Eurographics Italian Chapter Conference (2008)
V. Scarano, R. De Chiara, and U. Erra (Editors)

A Virtual-Reality-based evaluation environment for wheelchair-mounted manipulators

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Abstract

The design of solutions for robotic extenders of wheelchairs must take into account both objective and subjective metrics for everyday activities in human environments. Virtual Reality (VR) constitutes a useful tool to effectively test design ideas and to verify performance criteria. This paper presents the development of a simulation environment, where three different manipulators to be mounted on a commercially available wheelchair have been considered. Experimental results are discussed in a significant case study, based upon users' feedback.

Keywords: Virtual Reality, Rehabilitation robotics, Human Robot Interaction, Kinematics.

1. Introduction

Research in the field of assistive applications is playing a key role in the international robotics community. Several research groups are developing systems aimed at assisting disabled people in the actions and assignments typical of everyday life in both structured and unstructured domestic environments [GBSG03]. The main goal of robotics for assistance is to increase the quality of life of disabled people; in particular, robot manipulators are required, able to replicate human abilities in terms of strength, speed and accuracy in the manipulation of objects and tools. While such systems can offer autonomy to impaired persons, great challenges are presented by the study of the interface, the suitability of available robotic systems for special users, the usability, especially related to the kind of disability.

While wheelchair-mounted manipulators are becoming common [EB99], [HG94], realistic simulation tools for studying their use are required. The design of human-robot collaboration tools has to pay particular attention to the following issues:

- user's safety,
- system ergonomics and usability,
- cost-effectiveness.

The study of the aforementioned issues requires design tools able to simulate not only the robotic system and its control interface, but also unexpected behaviours in anthropic environments, depending both on the user and the system, such as the occurrence of mechanical/electronics failures or unexpected user movements within the robot workspace. Moreover, a realistic interface can be helpful for appreciating the cognitive Human–Robot Interaction (cHRI). The main advantage of the immersive Virtual Reality (VR) technology in the field of human–robot interaction is the ability both to evaluate the control interface usability and to simulate the aforementioned dynamic events [BC03], [BC99].

Hence, the objective of this paper is to demonstrate the effectiveness of a VR-based simulator (Fig. 1) for testing the usability and possible applications of wheelchair–mounted robot manipulators, with an effective solution for mounting available robot manipulators on commercial wheelchairs via a sliding rail (Fig. 2).

2. Wheelchair-mounted manipulators

Assistive robots can be divided in fixed structures and moving platforms. While the first solution often requires modifications of the infrastructures in order to provide a known environment, manipulators mounted on mobile vehicles or

Figure 1: *The proposed wheelchair and the virtual immersive anthropic environment used for the simulations*

on wheelchairs offer higher flexibility. A good discussion of these issues has been addressed in [GBSG03]. It is worth noticing that often disabled people with upper-limb limitations also present mobility impairments which force them to use wheelchairs. A wheelchair-mounted manipulator [EB99], [HG94], [AMED05] can be an effective extender but, on the other hand, realistic simulations of the environment and extensive experimental activities have to be conducted for testing the effectiveness of their applications in unstructured domains. Moreover, safety issues have to be addressed in depth [AASB*06].

Finally, manipulators which almost replicate the kinematic structure of the human arm can be chosen for the legibility of their motion, which could improve the confidence of the users during physical Human-Robot Interaction (pHRI).

The use of Virtual Reality could speed up the design of such robotics solutions, because it is possible 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.

The research work described in this paper has consisted of two stages; namely, a concept stage in which the functional parameters of the wheelchair and the robotic arm have been defined, and an evaluation stage in which a VR architecture has been developed in order to evaluate the usability of the system.

3. Concept stage

3.1. Requirements and robot choice

The integrated system has to guarantee the maximum effectiveness and usability. At the same time, the introduction of the robotic arm does not have to require any significant change on its surrounding environment. Moreover, the wheelchair-mounted manipulator has to satisfy the following requirements:

- reduced weight,
- intrinsic safety toward accidental collisions with the user.

