Robotics and Computer–Integrated Manufacturing 50 (2018) 168–180

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Full length Article

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

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ARTICLE INFO

*Keywords:*
Human-robot collaboration
Virtual environments
Human-robot interaction
Safety
Proactive techniques
Adaptive trajectory
Collision Avoidance

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.



## 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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http://dx.doi.org/10.1016/j.rcim.2017.09.005
Received 30 October 2016; Received in revised form 11 August 2017; Accepted 18 September 2017
Available online 28 September 2017
0736-5845/

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™ 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

**Fig. 1.** Third person perspective of virtual scene.

film is removed, the robot transports it to the mould with suitable orientation; one of the fabric patch's edges touches the respective mould's edge (which is highlighted in red colour), to enable the human position the rest of the patch on the mould, see Fig. 2(g). Since the bottom side of the fabric patch is sticky, the robot provides the crucial alignment of one edge sparing the human a lot of small movements. In order to properly lay the fabric a blue semi-transparent palm acts as a motion aid for the human to follow as precisely as possible in reciprocal fashion for a few cycles, constituting a fabric layup metaphor [33], see Fig. 2(h). Then, the fabric patch is released on the mould as required and the process is repeated for the rest of the fabrics.

This scenario is deemed relatively complex compared to those typically represented in VEs, involving simultaneous, parallel and joint collaboration. Thus, full spatial coincidence is applicable and workspace sharing concerns the whole of the collaboration scenario. Temporal distribution, during backing paper removal concerns simultaneous HRC on the same part. During collaborative fabric laying, at a specific position and with specific orientation, human and robot work jointly on the same part (assisted H-R collaboration type) with physical contact possibility. The overall tasks are of higher level as far as collaboration is concerned, in relation to the individual tasks of handover, holding and transportation, which are typically encountered in literature. The robot relieves the human from low added value tasks leaving him/her to perform less cumbersome tasks requiring higher level cognitive abilities.

### 3.2. Application setup

Following the scenario presented above, a novel interactive VE was developed on Unity 3d™ game engine platform as a standalone Windows™ application, "beWare of the Robot v2.0". Two main 3D user interfaces are employed: (i) a Microsoft Kinect™ 2 sensor as an input device for skeletal tracking of the user, and, (ii) a stereoscopic HMD (Oculus Rift DK2) as an immersive output device for stereoscopic visual display, and as an input device for head motion tracking. Communication between Kinect™ and the VE is established with the use of Microsoft Kinect SDK v1.8. Furthermore, in user tests a video projector was used to reproduce on a screen behind the user the same scene so that user experience can be recorded, see Fig. 3. The scene arrangement and scenario formulation were done in such a way that tracking constraints became irrelevant, e.g. the human will always face the Kinect sensor, will not need to turn his/her body by more than 60° to collaborate with the robot etc. Details about this as well as immersion, presence and other VE issues are fully discussed in [35].

Immersion and presence feelings are enriched with 3d sound sources, i.e. robot motion sound, alarm, shop-floor sounds, real-time shadows, and the video of a real manufacturing work-cell which is reproduced on the background wall, in form of a video texture. More detail can be found in [35].

The user can see the robot moving stereoscopically and hear it stereophonically. The robot's workspace is continuously visible as a toroidal-like red semi-transparent 3D surface, whereas its projection on the floor is also shown as a red line circle, see Fig. 4. A further auxiliary aid is the robot movement volume, which is a yellow semi-transparent 3D wedge, attached to the arm of the robot. During interaction when robot movement volume interferes with the human the former turn red and an ATTENTION warning is displayed together with an audio emergency signal, see Fig. 2(c-d).

In Unity 3d™ code may be embedded in objects in order to add behaviour, motion, physical properties and interaction, as well as collision detection capabilities, ray tracing capability, hierarchical relationships, inheritance, motion tracking as well as code to implement safe HRC techniques. The application implements all four of the basic VR interaction tasks (navigation, selection, manipulation and control). Triggering of events and implementation of most of the interaction techniques are based on colliders (mesh for precision, or approximate basic shape for speed). The robot motion is supported by forward kinematics, i.e. quaternions in Unity and Euler angles for defining motion and for calculating TCP position and orientation. Robot geometry is defined according to Denavit–Hartenberg method. Shop-floor environment and its components were developed using Rhinoceros™ and 3ds Max™ software, and the skinned model of the avatar was created online in the Evolver avatar builder. Total size of the application is 390 MB, 100 MB of which are texture files (materials, images, sounds and videos). Overall functionality, interaction, and use case scenario activities, are implemented with 41 original C# scripts in 7281 lines of code.

## 4. Techniques for safe HRC

Two classes of techniques for ensuring safe collaboration between human and robot were implemented in the VE described above, as summarised pictorially in Fig. 5. The first one is passive and aims at cultivating proactive human behaviour by making use of cognitive aids

