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EVALUATION OF A FORCE FEEDBACK (HAPTIC) COMPUTER POINTING DEVICE IN ZERO GRAVITY

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ABSTRACT

Haptic devices and specialized force-feedback hand controllers have been proposed as alternative Input/Output devices for use in challenging operational environments such as space. In the case described here, it is proposed that a pointing device with force-feedback (a haptic mouse) be used as a generic cursor device for operating computers in weightlessness. It is believed that such devices will decrease the effective workload of operators while increasing their efficiency in space. This paper describes an experiment that was designed to measure the effectiveness of a haptic device (hereby called Pantograph) in zero gravity conditions. The Pantograph was compared to a standard trackball pointing device. Both devices were tested on the ground and aboard a NASA reduced-gravity aircraft using a common graphical test interface (GUI). Results have shown that in zero gravity, the haptic device has proven more time efficient and has provided more pointing accuracy than the trackball in performing standard GUI operations such as clicking, dragging, and selecting.

[Key words: haptic device, cursor pointing device, force feedback, weightlessness, microgravity, trackball]

1. INTRODUCTION

Space hardware and mission complexity have increased tremendously over the past years as instrumentation and scientific objectives in orbit have become more sophisticated. Recent developments in robotics and computer applications have led to striking changes in the way systems are monitored, controlled, and operated [1]. Moreover, an increasing number of graphical user interfaces (GUI) are currently being introduced in space vehicles to operate standard equipment, such as the Shuttle Remote Manipulator System SRMS[1]. It is clear that a significant portion of the time of astronauts, in the future, will be spent interacting with graphical user interfaces (GUI). It is known that a well designed interface operated with a *comfortable* pointing device should augment operational performance, but extreme working conditions, cramped working quarters or sensorimotor impairment may hamper or even eliminate the effectiveness of graphical interfaces. In fact, the decision speed and operational demands of many current space systems now call for new approaches to improve the efficiency of basic operator-machine interaction in space.

Among the interactive technologies under investigation at the Canadian Astronaut Program is the use of a haptic device as a generic cursor Input/Output device. This research is concerned with the evaluation of the effects of a haptic device on user performance when operating a graphical interface in zero gravity. In particular, an experiment was designed to investigate the effectiveness of a custom-designed haptic device called the Pantograph. This new pointing device was initially designed to provide assistance to visually impaired persons for the operation of conventional graphical interfaces. The Pantograph was developed at Industry Canada's Centre for Information Technology Innovation (CITI) and McGill University [2] and was adapted for reduced gravity experimental purposes.

The experiment described hereafter consisted in testing and analysing the performance of the Pantograph in zero gravity conditions, as compared with a standard trackball. The tests were conducted both on the ground and aboard a NASA operated aircraft that provides reduced gravity (weightlessness) conditions for research purpose. Operators who were veterans of zero gravity flights and familiar with GUI interaction, were trained on the system and asked to execute a series of tests on both devices in turn, using a common test interface display. This test interface was derived from a current Space Shuttle RMS robot arm graphical interface.

The quantitative evaluation of the devices was

[1] The Shuttle Remote Manipulator System (SRMS) is a Canadian-built teleoperated robot arm that is used in a semi-autonomous mode during spaceflight missions that require objects to be handled, captured and released into space.

performed using a window environment with standard tasks: button selection, menu navigation, moving, resizing etc. The experimental effort consisted in measuring the task accomplishment time and the error rate of these operators both in flight and on the ground. Within the constraints of such an effort, a statistically significant experimental methodology was devised.

The experiment was carried out at the Canadian Space Agency in Montreal and aboard a reduced-gravity DC-9 aircraft at the NASA Lewis Research Centre in Cleveland, Ohio, with the assistance of the Centre for Information Technology Innovation (CITI) and McGill University.

2. THE HAPTIC DEVICE

The haptic device used in this experiment is a slightly modified version of the device described in [3]. It is nicknamed the *Pantograph* and was initially devised to help visually handicapped persons interact with graphical user interfaces [4].

