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Immersive Augmented Reality Environment for the Teleoperation of Maintenance Robots

A.W.W. Yew[a], S.K. Ong[a],*, A.Y.C. Nee[a]

[a]Mechanical Engineering Department, Faculty of Engineering, National University of Singapore
9 Engineering Drive 1, Singapore 117576

* Corresponding author. Tel.: +65-6516-2222; fax: +65-6779-1459. *E-mail address:* mpeongsk@nus.edu.sg

Abstract

A teleoperation system for maintenance robots using an Augmented Reality (AR) environment as a human-robot interface is proposed. The components at the remote maintenance site are reproduced in the local environment of the operator using a mixture of physical and virtual objects. The AR environment enhances situational awareness and reduces cognitive load by immersing the operator in a representation of the remote site and overlaying information related to the maintenance task on the corresponding objects. Another contribution of the proposed system is an intuitive method for defining ad-hoc robotic maintenance tasks without the need for robot programming knowledge.

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Keywords: Augmented reality; human-robot interaction; teleoperation; maintenance

1. Introduction

In the age of Industry 4.0 and sustainable manufacturing, smart factories and other engineering facilities employ complex systems of machinery, sensors and controllers. The maintenance of such systems during their life cycle is important in ensuring that downtime is minimized, and sustainability goals, such as energy-efficiency and resource-efficiency, continue to be achieved. Maintaining these complex systems requires expert knowledge which may not always be available, or these systems may be located in places that are hazardous or hard to reach for human workers. The development of a tele-operated maintenance robotic system that allows a remote expert to carry out maintenance is thus valuable in the life cycle engineering and management of complex systems and facilities.

Augmented reality (AR) technology is used in many applications to superimpose computer-generated graphics on the physical environment, and to facilitate natural interaction with computer applications. Natural interaction methods are normally preferred over traditional keyboard and mouse interfaces when developing AR applications in order to free users from the confines of a desktop environment. Motion tracking of users has been implemented in AR applications [1, 2], enabling direct interaction with virtual objects in the physical environment. In other instances, user interaction devices are specially designed and customized to suit the applications [3, 4].

For maintenance, sensor data, equipment status logs, and data sheets are some of the information sources to which a maintenance expert would need to refer to in order to rectify faults. The sheer amount of data to trawl through could be overwhelming, which could complicate fault diagnostics and rectification. AR could be used to provide users with an augmented display over the real physical scene that filters information according to context and location while they carry out maintenance tasks.

The problems of robot teleoperation interfaces are well-documented. The lack of situational awareness by the human operators and the high cognitive load of having multiple sources of information for the maintenance tasks negatively impact the performance of the human operators. To alleviate these problems, this paper proposes a novel AR-assisted system for the teleoperation of maintenance robots. Through

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the use of a wearable immersive AR display system, the maintenance environment is replicated, with the equipment and machinery in the maintenance environment represented using a mixture of physical and virtual objects in the operator's workspace. The operator perceives the maintenance environment and controls the robot through interactions with the workspace. For example, the operator moves around the workspace to study different parts of the equipment and observe critical sensor and image data overlaid on the equipment. Natural and intuitive interaction with the system is achieved through a handheld pointer that enables the operator to define corrective maintenance tasks for the robot to perform by pointing at objects or drawing paths along objects. The implementation of the system and findings of preliminary evaluations are discussed in this paper.

2. Issues in Robot Teleoperation and Related Work

Operator situational awareness and cognitive load are important concerns in robotic remote maintenance that have been widely studied. Yanco et al. [5] analyzed human-robot interfaces developed for search and rescue operations and presented a set of guidelines for the design of human-robot interfaces. These guidelines include fusing sensor information to reduce mental fatigue due to cognitive load on the user, minimizing the use of multiple windows in the graphical user interface, and providing spatial information about the robot in its environment, such as in the form of a map. Subsequently, Nielsen and Goodrich [6] showed that presenting spatial information in the form of a map and video combined in a 3D interface results in significantly improved operator performance in exploratory robot tasks as compared with map-only, video-only, or map and video combined in a 2D interface.

