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A novel augmented reality-based interface for robot path planning

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Abstract Intuitive and efficient interfaces for robot task planning have been a challenging issue in robotics as it is essential for the prevalence of robots supporting humans in key areas of activities. This paper presents a novel augmented reality (AR) based interface for interactive robot path and end-effector (EE) orientation planning. A number of human-virtual robot interaction methods have been formulated and implemented with respect to the various types of robotic operations needed in different applications. A Euclidean distance-based method is developed to assist the users in the modification of the waypoints so as to update the planned paths and/or orientation profiles within the proposed AR environment. The virtual cues augmented in the real environment can support and enhance human-virtual robot interaction at different stages of the robot tasks planning process. Two case studies are presented to demonstrate the successful implementation of the proposed AR-based interface in planning robot pick-and-place tasks and path following tasks.

Keywords Robot path planning · End-effector orientation planning · Augmented reality · Human-robot interface

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1 Introduction

Human-robot interaction (HRI) is generally referred to as the process that conveys the human operators' intention and interprets the task descriptions into a sequence of robot motions complying with the robot capabilities and the working requirements. The identification of suitable interaction methods and interfaces for HRI has been a challenging issue in robotics as it is essential for robots to support humans in key areas of activities.

Robots can be classified into two general categories, namely, industrial and service robots. Industrial robots are used in various industrial processes where the tasks are often executed in structured environments. These industrial robots, often with little autonomous capability, need to be re-programmed for a new task, in which the robots may need a different tool, fixture or environment [1]. Service robots are usually operated semi- or fully autonomously for the well-being of humans or equipment. For instances, professional service robots are employed to reduce physical workloads and intervene in hazardous environments; personal service robots are designed to improve personal well-being, security, as well as provide entertainment. It has been reported that [2] there is a strong recovery in the sales of industrial robots, and the installations of industrial robots will continue to increase in the next few years. Meanwhile, the demand for service robots has risen significantly, led by countries such as Japan where robots have provided services and become home companions of the lonely and the elderly. The expected growth in demand is largest for service robots, followed by industrial robots. For the latter, the working environments have been changing from mass production lines towards batch production work cells in small and medium-sized enterprises (SMEs). This has eventually prompted the collaboration among research institutions and industries towards multi-purpose robotic systems that can facilitate access to diverse robotic applications for easier robot installation and re-programming, as well as intuitive and effective interfaces for different levels of HRI.

Robotic safety is of upmost priority and needs to be addressed in HRI. Manual programming is unintuitive, time-consuming, and requires an operator to be present within the workspace of the robot, which may pose safety concerns. Automatic programming requires advanced hardware and infrastructure, as well as sophisticated software for environment sensing, motion control, exceptions processing, robust error handling and recovery, etc. Currently, most industrial robotic systems adopt semi-automatic programming approaches. One key requirement that has been identified for effective HRI is the overlapping space that can be perceived by both the human user and the robot programming system [3]. It would be desirable to have economically feasible solutions where the operators can work as assistants with the complex robots to solve unpredictable problems [4]. Hence, HRI is a vital component in the robot programming process, which involves understanding and shaping the interactions between the operators and the robots.

The rest of the paper is organized as follows. Sections 2 and 3 review the various levels of HRI and the current HRI methods. Section 4 presents a novel AR-based interface for human-virtual robot interaction, where a number of interaction metaphors have been developed in terms of the operations associated with different robotic applications. Section 5 presents the implementation results with two case studies. Section 6 presents the conclusion and suggestions for future work.

2 Human-robot interaction

Robots have been applied in manufacturing operations to provide assistance to human daily activities. Therefore, the levels of HRI required for these applications vary accordingly. For a robotic system, two prominent principles adopted in the identification of the HRI level are namely, (1) the level of autonomy (LOA) [5] achievable by the robotic system, and (2) the proximity of the human and the robot during operation [6].

For a robotic system, the LOA describes the degree to which the robot can act on its own accord, or alternatively, the degree to which the HRI is involved in completing a robotic task [5]. Industrial robots normally have lower LOA because they are designed primarily for carrying out programmed and repetitious tasks in structured environments. The interaction between the industrial robots and the human operator is vital as the motions of the industrial robots need to be pre-programmed and re-programmed, which would normally require a considerably longer period of time for testing and tuning. ABB has developed a control system for industrial robots that would prompt for interaction between a human operator and robot while allowing the robot to continue with the task [7]. Comparatively, the service robots have higher LOA as they are often employed in unprepared or unknown environments. This is to enable the service robots to anticipate the changes in the environment and act accordingly, e.g., a navigation robot in a museum needs to adjust its trajectory to give ways to unpredicted visitors [8]; an automatic guided vehicle for material transportation in a factory environment needs to recognize the roadway and avoid obstacles [9], etc.

