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Development of a 3D AR-Based Interface for Industrial Robot Manipulators

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***Abstract*—Along with the progress in automation and Industry 4.0, the use of industrial robots becomes much more popular. Meanwhile, the conventional manipulative devices, such as teaching pendant and joystick, are not intuitive enough and very time-consuming for task teaching. In facing more complicated tasks these days, it then induces high cost and demands experts with proper training. This paper thus aims to develop an intuitive manipulatory interface for assistance in simplifying the teaching process. We propose a wireless 3D manipulation system based on augmented reality (AR) with the tablet PC as the platform. The system allows the user to govern the movement of a real robot in a 3D space via a virtual one generated through AR. We also develop several intelligent tools to assist the manipulation, so that accurate and collision-free path can be generated for the robot to follow for task execution. In addition, the system can also be used for offline training, which yields salient training effect for the operator. Experiments are executed to demonstrate the effectiveness of the proposed system, and questionnaires conducted to investigate user's response.**

Keywords-3D intuitive manipulation; augmented reality; assistive tool; obstacle avoidance.

I. Introduction

Following the wake of Industry 4.0, more industrial robots have been introduced for automation. According to International Federation of Robotics [1], about 1.9 million robots will be in operation across Asia in 2020 alone. It also implicates that robot tasks will become much more complicated in facing more versatile requirements for flexible manufacturing. Consequently, it demands effective interfaces for task teaching. However, current manipulatory devices, such as teaching pendant and keyboard, cannot fit the need, as they might be too time-consuming and demand much effort. It thus motives us to develop an effective and intuitive interface for robot task teaching, which is based on Augmented Reality (AR) and realized in a 3D environment.

AR, which combines virtual object with the real environment, can expand the visual perception for the user and thus has been adopted for many applications, such as entertainment and business [2-4]. For its application in robot industries, AR has been used for intuitive teaching, object manipulation, and path planning, among others [5-7]. In our previous research, with the tablet PC as the platform, we have also developed two kinds of AR-based interfaces, which provide the functions of visual lead-through [8] and multi-touch gestures [9] for manipulation.

Based on the discussions above, most of these AR-based systems conduct 2D manipulation to govern robot motion in a 3D space, while using the depth sensor or auxiliary function for compensating for the third dimension. By employing the head-mount-display, Tsai [10] et al. developed an immersive 3D interface that can conduct direct manipulation in 3D space. However, it is realized in a virtual environment, instead of a real one. In response, in this paper, we propose combining the merits of AR and 3D manipulation, and come up with a 3D AR-based interface for industrial robot manipulators. To further enhance its effectiveness, we also develop several assistive tools, so that intuitive and collision-free manipulation can be achieved.

The proposed system is also *portable*, as the use of AR allows the virtual robot to be imposed on various working environments without actually installing a real robot. With this appealing feature, we thus design an offline training function, so that the user can simulate the operation in advance. The experimental results show that better performance can be achieved via the offline training. The remainder of this paper is organized as follows: In Section II, we describe the proposed system, including its two main assistive tools for intuitive 3D manipulation and collision-free path planning. System implementation is presented in Sec. III. Experimental results and questionnaires for user response are reported in Sec. IV. Finally, concluding remarks are given in Sec. V.

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II. PROPOSED 3D AR-BASED INTERFACE

Figure 1 shows a conceptual diagram of how a user can utilize the proposed manipulation system to operate an industrial robot. Two main devices are provided for the user: a wireless controller and the tablet PC showing the scene for the working environment. The AR technique [9] is used to generate the scene, in which a VR robot is overlaying with the real environment, so that the user may get hold of the interaction between the robot and environment. He/she can then use the wireless controller, which can be moved around freely in a 3D space, to govern the robot. Consequently, the system is able to furnish the user with intuitive manipulation in a 3D environment for task execution.

In order to place the virtual robot at the desired location on the scene, we adopted the marker-based method [8], which uses a marker to identify its precise position and orientation on the real environment. The selection of a suitable marker is very crucial. It should be with enough asymmetric features for a high recognition rate. Figure 2 shows the marker that fits the need, and Figure 3 shows the virtual robot placed on the real scene via the marker. By looking at the scene, the user can then use the wireless controller to conduct manipulation.

