

# VR Haptic Interfaces for Teleoperation : an Evaluation Study

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**Abstract**— We present the results of an evaluation study in the framework of user interfaces for teleoperation of vehicles. We developed a virtual cockpit with haptic feedback provided by a Haptic Workstation™. Four alternative teleoperation interfaces were implemented. Each interface exploits different aspects of Virtual Reality and haptic technologies: realistic 3D virtual objects, haptic force-feedback, free arm gestures. A series of tests with multiple users were conducted in order to evaluate and identify the best interface in terms of efficiency and subjective user appreciation. This study provides insights on how to take the most out of current VR and haptic technologies in the framework of teleoperation.

## I. INTRODUCTION

Teleoperation systems involving mobile robots have many applications such as exploration and mining, manipulation/inspection of underwater/outer space structures, removal of mines or surveillance of large spaces. Most teleoperation interfaces currently used commercially (e.g. mining robotics) are relatively unsophisticated [?]. They are constituted by ad-hoc controls such as joysticks or buttons, complemented with visual feedback obtained from robot-mounted cameras.

Other forms of feedback to the operator besides vision are important, and it is necessary to find efficient ways to display this information. Some research works on teleoperation interfaces focus on improving the efficiency of operation -task execution- by means of increasing the amount of feedback. Common approaches include using 6-DOF haptic interfaces in combination with Virtual Reality techniques, [?], [?]. A detailed overview of haptic devices such as exoskeletons and stationary devices, gloves and wearable devices, etc. can be found in [?].

The use of sophisticated technology such as Virtual Reality does not inherently increase system effectiveness. This depends on how technology is used to give solutions to the basic problems of human-machine interaction: how to select the content, how to present the information in an appropriate way to human operator [?]. Many teleoperation interfaces face the following problems: feedback information is not sufficient, the inner status of remotely controlled system cannot be presented properly, there are discrepancies between simulation model and actual environment, the interface is not flexible enough to support the multimodal teleoperation commands, etc. [?].

Our research is focused on finding better interfaces and interaction paradigms for teleoperation. We target most of

the problems mentioned before: providing additional feedback, finding new ways to present information, support multimodality and reconfigurability of the interface, etc. Virtual entities (3D models) can solve the problem of reconfiguration and adaptation of physical devices, but also have some drawbacks. The main disadvantage of an interface based on 3D models is the absence of physical feedback. “Feeling” a control tool is essential, otherwise the manipulation requires too much effort and becomes unprecise. Haptic technologies aim at solving this problem by enabling virtual objects to provide a tangible feedback to the user. Virtual interfaces can be used to provide a variety of feedback mechanisms to ease teleoperation: vibrating controls and audiovisual signals to inform the user about the robot status and the surrounding environment. Audiovisual feedback is essential to the usability of an interface. Some authors have even considered that traditional haptic feedback (mainly force/torque) can be replaced by the right combination of sound and visuals. For instance Liu et. al. [?] proposed using visual/tonal stimuli instead of traditional haptic interface devices to provide feedback based on the data acquired from the remote system.

Discussion is open about what are the key elements for an efficient and user-friendly remote-control interface. In this article we present the results of an evaluation study aimed at identifying the key factors for an intuitive and efficient teleoperation interface. We based our work on the concept of **mediators** [?] and experimented with different mediator interfaces for teleoperation. Mediators are virtual interfaces with haptic feedback. They are implemented by means of a Haptic Workstation™ [?].

Our study consisted on driving a mobile robot using four mediator interfaces that exploit different aspects of VR and Haptic technologies. The idea was to evaluate different alternatives and to determine which kind of mediator interface is the best in terms of efficiency and intuitiveness. Our initial hypothesis was based on the idea that a minimalistic interface with realistic controls (virtual steering wheel and throttle) would be the best way to remotely drive a mobile robot. User tests and observations guided the subsequent re-design of the interface.

