The role of augmented reality in robotics

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Abstract

Purpose – The purpose of this paper is to provide an insight into how augmented reality (AR) technologies are being applied to robotics.

Design/methodology/approach – Following an introduction and a brief historical background to AR, this first provides examples of AR applications in robot programming. It then gives examples of recent research into AR-based robot teleoperation. Research activities involving the virtual fixtures (VF) technique are then discussed and finally, brief conclusions are drawn.

Findings – Because AR concepts were first investigated in the 1990s, applications involving robotics have been widely studied. Programming with the aid of AR devices, such as the HoloLens headset, can be simplified and AR methods, including the VF technique, can improve the accuracy and speed of teleoperation, manipulation and positional control tasks. They can also provide visual or haptic feedback which leads to more intuitive operation and significantly reduces the cognitive load on the operator.

Originality/value – This provides an insight into the growing role of AR in robotics by providing examples of recent research in a range of applications.

Keywords Programming, Robots, Augmented reality, Teleoperation, Virtual fixtures

Paper type Technical paper

Introduction

Augmented reality (AR) can be defined as the technology that expands or augments the physical world by adding layers of computer-generated information onto it, sometimes across multiple sensory modalities, such as visual, auditory, haptic or somatosensory. Unlike virtual reality, AR does not create an entirely artificial environment to interact with or be immersed in but simply adds to the physical reality one would normally experience.

The term "augmented reality" was first coined by two Boeing employees in 1990 to describe a system comprising a head mounted, transparent display which was aimed at helping workers to assemble the long and complex bundles of wires on the then new 777 airliner. This technique was further developed and was described by Caudell and Mizell (1992). In the same year, the first AR system that provided an immersive experience was developed at the US Air Force's Armstrong Laboratory, the "virtual fixtures" (VF) technique, which has since been applied to a wide range of robotic applications (Rosenberg, 1992). The aim was to improve human performance in direct and remotely manipulated tasks via an overlay of virtual sensory information on a workspace. It used two physical robots, controlled by a full upper-body exoskeleton worn by the user (Figure 1). To create the immersive experience, an optical configuration was used that involved a pair of binocular magnifiers aligned so that the user's view of the robot arms was brought forward so as to appear in the exact location of the user's real arms. The result was a spatially registered, immersive experience in which the user moved their arms while seeing robot arms in the position where their arms should be. The system used computer-generated virtual overlays in the form of simulated physical barriers, fields and guides, which were designed to assist the user while performing physical tasks.

This article aims to provide an insight into recent robotic developments involving a range of AR techniques.

Augmented reality as an aid to robot programming

The potential of AR techniques to aid and simplify robot programming has been studied for over a decade and research has recently gained momentum with the lunch of the Microsoft HoloLens in 2016, a head-mounted mixed-reality unit. Now in its second iteration, the HoloLens 2 (Figure 2) was launched in 2019. This is a significant technological development as it integrates several AR capabilities that formerly required separate pieces of hardware and software into a compact and versatile device. It features an inertial measurement unit which includes an accelerometer, gyroscope and magnetometer, four "environment understanding" sensors, a depth camera with a $120° \times 120°$ field of view, a 2.4 megapixel video camera, an array of microphones and an ambient light sensor. It offers eye and hand tracking and both speech and gesture recognition. In addition to the CPU, it includes a custom holographic processing unit and a co-processor manufactured specifically by Microsoft. Wireless connectivity is through IEEE 802.11ac, Wi-Fi and Bluetooth.

