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SAFETY ISSUES FOR HUMAN–ROBOT COOPERATION IN MANUFACTURING SYSTEMS

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SOMMARIO

La più rivoluzionaria e impegnativa caratteristica della prossima generazione di robot sarà l'interazione fisica diretta con le persone (physical Human–Robot Interaction, pHRI), per la quale *sicurezza* e *affidabilità* sono concetti-chiave, anche per preparare la strada all'avvento dei robot negli ambienti umani di ogni giorno. Per aumentare la sicurezza dei robot, occorre considerare ogni aspetto inerente il progetto di manipolatori, comprendendo meccanica, elettronica e software. Tra le possibili strategie per ottenere sicurezza, uno degli aspetti principali è rappresentato dalle strategie per la prevenzione delle collisioni. Per ambienti non strutturati, una descrizione dettagliata della scena è molto difficile, se non impossibile, da ottenere. Pertanto, si può usare un controllo reattivo, in presenza di un buon sistema sensoriale. Strategie di controllo dell'interazione, come il controllo d'impedenza, unite a strategie reattive per evitare gli urti, possono aumentare la sicurezza attraverso il controllo. La realtà virtuale (VR) può essere adoperata per simulazioni realistiche di compiti di interazione uomo–robot, comprendendo urti ed errori deliberatamente introdotti. Inoltre, misure soggettive di comfort in relazione all'uso di un manipolatore robotico possono essere ottenute anche in relazione alla sicurezza percepita durante il movimento di un robot, che dipende da forma, velocità e postura del robot stesso.

Parole chiave: interazione fisica uomo–robot, sicurezza, controllo reattivo, simulazioni in realtà virtuale

ABSTRACT

The most revolutionary and challenging feature of the next generation of robots will be physical Human–Robot Interaction (pHRI), where safety and dependability are the keys, also for paving the way to a successful introduction of robots into everyday human environments. In order to increase robot safety, all aspects of manipulator design, including mechanics, electronics, and software, should be considered. Among the possible strategies for achieving safety, one of the focuses is on strategy to prevent collisions. For unstructured domains, a detailed description of the environment is very difficult, if not impossible, to obtain. Therefore, reactive control can be used, in the presence of a good sensory system. Interaction control strategies as impedance control, together with reactive collision avoidance may increase safety by mean of control. Virtual reality can be used for realistic simulations of HRI task, including collisions and injected errors. Moreover, subjective comfort measures related to the use of a robotic manipulator can be accomplished, also related to the perceived safety during robot motion, depending on robot's shape, speed and posture.

Keywords: physical Human–Robot Interaction, safety, reactive control, VR simulations

1. Introduction

Rigth now, safety of the users interacting with industrial robot manipulators has been addressed by segregation between robots and people. This assumption cannot be considered if humans and robots have to share the physical environment or collaborate. The next generation of robots, both for service or cooperative work, is expected to interact with people more directly than today. Cognitive Human-Robot Interaction (cHRI) has been widely addressed in the scientific community. However, robots are distinct from computers or other machines: they physically embody the link between perception and action, whose “intelligent connection” is a definition for robotics. They generate force and have a “body”: hence, the most revolutionary and challenging feature of the next generation of robots will be physical Human–Robot Interaction (pHRI). In pHRI, humans and robots share the same workspace, come in touch with each other, exchange forces, and cooperate in doing actions on the environment. This approach is affordable if robots guarantee human safety and autonomy. An effort is keeping the “physical viewpoint” while considering the importance of inferences and evaluation on unstructured environments. This viewpoint influences the new paradigms for the design and control of robot manipulators [DeSantis2008].

Robots designed to cooperate with humans must fulfil different requirements from those typically met in conventional industrial applications. Typical conventional robot systems and applications require fast motions and absolute accuracy, without external sensing, provided that the operational environments are perfectly known. The most important change of perspective is related to the optimality criteria for the considered manipulators: *safety* and *dependability* are the keys for direct interaction, and to pave the way to a successful introduction of robots into human environments [Heinzmann2003][Ikuta2003][Kulic2005][Yamada1997]. Only dependable robot architectures can be accepted for supporting “human-in-the-loop” conditions and human–robot teams, and the safety of humans cooperating with robotic systems is the main need for allowing pHRI. In addition, physical safety has to be complemented by the “mental safety”, i.e., by the awareness of robot motion, avoiding scaring postures and abrupt movements [Nonaka2004].

