COMPARING ABILITY TO COMPLETE SIMPLE TELE-OPERATED RESCUE OR MAINTENANCE MOBILE ROBOT TASKS WITH AND WITHOUT A SENSOR SYSTEM.

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COMPARING ABILITY TO COMPLETE SIMPLE TELE-OPERATED RESCUE OR MAINTENANCE MOBILE ROBOT TASKS WITH AND WITHOUT A SENSOR SYSTEM.

Structured Abstract

Purpose: The effect on completion of mobile-robot tasks is investigated depending on how a human tele-operator interacts with a sensor system and a mobile-robot.

Design/methodology/approach: Interaction is investigated using two mobile-robot systems, three different ways of interacting with the robots and several different environments of increasing complexity. In each case, the operation is investigated with and without sensor systems to assist an operator to move a robot through narrower and narrower gaps and in completing progressively more complicated driving tasks. Tele-operators used a joystick and either watched the robot while operating it, or sat at a computer and viewed scenes remotely on a screen. Cameras were either mounted on the robot to view the space ahead of the robot or mounted remotely so that they viewed both the environment and robot. Every test was compared with sensor systems engaged and with them disconnected.

Findings: A main conclusion is that human tele-operators perform better without the assistance of sensor systems in simple environments and in those cases it may be better to switch off the sensor systems or reduce their effect. In addition, tele-operators sometimes performed better with a camera mounted on the robot compared with pre-mounted cameras observing the environment (but that depended on tasks being performed).

Research limitations/implications: Tele-operators completed tests both with and without sensors. One robot system used an Umbilical Cable and one used a radio link.

Practical implications: The paper quantifies the difference between tele-operation control and sensor assisted control when a robot passes through narrow passages. This could be useful information when system designers decide if a system should be tel-operated, automatic or sensor-assisted. The paper suggests that in simple environments then the amount of sensor support should be small but in more complicated environments then more sensor support needs to be provided.

Originality/value: The paper investigates the effect of completing mobile-robot tasks depending on whether a human tele-operator uses a sensor system or not and how they interact with the sensor system and the mobile-robot. The paper presents the results from investigations using two mobile-robot systems, three different ways of interacting with the robots and several different environments of increasing complexity. The change in the ability of a human operator to complete progressively more complicated driving tasks with and without a sensor system is presented and the human tele-operators performed better without the assistance of sensor systems in simple environments.

***Keywords**: tele-operation, mobile robot, sensor, ultra-sonic.*

1. INTRODUCTION

This paper investigates the effect on completing tele-operated tasks depending on the way in which a human operator interacts with a mobile-robot and whether a sensor system is connected to assist them. That interaction is investigated using two tele-operated mobile-robot systems, three different ways of interacting with mobile-robots and several different environments. One mobile-robot system used an Umbilical Cable and one used a radio transmitter and receiver. An ultrasonic sensor system could be installed to assist tele-operators.

Tele-operators were observed completing a series of tasks using a joystick to control a mobile-robot. Tele-operators either watched the mobile-robot while they were operating it, or they sat at a computer screen and viewed the mobile-robot on a screen display. Cameras were either mounted on the robot or so that they could view both the environment and the robot. In each case the tele-operators completed tests both with and without the sensor system.

A main conclusion is that in simple environments, a tele-operator may perform better without a sensor system to assist them but in more complicated environments then a tele-operator may perform better with a sensor system to assist. A secondary conclusion is that tele-operators may tend to perform better with a radio link than with an umbilical connection because umbilical cables can affect the steering of the mobile-robot.

2. BACKGROUND

Mobile-robots and unmanned vehicles are being increasingly used (and considered for future use) in nuclear plants [1,2], for search and rescue [3-8], surveillance [9], security [10] and inspection [11,12].

Although wheeled vehicles find it difficult to move freely over some terrain, wheeled mechanisms are still the main mechanisms for moving over ground [13] and they are considered in this paper.

In some environments, materials handling must be carried out remotely, and tele-operated handling systems can keep operators at a safe distance from hazardous material and reduce costs associated with human work [14].

