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Enabling Human-Robot-Interaction via Virtual and Augmented Reality in Distributed Control Systems

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Abstract

Production and assembly lines are nowadays transforming into flexible and interconnected cells due to rapidly changing production demands. Changes are, for example, varying locations and poses for the processed work pieces and tools as well as the involved machinery like industrial robots. Even a variation in the combination or sequence of different production steps is possible. In case of older involved machines the task of reconfiguration and calibration can be time consuming. This may lead, in addition with the expected upcoming shortage of highly skilled workers, to future challenges, especially for small and medium sized enterprises.

One possibility to address these challenges is to use distributed or cloud-based control for the participating machines. These approaches allow the use of more sophisticated and therefore in most cases computationally heavier algorithms than offered by classic monolithic controls. Those algorithms range from simple visual servoing applications to more complex scenarios, like sampling-based path planning in a previously 3D-reconstructed robot cell. Moving the computation of the machine's reactions physically and logically away from the machine control complicates the supervision and verification of the computed robot paths and trajectories. This poses a potential threat to the machine's operator since he/she is hardly capable of predicting or controlling the robot's movements.

To overcome this drawback, this paper presents a system which allows the user to interact with industrial robot and other cyber physical systems via augmented and virtual reality. Captured topics in this paper are the architecture and concept for the distributed system, first implementation details and promising results obtained by using a Microsoft HoloLens and other visualization devices.

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Keywords: Augmented reality, Robot, Human-machine interaction

1. Introduction

Recent international trend aims towards highly networked production environments. This is promoted by lower lot-sizes and shorter production sequences demanding an overall increased flexibility in production and manufacturing environments [1]. Many approaches to increase this flexibility come with the cost of high computing power and increased expertise of the users. Especially for small and medium enterprises (SMEs), this trend poses a challenge due to the fact that these companies are often unable to invest in modern machines as well as in the experts needed to program, maintain and operate the systems.

Current research in the field of robotics tries to compensate the missing computing power by outsourcing certain algorithms to distributed or cloud-based robot control. The outsourcing comes in hand with a lower ability to predict and control the robot's movements inside the physical robot cell. Since most of the manufacturing environments are not fully automated and have operators that interact or collaborate with the robot, this poses a potential danger for the operator and the surrounding environment. Furthermore the required expertise to use this new technology increases.

In this paper we address the current state of the art of distributed robot control and augmented reality (AR) and our approach of an intuitive AR Human-Robot-Interaction and path-planning. By planning trajectories and robot paths in the cloud, a potential risk for workers is caused, since the planned paths are not easily predictable. A mixed reality based solution to evaluate the robots movements before execution is introduced to overcome this drawback.

2. Related Work

2.1. Distributed robot control

General cloud robotics and cloud-based robot control are emerging fields within robotics. Any application that requires data of the cloud or distributed frameworks to control a machine or generate robot programs can be considered. Multiple

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new technologies, systems and approaches aim to compensate the lack of computing power of a standard robot control or try to integrate higher-level robotic operations like perception, recognition and action algorithms.

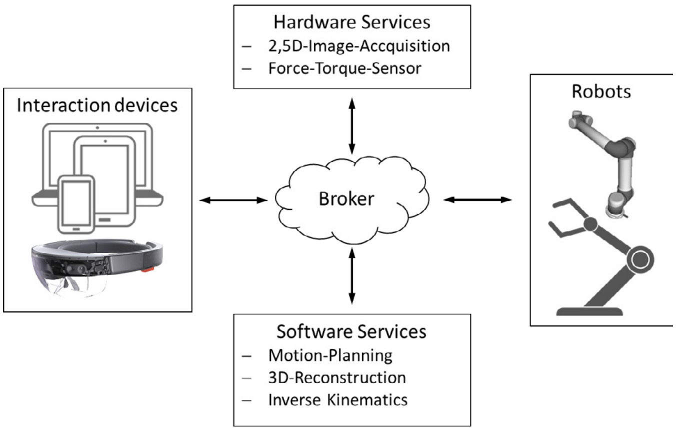


Fig. 1. The realized architecture connecting various communication participants via a centralized broker. Connected devices are grouped into functional units according to their main purpose.