The proximity between the human user and the robot is used to classify the level of HRI into direct and indirect interactions. Service robots, such as mobile robots, and personal service robots exhibit direct interactions with operators. They often adopt high-level interfaces, such as tactile-based or vocal-based sensors, to facilitate intuitive and efficient HRI. For industrial robots, it is advised to adopt indirect HRI due to safety concerns. However, increasingly more industrial robots have been used in the SME environment, where the operators are frequently engaged in direct interactions with the robots. This has raised challenges on the development of efficient interfaces though the integration of suitable sensors [7,10].

3 Human-robot interaction methods

HRI in industrial robotics has been largely confined to finding ways to reconfigure or program the robots [6]. The use of controller-specific languages is the original method for programming industrial robots as each robot controller has some form of machine language that can be used to create executable robot programs. A few examples of controller-specific languages are advanced control language (ACL) for Scorbot robot, KUKA robot language (KRL) and ABB robot programming language (RAPID). Icon-based programming methods are developed based on the controller languages, where an icon usually consists of one or more common robot functions to represent a robot program in the form of a flowchart. MORPHA [11] is a prototype style guide for defining the icons based on the KRL. In these systems, the interaction between the human operators and the robot is restricted to either a text editor-based or graphics-based interface. Lead-through and walk-through programming methods represent the two forms of direct interaction where the users need to be present within the working environment of the industrial robots. In lead-through programming, a teaching pendant is used to prompt the HRI. These two methods usually adopt a text editor-based or graphics-based interface to facilitate the storing of robot configurations being taught and the generation of robot programs.

Numerous research efforts have been reported on the development of more efficient and suitable interfaces for HRI as more enabling technologies are being made available, such as multimodal interaction, programming by demonstration (PbD), virtual reality (VR), and augmented reality (AR), etc.

3.1 Human-robot interaction modals and devices

In industrial robotics, the interaction takes place where the human operators usually possess sufficient knowledge on specific controller programming languages, or at least have expertise in task planning and task automation. However, service robots mandate new forms of HRI, as the users may not have any knowledge in robotics. Natural human interfaces for richer HRI have been explored for service robots. Vision-based interfaces in mobile robot navigation [8,9,12,13], haptic feedback interfaces in teleoperations and surgeries [14–16], voice-based interfaces [17,18], and multimodal interfaces which integrate two or more interaction modals [19,20], are some of the most commonly used approaches.

Robotic systems that employ vision-based interfaces are usually equipped with optical tracking devices, like cameras or laser range finders, to facilitate the HRI. These types of sensors have been widely used in acquiring information of the robot operating environment [8], hand posture segmentation and recognition [13], human gesture recognition [12], etc. Haptic interfaces, where a master-slave configuration is often employed, have been developed for indirect interactions, offering scaled force feedback to the operators. Voice-based interaction can be used to control the industrial robots [17] or mobile robots [18]. However, the presence of noise in the operating environment may lead to incorrect task interpretations. Multimodal interaction interfaces, which use a combination of sensing techniques, compensate the weaknesses of one modal with the strengths of another modal. In the system described by Iba et al. [19], gestures and speeches are responsible for different groups of robot functions. Marín et al. [20] have proposed a system which combines a voice control and an offline programming interface to assist the users, who may be novice users or have robotic expertise, in programming a robot at a remote site.

Apart from multimodal interaction, many interactive devices have been developed to facilitate intuitive HRI. In industrial robotics, hand-held devices, such as digital pen [21], interactive stylus [22], or mobile devices, like PDA [23,24], have been used in task planning and robot programming. MINERVA, a tour guide mobile robot, has adopted a touch-screen by which tourists can choose tours within a museum [8].

3.2 Programming by demonstration

Programming by demonstration (PbD) is an on-line robot programming approach where a user performs a task manually, and leaves the robot to observe, follow and learn the human demonstrations in real-time. This enables a user who may not have any robotic programming skills to program a robot. PbD has been used in many industrial robot applications, such as maintenance, assembly, etc. The PbD approach has also been applied to program professional robots and humanoid robots [25]. However, there are several constraints in the PbD approach that need to be addressed. One key issue is that sub-optimalities often exist in the demonstrations with respect to both the robot and the learning system [26]. Another issue is the presence of noise in the data collected due to variations in human demonstrations. Multiple demonstrations are more practical when the task is to be executed many times. Skill models, e.g., position/force control model [27], hidden Markov model [28], etc., have been developed to generalize across multiple demonstrations to reduce the inaccuracies introduced during the data collection stage. Researchers have used force/position sensors to locate the object and sense the scaled contact force between the gripper and object in assembly applications [27] during the data collection process.