The powered wheelchair Indoor 2003 by Neatech [Nea] has been chosen, based on consideration on its features, which are reported in Fig. 3.

Figure 2: *The virtual environment with a wheelchair-mounted manipulator on a sliding rail*

In order to obtain a wider workspace for a robotic extender mounted on the wheelchair, a sliding rail has been considered around the powered wheelchair, with proper modeling of such a joint for exploiting it as an additional degree of freedom (DOF) available for robot control.

The manipulator can move around the wheelchair by sliding along the rail; the rail is able to rotate around an horizontal axis, providing a way to change its inclination, for adapting the workspace to user's needs (e.g., better dexterity on the ground). Such characteristic widely increases the robot workspace.

Rigid and foldable frame
Dismountable and adjustable armrest
Footrest adjustable in flex-estension
Footrest dismountable and ajustable
Speed 4,3 to 5,6 mile
Drive with programmable microchip
2 batteries of 45Ah extractable separately
Draw back Joystick
Possibility to tilting seating
Reclining and pull-down backrest
Small size for tight space

Figure 3: *The real Neatech Indoor wheelchair is lightweight and powered*

Three different lightweight robot arms (see Fig. 4), have then been considered for integration with the wheelchair:

a. KUKA Light Weight Robot (LWR),
b. Amtec Ultra Light Weight Robot (ULWR),

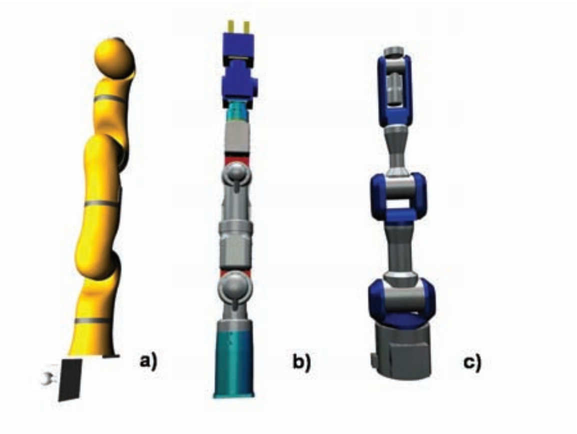

Figure 4: *The compared manipulators are: (a) KUKA LWR, (b) Amtec ULWR, (c) Mitsubishi PA-10*

c. Mitsubishi PA-10.

These manipulators have a kinematic structure similar to the human arm: moreover, the reduced weight allows using them for service robotics, while quantitative evaluation of intrinsic safety in case of rigid impacts are available only for the KUKA arm [ASH07].

Since the robotic arm and the rail mounted on the wheelchair introduce static balancing issues, it has been necessary to verify also the stability of the integrated system, which has been verified for all the three robots considering the wheelchair both with and without a person sitting on it.

3.2. Kinematic modeling

A key point for wheelchair-mounted manipulators is the possibility for the robot of moving around the sit, and extending this way its workspace around the user, without passing trough the front part of the wheelchair [BGH*06].

For the proposed application, the kinematic model of the considered manipulators has been extended for including the motion on the base joint.

With reference to Fig. 5, the base joint is modeled as a prismatic joint on the left, right and rear side of the wheelchair, while the sections between these segments are modeled as rotary joints. Smooth transitions between different segments have been considered.

For controlling the motion of every point of the robotic systems, the approach described in [DASO*07] has been adopted. The user (or an automatic module for safety procedures) can control the position not only of the end-effector, but also of an arbitrary point on the articulated structure of the manipulator, moving on the robot.

For instance, a control point can be the point of the robot which is closest to a collision (monitored with exteroception), or a point (e.g., the “elbow") that it is wished to move away from its current position.

