HAPTIC COMMUNICATION FOR REMOTE MOBILE MANIPULATOR ROBOT OPERATIONS

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ABSTRACT

Teleoperations in hazardous environments are often hampered by the lack of available information regarding the state of the remote robotic device. Typically, ideal camera placements are not possible, and an operator is left with the problem of performing complex manoeuvres in the presence of severe ‘blind-spots’. A telerobotic approach can be adopted that allows a robot to detect and avoid environment collisions automatically, however while this simplifies the task for an operator, total robot autonomy is inadvisable in safety critical applications. At all times an operator must be in total control, yet the remote robot must be allowed to perform its local problem solving autonomously. To address this dilemma, we have been investigating the use of a haptic interface which not only allows an operator to communicate motion commands to a robot, but also allows the robot to communicate to the operator its motion when performing autonomous collision avoidance. This haptic communication thus providing total operator control, plus vital information that can be used to decide if and how a robot’s autonomous operation should be overridden. This paper details our work in this area and presents the results we have obtained from operator/task performance experimentation with this new haptic communication method.

1. Introduction

Hazardous environment operations such as nuclear plant decommissioning or terrorist bomb disposal typically require the use of a remotely operated mobile manipulator vehicle. Visual information concerning the vehicle and its environment is essential if a remote operator is to successfully achieve a given task. However, ideal camera placements within such environments are not always possible and in most cases, an operator has to depend upon the information provided by a single camera mounted on the vehicle. This provides a very restricted ‘window’ onto the vehicle and its environment and a number of ‘blind-spots’ exist. The lack of visual information when operating in cluttered environments makes vehicle manoeuvring very difficult, and when this situation is exacerbated by strict time limits for task completion, then vehicle/environment collisions and resultant damage can occur.

To counter the problem of limited visual information, we have been investigating the application of haptic communication. An Immersion Corp. Impulse Engine 2000 haptic joystick has been used that can be programmed to simulate a wide variety of force sensations. An operator can generate x, y motion commands from the joystick whilst feeling appropriately synthesised haptic sensations via the joystick handle. We realised that this bi-directional exchange of information could be used as a low band width communications method, thus allowing an operator to control a remote robotic device, whilst receiving information regarding the robot as it encounters objects with its environment. Furthermore, we also realised that haptic communication could be used not only for standard teleoperation tasks, but also for those applications requiring a telerobotic approach. It has long been recognised that the cognitive loading placed upon an operator could be alleviated if a remote robot was equipped with appropriate sensors and was allowed to make its own local decisions regarding problems such as collision detection and avoidance. However, while in principle this may appear desirable, for safety critical applications, total robot autonomy is inadvisable. It can be very disconcerting for an operator to realise suddenly that a robot is apparently ignoring his instructions and instead executing its own set of commands!

An operator must be in total control at all times, hence a telerobotic approach is preferable to total robot autonomy. However, the problem remains of how to communicate to a remote operator exactly what the semi-autonomous robot is doing so that its behaviour can be overridden, as and when required. We realised that haptic communication may be of use in this area, and we have conducted a number of telerobotic experiments using the haptic joystick.

This paper details our work in the areas of teleoperation and telerobotics, with and without haptic feedback to the operator, and the results we have obtained from operator/task performance experiments are presented.

2. Hypotheses

Based upon our investigations into previous haptic research [1,2,3], and our prior experience of teleoperations and autonomous robot control, [4,5,6] a number of related hypotheses were proposed:
1) *If haptic feedback was present during a teleoperation task, then improved operator performance would be obtained.*
2) *If a telerobotics approach was adopted, as opposed to teleoperations, then further improved operator performance would be obtained.*
3) *If haptic feedback was present during a telerobotics task, then even greater operator performance improvements would be obtained.*

To test these hypotheses, a number of experiments were devised, and these are described as follows:

3. Experimental Apparatus

The haptic joystick used for the experiments was an Immersion Corp. Impulse Engine 2000, which is a two degrees of freedom device. It uses a local processor to read buttons and encoders, and to control two DC motors which generate the desired haptic sensation. The processor also provides high level communications to a PC via an ISAbus card. For our experiments, the joystick was programmed to generate ‘spring’ sensations, each with a spring constant *k* that could be assigned to a particular robot sensor input. The haptic device can thus be visualised as a system containing four virtual springs, see Fig. 1, and *k* and the null position for each spring were dynamically adjusted in proportion to the sensed distance of the robot to an object. The resultant haptic sensation was one of pushing against a stiffening spring, as the robot got closer to an obstacle.