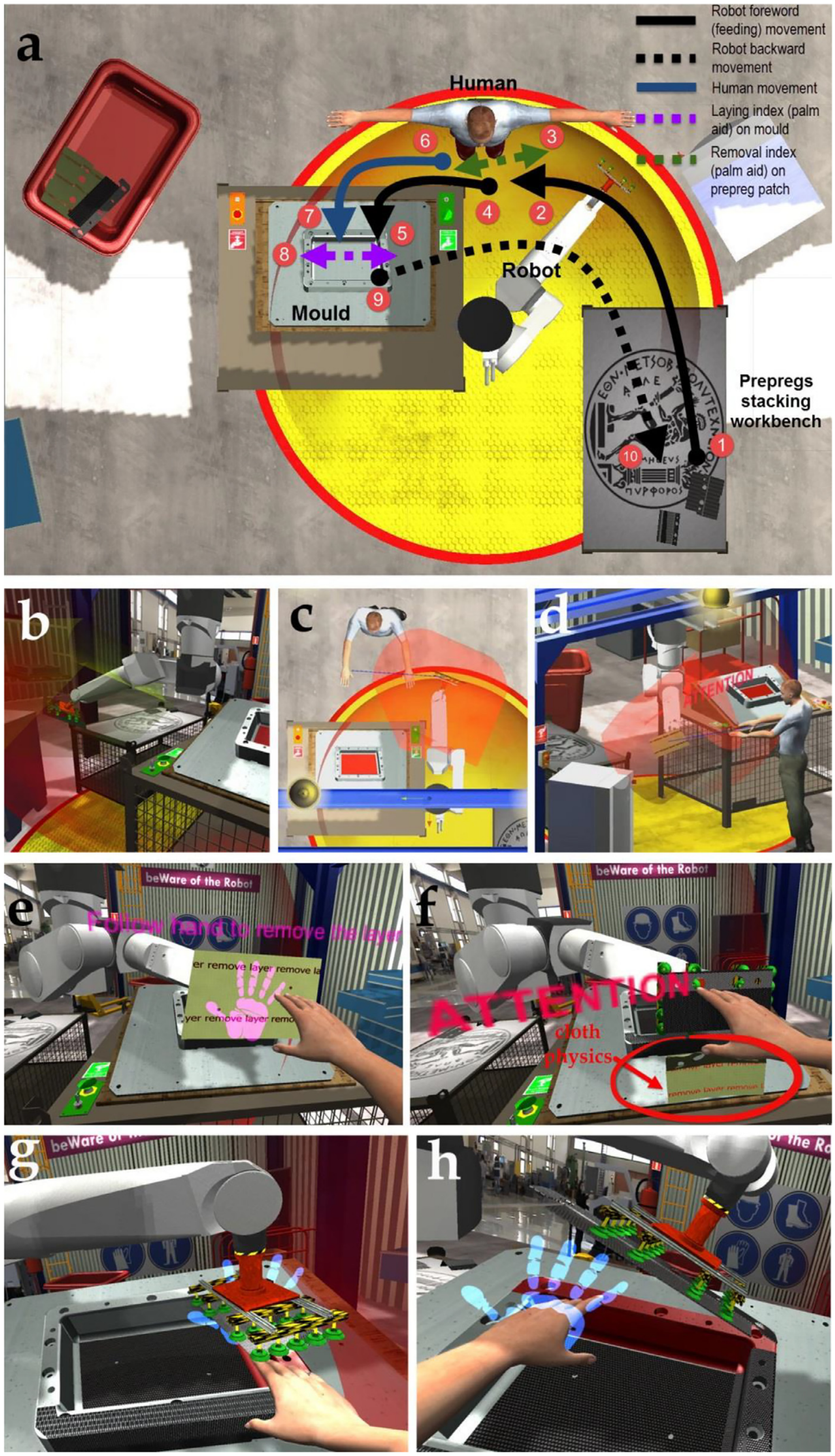


**Fig. 2.** HRC Scenario (a) general setup, (b) Fabric transport by robot to human, (c, d) HR interaction within robot workspace, (e, f) Backing strip removal metaphor, (g) Fabric transportation and positioning over the mould, (h) layup palm metaphor.

embedded in the VE to raise levels of situation awareness [36]. The second class is active and aims at ensuring adaptive robot behaviour, through two implementations, i.e. (i) deceleration along same trajectory (slowdown technique) and (ii) trajectory modification (retract technique). The conditions of activation of these techniques are composite and applied gradually: first proactive techniques are applied based on human-robot distance and then adaptive techniques involving more complex and combinatorial conditions (robot velocity, robot direction of move with respect to the human, distance between robot gripper and 8 different human joints, time to collision).

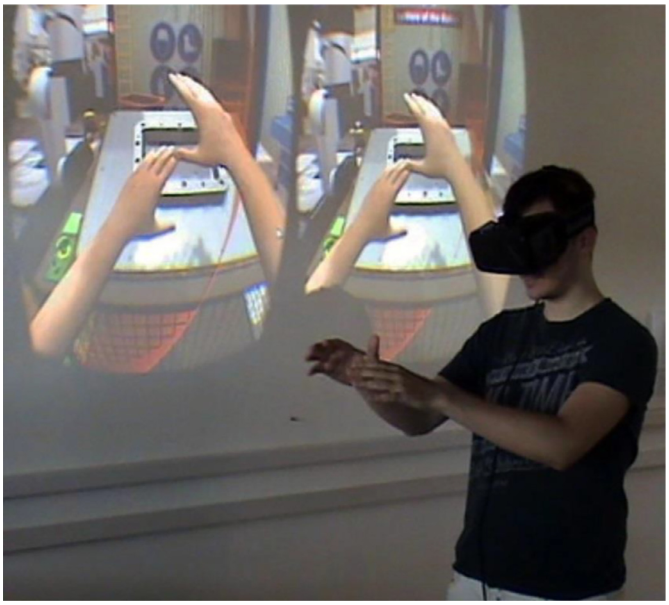

**Fig. 3.** Typical user aspect of the system 'beWare of the Robot'.

### 4.1. Proactive technique

This ultimately concerns visual or sound alarms connected with potential threats for human safety. The human processes these alarms together with all other information received from the environment in order to first interpret the cause of the alarm. Human's responsiveness and reaction depends on the comprehension of the cue based on the user's experience with the system, the pertinent mental model of the event (perception), the expectancy, and the developed situation awareness by the human.

Users develop situation awareness in a spatial and temporal frame [18,36,37]. In this case, this frame must be dynamic and depend in real time on the movement capability of the robot with respect to the moving human. In order to enable effective, reliable and gradual activation of alarms different rigorously defined activation criteria are set. In particular, a point was made of supporting the first two steps in achieving situation awareness (perception of the elements in the environment, and comprehension of the current status) through the activation criterion already, so that the desired information or the future state of the system (third level of situation awareness) can be directly projected to the user.

Proactive technique is exclusively implemented through (a) colliders (b) visual cues added to the virtual scene as cognitive aids (c) alarm elements based on suitably modified visual cues.

Further to colliders employed for the objects of the virtual scene, see Section 3, colliders employed in implementing proactive techniques are shown in Fig. 6. Capsule collider A is used for checking the direction of motion of the robot end-effector with respect to the human and is widened in order to identify a larger range of movements around the human. The aim is primarily to avoid false alarms, and, secondarily, to identify movements whose direction does not currently seem to be towards the human body, but with some modification they could ultimately become so. The rest of the collision detection elements shown in Fig. 6 cover effectively almost all motions of the respective human body members according to the collaboration scenario. For instance, capsule collider C covers the whole of the human body in upright posture, whilst capsule B covers the torso in bending or turning and capsules D contain the avatar's forearms.

The visual cues embedded into the VE as cognitive aids concern the robot workspace volume and the robot motion volume, which are displayed in Fig. 7 as semi-transparent mesh-type surfaces. In contrast to the robot workspace, which is a well-established notion in robotics, the motion volume is novel; it has a wedge or pie-slice shape curved to one side, is attached to the robot forearm and moves with it. Its size increases linearly from the 4th joint to the end-effector from where a cylindrical section with radius 0.5 m starts. The produced robot motion volume is designed as a second-level and more accurate aid for this collaboration scenario, aiming at (i) representing in the 3d space the potentially dangerous moving area which is produced around the maximal-inertia robot links, and (ii) serving as a more reliable, dynamic and motion-based warning cue. Workspace volume is always visible around the robot.

The pie sliced shape of the motion volume was considered suitable for a 6 rotary joint robot because it combines a wedge starting from the 4th joint, i.e. the area with the lowest danger and expanding linearly in size towards the end effector, i.e. the area with the highest danger, and a cylindrical section centred at the end effector, encompassing all possible next moves of the robot. As a geometric shape it delineates a moving area of increased potential danger from the point of view of its proximity to the human, outperforming alternative simple shapes such as a sphere, doughnut, cube etc., which would have embedded a much larger area than what is actually dangerous.

