Evaluating Human-Robot Interaction during a Manipulation Experiment Conducted in Immersive Virtual Reality

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Abstract. This paper presents the main highlights of a Human-Robot Interaction (HRI) study conducted during a manipulation experiment performed in Cave Automatic Virtual Environment (CAVE). Our aim is to assess whether using immersive Virtual Reality (VR) for testing material handling scenarios that assume collaboration between robots and humans is a practical alternative to similar real live applications. We focus on measuring variables identified as conclusive for the purpose of this study (such as the percentage of tasks successfully completed, the average time to complete task, the relative distance and motion estimate, presence and relative contact errors) during different manipulation scenarios. We present the experimental setup, the HRI questionnaire and the results analysis. We conclude by listing further research issues.

Keywords: human-robot interaction, immersive virtual reality, CAVE, presence, manipulation.

1 Introduction

One of the most important goals of robotics researchers is achieving a natural interaction between humans and robots. For attaining this, a great deal of effort is spent in designing and constructing experiments involving both robots and human operators. Using real physical structures in everyday experiments implies time consuming testing activities. Considering VR has lately emerged as a prolific approach to solving several issues scientists encounter during their work, some recent robotics studies propose the usage of immersive VR as a viable alternative to classic experiments.

But what are the advantages gained by using simulated robots instead of real ones? Modeling robot tasks in VR solves hardware troubleshooting problems. From programmer's point of view, when implementing i.e. a new attribute for real robots, a lot of time is spent on setting up collateral systems, time that can be saved using simulation software [1]. VR solves uniqueness problems. Most research laboratories have one or two study platforms which have to be shared between several researchers. Using simulation eliminates the problem of concurrent use [2]. Simulation lowers the

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entry barrier for young scientists and improves education process [3]. Using only a personal computer, inexperienced robot researchers can develop complex applications in which they can program physical constrains of virtual objects, for obtaining results close to reality [4].

When developing an experiment that involves both robots and humans, aside solving trivial problems, one must also handle aspects concerning HRI. HRI has been defined as the process of understanding and shaping the interaction between humans and robots. By some recent studies [5], HRI has 5 primary attributes: level of autonomy, nature of information exchange, the structure of human and robot teams involved in interaction, the human/robot training process and the task shaping process. Assessing HRI translates into a methodical “measurement” of its 5 attributes [6]. As humans use their hands all the time, the transfer of objects between humans and robots is one of the fundamental forms of HRI that integrates these attributes. Thus, analyzing a manipulation scenario is a straight way to assess fundamental HRI particularities [7]. Some scientists have identified a set of generic HRI metrics (intervention response time, judgment of motion, situation awareness and others) and a set of specialized HRI metrics for manipulation experiments (degree of mental computation, contact errors and others) [8].

In this paper, we are focusing on conducting a manipulation experiment within CAVE immersive VR environment. As it is not yet clear whether using virtual robots has the same impact on HRI as using real equipment, we propose assessing the difference between using real robots in real physical scenarios versus using virtual robots in virtual scenarios, based on previous work in presence-measuring [9; 10]. In order to validate the experiment setup, a questionnaire which targets both types of HRI metrics was designed and applied to several subjects. The variables identified as conclusive for the purpose of this study are: the percentage of tasks successfully completed, the average time to complete a task, the average time to complete all tasks, relative distance and motion estimate for VR tests and relative contact errors. In order to measure presence, some of these variables are also assessed during tests with the real robot.

2 Contribution to Technological Innovation

Although there have been several attempts to clearly determine the nature of HRI within VR, most of the literature focuses on scenarios built upon non-immersive simulation software. Most work in presence-measuring uses non-immersive VR as comparison term. Furthermore, most of the studies focus on measuring the “sociable” part of robots as seen by human operator, rather than measuring the performance attained by direct collaboration between humans and robot, as in the case of a hand-to-hand manipulation scenario [9; 10].

Although the presented manipulation experiment is intended to be a proof-of-concept (as several equipment, administrative and implementation issues need to be solved before using the results presented this paper), the computed questionnaire data shows that the proposed approach is suitable to be extended to generic research in HRI and robotic testing.