Virtual reality (VR) is a common approach for robot programming and control as a 3D representation of the robot and its environment is presented to the user, thus enhancing the situational awareness of the operator. For controlling a remote maintenance robot, a human-robot interface proposed by Soares et al. [7] employs a third-person VR view of the robot and its surroundings displayed through a head-mounted display to immerse the user in the environment. The user can switch to several different view modes that present different information, including a general view that presents a mosaic of all the different views. A joystick is used to control the manipulators and end-effectors.

A more intuitive and efficient control method was developed by Netland et al. [8] for a remote robot inspection of wind turbines. The system utilized a tablet for viewing information and its touch-screen was used for controlling the robot that was confined to motion along rails. Image processing techniques were used to detect differences in the state of the machinery based on historical images, and these differences were highlighted to the user on the tablet screen.

3. Augmented Reality Interface for Remote Maintenance

Two guidelines from the reported works discussed in the previous section have been taken into consideration to formulate the design of the proposed system, namely, that information should be fused into a single view to reduce mental fatigue and cognitive load, and that spatial information about the robot in its environment should be provided.

The proposed system transforms the operator's environment into an AR environment, which is a reconstruction of the remote site where the robot is located to conduct the maintenance tasks. A mixture of physical and virtual objects, including a virtual robot, is used to represent components that are present at the remote site. Henceforward, "real robot" refers to the robot at the remote site and "virtual robot" refers to the virtual robot in the AR environment.

The AR reconstruction of the remote site is used as a 3D map of the surrounding of the real robot; the operator is physically immersed in this reconstructed AR environment and can freely explore the surrounding. The physical objects provide the key components present in the remote site and serve as a haptic reference to the operator, i.e., these objects can be felt by the operator making it easier to define robotic tasks to be executed on or around them, while the virtual objects provide the more intricate components that would be too costly to reproduce physically.

The AR reconstruction of the remote site is focused on one main physical component, with virtual components attached to this main component. For example, for a remote site containing an air handling unit (AHU), the AR environment could be made up a virtual model of the AHU box, while a physical pipe prototype serves as the main physical component and the pipe fixtures and other branching pipes are modeled as virtual components (Figure 1).

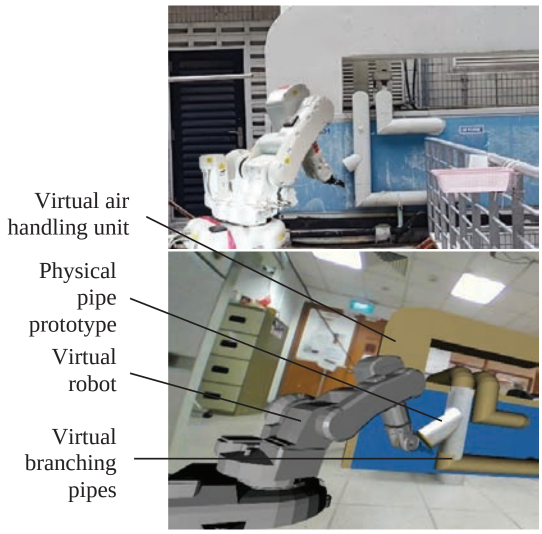

Fig. 1. A remote site (top) represented in the local AR environment (bottom) using a mixture of physical and virtual components.

The level of details in which the physical components should be reproduced would depend on the nature of the maintenance procedures. It might be desirable to reproduce pipes accurately so that robotic maintenance tasks of repairing cracks along the surface of the pipes can be defined by the user through drawing gluing paths on the surfaces using the handheld manipulator. It might also be desirable to use abstract representations of some physical components in the AR environment to make it easier for the operator to keep track of the roles of the different parts of the physical component during the maintenance task.

Graphical overlays provide information that is spatially-registered to the components that are relevant, thereby filtering and reducing the cognitive load on the user. The handheld manipulator has buttons and serves as a pointing and interaction tool. It provides a natural interaction method for the users to create paths for the real robot end-effector, such as welding path definition, and interact directly with objects in the AR environment so as to define tasks for the real robot.

In the proposed system, remote maintenance tasks are categorized into two phases, namely visual inspection or corrective task execution. Each phase can be activated as required by the operator. For example, during visual inspection, the operator might find a damaged part. The operator can proceed on to the corrective task execution phase to replace the part before returning to visual inspection to look for other damaged parts.