## II. A TELEOPERATION SYSTEM

Mediators are virtual objects with haptic feedback which act as intermediaries between the user and a complex environment. We introduced this concept in [?] and demonstrated its application within an interactive Virtual Environment. In [?] we took the next step and presented the implementation of a mediator interface to drive a mobile robot. For the study we are presenting in this paper we are using the same robot. The system architecture can be divided into two main parts:

- Controlled world: a mobile robot made up with the Lego® Mindstorms [?] toolkit controlled by a laptop.
- Mediator world: a Virtual Environment with haptic feedback provided by a Haptic Workstation™.

Both systems are connected to the Internet and communicate between each other using the TCP/IP protocol.

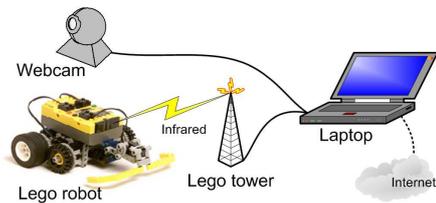


Fig. 1. Elements of controlled world.

Controlled world elements are illustrated in figure 1. The robot is equipped with a collision detection sensor on the front-side and a web-cam. Direct control of motors/sensors is done through a laptop (infrared communication). The video stream is acquired with a webcam located on top of the robot and connected via USB to the laptop.

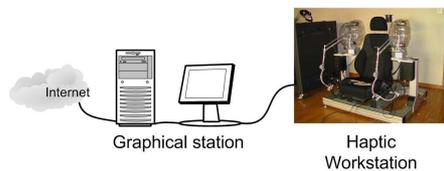


Fig. 2. Elements of mediator world.

The mediator world (see Figure 2) is composed by a PC and a Haptic Workstation™. The PC renders the Virtual Environment for the user sitting inside the Haptic Workstation™. To drive the robot, the pilot has different types of virtual cockpits which will be described in the next section.

Graphic rendering is done with OpenGL. VHT [?] is used for the haptic feedback. VHT is a library provided by the manufacturer of the Haptic Workstation™ to avoid programming haptic effects with low-level functions. VHT analyzes the shape primitives of which 3D objects are composed (spheres, cylinders). It calculates the forces applied on the Haptic Workstation™ as a function of the position of the hands relative to the shape primitives.

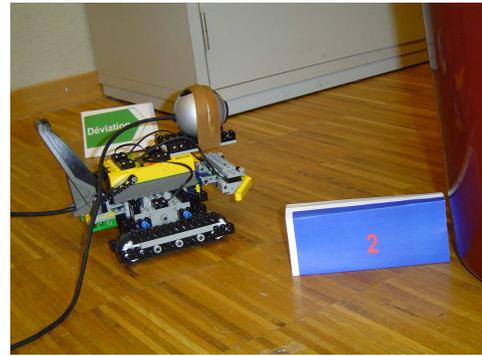


Fig. 3. Tele-operated robot.

The Haptic Workstation™ is composed by a pair of 22-sensors CyberGlove™ which are used for acquiring the posture of the hands when interacting with the virtual cockpit elements. The CyberGrasp™ system applies ground-referenced forces to each of the fingers and wrists. The user can grasp the devices of the control interface and “feel” them with the hands. The CyberForce™ is an exoskeleton that conveys force-feedback to both arms and provides a six-degree of freedom hand tracking, allowing the user to touch the elements of the virtual cockpit.

Both systems are connected to the Internet, the robot uses the built-in WiFi card of the controller laptop. Three main kinds of data streams are exchanged between both worlds, they are illustrated in figure 4.

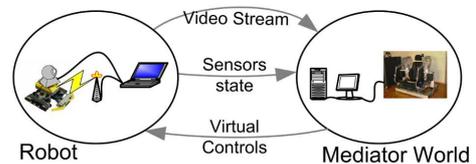


Fig. 4. Teleoperation data streams.

Access to the webcam is provided by the VidCapture library [?]. Infrared communication between laptop and robot is done with the “small direct interface” developed by Berger [?]. It allows for sending simple commands such as “go forward at speed 3”.