Figure 5: *The proposed base rail for manipulator’s motion around the wheelchair*

The control interface gives reference directions, which are interpreted as desired velocities, and a closed-loop inverse kinematics (CLIK) scheme is adopted for computing the reference joint values.

With reference to the control of the end-effector of one of the considered 7-joint robots mounted on the presented base joint, the well-known relation

$$\dot{\mathbf{p}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}} \tag{1}$$

maps the joint space velocity $\dot{\mathbf{q}}$ into the task space linear velocity $\dot{\mathbf{p}}$, where $\mathbf{J}(\mathbf{q})$ is the (3×8) Jacobian matrix.

This mapping may be inverted using the pseudo-inverse of the Jacobian matrix, i.e.,

$$\dot{\mathbf{q}} = \mathbf{J}^{\dagger}(\mathbf{q})\dot{\mathbf{p}} \tag{2}$$

where $\mathbf{J}^{\dagger} = \mathbf{J}^{T}(\mathbf{J}\mathbf{J}^{T})^{-1}$ is a (8×3) matrix, which corresponds to the minimization of the joint velocities in a least-squares sense [SS00].

To avoid numerical drift due to discrete-time integration, a closed-loop inverse kinematics (CLIK) algorithm; the joint values $\mathbf{q}$ are computed by integrating the vector:

$$\dot{\mathbf{q}} = \mathbf{J}^{\dagger}(\mathbf{q})\mathbf{v} + \left(\mathbf{I}_8 - \mathbf{J}^{\dagger}(\mathbf{q})\mathbf{J}(\mathbf{q})\right)\dot{\mathbf{q}}_a \tag{3}$$

with $\mathbf{v} = \dot{\mathbf{p}}_d + \mathbf{K}(\mathbf{p}_d - \mathbf{p})$, where $\mathbf{K}$ is a (3×3) positive definite matrix gain to be chosen so as to ensure convergence to zero of the error $\mathbf{p}_d - \mathbf{p}$ between reference and actual position of the control point. Notice that in (3) the subscript d denotes the components of the position and velocity vectors that are input to the CLIK algorithm; the position components without subscript d are those computed from the joint position vector $\mathbf{q}$ (the output of the algorithm) via the direct kinematics equation.

If a moving control point is considered, other parameters besides the joint value change during motion. Therefore, a Jacobian for taking into account the motion of the control point on the structure has to be considered.

Looking at the Denavit-Hartenberg kinematics parameters of the considered manipulators, only the "d" distances, whose values are included in the vector $\mathbf{d}$, may change while the control point moves. Therefore the following equation holds

$$\dot{\mathbf{p}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}} + \mathbf{J}_d(\mathbf{d})\dot{\mathbf{d}} \tag{4}$$

where the second term on the right-hand side has to be subtracted from the desired velocity before inverse kinematics.

Moreover, an implementation has been realized with a second-order CLIK scheme, leading to compute joint accelerations starting from desired position, velocities and accelerations in the task space.

The algorithm has been first tested in MATLAB/Simulink and then implemented in C language for the application in the VR simulator, as described in the next section 4.1.

Notice that the Jacobian matrix has to be computed for every possible control point. Therefore, a symbolic expression for the matrix has been provided, where one must substitute the kinematic parameters corresponding to the considered control point for getting the particular solution needed.

Some properties for the evaluation of the considered robots can be described via objective indicators such as the well-known manipulability measure [SS00], which gives an indication of the ability of the robot to change posture and, therefore, of its ability in manipulation from the current position (and orientation). It is the volume of the so-called *manipulability ellipsoid*, which gives a graphical interpretation of robot dexterity.

With a dynamic model of the arms, it is also possible to compute a dynamic version of such indicator and an additional safety measure, namely, the impact ellipsoid [Wal94].