2.1 Designing the Virtual Robot and Working Environment

Nowadays, scientists have at their disposal several pieces of software that can help them to achieve a satisfying simulation of their scenarios. Starting from modeling and ending with the simulation itself, one can use various programs such as SolidWorks or CATIA for CAD design, low level file formats built for 3D applications such as VRML/X3D or COLLADA, for animating their designs, or more focused robot simulators like Player Project, Webots or Microsoft Robotics Developer Studio.

For our experiment, we have modeled PowerCube robot arm using CATIA software. The resulted CAD model has been exported as meshes in C++/OGRE (see Fig. 1) and XVR programming environments, as these offer stereo vision capabilities needed to include the arm model in CAVE.

Fig. 1. PowerCube arm exported from CATIA in C++/OGRE

The collision detection of the arm with itself and with objects from the virtual world is handled by MATLAB, within the arm controlling algorithm. In real world, working environments have irregular shaped obstacles. These may vary in size and location with respect to the arm position. For simplicity reasons, we have defined 3 classes of obstacles which may be added to the virtual workspace:

- Spheres: (x,y,z, sphere radius).
- Parallelograms: (x,y,z, length, width, height).
- Cylinders: (x,y,z, radius, height).

The collision detection is implemented using sphere covering technique (see Fig. 2). The representation of the world is a set of radii and centers that models each object as a set of spheres. During arm movement, the world is checked to verify that no collisions happen between spheres (the distance between any 2 circles belonging to different sets is higher than the sum of their radii). The clustering into spheres is done using k-means clustering algorithm [11]. A number of clusters is chosen based on the resolution of the world.

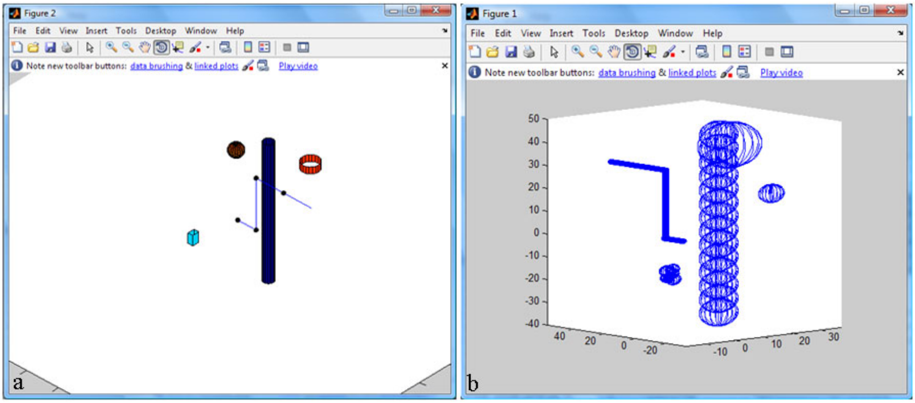

Fig. 2. In left (*a*) it is presented a configuration space with 4 obstacles and in right (*b*), its equivalent after applying the sphere covering function

2.2 PowerCube Control

Manipulation assumes solving inverse kinematics and planning the motion for the robot arm used in our experiments. In a previous study [12], an arm controller was developed based on a double neural network path planner. Using reinforcement learning, the control system solves the task of obstacle avoidance of rigid manipulators, such as PowerCube. This approach is used for the motion planning part of the virtual and the real robotic arm from our study. According to algorithm performance specifications, the average time for reaching one target in an obstacle free space is 13,613 seconds, while the average time for reaching one target in a space with one obstacle (a cylinder bar located at Cartesian coordinates 5;15;-40) is 21,199 seconds.

The proposed control system is built in MATLAB. In order to achieve a stand-alone application, a link between MATLAB and C++ is needed (see Fig. 3). Unfortunately, creating a shared C++ library using MATLAB compiler is not a valid solution, as custom neural network directives cannot be deployed. Using MATLAB Engine to directly call for .m files is also not suitable for bigger projects. In the end, a less-conservative method was chosen: a TCP/IP server-client communication. The MATLAB sender transmits trajectory details (the angles vector captured at discrete amounts of time) to C++ receiver.