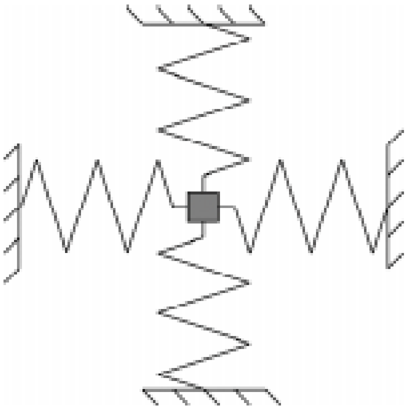

Fig. 1. Haptic joystick model. Plan view.

The robot in our experiments was a simulated Cybermotion K2A with a Puma 560 manipulator mounted on top. PC software was developed which contained a mathematical model of the Cybermotion K2A and its environment. The visual output of the simulation was provided by a Silicon Graphics (SG) workstation running the Deneb Telegrip modelling and simulation software. Fig 2. shows a screen dump of the Cybermotion K2A with the attached Puma 560. (Future research into mobile manipulators will use the Puma 560, however, these experiments were focused solely upon the motion of the K2A). The SG software was responsible for handling the PC/SG communications, and passing the data to Telegrip. Communications between the PC and the SG were via serial RS232. Fig. 3 shows an overview of the experimental apparatus.

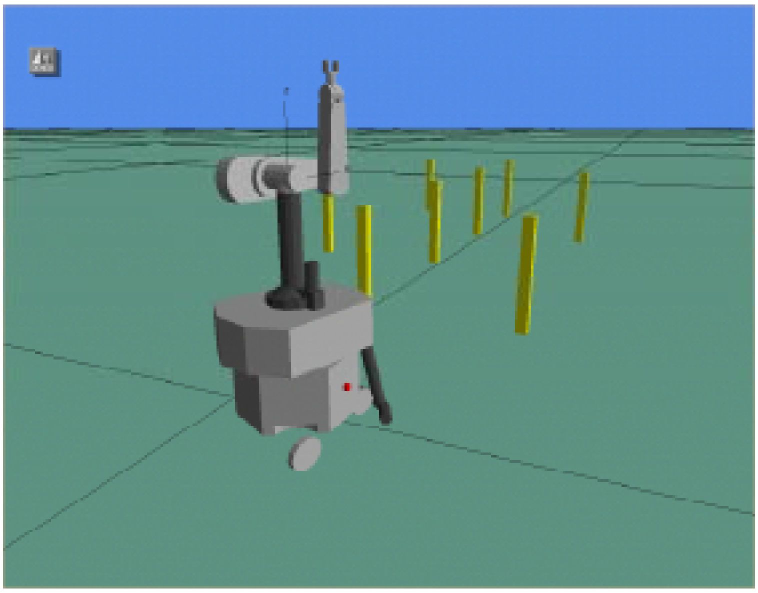

Fig. 2. Telegrip screen dump showing the K2A and attached Puma 560.

The telerobotics experiments required that the K2A vehicle possess obstacle detection and avoidance capabilities. A behavioural control approach was adopted, and while many such architectures exist [7, 8], we opted for the Behaviour Synthesis Architecture (BSA) [9, 6]. This was developed to address the problems of behaviour conflict resolution, behaviour adaptation and behaviour scheduling and is based upon the assignment of utilities to sensor/response functions called *behaviour patterns* (**bp's**). The BSA has been demonstrated to work well for real mobile robots and is a simple architecture to implement. Fig. 4 shows an example of a behaviour pattern. Here the *sensory stimulus* is a forward facing proximity sensor, and *utility* and *response* functions have been chosen so that as the robot gets closer to an obstacle, the motion value decreases, thus decreasing the forward velocity of the vehicle. At the same time, the utility (or importance) of this motion increases. Thus as the robot gets nearer to an obstacle the more important it becomes to slow the robot down. The response and utility values form a *utilitor* and should a situation arise where competing utilitors are generated, these can be resolved by simple vector addition. For these experiments, a proximity sensor system was simulated which generated K2A to obstacle distance and direction data. Behaviour patterns were chosen that reduced the forward velocity of the robot as it approached an object, and turned the robot in a direction away from the detected object. Thus implementing a simple obstacle detection and avoidance capability.

