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Augmented Reality for Telemaintenance and -inspection in Force-Sensitive Industrial Robot Applications

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Abstract: Telematic solutions allow fast remote support in industrial robot work cells: Robotic experts can assist the local staff in work process modifications or in tracking down errors without having to actually travel to the remote site. In order to be able to perform such teleinspection and telemaintenance tasks the operator needs to establish a data connection to the robot and get an understanding of the remote work process, as well as of the transmitted data.

This contribution introduces a telematic control system developed for remote monitoring and control of an industrial robot performing force-sensitive work applications. An Augmented Reality interface is proposed for intuitive representation of complex robotic data, allowing quick analysis of the current working cycle and process data and altering the robot's program remotely while still having a clear spatial reference to the work environment.

Keywords: Industrial Robots, Augmented Reality, Telecontrol, Human-Robot-Interaction, Tele-robotics, Control Interfaces.

1. INTRODUCTION

Industrial robots nowadays are employed in a number of different application areas: from traditional fields like material handling over welding and spray painting up to industrial processing tasks like cutting, grinding, deburring or polishing. While they used to be employed in a "program-once, run-forever" manner, today, declining life-cycles for products and an increased variety of product ranges require a more flexible automation (IFR (2014)), thus also requiring more frequent modifications to the robots' work programs.

Since not all companies employ robotic experts these modifications prove problematic for some, especially in case of complex applications like grinding or deburring (Thomessen (2000)), when working in direct contact with the work piece and where workpiece geometry is often complex. This raises a demand for robotic experts that assist users with modifications of their programs or can provide support in case of errors or undesirable results.

While formerly, such an expert had to be summoned from the manufacturer or robotic service provider, nowadays several of these tasks can be approached using telematics: this means establishing a communication link to transmit the relevant data from the work cell and analyzing and solving the problem remotely. There are several advantages for using telematics in inspection and maintenance scenarios: being able to perform work program modifications or analyze and correct erroneous behavior of the industrial robot completely remotely allows for a fast intervention – the experts do not have to travel to each customer, allowing for a quicker response and alleviating travel time and costs. The customer can request short-hand support right when he needs it; the robotic service provider can bundle his expertise in one central telematics center, from where he can provide support to users from all over the world. Of course, some work modifications or maintenance tasks may require physical intervention in the work cell: in these cases, the telematic support should be conducted together with the personnel in place. In this case, the operator provides instructions and oversees the execution by the local staff. If this does not prove sufficient, a technician can still be dispatched.

However, in order to allow such telemaintenance and inspection tasks to succeed in the first place, the teleoperator needs to get a good understanding of the transferred data and of the situation in the remote work cell. This understanding of the remote circumstances or the feeling of even "being at the location occupied by the slave device" (Loomis (1992)) is often termed situational awareness (Endsley (1988)). Only after gaining this awareness, the teleoperator can analyze the task/problem properly, come up with a solution and provide the necessary work program modifications.

In order to help the teleoperator gain this awareness, we propose the use of Augmented Reality (AR) to intuitively visualize the transmitted robotic data at the teleoperation center. This technique allows showing the user an enhanced view of the work surroundings which displays data in an easily understandable way, at the position it corresponds to. This relieves the mental workload of the teleoperator (Wickens (2005)) and thus leads to higher efficiency in the teleoperation process.

This contribution introduces an AR-supported teleinspection and -maintenance interface developed in the context of the

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project *ForTeRob* (Force Controlled Teleoperated Machining with Standard Industrial Robots). As the name indicates, the interface is developed for teleoperation of standard industrial robots, with special emphasis placed on force-sensitive applications like grinding or polishing. This article first gives a brief introduction into the goals and architecture of the system and AR in general. Afterwards, the developed control interface is presented, with focus on the AR-based display of robotic and process data for analysis and modification of the work process. Finally, the conducted experiments and evaluation of the developed system are described, and a brief summary of the results is given.

