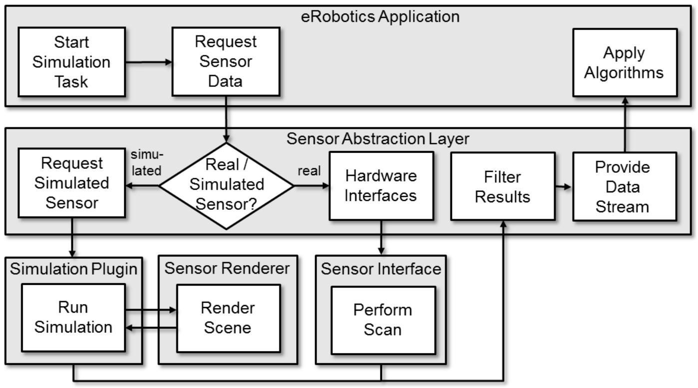

Fig. 9. A hardware abstraction layer is used to decouple application development from the applied sensors, regardless if real world or simulated ones.

The possibilities for the accurate real-time simulation of a broad range of optical sensors has been detailed in a recent publication [27]. Figure 10 shows the results of a LiDAR simulation compared to data acquired from a physical testbed. Areas that lead to measurement errors due to their reflection properties are marked in red (e.g. the highly reflective metal rails). These areas could not been identified correctly without the usage of rendering information and techniques and, consequently, could cause instable behaviors in real world applications.

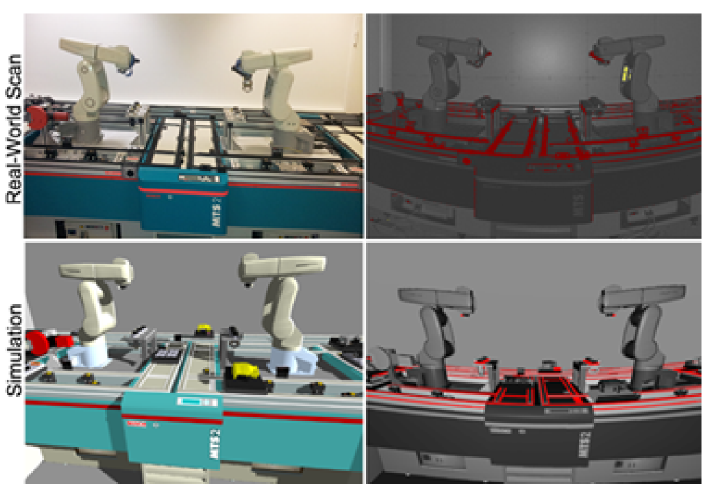

Fig. 10. Comparison of a real world and a simulated intensity image of a 3D LiDAR scan of a robot workcell. Areas marked in red illustrate scanning errors.

Fig. 11 shows a simulation of the Seekur Jr mobile robot equipped with various optical sensors. This simulation is currently used as a testing platform for virtual development and testing of navigation and mapping approaches [28]. The realistic virtual environment as well as the accurate mapping of typical measurement errors observed with current ToF sensors, e.g. noise and flying pixels, lead to simulated sensor data streams that are comparable to those acquired from real world scans.

Fig. 11. Simulation of the Seekur Jr mobile robot platform equipped with a 2D LiDAR scanner, a stereo camera and a ToF camera for virtual testing and development of navigation and mapping approaches.

IV. Applications

A broad range of eRobotic applications have been realized that connect attractive eLearning scenarios with virtual training and engineering tasks. In this section, a selection of applications in the domains industry, environment and space are introduced.

A. Industry

The first examples are related to large scale virtual factories, as shown in Fig. 12. The left image shows a simulated production line that has been modeled and simulated in the context of eSystems engineering. It illustrates the capabilities of newly developed production lines in an interactive eRobotics application. The simulation was developed in coordination with our industrial partners and acts as attractive demonstrator for the testing and presentation of novel production processes. The right image shows an eRobotics application for the development and testing of an autonomous, LiDAR-based transportation system in an associated automated warehouse. In a corresponding eLearning scenario, engineering students are motivated to develop optimized path and resource planning or obstacle avoidance strategies, which can directly be integrated into the simulation scenario in order to gain instant feedback.