Some approaches use established solutions and middleware like the Robot Operating System (ROS) [2] to connect their control algorithms to the real robots. Industrial communication standards as OPC UA [3] or MQTT are also widely used. An overview of innovative control of assembly systems can be found in [4].

Other approaches use a custom tailored communication graph between the different systems. Vick et. al propose a new concept for flexible motion planning and robot control for industrial robots as a service, based on a cloud infrastructure [5]. The goal is to split the classic monolithic control pyramid into an open service-based framework, where each service can be run hardware- and location-independently.

In [6] the authors identify four benefits of cloud-computing for robotic and automation: the access to Big Data, the possibility to use parallel grid computing on demand, the option for collective robot learning and the ability to include crowd sourcing. In this context collective robot learning means that robots are able to share their trajectories, and the ability to include crowd sourcing aims to make use of the operator's skills to analyze scenes and to collaborate on harder to solve problems.

Autonomous robots require a lot of computation for their localization and mapping. Reducing the computational cost by up to 83,6% can be achieved by freeing the onboard system of this heavy workload through shifting the task to the cloud [7]. In [8] Niebuhr et. al show a network service framework based on distributed communication graphs. Using existing components and technologies as ZeroMQ and Protocol Buffers, they developed a concept for a distributed control framework for human-robot interaction scenarios.

2.2. Augmented and Virtual Reality for robot programming

Augmented Reality (AR) and Virtual Reality (VR) are computer generated ways of displaying information to users. In VR the user is immersed in a computer generated reality via a head mounted display (HMD) and is not able to see the real world around him. In AR, on the other hand, the user sees the reality superimposed with virtual objects introducing a so called mixed reality. AR is not bound to HMDs but can also be visualized on hand-held devices like tablets or smartphones. The wide range of applications and the capability of this technology for use cases like entertainment, manufacturing, maintenance and overhaul as well as robot path planning was already recognized in the mid 90s of the last century [9].

Most applications introducing augmented reality in manufacturing processes are still exploratory prototypes. But with the significant improvements regarding the computing power of the hardware and better spatial tracking algorithms and sensors, it is now possible to implement AR applications for factory tasks [10]. [11] presents a modular-based implementation of AR to provide an immersive experience in learning and teaching, covering the planning phase, control systems and machining parameters of a fully automated work cell. A marker-based robot arm module simulates pick-and-place operations offline for collision detection and inverse kinematics. [12] present an AR system to define virtual obstacles, specify tool positions and robot tasks with a 3D pointing device to set the robot postures. The conducted user study indicates that augmented reality is a promising method for robot programming regarding the intuitiveness. Similar results can be found in [13], [14] and [15], where the authors present a gesture based robot programming with augmented reality feedback on common hand-held devices and via projection.

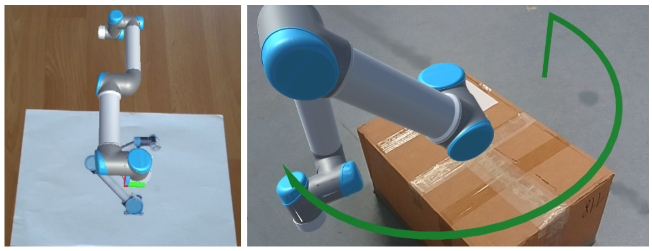


Fig. 2. Visualizing a model of an industrial robot (Universal Robot UR5) captured on a HoloLens using our system. Left: The model is placed relative to a marker to ensure correct spatial positioning and orientation. Right: The visualization can be enriched with useful information like a planned path.