## III. TELEOPERATION SCENARIO: A ROBOT “GRAND-PRIX”

The teleoperation scenario is a car race around obstacles with a few bends as illustrated in figure 5. The goal is to complete it as fast as possible. The very limited speed of the robot and the ease of the circuit guarantees that the driver’s expertise will not be determinant in the time required to complete a lap. We measured the optimal time required to complete the circuit, by driving the robot directly from the controller laptop, using the keyboard and watching the robot directly (see Figure 5). The optimal time calculated was 1m30s.

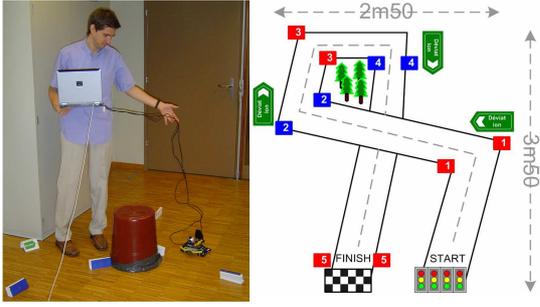


Fig. 5. Direct driving of the robot to calculate optimal time and plan of the “grand-prix”.

Four different types of mediator interfaces -to be defined in next section- were tried by each test user in order to evaluate the efficiency and intuitiveness of each variation. Efficiency is defined as capacity of the interface to accomplish the workload satisfactorily. The workload in this case consists on: first, finishing the race; second, avoiding all the obstacles; and third, doing it as fast as possible. Intuitiveness is a more subjective criteria and depends on the user’s preferences and impressions, it refers to the ease of learning and using the interface. Efficiency can be objectively measured in terms of the time taken to finish the lap and the number of obstacles touched. Intuitiveness is measured by means of a questionnaire and direct observations of the user’s behavior when using each interface. Test users are from 25 to 40 years old, four men and one woman, all of them with a Computer Science background.

#### A. Evaluation protocol

Each user must test four different interfaces, but the order in which each interface is tried by each user is random. This was done to minimize the effect that after some trials, people can get used to driving the robot and finish the lap successfully even with an inefficient interface. The robot running the race is put in a room separated from the Haptic Workstation™.

Before the tests, the driver is allowed to do a lap with a remote-control and direct view on the robot to study how it turns and moves. This gives some reference points which can be helpful to decrease the difference between the first and the last test performed by the driver.

#### B. Evaluation parameters and analysis

Two evaluation parameters are used to benchmark the interfaces: global time spent on each interface, and ranking each interface on a per-driver basis. First parameter is obtained by adding the time spent by each driver to finish the race using a given interface. Then the best interface will be the one with the shortest time. Second parameter is calculated by ranking the interface according to the performance of each person. On a per-driver basis, the best interface is the one that allowed finishing the faster lap. The best interface will be the one that was best ranked by all users.

This benchmark does not take into account subjective criteria required to evaluate the intuitiveness. For this the testers

answered a small questionnaire and we complemented the analysis making an evaluation of the overall performance of each interface.

#### C. Measuring intuitiveness

The questionnaire used to evaluate the driver’s impressions about an interface was composed by 3 questions:

- Is the interface easy to learn?
- Do you think this interface is efficient to drive the robot?
- Do you have any remarks about this interface?

We asked these questions to the users after they tested each interface. The objective was to identify contradictions between performance to complete a lap and user perceptions (interface intuitiveness).

#### D. Overall evaluation

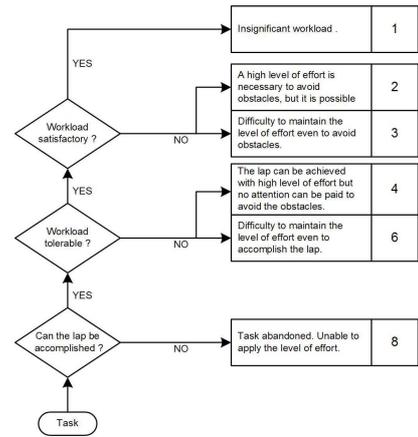


Fig. 6. Rating scale for teleoperation systems.