2. Industrial standards and robot safety

Related to safe robotics in factories, one has to consider: a) robots explicitly designed for cooperation (in contact with users), b)I robots to be “worn” by the users (e.g., exoskeletons), c) autonomous robots, for contactless HRI. A category already present is represented by the intelligent assist devices (IADs), intended principally for *comanipulation* [Bicchi2008] of payloads along with a human partner, in order to augment the strength of a human. They may also guide the motion via virtual surfaces [Gillespie2001], tracking of a moving assembly line. International standards for robotics, however, still do not address directly the safety in pHRI.

The most important example of standard for robot safety in factories is the ANSI/RIAR15.06-1999 (American National Standard for Industrial Robots and Robot Systems – Safety Requirements). This standard addresses the requirements for personnel safety in industrial environments where robotic manipulators are employed.

The complementary design standard ANSI/UL 1740 states hardware requirements and specifications, harmonised with R15.06: if the hardware is built in compliance with UL 1740, the safeguarding requirements in R15.06 are met. Other standards are present worldwide, as the European standard EN 775, and their international equivalent is the ISO 10218. This standard has been revised in 2006, while the modifications are not already effective. The modifications allow cooperation with prescribed limits for speed and power. It must be pointed out, however, that the case when robots and people have to share the operational space is not clearly discussed. Actually, the standard poses human–robot segregation in the workplace as the way to obtain safety. Work has been ongoing since, gradually turning what started as a simple harmonisation effort into a genuine development effort introducing new concepts to the world of industrial robot safety. The revised ISO 10218 ("Robots for Industrial Environment - Safety") will be a two part document. Part 1, entitled "Design, Construction and Installation", is intended to be fully compliant with the European Machinery Directive and expected to replace the existing EN775 in due course. Part 2, work on which has recently begun, has a working title of "Application and Use of Robots in the Work Place" and is intended to address work place safety requirements and is directed more to the end-user than the manufacturer. Most salient changes under consideration involve control reliability and safeguarding criteria. Revised standards will allow safety-related control circuitry to use state-of-the-art electronic, programmable, and network based technology (including wireless). Related to clearance, minor changes in requirements are expected (from 18 inches to 0.5 meters), while attention is devoted towards completely removing the requirement for safeguarding in the presence of enhanced capabilities and features of the robot control system. In addition, new modes of operation will be considered: the committee is developing requirements for "synchronised" robot control, "mobile" robots mounted on Automated Guided Vehicles (AGV), and "assisting" robots which work in a "collaborative workspace" with the operator. It is worth pointing out that the ISO Technical Committee (TC 184/Subcommitee 2) dealing with standardisation activities on robotics is still working also on "Robots in Personal Care". Available standards, before their possible revision, are not very useful for environments different from industry.

Criteria for defining safety levels in HRI (inside and outside factories) are strictly related to the possible injuries caused by robots [PHRIENDS]. Note that recently some European robot manufacturers (ABB, KUKA, Reis) have included software modules that monitor through external sensing the Cartesian space around the robot and stop operations in case of danger. Several standard indices of injury severity exist in other, non-robotic, domains. For evident reasons, the automotive industry was the first to define quantitative measures, indices and criteria for evaluating injuries due to impacts. These sets of studies have been suggested as a starting point for safety evaluation in robotics, using the automotive crash testing which considers two distinct types of loading concerning head injuries. The first type is a "direct interaction", i.e., a collision of the head with another solid object at appreciable velocity. The second type is an "indirect interaction", i.e., a sudden head motion without direct contact. The load is generally transmitted through the head-neck junction upon sudden changes in the motion of the torso. In order to quantify the injury severity produced by the impact with a robot, a scaling is needed. A definition of injury scaling developed by the automotive industry is the Abbreviated Injury Scale (AIS). If more than one part of the body is involved, the one with maximum injury severity is considered as the overall injury severity, which is indicated as Maximum AIS (MAIS). The type of injuries are divided in a classification, which relates the type of injury ("Minor", "Moderate", up to

"Critical"), to its consequences ("Superficial", "Recoverable", "Not fully recoverable with care" and so forth), and gives a number in a scale from 0 to 6 (for fatal injuries) in the injury scale. Such a qualitative scaling gives does not give any indication on ways to measure injury. This is provided by the so-called severity indices, coming from car industry, which have been used for comparison in robotics. However, their reduced effectiveness for robotics has recently been demonstrated [Haddadin2007].