Figure 4 shows the system block diagram for task execution. In Figure 4, the lighthouse tracking system is used to obtain the position and orientation of the wireless controller. Two tools, intuitive 3D manipulation and collision-free path planning, are provided to assist the user to generate a feasible path for robot execution, which will be discussed below. Through the functions of inverse kinematics and feasibility checking, the resultant robot pose can be determined and then sent to both the table PC for the user to determine next action and the robot for execution via respective communication channel. This system can also be used for offline training with the robot unconnected. For this function, the scene on the table PC should closely approximate the real environment, such that the user can enhance his/her capability when experiencing a realistic simulation in advance.

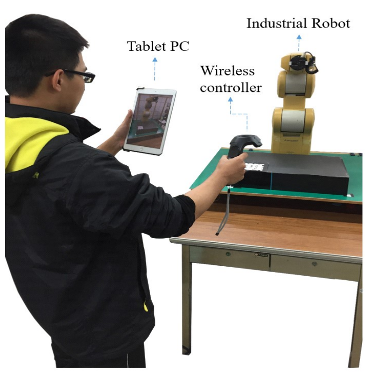


Figure 1 Conceptual diagram of a user operating a robot via the interface.

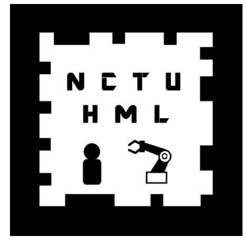


Figure 2 The marker used in the system.

Figure 3 The virtual robot placed on the real scene via the marker.

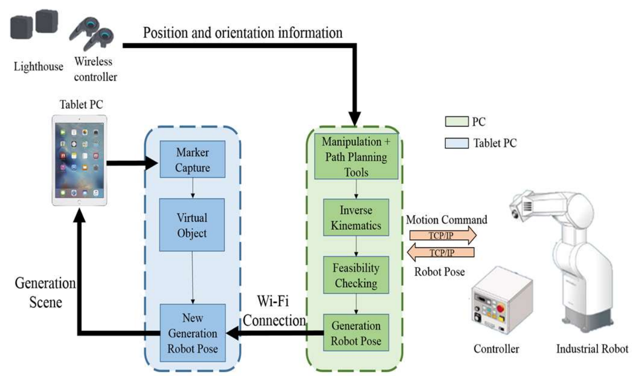


Figure 4 System block diagram for task execution.

A. Intuitive 3D Manipulation

In realizing the intuitive 3D manipulation tool, we need to have a wireless controller that can be moved freely in a 3D space. In [11], a 3D pointing device has been designed for their proposed AR-based teaching system, but it has limitation in demanding the user to specify the waypoints during the teaching process. In our previous research [10], the wireless controller of HTC Vive was used for the proposed immersive 3D interface, which is suitable for the virtual environment. To let it be applicable for our proposed AR-based system, we thus modify the related interface for connection with our system and also develop new functions to support intuitive manipulation.

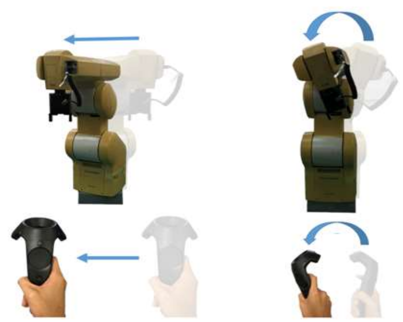


Figure 5 Illustration for the functions for intuitive manipulation.

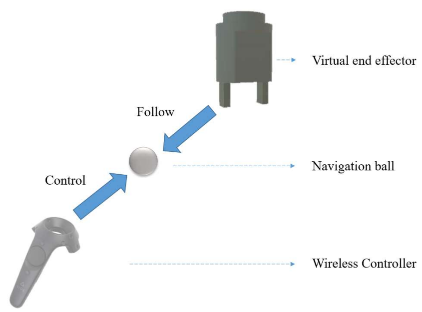


Figure 6 Conceptual demonstration with a navigation ball.