Fig. 12. Examples of industrial eRobotics applications, which show scenes of a simulated production line and an automated warehouse.

The presented eRobotics system supports multiple state of the art VR devices. The top left image of Fig. 1 already showed an interactive multi-screen stereo projection for virtual training in industrial applications. Fig. 13 shows a virtual inspection of a fully simulated digital factory in the aixCAVE. The aixCAVE is a five-sided immersive Virtual Reality environment built at the IT Center at the RWTH Aachen University in 2012 [29]. With a projection size of $5.25m$ x $5.25m$ x $3.30m$, it is one of the biggest Virtual Reality labs in the world. The 360 degree view in combination with head tracking and active stereo leads to a nearly perfect immersion, where objects seem to freely float inside the projection room. Due to the room size of approximately $30m^2$, users can actually move around in the virtual scene in a natural manner, giving the impression of being part of the simulated environment.

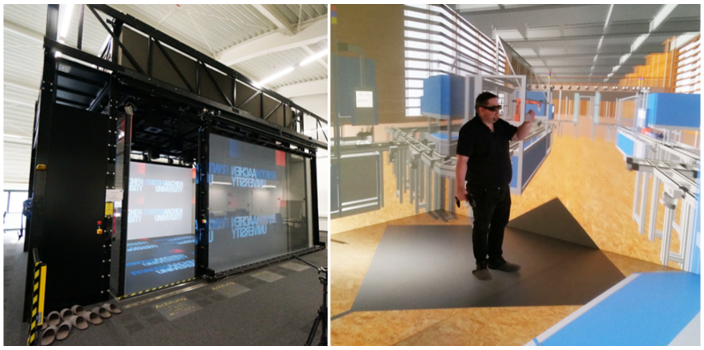

Fig. 13. Left: picture of the aixCAVE, one of the world's largest Virtual Reality labs. Right: virtual inspection of a simulated factory.

B. Environment

Considering mobile robotics applications, realistic, large scale virtual models of outdoor scenarios are vital for the accurate testing of newly developed robot systems and approaches. Corresponding examples have already been shown in the top right image in Fig. 1 as well as in Fig. 11. This cost-efficient way to develop mobile robotic applications can act as an adequate replacement for physical testbeds in early project phases in order to make the developed approaches more robust before testing them under real world conditions. Since no real world prototypes are required in the development phase, these eRobotics applications are also suitable for student projects. Students can experiment with different sensor types and robot platforms to virtually develop novel navigation and mapping approaches.

To generate large scale testing scenarios with little effort, the presented semantics-based eRobotics system architecture enables the usage of readily available data as provided by Geographic Information Services (GIS). GIS servers are widely available to the public nowadays; however, corresponding data usually contain only minimal geometric information such as the terrain geometry or surface textures. They provide a lot of semantic information that describe the environment more detailed, e.g. with digital elevation models (DEM), satellite imagery, land coverage, infrastructure or even weather conditions. Multiple semantics-based render modules have been developed that interpret this data and integrate corresponding effects, such as realistic ground vegetation or a dynamic sky with clouds and weather effects. These scene descriptions have the potential to go way beyond common, hand-modelled digital environments regarding realism, accuracy, scale and rendering quality. Example are given in the top row of Fig. 14.

The middle image of the figure shows the currently developed wood harvester simulator. Instead of using manually created models, the simulator imports relevant data directly from GIS servers to generate a realistic virtual mapping of the real environment; hence, the machine operator can not only be trained in a realistically looking virtual environment, it further represents the area that he or she will later work in.

The bottom images of Fig. 14 demonstrate the aspects of knowledge transfer as well as the possibilities of early, visually

Fig. 14. Top: outdoor environments rendered with state of the art rendering techniques. Middle: virtual training with a wood harvester simulator. Bottom: virtual testbed for the development of a LiDAR-based wood harvester navigation system and real world setup that was realized after detailed testing and optimization in the eRobotics application.

attractive presentations of project ideas and first results with low effort. The basic idea of the project was to mount 2D laser scanners on a wood harvester to develop a wood harvester navigation system. This navigation system should support the machine operator by guiding him to selected trees in the stand marked for felling in order to improve the wood harvesting effectiveness. With the help of the close-to-reality virtual forest models, the simulated LiDAR scanners and the computer vision algorithms developed with the Seekur Jr testbeds shown in Fig 11, a fully functional simulation of such a harvester was created within a short period of time. The simulation was used to vividly demonstrate the possibilities and advantages of the project ideas in an attractive virtual environment. Subsequently, the simulation models and approaches were refined for efficient testing of the newly developed algorithms before they were applied to the real wood harvester, as illustrated in the lower right part of Fig. 14. Due to high running costs of the real harvester and the little time it was available for testing reasons, it becomes clear that the project strongly benefited from the developed eRobotics application.