2. OBJECTIVES, SYSTEM ARCHITECTURE AND COMPONENTS

2.1 Objectives of ForTeRob

The project ForTeRob was mainly concerned with industrial robots performing force-sensitive operations like grinding or polishing of work pieces. One project task was to develop a novel control system to improve force control capabilities of standard industrial robots (Lotz (2014)). The other task described here was to develop a telematic user interface for those application scenarios that would allow an expert to monitor, analyze and modify the robot's behavior remotely. Data analysis and program modification options should be suited to the needs of the support staff and allow quick intervention in case it is needed.

To further detail the requirements of the telematic interface, an initial survey was conducted with the technical support personnel of the robot manufacturer Reis Robotics. Three main tasks for it were identified:

- Easy and fast analysis of the current work program execution and work results
- Autonomous, permanent monitoring of work execution to detect anomalies, deficiencies or errors
- Intuitive modification, and afterwards testing of altered work programs in the remote work environment of the manipulator,

all with special emphasis on force-sensitive applications. The second point involved developing an autonomous monitoring system that could track system and process related events, and report or react to them, and will not be detailed further in this article. The other two objectives were solved using image and video data from the work cell together with logged or live machine data – visualized with Augmented Reality; this will be further detailed in the following sections.

2.2 Augmented Reality (AR)

In order to allow the desired intuitive representation and analysis of the data transmitted from the remote robotic work cell, an Augmented Reality interface for the teleoperation system was proposed. Augmented Reality – as a form of Mixed Reality (Azuma (2001)) – is a technique that enhances the view of the natural surroundings of a user with additional helpful virtual information to aid him in his tasks; these virtual additions need to be correctly registered (integrated, positioned and oriented) within his view of the surroundings and should be dynamic and interactive in real-time (Azuma (2001)). Several techniques exist to actually enhance the view of a user, ranging from head-mounted displays in helmet systems over portable displays like smartphones, enhanced camera images on stationary monitors as in (Sauer (2010)) up to visualizations being projected directly into the workspace (Leutert (2013)). Since the operator here can only enter the work environment remotely, AR visualizations with enhanced camera images on monitors were used.

The goal of the AR system here is to take complex robotic or process data and make it easily understandable by visualizing it in an intuitive manner and showing it at the correct place in the work environment. By enabling the user to simply *see* the necessary complex information at the corresponding position, he on the one hand does not need to locate the data in relation to the robot; on the other hand, interpretation is made easy by choosing an appropriate visual representation for the data (see Section 4). This approach has been shown to reduce the mental workload of the teleoperator (Wickens (2005)) and will allow him to analyze and solve remote tasks quicker.

2.3 System architecture

In order to make any teleoperation process possible, data first has to be transmitted between the remote location and the teleoperation center. The operator there needs to gain an understanding of what is happening at the controlled plant, and the controlled device needs to be able to receive commands to allow modifications to be made to the process.

The developed basic system architecture in ForTeRob to allow remote monitoring and modification of an industrial manipulator robot performing force-sensitive applications is depicted in Fig. 1.

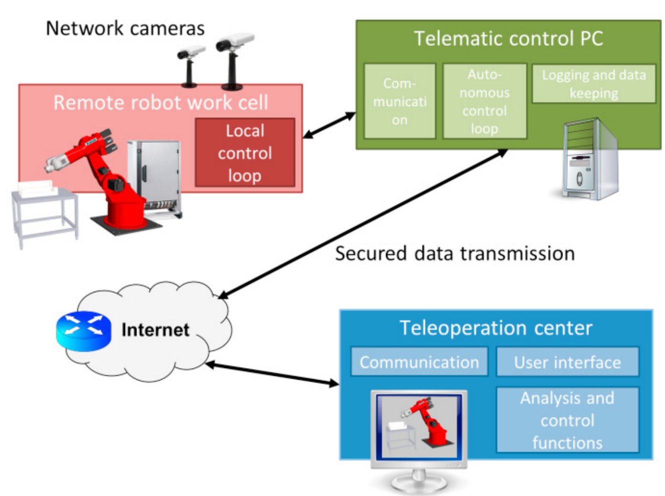

Fig. 1. Basic system architecture of the telematics interface in ForTeRob.