3.3 Virtual reality

In VR-based HRI, a virtual environment (VE) aided by the necessary sensors provides the operator with an immersive sense of his/her presence at the real location undertaking the tasks [29]. The VR-based HRI allows the operator to project actions that are carried out in the virtual world onto the real world by means of robots. Several VR-based applications have been developed to enhance HRI in robotics, such as tele-operations, surgical operations, and many other operations in industrial environments. Tele-operation tasks are usually performed in highly dangerous environments where the presence of human is not advisable due to safety issues. The use of an interaction device, such as a PHANToM [30], etc., can facilitate the indirect interaction such that the operator can feel the scaled representation of the dynamics of the slave manipulator. Chen et al. [31] have developed a haptic interface using a PHANToM for interactive path planning, verification and training of a robot arm in a virtual environment. The use of VR in surgical robots permits a virtual training environment so that the medical operations can be practiced before moving to a real operation on a real patient. In these applications, force feedback using a haptic interface is normally acquired to achieve realistic simulations [32].

From the perspective of HRI, a major advantage of using VR is the provision of intuitive interfaces due to its scalable modelling capability of the entire environment where a robot works in [33]. Di Gironimo et al. [34] have demonstrated the possibility of planning collision-free paths for multiple robots in a VR environment, considering the safety issues of the operators who work on the assembly line. Andrisano et al. [35] have presented the design and optimization of a reconfigurable system through virtual prototyping and digital manufacturing methods, offering support to efficient human-robot cooperation in hybrid industrial environments. In VR-based robot programming, interaction with the virtual robot model will not affect the task to be performed by the real robot. However, an issue that needs to be addressed is the delay between the VR display of the movements of a remote robot and its physical movements [20]. Despite the use of various types of sensors in the remote working place for retrieving as much information as possible, feedback from sensors is usually delayed. This is essentially not suitable for tasks that are carried out in a frequently changing environment.

3.4 Augmented reality

AR can assist the users to interact intuitively with the virtual objects and spatial information for task planning within the actual working environment. Valentini [36] reported an AR-based system for virtual assembly and simulation, in which a data glove is used to manipulate the virtual components. In another work reported, Valentini [37] developed an interactive AR-based method for cable harnessing, in which virtual cables can be created and collimated directly into a real scene with physical objects. In robotics, AR-based visualization offers the possibility to perceive spontaneously the information that is useful during robot programming and tasks planning, as well as tele-operations [20,38,39].

Some AR-based systems have been reported in industrial robotics. Chong et al. [40] presented an interface through which the users can guide a virtual robot using a probe attached with a single marker. Zaeh and Vogl [22] introduced a laser-projection-based approach where the operators can manually edit and modify the planned paths projected over a real workpiece using an interactive stylus. In mobile robot applications, AR-based visualization can provide situational awareness to the users for navigation and localization, such as the museum tour guide robot [41].

Various types of sensors that have been integrated into AR-based interfaces assist the users in understanding the environments, e.g., the vision-based sensors used to acquire information of the work cell, the data gloves used to obtain the posture and gestures of the hands [36], etc. However, the types of interactions that can be achieved depend on the progress in the computer vision field [42].

4 An AR-based interface for human-robot interaction

A novel intuitive interface for HRI based on AR has been developed in this research. Figure 1 shows the overview of this AR-based interface. The AR environment where HRI has taken place consists of the physical entities in the robot working environment, such as the robot arm, the tools, workpieces, etc., and a parametric virtual robot model. An ARToolKit-based tracking method is adopted for tracking a handheld device, which is a marker-cube attached with a probe, and virtual robot registration. The tracked interaction device allows the users to interact with spatial information of the working environment. It can be used to guide the virtual robot to intervene in the path planning and end effector (EE) orientation planning processes. The actual working environment, the virtual robot model, the trajectory information, as well as the interaction processes are visualized through a monitor-based display.

4.1 Interaction device

The hand-held device attached with a marker-cube offers an effective way for manual input of the spatial coordinates and six degree-of-freedom (DOF) interaction. To guide the EE of the robot with a reduced wrist configuration, e.g., the Scorbot-ER II type manipulator, a pose tracked using this interaction device needs to be mapped to an alternative pose which permits valid inverse kinematic solutions. Figure 2b gives a valid robot pose mapped from an arbitrary pose tracked using the device (Fig. 2a), in which the positional elements of the pose remain unchanged and rotational elements need to be adjusted adequately.