The Pantograph is a relatively simple device consisting of a small planar linkage driven by two stationary electric actuators and instrumented with position sensors (see Figure 1). The work area has the shape of a rectangle of 10 by 16 centimetres that constrains the pointer's movements in the horizontal plane. The Pantograph's workspace exactly maps, in proportion, the area of the graphical user interface. One of the most attractive features of the Pantograph is that high quality kinesthetic and tactile stimulation (force feedback exerted on the pointer of the Pantograph and felt by the fingers of the operator) may be obtained for a rather moderate system complexity. For the purposes of this experiment, the pointer (knob) was equipped with a miniature push-button enabling the device to fulfill the clicking functions of a computer pointing device. The Pantograph is driven from a computer via a conventional data acquisition chain and its operation requires only modest computational capabilities.

The forces experienced by the operator's finger tips are applied in the horizontal plane. It is difficult to report the magnitude of these forces since they depend on the tuning of the interface and on each operator. It can however be said that effective haptic feedback was achieved with surprisingly low levels of forces, smaller than one Newton in peak value. These forces are synthesized at high rate during the course of the interaction. They are calculated from simple mechanical models of the graphical objects on the screen, translated into algorithms, calculated in real time and finally reconstructed for the user by means of the Pantograph.

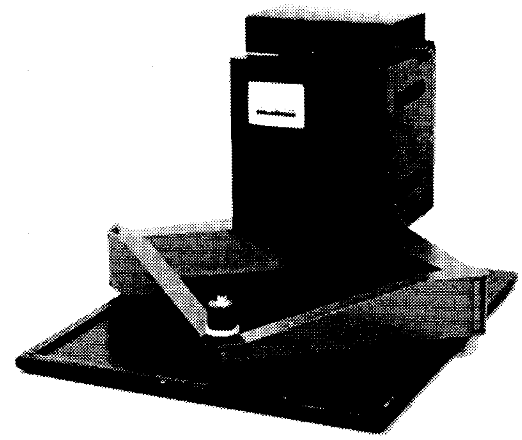

Figure 1: The Pantograph

Each interface object on the GUI (window frames, buttons, icons and pop-down menus) is defined as a three-dimensional polygon with a certain viscosity. To simplify programming and provide a uniform method to create such mechanical representation, the screen is viewed as a surface having features: depressions and embossings. On the surface, the cursor is viewed as an object of unit mass subject to a gravity field which can be moved about the visible surface of the graphical objects on the screen. As the cursor is moved, the unit mass tends to "fall" in depressions or "resist" entry into an embossing. Surface material properties are specified with a combination of viscous and solid friction terms.

The actual forces transduced by the Pantograph at any given time are the tangential components of the forces present: gravity, friction and object reaction. The tangential components of the force associated to the cursor are then applied to the fingers of the operator via the actuators (up to a factor). When transitions from one graphical element to another occur, rapid force transients are also experienced by the operator, since the Pantograph is capable of transducing forces in a range of several hundred Hz. It is the combination of the sensations created by each object *and* of the intervening transients that informs the user of the presence and location of the various elements of the interface.

In this experiment, the graphical and haptic rendering of the objects of an interface was programmed as a toolbox in C++ and given the acronym MUIS for Multimodal User Interface System. The interested reader may find further details in [5].

3. OBJECTIVES

Given the complexities and costs involved in setting up our experiment, the research was designed to address several objectives at once.

3.1 Feasibility

The first question which arose was simply about the feasibility of using haptic feedback in weightlessness since it had never been tried before. Questions were also raised about the safety of a device capable of imparting forces on a weightless operator, as well as concerns with equipment failure.

It must first be understood that the Pantograph is constructed in such a manner that its displacements are limited in amplitude and force. We found that typically, haptic sensations were felt by operators with rather low levels of forces (of the order of fractions of Newtons). It was found that only a minimal amount of restraint (i.e. the need to anchor oneself to a frame or handle in order to counteract the effect of free floating in weightlessness) was necessary on the part of operators, for example with the unoccupied hand. In fact, experience showed that restraint was more needed to compensate for the imperfections of the simulation of zero gravity conditions aboard a reduced-gravity aircraft than to counteract the effects of the haptic device.