Tele-operation and sensors have been well used for a variety of applications [15, 16] and the real challenge in unstructured and difficult environments such as hazardous areas is primarily for mobile-robots [17, 18].

Tele-operated mobile-robots are generally directed along a path using manual controls and the master system has often been a joystick [19-20] although other input devices are available, for example a pointer [21, 22], switches [23] or can be custom built such as Virtual Reality interfaces [24] and other more complex systems are being considered [25]. Generally they are fitted with controllers that interface low current input devices to high current servo amplifiers, sometimes remotely through a radio connection or umbilical cable.

Much research has aimed to improve tele-operation and robotics for inspection and maintenance in hazardous or unpleasant environments [18], or in places where conventional techniques require cost intensive supporting infrastructures [26-31].

For many applications, mobile-robots may not need autonomous control [32]. Instead a human operator may help a mobile-robot to explore environments. Other tasks may be best achieved with a wheeled base [33, 34] and on-board manipulator(s) [35]. This research is timely because many nuclear power plants are coming to the end of their service and decommissioning plans are being formulated [36]; nuclear facilities are aging and many will close in the next two decades [37].

The way in which a human operator interacts with a mobile-robot can affect efficiency, and time-critical operations in emergencies require especially efficient human-machine interaction. This paper investigates that interaction using tele-operated mobile-robot systems.

Systems have tended to be open loop. Users have indicated a direction and the mobile-robot then moved in the required direction. Common disturbances include differences in mobile-robot wheels or tractors or their different reaction to surfaces and surface or gradient [38]. Users have been left to react to disturbances and correct trajectories.

Tele-operating systems are described in [39 - 41]. Automatic guided vehicles (AGVs) are described in [42] and standardisation in mobile-robotics is described in [43]. They are included here for reference and wider reading. Current challenges being faced in tele-operation are described in [44] and some seminal publications are by Sheridan [45, 46].

3. THE MOBILE ROBOT SYSTEMS

Sonar sensors are simple and have been widely used for mobile-robots [47] and ultrasonic ranging was selected, as it was simple and robust. A human user guided the tele-operated mobile-robot (sometimes also using a camera mounted on the mobile-robot and at other times using a camera to observe the local environment). Ultrasonic transmitter and receiver pairs could be mounted at the front of the mobile-robot. With suitable processing the ultrasonic signals were converted to a simple representation of the environment. An integral function was used with joystick signals so that the tendency to turn when approaching an object could be over-ruled by the user, for example to align properly with another gap beyond the first.

The apparatus consisted of a dedicated controller with analogue interfacing, DC servo-amplifiers and joystick, and a BobCat II base was modified to include the control and sensor systems. Two driven wheels were at the front and two trailing castors at the back. A camera could be mounted between the driving wheels and ultrasonic sensor pairs could be mounted over each driving wheel. Altering the differential of rotational speed of the driving wheels affected steering.

Software algorithms to intelligently mix the inputs to the tele-operated vehicle were described in [48] and the mobile-robot was driven under computer control by "fly-by-wire". The system is described in [49].

3.1 Mobile-robot with an umbilical cable

The direct link between the mobile-robot and joystick was severed and a computer processed control information. Sensors were activated and interrogated by the computer and the computer was programmed to modify the mobile-robot path. Alternatively, joystick control data could be processed and sent to the mobile-robot controller without modification. In this case the mobile-robot responded to joystick inputs as if it was an unmodified mobile-robot system. Software systems were constructed using methods discussed in [50-56]. Systems had three main levels: supervisory, strategic and servo control. These were similar to the levels described in [57-59].

Algorithms applied the following rules:

- The user remained in overall control.
- Systems only modified the trajectory of the mobile-robot when necessary.
- Movements of the mobile-robot were smooth and controlled.

An imaginary potential field was generated around objects by the computer in response to information supplied by the sensor system [60]. These algorithms assisted users if the mobile-robot was approaching an object and could collide.