The motion volume is initially invisible and becomes visible when the robot forearm moves, thereby defining a directly-affected zone. Thus, use of these cues is made in order to ensure safe and readable motion, for the robot to 'communicate' to the user its 'intention' of

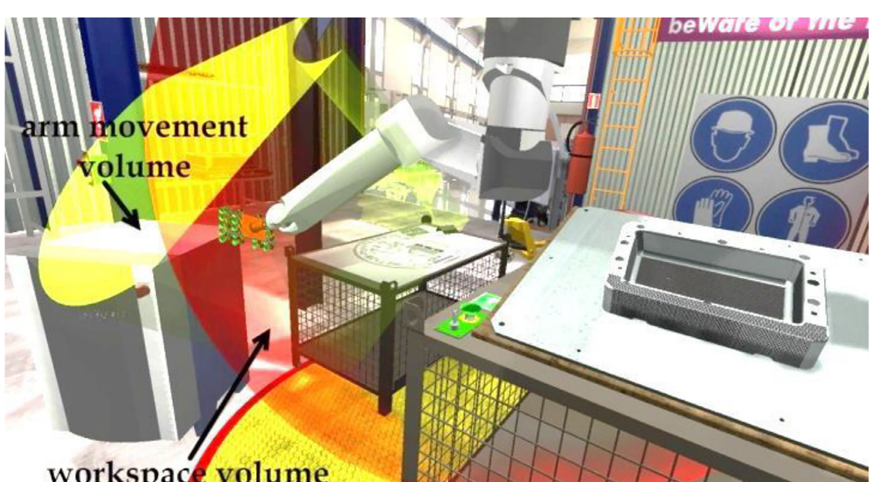


**Fig. 4.** Robot workspace, its projection on the floor and arm movement volume aids.

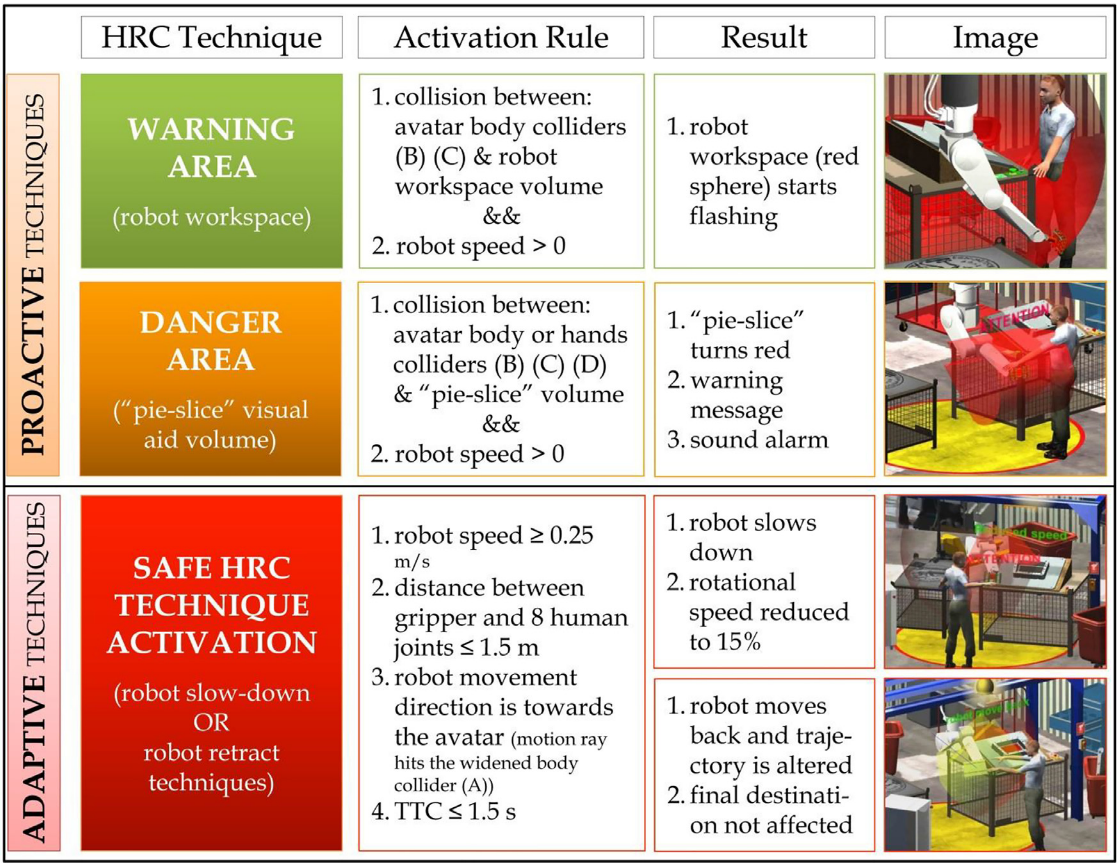


**Fig. 5.** Safe HRC techniques employed.

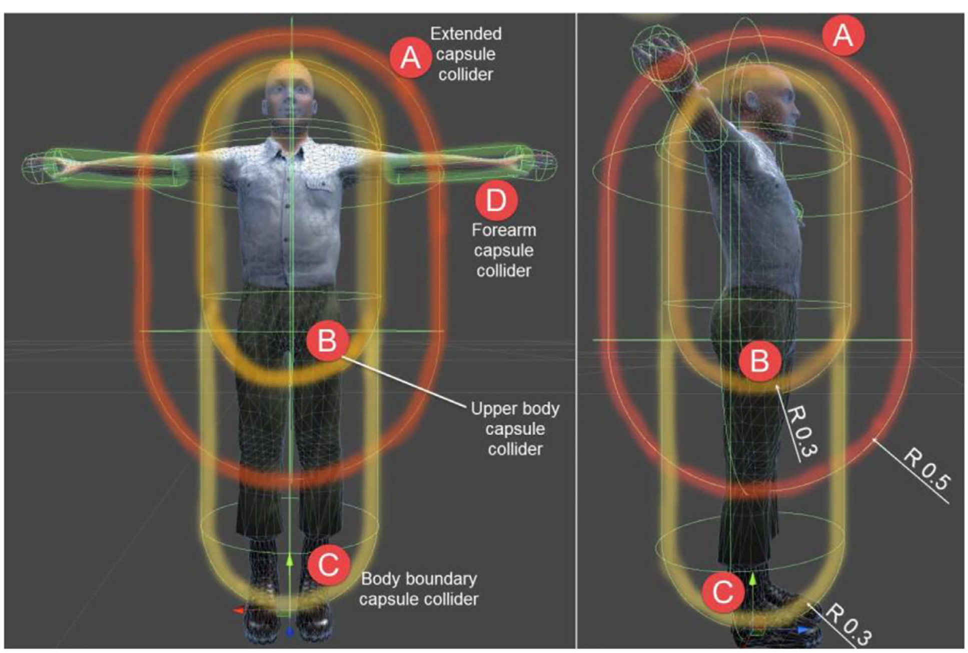


**Fig. 6.** Avatar colliders.

motion and, conversely, for the human to comprehend this intention and next motion of the robot in a timely manner.