It is interesting to report an interesting issue addressed in [Bicchi2008]: since people in the manufacturing environment are often injured even in the absence of robots, paradoxically, this provides a motivation for an increasing use of robots, in well designed pHRI schemes.

3. Safety in human–robot cooperative tasks

Safety has many levels: compliance of the robot in case of contact, fast monitoring of the scene, precise collision checks with emergency stops. We can therefore consider 3 steps for safety tactics: those related to intrinsic safety, those which can prevent collisions, and those which are activated in the event of a crash. The second step in the proposed approach is addressed more in depth in [DeSantis2007], providing a manipulator's and world's model for fast deliberative/reactive motion, with arbitrary control points on the robot and the possibility of combining different trajectories for the fulfilment of different tasks, to be specified at an higher level.

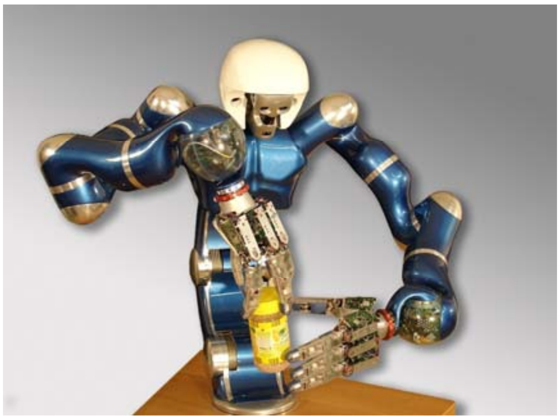

Figure 1. The DLR service humanoid manipulator Justin

In detail, since pHRI has the two complementary directions of intrinsically safe (future service) robots and safe by control (current industrial) robots, the proposed contribution can be considered useful for completing the safety tactics for a service manipulator, and constitute a modelling base for multiple-point control. The role of planning and control is evident both in cHRI and pHRI: while legible motion and smoothness of movements have also cognitive relevance, the possibility of having a very fast modelling and control of the interaction environment is a key issue for quickly detecting and moving interacting robots, giving control to different interfaces and control approaches at the same time. Among the main aspects, the necessity of controlling multiple point of a robot in pHRI is central, both for multiple input channels to a robotic assistant (impedance control, safety tactics, teleoperation, emergency paths), and for the presence of multiple possible colliding parts, e.g., of an humanoid.

Humanoids are a special case because they intrinsically present multiple control points for grasping, moving the head for perception, assuming postures, walking, balancing, and so on. Finally, whole-robot motion behaviour via multiple point control and reactive motion has to be cast into a task management policy, in order to complete a robot model for interaction. For the purpose of moving a robot manipulator away from possible collisions, or driving it towards a desired goal, the need for controlling all the parts of the articulated structure can be faced via multiple point control. An arbitrary control point can be selected, according to the a skeleton-based approach, as in [DeSantis2007]. The trajectories, resulting from timed paths or potential fields [Khatib1986], can be scaled according to distances. Of course, other indicators such as inertia and danger from sharp edges can be considered. New insights about injury criteria are expected to identify cost functions for such purposes.

3.1 Intrinsic safety and actuation

In order to reduce manipulators arm inertia for safety, while preserving performance, the methodology of distributed macro-mini (DM^2) actuation has been introduced [Zinn2002]. For each degree of freedom (joint), a pair of actuators are employed, connected in parallel and located in different parts on the manipulator. The first part of the DM2 actuation approach is to divide the torque generation into separate low and high frequency actuators whose torque sum in parallel. Gravity and other large but slowly time-varying torques are generated by heavy low- frequency actuators located at the base of the manipulator. For the high-frequency torque actuation, small motors collocated at the joints are used, guaranteeing high-performance motion while not significantly increasing the combined impedance of the manipulator–actuator system. Finally, low impedance is achieved by using a series elastic actuator (SEA)

An approach which allows a gain in performance for guaranteed safety joint actuation is to allow the passive compliance of transmission to vary during the execution of tasks. The variable impedance approach (VIA) [Bicchi2004] is a mechanical/control co-design that allows varying rapidly and continuously during task execution the value of mechanical components such as stiffness, damping, and gear-ratio, guaranteeing low levels of injury risk and minimizing negative effects on control performance. The best possible trade-off between safety and performance is desired: for a mechanism with given total inertia and actuator limits, one can formulate an optimal control problem to be used for comparing mechanical/actuation alternatives at their best control performance. One interesting formulation is the following: find the minimum time necessary to move between two given configurations (with associated motion and impedance profiles), such that an unexpected impact at any instant during motion produces an injury severity index below a given safety level.