The data gathered at the remote location can be divided into three categories: first, data from the robot itself and from the performed work process. Second, visual data from deployed network cameras that are essential for an AR-visualization of said data, and third, (optional) additional data from external sensors (depending on the work application and the data needed to properly analyze and/or control it). All this data is being gathered, encoded, encrypted and transmitted by a computer set up in the remote work cell. This PC acts as a relay between the teleoperation center and the controlled robot, transmitting data and commands between the two stations using standard Internet protocols. It also monitors and logs work execution, with the capability to send warning messages to the teleoperator, or even react autonomously in case serious time-critical events are being detected. Log files (for example videos depicting work execution) are stored locally and transmitted to the teleoperation center on demand. This setup was chosen since the teleoperator will not permanently control the robot, but mainly monitor execution or make program modifications (supervisory control, (Sheridan (1992))). With this setup, the data transmission delay times of up to 80ms are of no issue to the system. However, local control loops are needed to allow autonomous and timely reactions for controlling the work process or in case of events where waiting for a reaction of the teleoperator is not feasible. Three control loops for adapting the behavior of the robot have been realized: one directly on the programmable logic control system running on the robot, one sending commands from the autonomous control PC at the remote location to the robot control via Ethernet, and one involving the teleoperator, using the telematic link to the external teleoperation interface. Data and commands are sent and tunneled through the local network of the robot plant via Internet to the teleoperation center, where they are received and processed for display in the telematic interface there.

3. TELEMATIC USER INTERFACE

The telematic user interface in the teleoperations center consists of two main parts: one window showing different views of the work environment (Fig. 3), and one displaying system status information as well as control elements for data display, customizing visuals, work process analysis and remote control of the robot.

The first component – showing the current (or recorded, in case of analyzing recorded data) situation at the remote location – is necessary for the teleoperator to gain a general understanding of the situation at the remote work cell (situational awareness). Cameras were installed in the work cell, allowing an overview of the situation as well as detailed views onto the workpiece to be processed. One camera was mounted directly to the flange of the manipulator, allowing detailed images from variable perspectives by moving the manipulator. Size and combination of the remote views can be altered by the operator as well as the type of view: besides pure camera images, the operator can choose a purely virtual environment model (Virtual Reality (VR) view, that is, a virtual three-dimensional environment model permanently updated with the received robot data). The third option is the aforementioned Augmented Reality view of the environment: additional virtual information is three-dimensionally embedded into the camera images to enhance the user's view of the robot's surroundings (see Sauer (2010) for more details on how this is realized). The user thus needs no longer localize the transmitted data – he simply sees it at the appropriate location. He also can easily understand this complex data by seeing it appropriately visualized. The AR representations of the teleoperation data are a core component of the telematic user interface proposed here and will be further detailed in the following sections.