Figure 5 illustrates how the function of intuitive manipulation can assist the user for operation. During the process, he/she can just move and rotate the controller toward a location with a certain orientation, and the robot will then follow it to reach that specific positon and orientation precisely. In Figure 6, we use an invisible navigation ball to demonstrate the concept. It can be viewed as a target for the robot to follow in a 3D Cartesian space, with its position and orientation specified by the wireless controller.

For its realization, we first define $\boldsymbol{C}$ and $\boldsymbol{N}$ as the coordinate systems for the wireless controller and navigation ball, respectively. Their relative orientation, ${}^{C}R_N$, can then be formulated as

$$ {}^{C}R_N = (R_{C0})^{-1}.R_{N0} \quad (1) $$

where R_{C0} and R_{N0} are the initial orientations for the controller and navigation ball, respectively. As the controller moves, the navigation ball shall adjust its position and orientation accordingly, as described in Eqs. (2) and (3):

$$ P_{NF} = P_C + P_{N0} \qquad (2) $$

$$ R_{NF} = R_C.\,{}^{C}R_N \qquad (3) $$

where P_C and R_C are the new position and orientation for the controller, respectively, and P_{NF} and R_{NF} those corresponding to the navigation ball, with P_{N0} as the initial position. Based on the discussions above, the algorithm for intuitive 3D manipulation is listed in Table I.

TABLE I. ALGORITHM FOR INTUITIVE 3D MANIPULATION

	Algorithm for intuitive 3D manipulation:
1:	// Obtain the image of the marker via camera. Display a superimposed image of the virtual and real robots.
2:	// Locate the position and orientation of the controller via the lighthouse system.
3:	// Find the relative orientation ${}^{C}R_N$ between the controller and navigation ball using Eq.(1).
4:	// Let the navigation ball follow the new position and orientation of the controller using Eqs. (2)-(3).
5:	// Send P_{NF} and R_{NF} of the navigation ball to the robot for execution.
6:	// Repeat the process until the task is completed.

B. Collision-free Path Planning

As obstacle(s) may be present in the working environment, we also provide a tool of collision-free path planning to assist the user for manipulation. For real-time concern, the tool does not look for an optimal path, but a feasible one. We thus adopted the approach of Rapidly-exploring Random Tree (RRT), among others, such as artificial potential field, cell decomposition, etc. [12-13]. The RRT basically employs a random sampling approach to find a feasible path. Because it does not attempt to build a complete environmental model in facing the high complexity exhibited by the configuration space (C-space) of the industrial robot manipulator of multiple degrees of freedom, the RRT thus leads to low computational load.

Here, we briefly describe the process for the RRT [12]. From an initial point q_{init} where the robot is located to reach the final goal point q_{goal}, the algorithm is used to find all the intermediate points connecting them. Referring to Figure 7, the point q_{rand} is first randomly chosen as a reference, several points around q_{init} will then be generated, and the point q_{near} closest to q_{rand} is selected to indicate a direction to reach q_{rand}. A new intermediate point q_{new} is then derived to approach q_{rand} following Eq. (4):

$$ q_{new} = q_{near} + \frac{v*(q_{rand}-q_{near})}{\|q_{rand}-q_{near}\|} \qquad (4) $$

where v is a step size. The derived q_{new} will be checked to see if it would collide with the obstacle, specified by *Obs*, or it has reached the goal point q_{goal}. For the former, another q_{rand} will be chosen and the process be repeated to find a new intermediate point q_{new}. As for the latter, the search is completed with a collision-free path. If none of the these two cases happens, it indicates that the search needs to be continued, and the algorithm goes on to randomly select a new q_{rand}, and conducts the procedure again, until q_{goal} is reached. As the resultant path may be in a zig-zag shape, it can be smoothened via filtering.

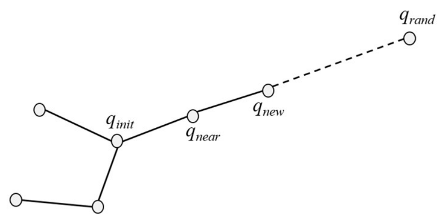


Figure 7 The process for generating a new intermediate point for the RRT.

Based on the discussions above, the algorithm for collision-free path planning is listed in table II.