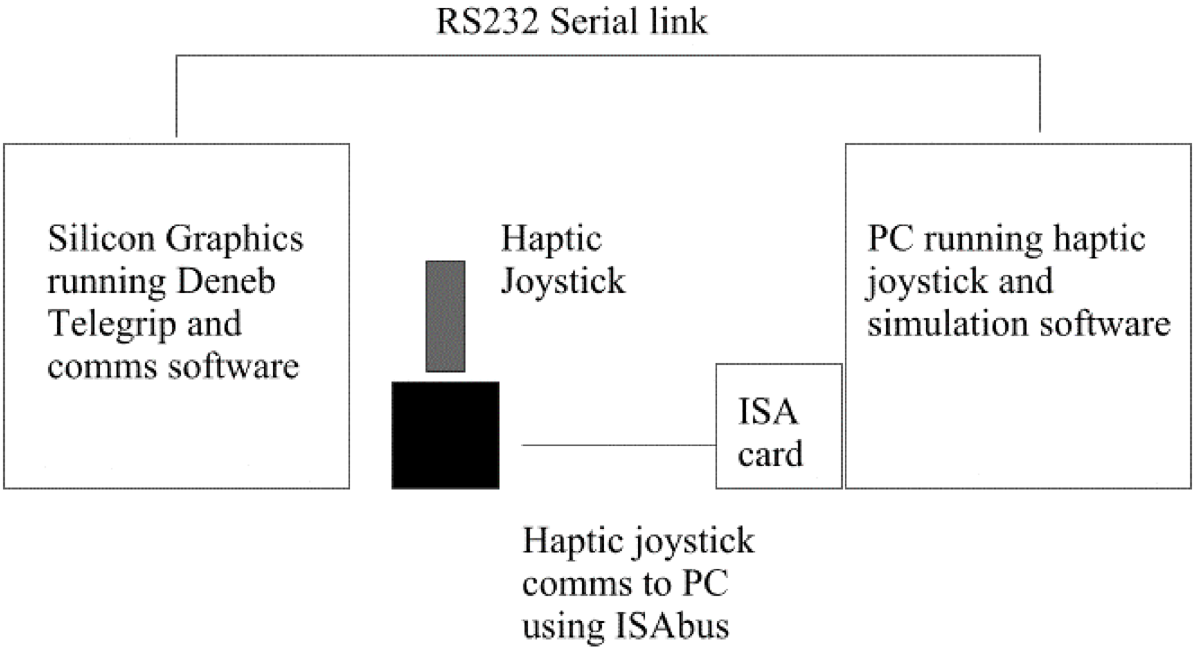

Fig. 3 Experimental apparatus overview

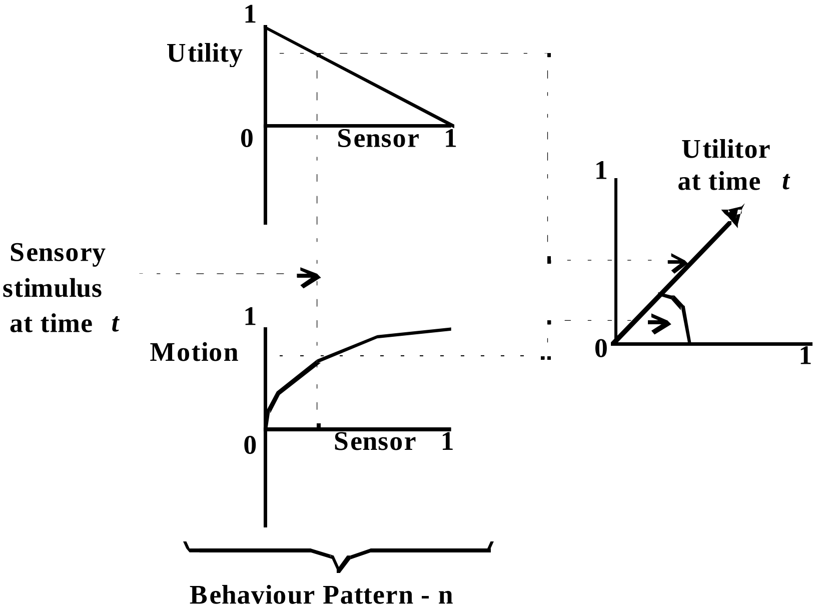

Fig. 4. Behaviour Pattern example.

4. Experimental Procedure

In a series of experiments with ten different operators, five modes of teleoperation/telerobotics were tested, some with and some without haptic communication. As can be seen from Fig. 2, the exercise was to successfully manoeuvre the K2A vehicle through an obstacle course which comprised pairs of posts (gates) arranged in a slalom fashion. Operator performance measurements were based upon the total number of collisions with the posts, the total distance travelled through the course and the total time taken to negotiate the course. A 'camera' view similar that shown in Fig. 2 was used throughout. Each operator was allowed two minutes to familiarise themselves with driving the K2A using the joystick interface, and with the correct route through the slalom course. The five modes are described as follows:

A. Mode 0: Teleoperation without haptic feedback

In this mode, the operator was in total control of the K2A at all times. There was no haptic feedback and hence an operator had to rely entirely on visual information to manoeuvre the K2A through the slalom course. The forwards and rotational velocities of the K2A were proportional to the displacement of the joystick. The joystick spring constants, *k*, were set to a small value simply to allow the joystick to return to a centre position and hence provide the operator with the sensation that they were using a standard passive joystick.

B. Mode 1: Teleoperation with haptic feedback

As with mode 0 the operator was in total control of the K2A at all times. However, unlike mode 0 the joystick spring constants, *k*, were dynamic. In addition to the available visual information, haptic data was communicated to the operator in the form of forces that intuitively conveyed information regarding the K2A's environment. Beyond a preset sensor range the joystick behaved as a regular passive device, as in mode 0. Within this preset range, the joystick provided an operator's hand with force sensations that conveyed when motion in a particular direction was likely to cause a collision. The generated x and y haptic force data were inversely proportional to the range d, and the orientation θ, of the K2A relative to a sensed obstacle. Hence $Force_x \propto 1/(d.