As an example of recent research, workers from Leibniz University and AR specialist Viewlicity GmbH recently reported an AR technique for robot pick-and-place programming using

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Figure 1 Louis Rosenberg at the US Air Force Armstrong Laboratory testing the virtual fixtures AR system

Source: Wikipedia

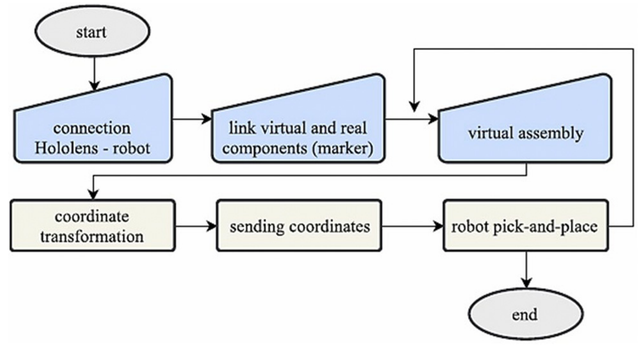
Figure 2 Microsoft HoloLens AR headset

Source: Microsoft

the HoloLens. This is based on a complex technique, described in detail by Blankemeyer *et al.* (2018), which converts virtual assembly steps into a robot programme. The product is assembled virtually by the user and physically by the robot. To programme an assembly step, the user first conducts the assembly step virtually by moving the virtual component to the required position. The virtual component is displayed by the HoloLens and is in the same position as the real component, whose position is determined by marker tracking. The start and end coordinates of the assembly step are determined and saved with respect to the internal coordinate system of the HoloLens (CSH). To enable the robot to manipulate the real components, these coordinates must be transformed from CSH into the robot's base coordinate system. The transformed coordinates are subsequently sent to the robot, which then performs the manipulation in reality. The programming flow chart is shown in Figure 3. The concept was tested by assembling two parts of a model helicopter using a Kuka KR6 R900 robot (Figure 4) which was connected to the HoloLens by the Kuka "Robot Sensor Interface". Although the assembly process was successfully demonstrated, it was found that positional accuracy was limited, typically in the mm range and the authors suggest that improvements may arise from alterative marker tracking software or by replacing it with object recognition techniques.

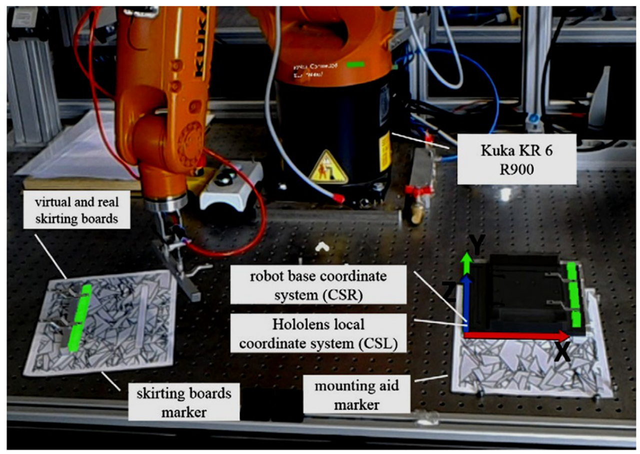
Several other groups have recently exploited the capabilities of the HoloLens as a programming aid. For example, a group

Figure 3 Programming flow chart



Source: Blankemeyer *et al.* (2018)

Figure 4 Robotic cell showing real and virtual assemblies



Source: Blankemeyer *et al.* (2018)

from the Karlsruhe Institute of Technology has developed a system consisting of the HoloLens, a PC running the open-source ROS and a Kuka KR-5 robot (Puljiz *et al.*, 2019). The technique allows the programming of collaborative robots without the need for torque/position sensors on the robot and exploits the in-built hand tracking capabilities of the HoloLens, together with its ability to create a holographic robot with the same geometry and kinematics as the real one.

Researchers at the University of British Columbia are developing an AR robot programming interface system by combining the HoloLens with a pair of surface electromyography (EMG) and gesture sensing armbands (Quintero *et al.*, 2018). The system allows trajectory specification, virtual previews of the robot's motion, visualisation of operating parameters, on-line reprogramming during simulation and execution, gesture- and EMG-based control of trajectory execution and on-line virtual barrier creation and visualisation. A video showing the system can be viewed at https://youtube/amV6P72DwEQ. The system has been validated by comparing it with kinaesthetic teaching and other standard methods and the group is now collaborating with the DLR, the German aerospace agency, in applying the system to the pleating process of industrial carbon fibre-reinforcement polymer manufacturing.