Audio cues are also widely employed, e.g. an alarm sound when the human contacts the motion volume, a long 'beep' just before the robot starts moving, 3d sound sources of the robot motors that follow their position in space, etc. Such 3d sounds correspond to the distance between the user and the sound source, the motion of the latter and the reflections on different objects and materials of the virtual scene. In addition, the audio cues have been selected so as to point directly to the respective situation, and to create a cognitive link with it.

If during execution of the application some of the activation criteria are met (Warning or Danger Area Conditions), see Fig. 5, then the above

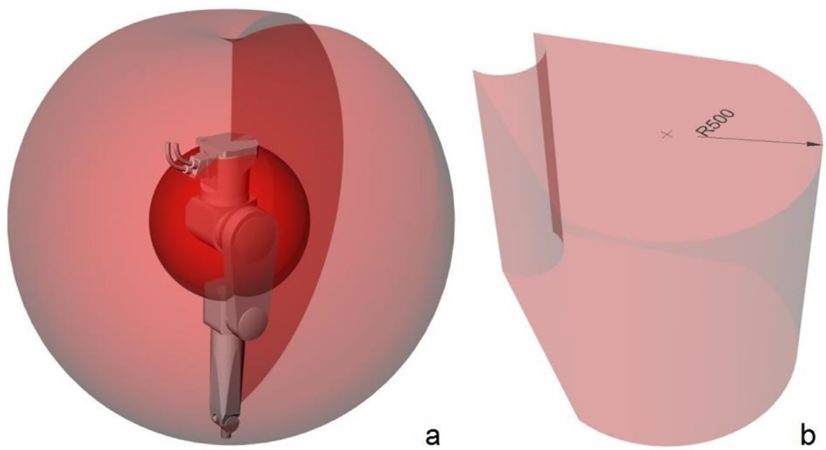


**Fig. 7.** Graphic representation of visual aids (a) robot workspace volume (b) robot motion volume.

mentioned visual cues are transformed from cognitive aids to vigilance alarms, through modification of some of their parameters, e.g. colour, brightness, transparency, blinking etc.

The first alarm (Warning Area Alarm in Fig. 5) is visual in nature, concerning a blinking envelope of the robot workspace and is activated, see Fig. 8(a), when both of the following conditions are met: (i) the torso (upper body) or legs of the human (colliders B and C in Fig. 6) come into contact with the robot workspace volume and (ii) the robot is moving, i.e. TCP velocity V is non zero. Practically, a limit of 0.01 m/s has been set, so as to not take into account subtle movements with negligible velocity.

The next alarm (Danger Area Alarm in Fig. 5) is audio-visual in nature, concerning a change in colour and transparency of the warning visual display of the motion volume / "pie-slice" from yellow to bright red accompanied by an audio signal. This alarm is activated when, see Fig. 8(b), both of the following conditions are met: (i) any part of the human's body (torso, legs, arms, i.e. colliders B, C and D in Fig. 6 in this order) comes into contact with the robot motion volume and (ii) the robot is moving, i.e. $V > 0.01$ m/s).

### 4.2. Adaptive techniques

Activation of adaptive techniques is based on a composite criterion which is defined by a combination of metrics, in the order stated in Fig. 5, namely: (i) end effector velocity has to exceed the maximum safe limit as defined in [5], i.e. 0.25 m/s, (ii) the distance between the end effector and at least one of the total of 8 points on the upper body of the human (head, shoulders, elbows, hands, spine) has to be less than 1.5 m, (iii) the ray of length 0.5 m which is cast by the end effector along its direction of motion (normalised velocity vector), has to hit the enlarged collision element of the avatar, (collider A in Fig. 6), i.e. to be ensured that the robot is directed towards the human, see Fig. 8(c), and (iv) the time to collision (TTC) has to be less than 1.5 s. TTC is a performance (time) measure, referencing a potentially upcoming collision, and is calculated from the instantaneous velocity of the end effector and its distance to the closest joint of the avatar in the direction of motion. The direction of motion of the end effector is calculated as the normalized velocity vector at any time point. TTC and distance are combinatorial criteria. The distance obviously relates to the robot's working volume whilst TTC relates to the robot velocity and the reaction speed of the human in case of alarms. Their values are determined by an informal risk analysis, based on the specific robot trajectories defined as well as the human's movements during collaboration based on two criteria: (i) reliable activation (no false alarms) (ii) uninterrupted flow of collaboration (no continuous safety technique activations). In this case, the value of 1.5 s for TTC resulted by adopting robot velocity 1 m/s and human-robot distance of 1.5 m in the equation: (H-R distance) $\leq$ (robot velocity) $\times$ TTC corresponding to the activation criterion (i) stated above.

#### 4.2.1. Robot slow-down technique

This is the simpler of the two adaptive techniques employed. If, in the course of robot movement, the activation criterion presented in Fig. 5 is satisfied, then angular velocity of robot joints is reduced to 15% of the originally prescribed values, see Fig. 8(c). Reduced velocity is retained for as long as activation criterion is satisfied, see Fig. 9(b-d), or for a minimum of 1 s if the human recedes earlier; at the same time the information 'reduced robot speed' is displayed in the human's field of view (visual alarm). If the activation criterion ceases to be satisfied, robot velocity reverts to its original value, see Fig. 9(f). Note that the original robot trajectory remains unaltered. It is only executed at reduced speed.

The reasoning behind this technique is based on the assumption that slowing down the robot will give the human the necessary time to perceive the possibility of collision and to back off the robot path. Even if the human does not back off, it is assumed that the robot's velocity has been so much reduced that it is within allowable contact limits according to ISO 10218/2011. Note that the human can avoid activation of this technique during collaborative task execution by closely observing the cognitive aids and reacting appropriately, i.e. recedes or changes posture, when the robot moves towards him/her.

As a technical note, robot moves in Unity$^{TM}$ are programmed using interpolation between the initial and final Euler angles of each joint orientation in joint space for each time frame.

#### 4.2.2. Robot retract technique

This is activated when the robot moves along a specific path. Safe points for the robot to recede to have been selected based on the moves of the collaboration scenario. For each particular motion of the robot (fabric feeding, transportation to and departure from the mould etc.) individual zones are defined; thus, knowing each time the human's position and the zone in which the robot is moving, immediately after activation of the retract technique, the robot is led to the corresponding safe point. Thus, all paths are pre-determined and no dynamic path planning is performed; this has become possible because of the pretty standard tasks that have been assigned to the robot and associated movements implementing them. Motion of the robot from the intermediate safe point to its original destination is implemented by interpolation in joint space. Technically, as in the robot slow-down technique, motion is programmed using interpolation between initial and final Euler angles of joint orientation in joint space.