C. Space

Even though nature environments as introduced in the previous section build the basis for a broad range of robotics applications, many more domains are currently covered by the presented eRobotics system. Simulations and virtual testbeds are of significant importance in domains that do not allow for real world testing at reasonable costs. Space and extraterrestrial environments are typical examples for these hardly accessible domains; consequently, novel systems or experiments to be carried out heavily rely on simulation technology to develop and test the components and to train corresponding procedures; hence, space robotics are a key domain for eRobotics. Currently realized space applications range from novel satellite design studies over the simulation of rovers for planetary explorations up to a simulation of the International Space Station (ISS). Last but not least, space, extraterrestrial environments and systems that are operate in these domains have always fascinated people, which makes this domain predestinated for edutainment and eLearning applications to comprehensively explain technological challenges and corresponding solutions.

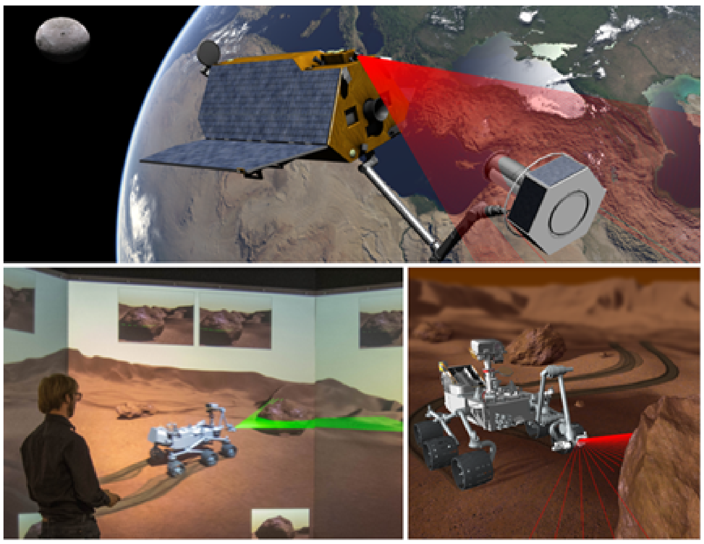

Fig. 15. Examples of currently realized eRobotics applications in space environments.

The top image of the Fig. 15 shows the simulation of a satellite on-orbit-servicing (OOS) mission. It illustrates a novel design concept of a servicer satellite that can capture and repair defective components in a client satellite or initialize controlled deorbiting of space debris. Different sensors, such as space qualified LiDAR and digital camera systems are applied to locate the target. The shown scenario is a good example to illustrate the challenges of a multidisciplinary eRobotics system. It combines multiple technical domains, such as the dynamic simulation of the satellite and the robot manipulator, the simulation of the corresponding control algorithms as well as the simulation of various sensors, which need to be considered in order to achieve the desired mission goal.

The bottom image of Fig. 15 shows a simulation of the current Mars rover MSL in an interactive multi-screen stereo projection. The rover simulator was firstly intended as a "gamified" edutainment and eLearning application, where students can take over the control of the rover and interactively explore a highly realistic model of the Mars surface in order to fulfill goals, e.g. taking surface samples or scanning and mapping specific parts of the environment. Currently, the model is further used in multiple projects that aim to develop and test planetary landing missions, rover navigation approaches as well as the development of novel rover concepts. Knowledge and approaches gathered and developed in previous projects can be transferred from industry and forest scenarios to space robotics domains with little effort.

