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Support of Power Plant Telemaintenance with Robots by Augmented Reality Methods

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In power plants, in many cases direct human access to crucial sites for inspection or maintenance is impossible. Here, remotely operated robots offer good potential to handle these tasks. This relates to technology challenges for remote operations. In this contribution we propose the use of an Augmented Reality interface as a means to directly and intuitively visualize complex information to overcome some of the challenges and support the teleoperator in his duties. Support functions that could be employed for several tasks in the context of inspection or maintenance are introduced.

Index Terms: **Augmented Reality, Manipulators, Teleinspection, Telemaintenance, Teleoperation.**

I. INTRODUCTION

Remotely operated robot manipulators play a significant role in power plant inspection and maintenance for already more than 50 years. Robotic master/slave systems were substantially promoted to enable handling of radioactive materials since 1945 [18]. These technologies were directly transferred to material handling in nuclear power plants, too [9, 17]. Similar techniques are also transferable to remote inspection of distant conventional power plants, where mobile robots play a significant role for inspection of narrow or polluted spaces, in which human access is impossible [3, 5]. In particular, in case of emergencies – like the Fukushima accident emphasized in 2011 – remotely operated robots would be very much needed. Nowadays, nuclear plant technology is being abandoned in several countries, thus also robotic technologies for dismantling and removing crucial sections are urgently required.

The emphasis of this contribution is on support systems for the human teleoperator: his information about the remote location is limited to sensor data characterizing the situation on-site. This limits his *situational awareness*. Limited field of view, image resolution and update rates can further deteriorate his perception. Remotely controlling and steering a manipulator is a difficult task by itself, and obstructed views or cramped environments with lots of obstacles make collision-free movement a challenge. Time delays will further lead to a deteriorating performance in controlling the robot, if not anticipated in the control system.

Therefore supporting systems for teleoperating manipulator robots have been investigated and developed in the past, such as visual servoing [10], predictive displays [4], impedance control [11] or force-feedback [6]. Another technique with promising potential to increase the performance of teleoperation and telemaintenance is *Augmented Reality* (AR).

Augmented Reality – as a form of Mixed Reality [13] – is a technology that combines a direct view of the working environment with computer generated three-dimensional graphics based on sensor measurements. These virtual graphic objects have to be correctly aligned with the real environment, thus augmenting the natural view of the operator with the virtual annotations and realizing a three-dimensional integrated graphical user interface. The data to be used for augmentation depends on the application and current situation in the remote work area, and is not limited to a specific source: input from different kinds of sensors or other sources can be used. It has to be properly visualized in the combined mixed reality view, and is supposed to aid the operator in completing his tasks.

This technique addresses the aforementioned problem in teleoperation: since the operator of a telecontrolled system cannot walk around in the work environment he needs a different approach to get a good understanding of the remote site, to assess the problem/task to be solved and find a suitable solution. In the context of telemaintenance of a power plant system and environment data as well as video streams of the remote manipulator's workspace are usually available – however, there still remains a high cognitive load on the operator to perform the mental transformation from the available data to the remote situation, in particular under time pressure. Augmented Reality integrates the available data from the remote site and has been demonstrated to alleviate some of these necessary mental transformations (since all data is available in one image), which in turn reduces the workload for the operator [19] and thus results in higher efficiency [14], less failures and higher safety [18].

Systems for remote operation and monitoring of industrial robots using Augmented Reality have been developed [16] and are still a topic of research with respect to appropriate interactive displays for reactions in real-time. In this contribution, specific adaptations are addressed for telemaintenance, inspection or even dismantling of power plants. The key task is the design of an Augmented Reality system to aid teleoperators in their tasks. Specific tools for possible deployment in the mentioned areas are presented in the following sections.

II. Prerequisites for realizing AR-applications

Key requirements for Augmented Reality systems are that they are able to combine real and virtual objects in a real environment, aligning (*registering*) those objects correctly relative to each other in 3D, and that they run interactively in real time [1]. Thus, in order to provide the basis for a beneficial AR display, teleoperator interfaces in the context of inspection/maintenance in the power industry must fulfill certain prerequisites.