3.1 Visual Inspection

During visual inspection, situational awareness of the fault symptoms and their locations are vital to the operator's understanding of the faults. There can be multiple sources of information that are pertinent to the maintenance operations, such as a color video camera, thermographic camera and gas sensor.

The AR environment serves as a map on which the operator is able to determine the specific component at the remote site that he is looking at. This aids in the understanding of the locations where the symptoms are occurring. All sources of information are fused into a single view such that the operator can focus on to ensure that no sources of information are neglected.

Sensor data can be displayed in the AR environment over the components to which they are related. Using the handheld manipulator, the operator can lead the virtual robot arm to the areas of interest in the AR environment. The position of the virtual robot arm is transferred to the real robot in the remote environment, causing the camera on the real robot arm to point to the corresponding areas of interest at the remote environment. The camera images are superimposed on the operator's view of the corresponding components in the local AR environment so that the operator is spatially aware of where he is looking. The components in the remote site can be represented in the AR environment with additional annotations and labels to highlight their potential importance so that the operator can decide quickly the location to lead the real robot arm. By pointing to the component representations in the AR environment that correspond to those in the remote site, the operator can be made aware constantly of the locations of the symptoms.

3.2 Corrective Task Execution

Corrective task execution refers to various robotic operations that are carried out in order to rectify faults that are discovered during visual inspection. There are many types of maintenance operations, such as disassembly, fastening, cleaning, spraying, welding and parts replacement, that may be required depending on the type of equipment and faults to be rectified. Through the use of automated tool changers, a single robot arm can perform different operations using different tools and end-effectors.

The user defines the motion of the real robot arm to perform corrective maintenance tasks by using the handheld manipulator to lead the virtual robot arm. The virtual robot helps the operator in visualizing the movement of the real robot arm before the task is executed on the real robot. Using physical objects to represent components at the remote site, the user can plan and define paths easily along objects due to the tactile feedback when the manipulator comes into contact with the objects.

Pre-programmed operations for the real robot arm, such as fastening and disassembly, can be executed easily through the AR interface. These pre-programmed operations are operations that the real robot arm has been trained to perform off-site prior to the maintenance work being carried out. The operator can select a component at the remote site and choose a pre-programmed operation for the real robot to work on for that component. For example, in order to disassemble a plate, the operator can point the handheld manipulator at each of the screws that are represented in the AR environment and select the unfastening operation from a menu that is displayed and augmented over the screws. Thus, complex corrective tasks can be executed through the AR interface by defining combinations of paths for the real robot arm and pre-defined operations for specific components at the remote site.

4. Methodology

4.1 System Architecture

The system architecture is illustrated in Figure 2. The proposed system consists of the real robot at the remote site and the AR system in the operator's local environment. At the remote site, the real robot includes the camera mounted on one arm, and is connected to a processor that controls the motion of the robot and transmits camera images and other data to the system in the AR environment wirelessly.

The AR system consists of an optical tracking system, a handheld manipulator for interaction with the virtual robot and the objects in the AR environment, and a head-mounted display (HMD) worn by the operator to see the AR scene. The optical tracking system is used for tracking the pose of the handheld manipulator and the HMD. Commands that are given by the operator using the handheld manipulator are transmitted to the processor of the real robot wirelessly.

4.2 Environment Reconstruction

The reconstruction of the remote site in the AR environment is based on the relative pose between the real robot and the main physical component at the remote site. The main physical component is represented by a physical object in the AR environment, and the virtual robot is placed in the same relative pose to the physical object. Assuming the layout of the components at the remote site is known *a priori*, the virtual representations are placed accordingly with respect to this main physical component.

At the remote site, the registration of the transformation between the real robot and the main physical component can be accomplished using the camera mounted on the real robot arm to track recognizable features at the remote site, e.g., a fiducial marker that has been placed there. Tracking algorithms are used to compute the camera-to-marker transformation, while the robot-to-camera transformation is measured when the camera is mounted on the real robot arm. The robot-to-marker transformation, which is equivalent to the transformation between the real robot and the main physical component, is thus given by the addition of the robot-to-camera transformation and the camera-to-marker transformation.