4. VR architecture for evaluation

4.1. Experimental setup

The experimental activity has been carried out using VR technologies in the laboratory of the Competence Centre for the Qualification of Transportation Systems, set-up by Campania Regional Authority [CDP04] in Caserta. VR-Test is a semi-immersive VR laboratory, which is endowed with a powerwall (s. Fig 6), three DLP projectors and shutter glasses for active stereoscopic view. The Simulation Manager software is Virtual Design 2, by vrcom. This application provides a user-friendly interface to handle all VR devices used in the laboratory. Moreover, the availability of a Software Development Kit allows enhancing and customizing the basic functionalities of the Simulation Manager with new software modules, that are fully integrated with the underlying VR framework. In order to simulate the movement of a kinematic chain in VR, a new module has been developed [DMT07]. The inverse kinematic algorithm described in the previous section has been implemented into the module. In this way, the plug-in allows the user to handle a robotic arm in real-time through a multidimensional input device, such as the joystick or the space-mouse, or the flystick.

Figure 6: *The immersivity is a key issue for capturing subjective evaluation about the virtual model which can be useful for the design of a physical prototype*

Moreover, the kinematic chain can be handled both in the joint and the operational space and the user can provide reference positions or velocities to the robot.

Each posture can be saved and reproduced in real-time. Moreover, the possibility to display the manipulability ellipsoid and the Jacobian matrix related to a certain posture is given (Fig. 8)

Therefore, the control module can be adapted to every kind of manipulators, where proper static analysis and evaluation about the risks of collisions with such manipulators allow using it for assistance tasks.

4.2. Experiment design

In order to enhance the illusion of using a real appendix of a wheelchair, a physical wheelchair has been placed in the laboratory in such a way that the user viewpoint coincided with the virtual wheelchair starting position.

The user can move the wheelchair in the virtual space, by means of the flystick. Moreover, in order to increase the immersion feeling, the shutter glasses are endowed with optical targets, and the user can also adjust the point of view on the virtual scene by moving the head.

The robotic arm can be moved by means of a joystick. The joystick is a 3D input device, but it has only 4 DOFs. Therefore, the joystick only handles the positional component of the end-effector, and consequently any orientation adjustments have to be done by operating in the joint space. For this reason, the user can individually control each joint angle by means of the joystick buttons.

In alternative, it is possible to use a 6-DOF input device, such as the space-mouse, but this choice has been discarded mainly due to the difficulty for training a disabled user in controlling both the position and the orientation of the end-effector at the same time.

Moreover, some buttons of the joystick are related to predefined postures. This feature simplifies the handling of the kinematic chain, since generally it reduces the time needed to reach a desired posture. Finally, a 2D-Menu allows the operator to select the robot to be evaluated and a set of test environments, as described in the following.

It is worth noticing that other kinds of input devices can be tested with minor modifications to the interface.

The second step of the experimental phase is the training of the users. The experimenter has to be briefly trained to the use of the interaction devices and also informed about the importance of their experience [DG07]. The training stage has been carried out in two phases: in a first phase, the operator has simply to move the end-effector along the three axes of the virtual space; then, in a second phase, the operator has to move the end-effector following a defined path. Only once the user is able to use properly the virtual devices, the experimental session can begin.

In order to compare the proposed robots for the considered application, an appropriate methodology of usability analysis has been developed.

The usability denotes the ease the user can handle the kinematic chain. It strictly depends on the robot type, the inverse kinematics algorithm, the user-robot interface, and the level of training of the user. In order to quantify the usability for a specific robot, we defined a set of time-based experiments. For the considered tasks, the usability measure is based on the elapsed time for completing the required motion.

In particular, four tasks have been conceived:

1. book positioning on a shelf (reaching);
2. objects relocation on a shelf (dexterity);
3. moving a chess piece on a board (fine motion between obstacles);
4. moving objects between two different planes (free motion);

4.2.1. Book positioning on shelves

Twelve books of four different colors are positioned (s. Fig. 7) on four different shelves. The task consists of moving every book on the shelves of the same color. This test allows determining the feasibility of operations performed by disabled people, as well to measure the manipulability and the usability of the robot for different levels of height of the end-effector.

