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The effectiveness of virtual environments in developing collaborative strategies between industrial robots and humans

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ABSTRACT

Testing and implementation of Human-Robot Collaboration (HRC) could be dangerous due to the high-speed movements and massive forces generated by industrial robots. Wherever humans and industrial robots share a common workplace, accidents are likely to happen and always unpredictable. This has hindered the development of human robot collaborative strategies as well as the ability of authorities to pass regulations on how humans and robots should work together in close proximities. This paper presents the use of a Virtual Reality digital twin of a physical layout as a mechanism to understand human reactions to both predictable and unpredictable robot motions. A set of established metrics as well as a newly developed Kinetic Energy Ratio metric are used to analyse human reactions and validate the effectiveness of the Virtual Reality environment. It is the aim that Virtual Reality digital twins could inform the safe implementation of Human-Robot Collaborative strategies in factories of the future.

1. Introduction

The use of industrial robots in manufacturing and assembly lines is continuously increasing due to the need for high efficiencies, high accuracy, high production rates and repeatability. However, in some industries, the production line cannot rely on the use of robots only, and still require humans to perform some tasks that require creativity, adapting to unpredictable changes in the environment, fine motor skills and high dexterity such as cable assembly on a production line. As a result, interest and research in harnessing the natural and unique capabilities of both robot and human in collaboration tasks is increasing [1,2].

This has led to the development of collaborative robots such as Baxter [3], Sawyer [4], and the FANUC CR-4iA [5]. Nevertheless, in compliance to regulations, they move at a low speed in order to ensure that they do not cause damage when they collide with a human. They also have low payloads. This is because Human collaboration with an industrial robot could be dangerous due to the high-speed movements and massive forces generated by the robots.

Wherever human and industrial robots share a common workplace, accidents are likely and always unpredictable. As a result, in highly automated manufacturing systems industrial robots are located inside cages to constrain the physical interactions and proximities with humans. This leads to bigger size layouts, unused spaces and limited HRC operation. In order to avoid these drawbacks, the manufacturing sector is looking for new concepts beyond the current pre-defined safety measures to develop novel HRC strategies [1,2,6–10]. Novel HRC strategies that are currently being researched include turn-based strategies [8], automatic task allocation based on predefined metrics [10] and multi-modal communication with robots [2,7–9].

Nevertheless, the potential risk of injury to humans has reduced the progress of research in human robot collaborative strategies. This is because accidents could occur during the development of intelligent collaborative software and during the empirical experimental process of trial and error. Eliminating or reducing risks to humans during experiments could further aid the ability of authorities to pass regulations on how humans and robots should work together in close proximities.

A way to carry out this investigation is through Virtual Reality. The main idea behind Virtual Reality is the creation of a digital world in which a user can be immersed and interact with objects [11]. Although research in Virtual Reality has made significant progress in the last decades, the application within robotics is still in its infancy.

In manufacturing, Virtual Reality has started to be considered for several applications, such as programming [12,13], maintenance [14],

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process monitoring [15], product assembly [16], design and training [17] to mention a few. Virtual Reality provides a cost effective and safe environment to test various concepts and hypotheses before deployment in the real world. For example, Virtual Reality-based Training Systems (VRTSs) provide trainees with an environment to test and operate new equipment before it is installed. Important perceptual cues and multi-modal feedback (e.g., visual, auditory, and haptic) can be accessed in a Virtual Reality environment thereby enabling effective transfer of virtually acquired knowledge to real-world operation skills [18].

Virtual Reality also provides an opportunity to optimize factory layouts before construction [19–21]. In these cases, Virtual Reality has the potential to enable well designed layouts resulting in saving of up to 50% of operating costs. Optimization of manufacturing processes and tasks is another area that Virtual Reality lends massive benefits [22]. For example, complex tasks such as welding, drilling and screwing of parts require optimization of robot arm movement between different points in order to minimize span and maximize production rate. Achieving this via the programming of a robot arm is quite laborious and time consuming [12,13]. Nevertheless, VR's capability to represent virtual models of real world objects as well as present an intuitive programming interface makes it possible to simplify and speed up programming tasks. This also enables the generation of an optimization model that could be transferred onto a real world robot arm [12,23].

However, in order to achieve this seamless transfer, a digital twin of existing physical robotic cells is required. Development of digital twins requires a full synchronization between the real world at the shop-floor level and its digital twin. The synchronization enables a true reflection of the real factory and can be exploited to obtain current factory states as well as extrapolated to predict future factory states. It also opens up the possibility of experimenting with varying human presence sensing modalities in the robotic cell without comprising human safety [24].