Teleoperation and augmented reality

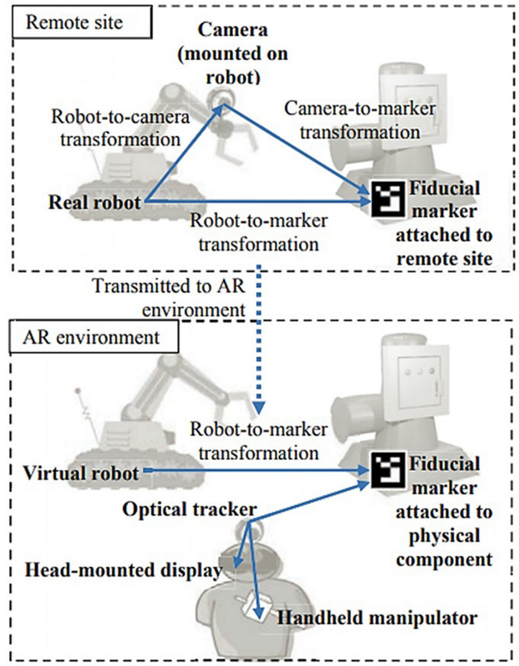
The main telerobotic applications are presently in the surgical and military contexts, but AR technologies have the potential to expand uses into other areas and enhance capabilities by yielding greater levels of control and reduced cognitive load on the operator. As with programming, several groups are experimenting with commercially available AR products. An example is work by a Chinese group which has developed a teleoperation system based on a Leap Motion controller, a HoloLens and a 6-DOF robotic arm (Liang *et al.*, 2019). The Leap Motion includes three IR LEDs and two depth cameras and is used to capture the operator's hand motion and positions. An algorithm developed by the group converts the Leap's coordinate system into the coordinate system of the robot and generates positional information for controlling the robot. The system creates real-time visual feedback to the operator by generating a mixed reality scene and displaying it via the HoloLens (Figure 5). In this way, the operator is able to observe the slave robot and a virtual model of the hand, thereby making the teleoperation process more intuitive. In trials, a human operator successfully used the system to teleoperate the robotic arm to write a simple Chinese character "Wang"(王).

Workers from the National University of Singapore have developed an immersive AR system for conducting remote robotic maintenance tasks (Yew *et al.*, 2017). The system, illustrated schematically in Figure 6, consists of the robot at the remote site and the AR system in the operator's local environment. At the remote site, the robot has a camera mounted on one arm and is connected to a processor that controls its motion and wirelessly transmits images and other data to the system in the AR environment. The AR system consists of an optical tracking device, a handheld manipulator (Figure 7) for interaction with the virtual robot and the objects

Figure 5 Image displayed by the HoloLens

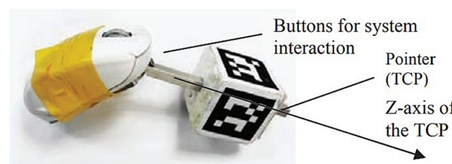
Source: Liang *et al.* (2019)

Figure 6 Schematic representation of the system



Source: Liang *et al.* (2019)

Figure 7 Handheld manipulator is a representation of the robot end-effector in the AR environment



Notes: Fiducial markers are attached so that its motion can be tracked by the camera on the 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 centre point of the real robot
Source: Yew *et al.* (2017)

in the AR environment and a head-mounted display (HMD) worn by the operator to view the AR scene. The optical tracking system is used for monitoring the pose of the handheld manipulator and the HMD. Commands from the operator using the manipulator are transmitted to the processor of the real robot. A prototype system based on an ABB IRB 140 robot arm was used to conduct three tasks to inspect the network connections inside the robot controller which aimed to simulate the visual inspection of a service panel, to remove the nozzle on a pipe by removing the screws and to define a path for the robot arm to fill a crack on the pipe with adhesive. The system was tested by five subjects who were each given a 5 min introduction and familiarisation session with the system. They were then asked to perform the tasks and it was found that after providing instructions in simple language, they were able to do so. The group maintains that, by immersing the operator in a representation of the remote site and overlaying information relating to the task, the AR environment enhances situational awareness and reduces cognitive load.