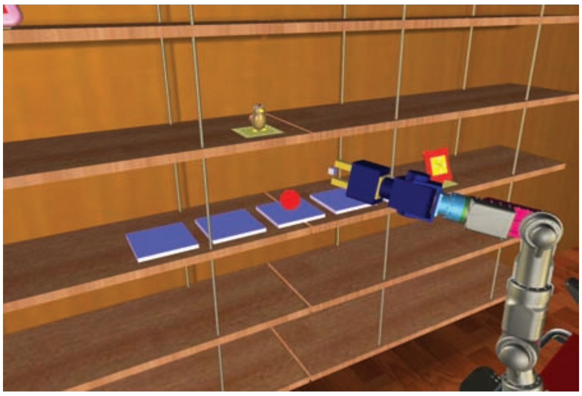

Figure 7: *Execution of the object relocation task on a bookshelf*

4.2.2. Objects relocation on shelf

The user is 0.4 m far from a shelf of height 1 m, where five equidistant markers are set. The distance among the most external markers is set to 1 m. It deals with the normal dimension of the human arm workspace. A spherical object is set on the central marker. The user first has to grab the object from the central marker and then release it on the others. The test evaluates the horizontal usability of the robot.

Figure 8: *Execution of the task at a chessboard: the manipulability ellipsoid is displayed on the screen*

4.2.3. Moving a chess piece on a board

The user is 0.380 m far from the chessboard (measured by the chest to the centre of the board). The violet horse (Fig. 8) is the piece to be moved, the yellow box represents the starting position of the horse and blue boxes highlight the final destination of the piece. The user has to move the piece from the yellow box to the blue one. This test evaluates the ability to handle small objects among some obstacles.

4.2.4. Moving objects between two different planes

In this test, the user has to move some glasses from a table to another and back again. The two tables are 0.9 m far. The starting position and the final destination of the glasses are signaled by different colored markers.

5. Experimental results

Experimental sessions have been performed by able-bodied users. We have considered a random sample of 10 users and we have asked them to carry out the four tasks using the three manipulators in a random order. The task execution time t has been considered as a performance index. In order to take in account both the mean μ and the standard deviation σ of the measured times, the *score* E for each test has been calculated in the following manner:

$$E = (\mu^2 + \sigma^2) \tag{5}$$

With this choice, lower scores mean better performances.

The performance of the manipulators is summarized in figures 9-12.

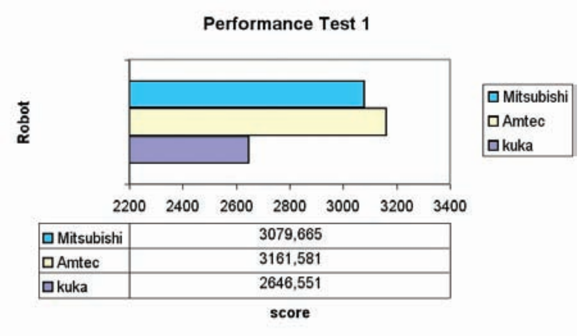

Figure 9: *Test 1 - Book positioning on shelves*

In conclusion, the KUKA LWR has obtained the best score in terms of usability in each test.

These preliminary results suggest the potential impact of the proposed tool for the evaluation of robotic extenders: with increasing users and criteria, the design can focus on some solutions which are preferred by the users.

Different indicators can be considered as well depending on the application: the possibility of carrying heavy objects, e.g., is considered important by the participants, for autonomy in their houses, while the central requirement of safety is considered somehow less central, due to the will of taking the control of the robot without autonomous robot behaviours. It is worth noticing that some weights chosen by the users can be quite surprising for an engineer. This shows that the appearance of the robot has a strong impact on the user, and even the intrinsic safety and versatility can be appreciated not enough, if not accompanied by a proper design.