Finally, Fig. 16 shows pictures of the latest implementation of a virtual galaxy as part of a highly immersive space journey in the aixCAVE. The Virtual ISS shown in the top image is a highly detailed model of the International Space Station, where students can do a virtual space walk and get a life-like experience as an astronaut. In addition to the ISS, students can virtually visit several planets and inspect different satellites orbiting the earth.

Fig. 16. Pictures of a virtual space journey in the aixCAVE.

V. Conclusion

In this contribution, we presented the concepts of eRobotics and a corresponding holistic and comprehensive multi-purpose tool for the application in a wide range of applications dealing with robotics. eRobotics can be seen as a bridging element to overcome structural limitations of current multipurpose VR simulation systems by applying the concepts of semantic world modeling, micro-kernel-based system design as well as a central, active graph database. The unifying approach of eRobotics systems combines the benefits of scientific simulations, aesthetic computer graphics and state of the art Virtual Reality devices to create interactively explorable, highly attractive engineering applications. Due to the close interplay between simulation and rendering modules, rendering-supported optical sensor simulations that provide close-to-reality sensor data streams could be realized. The presented range of practical applications further demonstrated that the unifying eRobotics approach combined with aspects of gamification make scientific engineering applications suitable for realistic virtual training and motivating eLearning scenarios. Our future work will concentrate on the application of the concepts of eRobotics to further application areas and interdisciplinary domains, e.g. scientific data visualization. The shown eRobotics applications already demonstrated that a modern multi-domain VR simulation system can similarly provide accurate simulations at a scientific level as well as attractive, high-quality visualizations for comprehensive presentations of the results. The outcome is an intuitive, easily expandable multi-purpose development tool that successfully connects the areas of eLearning, virtual training and engineering.

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REFERENCES

[1] J. Lee, B. Bagheri and H.A. Kao *Recent Advances and Trends of Cyber-Physical Systems and Big Data Analytics in Industrial Informatics*. 12th IEEE International Conference on Industrial Informatics (INDIN), Porto Alegre, Portugal, 2014.

[2] J. Schlick *Cyber-physical systems in factory automation - Towards the 4th industrial revolution*. 9th IEEE International Workshop on Factory Communication Systems (WFCS), Lemgo, Germany, 2012.

[3] R. Baheti and H. Gill *Cyber-physical Systems*. The Impact of Control Technology, T. Samad and A.M. Annaswamy (eds.), IEEE Control Systems Society, available at www.ieeecss.org, 2011.

[4] J. Rossmann, *eRobotics: The symbiosis of Advanced Robotics and Virtual Reality Technologies*. 32nd ASME Computers and Information in Engineering Conference, vol. 2, pp. 1395-1403, Chicago, USA, 2012.

[5] D. Gorecky, M. Schmitt, M. Loskyll and D. Zhlke *Human-machine-interaction in the industry 4.0 era*. 12th IEEE International Conference on Industrial Informatics (INDIN), pp. 289-294, Porto Alegre, Brazil, 2014.

[6] G. Barata, S. Gama, J. Jorge and D. Goncalves, *Engaging Engineering Students with Gamification*. 5th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES), pp. 1-8, Bournemouth, UK, 2013.

[7] J.R. Morelock, *Systematic literature review: An exploration of gamification in the context of engineering education*. 63rd Annual Conference and Expo of the Institute of Industrial Engineers 2013, pp. 453-462, San Juan, Puerto Rico, 2013.

[8] M. Wardaszko, *The Game Within the Simulation Game the Research Method Concept and Project With Game Design Implementation*. Developments in Business Simulation and Experiential Learning, vol. 40, 2013.

[9] B. Balaguer, S. Balakirsky, S. Carpin, M. Lewis and C. Scrapper, *USARSim: a validated simulator for research in robotics and automation*. Workshop on Robot Simulators: Available Software, Scientific Applications, and Future Trends at IEEE/RSJ, 2008.

[10] N. Keonig and A. Howard, *Design and use paradigms for gazebo, an open-source multi-robot simulator*. IEEE/RSJ International Conference on Intelligent Robots and Systems IROS, vol. 3, pp. 2149-2154, 2004.

[11] A. Jain, J. Huineau, C. Lim, W. Lincoln, M. Pomarantz, G. Sohl and R. Steele, *Roams: Planetary surface rover simulation environment*. Proc. of iSAIRAS 2003, pp. 19-23, 2003.