As mentioned earlier, Augmented Reality is a form of mixed reality visualization, meaning a natural view of the deployment area is combined with artificially created image enhancements to achieve an augmented view of the surroundings. As such, AR requires some imaging sensors in the remote location of the telemanipulation area. Some possible deployment areas of the power industry already have cameras installed for situation monitoring which could be used as input for the AR support interface. Another possibility would be to install cameras on the remote inspection/ maintenance robot itself; mounting a camera on a robot arm can possibly provide more flexibility in viewing obstructed areas than a just stationary camera could. In any case, some form of visual representation of the real world is always required to achieve an AR view – areas too dark or with low visibility conditions could be handled with a complete artificial display of the environment (*Virtual Reality* (VR)), but it would lack the relation to the current state of the real world that AR can provide.

Next, AR systems need to be precisely calibrated and aligned: the virtual information augmenting the real environment view needs to be presented to the user at exactly the location it is expected to be – even an offset of few pixels is easily detectable by human operators [2] and will deteriorate the accuracy and usability of the system. This process of aligning real and virtual objects is called *registration*, and several methods for achieving and keeping it have been proposed in the past (see [2]). The system developed [16] uses pre-calibrated cameras, whose location in the environment or at the robot arm have been determined beforehand, and an a-priori known environment model for assessing the robots' position in the workspace. The same could be done for most of the application scenarios here (since environment and camera data should be readily available in the deployment scenarios), although precise location systems might be necessary in cases where absolute positional data are displayed and freely moving (mobile manipulator) robots are employed.

Finally, a data connection to the telerobotic system and any sensors that are to be used for augmentation must be established for being able to provide real-time capable visualizations. This, however, should cause a minimum of problems, since every telecommanded system needs a link to the teleoperation center for exchanging telemetry and commands.

The developed AR-system is able to provide an annotated view of the environment of industrial manipulator robots, providing the teleoperator with different kinds of virtual additional information with realistic occlusion between real view and virtual objects. It could be extended to include augmentations and tools for the demands of typical tasks in the Power industry.

The next paragraph addresses AR tools that are used for supporting personnel in remotely controlling a manipulator.

III. Augmented Reality support functions

A. Robot movement

When remotely controlling a manipulator, the operator will not always exclusively guide the robot manually, but sometimes also use programmed pre-defined movement. This movement can first be safely tested in the real environment by superimposing the camera image of the real robot with a virtual model, and have this model perform the programmed motion (cf. Fig. 1).

This can be used to pre-check for collision free paths in cramped surroundings, but also to deal with delays when manually steering the robot (i.e. first, only the virtual model in the local interface is moved manually (without delays); the real robot follows the model on an admissible trajectory [7].)

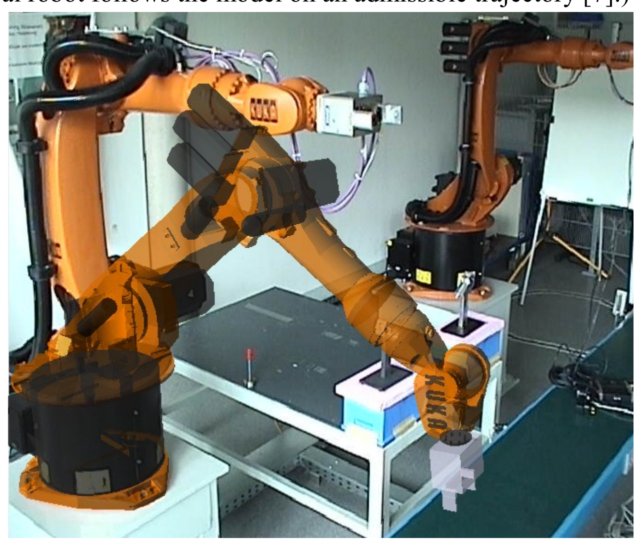

Fig. 1. Real manipulator superimposed with a virtual model, which is executing a pre-defined movement program.

During movements, visualizing movement direction/speed vectors for the individual axes of the robot (Fig. 2) allows for a quick understanding of where to and how fast a robot is moving. This can be helpful for predicting potential collisions not only for one point of the robot but for its whole body.

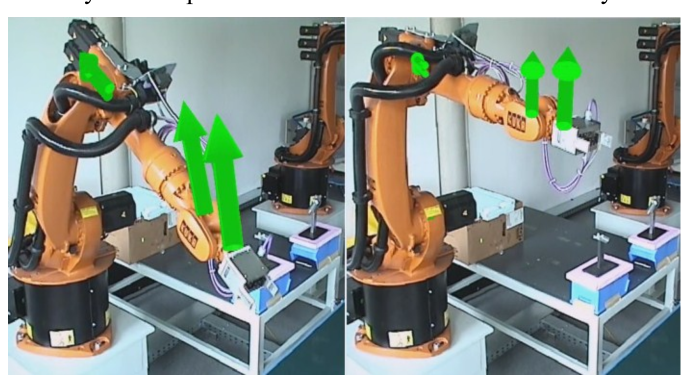

Fig. 2. Speed vector visualization of the individual robot axes during movement: the size of the vector correlates to the axis speed.