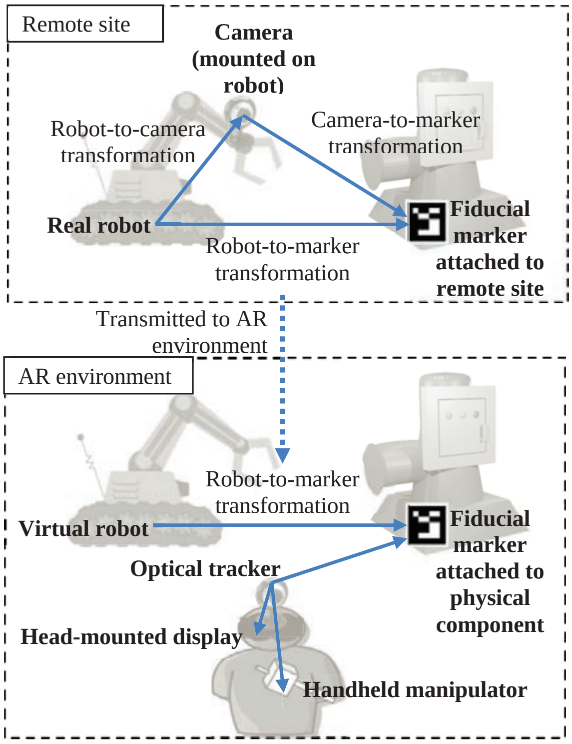

Fig. 2. Architecture of the proposed system.

After the transformation of the real robot has been registered to the main physical component on the remote site, the virtual robot is displayed in the AR environment using the same transformation with respect to the representation of the main physical component.

The optical tracking system tracks the pose of the handheld manipulator, HMD and representation of the main physical component in the AR environment. The poses of all the objects tracked by the system are expressed in the coordinate system of the virtual robot base. This allows virtual graphics to be displayed in their respective positions around the virtual robot. This also allows the handheld manipulator to represent a position and orientation with respect to the virtual robot, which can be transferred to the real robot so as to move its end-effector to the corresponding position in the remote site in the same orientation.

4.3 *Robot Arm Target Point and Path Definition*

The handheld manipulator is a representation of the robot end-effector in the local AR environment (Figure 3). Fiducial markers are attached on it so that its six degrees-of-freedom (6DoF) motion can be tracked by the camera on the user's HMD. The tip of the manipulator is used as a pointer for interacting with components in the reconstructed AR environment; it can also be defined as the tool-center-point (TCP) of the real robot.

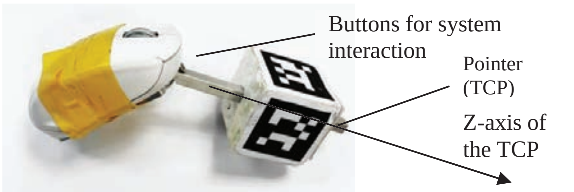

Fig. 3. Handheld manipulator for interacting with the reconstructed AR environment.

The operator defines the target points and paths of the virtual robot arm by using the handheld manipulator. Paths can be "drawn" directly in the 3D space of the AR environment. The corresponding required joint trajectories of the real robot arm to move the arm along these paths are calculated using the inverse kinematics of the real robot. The pose of the handheld manipulator with respect to the real robot base is used as input to the inverse kinematics solver, which computes the joint angles of the robot arm. The inverse kinematics is solved in real-time, so that the trajectory of the virtual robot arm can be simulated according to these joint angles. Consequently, the virtual robot arm follows the handheld manipulator as the operator defines the paths. This is akin to lead-through programming of the virtual robot, and allows the operator to visualize the motion of the virtual robot arm to ensure that the path is reachable before defining a path and executing it on the real robot.

For the execution of the user-defined points and paths, the full motion of the real robot is planned automatically using a motion planning algorithm. This allows the user to focus on defining maintenance tasks and moving the camera on the real robot for visual inspection rather than be concerned with defining the full path of the robot.

