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Remote Control of Mobile Robot via Internet

Ulrich Nehmzow, Andreas Bühlmeier,
Holger Dürer and Manfred Nölte

Department of Computer Science

University of Manchester

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Remote Control of Mobile Robot via Internet*

Ulrich Nehmzow†
ulrich@cs.man.ac.uk

Andreas Bühlmeier‡
andreas@informatik.uni-bremen.de

Holger Dürer‡
duerer@uni-bremen.de

Manfred Nölte‡
mn@pc-labor.uni-bremen.de

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*Refereed by: Alan Murta

†University of Manchester / Department of Computer Science / Manchester M13 9PL / Great Britain
‡Universität Bremen / FB 3, Mathematik und Informatik / 28334 Bremen / Germany

Abstract

The paper describes experiments in telerobotics via low-bandwidth communication channels. A mobile robot with sonar and infrared range-finding sensors as well as tactile and proprioceptive sensors at Manchester University in the United Kingdom was controlled by three of the authors from Bremen University in Germany in real time, using low bandwidth internet communication facilities.

The experiments comprised remote surveying, fine motion control and object manipulation tasks. The purpose of the investigations was to determine whether remote access to robotics facilities can be achieved in this way (training and sharing of resoures), and whether the limited bandwidth of the internet is sufficient for more complex tasks than just crude motion control.

1 Introduction

Remote manipulation of objects has been an issue for centuries (blacksmiths' tongs, for example), and following the development of suitable technology the field has progressed from purely mechanical manipulators to more sophisticated master-slave manipulators, passing control signals from the master to the slave by means of electrical or pneumatic connections ([Vertut & Coiffet 85]).

Early interest in teleoperation concentrated solely on object manipulation (chiefly in the nuclear industry), and it was only in 1967 when remotely controlled mobile vehicles were used for exploration tasks (the Soviet Lunakod was used to explore the surface of the moon, see [Vertut & Coiffet 85]). In 1992 a remotely controlled legged robot explored Mount Erebus ([Wettergreen *et al.* 92]) and Mount Spur. Both these remotely controlled mobile robots used dedicated, high bandwidth communication links.

Such communication links are not always available, but it is usually easy to establish low-bandwidth communication to a control site (e.g. by serial link). If (expensive) robotics facilities are to be shared between sites, or if mobile robots are to be used at short notice (e.g. in disaster areas), such narrow channels may be the only means of telerobotic control available.

The paper presents telerobotics experiments in which a mobile robot was controlled via such a low bandwidth communication link, the internet. In this particular case, we faced not only the problem of low bandwidth communications, but also that of unpredictable delays. The purpose of the experiments was to establish

- whether telerobotics via a long-distance, low bandwidth internet connection is feasible,
- whether such a connection can be used for training purposes, i.e. to teach people to use the robot without physical access to the machine, and
- whether it is possible to achieve more complex tasks such as remote surveying, model building and object manipulation using range finding sensors, tactile sensors and wheel encoders only.

2 Experimental setup

"FortyTwo," (see figure 1) the robot used in the experiments, is a Nomad 200 mobile robot, equipped with 16 sonar and 16 infrared range-finding sensors spaced evenly along the perimeter of the robot, 20 tactile sensors and an odometric system that estimates the current position of the robot with reference to the starting location in the room. The resolution of the sonar sensors is 2.5 cm, with a maximum range of 10.5 m. The maximum range of the infrared sensors is approximately 50 cm. The resolution of the odometry sensors is 0.25 cm. A monochrome camera mounted on top of the robot was not used in these tests.

The experiments took place in an open area of about 8m by 4m in the Manchester robotics lab, the exact dimensions of the experimental arena are given in figure 2.

Whilst the progress of the experiment was being monitored by U.N. at Manchester, FortyTwo was controlled throughout the experiments from Bremen via internet remote login. At no time was the robot

Figure 1: *FortyTwo*, the Manchester mobile robot.

