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Full length Article

Prototyping proactive and adaptive techniques for human-robot collaboration in manufacturing using virtual reality

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ABSTRACT

Human-Robot Interaction (HRI) has emerged in recent years as a need for common collaborative execution of manufacturing tasks. This work examines two types of techniques of safe collaboration that do not interrupt the flow of collaboration as far as possible, namely proactive and adaptive. The former are materialised using audio and visual cognitive aids, which the user receives as dynamic stimuli in real time during collaboration, and are aimed at information enrichment of the latter. Adaptive techniques investigated refer to the robot; according to the first one of them the robot decelerates when a forthcoming contact with the user is traced, whilst according to the second one the robot retracts and moves to the final destination via a modified, safe trajectory, so as to avoid the human. The effectiveness as well as the activation criteria of the above techniques are investigated in order to avoid possible pointless or premature activation. Such investigation was implemented in a prototype highly interactive and immersive Virtual Environment (VE), in the framework of H-R collaborative hand lay-up process of carbon fabric in an industrial workcell. User tests were conducted, in which both subjective metrics of user satisfaction and performance metrics of the collaboration (task completion duration, robot mean velocity, number of detected human-robot collisions etc.) After statistical processing, results do verify the effectiveness of safe collaboration techniques as well as their acceptability by the user, showing that collaboration performance is affected to a different extent.

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1. Introduction

Human-Robot (HRC) collaboration in manufacturing systems is aimed primarily at supporting the human in exploiting his/her abilities and aptitude for performing high-value added work more effectively [1], with reduced burden [2], or, finally, with overall positive effect on the efficiency of the cooperative system [3]. Until today safety in HRC in industry is ensured primarily through separation of human from robot, spatial and/or temporal, and with the implementation of pre-collision safety systems, such as optoelectronic protective devices (light curtains), sensing devices, laser scanners, robotic vision and alarms.

At a research level, two directions are followed: (i) design of safety techniques applicable during robot movement (e.g. collision avoidance techniques) so that collaboration flow, communication and ease are not hampered, in particular ensuring that techniques are not activated too early or without particular reason, which would lead the user to ignore cues and alarms or would dramatically prolong collaboration time or cancel the essence of collaboration and establish a delay pattern in a stop-and-go fashion (ii) cognitive facilitation of situation awareness, anticipation of intent and behaviour, in both directions, i.e. from the human's side and the robot controller's side [4].

The current safety standards [5–7], as well as the recently released [8] address criteria, methods and biomechanical limits for injury elimination and safe HRC in a common workspace. However, many issues remain unresolved, such as (i) defining control points for tests when human and/or robot motion is intricate and no critical collision points can be defined (ii) prediction and resolution of human errors during collaboration and generally human behaviour and response in non-anticipated robot movements (iii) investigating different acceptable velocity patterns depending on the task performed as well as the robot before their actual implementation (iv) understanding of the safety techniques by the human and reaction to them. These issues can certainly be investigated and to some extent resolved by using interactive Virtual Environments (VEs), which is the line advocated in this work, too.

Virtual and Augmented Reality interactive environments enable reproduction of the main characteristics of HRC, highlighting or even emphasizing particular aspects of the collaboration, e.g. malfunctions [9], human error [10], making available cognitive aids that are difficult to include in the real world, and downgrading undesired aspects of the col-

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laboration [11]. For instance, different robot arms have been successfully tried using different velocity profiles and trajectories [12], and user acceptance of HRC has been studied [13].

This work investigates using a highly interactive and immersive VE, two different classes of safety techniques, namely a passive one targeted at the human and providing several cognitive (audiovisual) aids and alarms to foster users' proactive and anticipatory behaviour, and an active one, targeted at the robot, which reacts to and avoids potential collisions, using safety-based, adaptive motion techniques. In the latter case, two different techniques and activation criteria are compared. The main motivation for pursuing a VR approach against using a real industrial robot is primarily safety of the human, especially when experimenting with different techniques which have not been standardised yet. Secondarily, accessibility of commercially available robot hardware that may allow such experimentation, e.g. robots with flexible joints and smart controllers, is still restricted; moreover, such hardware is certainly not open enough to accommodate the degree of experimentation that a virtual robot would allow.

The paper is structured as follows. Section 2 presents basic HRC notions. Section 3 briefly describes the VE created. Section 4 focuses on the particular safety techniques used and Section 5 presents the pertinent assessment experiments. Results are consolidated in Section 6.

2. Human-robot collaboration (HRC)

The collaborative operation is defined as a state in which purposely designed robots work in direct cooperation with a human within a defined workspace. ISO/TS 10566:2016 defines the collaborative workspace as the space within the operating space where the robot system (including the workpiece) and human can perform tasks concurrently during production operation [5].

In contrast to cobots and robot manipulators, which are passive and may not employ sensors and actuators, industrial robot assistants constitute flexible devices of direct interaction with the human, which aid the human by using sensors, actuators and data processors [14]. In this research, the term collaboration includes interaction and all actions that create communication and common understanding between the human and robot in jointly performing the task at hand.