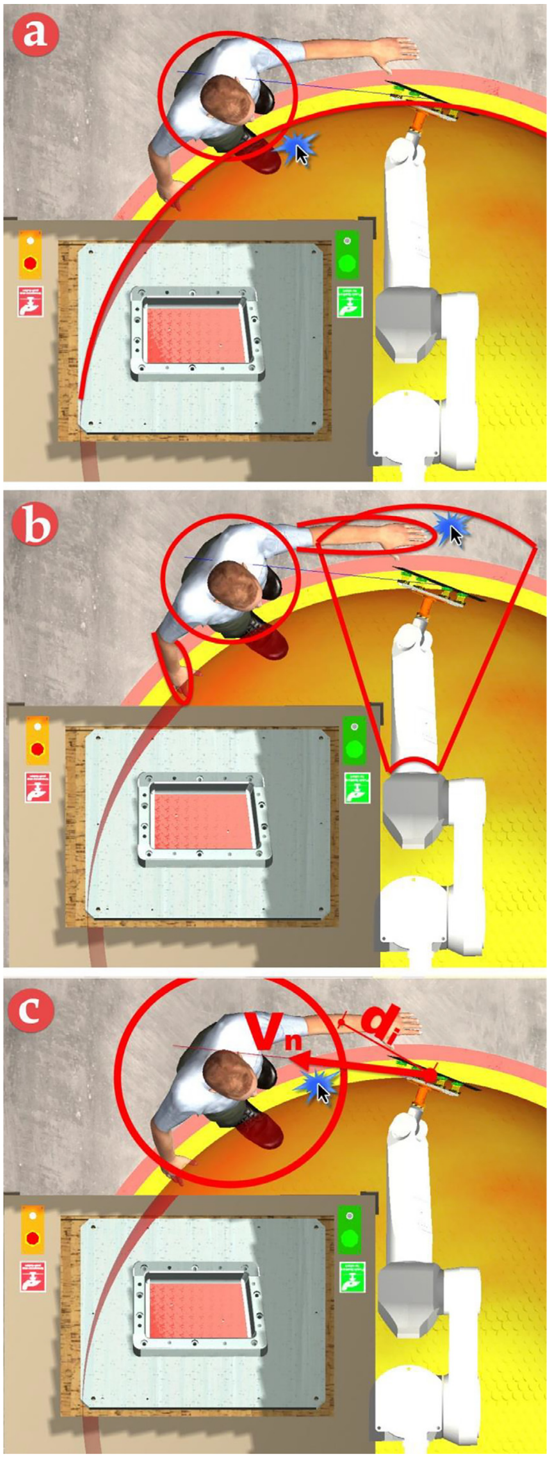


**Fig. 8.** Safe HRC technique activation (a) contact of human body collider with robot workspace volume (b) contact of arm collider with robot motion volume, (c) intersection of normalized velocity ray ($V_n$) and enlarged avatar collider, and distance between gripper and eight human joints ($d_i < 1.5$ m).

For instance, given the originally intended white-coloured path AE of the robot end-effector in Fig. 10, if the human intercepts it, e.g. at point B in Fig. 10, in a way that satisfies the activation criteria presented in Fig. 5, retract technique is activated. The motion coroutine running at the moment of activation is interrupted and a new routine is started, which sets as new destination a new intermediate 'safe' point away from the user (point C in Fig. 10). The robot moves to this transient destination (path BC in Fig. 10) so as to avoid the human and as soon as it reaches point C a new movement to the original destination (E in Fig. 10) starts. If, in the meanwhile the human has receded and no imminent collision is detected, the robot will follow directly path CE thereby concluding its movement. However, if the human does not recede, as is the case in Fig. 10, then imminent collision is detected again and robot retraction technique is again activated from point C, i.e. the robot recedes further moving to a new intermediate position (point D in Fig. 10), from where the robot concludes its movement to its original destination, i.e. point E.

Transition between motion routines has been programmed in such a way as to ensure continuity, i.e. absence of stoppages and any perceivable intermediate gaps (transition time equals 1 frame, ≈ 0.015 s). For the first 5 s after activation of this technique collision detection ceases in order to avoid repeated occurrence of startups and new calculation of intermediate safe positions which would result in 'vibratory' movement of the robot.

The reasoning behind this technique is based on the assumption that retraction of the robot alone is sufficient in order to avoid collisions or dangerous contacts between robot and human. Theoretically, even if the human stays motionless, the robot will modify its path and recede as many times as necessary to avoid him/her. However, ideally, user interaction after activation of the retract technique results in avoidance of repeated re-activations which would lead to long task duration and to unacceptably low performance.

During retract technique execution, the message 'robot move back' is displayed in user's field of view, see i.e. the need for his/her reaction is made explicit. During execution of the collaborative task the user has the possibility and the time to avoid activation of the retract technique, by taking into account the cognitive aids and cues provided, in order to recede or change posture when the robot moves towards the user, either before or after activation of the techniques, i.e. proactively or adaptively, respectively.

## 5. Experiments, results and discussion

### 5.1. Description

A series of experiments was conducted in which a group of 30 final year Mechanical Engineering students participated, all of whom were familiar with basic notions of robotics and manufacturing systems. In addition to user data logging, a video camera was employed to record user experience and enable observation of user behaviour in the VE. Each user conducted sequentially three variations of the 'beWare of the Robot v2.0′ application in random order, namely: (i) without any HRC technique (control version), (ii) with robot slow-down technique, (iii) with robot retract technique. Total duration of the three tests per user was 30–45 min. At the beginning each user was briefed orally after a 2–3 min familiarisation session with the VE, motion tracking and basic interaction tasks. Each user had to layup fabrics as described in Section 3. After setting up and putting on the HMD (Oculus Rift DK2), the user would stand opposite the motion tracking device at a 2.5 m distance from it to undergo skeletal tracking to enable starting of scenario execution. Each variant should be completed in 5–8 min. Output variables (collisions, events, time, velocity) were recorded in log files. At the end of the session a short conversation was conducted with the user regarding his/her experience before being allowed to fill in the relevant online questionnaire.

### 5.2. Subjective assessment of proactive and adaptive techniques

The opinion of the users regarding use of safe HRC proactive techniques was registered using five statements requiring expression of degree of agreement or disagreement in the range 1–5 in a descriptive scale (Likert type), where 1 stands for full negation (disagreement with the statement) whereas 5 stands for full affirmation (agreement with the statement), see Table 1. Following the results, use of audio-visual cues