The role of virtual fixtures

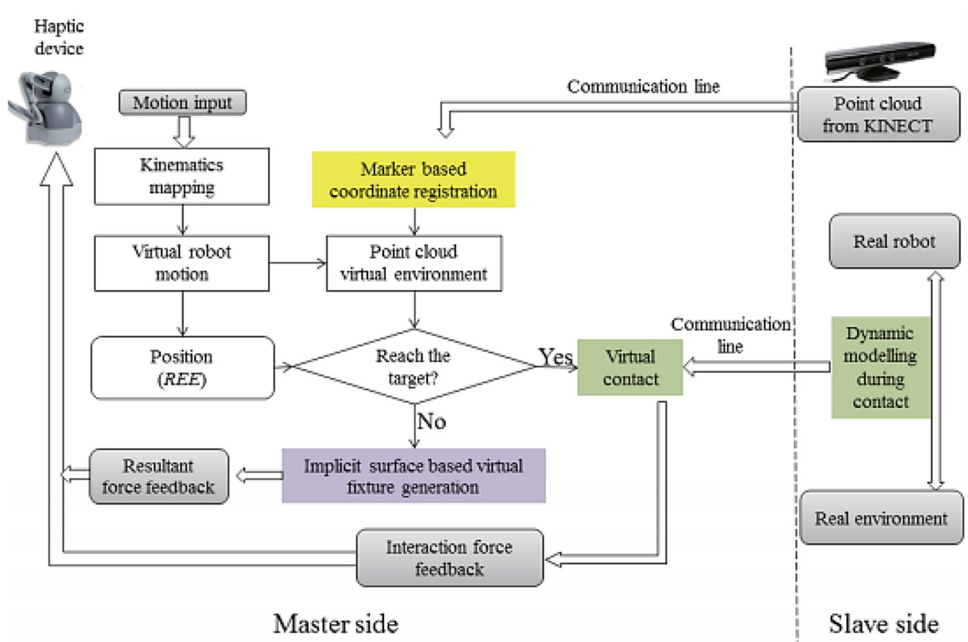
VF is a technique that uses software-created algorithms to generate spatial motion control in the virtual environment. The main forms are "guidance virtual fixtures" (GVFs), which assist the user in moving the robot/manipulator along the required paths or surfaces in the workspace and "forbidden region virtual fixtures" (FRVFs) which define forbidden spaces or paths and are generally used to prevent a robot's end-effector from entering a specific area. The feedback to the human can be visual or haptic and many developments covering varied applications have been reported in recent years.

Workers from China's Southeast University have developed a haptic-assisted teleoperation system that generates VFs for motion guidance and haptic feedbacks for dynamic interactions with the environment (Ni *et al.*, 2017). A novel VF generation method was developed in a point cloud augmented virtual environment for human operational guidance. Forces generated from both FRVFs and GVFs were fed back in real time to the human operator through a haptic device. The operator controls the virtual robot using a 6-DoF positional sensing and 3-DoF haptic device. As the virtual robot moves in the transmitted point cloud, when it is far from the target the VFs are established in real time and fed back to the operator for motion guidance. Simultaneously, the regulated commands are forwarded to the slave robot for real-time control. When the operator reaches the target, the dynamic modelling on the slave side is implemented to generate haptic feedback. Trials showed that teleoperation tasks, including obstacle avoidance, were significantly faster and resulted in fewer collisions with the system than when using conventional teleoperation. Figure 8 shows a schematic representation of the system.

Many applications in health care have been reported and there is an extensive literature. A recent example is research by workers from the Shenzhen Institute of Advanced Technology at the Chinese Academy of Sciences and the University of Hamburg who have developed a human/robot cooperative control method based on VFs for use in endoscopic sinus surgery (He *et al.*, 2019). Firstly, through endoscopic trajectory analysis, the endoscopic motion constraint requirements of different surgical stages were obtained and three VFs suitable for endoscopic sinus surgery were designed and implemented. Based on these VFs, a composite VF is constructed and the overall robot motion constraint model was obtained. Based on the constraint model, a human–robot cooperative control method was developed in which the VF is used to restrain and guide the robot, thereby ensuring safe motion. The method was evaluated through a robot-assisted nasal endoscopy experiment and the results show that it can improve the accuracy and safety of endoscopic sinus surgery. A system schematic representation is shown in Figure 9.