According to regulations, human safety is achieved in HRC strategies by ensuring that collaborative robots do not exceed a certain size or exhibit certain speed profiles when interacting with a human. For example, the speed of a robot is reduced or stopped once a human is detected within a zone or minimum distance from the robot [23–28].

Other safety approaches being researched is through the modification of the robot's current trajectory via collision risk informed control strategies. For example, in [29], the authors introduced a proactive control strategy based on risk analysis while in [30], the authors developed a Danger Index based on likelihood of an impact with a human. The danger index was increased when the human was facing away from the robot, because of the reduced likelihood of observing and being aware of the robot's motion.

Nevertheless, despite the control strategies discussed above, it has been shown that during a human-robot collaboration session, an operator's stress increases when the robot's speed increases; when the distance between human and robot decreases or when the operator does not know what the robot is going to do next [2,28]. This is partly due to the lack of awareness of the safety functionalities present on the robot as well as the lack of knowledge of safe working areas. New emerging technologies such as the use of augmented reality techniques that allow for the visualization of the robot operating and safe areas might alleviate this [31].

Another way to equip operators with knowledge of expected robot actions and an awareness of safety is through the use of Virtual Reality to construct a digital twin of the Human-Robot collaboration task. Virtual Reality also provides a safe environment to test and validate various Human-Robot collaborative strategies. However, what is the effectiveness of using such an environment considering that the participants would know it is a virtual environment?

Consequently, in this work, we investigate the effectiveness of using a virtual environment to develop Human-Robot collaboration strategies that involve proximate interactions on a task [7]. This involved developing a digital twin of a real physical layout of a manufacturing cell and then using a questionnaire to gather responds from participants regarding their experiences to various robot motions including unexpected ones. This enabled us to measure the effectiveness of using a virtual environment to represent a real manufacturing cell for human-robot collaboration sessions.

Furthermore, we developed and tested a set of new metrics (based on Kinetic energy as well as human direction of reaction) to gauge human reaction and behaviour to various robot motions in the virtual environment. The aim is that these metrics could be used to inform robot control strategies in the future. This is unlike the approaches used in [28–30].

The rest of this paper is organised as follows: In Section 2, the methodology used in this paper is presented while in Section 3, the experimental setup is discussed. This is followed in Section 4 by experimental results while discussions are presented in Section 5. Conclusion and future work is presented in Section 6.

2. Methodology

In this section, we will discuss our experimental design. In order to use a Virtual Reality environment for accurately capturing and understanding human responses to robot actions, the realism of the virtual environment is essential. Furthermore, a mechanism to collect and analyse data is important. How these were achieved in this work are discussed in the next subsections.

2.1. Development of the virtual environment

The real world workshop consisted of a robot arm that can be programmed to carry out automated tasks of object placement, drilling, welding and visual observation of components. Currently, these tasks are done in a cage in order to separate humans and the robot arm.

In order to create a digital twin of the workshop, physical measurements as well as photographs of real artefacts in a workshop were used to create corresponding CAD models (Fig. 1). The real-world robot is an ABB IRB 2600 12-1.85 [32], whose predefined workspace is also depicted in Fig. 1. The CAD models were transferred to Unity3D, a virtual gaming environment. The CAD models were placed in the virtual environment so that the physical dimension relationships between the objects in the workshop (real world) was respected in the virtual environment. This resulted in a 1-to-1 mapping of the real environment to the virtual environment.

The virtual environment was experienced by the user via a HTC vive while interaction with elements in the environment was achieved through the use of hand controllers. This enabled the user to move freely in the 3D space of the real world as well as in the 3D space of the virtual environment (Fig. 2).

The digital twin of the robot arm was capable of receiving coordinate data from the real robot arm on the factory floor. However, for investigating HRC strategies, the digital twin of the robot arm was programmed using the Denavit-Hatenberg method for forward kinematics.

In order to measure human reaction during experiments, two classes of robot arm trajectory were programmed. The first class of trajectory was smooth and predictable. The robot was programmed to use this trajectory at the beginning of an experiment. The experiment consisted of the transportation of boxes from one location to another. In order to make the user experience a HRC session, the robot waits until it is fed with a box by the human. When fed, the robot arm moves and places the box at a predefined place in the Virtual environment. After dropping the box, it goes back to the place where the user is located and waits for the next box. This loop is repeated about 4 times in order to draw the user into the experience and build user confidence (Fig. 2).

Then, the robot arm performs the second class of trajectory which consists of an unpredictable and dangerous movement that attacks the user and moves against the user's forehead. During these two classes of