The test and responses to the questionnaire were complemented with an overall performance evaluation of the efficiency: the capacity of the interface to help the users complete the workload. The overall evaluation was done by giving the interface a mark according to the rating scale for teleoperation systems shown in figure 6. This method was proposed in [?] to evaluate military cockpits. It was later applied in [?] to the evaluation of interfaces for robotic surgical assistants. We have adapted it to our own task: evaluating efficiency of a teleoperation interface for driving a robot on a circuit (primary task) while avoiding obstacles (secondary task). This rating scale allowed us to have a unique mark characterizing each interface.

#### IV. ALTERNATIVE MEDIATOR INTERFACES

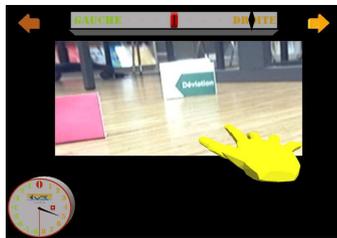
To control the robot, four alternative mediator interfaces have been designed. Design was driven by the tests with users and observations. Subsequent improvements consisted on going from physical/realistic cockpits up to “free-form” interfaces (interpreting arm motion). The first interface is based on real car cockpits whereas the last one takes full advantage of the Haptic Workstation™ as a system designed to acquire and drive (through force-feedback) the arm motion.



First interface



Second and third interface



Free-form Interface

Fig. 7. Alternative mediator interfaces.

All interfaces have a common visual part: a virtual screen that displays the video stream sent by the robot webcam. This element is essential to know the location of the robot in the remote scenario. Moreover, all interfaces have a common haptic behavior: in case of collision between the robot and an obstacle, a signal is sent to the interface and controls are blocked to prevent the user from keep moving toward the obstacle. The four next subsections present the description of the alternative mediators interfaces and the results of the tests.

#### A. First approach: virtual elements resembling reality

The first approach tended to reproduce a standard vehicle cockpit as shown in figure 7. Steering wheel and throttle are universal interfaces used to control a car, so it seemed logic to use a virtual cockpit which looked like a real one. The mediator interface was thus composed by a haptic and visual steering wheel and a throttle. The haptic shapes of the steering wheel and the throttle are exactly the same as the corresponding visual shapes. When a collision is detected by the contact sensors of the Lego® robot, the virtual steering wheel shakes for a moment, and the throttle is blocked so that the user cannot go forward. The steering wheel is blocked in the direction of the obstacle. This behavior is the same for all three interfaces with these controls.

The time taken by each driver to perform a lap and the per-driver-rank of the first interface are shown in Figure 8. Last line presents the number of missed or touched gates:

People	A	B	C	D	E
Time	3m30	10m00	4m05	5m20	5m10
Rank	3 <sup>rd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	2 <sup>nd</sup>	4 <sup>th</sup>
Obstacle	1	5	1	1	1

Fig. 8. Results of simple interface test.

In this test, the driver B reached the time limit: he drove during 10 minutes without passing through the 5 gates. Thus we decided to set his time to the maximum time to avoid penalizing too much the interface in the global time ranking.

After discussing with the users, we found that the first advantage of this interface was its intuitiveness. However, drivers criticized the visual feedback. Everybody touched at least one gate. Frequently, obstacles were not visible on the screen because the camera was placed in front of the robot, and the view angle was not large enough. Moreover, there was no speed or direction perception. These two points often made the driver think he was too far and he stopped the robot before passing through the gate.

In order to improve the perception of speed and direction we added complementary visual feedback to give a better idea of the robot motion to the driver. We followed a principle similar to the one applied by the HMDs used by jet pilots, which provides useful information such as artificial horizon line, altitude and so on.

#### B. Second approach: adding visual feedback to enhance control

The drivers required more information about speed and yaw of the robot. Thus we added two visual elements (see figure 7): a visual speedometer and two indicators flashing when the user turns. Figure 9 presents the results obtained for the second interface.