HR collaborative operations are classified based on: (i) work distribution [15], (ii) spatial distribution, (iii) temporal distribution (independent, synchronized, simultaneous and, assisted HR collaboration types) [16], and, (iv) collaboration level [17]. High collaboration level requires situation awareness [18], joint understanding of the task and prediction of the next steps both by the robot and the human [4].

As far as HRC applications in manufacturing are concerned, there are several examples and reports mainly concerning assembly. Early examples of cobots include *rob@work* for assembling hydraulic pumps [14] and for welding large parts [16], the collaborative assembly cell *team@work* [16] and the *PowerMate* system for transport and assembly operations [19]. A comprehensive review of HRC in assembly is given in [3] and high potential applications in automotive assembly are reported in [17].

ISO 10218/2011 states that HRC is allowed, if one of the following conditions is satisfied: (i) Velocity of the end-effector (TCP) not exceeding 0,25 m/s (ii) Maximum dynamic power not exceeding ≤ 80 W (iii) Maximum static force not exceeding 150 N [6]. These conditions may be challenged because they do not take into account the size and shape of the robot, the distance between human and robot and the control strategies [20]. Moreover, even if the TCP velocity constraint holds, the robot may still be dangerous if it is operating near a singularity point. ISO/TS 15066:2016 supplements the industrial robot safety standards and is based on collision and injury criteria limit values (force and pressure injury criteria) [8]. ANSI/RIA R15.06–2012 states that in HRC the distance between human and robot needs to be larger than their relative velocity multiplied by the time needed for decelerating the robot to zero velocity, depending on the payload [7].

A widespread technique for safe HRC limits TCP velocity based on data regarding injury, inertial load and the configuration of the end-effector [21]. A phased reaction may involve reducing velocity by 50%, then the robot may try to recede and finally come to a standstill [22]. Alternatively, a kinetic energy criterion may be satisfied in real time [23]. Several strategies have been suggested involving safe distance metrics for a given trajectory [24] and human support strategies in different collaborative applications [25]. In [26] robot velocity is adapted according to data from depth cameras. In [27] HRC in grinding is dealt with, tracking the user and using NURBS surface control points to modify robot trajectory. Sensor-driven real time monitoring and collision avoidance, by combining depth images of humans and robots in an augmented environment is reported on in [28].

Simulation for assessing HRC risks and modifying robot design and control has been used in the past through graphical simulators, e.g. [29], but Augmented Reality is mostly used nowadays, e.g. [9–11,30–32]), whereas HRC acceptability has been studied using pure VR in [13]. There are significant advantages in using VEs for studying HRC. Setup of different collaborations scenarios including control strategies and parameters is relatively straightforward. Assessment of perceived safety for different scenarios is possible. In addition, increased perception and situation awareness in collaborative domains is supported, thereby adding to the enhance collaboration performance. Modelling system malfunctions, highlighting human error and monitoring resulting behaviour or even designing predetermined errors into the system for hypothesis testing is easy and, what is more important, harmless to the human. Already published findings concerning HRC modelling efficiency (modelling capacity, VE efficiency, presence, user involvement and acceptance) are very positive and confirm interactive VEs' efficiency on such skillful collaborative tasks modelling, and thus suggest a positive prospect for the use of VR for training or testing on HRC [33].

3. Constructed Virtual Environment (VE)

3.1. Collaboration scenario

The HRC scenario refers to hand lay-up process of pre-impregnated (prepreg) carbon fabric in an industrial workcell and was based on in-situ observation of an analogous workcell at Hellenic Aerospace Industry. The virtual scene comprises: (i) a shop-floor environment (42 original 3d models, forming the virtual model of a hybrid composites hand layup work-cell), (ii) the model of a Stäubli^{TM} RX90L industrial robotic manipulator, (iii) the skinned model of an avatar with a biped skeleton attached to it, (iv) image, video and audio textures from real industrial workplaces making for a more realistic environment, and, (v) several auxiliary parts and objects, as depicted in Fig. 1. The robot is suspended from a structure, between the mould workbench and the carbon-fibre fabrics workbench, so that it can easily collaborate (feed, hand-over, hold, position) with the user. The fabrics are already cut in their final dimensions and stacked on a bench that is close to the main workbench on which layup takes place. The robot manipulates fabric using its vacuum end-effector. The user has a first person perspective and he is able to see his virtual body, for increased presence and sense of embodiment [34].

The scenario is depicted in Fig. 2, starting after the user pushes the start button with his/her hand; the robot, then, moves towards the fabric stack workbench, picks and transfers the first fabric to the user. The fabric is properly oriented, so that the user removes the backing film with his hands, while the robot is holding the reverse, non-adhesive side of the prepreg, with its vacuum gripper, see Fig. 2(b). The robot workspace is soon shared by the human, see Fig. 2(c–d). A semi-transparent magenta coloured palm aid is displayed on the backing strip demonstrating the motion pattern that the human is required to perform in order to remove this strip, Fig. 2(e), and let it fall on the ground under gravity governed by fabric folding and strip crimping physics, see Fig. 2(f) . This constitutes the adhesive film removal metaphor [33]. Once the backing

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