In case of equipment failure, the largest quantity of mechanical momentum supplied to the operator can be guaranteed by design to be quite small. The design of the rendering also guarantees that the average body position remains stationary over the course of haptic icons interactions. The conclusion, now backed with the experimental evidence provided here, is that haptic feedback is eminently feasible in zero gravity, both in terms of haptic perceptions and reliability.

3.2 Relative Device Performance

The main objective of the experiment is to measure the effectiveness of a haptic mouse in zero gravity conditions. Here we have attempted to establish some quantitative performance criteria and obtain an indication of their value. The first criterion used for performance evaluation is the speed at which the operators can accomplish the elementary tasks needed to interact with a graphical user interface. The speed was compared for both the Pantograph and the trackball devices by setting up a realistic interface. The second quantitative criterion is the proportion of erroneous elementary operations made by the operators.

In order to demonstrate that the relative performance change is similar in weightlessness and on the ground, independent from the absolute performance change, we conducted the exact same series of tests with the same operators, in normal gravity (on the ground) as well as in zero gravity. Moreover, we added an additional series of tests to demonstrate that the haptic feature, rather than the ergonomics of the Pantograph, is at the origin of the change in performance of the operator. This was accomplished by comparing task performance with the Pantograph, with and without haptic feedback. The results are reported and discussed in section 5.

3.3 Impact in Terms of Comfort

Lastly, some of the characteristics of a user interface cannot be captured quantitatively. Such is the "comfort" of an interface. The operators of the experiments were asked to fill a qualitative questionnaire at the conclusion of their participation. The results are reported in section 5.

4. EXPERIMENT DESCRIPTION

4.1 NASA Reduced-Gravity Aircraft

The working conditions in space were approximated by conducting parts of the experiment aboard a modified DC-9 aircraft operated by the NASA Lewis Research Centre in Cleveland [6]. This DC-9 provides brief periods of weightlessness by flying parabolic trajectories. A typical mission is 2 to 3 hours in duration and consists of up to 60 parabolic manoeuvres, providing a total of approximately 20 minutes of reduced gravity. In a given parabola, the aircraft climbs for 30 seconds to an altitude of 35,000 feet, stalls and then free-falls for 25 seconds to an altitude of 23,000 feet. During the free-fall portion, reduced gravity (0.00 ± 0.01 G) occurs inside the aircraft, similar to what can be experienced in space. Trajectories exhibit variations in acceleration that reflect the dynamics of the flight profile and the meteorological conditions. For the purpose of our experiment, a series of four flights were performed during the week of December 11, 1995 and the number of consecutive parabolas averaged 45.

4.2 Experimental Setup

The experimental setup consists of a personal computer, amplifiers and a tablet on which the cursor pointing device, alternatively the trackball or the Pantograph, is installed (see Figure 2). The operators interact with the display in a upright position. The system is completely operated with a single hand via the pointing device and a button. All hardware components are mounted in a custom designed rack, rigidly connected to the floor of the aircraft. (Note: the same arrangement is used for both ground and zero gravity testing.) During reduced gravity operation, operators secured their feet to the floor with adjustable straps.

A conventional 486-PC workstation was used to run the test GUI, the haptic control of the graphical elements present on the screen, the protocol handling, and the data logging. The GUI layout used in the tests (see Figure 3) was derived from an actual interface proposed to control the robot arm on the Space Shuttle. It is made up of icons, windows, a menu bar, pull-down menus, buttons, selection indicators, dials, sliders and dialogue boxes.

4.3 Operators

Due to the limited number of seats aboard the NASA experimental aircraft, only four operators were selected to conducted both the ground and zero gravity testing. For the ground portion, a total of seventeen operators, including the four flight operators and thirteen staff members from NASA and the Canadian Space Agency, carried out the tests in normal gravity conditions. All operators were right-handed (necessary characteristic due to the apparatus setup) and familiar with conventional mouse operation and graphic display interaction. Among the seventeen ground operators, five had experience with the trackball. None had any with the Pantograph.