\sin\theta)$ and $Force_y \propto 1/(d.\cos\theta)$. Mode 1 can be regarded as a primitive type of *telepresence*.

C. Mode 2: Telerobotics without haptic feedback

This mode introduced a semi-autonomous capability to the K2A, which provided a simple collision avoidance behaviour. The BSA synthesised an operator’s joystick generated forward and rotational velocity commands (implemented as **bp’s**), with appropriate obstacle avoidance **bp’s**, to produce a resultant forward and rotational motion for the K2A. As the vehicle approached an obstacle, the utilities associated with an operator’s command **bp’s** were decreased, whilst those utilities associated with the collision avoidance **bp’s** were increased. Hence as the K2A was commanded by an operator to move closer to a post, in a manor that may have caused a collision, control was dynamically moved away from the operator and greater control was given to the K2A’s autonomous capability. Thus preventing an operator from colliding the K2A with an obstacle. Once past a potential collision situation, control was dynamically returned to the operator. This mode had no joystick haptic feedback, and was similar to using a standard passive joystick device.

D. Mode3: Telerobotics with obstacle haptic feedback

As with mode 2, this mode provided autonomous collision detection and avoidance. However, it also provided haptic feedback to an operator in the same manner as mode 1. The major difference of this mode as compared to mode 2, was that as the K2A solved it local collision avoidance problems, the operator was able to *‘feel’ what the K2A was sensing* within its environment. Thus allowing an operator to experience the presence of a post, and hence infer as to why the K2A was responding in a particular manner, even when such an obstacle was out of the camera’s field of view.