[12] O. Michel, *Cyberbotics Ltd. Webots TM : Professional Mobile Robot Simulation*. Int. Journal of Advanced Robotic Systems, pp. 39-42, 2004.

[13] J. Alemany, E. Cervera, *Design of High Quality, Efficient Simulation Environments for USARSim*. Technical Report ICC 2011-10-1, University Jaume I, Castello, Spain, 2011.

[14] R. Rathnam, M. Pfingsthorn and A. Birk, *Incorporating large scale SSRR scenarios into the high fidelity simulator USARSim*. IEEE International Workshop on Safety, Security and Rescue Robotics SSRR 2009, Denver, USA, 2009.

[15] A. Staranowicz and G.L. Mariottini, *A survey and comparison of commercial and open-source robotic simulator software*. Proc. of the 4th International Conference on Pervasive Technologies Related to Assistive Environments PETRA 11, vol. 1, pp. 39-42, 2011.

[16] L. Atorf, E.G. Kaigom, J. Romann, *A new eRobotics approach to simulation-based analysis and optimization*. 6th International Conference Developments in eSystems Engineering, Abu Dhabi, UAE, 2013.

[17] L. Atorf, E.G. Kaigom and J. Romann, *Simulation-based Optimization, Reasoning and Control: The eRobotics Approach Towards Intelligent Robots*. Proc. of the 12th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), pp. 1-8, Montreal, Canada, 2014.

[18] J.R. Abrial, *Data semantics*. Data Base Management : Proc. of the IFIP Workshop Conference on Data Base Management, pages 1-60, Cargse, Frace, 1974.

[19] M. Gyssens, J. Paredaens, J. Van Den Bussche and D. Van Gucht, *A graph-oriented object database model*. IEEE Transactions on Knowledge and Data Engineering, vol. 6(4), pp. 572-586, 1994.

[20] M. Summerfield, *Advanced Qt Programming: Creating Great Software with C++ and Qt 4*. Prentice Hall International, 2010.

[21] D.B. Golub et al., *Microkernel Operating System Architecture and Mach*. Proc. of the USENIX Workshop on Micro-Kernels and Other Kernel Architectures, pp. 11-30, 1992.

[22] J. Rossmann, M. Schluse, C. Schlette and R. Waspe, *A New Approach to 3D Simulation Technology as Enabling Technology for eRobotics*. 1st International Simulation Tools Conference & EXPO 2013 (SIMEX'2013), pp. 39-46, Brussels, Belguim, 2013.

[23] E. Mendez, G. Schall, S. Havemann, D. Fellner, D. Schmalstieg, and S. Junghanns, *Generating Semantic 3D Models of Underground Infrastructure*. IEEE Computer Graphics and Applications, vol. 28(3), pp. 48-57, 2008.

[24] R.F. Tobler, *Separating semantics from rendering: a scene graph based architecture for graphics applications*. Visual Computer, vol. 27(6-8), pp. 687-695, 2011.

[25] N. Hempe and J. Romann, *A Semantics-Based, Active Render Framework to Realize Complex eRobotics Applications with Realistic Virtual Testing Environments*. 7th European Modelling Symposium on Computer Modelling and Simulation, pp. 733-738, Manchester, U

[26] J. Romann, N. Hempe, M. Emde and T. Steil *A Real-Time Optical Sensor Simulation Framework for Development and Testing of Industrial and Mobile Robot Applications*. In Proceedings for the Conference of ROBOTIK 2012 - 7th German Conference on Robotics, VDE Verlag GmbH Berlin, 2012.

[27] N. Hempe and J. Romann, *Combining Realistic Virtual Environments with Real-Time Sensor Simulations for Close-to-Reality Testing and Development in eRobotics Applications*. In Proceedings of the IEEE International Symposium on Robotics and Manufacturing Automation (ROMA2014), pp. 6-11, 2014.

[28] J. Romann, N. Wantia, M. Springer, O. Stern, H. Mller and M. Ellsiepen *Rapid Generation of 3D Navigation Maps for Extraterrestrial Landing and Exploration Missions: The Virtual Testbed Approach*. Proc. of the 11th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), 2011.

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