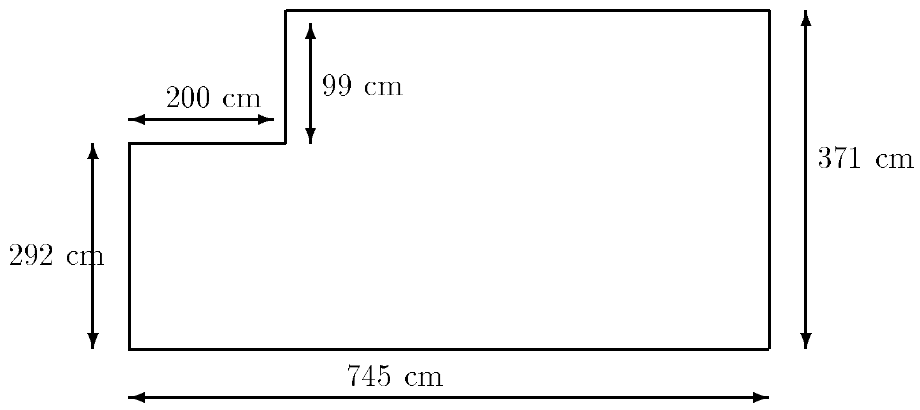

Figure 2: The laboratory's actual dimensions.

controlled by the Manchester side. Initial communication between the supervisors at the local end and the operators at the remote site was by telephone, later an internet teletype ("talk") connection was used instead (see also figure 3). Throughout all experiments this connection was exclusively used to specify global tasks (such as "find a doorway and traverse it"). Indications regarding success, failure, collisions etc. were not given.

At the time of the experiment, A.B., H.D. and M.N., who were controlling FortyTwo remotely, had no knowledge about the layout of the Manchester robotics lab, nor had they ever seen the robot before. They had, however, used the robot control interface shown in figure 4 for controlling a simulation of FortyTwo ([Nomad 93], and therefore knew the control mechanisms. There is, however, a notable difference between a robot simulated by the system and *FortyTwo*: simulated sensor signals are virtually free of noise, whilst real sensor signals are not (compare the main window of figure 4, which shows simulated sensor readings, with, for example, figure 8).

The X11-interface allows the user to switch between controlling the simulated and the real robot and shows current range readings obtained from the sonar and infrared sensors (see figure 4. Sonar readings are shown in the top right hand corner, infrared readings in the bottom right hand corner). These range

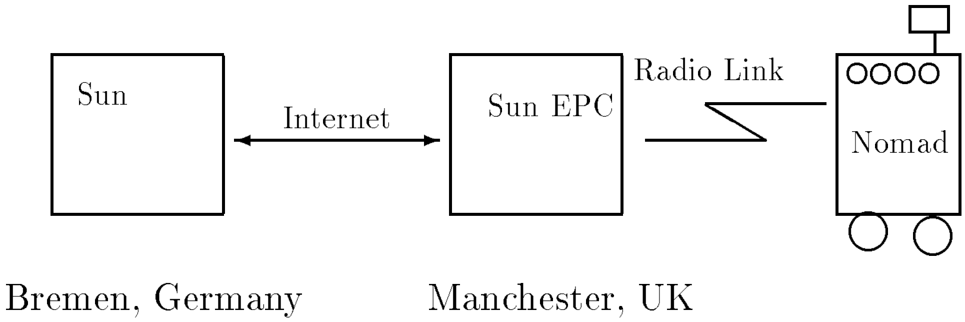

Figure 3: The experimental setup

values, together with the measured position of the robot obtained from the wheel encoders (see bottom of the main window in figure 4), is used to build a twodimensional floor plan of the robot's environment (see, for example, figure 5).

The robot is steered using the mouse of the controlling workstation.

3 Experiments and Results

3.1 Remote Surveying and Modelling

The first task was to survey the robotics laboratory at Manchester via the tele-operated robot. None of the operators at Bremen had ever been to Manchester before, nor had they been given any information about the room layout or starting position and orientation of the robot.