E. Mode 4: Telerobotics with collision avoidance haptic feedback

As with modes 2 and 3, this mode incorporated the K2A autonomous collision avoidance behaviour. However, the generated haptic sensation was considerably different. Instead of an operator being able to ‘feel’ what the K2A was sensing, an operator was provided with force feedback relative to the resultant motion generated by the BSA. This was achieved by feeding the velocity and rotational velocity components from the collision avoidance behaviour, back to the joystick as an updated centre position. Thus, in addition to the operator driving the K2A via the movement of the joystick, the K2A was also able to drive the joystick in a way that conveyed its motions to the operator. Hence an operator was able to *‘feel’ what the K2A was doing*. This mode can be regarded as bi-directional haptic communication as an operator had to impart forces onto the joystick, so as to communicate desired motion to the K2A, meanwhile, the K2A also generated forces onto the joystick so as to communicate to the operator its actual motion.

5. Results

The run time between the first and last gate, total distance travelled and total number of collisions were recorded for each operator when conducting each mode. These results were averaged for the ten operators and are presented as follows:

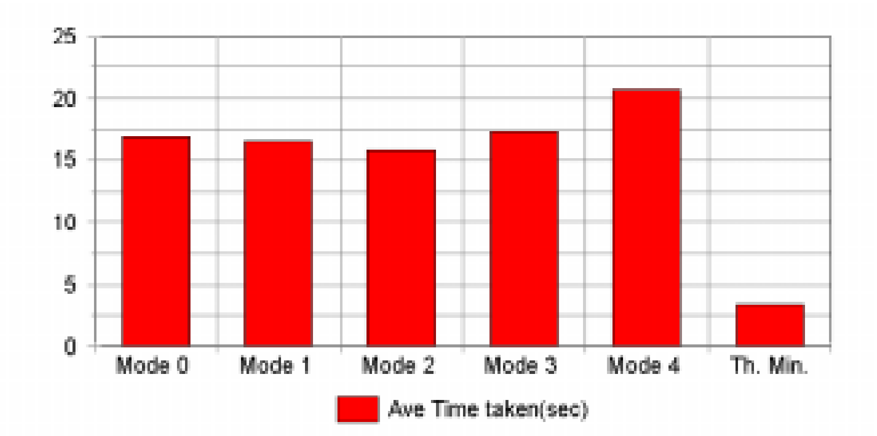

Fig. 5. Bar chart of average time taken.

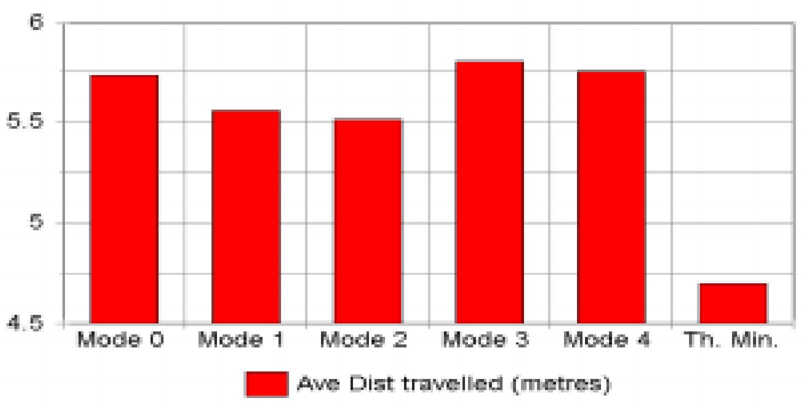

Fig. 6. Bar chart of average distance travelled.