It is worth noticing that innovative actuation is thought principally for service robotics, while current industrial robots have to benefit also of safety by mean of control.

3.2 Safety by mean of control

Typically, current industrial robots are position-controlled. However, managing the interaction of a robot with the environment by adopting a purely motion control strategy turns out to be inadequate; in this case, a successful execution of an interaction task is obtained only if the task can be accurately planned. For unstructured domains, such a detailed description of the environment is very difficult, if not impossible, to obtain. As a result, pure motion control may cause the rise of undesired contact forces. On the other hand, force/impedance control [Siciliano2000] is important in pHRI because a compliant behavior of a manipulator leads to a more natural physical interaction and reduces the risks of damages in case of unwanted collisions. Similarly, the capability of sensing and controlling exchanged forces is relevant for cooperating tasks between humans and robots.

Interaction control strategies can be grouped in two categories; those performing indirect force control and those performing direct force control. The main difference between the two categories is that the former achieve force control indirectly via a motion control loop, while the latter offers the possibility of controlling the contact force to a desired value, thanks to the closure of a force feedback loop. To the category of indirect force control belongs impedance control, where the position error is related to the contact force through a mechanical impedance of adjustable parameters. A robot manipulator under impedance control is described by an equivalent mass–spring–damper system, with the contact force as input (impedance may vary in the various task space directions, typically in a nonlinear and coupled way). The interaction between the robot and a human results then in a dynamic balance between these two ‘‘systems’’. This balance is influenced by the mutual weight of the human and the robot compliant features. In principle, it is possible to decrease the robot compliance so that it dominates in the pHRI and vice versa. Cognitive information could be used for dynamically setting the parameters of robot impedance, considering task-dependent safety issues. Certain interaction tasks, however, do require the fulfilment of a precise value of the contact force. This would be possible, in theory, by tuning the active compliance control action and by selecting a proper reference location for the robot. If force measurements are available (typically through a robot wrist sensor), a direct force control loop could be also designed. Note that, a possible way to measure contact forces occurring in any part of a serial robot manipulator is to provide the robot with joint torque sensors. The integration of joint torque control with high performance actuation and lightweight composite structure, like for the DLR-III lightweight robot [Hirzinger2001], can help merging the competing requirements of safety and performance.

3.2.1 Reactive control

When the environment is time-varying, potential fields are often adopted for reactive motion of robots modelled as particles under the effect of the field. For collision avoidance, one has to consider the motion of any point of the robot for a possible reactive movement; then, continuous repulsive forces have to be generated, resulting in corresponding nominal torque commands. One feature is arbitrarily shaping the potential functions used for protecting objects from collisions, and summing the reactive motion/torque commands with any kind of current motion during interaction of the robot with the environment and people. The collision avoidance paths can also be seen as general paths among attracting and repelling objects, which can constitute a base for gross motion of interacting robots, while fine motion can be accomplished after checks on possible impacts. Deliberative/reactive motion can therefore be accomplished using models where selected regions of the environments are labelled as attracting or repelling volumes.

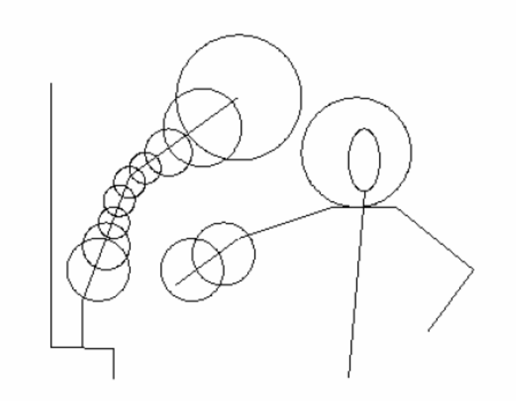

Figure 2. Skeletal models and protective volumes for HRI

The automatic selection of control points on a manipulator is needed too, based on sensor information and analytical computations on a model of the manipulator's kinematic chain. In addition, such arbitrary control points should be computed fast, based on a model of the environment which leads to simple distance computation and trajectory determination. These considerations lead to the so-called "skeleton algorithm". The problem of analyzing the whole volume of the parts of a manipulator is simplified by considering a *skeleton* of the structure, and proper volumes surrounding it.