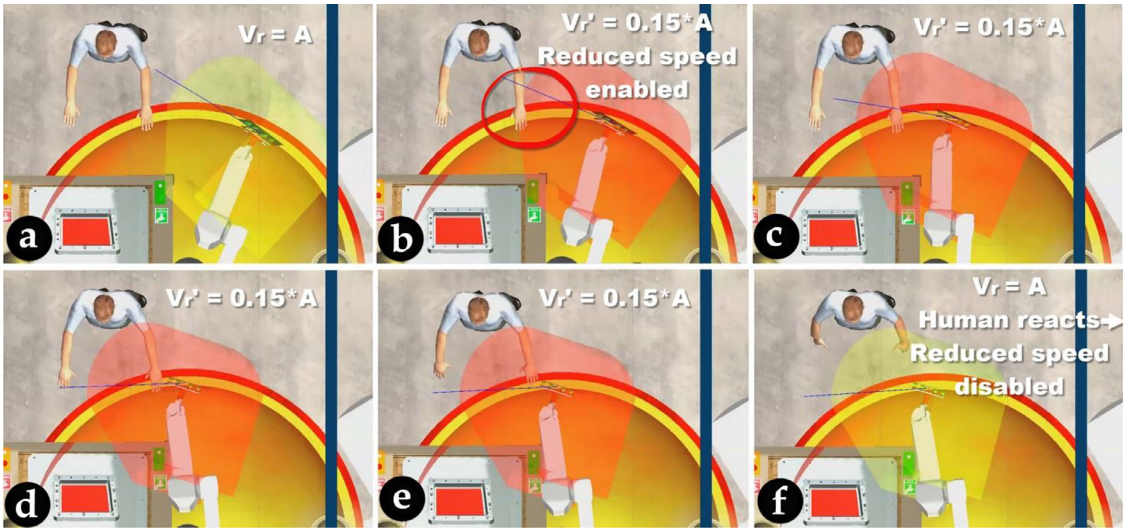


**Fig. 9.** Sequential snapshots of slowdown technique activation.

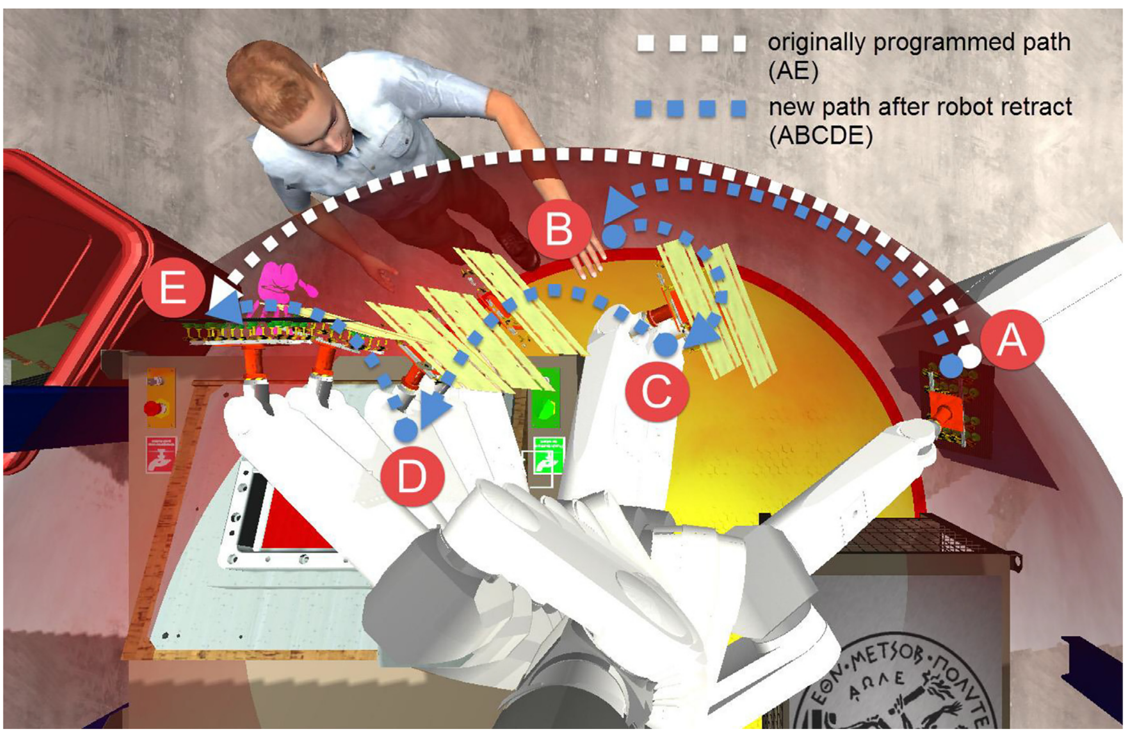


**Fig. 10.** Representation of robot retraction technique activation.

and alarms was very effective in identifying the existence of a potentially dangerous situation (perceived efficiency), and in avoiding HR collision, hence their substantial contribution to perceived safety. Moreover, the cause of alarm activation was easily identified, pointing to making clear mental assignments, whilst no user expressed a negative opinion about these techniques or reported an excessive cognitive load associated with their use.

In Table 2 the opinion of the users regarding use of safe HRC adaptive techniques was registered using five statements or questions to which agreement/disagreement or answers were given. Based on the first three statements, both the activation criteria and the post-activation behaviour of the robot are considered successful. Comparing the two techniques, there is no clear difference in terms of collision avoidance (question 4), whereas slow-down is superior in terms of collaboration flow and quality (question 5).

### 5.3. Objective assessment of adaptive techniques

#### 5.3.1. Methodology

Comparison between the two adaptive techniques in terms of safety and performance of collaboration follows the mode of repeated measurements in the same sample of users. The dependent variables are essentially the metrics used. The main metric regarding safety of collaboration concerns the number of detected collisions between human and robot. Ideally, no collisions should occur. Two performance metrics are employed regarding efficiency of collaboration: (i) net motion time of robot from or towards the human, i.e. not counting idle times, e.g. when the robot is stationary, during fabric layup, backing paper removal etc. The smallest the net motion time is the higher the performance (ii) Mean velocity of robot end effector. High values of mean velocity denote that HRC techniques were either seldom activated or did not influence robot

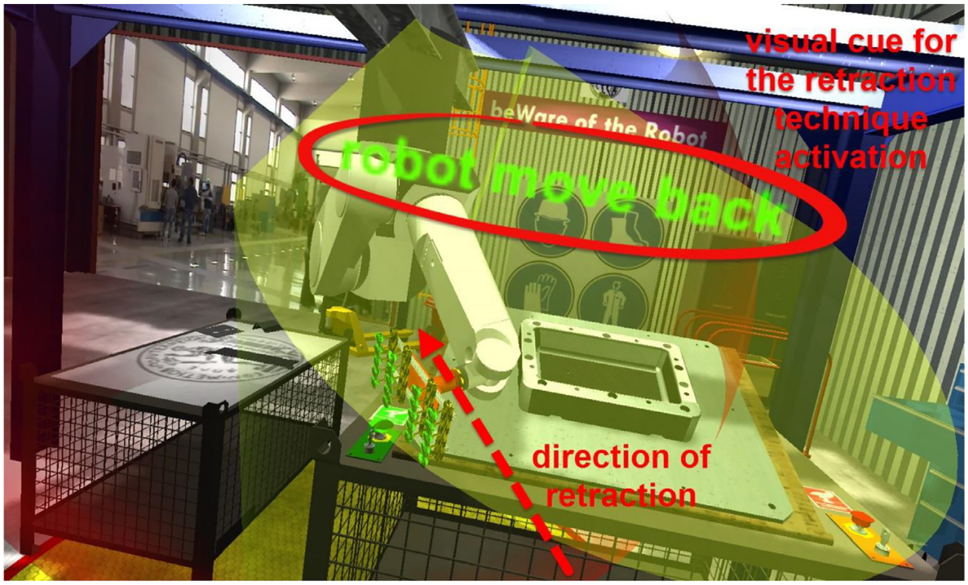


**Fig. 11.** Projection of message «robot move back" for robot retraction technique activation.

**Table 1**
Users opinion (% of total) on safe HRC proactive techniques (SD: strongly disagree, D: disagree, N: neutrality, A: agree, SA: strongly agree).