People	A	B	C	D	E
Time	3m45	10m00	3m40	6m45	4m00
Rank	4 <sup>th</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>
Obstacle	1	5	0	1	0

Fig. 9. Results of added visual feedback interface test.

This second interface obtained results similar to the first one. Total sum of drivers times is 28m05s for the first one and 28m10s for the second one. Means of rank are and obstacle collision are almost the same. We concluded that the additional visual feedback does not provide enough helpful information.

By discussing with the drivers, we discovered that they didn't really look at the speedometer because they gave priority to the task of controlling the robot. These tasks were so hard that they considered collision avoiding as a secondary problem they did not have time to deal with. A new question raised: why is it so hard to control the robot ?

The steering wheel is hard to turn because the Haptic Workstation™ library does not allow for defining 1DOF objects such as the steering wheel or the throttle. Thus we were forced to implement a customized solution that resulted into an unintuitive grasping mechanism. This implied that the driver had to concentrate more on grasping the steering wheel than on driving.

To simplify the use of the cockpits elements, we chose to improve them with a “return to zero” functionality: when the driver releases a control, it comes back to its initial position. This way the driver spares the movement necessary to reset it. On the other hand the effort to aim the center (the initial position) of the control is spared as well. The third interface takes advantage of this constatation.

*C. Third approach: adding assisted-direction to interface elements*

The visual aspect of the third interface is exactly the same as the second (see Figure 7). It differs from the precedent by incorporating the “return to zero” functionality.

Results for the third test are presented in Figure10.

People	A	B	C	D	E
Time	2m50	2m30	3m10	5m25	3m40
Rank	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	2 <sup>nd</sup>
Obstacle	0	1	1	1	0

Fig. 10. Results of assisted direction interface test.

Except for the user D (this interface was the first one he tried), every driver found that this interface was better than the previous ones. Total time spent on it was 17m35s, a significant decrease in comparison with the first and second one. Responses to the questionnaire showed that the “return to zero” functionality is very helpful.

Nevertheless the lap times are the double of the ideal time. In fact, from time to time, the drivers did unintentional changes of orientation because the Lego® robot does not have a smooth behavior while turning. When this happens the time taken to recover the right direction could be significant, and increase even more if the driver tries to turn faster to spare time.

Some people used only one hand to manipulate both controls, because they found too hard to use both controls at the same time. This problem is due to the bad interaction system between the hand and the controls and from the approximative haptic response.

Currently, hands interact with the controls (steering wheel, throttle) and then a mapping between controls position and robot engines is done. In this process, the controls are an additional intermediary component which could be eliminated in favor of a direct mapping between the hands position and the robot engines, see figure 11. This is how we came up with the fourth mediator, a free-form interface.

*D. Fourth approach: free-form interface*

This interface takes its name from the interaction design framework proposed by Igarashi [?]. A free-form interface

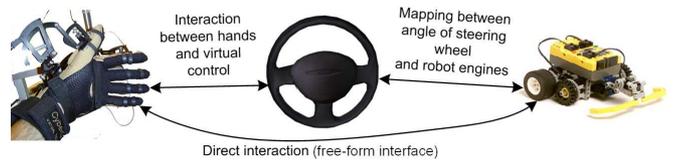


Fig. 11. Mapping between hands, virtual controls and robot engines and short-cut used to create a free-form interface.

allows the user to express ideas or messages as freeform strokes. The computer takes appropriate action by analyzing the perceptual features of the strokes [?]. Freeform user interfaces as proposed by Igarashi are pen-based systems. We applied the concept of using relatively unconstrained motions to convey a message or intention. In this case, the user uses relatively freeform arm gestures to indicate the direction in which he wants the robot move.

We removed the virtual controls and the left hand (see figure 7), but we let the indicators and the speedometer because they don’t complicate the visual interface and drivers may use them occasionally.

A force field constraining the right hand at a comfortable position is introduced. The driver can still move his hand everywhere, but the force becomes stronger proportionally to the distance between his hand and the neutral position.