4.4 *Visual Inspection*

For visual inspection, the camera is mounted on the real robot arm such that it faces the z-axis of the real robot end-effector. The z-axis of the handheld manipulator is aligned along the z-axis of the real robot end-effector. Therefore, for the operator to look at a specific area of the remote site, he has to lead the virtual robot to the corresponding location in the local AR environment and point the handheld manipulator at this location.

Each camera image transmitted to the AR environment is displayed as a planar texture over the object pointed to by the handheld manipulator. An algorithm has been that computes the position and orientation to display the planar texture in the AR environment. For this algorithm, digital 3D models of the objects at the remote site are required. The faces of the 3D models are indexed, and 2D texture coordinates are defined for each face. The algorithm consists of three steps to register the camera image to the correct face of the virtual object and the correct region of the face (Figure 4):

1. Determine the face that is in the view of the camera using an intersection test between the direction vector of the camera (z-axis of the robot) and all faces of the object.
2. Determine the region of the face obtained from step 1 by projecting the camera view onto the face.
3. Assign the 2D texture coordinates to the camera image such that it is mapped to the region of the face obtained from step 2.

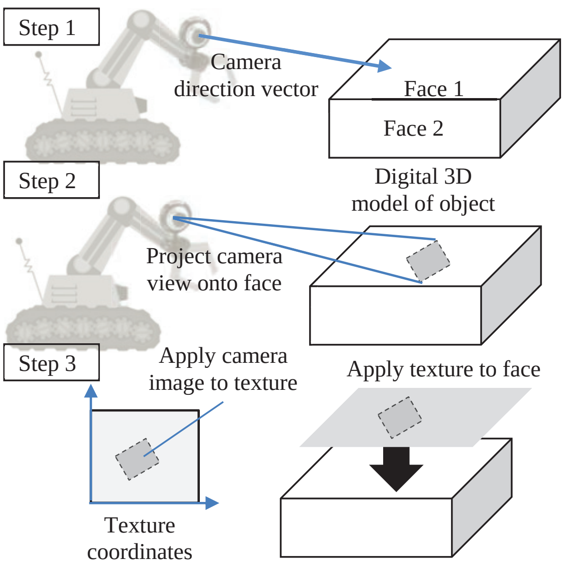

Fig. 4. Determination of planar texture to display camera images over objects in the AR environment.

4.5 Pre-programmed Operations

Operations, such as tool-changing, picking up replacement parts from a holder, and fastening and unfastening are pre-programmed as subroutines before the robot is deployed to perform maintenance work. These operations can be executed automatically during maintenance when needed; thus, this will reduce the time and effort needed to perform ad-hoc programming of the robot motion for these operations.

For operations that are to be performed on specific components, such as the unfastening of screws, the operator only needs to pick the target components using the handheld manipulator and point at their corresponding representations in the AR environment. Based on the 6 DoF tracking of the manipulator, the 3D position of the pointer can be used to determine the component that is being pointed at using the same ray-casting technique as shown in Figure 4. However, instead of casting the ray from the camera, the ray is casted from the pointer of the handheld manipulator instead.

5 Prototype Implementation

5.1 Prototype System

A prototype of the proposed system has been implemented based on an ABB IRB 140 robot arm with a PC camera mounted on it. A processor connected to the real robot receives joint trajectories from the AR system and executes them on the real robot, and transmits images from the camera to the AR system.

The AR system comprises an Oculus Rift DK2 HMD with a PC camera attached to it (Figure 5), and a PC used as the processor. An AR viewing and interaction software application that the authors have developed runs on this PC. The camera attached to the HMD serves as the optical tracking system. It tracks the pose of the HMD and handheld manipulator using the attached camera, and generates and displays the AR environment in the HMD.

A mixture of marker-based tracking and natural feature tracking is implemented in the software application to track the HMD. The pose of the HMD is computed when a fiducial marker attached to a physical component in the AR environment is detected by the camera, or by detecting physical features in the AR environment when the fiducial marker is out of the field of view of the camera. This allows greater freedom of movement by the user without losing continuous tracking of the HMD. Marker tracking and natural feature tracking are implemented using the Aruco library [9] and parallel tracking and mapping library [10] respectively.