Figure 3. Reactive control for collision avoidance

Segments "span" the kinematic structure of a manipulator (see Fig. 1), and a variable-radius surrounding volume is created . The underlying idea is that a solid of revolution can express the shape of a link: this can be partially modified considering different behaviours at different angles around the segment. The resulting multiple volumes form a virtual region which has to approach the real volume of the considered part of a manipulator

Experiments have been performed at DLR and PRISMA Lab, in order to test the effectiveness and robustness of the algorithm. In the first case, only self-collision avoidance has been considered for the Justin humanoid manipulator (see Fig. 1), whose "arms" are DLR LWR-III manipulators. Current trajectories have been acquired during manual guidance of the manipulator in torque control, where gravity has been suitably compensated. The manipulator has successfully avoided all collisions, and different potential functions have been tested.

Figure 4. Face detection and avoidance in an industry-like robotic cell

The parameters that can be adjusted, according to the approach, are the critical distance where the effect of the repulsion vanishes, and damping terms, which can be added in order to slow down the lightweight robot arms after repulsion forces moved them away, avoiding collisions. From the repulsion force, the corresponding torques have been computed. Details related to the experiments with the humanoid manipulator are presented in [DeSantis2007].

A critical aspect related to the skeleton algorithm is its possible use for human head avoidance. If a safe robot is used, the additional safety can be enough. With respect to situations where collision-free operation is more important, a quantitative analysis is to be faced in the next future, in order to appreciate the maximum errors in sensors and communication that can be accepted while still avoiding collisions. Avoidance motion has been successfully tested with dummy users (poles holding pictures of human faces, in order to safely tune the parameters for head avoidance) and persons. In these two cases, possible communication problems result in an emergency stop of the robot.

It is worth pointing out, however, that dependability of complex robotic systems during normal operation is threatened by different kinds of potential failures or unmodeled aspects in sensors, control/actuation systems, and software architecture, which may result in undesirable behaviours. Due to the critical nature of pHRI, dependability must be enforced not only for each single component, but for the whole operational robot. A number of issues in the above discussion are related to the dependability of the interaction. The approach to modelling and reactive control using skeletal models allows fast modelling the scene. Having a fast model is good for prompt reaction to environmental changes, but the automatic computation of control points, depending on proprioception and exteroception, can result both in wrong evaluations and sudden motion on the manipulator’s structure, and in delays. With reference to collision avoidance, the provided tools for fast modelling and control, only in an ideal case guarantee absence of impacts, when the positions of the possibly colliding parts are known with a precision coming from the dependability of encoders, as well as the accuracy of the kinematic model. When exteroception is used for crucial point detection, following automatic computation, e.g., of distances, results in selecting a control point. This control point can be wrong, the distance computation can then be wrong, and also the resulting reactive forces for attraction or repulsion. The error in sensing can affect the position of the control point in two ways: at first, just changing its position on the same segments of the ideal computed control point; however, another possibility is the change of the control point on another segment.

4. Role of simulation

According to the previous discussion, a very important point is using simulators before real implementations of HRUI task. In fact, dynamics of the system and possible malfunctioning can be simulated. A turning point is the possibility of considering the human in the simulation loop, in order o consider his/her unpredictable motion. This can be performed with the help of immersive Virtual Reality (VR) tools. In addition to ergonomics evaluation and user-friendly design in the presence of dynamic events , VR allows also subjective comfort measures related to the use of a robotic manipulator.