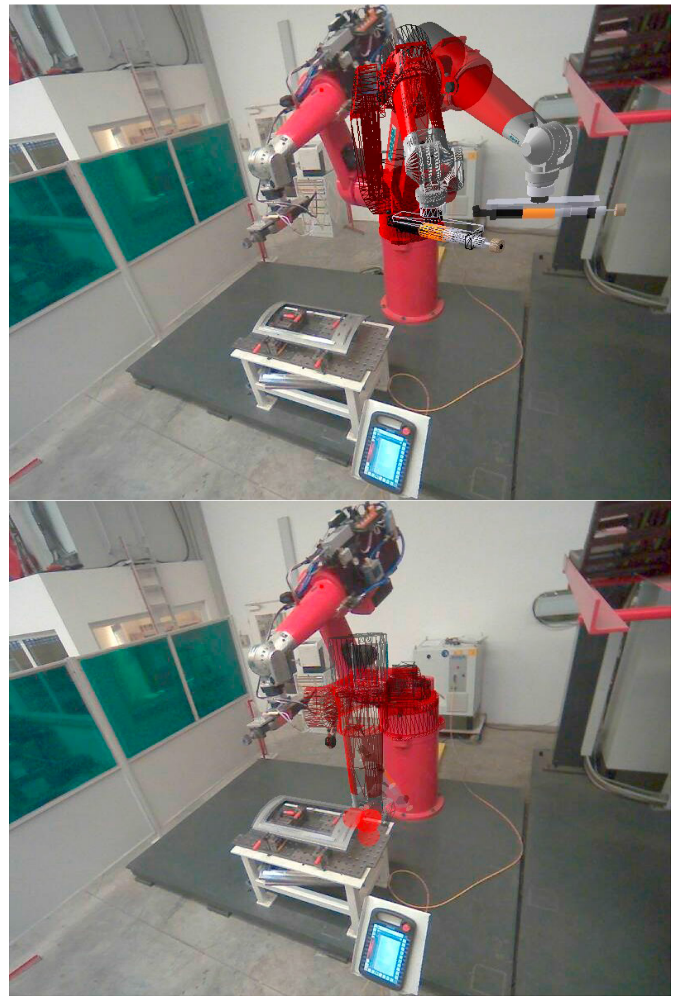

Fig. 2. Movement pre-visualization with AR in the user interface, using a wireframe overlay (top); potential collisions with known obstacles are marked in red (bottom).

4. AR FOR DISPLAY OF ROBOTIC DATA

4.1 Data to be visualized

The data a teleoperator will want to analyze will vary a lot, depending on the work application the robot is performing (for example handling packages, or grinding metal workpieces?), the actual task of the operator (optimizing the execution time of the current program, or trying to correct a runtime error?) and his individual approach to solve the task. With these distinctions made, also the amount of data that can be displayed with AR in a way meaningful to him will vary.
The strength of AR lies in intuitively visualizing complex information that cannot be grasped at a glance, and which has a distinct spatial location at the observed environment. As an example, visualizing ambient room temperature with AR does not make much sense – on the other hand, showing the

spot on the workpiece where the robot is going to drill with the current settings of the work program makes the job of the operator a lot easier.
As such, sometimes showing the numerical value or a plot of transmitted data variables will be sufficient for the teleoperator (for example to check whether a variable is out of nominal bounds), and he can choose those simple representations in the telematic interface developed here. Other, complex data can be grasped much better when visualized using AR. Of course, there is no single specification on how to visualize data using AR – several possibilities for the same information can be thought of; the choice might depend on the actual application, or just on the preferences of the operator. The essential point is that the chosen visualization makes this data easily understandable. The following section will introduce general possibilities to intuitively visualize data as well as several examples for data that can be easier understood and analyzed using AR, with special emphasis on data of force-sensitive applications.

4.2 AR for visualizing robot movement

One type of data the teleoperator will always rely on when remotely controlling an industrial robot is position and movement data. Whether checking processing spots, analyzing the processing trajectory or remotely moving the manipulator, the user will want to know the posture and the path of the robot. Manipulator positional data is usually encoded and transmitted as Cartesian coordinates of the tool tip in some chosen coordinate system, or as current positional values of the individual robot axes, where the tool position can be derived using a kinematic model of the robot. As such, the received data in its raw state is difficult to grasp even for experienced users. It can be made immediately comprehensible with AR by overlaying the image of the real robot with a virtual wireframe model of said robot that has been set to be in the received posture (Fig. 2 top). Here, the user simply *sees* where the tool will be and the pose of the robot – no further interpretation of the otherwise complex data is necessary. Further advantage of the AR representation versus a pure VR display is the reference to the current state of the real work environment that is maintained with AR, while in VR the user has to rely on his virtual environment model and does not know about the current situation there.
This technique can be used to show robot poses (for example, where the robot was when a certain event occurred, information on the orientation of the tool when contact to the workpiece is made), but also to analyze trajectories (recorded, or even modified, before actual execution with the real robot) by animating the wireframe model to see the whole movement of the manipulator beforehand. It can also be used for control: When remotely moving the robot, time delays can be troublesome and lead to overshooting and potentially collisions (Varnell (2013)). By controlling only the virtual model in the telematic interface, checking its movement and sending a command to trigger the actual movement of the real robot afterwards, the manipulator can remotely be moved securely and independent of time delays. Collisions can be detected before movement execution and marked in the AR image, if an environment model with potential obstacles is available (Fig. 2 bottom).