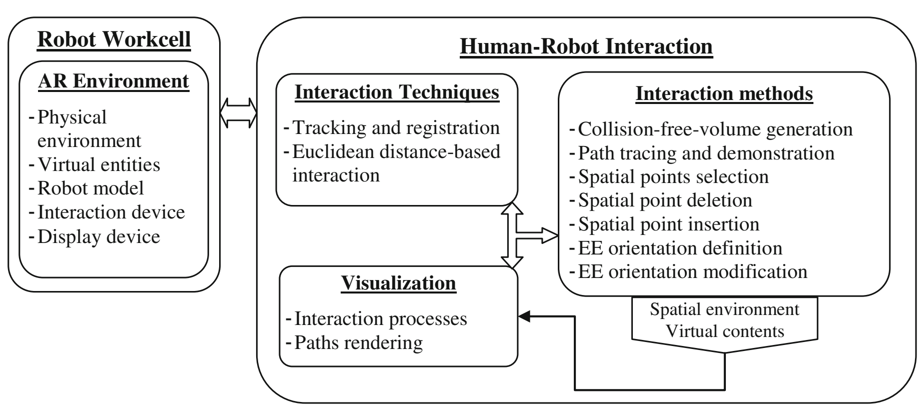

Fig. 1 Overview of the AR-based interface for human-virtual robot interaction

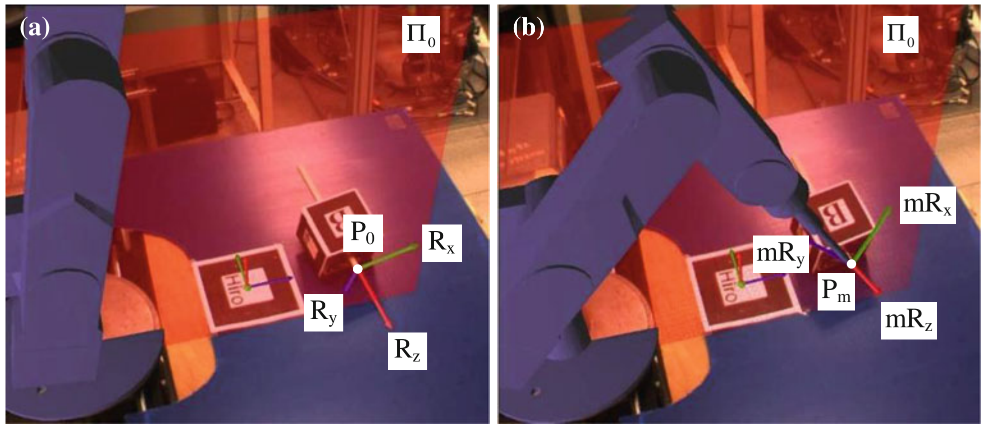

Fig. 2 Coordinate mapping based on a tracked marker-cube **a** an arbitrary pose, **b** resulting pose

4.2 Euclidean distance-based method

In the AR environment, it may be difficult for a user to locate a point among a number of spatial points defined in the spatial workspace using the probe on the interaction device. Therefore, a Euclidean distance-based method is proposed to assist the user in selecting the point of interest. Unlike the methods reported earlier [22,43], in which a point is selected when it is closer than a predefined distance from the tip of a probe, this Euclidean distance-based method computes the distances between the probe and each spatial point, and associates this value with the corresponding point. The values are updated automatically when the probe moves in the workspace and the one that has the minimum distance to the probe will be highlighted as a candidate point for selection.

In a pick-and-place operation, Eq. (1) gives the definition of a spatial point (e.g. $v_{poi}\,(x, y, z)$) to be selected, where $\mathbf{o}_0\,(x_0,\ y_0,\ z_0)$ defines the origin of the coordinate system of the interaction device (tip of the probe); $\mathbf{v}_i\,(x_i,\ y_i,\ z_i)$ is the ith spatial point; $S\,(\mathbf{o}_0, \mathbf{v}_i)$ is the Euclidean distance between $\mathbf{o}_0$ and $\mathbf{v}_i$. N_p is the number of the spatial points that have been created.

$$\boldsymbol{v}_{poi}\ :\ S\left(\mathbf{o}_0, \boldsymbol{v}_{poi}\right) = \min\left\{S\left(\mathbf{o}_0, \mathbf{v}_i\right);\ i = 0,1,2,\ldots,N_p\right\} \quad (1)$$

In a path following operation, the definitions of the parameters given in equation (1) are slightly different. In this case, $\mathbf{v}_i\,(x_i,\ y_i,\ z_i)$ will be the ith sample point of the curve model, and N_p the total number of the sample points.