If the movement of the manipulator is constrained, e.g. due to preconditions of handled material or tools, compulsory trajectories or because of some automatic collision avoidance system, these boundaries and constrictions can be visualized and shown to the operator, enabling him to quickly understand as to why and where his movement is limited and where he should guide the robot to, or which part of the surroundings is threatened to be collided with (which might not be obvious due to occlusion). In Fig. 3, a virtual barrier which the robot is not supposed (and able) to cross to avoid collisions is visualized in an AR-view of the surroundings.

Fig. 3. Virtual barriers the manipulator robot cannot cross made visible in the AR view.

B. Environment interaction

Different kinds of information can be used to augment the view when interacting with the environment via the remote manipulator:

For example for insertion of parts in an assembly, the desired goal position – i.e. the part in its mounting spot – could be pre-visualized and overlaid in the camera image as guiding help in a similar way as in Fig. 1. Distance or other guiding information (like the optimal path to be taken, or necessary changes in angle for a perfect insertion orientation [12]) can be visualized directly in the remote view, enabling the operator to see the necessary adaptions without having to rely solely on his understanding of the camera image or interpreting abstract manipulator position information. Also, for gripping parts, predetermined optimal gripping points and areas can be highlighted directly on the workpiece, relieving the operator of the task to determine these points himself or identifying them on the object from some abstract data representation in some coordinate system. Examples for these kinds of environment annotations can be seen in Fig. 4.

When in direct contact with a surface, the measured resulting forces could be shown for the workpiece and individual tools to avoid overstressing. Similar image augmentations could be done for (de-)construction or maintenance tasks: For example, areas that have to be grinded and have not been processed yet, or planned seams for welding or cutting an object could be marked directly on the respective object and thus easily visually confirmed, before having to start the actual intervention. This would give the operator pointers to where and how to proceed on a possibly markerless surface. He could also be assisted with procedures and step by step instructions for his task directly in his view of the working area without having to confer to a manual, whose information has to be transferred back to the remote area. During the actual process, the operator would then have a visual guideline to follow without actually having to prepare the environment first.

C. Teleinspection

Another common task in the maintenance of power plants is inspection of hazardous or difficult to reach areas. Inspection goals can vary from detecting faulty hardware to surface examination or checking for leaks in containment installations. Depending on the inspection tasks and sensors employed, different AR annotations could be used in those scenarios.

For close visual inspection of a large area with cameras, a scene overview might be provided in which areas already passed by the robotic inspection system could be marked to ensure complete coverage of the desired region (and avoid double checking). Noticeable points and faults detected could be directly marked (by the operator or – if possible – automatically) and kept visible for later re-inspection or intervention, or to get an overview of all critical spots and their distribution.