3. Methods and Material

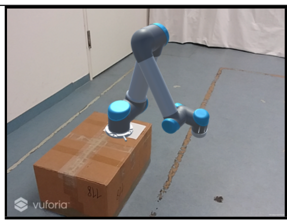
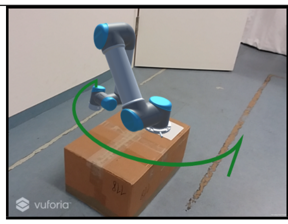
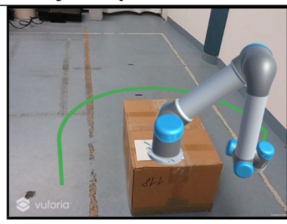
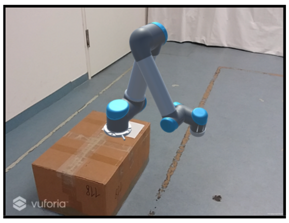
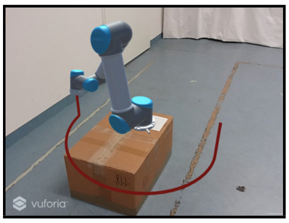
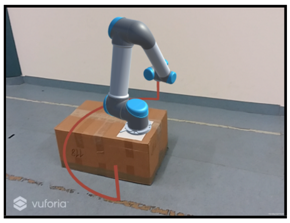
3.1. System architecture

In order to connect various robots, services and interaction devices, we use an architecture shown in figure 1, as proposed in [16]. It can be observed that the broker is the central communication instance. This is advantageous, as all other involved communication partners only need to know the address of the broker. Further, we split the architecture into functional units according to the main purpose of the connecting participants.

There are robots which need to be programmed and are able to share their actual state. They need to publish their type, physical structure and abilities to ensure that the interaction devices are able to load and visualize the correct models. These robots also offer a way to share their up-to-date data, for example joint angles, speed or information about gripped real world objects, with other participants.

The augmented reality and human-robot interaction is achieved using the interaction layer. Every device that has a dis-

Table 1. Visualization of planned paths for a pick and place operation in the realized application. Up: collision-free trajectory, bottom: movement with possible collision

Experiment	Start Pose	Final Pose with Trajectory	
Collision-free Pick and Place			
Pick and Place with Collision			

play and offers some sort of user input, for example via touch gestures, can possibly be used in our architecture. Interaction devices represent all devices that are able to realize a human-machine interaction. By using visual feedback, the operator is capable of inspecting the robots movement and programs. Thus, we are able to simulate a whole programmed cycle before the robot will start its actual movement. Providing the ability to interact with the robot is performed by using gestures. These can be touch signals in case of tablets or spatial gestures in case of the HoloLens.

Devices and services not directly mapped to any attached robot or interaction device can be integrated into the architecture using hardware or software service templates. Examples for hardware services are image acquisition via camera or obtaining measured values of a force-torque sensor. Software services result in higher level robotic algorithms like path-planning, real world reconstruction with SLAM-approaches and alike or providing inverse kinematics for different robots.

3.2. *Augmented and Virtual Reality on various devices*

Realizing augmented and virtual reality on various devices is a challenging task, since the devices vary widely in several criteria such as display and input type, operating system and computing performance. Cell phones, tablets and laptops, for example, are targeting different user groups and usage scenarios. In order to decrease development and deployment efforts, it is advantageous to rely on one code basis for all devices. Therefore, we use Unity to implement the visualization and interaction as it was the only game engine supporting the HoloLens at time of choosing. To enable spatial positioning of the robot in its natural environment, we initially use marker tracking as a base, namely a software framework called Vuforia. Data exchange between all participants is realized with standard TCP-/IP-sockets and (de-)serialization is done with protocol buffers. In figure 2 a screenshot of the running application is displayed. On the left side a robot is visualized relative to its marker which is simply an image of robot itself. Spatial positioning and orientation of the model is achieved by adjusting the marker. The right side shows a visualized planed path, an example for integrating useful additional information such as joint limitations, artificial walls or maintenance instructions.

To show the feasibility of our approach we implemented the application on multiple devices. Tested devices in the setup include:

- a 9.7 inch Android Tablet,
- a 13.5 inch Windows Tablet,
- a Microsoft HoloLens and
- a Laptop running Windows 10.