2.3 Experiment Design

The experiment is spit into 2 parts, one handling tests in VR and the other handling tests in real environment. The VR tests have the following prerequisites:

- A virtual target object (a bottle) is attached to the position returned by the hand trackers (see Fig. 4).

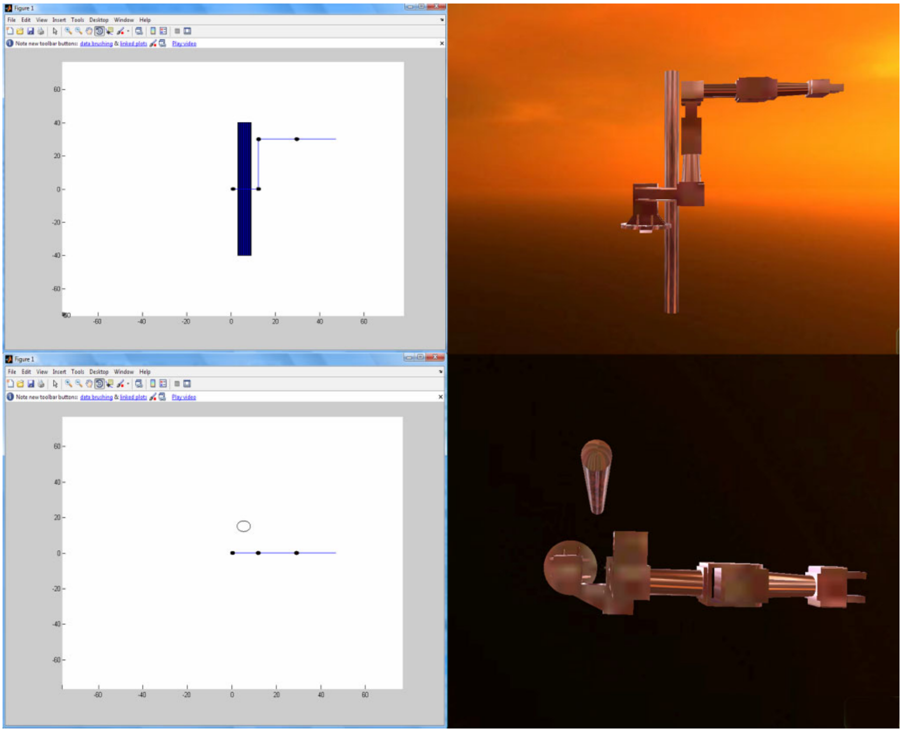

Fig. 3. The correspondence between MATLAB and C++/OGRE programming environments, from XOY and XOZ perspectives

- Human subjects are mounted with optical sensors on their head (for CAVE head tracking) and on their hands (for determining the target position).
- The subjects are asked to perform consecutively 3 tasks in 3 different scenarios, briefly described before commencing the experiment.
- When the robotic arm reaches targets' Cartesian coordinates (with a small error of 0.5cm), we suppose it automatically grasps the bottle.
- In all tests, the modeled robot arm starts with the angle configuration (0;90;0;-90;0;0) which translates in the position presented in Fig. 3.

Scenario 1. In the first VR scenario, the subject is asked to place the virtual object that is automatically attached to his hand in a designated position. The workspace contains the PowerCube robot arm, an obstacle shaped as a cylinder bar with (5, 15, -40, 3, 80) parameters (see Fig. 3) and the target object, a 0.5l bottle. The manipulator waits until the subject correctly places the bottle, then using the motion planning algorithm from MATLAB which generates an obstacle free trajectory to the designated position, it moves towards target. After reaching the bottle, it automatically grasps it and moves it to a second designated position (see Fig. 5).