The four flight operators turned out to be males aged from 25 to 35, all staff members of the NASA Lewis Research Centre. Flight operators were chosen primarily for their experience in reduced gravity flights and for their known resistance to motion sickness, as they were required to fly without medication.

4.4 Experimental Protocol

In order to accomplish a test, an operator is asked to execute a sequence of requests (instructions). A given request is displayed at the bottom of the screen and a new request appears automatically once the previous one has been fulfilled. A timer is used to compute the completion time for a given request. The timer starts when a new request is displayed and stops when the operator has completed the task, ie, by selecting the right object and releasing the device-button. A series of indicators on the left of the screen summarize the state of the interface for the operator. The sequence of requests is randomly generated by the test interface software according to the current state of the display.

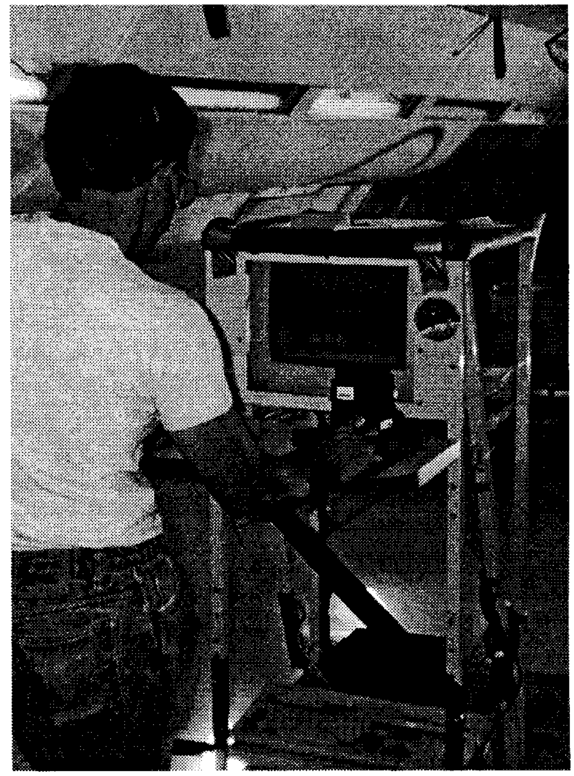

Figure 2: Experimental Setup

The random requests fall into three categories: move operations (click, double click, and release), dial reading, and sliding operations (icons, sliders). The proportion of each kind of operation was weighted to reflect actual operational use. During a test sequence (which consists in a sequence of 100 random requests), all the data resulting from the operator's actions is automatically logged to file.

Each operator was asked to perform the following tasks **on the ground**:

Demonstration: 45 minutes of familiarisation under supervision.

Training: Individual practice with each device (including Pantograph with and without haptic feedback) for a series of a hundred requests.

Testing: Three testing sequences (100 requests) with the trackball and the Pantograph with and without haptic feedback.

In addition, the four flight operators were asked to repeat two testing sequences (with the Pantograph and