| Extent of agreement<br>Statement | SD<br>1 | D<br>2 | N<br>3 | A<br>4 | SA<br>5 |
|---|---|---|---|---|---|
| 1. You perceived the robot's workspace easily. | 0 | – | – | – | **100** |
| 2. You perceived easily the yellow semi-transparent robot motion volume. | 8 | – | – | – | **92** |
| 3. You found it difficult to avoid the robot as it was moving towards you. | 28 | **36** | 28 | 8 | 0 |
| 4. If you perceived an alarm, you were able each time to determine its cause. | 0 | – | – | – | **100** |
| 5. Audiovisual aids helped you avoid potentially dangerously moving robot. | 0 | 4 | 24 | 24 | **48** |

**Table 2**
User opinion on safe HRC adaptive techniques.

| Statement/Question | Answer 1 | Answer 2 |
|---|---|---|
| 1. In Slow-down technique as the robot was approaching me I managed to recede or change position and thus avoid it. | agree **96%** | disagree4% |
| 2. In Retract technique as the robot was approaching me I managed to recede or change position and thus avoid it. | agree **96%** | disagree4% |
| 3. In Retract technique as the robot was approaching me I did not even need to change position in order to avoid it. | agree **64%** | disagree36% |
| 4. Which technique was most effective to avoid collisions with the robot ? | Slow-down **52%** | Retract48% |
| 5. Which technique was most effective in terms of quality and continuity of collaboration flow with the robot? | Slow-down **79%** | Retract21% |

velocity much (HRC efficiency). The independent variables are the two adaptive techniques of safe HRC plus the null one, i.e. (1) the robot does not react in the presence of human, (2) the robot slows down to 15% of its velocity, if danger of collision with the human is detected, (3) the robot is retracted and follows a different path, if danger of collision with the human is detected.

In the tests, null hypothesis is tested: $H_0$: $\mu_1 = \mu_2 = \mu_3$, where $\mu_k$ is the mean value of the variable under test in sample k ($k = 1,2,3$). The alternative hypothesis $H_1$ is that at least two mean values differ in a statistically significant way. Hypothesis testing is conducted at a significance level of $\alpha = 0.05$. Repeated Measures ANOVA model was employed, which can be considered as an extension of paired *t*-test for dependent samples, with $k > 2$. Simple ANOVA is unsuitable, because it does not take into account any correlation between repeated measurements and violates the precondition of independence [38,39]. Calculations were performed on statistics package Minitab™.

#### 5.3.2. Safety of collaboration results

Results are shown in Fig. 12. It is immediately observed that number of collisions when employing safe HRC techniques is severely reduced compared to the control case. Furthermore, there is some differentiation between slow-down and retract techniques, see Fig. 12(a). ANOVA results indicated a significant difference between mean values for each technique, thus post-hoc tests followed (multiple Tukey or Fischer test, pairwise between samples) in order to determine whether the objects can be classified into homogenous groups, the members of which do not differ significantly. In particular in Fig. 12(b), it is obvious that the difference is significant between pairs of techniques 2–1 ($P\text{-Value} = 0.027 < 0.05$) and 3–1 ($P - \text{Value} = 0.049 < 0.05$). On the contrary, there is no significant difference between retract and slow – down techniques, i.e. pair 3–2 ($P\text{-Value} = 0.964 > 0.05$).

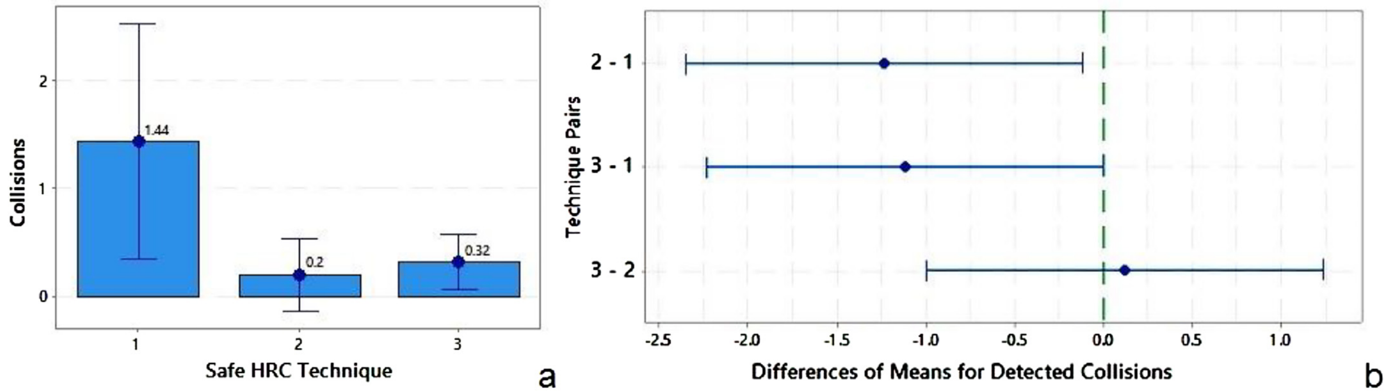


**Fig. 12.** Number of collisions between human and robot for safe HRC techniques (a) Mean and std deviation (b) Tukey test (1: no technique, 2:slow-down 3: retract).