Fig. 4. Passive optical markers mounted on subject's hand

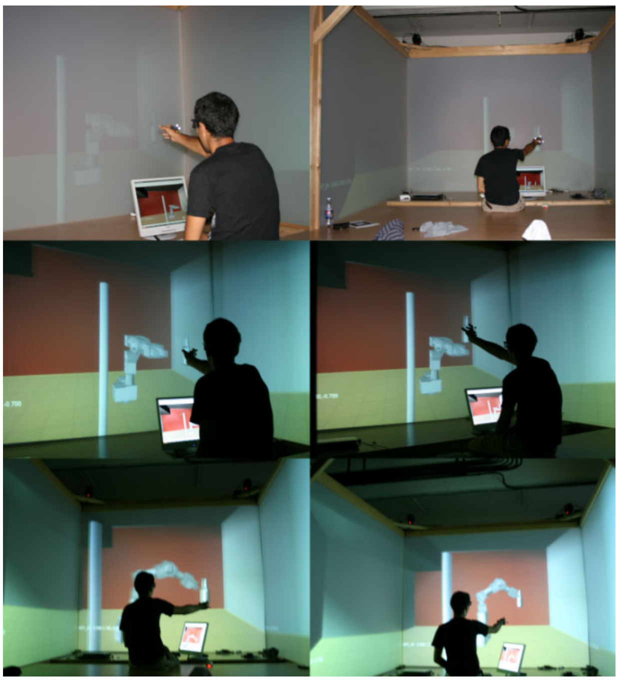

Fig. 5. Scenario 1 of the HRI experiment in CAVE

Scenario 2. In the second VR scenario, the subject is asked to freely move the virtual object automatically attached to his hand within the workspace, which is, in this case, obstacle free. Using the motion planning algorithm from MATLAB, the manipulator dynamically follows the Cartesian coordinates of the bottle. Subjects are allowed to move the target maximum 30 seconds. After this timeframe, if the robotic arm hasn't already reached it, the bottle will keep fixed its last Cartesian coordinates. After reaching the bottle, the arm automatically grasps it and moves it to a designated position.

Scenario 3. The third VR scenario assumes the arm has the target object in its gripper. The role of the subject is to reach the bottle, and then place it at a designated position. When the Cartesian coordinates returned by the passive optical markers placed on the subjects hand reach the bottle with same small error of 0.5cm, the virtual bottle is automatically attached to subject's hand.

In order to measure presence, a scenario similar to scenario 1 was tested in the real environment. Subjects are asked to place a bottle in the arm's gripper. PowerCube is then controlled to place the bottle in a designated position (see Fig. 6).

Fig. 6. Real environment scenario; the robot receives from subject a plastic bottle, which will be placed on a chair

2.4 HRI Questionnaire Design

The HRI questionnaire was developed to gain information about subjects' perception when interacting with the real and the virtual PowerCube manipulators. All questions may be answered with a grade from 1 to 10.

The proposed HRI questionnaire contains 12 questions divided into 3 parts:

- *The biographical information section* contains data related to the technological background of the study participants. Using questions from this section, we are trying to categorize subjects by their bio-attributes (age, sex), the frequency of computer use and their experience with VR technologies and robotics. Some examples of questions addressed here are: „How often do you use computers?", „How frequent are you interacting with robotic systems?", „How familiarized are you with VR?"
- *The specific information section* refers to the particularities subjects encounter during the manipulation experiment. In order to measure the relative motion of the

arm, this section includes questions such as „How fast do you think the robot arm was moving?”. The relative distance and relative contact errors are measured using questions such as „How exact was the robot arm in picking/grasping/placing the target?”. Overall impressions are measured by questions such as „How often did you feel that PowerCube (both virtual and real) was interacting with you?” and „How satisfying do you find the control algorithm of PowerCube?”.

The presence measuring section contains questions that try to assess the difference between using a real PowerCube versus using a simulated one. Considering other studies in presence, we have settled to measure 2 types of presence: presence as perceptual realism and presence as immersion [9]. In order to measure presence as perceptual realism, we asked „How real did the overall VR experience feel, when compared with the real equipment?”. Presence as immersion was measured by questions such as „How engaging was the VR interaction?”. We have also addressed some open-ended questions at the end of this section, such as „What was missing from virtual PowerCube that would make it seem more appropriate to the real PowerCube?”.