Figure 12 presents the results of each driver with the free-form interface.

People	A	B	C	D	E
Time	2m00	2m00	1m50	3m30	3m20
Rank	1 <sup>st</sup>				
Obstacle	0	1	1	0	0

Fig. 12. Results of free-form interface.

All users did their best lap with this interface, including user E who started the test with it (and didn’t have the same level of familiarity with the system). Best lap times are nearly the same than the optimal lap (1m30s). The difference may come from the view angle of the webcam, which is much more limited compared to the direct visual driving. The unique disadvantage we found was that this interface is less intuitive at first sight.

The control on the robot is precise. User can change direction in a simple movement, and go forward and backward by the same manner. When a collision is detected with a gate or a wall, the haptic response is more intuitive than shaking the controls. Moreover, one really feels a “wall” preventing any further motion of the hand towards the obstacle. In contrast, with the virtual controls, users often thought the blocked control was either a bug in the system or a lack in their driving skills.

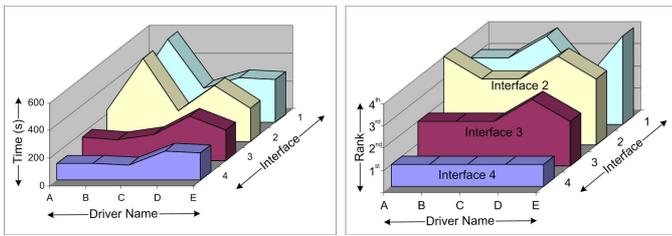


Fig. 13. Overall results of the driving tests.

## V. DISCUSSION OF RESULTS

Figure 13 sums up all tests results, and confirms that our intuition about the free-form interface was well founded: it revealed to be the most efficient interface, but perhaps not the most intuitive one.

The overall evaluation obtained using the method described in Figure 6 confirmed the ranking obtained with the other benchmark (time to finish the lap, per-driver ranking): the most efficient interface, the one that minimized the effort to accomplish the workload was the free-form interface. In second place we have the one with “assisted-direction” and the last places are shared by the two first approaches. We believe we were able to avoid influence from the driver’s skills when evaluating the interfaces, since even with the worst performer, the free-form interface was the best evaluated.

The free-form interface eliminates the interaction between the hands and virtual controls and for the moment seems to be the best approach. As long as hardware doesn’t allow more precise haptic feedback on both hands and arms, it will be difficult to have a good perception of grasping and manipulating objects such as a steering wheel. Based on the presented tests we draw the following general conclusions about efficiency and intuitiveness of an interface for teleoperation:

An efficient interface for direct teleoperation must have rich visual feedback in the form of passive controls such as speedometers, direction indicators and so on. Such visual aids were appreciated by users once they were released from the burden of manipulating the virtual steering wheel and throttle.

Force feedback shall be exploited not as a way to simulate tangible objects (interfaces resembling reality) but to drive the user movements (gestures-based interface). The free-form interface was efficient because it didn’t required precise manipulations. It reduced the amount of concentration required to drive. The user could direct her attention to the rest of the visuals and use them to improve the driving.

Virtual interfaces resembling reality were the most intuitive ones, in the sense that users knew immediately how they worked (previous real-world experience). Nevertheless, the available hardware made them less efficient due to the problems with the grasping mechanism explained before.

Finally, it is important to note that the observations and assumptions presented here can be strongly dependent on the hardware used and the teleoperated robot. Perhaps an ad-hoc designed hardware could give better results in terms

of grasping and manipulation. However, since the Haptic Workstation was conceived as a multi-purpose equipment and is commercially available, we believe it is worth finding the interface that allows for taking the most out of it. This way our results have more possibilities to be reproduced, researchers do not need to build a house-made device but to rely on one that is available in the market. Moreover, even if teleoperation systems and other applications do not make use of a Haptic Workstation, the ideas and observations we acquired can be good starting point to drive the design of novel interfaces.

## REFERENCES