4. Experiments and Results

4.1. *Robot program evaluation*

Path-planning for industrial robots is a computationally heavy task and therefore predestined to be computed not on the local robot control but on some remote computer or even a cloud infrastructure. Finding a collision-free path requires not only the model of the robots but also a representation of its environment. If the environment changes in between computation and movement execution, the whole trajectory needs to be re-computed. The operator of the robot cell who needs to evaluate a planned path before starting the robot must determine if the current trajectory is collision-free. Therefore, a visualization in the robots environment is beneficial. Table 1 shows a pick and place operation where two trajectories can be compared. One is a collision-free path and the other one is a movement with possible collision. By simply looking at the movements it is not easy to determine whether one or both trajectories are valid. Nevertheless, using techniques of augmented and virtual reality, the paths are distinguishable. Coloring the computed and predicted movements of the end effector helps the operator to determine which one is to prefer.

4.2. *Augmented Reality with the Microsoft HoloLens*

The most promising results where achieved using the Microsoft HoloLens. It is a head-mounted display unit able to project different images for each eye, resulting in an three dimensional perception for the users. The spatial tracking, positioning and orientation of the holograms are handled completely by the built-in soft- and hardware. No external camera or marker tracking is necessary to retain correct visualization of the robot and its state or planned paths. Viewing the robot in its environment without computing or network induced latency results in a good user experience. Another advantage in comparison to hand-held devices like tablets is that both hands are free to perform gestures and interact with the system. A manipulation of the trajectory with an augmented reality based spatial programming environment as proposed by Lambrecht et. al [17] is possible. Additionally, the operator is enabled to manipulate the robotic cell in case of the trajectory crossing a dangerous zone or obstacles getting in the way of the manipulator. An operator wearing the HoloLens and his natural field of view is depicted in figure 3.

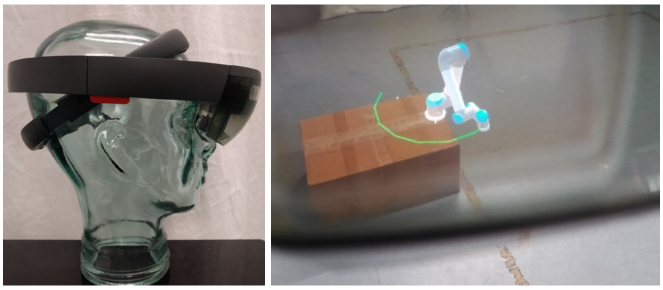


Fig. 3. The Microsoft HoloLens (left) and a captured view through one of the head-mounted displays (right)

5. Conclusion and Future Work

We proposed and implemented an augmented reality based interaction system for industrial robots. By using our broker architecture we are able to integrate and control various robots from different manufacturers and types. Even older robots which are not capable of higher level robotic tasks can be equipped with state of the art algorithms and approaches through the use of cloud-based computing and control. Supported by the augmented reality, an operator is able to react in a safe and fast manner according to changes in the production line. The current state of work focuses mainly on visualizing cloud computed data like planed paths for standalone robots. Nevertheless, the systems architecture is designed to use user input as a help for the cloud system to effectively compute manufacturing operations. Even new obstacles can be considered by verification of a computed robot program and trajectory in the current robot setup. Those obstacles can be arbitrary bodies or even other moving robots in the same environment and shared workspaces. The most suitable device for interaction with the robotic system and visualization of its state is found to be rather head-mounted than hand-held since it leaves both hands free for physical interaction with the robot cell.

Future work will include the realization of a spatial programming environment based on both augmented and virtual reality. Building a model of the robots environment will further increase the feasibility of our approach, since interaction with real world objects and their virtual representation is achievable. When focusing on augmented and mixed reality, the positioning accuracy of the holograms needs to be further investigated. Integrating more interaction devices as mixed-reality headsets or pure virtual reality headsets, as a HTC Vive, is suitable. A test in a real production environment will generate useful information and experiences that can be applied for a safe and secure industrial realization.