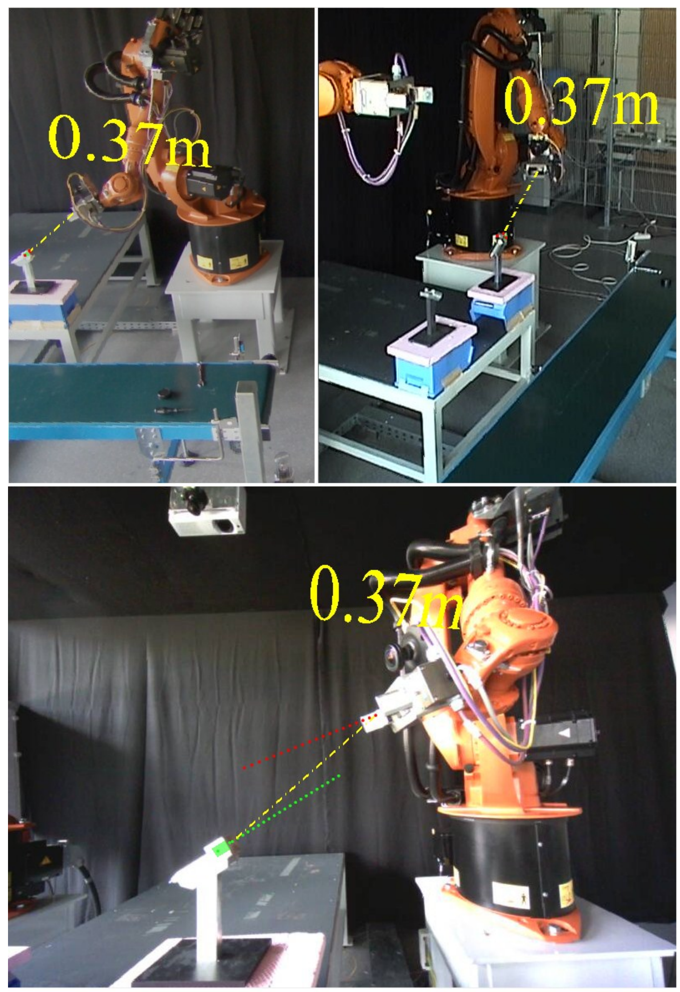

Fig. 4. Supporting annotations for grapping a metal pen from its rack: distance information, vector to gripping position (yellow) and gripping points (top row); gripping area on workpiece (green area), and robot hand and workpiece orientation (red/green vector) (bottom).

When sensors are employed for inspection, their data could be directly visualized in the AR-display if it can be spatially located and represented in a meaningful way. One example might be to inspect for heat distribution: in the AR-display, the operator could be shown color-coded temperature measurements directly on the object inspected, allowing for a quick grasping of the distribution, any irregularities in the data and where they are located. Another example might be measurements from a depth camera which could be integrated into the live view of the operator (Fig. 5) and viewed from different directions to give the teleoperator a fast understanding of the spatial surroundings at the remote site.

Fig. 5. Display of depth measurements in a real camera view; a manipulator robot is added as exemplary virtual addition to the image (left); side-view of this scene with visible depth measurements (right) (images from [15]).

D. Performance Assessments

The support functions presented here were some examples of how Augmented Reality can help a teleoperator to perform his tasks more easily and securely. Depending on the deployment scenario and tasks to fulfill, specific AR-tools will have to be designed for specific applications, adapted to the surroundings and to the available data in order to provide an optimal Augmented Reality display for the tasks of the teleoperator.

For specific scenarios evaluation criteria are to be established to measure the changes in the operator's performance and reaction time. In the past, our team performed such evaluations of AR user interfaces in the similar field of search and rescue [8] as well as in navigation and search tasks using mobile robots [14]. Augmented Reality was shown to increase the operators performance in all cases; for example in navigation tasks, average navigation time could be decreased down to 38,2% compared to using only the camera image by using the AR interface (see [14])– similar results are expected for the AR support functions proposed in the power plant scenarios.

IV. POSSIBLE DEPLOYMENT SCENARIOS

The AR-functions emphasized here focus on teleoperation of manipulators, as being of relevance for remote material handling or for disassembly of nuclear power plants. Manipulators will be moved on vehicles to various locations, to follow the work progress moving to different sites. Manipulations are only executed after those movements are complete. For inspection scenarios where sensor characterization of several locations is essential, similar AR-techniques are used to support safe navigation in an only partially known working environment. As for example hydropower plants are often located far from civilization, inspection and maintenance approaches by remotely controlled mobile robots play a crucial role for keeping non-operational periods at a minimum, or to assess the situation in case of an emergency.

V. CONCLUSIONS

Augmented Reality methods support tele-operators by intuitive representation of sensor data in a visual framework. This way, relevant information from different sensor sources can be well integrated and the situational awareness of the teleoperator heightened. In particular for situations requiring quick reaction capabilities, AR-techniques can be employed in an efficient and intuitive way to support a human teleoperator in robot control applications. In scenarios for power plant inspection and maintenance, only special remotely controlled robots enable access to crucial locations. The proposed AR-methods will thus enhance reliable and safe operations of the remote robots in complex and challenging situations, as demanded by future robotic telemaintenance of power plants.

VI. REFERENCES

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VII. BIOGRAPHIES

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His research interests include networked mobile robots and networked distributed spacecraft systems. He published more than 275 papers and received several awards, including the Walter-Reis-Award in Robotics 2008 and 2012. He was appointed Consulting Professor at Stanford University (2002 - 2006). At scientific journals he served as member on editorial board of “Control Engineering Practice” (1993- 2005) and as topic-editor of “Space Technology” since 1998. The International Federation on Automatic Control (IFAC) appointed him 2008 as Chairman of Technical Committee on “Telematics: Control via Communication Networks“, and IEEE in 2005 as chairman of the “Technical Committee on Networked Robotics.”