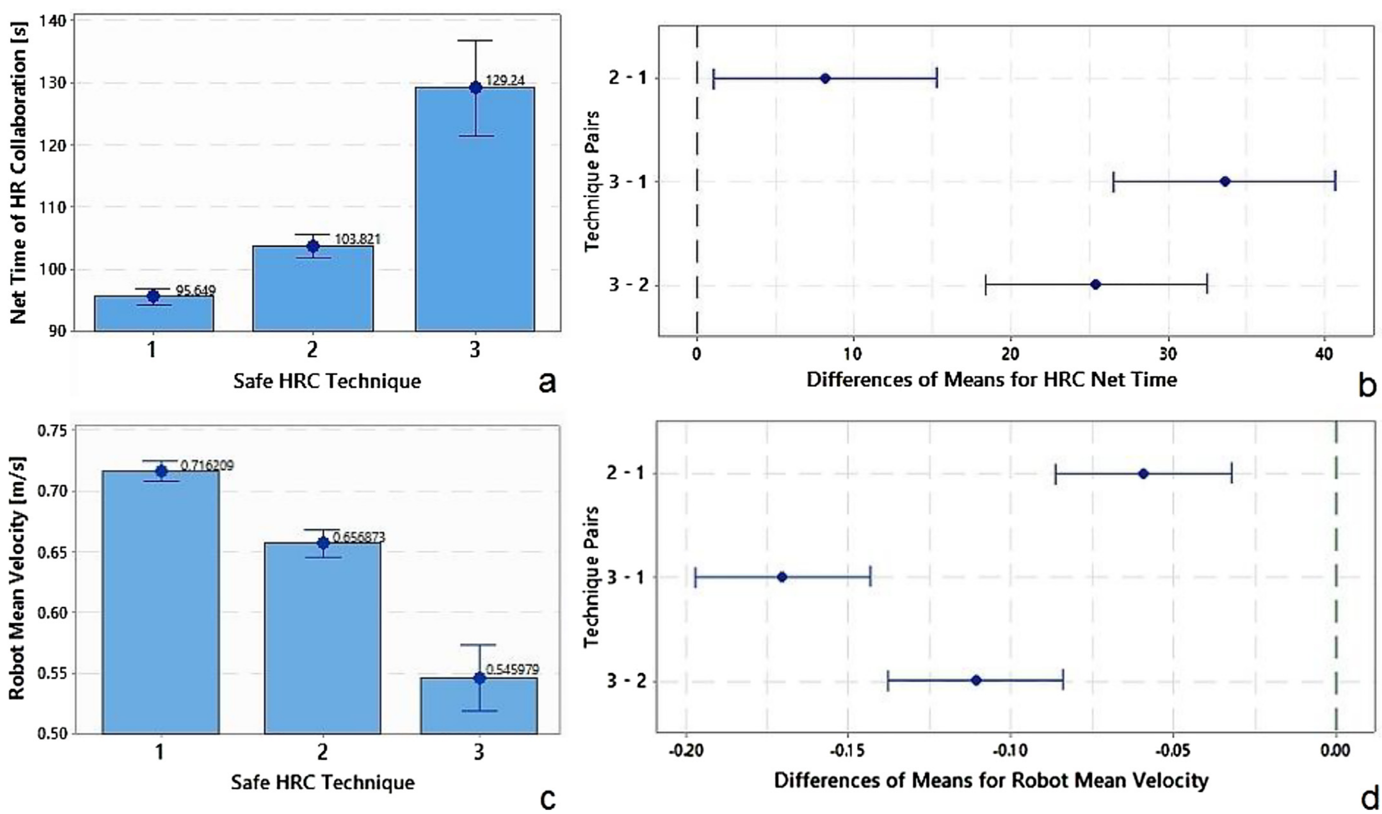


**Fig. 13.** (a) Mean and std deviation of net robot motion time per safe HRC technique examined (b) Tukey test for pairwise comparison of safe HRC techniques regarding net robot motion time (c) Mean and std deviation of robot end-effector velocity per safe HRC technique examined (d) Tukey test for pairwise comparison of safe HRC technique regarding robot end-effector velocity (1: no technique, 2:slow-down 3: retract).

### *5.3.3. Performance of collaboration results*

Results shown in Fig. 13(a) indicate that net motion time of the robot significantly rises when using any of the two adaptive techniques and also there is a difference between the results of these techniques. In Fig. 13(b) mean velocity is clearly reduced when using these techniques, whilst there is again a clear difference between them, too. ANOVA results (P-Value = 0.000 < 0.05 for both time and velocity metrics) point to a significant difference between mean values. Thus, post-hoc tests followed (multiple Tukey pairwise between techniques) as in Section 5.3.1.

In Fig. 13(b) it is clearly shown that there is a statistically significant difference between all three technique pairs examined: 2–1 (P-Value = 0.02 < 0.05), 3–1 (P-Value = 0.000 < 0.05) and 3–2 (P-Value = 0.000 < 0.05), indicating that safe HRC techniques do affect net robot motion time and, in addition, slow-down technique is superior than retract technique in this sense (collaboration efficiency).

In Fig. 13(d) it is clearly shown that there is a statistically significant difference between all three technique pairs examined: 2–1 (P-Value = 0.00 < 0.05), 3–1 (P-Value = 0.000 < 0.05) and 3–2 (P-Value = 0.000 < 0.05), indicating that safe HRC techniques do affect robot end-effector velocity and, in addition, slow-down technique is superior than retract technique in this sense, too (collaboration efficiency). Moreover, differences in mean velocity achieved between the three scenario are so clear-cut (p = 0.098), that results can be classified into three different homogenous groups.

Referring back to subjective assessment (Section 5.2) it is pointed out that as regards perceived effectiveness (performance) of the two adaptive techniques, users indicated a clear preference to slow-down technique, hence being in line with the objective assessment findings. Users also indicated a marginal preference to slow-down technique as regards perceived safety (collision avoidance); indeed, *t*-test results yield no statistically significant outcome.

## 6. Conclusions

In this work it was demonstrated how a VE can be used for trying out safe HRC techniques and, in particular, of two types: proactive and adaptive. In every scenario involving collaboration between humans and industrial robots with joint actions, in particular, both proactive and adaptive techniques are necessary, implementing situation awareness as well as anticipation of intent and behaviour. They rely on human decision making as well as robot speed and trajectory modulation. Thus, the application presented is considered to be representative of industrial collaboration scenarios in assembly, cleaning, welding, painting, punching etc.

The most important thing regarding the safety-sensitive area of HR interaction is that such trials are performed without any danger for the human user and are easy to tweak in terms of parameters as well as in terms of the collaboration scenario as such.

The system can also be used as a training platform for familiarising human users, as well as cultivating automated reaction modes of the human to non-expected events occurring in the manufacturing cell.

These techniques are activated in a composite and progressive manner starting with proactive ones and moving towards adaptive ones which are more complex and involve more calculations. According to user subjective and objective feedback, these techniques are deemed satisfactory. However, performance (time) and safety (collisions) can be affected by changing parameter values of these techniques.

Cognitive aids (robot workspace and robot motion volume) could be accused of being inaccurate, unrealistic, unnatural etc.; however, they proved to be very effective as a proactive technique in HRC, given that the latter is an archetypical application of cognitive nature pertaining, in particular, to danger warning. Of the adaptive techniques explored, robot slowing down was superior to robot retract as far as effectiveness is concerned, whereas safety-wise there was no considerable difference, for the particular collaboration scenario and technique parameters used.

After being prototyped in the VE, it is expected that proactive and adaptive techniques for human-robot collaboration can be implemented in real robotic cells, i.e. in the robot or cell controller with or without inclusion of the physical analogues of the cognitive aids involved in the VE. Infrared cameras, wearable IMUs, multiple Kinect Sensors, VR goggles and AR multimedia devices are some of the possible hardware that might be exploited. However, alternative ways to transcribe the application from a virtual to a real environment constitute a topic open to research. In general, further work should certainly include experimentation with further safe HRC techniques for the scenario at hand, new path planning algorithms for the retraction technique, different end effector velocity profiles, new activation criteria, alternative cognitive aids or even no cognitive aids at all, new collaboration modes and collaborative tasks and equipment. The Virtual Manufacturing paradigm does cater for all of the above.

## Acknowledgement

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Heracleitus II Investing in knowledge society through the European Social Fund.

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