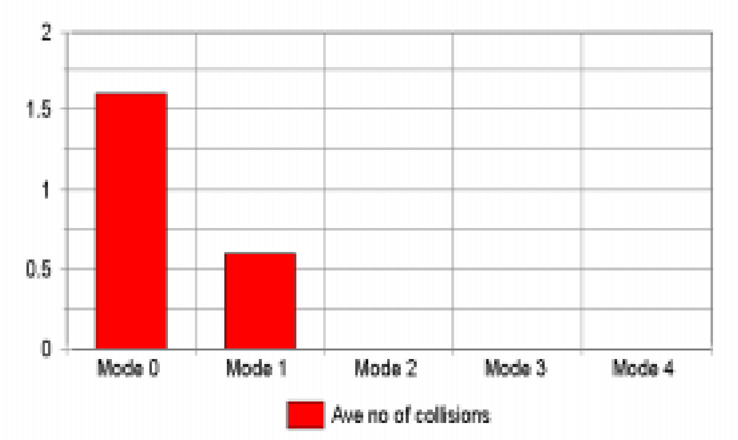

Fig. 7. Bar chart of average number of collisions.

6. Discussion

Given the operator performance measurements chosen for our set of experiments, we were looking for the mode(s) that yielded the minimum number of collisions, time taken, and distance travelled. Fig. 7 clearly shows that for the teleoperation modes 0 and 1, collisions did occur. Whilst the haptic feedback of mode 1 greatly improved the average number of collisions, an operator was still able to ignore this information and drive the K2A into one or more of the posts. The introduction of telerobotics, and the ability of the K2A to autonomously avoid a potential collision, meant that an operator was completely prevented from causing such an accident, no matter how careless a driver. Hence modes 2, 3 and 4 yielded no collisions.

From Figs. 5 and 6, one can see that for modes 0, 1 and 2, there is a gradual improvement in the average time taken and distance travelled. As mode 2 produced no collisions, one might conclude therefore that this mode generated the best operator performance. However, as stated in the introduction, a remote operator needs to know exactly what a semi-autonomous robot is doing so that if required, its behaviour can be overridden. Hence modes 3 and 4 are of particular interest. No collisions occurred during these modes, but there is definitely a ‘cost’, (greater time and distance as compared to modes 0, 1, and 2), when haptic feedback is introduced. It is interesting to note that there is a relatively small distance travelled difference (<1%) between modes 3 and 4, but the difference in time is noticeably greater (~19%). Clearly, mode 3 is better than mode 4 with respect to time taken. However, whilst the haptic feedback provides an operator with greater information regarding the K2A’s environment, and hence the knowledge that the K2A may be about to take some avoiding action, quite what this action will be is unknown until after the event has occurred. This situation may be satisfactory provided an operator has complete trust in the autonomous behaviour of the robot. Our experiments involved a very simple collision detection and avoidance behaviour, if a robot’s behaviour were made more complex for a given sensory input, then mode 3 may be less attractive. Mode 4 on the other hand, does inform an operator as to the motion of the K2A as it is occurring but, the operator has to rely upon any available camera information to appreciate why the K2A is executing this action.

It is interesting to note that when conducting the experiments, some operators preferred mode 3 whilst others preferred mode 4. We strongly suspect that the two minute familiarisation period was inadequate for these two modes, and operators will require a far greater training period for future experiments.

Figs. 5 and 6 also show the theoretical minimum for the time taken and the distance travelled. Note, theoretical does not necessarily mean practical or desirable as these figures are based upon the K2A travelling at its maximum velocity (0.75m/sec), whilst just skimming past the posts. However, these values do highlight the fact that even greater performance improvements are there to be made, and further investigations are required.

7. Conclusions

A number of experiments have been performed to test the hypotheses: 1) that teleoperation performance can be improved upon if haptic feedback is introduced, 2) telerobotics yields improved performance over teleoperation alone, and 3) telerobotics when combined with haptic feedback yields improved operator performance over that of telerobotics alone. Whilst the results obtained have substantiated hypotheses 1 and 2, hypothesis 3 has proved more illusive. When a remote robot is equipped with some autonomous behaviour, e.g. collision avoidance, then this telerobotic capability is extremely useful when manoeuvring the vehicle in a cluttered environment. In the absence of ideal camera placements, haptic communication can be used with good effect to augment the information available to an operator. However, when this communication method is combined with telerobotics, there are likely to be additional costs in terms of operator performance, e.g. a greater task completion time. Nevertheless improved safety is achieved, with zero collisions and greater information for the operator regarding the remote robot and its environment.

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