TABLE II. ALGORITHM FOR COLLISION-FREE PATH PLANNING

Algorithm for collision-free path planning:	
1:	// Initialization: set the initial point of the robot as q_{init}, goal point as q_{goal}, and obstacle as *Obs*.
2:	// Randomly choose a reference point q_{rand} in the C-space.
3:	// Find the point q_{near} nearest to q_{rand} from those around q_{init}.
4:	// Find a new intermediate point q_{new} using Eq. (4).
5:	// if q_{new} would hit *Obs*, go to Step 2; else { if q_{new} = q_{goal}, the process is completed. Go to Step 6; else go to Step 2.}
6:	// Connect q_{init} with all q_{new} to form a path. Smoothen the resultant path via filtering.

III. SYSTEM IMPLEMETATION

In implementing the proposed 3D AR-based interface, we employ the Unity and Vuforia, which provide the cross-platform support for Android, iOS, etc., as the tools for developing the AR scene. They also possess several useful features for AR applications, such as virtual object positioning, ground plane detection, and object recognition. The tablet PC adopted is the iPad Pro 9.7, and the robot is the Mitsubishi RV2A 6-DOF industrial robot manipulator. We adopted the wireless controller of HTC Vive for 3D manipulation, as shown in Figure 8. Its Grip button at the front is used to open/close the gripper, Trigger button at the back to manipulate the virtual robot, and Side button at the side to send out the motion command. For locating the position and orientation of the wireless controller, the lighthouse tracking system scans the environment via a laser of 60 Hz. The user interface, with its outlook shown in Figure 9, is designed to be concise, in providing the connection status between PC and tablet PC, the tracking status of the marker, and also the lock buttons for locking specific position or orientation, in addition to a button for showing or hide the virtual robot.

To accurately overlay the virtual robot with the real one on the scene shown on the tablet PC, the spatial relation between the marker and real robot, shown in Figure 10, needs to be identified. In Figure 10, the coordinate of the robot was set to be (0, 0, 0), and that of the marker, located at the corner was measured to be (20.6, 49, 10.6), which was sent to the system to adjust the VR robot on the scene accordingly. We found that the distance between the camera and marker and also the size of the marker would affect the accuracy for identification. From the testing, the size of the marker should be at least 1/10 of the distance between the camera and marker. In this case, we let the marker be with a size of 18 cm for responding to a working range of 1.8 m. Meanwhile, a stable and bright light may also help.

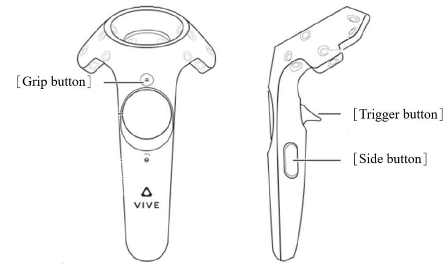


Figure 8 The wireless controller for 3D manipulation.

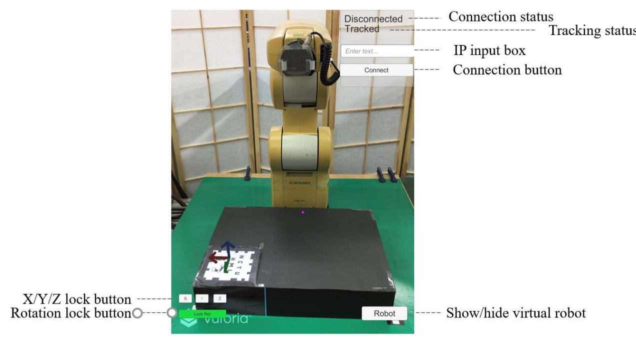


Figure 9 The outlook of the user interface.