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References

[1] Schirner G, Erdogmus D, Chowdhury K and Padir T. The Future of Human-in-the-Loop Cyber-Physical Systems. In: Computer (Volume: 46, Issue: 1, Jan. 2013). p. 36-45. DOI: 10.1109/MC.2013.31

[2] Quigley M, Gerkey B, Conley K, Faust J, Foote T, Leibs J, Berger E, Wheeler R and Ng A. ROS: an open-source Robot Operating System. ICRA workshop on open source software. Vol. 3. No. 3.2. 2009.

[3] OPC Foundation (2018) [Online] www.opcfoundation.org

[4] Krüger J, Wang L, Verl A, Bauernhansl T, Carpanzano E, Makris S, Fleischer J, Reinhart G, Franke J and Pellegrinelli S. Innovative control of assembly systems and lines. In: CIRP Annals, Volume 66, Issue 2, 2017, p. 707-730, ISSN 0007-8506, DOI: 10.1016/j.cirp.2017.05.010

[5] Vick A , Vonasek V, Penicka R and Krüger J. Robot control as a service; Towards cloud-based motion planning and control for industrial robots. In: 2015 10th International Workshop on Robot Motion and Control (RoMoCo). p. 33-39 DOI: 10.1109/RoMoCo.2015.7219710

[6] Kehoe B, Patil S, Abbeel P and Goldberg K. A Survey of Research on Cloud Robotics and Automation. In: IEEE Transactions on Automation Science and Engineering (Volume: 12, Number: 2). p. 398-409 DOI: 10.1109/TASE.2014.2376492

[7] Ali SS, Hammad A and Tag Eldien AS. FastSLAM 2.0 tracking and mapping as a Cloud Robotics service. In: Computers & Electrical Engineering (2017). DOI: 10.1016/j.compeleceng.2017.11.012

[8] Niebuhr CA and Vick A. Distributed real-time control service framework for human-robot interaction applications. In: 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA), Berlin, 2016, pp. 1-8. DOI: 10.1109/ETFA.2016.7733514

[9] Azuma RT. A Survey of Augmented Reality. In: Presence:Teleoperators and Virtual Environments (Volume: 6, Number: 4, 1997). p. 355-385. DOI: 10.1162/pres.1997.6.4.355

[10] Makris S, Karagiannis P, Koukas S and Matthaiakis AS. Augmented reality system for operator support in humanrobot collaborative assembly. In: CIRP Annals (Volume: 65, Number: 1, 2016). p. 61-64. DOI: 10.1016/j.cirp.2016.04.038

[11] Pai YS, Yap HJ, Dawal SZM, Ramesh S and Phoon SY. Virtual Planning, Control, and Machining for a Modular-Based Automated Factory Operation in an Augmented Reality Environment. In: Scientific Reports (Volume: 6, August 2016). DOI: 10.1038/srep27380

[12] Gaschler A, Springer M, Rickert M and Knoll A. Intuitive robot tasks with augmented reality and virtual obstacles. In: 2014 IEEE International Conference on Robotics and Automation (ICRA). p. 6026-6031. DOI: 10.1109/ICRA.2014.6907747

[13] Lambrecht J and Krüger J. Spatial programming for industrial robots based on gestures and Augmented Reality. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems. p. 466-472 DOI: 10.1109/IROS.2012.6385900

[14] Hügle J, Lambrecht J and Krüger J. An integrated approach for industrial robot control and programming combining haptic and non-haptic gestures. In: 2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), Lisbon, Portugal, 2017, pp. 851-857. DOI: 10.1109/ROMAN.2017.8172402

[15] Heimann O, Hügle J and Krüger J. Gesture based robot programming using process knowledge An example for welding applications. In: 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus, 2017, pp. 1-4. DOI: 10.1109/ETFA.2017.8247761

[16] Guhl J, Nguyen ST and Krüger J. Concept and architecture for programming industrial robots using augmented reality with mobile devices like microsoft HoloLens. In: 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus, 2017, pp. 1-4. DOI: 10.1109/ETFA.2017.8247749

[17] Lambrecht J, Kleinsorge M, Rosenstrauch M and Krüger J. Spatial Programming for Industrial Robots through Task Demonstration. In: International Journal of Advanced Robotic Systems (2013). DOI: 10.5772/55640