3.2 Mobile-robot system with a radio link

A second test rig used a radio link instead of an umbilical cable. Most apparatus was re-used (mobile-robot base, sensor system, joystick, micro-computer, dedicated controller with analogue interfacing, DC servo-amplifiers, joystick and camera mounted between the driving wheels). The umbilical cable was replaced by a radio link and the parallel interface was replaced with a serial interface.

Wireless signals have low energy and can therefore be safer on some environments, and wireless is especially useful where relative motion is involved [61], as is the case here.

EMC testing was conducted with the radio link to avoid frequencies that might interfere with the controller, sensors and cameras. Once an operator had safely tested the new prototype mobile-robot system with the radio link then the cable link between the mobile-robot and the joystick was severed and the computer processed all the control information.

4. TESTING

Mobile-robot systems were tested in a laboratory and then in a variety of environments. The longest test runs were limited to just under 30 metres by the lengths of the umbilical cables used. The cables were up to 15 meters long and that allowed a distance of 15 metres out and back. Users quickly learned how the mobile-robot responded and learned to apply control signals earlier and to estimate stopping distance.

A set of early tests were conducted to gauge the reaction of users to the system and capture potential improvements to the operation and interfacing. These are described in [3, 4, 49]. Once the prototype systems were complete then the main tests were conducted to:

- Observe the operation of the system under joint computer and human control.
- Measure the minimum gaps that human tele-operators were able to move through by themselves and then again with the assistance of sensor systems.

- Measure time taken by human tele-operators by themselves and then again with the assistance of sensor systems as gaps were slowly reduced in width.
- Measure the improvement (if any) of the assistive systems.

For each course, up to twelve sets of tests took place (four sets of three tests). For each mobile-robot, three sets of tests took place without the sensor system or any automatic assistance. Then the three tests were repeated with the sensor system engaged and assistance provided by the computer system: The form of the three tests were:

- Tele-operator watching the mobile-robot and just using the joystick.
- Tele-operator watching the space ahead of the mobile-robot using a camera mounted on the mobile-robot.
- Tele-operator watching the general area of the robot through a camera viewing the robot within the environment.

For each test, a standard obstacle course was set up in an environment. The environments are described in [3,4 49].

Tele-operators were human beings and as such they were variable in their performance and so where possible, for each of the series of tests, the tele-operators were allowed to repeat tests (with or without computers assisting them) as many times as they liked, or hours available allowed. That allowed them to learn the systems and to perform at their best in the time available. Testing was regarded as fun by participants and was popular. Competition was encouraged and people tried to beat their best in each test and tried to beat others at the same tests. In several cases, some people only managed to complete a test with the sensor system or only managed to complete a test without the sensors and their results were discarded so that comparisons were only made between the same tele-operators.

The first set of tests used the umbilical cable and was conducted to compare the ability of human tele-operators to move through a set course with gaps between obstacles set at a width of 88 cm. That was 8 cm wider than the mobile-robot (4 cm at each side). This was compared with computer-assisted operation in a series of standard environments. If a smaller gap was achieved by any participant in one set of the tests then they made at least one attempt again at the other test to check that the result was not just due to learning the operation of the systems. If they then managed to get the robot to pass through smaller gaps then they made at least one attempt at the original test. Tests began at a pre-determined and constant start-position (and from a standing start) and widths were measured by two researchers using a ruler and a measure. Only successful attempts were recorded. That is, any attempt that resulted in a collision was discarded. If too few sets of results were recorded or if there were no pairs of results then results for that environment were discarded. A second set of tests was then conducted but using a radio link instead of an umbilical cable.

Figures 1 shows a tele-operator navigating through one of the complicated corridors (with some obstacles) and using the ultrasonic sensor system to assist in steering.

Figure 1 *Tele-operator navigating through one of the complicated corridors using the ultrasonic sensor system to assist in steering.*

Figure 2 shows another tele-operator in a laboratory controlling the robot using an Ethernet connection to an outside wall and then an umbilical cable to control the robot. A camera is observing the environment and the robot and displaying the scene on a computer screen. The tele-operator is using the joystick to guide the robot.