To obtain precise mappings of the environment, it is best to use short-range sensors. This is because the sensitivity cone of sensors introduces a localisation error proportional to range.

Using a wall following technique and superimposing the infrared range readings of FortyTwo, they obtained the image of the Manchester robotics laboratory shown in figure 5.

With the help of the wheel encoders of the robot, which measure the robot's current position in tenths of inches, they could use the obtained 2D floor plan to estimate the scale of display and thus draw the derived floor plan of the laboratory shown in figure 6. Comparing figures 2 and 6 shows that the qualitative result of the surveying experiment is correct. The dimensions estimated through remote exploration differ from the actual measurement by +1.5% to +15%.

In a second experiment the task was to negotiate and measure a maze which was set up for this purpose in Manchester. This was to investigate how detailed a structure could be surveyed remotely, and to what accuracy. Some of the passageways of the maze had a width of less than twice the robot's diameter.

Figure 7 (a-c) shows how the maze gradually appeared on the computer screen in Bremen[1]. Part d) displays the final floor plan of the maze estimated from these measurements. The general layout of this plan is correct apart from one corner which is shown hatched (from figure 7 a-c it can be seen that that particular corner did not show up very clearly on the infrared sensor readings). Actual dimensions are given in parentheses. The estimated dimensions of the maze differ from the actual dimensions by -7% to +15%.

3.2 Fine Motion Control

The next task was to find a door that had been opened and to steer FortyTwo through it. The door's width was less than twice the diameter of the robot. The goal of this experiment was to establish whether the range information obtained from sonar and infrared sensors is accurate enough for fine motion control.

[1] The "ghost" display of the robot is a marker that indicates the robot's initial position before entering the maze.