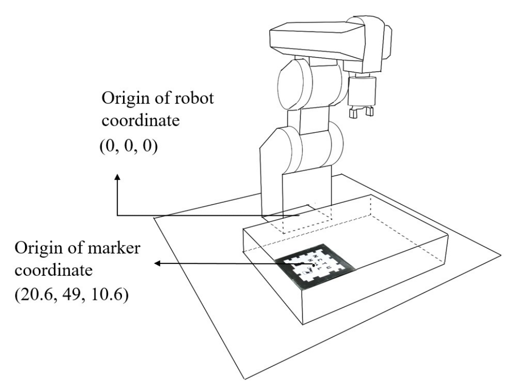


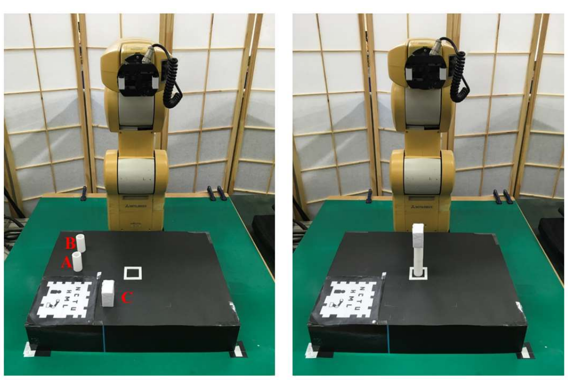
Figure 10 The spatial relation between the marker and robot.

IV. EXPERIMENTS

We conducted a series of experiments to evaluate the performance of the proposed manipulation system, and also administered a questionnaire to obtain subjects' responses. The subjects were asked to use three kinds of interfaces to manipulate the robot: (1) the proposed system (Sys 1), (2) AR-based system with 2D manipulation (Sys 2) [9], and (3) VR-based system with 3D manipulation (Sys 3) [10]. Twelve subjects were invited. They were engineering students with their ages ranging between 18 ~ 25 years old. Before the experiments, the subjects were given an introduction on these interfaces, and used some practice to be familiar with them.

In the first set of experiments, the subject needed to stack three objects, A, B, and C at a specified position successively using these three interfaces, as shown in Figure 11. It was deemed as a failure if either one of the objects fell off or was not put on the correct position. The success rates were 58.3%, 25%, and 8%, respectively, with Sys 1 the highest and Sys 3 lowest. The experimental results demonstrate that realistic AR scene along with 3D manipulation did assist the subjects for task execution. After the experiment, the participants were asked to fill out a questionnaire, which was designed referring to the System Usability Scale (SUS) [14]. The questions are listed in Table III. We collected and evaluated the answers to yield a final SUS score, with a higher SUS score implicating the user favors that particular system [14]. The SUS scores were 76, 39, and 59, respectively, with Sys 1 the highest and Sys 2 lowest. From the feedbacks of the users, a more realistic presentation of the working environment with a flexible manipulation tool was supported.

To further investigate the effect in using 2D and 3D manipulation, we went on to conduct the second set of experiments by using only Sys 1 and Sys 2. During the experiment, the subjects were asked to reach 5 specific points of various heights inside a 3D space, as shown in Figure 12. The task was executed 5 times. The average time for using Sys 1 and Sys 2 were 247 s, and 679 s, respectively. As for the accuracy, the average position and orientation errors for Sys 1 were (1.3 mm, 1.0 mm, 0.9 mm) and (4.9°, 4.2°, 4.2°), respectively, and those for Sys 2 were (3.7 mm, 2.4 mm, 1.8 mm) and (8.9°, 9.7°, 8.6°). It further confirms that the proposed system led to a shorter and more accurate manipulation. We also asked the subjects to fill out a questionnaire, which is similar to that in Table III, but modified according to experiment 2. The SUS scores for Sys 1 and Sys 2 were 72.6, and 40.6, respectively, indicating the superiority of 3D manipulation over the 2D one.



(a) Before (b) After

Figure 11 The scene for the first experiment.

TABLE III. THE QUESTIONNAIRE FOR EXPERIMENT 1

No	Question
1	I would like to use this system to do accurate task.
2	I found the system unnecessarily complicated.
3	I thought the system was easy to use.
4	I think I need the support of a technical staff to be able to use this system.
5	I found the functions in this system were well integrated.
6	I thought there was too much inconsistency in this system.
7	I would imagine that most people shall be familiar with this system very quickly.
8	I found the system very cumbersome to use.
9	I felt confident in using the system to finish the stack task.
10	I was not sure if I could finish this stack task successfully using this interface.