Besides only the position, also the movement speed of the robot can be relevant, for example when analyzing tool speed in process control, or to understand at a glance where each axis of the robot is currently moving to. The transmitted data here consist of vectors of either axis or Cartesian speed data. This information can be made easily understandable by drawing a three-dimensional arrow that is pointing into the direction of those speed vectors with size proportional to the absolute speed at the image position of the tool or the individual robot axes (Fig. 3). Using this AR visualization, the operator can easily see how fast and where the robot is moving to at this instant.
This speed vector display is representative for a more general approach to visualize various kinds of data with AR intuitively; this approach will be discussed in more detail in the following section.

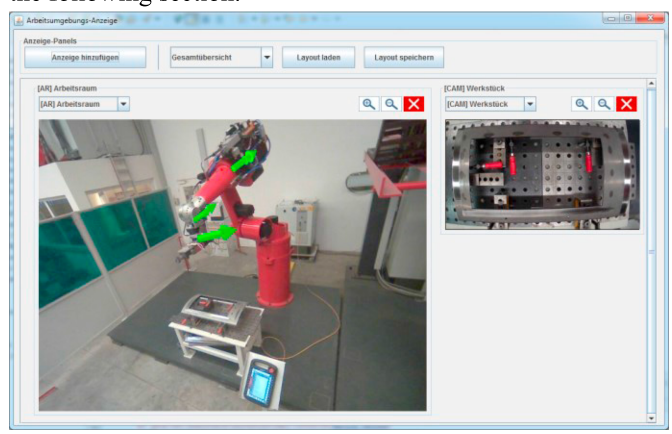

Fig. 3. Visualization of movement speed in the telematics GUI: direction and magnitude of the individual axes is visualized with AR using sized vectors.

4.3 Intuitive data display with AR

Most of the data transmitted when teleoperating or -monitoring an industrial robot has a well-defined spatial reference: Data recorded in the robot control system is usually related to the robot base or tool coordinate system, and as such, can be located in the robot environment and thus in the AR camera image. Besides its position, often some value or magnitude information is connected to the data, for example the absolute speed of the tool at that position, or the measured amount of force the robot is applying to the workpiece. This data then can easily and intuitively be visualized in the camera image: the position *where* it should be shown in the image is given by its location in the robot coordinate system (and applying appropriate image transformation calculations). The visual representation – *how* it should appear – is not predefined; it depends on the data (and possibly also on preferences of the user): a first simple possibility to visualize localized continuous data with a magnitude is to use a line following the given locations, whose thickness is proportional to the given value of the data at those locations (relative to some predefined reference value) (see Fig. 4 top left). Another example to represent such data with positional and value information is a box-plot-like visualization following the given locations (Fig. 4 top right). If additionally orientation data is available one can use directional symbols like the arrow from the previous section: here, the position (base of the arrow), direction (tip of the arrow) and value/magnitude (size of the arrow) of the received data can be shown in one representation (Fig. 4 bottom). Besides size, the value of the data can also intuitively shown using color-coding: for example, by choosing some predefined value as nominal and defining that data with values close to it should be painted green, data with higher values should shift its color towards red, and data with lower values should shift its color towards white one can easily see, where at the given trajectory values were close to the nominal values (painted green), where they exceeded nominal values (red) or fell below it (white). Using these visualization guidelines, for example the amount of pressure a robot applied while polishing a workpiece can be easily located and analyzed (see Fig. 5). The operator can immediately spot outliers and deviations, and can also localize the positions where they occurred on the workpiece at a glance. This would be much harder to do using only a plot of the transmitted force values, where the reference to the corresponding work piece location is missing). Of course, while these kinds of AR data visualizations offer a quick overview of data trends, they do not allow seeing precise values. To remedy this, the telematic AR interface proposed here allows seeing the AR visualization, associated numerical value and the position in plot representation simultaneously: by clicking on any spot of the visual representation (or on the plot), the user is presented the precise value of the visualized variable at this spot highlighted in the AR view, as well as the position of this data value in the corresponding data plot (Fig. 5).