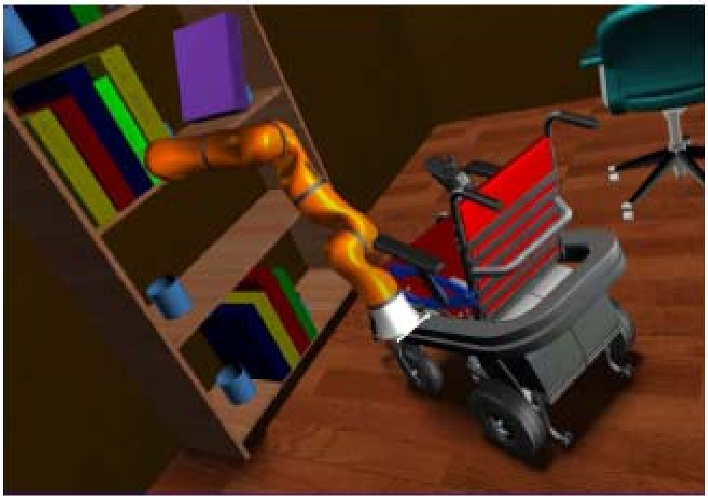

Figure 5. Virtual environment for assistive robotics evaluations

Another valuable possibility offered by realistic simulation in Virtual Reality is the possibility of simulating malfunctioning, by deliberately injecting errors. This can be used for simulating impacts and malfunctioning without harm for the users. After simulations, reactive control schemes can be implemented and tested on real robotics setup (see Fig.6). The use of Virtual Reality (VR) allows to set systems parameters based on feedback from experimenters, involving also cognitive aspects of the interaction with the robots. Such instrument can be used for a fast comparison of interface, appearance, kinematic parameters. VR technology can been adopted for evaluating the perceived safety during robot motion, depending on robot's shape, speed and posture. These considerations have been recently developed for the simulation of an assistive robotics scenario (see Fig.5 and Fig. 8), presented in [DeSantis2008,b].

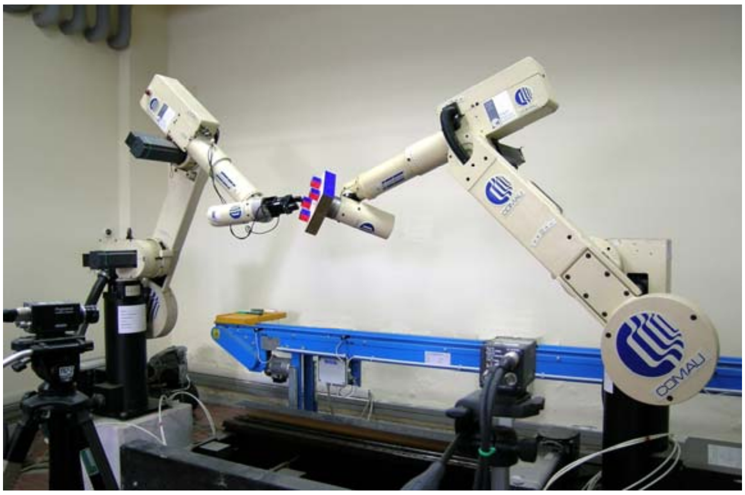

Figure 6. Real robotic cell for cooperative control

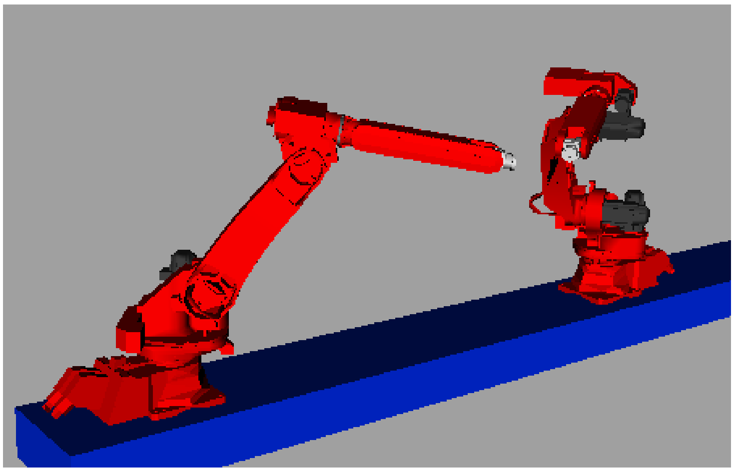

Figure 7. Virtual robotic cell for simulations

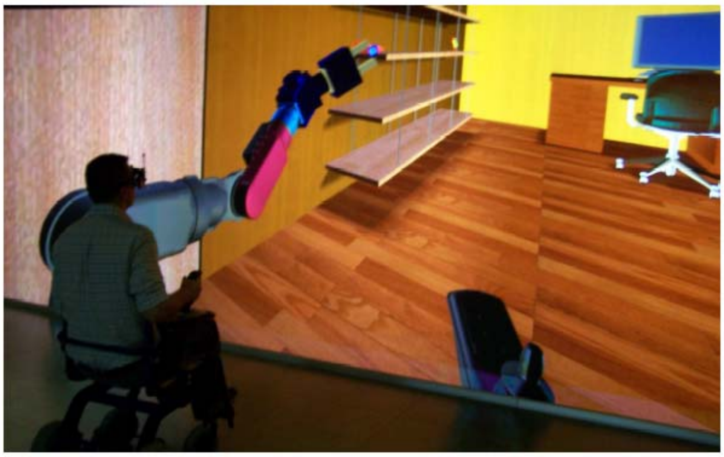

Figura 8. Immersive VR scenario for evaluating HRI

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