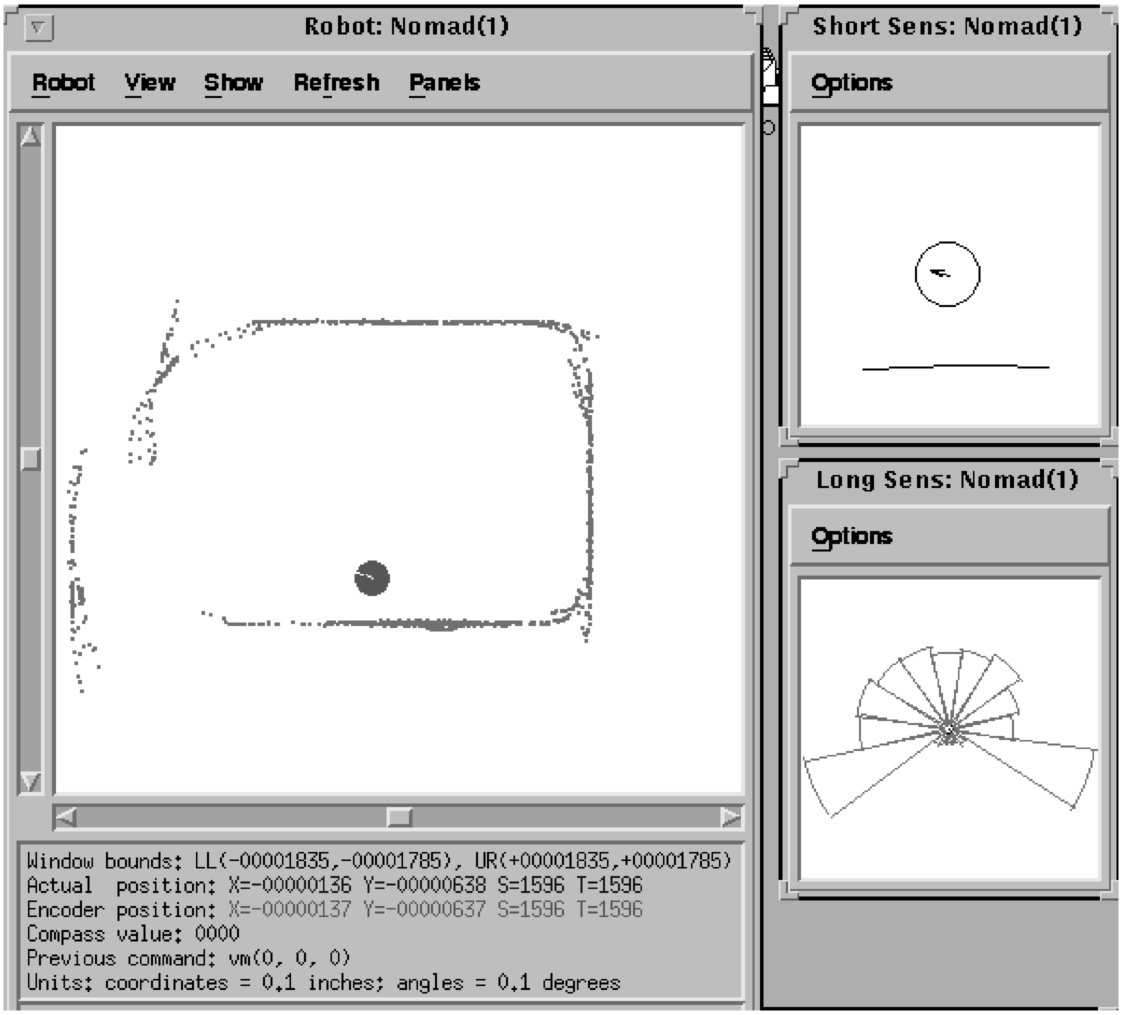

Figure 4: Telerobotic control screen.

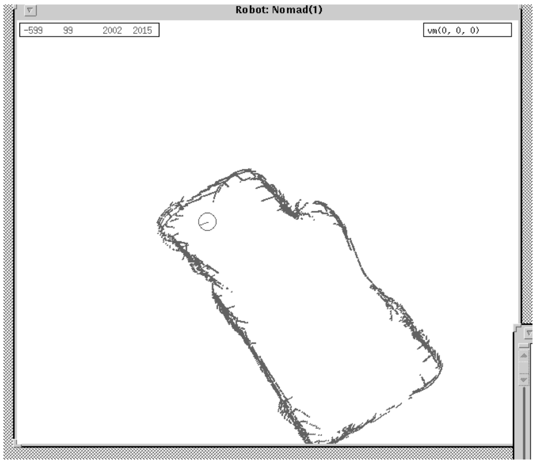

Figure 5: The laboratory as seen at the end of the exploratory experiment

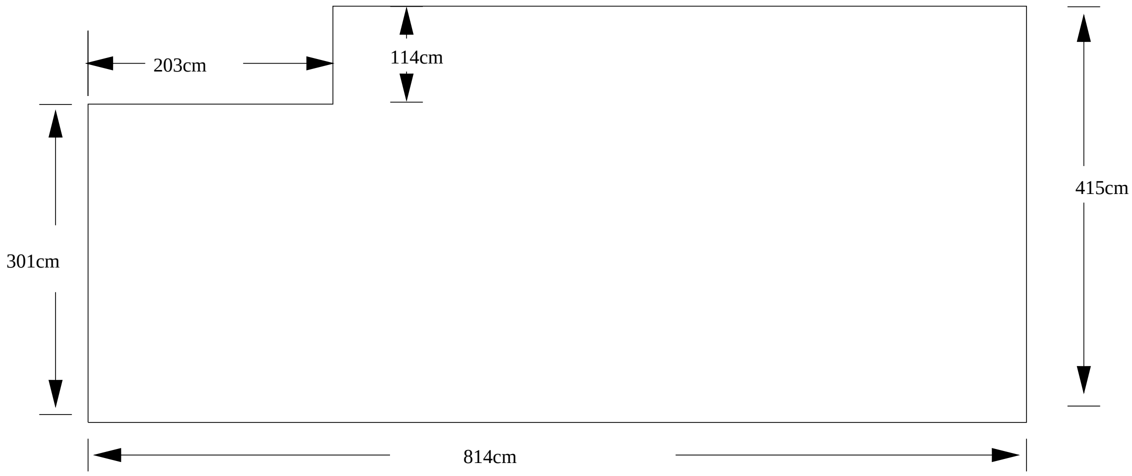

Figure 6: Estimated dimensions of the lab (compare with figure 2 and 5).