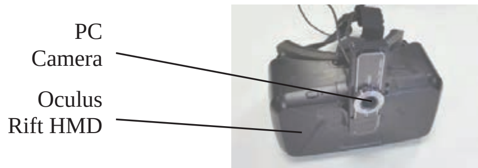

Fig. 5. Augmented reality display device.

5.2 Pilot Study

A laboratory-based pilot study was conducted to test the prototype with five users who do not have experience in robotics. An AR environment was set up in one area of the laboratory while the robot arm was in another area. The users were given a five-minute introduction and familiarization session with the system, after which they were asked to perform three tasks. The first task was to inspect the network connections inside the robot controller (Figure 6). This task was given to simulate the visual inspection of a service panel. The second task was to command the robot to remove the nozzle on a pipe by unscrewing the screws (Figure 7a), and the third task was to define a path for the robot arm to fill a crack on the pipe with glue using the AR interface (Figure 7b).

For the first task, the service panel was represented in the AR environment as a map indicated with words of the different sub-systems in the panel. For the second task, the nozzle and the screws were represented as virtual objects. For the third task, the pipe was represented in the AR environment as a physical replica of the object in the remote site. The latter two tasks were not executed with the real robot as geometrical verification and positional compensation methods to ensure that the real robot executes the tasks with accuracy have not been integrated with the system. From the pilot study, it was observed that after giving the users instructions in plain simple language, the users were able to conduct the maintenance tasks using the AR system quickly. The latter two tasks were verified to be executable by simulating the robot motion using the virtual robot.

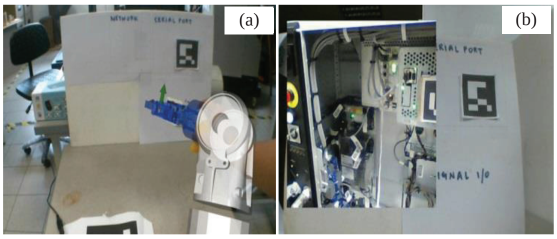

Fig. 6. (a) Representation of the inside of the robot controller in the AR environment, and (b) overlay of camera images from the real robot on the AR environment.

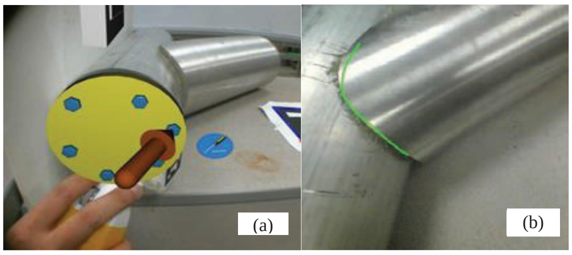

Fig. 7. (a) Selection of a virtual screw in the AR environment, and (b) a gluing path drawn on a pipe in the AR environment.

6 Conclusion and Future Work

An immersive AR environment for conducting remote maintenance via a robot has been proposed in this paper. The novelty of this approach lies in the use of a mixed reality to enhance the perception of the remote maintenance site by the user, and enhance human-robot interaction with the robot at the remote site via a virtual robot in the local AR environment. The AR environment has been designed to enhance the operator's situational awareness of the robot as well as the maintenance tasks so as to reduce the cognitive load on the operator; this is achieved through information filtering by spatially registering graphical information to relevant components. A handheld manipulator allows the user to control the robot arm naturally, while inverse kinematics and motion planning algorithms are used to visualize the reachability of the robot and automatically generate the motion of the robot in between user-defined tasks. This maintains the operator's intuition of the limitations of the robot and simplifies the process of visual inspection and the definition of paths and tasks for the robot arm by only requiring the user to define robot motion for maintenance tasks.

This research is still a work-in-progress. Two major issues remain to be solved before the system can be fully evaluated and put into practice. First, the insufficient accuracy of optical tracking methods hinders the ability of the robot to execute certain tasks defined through the AR interface. The authors plan to solve this problem by integrating more advanced optical tracking sensors and algorithms so that corrective task execution can be carried out accurately. Second, in a real application environment, there will be hazards and obstacles that are not known *a priori* and hence cannot be captured in the AR environment. The authors plan to solve this by integrating depth sensors to detect unknown objects in the remote site, and using this as input to generate robot paths that avoid obstacles.

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