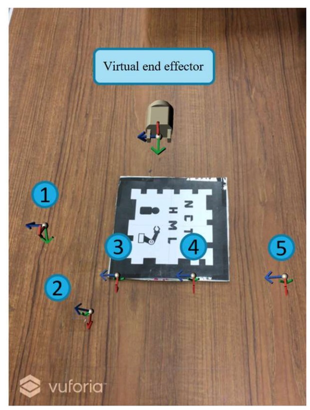
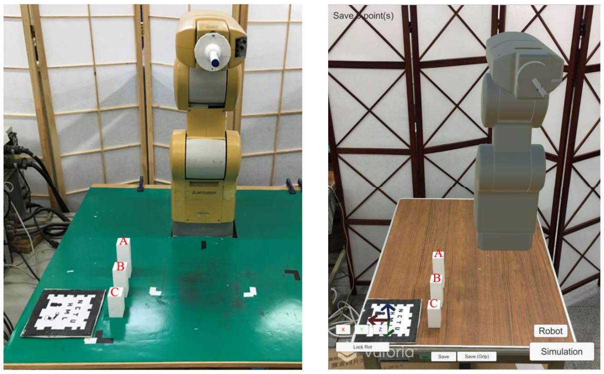


Figure 12 The scene for the second experiment.

In the third set of experiments, we intended to evaluate the effectiveness of the proposed system when used for offline training. In other words, we would like find whether the AR scene can yield a feeling realistic enough, so that the user may feel as if he/she is actually manipulating a real robot. Figure 13 shows the experimental scene, which emulates a wielding task. The subjects were asked to move the robot to reach three wielding points, A, B, and C. The subjects were divided into the experiment group (G1) and control group (G2). Those subjects in G1 used the proposed system for offline training first and then conducted the task online, while those in G2 conducted the task online directly. The execution time for G1 and G2 were 164 s and 209 s, respectively. The results show that the offline training did help the user to be familiar with the operation of the task. It was not only due to the learning effect, as an unrealistic training environment might lead to the counter effect. We also looked for the feedbacks from the subject. About 66.7% of them highly agreed that high similarity was present between the AR and real scenes. With this appealing feature, the proposed system is, in some sense, portable, as this AR-based system allows different kinds of virtual robots to be imposed on various working environments without actually installing the real ones.



(a) Online (b) Offline

Figure 13 The scene for the third experiment.

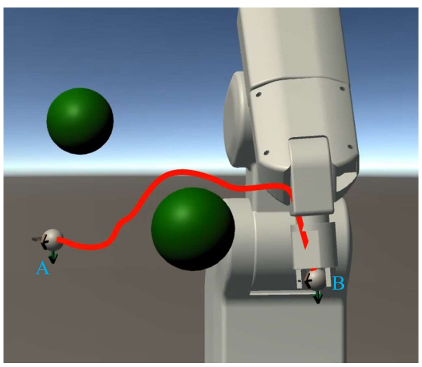


Figure 14 Example of applying the tool for collision-free path planning.

Finally, we conducted a preliminary study to evaluate the performance of the developed collision-free path planning tool. When the obstacle(s) is present within the working space, the tool can be applied to generate a collision-free path as a reference for the user. Figure 14 shows an example of its application, in which a smooth path is generated that passes two obstacles (in green) nearby the robot by using the algorithm for collision-free path planning in Sec. II(B). We will continue to refine the algorithm to deal with more complicated environments in a more efficient way later on.

V. Conclusion and Future Work

In this paper, we have proposed a 3D AR-based interface for industrial robots. The AR technique has been introduced to generate a more realistic scene, and the commercial wireless controller modified for providing 3D manipulation. Two assistive tools designed for manipulation and path planning have been developed to allow the user to govern the robot manipulator in a more natural and intuitive way. Experimental results and feedbacks from questionnaires have verified the effectiveness of the proposed system. In future works, we intend to make the AR scene even more realistic, and design more assistive tools for the proposed system, including learning algorithms for system optimization. More subjects of different backgrounds will be invited to evaluate its performance for general users. In addition, we also intend to apply it for factory environment to enhance its practicality.

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