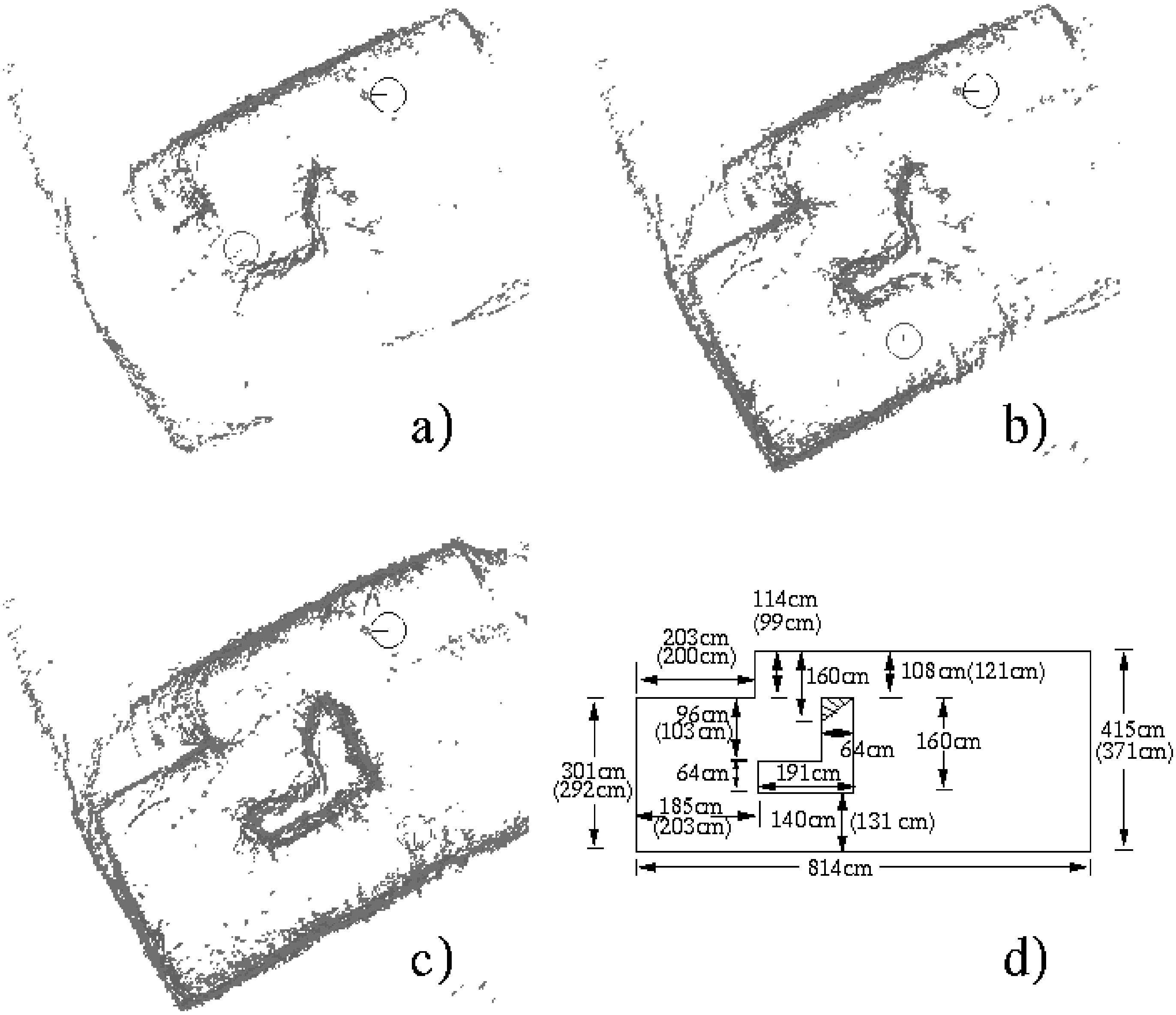

Figure 7: Sequence of screen shots as seen by the remote end while exploring the simple maze (a–c). Plan of derived measures and correct measures in brackets (d).