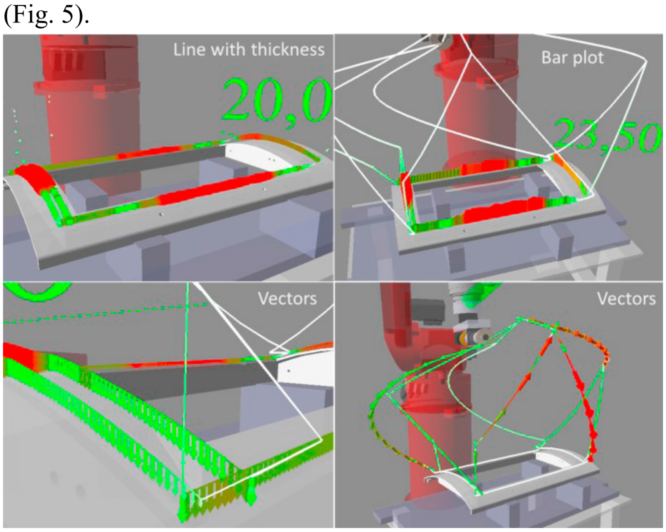

Fig. 4. Various possibilities for displaying spatial force (bottom right: speed) data (for better clarity shown in VR rather than AR); all visualizations color-coded (white = low, green = nominal, red = high).

This visual representation principle can be applied to various kinds of continuous spatial data values; the AR view allows for an easy overview, precise value analysis and a reference to the position on the processed workpiece for the teleoperator and thorough analysis of the work execution with reference to the real work environment even remotely.

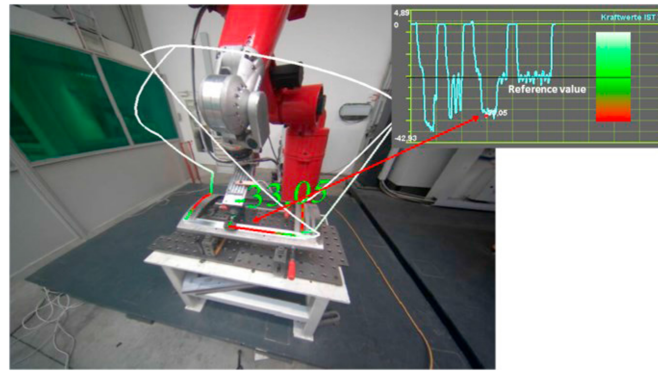

Fig. 5. Measured force applied to the workpiece color-coded; numerical values and reference to the plot can be obtained by simply clicking on a spot of the workpiece.