4.3 Spatial interaction mechanisms

Various spatial interaction mechanisms have been provided to the users for efficient and intuitive planning of a robotic task in an AR environment as shown in Fig. 1. These can be achieved through real-time tracking of the interaction device and the monitor-based visualization, which allows the users to perceive the virtual elements instantaneously while interacting with them. In a robotic pick-and-place operation, the orientation of the target frame for the EE of the robot may not be critical as compared to its position. In a robotic path following operation, the EE of the robot is constrained to follow a visible path on a workpiece at permissible inclination angles with respect to the path. A de-coupled method is adopted in the definition of a target frame for the EE of the robot, i.e., the positional and rotational elements of the target frame are determined separately since the orientation of the tracked interaction device cannot be used directly as the orientation of the target frame, as described in Sect. 4.1. The procedures for the AR-based human-virtual robot interaction, consisting of a series of interaction methods to facilitate two types of robotic operations, are shown in Figs. 3 and 4, namely, a pick-

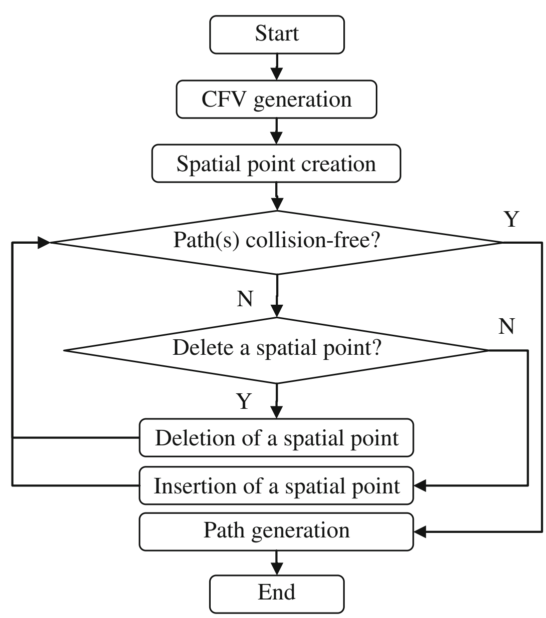

Fig. 3 Procedures for AR-based human-virtual robot interaction in pick-and-place operation

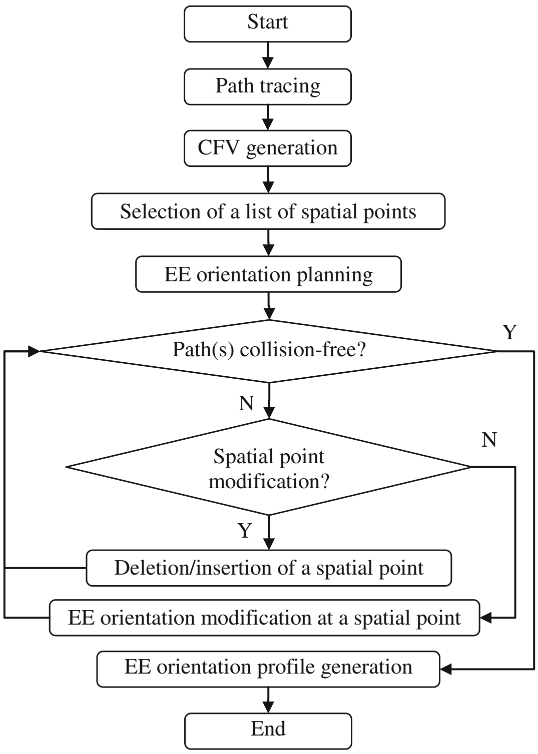

Fig. 4 Procedures for AR-based human-virtual robot interaction in path following operation

and-place operation (Fig. 3) and a path-following operation (Fig. 4). The detailed interaction methods are given next.