The task was performed three times without any problems, the robot moved accurately through the door into an adjacent workshop, and back into the robotics laboratory. The sensor perception that the researchers in Bremen saw on their screen after driving through the open door is shown in figure 8 (the opening is in the middle, the workshop on the right with a multitude of machines giving complex and unclear sensor readings).

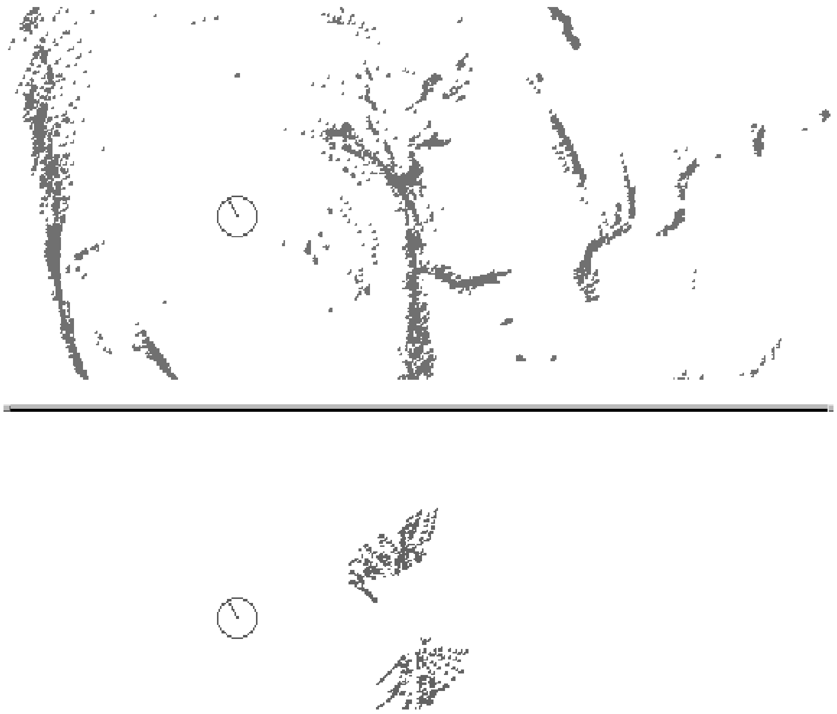

Figure 8: Sonar (top) and infrared readings (bottom) after having steered through a door.

Figure 8 shows clearly how sharp edges like doorposts act as sonar "beacons". In figure 8 the door is on the right hand side. That sonar data is strayed at sharp corners is visible in the top section of figure 8. In this experiment, detection of the open door was effectively only possible using the infrared sensors, with the sonar sensors merely giving additional cues.

3.3 Object Manipulation

The first object manipulation task was to find a box in the middle of the lab and push it to a specified location. There are two main difficulties in achieving this. Firstly, in order to push an object, the operator has to instruct the robot to go "through" an obstacle, having to make a decision as to whether the obstacle in question is pushable or not. Secondly, the robot's motion has to be planned carefully, because objects can only be pushed, not pulled. Figure 9a) depicts the accumulated view after some time of pushing, Figure 9b) show the view after clearing and exploring the world around the box, which can be seen to be pushed against the wall.

The experiment was successfully performed three times—the most difficult part was to determine the distance of the box from the wall. At the last stage, the controllers in Bremen pushed the box carefully against the wall until the robot's tactile sensors detected resistance. This situation is shown in figure 9b).