4.4 Intuitive program modification with AR

Besides analyzing the robot's work execution, the proposed telematic interface also allows easy modification of the force-sensitive processing remotely, while still allowing reference to the work piece: the operator is presented an overview image of the current workpiece with the current processing operations being visualized on top of it using AR. In order to gain up-to-date data of the current processing, the execution program of the robot in transferred, analyzed and visualized appropriately in the user interface. The operator can then make necessary modifications directly in this AR-view, for example moving the processing trajectory or changing parameters of the tool, while being able to see which part of the surface these changes will affect. Following this example, he can easily modify the work program to make the robot apply greater pressure on certain areas or change drilling locations according to some changed workpiece layout. The changes made are sent to the telematic control PC and either set directly in control variables, or transmitted to the appropriate receivers (like the force control system). The changes will come into effect right at the start of the next working cycle. As an example, modifications to a work program conducted during evaluation studies are shown in Fig. 6: The task of the robot here was to polish a metal workpiece to remove stains from welding. The path of the polishing tool on the surface and applied force in the normal direction are shown color-coded. The operator can now easily change the current processing instructions remotely: for once, he can shift individual points of or the whole processing trajectory in his interface, and will see the new processing path immediately visualized using AR. This makes it easy to predict where the robot will operate on the workpiece and change the program accordingly. For specifying the nominal force the operator can click on the path on top of the work piece AR image and specify new nominal values there. Depending on the process, other settings could be set here, for example turning speed or power of the tool, number of repetitions or others – the modification possibilities will always depend on the work scenario. The final result is visible in Fig. 6 on the right side: the robot now will process the welding spots, and apply higher force when polishing them than to other parts of the workpiece.

This example distinctly shows the advantage of the proposed AR interface over other tele-control approaches: with AR, it is possible to change a work program remotely while still having a reference to the processing positions on the workpiece. The combination of the intuitively visualized virtual information with reference to the real environment allow a teleoperator to quickly and easily analyze and modify the industrial robots behavior as needed.

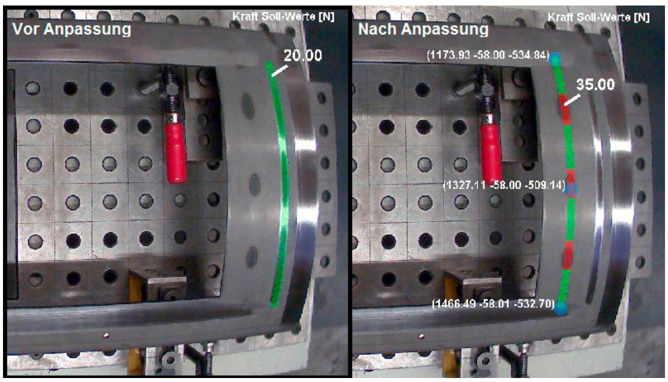

Fig. 6. Modification of processing remotely: work path and applied force are being corrected; changes can be made with reference to the real work-piece in the telematics GUI.

5. SYSTEM EVALUATION

To test the telematic interface and AR-based data visualizations introduced here, a demonstration system was set up and evaluated with support and technical personnel of the robot manufacturer Reis Robotics. The evaluating personnel was first introduced to the functionalities of the telematics interface, then as a working example, the work program of the metal polishing robot mentioned earlier was remotely analysed and then modified to test analysis, remote control and modification potential of the interface. Finally, an evaluation of the interface was formally conducted using interviews and questionnaires.

Regarding the AR visualization of the data in the remote work cell the testers found the AR pre-visualization of robot movement (and collision warnings) helpful and predominantly expected to be able to move the robot to a target position without causing any collisions. They unanimously agreed the AR visualization was the best solution to analyse transmitted data values with reference to the real workpiece remotely (as opposed to only images, numerical values/plots or VR). Main improvements suggested were a portable camera (which would require a tracking system to allow AR enhancements) and better methods to judge the work results remotely (in this case, the smoothness of the surface, which is hard to characterize with sensors/process data and thus cannot be visualized with AR).

6. SUMMARY AND FUTURE WORK

A telematics interface for remote monitoring, analysis and modification of force-sensitive work processes of industrial robots was presented. It was shown how transmitted complex robotic data can easily be made understandable to the teleoperator using Augmented Reality, allowing quick analysis and modification of work programs with reference to the workpiece even remotely.

Future work will focus on providing AR-enhancements also for portable cameras as well as developing and evaluating helpful visualizations for different kinds of robotic applications.

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