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ORIGINAL ARTICLE

Orientation planning of robot end-effector using augmented reality

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Abstract This paper presents a methodology for planning the orientation of the end-effector for an industrial robot based on the application of augmented reality. The targeted applications are those where the end-effector is constrained to follow a visible path, which position and model are unknown, at suitable inclination angles with respect to the path. The proposed approach enables the users to create a list of control points interactively on a parameterized curve model, define the orientation of the end-effector associated with each control point, and generate a ruled surface representing the path to be planned. An approximated time-optimal trajectory, which is a determined subject to robot actuators and joint velocity constraints using convex optimization techniques, is implemented to simulate a virtual robot, allowing the users to visually evaluate the trajectory planning process. A case study is presented and discussed.

Keywords Augmented reality · Robot programming · Human–robot interaction · End-effector orientation planning

1 Introduction

Recent studies on robotics have shown a high potential for employment of multipurpose industrial robots in the general industry (i.e., excluding the automotive industry), and its share has been constantly increasing over the years [1]. This trend entails the changing working scenarios of industrial robotic systems from mass production lines towards batch production work cells in small- and medium-sized enterprises. Therefore, there is a need to develop flexible solutions resulting in shorter time for robot installation and re-programming, where intuitive interfaces for effective human–robot interaction (HRI) are more suitable for users who may have minimal technical skills in robotics [2, 3].

Many applications of industrial robots, such as arc welding, laser welding, etc., require the end-effector (EE) to follow a predefined path at suitable inclination angle with respect to the surface where the path lies. Using teaching pendants is unintuitive for planning these types of tasks. The walk-through robot programming method suffers from joint resistance of the actuators, which makes it difficult for the user to drag the robot to follow a given path. Recent research on intuitive robot programming has shown that the use of virtual reality (VR) and augmented reality (AR) enables the users to interact with virtual robots in a simulated or real working environment, providing significant convenience for the users in robot programming and EE orientation planning [4–7]. In addition, research on AR in robotics has been widely reported, e.g., AVILUS [8], SMErobot [9, 10], ARVIKA [11], etc. Intuitive interfaces based on speech recognition, tactile feedback, or visual perception have been investigated using various types of sensors, e.g., force torque sensors and optical tracking devices [5–7, 9]. Compared with VR, AR has advantages in the following key aspects in robot EE orientation planning. Firstly, AR provides a semi-immersive robot programming environment with useful visual cues that can improve the interaction of the user with the virtual robot during EE orientation planning. This provides the users with better realism feeling when he sees the real world while performing a given robotic task [5, 12]. Secondly, an AR-based environment is relatively easy and inexpensive to set up compared with VR-based systems as all the entities in the working environment do not need to be modeled or replicated. These properties suggest that the use of AR in robotic systems can overcome the limitations of VR-based systems and retain

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the advantages of VR-based systems, such as the various simulation options, intuitive HRI interface, etc.

In this research, an AR-based interactive approach for robot EE orientation planning incorporating robot dynamics (RPAR-II) is proposed and presented. The targeted applications are those where the EE is constrained to follow a visible path on a workpiece at permissible inclination angles with respect to the path. Based on the programming by demonstrations (PbD) concept, the user guides a virtual robot to acquire the input data for the system to learn the unknown curve [5], and after that, the user selects a number of control points interactively from the curve and defines the orientation of the EE at each control point to generate a smooth orientation profile for the EE of the robot. A trajectory optimization scheme is implemented to obtain the approximated optimal trajectory, which is simulated with the virtual robot, and executed on the real robot. The rest of the paper is organized as follows. Section 2 presents the related studies on robot trajectory planning and AR applications in robots. Section 3 gives an overview of the RPAR-II system. Section 4 presents the RPAR-II approach for planning a path-following task with selected orientations of the EE along the path. Section 5 presents the implementation results. Section 6 presents the conclusion and suggestions for future work.

2 Related studies

Most industrial robots are equipped with a dedicated teaching pendant and an off-line programming interface for robot programming. VR has been proven to be useful in many robotic applications, such as arc welding [4] and tele-robotics for tele-operations [13]. However, the VR-based method requires the construction of the entire virtual environment (VE) and more computational resources to maintain/update the mapping between the VE and its real counterparts [4]. There are commercially available CAM systems that support the path planning of robotic systems, such as Vericut [14], Siemens Tecnomatrix [15], and Siemens NX Motion Simulation software [16]. Vericut supports a full range of six degree of freedom (DOF) robots to simulate machining operations, fastener insertion, etc., and the process can be viewed through a VR-based reviewer. The Vericut collision checking permits the user to stop the simulation at an exact collision point and resume the simulation to the next collision point or to the end of the motion. The Siemens Tecnomatrix provides a collaborative 3D VE in the development, simulation, and commissioning of robotic and automated manufacturing systems. Siemens NX Motion Simulation software offers developers a kinematic and dynamic motion analysis tool to understand, simulate, and optimize the complex motion behavior of rigid multibody. Nevertheless, the use of these CAM systems is computationally intensive and requires computer systems with fast processors and large memory capacities.

PbD is another robot programming approach by which a task is demonstrated manually by the users, leaving the robot to learn, follow, or replicate. This approach requires the understanding of the user's intention through human gesture segmentation or sensing techniques and the acquisition of the environment knowledge through vision- or sensor-based object recognition techniques. The integration of PbD with VR is beneficial when the environment knowledge has been acquired a priori. It may improve the programming efficiency, reduce the demonstrator's fatigue, and overcome difficulties, such as object recognition [17, 18]. However, it suffers from the drawbacks of VR-based robotic systems such that these systems may not be suitable for partially known or frequently changing environments. Recent research on robot programming has been moving towards multimodal interfaces. Gestures, voices, etc., have been used to program personal or companion robots. Methods using these forms of inputs are intuitive and natural; however, there are issues associated with the multimodal communication, such as, information redundancy, information ambiguity, presence of noise, etc. [19, 20].

Regarding the planning of the EE orientation in various robotic tasks, most reported approaches are computer-based methods, where the orientation profile of the EE can be generated given the geometrical models of the workpieces [4, 21–23]. He and Chen [24] developed a spring model with a haptic interface to select a point of interest for the EE configuration modification in a totally immersive environment. In the method presented in Ref. [4], the only input required from a user is the position of the point of interest, as the possible orientation is determined automatically by the design features associated with this point. Therefore, complex rules need to be established a priori for mapping between a design feature, geometrical feature, and orientation of the EE, and the modification of the EE orientation profile can only be achieved through insertion or deletion of control point.

AR has been applied in a wide range of manufacturing applications [25]. Studies on AR applications in robotic systems have shown advantages over the aforementioned approaches. Equipped with proper interaction devices, such a system can facilitate user–robot interaction in a real scene, such as the selection of a more suitable pose among all the possible poses of a robot in a robotic surgery operation [26] or the navigation of the EE of a robot in a tele-operation task under display-control misalignment conditions [12]. In addition, the use of virtual robots enables the operators to program the robots without the need to interact physically with the real manipulators [5–7]. Several approaches have been reported on the planning of the orientation of the EE of a manipulator along a path using AR. Ong et al. [5] presented an approach for planning the EE orientations through interactively defining