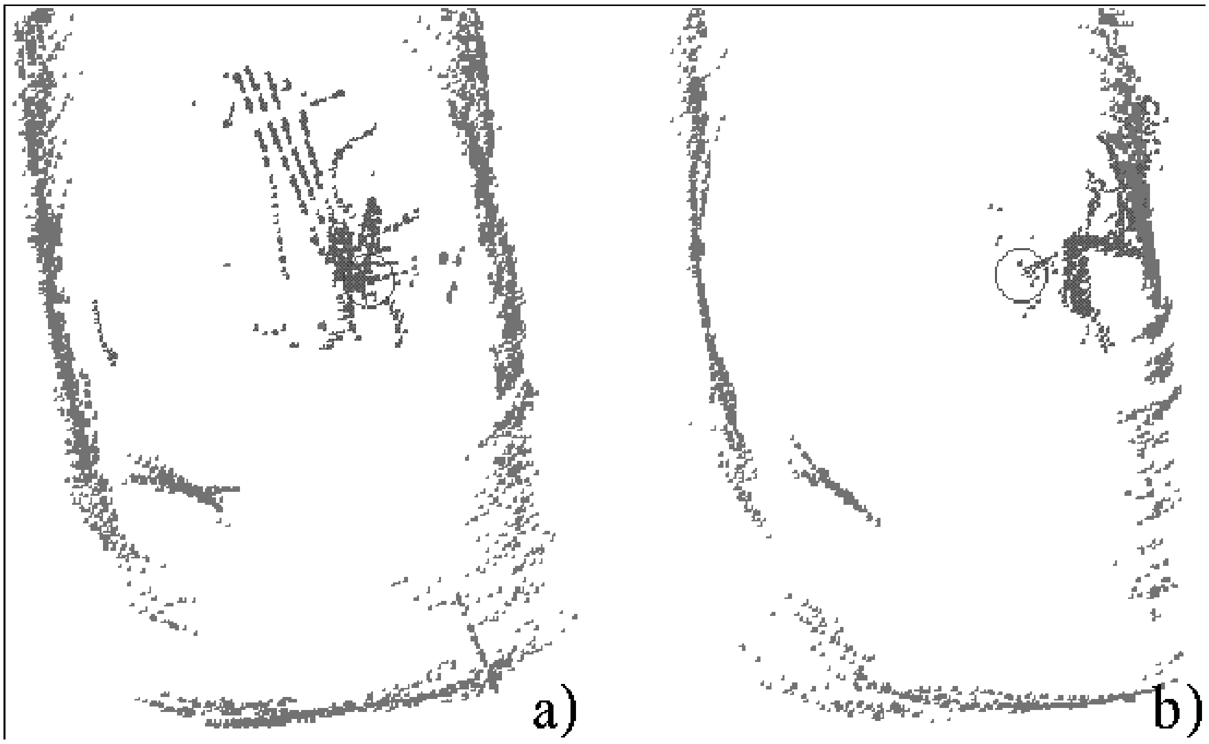

Figure 9: Pushing a box against a wall.

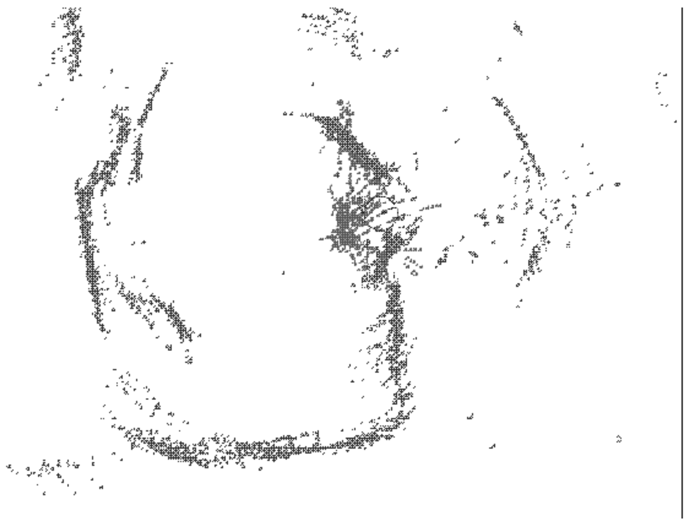

Figure 10: Box pushing through the opened door (pushing from left to right).