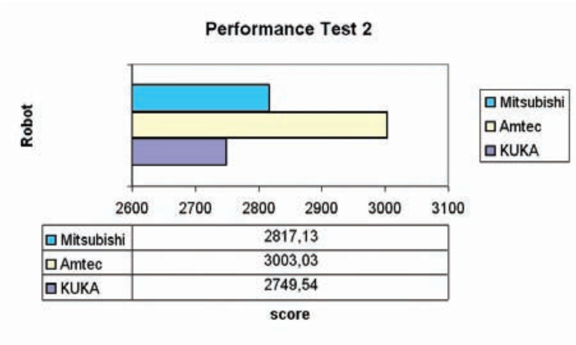

Figure 10: *Test 2 - Objects relocation on shelf*

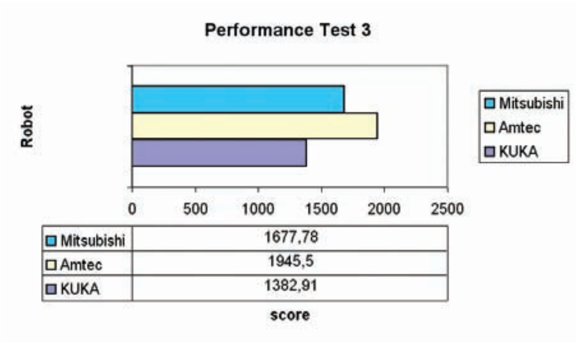

Figure 11: *Test 3 - Moving a chess piece on a board*

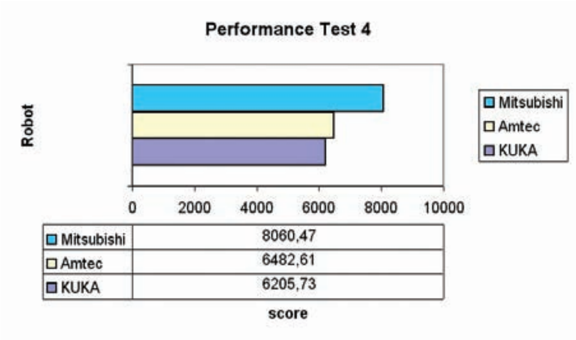

Figure 12: *Test 4 - Moving objects between two different planes*

6. Conclusion and future work

The proposed simulation environments can allow comparison between trajectory planning schemes, kinematic optimization of robots for wheelchairs, appearance and reliability of wheelchair-mounted manipulators.

With the addition of simplified dynamic models, joint torques due to the interaction with the environment can be generated as well for a better modelling of the environment.

The use of robots in unstructured and time-varying environments implies the need for implementing real-time reactive strategies to cope with possible collisions [DASO*07], which are going to be implemented for completing the simulator. The proposed tool can be used also for evaluating in a very realistic way the reactions during the approach and the motion of the robot on desired or unexpected trajectories. Force feedback can be added via a proper haptic interface [Bur96].

Finally, tests with disabled persons could provide additional insights in the cognitive and ethical aspects related to the introduction of robotic extenders in the everyday life.

The study on the interface should take into account the possible difficulty for a disabled user in controlling both the position and the orientation of the end-effector at the same time.

Virtual reality provides a time- and cost-effective tool for the proposed comparisons.

7. Acknowledgments

Authors deeply thank Prof. Francesco Caputo and Prof. A. Lanzotti for their helpful suggestions about evaluation and future work, G. Sorrentino and R. Del Vecchio for their collaboration in the experimental sessions. vrcom GmbH guaranteed technical support, while Neatech S.R.L. also provided the used wheelchair with corresponding CAD model. The present work has been developed with the contribute of MIUR-PRIN 2006: “PUODARSI” (*Product User Oriented Development based on Augmented Reality and interactive SImulation*).

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