- *Collision-free-volume generation* A virtual sphere with a known radius is defined where the centre is located at the tip of the interaction device (probe). A Collision-free-volume (CFV) is generated by recording the position of the tip while the interaction device is moved around the space relative to the task to be planned [40].
- *Path tracing from demonstrations* In a path following operation, by moving the interaction device along a visible path/curve, a set of discrete points is tracked and recorded. Multiple sets of points are used to obtain a parametric model of the original path/curve [44].
- *Spatial points creation/selection* The positions of a target frame for the EE of the robot are defined by pointing to the desired target positions in the spatial space. The spatial points that are created to form a collision-free path should be (1) accessible by the EE of the robot, and (2) within the CFV. In particular, the Euclidean distance-based method, as described in Sect. 4.2, is used to select a point of interest from a list of existing spatial points. During the definition of a number of spatial points on the curve model, the Euclidean distance-based method can be applied to all the parameterized points of the curve model.
- *Spatial point deletion* A spatial point can be deleted by firstly specifying this point using the Euclidean distance-based method within a list of spatial points that have been created. The numbering sequence of the remaining spatial points will be updated accordingly.
- *Spatial point insertion* Through specifying two consecutive spatial points within a list of spatial points that have been created, a new spatial point can be created and inserted between these two points to form a new spatial points list. The numbering sequence of the spatial points in the new list will be updated accordingly.
- *EE orientation specification at each spatial point* Given a parametric curve model, a coordinate frame at the start of the curve model can be defined with respect to the coordinate frame at the base of the robot [44]. The coordinate frames with origins at the rest of the spatial points selected along the curve can be defined by applying the transformation reflecting the changes in the curve direction. The orientations of the EE at the spatial points are defined according to the sequence of selection with respect to the coordinate frame at the corresponding spatial points. The EE orientation of a spatial point is represented with respect to the robot base frame.
- *Spline modelling* In a pick-and-place application, a cubic-Spline representation of the robots path is generated with the spatial points that have been created. By modifying the existing spatial points, an updated path can be fitted. In a path-following application, the angle between the orientation of each spatial point selected on the curve and the Z-axis of the robot base frame is interpolated to form an orientation profile for the EE of the robot.

With these spatial interaction mechanisms, the user can interact efficiently with the environment and the spatial points that are of interest in a robot task. For spline modelling, the parameterized points of the path are generated by taking their normalized accumulative path lengths to the start of the path as the interpolation parameter. The same parameter is used to generate the interpolated angles associated with the parameterized points.

With a robot path generated, a CFV check can be performed to determine whether the EE of the robot is within the CFV when it is moving along the path [44]. In addition, the proposed AR system can be extended to obtain collision-free paths for the whole kinematic chain of the robot. Given the robot model and the obstacle models, detection can be carried out between the EE and other parts of the robot and the obstacles using the V-COLLIDE [45].

5 Implementation and discussions

This section presents two case studies on the proposed AR-based interface for intuitive HRI in a robotic pick-and-