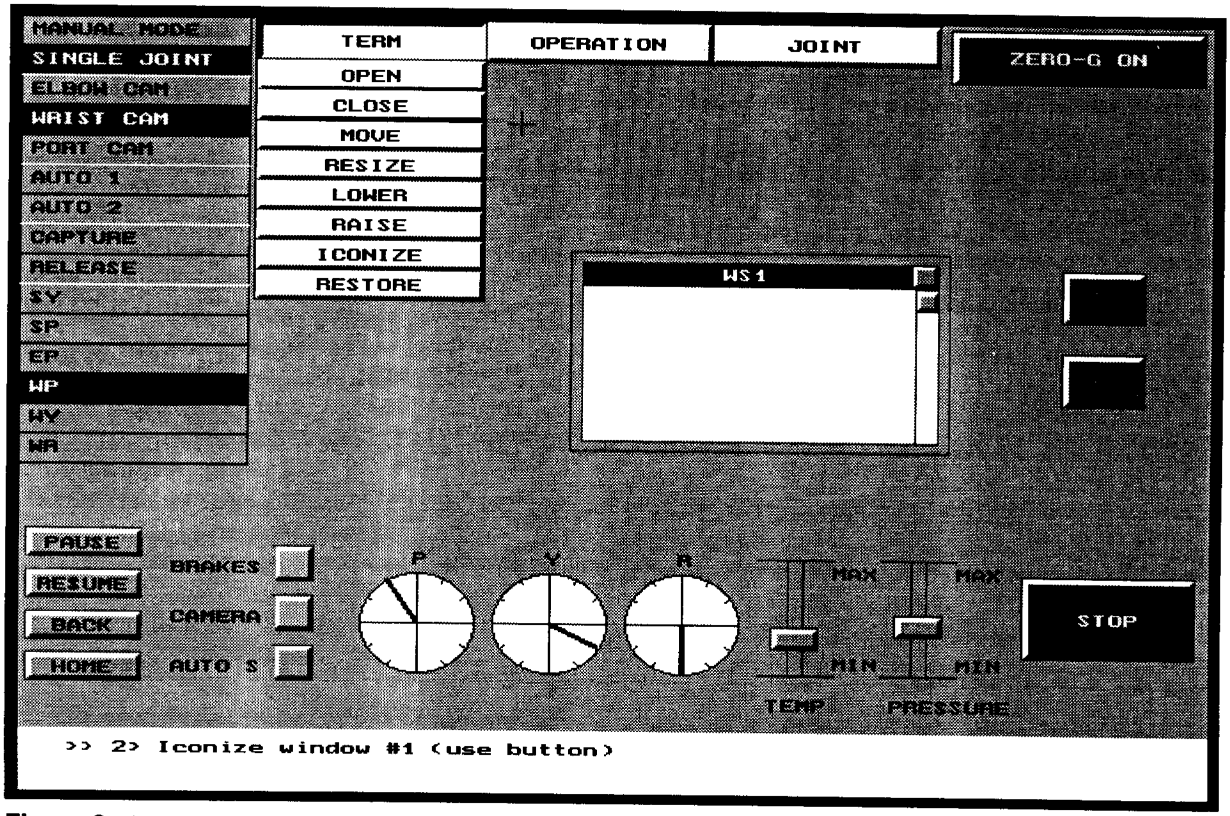

Figure 3: Graphical User Interface Display

with the trackball) in reduced gravity.[2] To minimize the effect of learning, operators were submitted to extensive training. Learning effects were further minimized by varying the order of testing of devices both on the ground and in flight according to a Latin square pattern.

5. RESULTS

5.1 Relative Device Performance

On average, task execution time is shorter in absence of gravity than on the ground ($p < 0.01$). On average again, user performance is better with the Pantograph and haptic feedback than with the Trackball ($p < 0.01$). On the ground, the performance improvement of the Pantograph with haptic feedback is slight, however, in absence of gravity the performance improvement is very significant ($p < 0.005$): the performance improvement is 15.8 percent.

[2] Due to flight time constraints, the tests with the Pantograph without haptic feedback could not be carried out in reduced gravity.

Device	Gravity	Zero gravity
Pantograph	2838	2274
Trackball	2868	2634

Table 1: Average operation execution speed (in milliseconds) with four operators in normal and zero gravity.

5.2 Effect of Haptic Feedback on Task Execution Speed (Ground only)

To determine if the origin of performance increase is due to the ergonomics and mechanical properties of the Pantograph or to the presence of haptic feedback, the same series of tests were carried on the ground comparing three modes: the trackball, the Pantograph, and the Pantograph without haptic feedback. Again, the results indicate a significant improvement of performance with the Pantograph as compared to the trackball (9.3%), but the presence or not of haptic feedback does not lead to any significant difference. See Table 2.

Pantograph with haptic feedback	2360
Trackball	2580
Pantograph without feedback	2310

Table 2: Average operation execution speed (in milliseconds) for 17 operators in normal gravity.