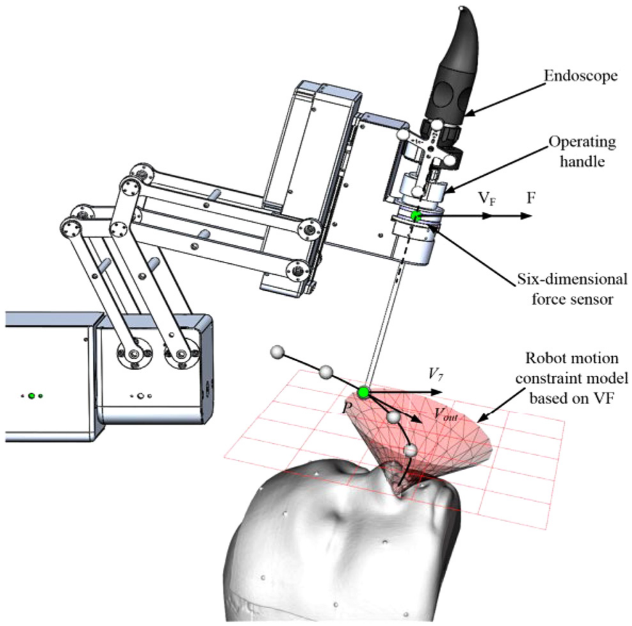
Another recent medical application has been reported by a group from the University of Tokyo (Marinho *et al.*, 2020). The limited workspace available in paediatric endoscopic surgery makes suturing a particularly difficult task and surgeons have to prevent collisions between tools and also with the surrounding tissues. A system that uses two VFs, namely, looping virtual fixtures (LVFs) and a trajectory guidance cylinder (TGC), together with Cartesian force feedback has

Figure 8 Schematic representation of the system



Source: Ni *et al.* (2017)

Figure 9 Schematic representation of the system



Source: He *et al*. (2019)

been developed. On the system's slave side, a constrained optimisation algorithm generates the LVFs and the TGC and on the master side a Cartesian impedance algorithm allows the user to "feel" safe and optimal directions during the looping stage of suturing. In simulations and experiments by surgeons with a robot, the method achieved more precise and safer looping in paediatric endoscopic procedures.

A very different application is the topic of on-going research at John Hopkins University, where a group is investigating the use of VFs and AR and visualisation in the remote, robotic servicing and maintenance of satellites (Vagvolgyi *et al.*, 2018). In-orbit servicing is complicated by the fact that almost all existing satellites were not designed to be serviced. This creates a number of challenges, one being the need to cut and partially remove the protective thermal blanketing that encases a satellite, prior to the servicing operation. Experiments on a ground-based telerobotic platform, with software-created telemetry delays, indicated that the method leads to enhanced teleoperation performance with a 30 per cent improvement to the cutting blade alignment and a 50 per cent reduction in the time required to execute the task. Another innovative application has recently been reported by a group from Nanjing Technical University who have developed a system for the remote control of the trajectory of a robotic excavator (Feng *et al.*, 2019). This involved the use of flexible VFs in the trajectory tracking process which rely on the current position at the excavator's bucket tip. Various different tasks were designed to validate the performances of the flexible VF system and trials showed it could achieve high tracking precision and good obstacle avoidance.

Concluding comments

Because AR concepts were first investigated in the early 1990s applications involving robotics have been the topic of extensive study. Robot programming can be simplified with the aid of commercially available AR headsets, such as the HoloLens and AR methods, including the VF technique, can improve the accuracy and speed of teleoperation, manipulation and positional control tasks. They can also provide visual or haptic feedback which leads to more intuitive operation and significantly reduces the cognitive load on the operator. Further applications will inevitably arise as AR technologies are developed further.

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