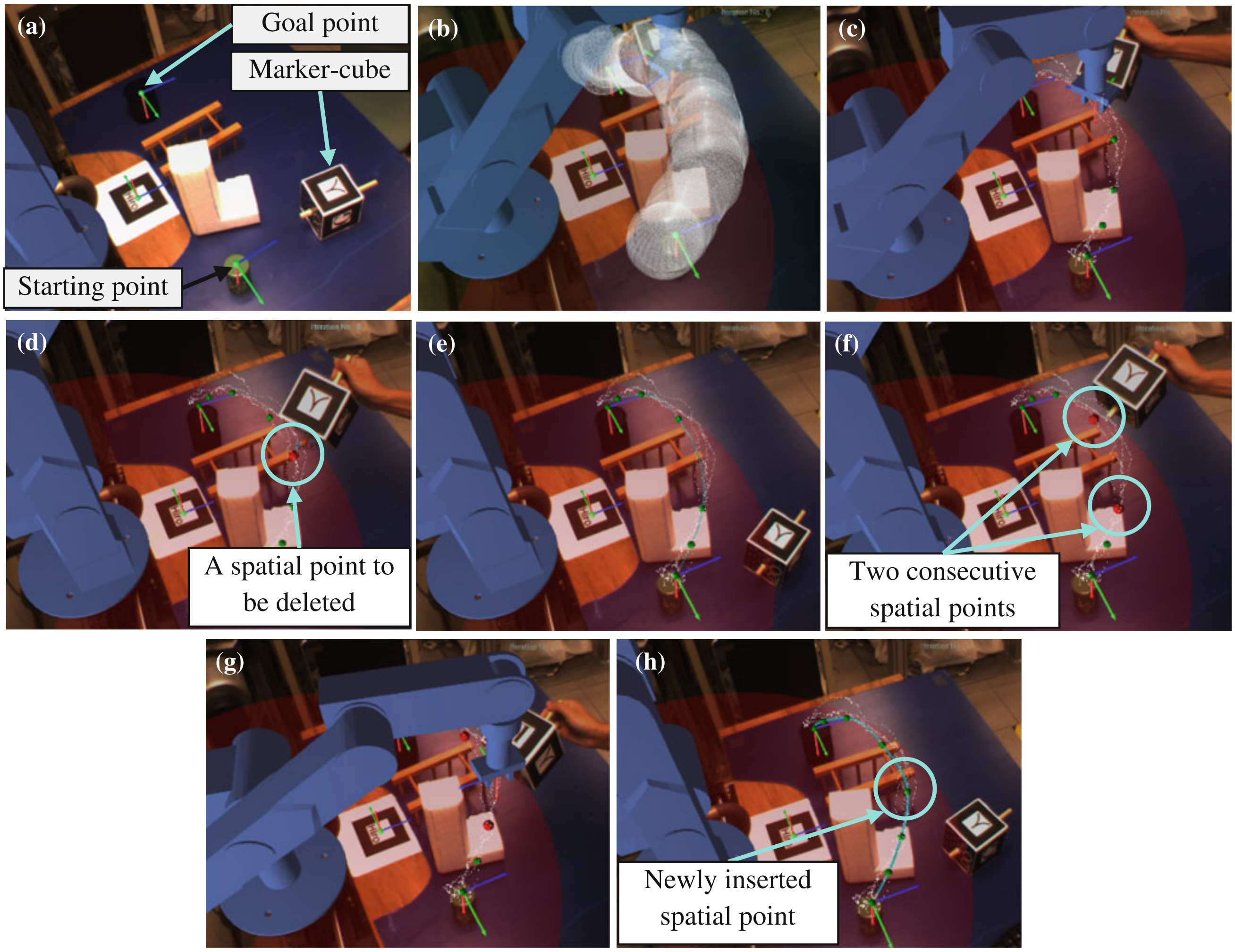

Fig. 5 A pick-and-place task: **a** setup; **b** CFV generation; **c** creation of spatial points; **d** selection of a spatial point to be deleted; **e** deletion of the spatial point; **f** selection of two consecutive spatial points; **g** insertion of a spatial point; **h** path re-generation

place application and a path following application. Figure 5 illustrates the application of the proposed spatial interaction mechanisms in planning a task for transferring an object from a start point to the goal point. In the example in Fig. 5, the spatial points are created to be within a predefined CFV, and the orientation of the EE at these points are predefined to be parallel to the z-axis of the robot base frame. Figure 6 shows an implementation of the interaction mechanisms in a task where the EE of the robot is required to follow a U-shaped curve and the orientation of the EE needs to be planned appropriately to avoid the edge along the curve. This case study is designed to demonstrate robot path following operations, such as robotic gluing, arc welding, etc.

The two case studies demonstrate the successful implementation of the proposed AR-based interface for human-virtual robot interaction. The average tracking errors in these two case studies are both approximately 11.0 mm with the camera installed at 1.5 m away from the workplace. The errors are largely caused by the tracking method adopted. In the first case study, the error is introduced during the generation of the CFV, the creation and insertion of waypoints; while in the second case study, the error is introduced during the acquisition of the parametric model of the spatial U-shaped curve. However, in the first case study, user demonstrations are used to generate a suitable CFV instead of a path for the EE of the robot to follow. Thus the path generated within the CFV will not be affected by the jitter and noise presented in the demonstration. In addition, the user can hardly perceive any misalignment between the actual path and the path model in the second case study. Thus, the tracking errors do not affect significantly the intuitiveness of the interface to facilitate human-virtual robot interaction.

Results from these two case studies have demonstrated that the AR-based HRI interface has advantages over the conventional *teach-in* method using a teaching pendant. First, novice users are able to learn the method quickly and per-