2.5 Experiment Trials

22 students, 4 PhD. students and 3 persons from the university administrative staff participated as subjects in this experiment. The experiment took an average of 20 minutes per subject, and answering the HRI questionnaire took an average of 5 minutes per subject. The results are centralized in Table 1.

Other variables that were measured during our experiment are the percentage of tasks successfully completed – 99.1379%, the average time to complete a scenario – 4 minutes and 8 seconds, and the average time to complete all 4 scenarios – 16 minutes and 32 seconds. The open question received suggestions such as paying better attention to environment details, objects texture and experiment lighting conditions. Some of the subjects inquired about the possibility of integrating haptic devices that could enhance the realism of the simulation.

2.6 Discussion of Results

Overall, the centralized results from the HRI questionnaire allow us to conclude that robot’s presence affects HRI. The result of question 10 (7.7586 on a 1-to-10 scale) shows that using immersive VR is a great way of simulating robotic scenarios. However, as reported in other studies [10], subjects gave the physically present robot more personal space than in VR. Most of our subjects enjoyed interacting with both the real and the virtual robot – on average, our test subjects found that interacting with the virtual PowerCube is an experience worth rated at 8.5862 on a 1-to-10 scale. The nature of the arm (fully mechanical, not anthropomorphic) made the subjects to rate question 8 with only 5.1724 on a 1-to-10 scale. However, the arms’ control algorithm seems to be fairly satisfying (7.6896), as it is very accurate (9.1379). Its main reported drawback is its low reaching speed (6.3103).

Table 1. Centralized data from HRI questionnaire

Section	Question	Answer
Biographical Information	1.Age?	21 years – 14; 26 years – 3; 22 years – 6; 39 years – 1; 23 years – 2; 40 years – 1; 25 years – 1; 44 years – 1;
	2.Sex?	M – 62% F – 38%
	3.How often do you use computers?	7.7931 (1 – never used; 10 – every day)
	4.How frequent are you interacting with robotic systems?	5.3448 (1 – never interacted; 10 – every day)
	5.How familiarized are you with VR technologies?	5.9655 (1 – never heard; 10 – very familiarized)
Specific Information	6.How fast do you think the robot arm was moving?	6.3103 (1 – very slow; 10 – very fast)
	7.How exact was the robot arm in picking/grasping/placing the target?	9.1379 (1 – completely inexact; 10 – perfectly accurate)
	8.How often did you feel that PowerCube (both virtual and real) was interacting with you?	5.1724 (1 – never; 10 – all the time)
	9.How satisfying do you find the control algorithm of PowerCube?	7.6896 (1 – completely unsatisfying; 10 – completely satisfying)
Presence Measuring	10.How real did the overall VR experience feel, when compared with the real equipment?	7.7586 (1 – completely unrealistic; 10 – perfectly real)
	11.How engaging was the VR interaction?	8.5862 (1 – not engaging; 10 – very engaging)
	12.What was missing from virtual PowerCube that would make it seem more appropriate to the real PowerCube?	-

3 Conclusions

Testing real life manipulation scenarios with PowerCube (and other robotic manipulators) imposes additional work in solving security issues, foreseeing and solving possible hardware and software malfunctions and preparing additional equipment for possible injuries. The proposed virtual solution eliminates all these problems. Although the presented virtual model is close to the real life robot, there still are some issues that need to be handled. The real robot has wires between each link, wires that have not been integrated into the simulated model. Another issue is the inconstancy between the real environment and the simulated one. Careful measures have been taken in order to have a good virtual replica of the real setup, however, due to the nature of the measuring process (which is inexact), the simulated arm slightly differs in some dimensions, as well as the real working environment. The simulated working environment had to be modified to include the robot body, chairs and the ground level as obstacles.

According to the discussion of results, the information computed from the HRI questionnaire shows that immersive VR is a good alternative to classical robot testing.

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