The final experiment was to push a box through a narrow doorway. This combines aspects of robot navigation and object manipulation, and is particularly difficult because the robot's sensors do not provide the operator with precise information as to whether the box is in the middle of a doorway, or askew, whether it is still on the threshold or already through the passage. Tactile information and odometry information are the most useful sources of information here. Figure 10 shows the box on the threshold.

This final task was successfully accomplished by using the odometry system for initial positioning of box and robot, and the tactile sensors and side-looking sonar and infrared sensors for monitoring the progress of the operation.

3.4 Network Communications

The number of packets sent from Manchester never exceeded 200 packets in every 5 second period, but was typically much lower. The number of packets received from Bremen was even lower than this, and in the worst case there were 4% collisions.

At 8 am German time, a time of low network traffic, delays did not affect control in a perceivable way. Later in the day (10 am) round trip delays up to 12 s (typically round trip delays were about 4 s at this time) made control difficult, but still possible. During periods of long communication delays the robot itself still moved smoothly, but the update of the control screen was delayed. This meant that effects of steering commands could only be monitored several seconds after they had happened. To counteract these delays, and to avoid possible collisions, slow robot movements had to be used, and a "move and wait" strategy had to be adopted. Nevertheless, control was possible and all tasks could be achieved, albeit very slowly.

4 Discussion

The experiments have shown that low bandwidth communication links can be used for basic surveying, exploration, navigation and object manipulation tasks. This makes possible remote access to robotics facilities as well as the extended use of mobile robots in exploration and transportation tasks.

In most telerobotic applications, communication line delays are the limiting factor. This applies to orbital space applications, where round trip delays are typically between 0.3s and 4s, as well as deep sea applications, where round trip delays can be as long as 10 minutes ([Sheridan 93]) in the case of cable-controlled submersibles.

Predictive control, local impedance control and wave transform techniques are ways to alleviate this problem [Sheridan 93].

Immersive sensor data visualization techniques (”virtual reality”) become counter-productive and confusing to the user if delays greater than 0.3s are encountered, particularly if the operator's body is displayed as well, because the natural correspondence between body movement and image motions is lost [Liu *et al.* 93]. We conclude that immersive techniques are unsuitable for applications where long delays are encountered (like internet communications). However, graphical display methods giving a third party view can be used successfully, as our experiments show.

Our experiments have shown that even in extreme delay situations visualization methods without body representation can still successfully be used for robot control. The map available to the operator is of central importance here, because it enables the operator to assess the robot's current position with respect to mapped obstacles, and to decide whether a “move and wait” strategy has to be adopted, or whether it is safe to move the robot continuously despite line delays.

For us it was encouraging to have established that a range of tasks can be solved via a general purpose link mechanism subject to line delays, such as the internet. Since then, we have successfully used this facility for remote training of robot operators. Apart from facilitating access to robotics facilities in this way, operators gain experience in dealing with communication line delays. Such delays influence, for instance, remote operations of space exploration robots.

4.1 Further Work

Ongoing research at Manchester investigates the use of *learning* controllers in telerobotic applications. Experiments have already been conducted in which FortyTwo acquires sensor-motor competences through remote control, and uses these skills to move autonomously, with only occasional interference by the operator (see [Nehmzow 92, Nehmzow 95] regarding the controller used for these experiments).

A second area of investigation is to add further sensor modalities to the telerobotics control system. In particular, we intend to use the robot's visual sensor for this purpose. Using image processing and data compression techniques such as edge detection and chain coding, the operator will be able to inspect particular objects visually. We do not intend to use the camera for real time control of the robot.

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