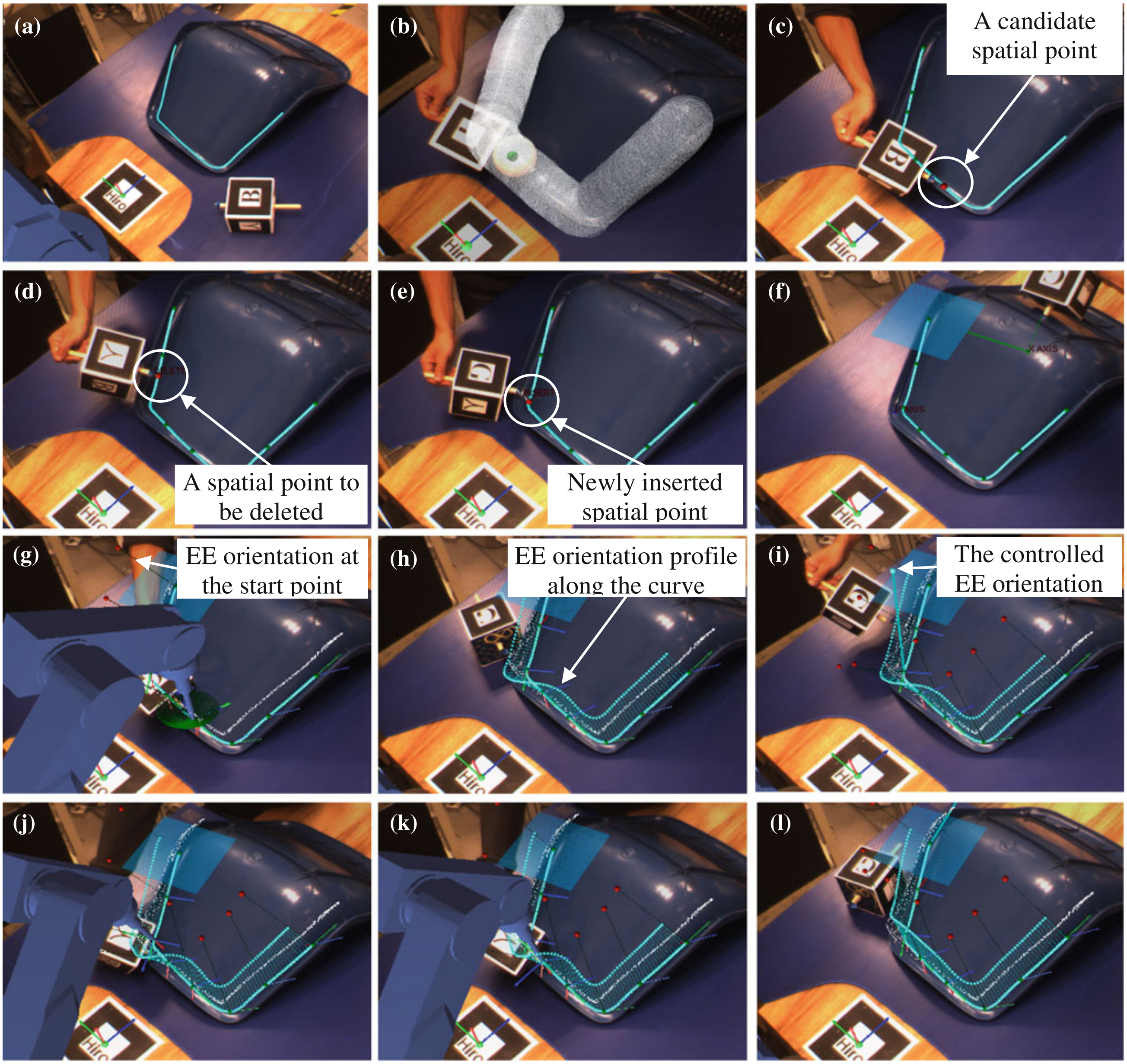

Fig. 6 A path following task: **a** curve model; **b** CFV generation; **c** selection of spatial points on the curve; **d** selection of a point to be deleted; **e** selection of a point to be inserted; **f** definition of target frame at the start of the curve model; **g** definition of the EE orientation at a spatial point; **h** generation of an orientation profile for the EE of the robot; **i** selection of a spatial point at which the orientation of the EE needs to be modified; **j** modification of orientation of the EE at a spatial point; **k** modification of orientation of the EE at another spatial point; **l** orientation profile re-generation

form robot path planning using the proposed HRI interface. Second, the Euclidean distance-based method is developed to assist the human-virtual robot interaction, thus enhancing the safety of the operator when he/she is present within the operating range of the robot. Third, the AR-based interaction method and visual cues support the intermediate modifications of the planned paths or the EE orientations when the simulation is not satisfactory. However, the *teach-in* method may offer a higher accuracy in robot planning since the paths are generated from the waypoints obtained through manipulating a real robot. The teaching pendant can be used to control the manipulators remotely for planning pick-and-place tasks. However, such a device may be inconvenient for planning path-following tasks, e.g., the EE of a robot needs to be planned to follow a visible spatial curve on a workpiece with consistent inclination angles. Although the *teach-in* method may have fewer errors in curve tracking, it tends to introduce additional variations in the EE orientations, resulting in possible axis oscillation when the robot moves along the recorded paths.

6 Conclusions and future work

In this research, an AR-based interface for intuitive HRI has been proposed and presented. A brief review on the various levels of HRI and the current HRI methods is presented. A number of interaction methods have been defined in terms of the various types of operations needed in an AR environment for human-virtual robot interactions for different robotic applications. A Euclidean distance-based method has been developed to assist the users in the selection of spatial points in s point deletion or insertion operation. The monitor-based visualization mode adopted allows the users to perceive the virtual contents augmented onto the real environment in the different interaction metaphors. The two case studies show successful implementation of the proposed interface in planning robotic pick-and-place operations and path following operations.

A number of areas can be further explored and developed to improve the AR-based HRI interface presented in this paper. A more accurate and robust tracking method can be developed to improve the performance of the interface. Improvement can be made to develop an easier, more intuitive and non-distracting interface for the users to perform EE orientation definition and modification. The current interface can be further enhanced to assist the users in tele-operations or tele-manipulations by integrating suitable sensors and devices at the remote operating sites and the control rooms.

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