5.3 Error Rate Performance in Zero gravity vs Normal Gravity

We compared the error rate performance for the Pantograph and the trackball. These numbers were obtained from the data produced by the four flight operators tested both on the ground and in flight. Generally speaking, errors are due to confusions (e.g. picking the wrong item in a menu, selecting the wrong icon, misreading of the prompt), pointing accuracy (e.g. missing a small button), or judgement inaccuracies (e.g. misreading of a dial). In normal gravity, the global error rate is 7.5% while in zero gravity it is 9.7%. The device has an influence on the error rate. On the ground, the trackball leads to a smaller error rate than the Pantograph while in flight the opposite occurs. The difference is quite significant since the error rate is almost divided by two. See Table 3. In normal gravity conditions, similar results were obtained for the remainder of the seventeen operators which did not fly: the trackball led to 33% fewer errors.

Device	Gravity	Zero gravity
Pantograph	9.22%	7.13%
Trackball	6.16%	12.4%

Table 3: Percent error rate with four operators in normal gravity and in zero gravity.

5.4 Evaluation of Comfort

All seventeen operators who have participated in the experiments, either in flight or on the ground, felt comfortable with the Pantograph and found it easy to use. Only two reported muscular fatigue. In contrast, only eight (47%) felt comfortable with the Trackball, nine (53%) found it easy to use, and ten (59%) reported muscular fatigue. More specifically, the four flight operators reported that the Pantograph was "*easier to use*" and "*more useful*" than the trackball. In contrast, among the thirteen operators of the ground experiments, only seven thought that the Pantograph with haptic feedback would be easier to use than the trackball; one thought the opposite and five were undecided.

6. DISCUSSION

The data shows that the use of a haptic device such as the Pantograph to operate graphical user interfaces may increase performance in a significant proportion, both from the view point of task execution speed and error rate. There are many factors which could be invoked to explain this result, ranging from sensory substitution (as in the case of visually handicapped persons) to ergonomic reasons, due, for example, to the absolute nature of the Pantograph used as a pointing device. The trackball is a relative device, so it is possible that this property becomes significantly detrimental in the absence of gravity, which affects the operators' notion of spatial reference (and may induce overshoot problems). Cursor movement traces have been recorded for both the trackball and the Pantograph during this experiment. This trace data is currently being analysed and will be the subject of an upcoming publication.

It is important to note that regardless of the device, the performance speed is greater during the reduced gravity flights than on the ground. This may be attributed to the time pressure experienced by operators in flight, when they feel compelled to complete their task during short periods of 25 seconds (concentration levels seemed higher in flight, as it was observed on the video recordings of the experiments). Nevertheless, the performance increase is much larger, and thus significant, for the Pantograph (25%) than it is for the trackball (9%). As far as the error rate is concerned, we have a reverse situation on the ground, with the trackball showing better pointing accuracy. The poor performance of the haptic feedback on the ground may be explained by the fact that the interface was tuned for what we thought would be optimal in reduced gravity. The results could certainly be improved by tuning specific to working conditions. Similarly, an optimization of the haptic rendering algorithms should be specific for each application and working condition. To date, these last two questions are very much open research topics.

The trackball was chosen as a comparison device in this experiment primarily because it is currently the proposed cursor pointing device for the workstations that will be used aboard International Space Station[3]. Other (non-feedback) absolute devices such as

[3] International Space Station is a multinational collaborative project to build a permanent laboratory in space. Construction is to begin in December 1997.

touchscreen and pen-based systems have recently been tested in similar conditions of reduced gravity [7]. Results of these experiments, similar in part to those obtained here for the trackball, have shown that operators took more time and made more errors in zero gravity than on the ground. It was also found that the touchscreen led to more errors, especially during precise pointing tasks. Moreover, when constant touch pressure was required for tasks, such as when drawing or dragging, both hand and foot restraints were necessary to hold the operator in place and allow him to complete the task. In comparison, the Pantograph with haptic feedback was the only device tested that showed overall performance improvement (speed, error rate and comfort) in zero gravity.

Finally, it is interesting to note that the operators' opinions of the haptic feedback are divided in normal conditions, while in reduced gravity, the consensus is unanimous regarding an increased satisfaction.

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