Figure 2 *A tele-operator in a laboratory controlling the robot through an umbilical cable with a camera set up to observe the environment and the robot.*

Figure 3 shows the robot moving though a complicated corridor and being controlled via a radio connection. The tele-operator in a laboratory is being assisted by the sensor system on the mobile-robot.

Figure 3 *Radio controlled robot moving though a complicated corridor assisted by the sensor system on the mobile-robot.*

Figure 4 shows another tele-operator in a laboratory and using a radio connection to control the robot. A camera is mounted on the robot and is observing the scene ahead and displaying the scene on a computer screen. The tele-operator is using the joystick to guide the robot through an outdoor course.

Figure 4 *A tele-operator in a laboratory controlling the mobile-robot through a radio link using a camera mounted between the driving wheels.*

Figure 5 shows a tele-operator guiding the robot though a complicated outdoor environment with different flat and sloping surfaces bounded by different vertical and sloping edges.

Figure 5 *A tele-operator guiding the robot around a corner at the bottom of a slope at the start of a complicated outdoor environment.*

Figure 6 shows the mobile-robot moving though the same complicated outdoor environment and being controlled via an umbilical cable. The tele-operator in a laboratory is being assisted by the sensor system on the mobile-robot.

Figure 6 *View observed by a tele-operator in a laboratory from an external camera while driving the robot though a complicated outdoor environment using an umbilical cable and assisted by the sensor system.*

5. RESULTS

The mobile-robot successfully negotiated obstacles in various set courses during testing. Assistive computer systems allowed automatic recovery from collision courses. Some chaotic factors existed. For example, trailing casters could throw the mobile-robot off-line and variation in floor surface, slope or wheel position could affect results.

5.1 Computer and sensor assistive systems.

Figure 7 shows the times taken for a mobile robot with an umbilical cable to complete various set courses while the tele-operators watched the mobile robot. The vertical scale is the time taken in seconds to complete tests. In the simple environments (shown on the left of the graph; laboratory and empty corridors), tele-operators completed tasks more quickly without any aid from the sensor systems. In the more complicated environments (shown on the right of the graph; complicated corridor and outside), tele-operators completed tasks more quickly with the aid of computer and sensor systems. That form of results was repeated when a camera was mounted onto the mobile-robot, when a camera was mounted in the environment so that the mobile-robot and the environment were visible to the user on a computer screen and in all cases when using a radio link instead.

***Figure 7** Time taken in seconds to complete tests when the tele-operators were watching the mobile-robot. The bars on the left are without the sensors and the bars on the right are with the sensor system activated.*

As the gaps between obstacles on the courses were reduced (by 0.5 cm each time) then the smallest gap achieved by each tele-operator was recorded. As expected, tele-operators consistently managed to complete set courses with smaller gaps when they were using the sensor system. That form of the results was repeated in all of the environments and the results for the system using the umbilical cable are displayed graphically in figures 8 to 10.

***Figure 8** Results from tests with the umbilical cable when the tele-operator was watching the mobile robot pass through smaller and smaller gaps (Y axis in cm). The bars on the left are without the sensors and the bars on the right are with the sensor system activated.*

***Figure 9** Results from tests with the umbilical cable when the camera was mounted on the mobile-robot and the robot was passing through smaller and smaller gaps (in cm). The bars on the left are without the sensors and the bars on the right are with the sensor system activated.*

***Figure 10** Results from tests with the umbilical cable when the camera was viewing the mobile-robot and the robot was passing through smaller and smaller gaps (Y axis in cm). The bars on the left are without the sensors and the bars on the right are with the sensor system activated.*

The form of the results was repeated again when the umbilical cable was replaced with a radio link. Figure 11 shows an example of the results when the camera was mounted on the mobile-robot.

***Figure 11** Results from tests with the radio link passing through smaller and smaller gaps (in cm) when the camera was mounted on the mobile-robot. The bars on the left are without the sensors and the bars on the right are with the sensor system activated.*

As the environments became more complicated (or the gaps were made smaller) then the human operators found it more difficult to judge the width of the gaps or the successful trajectory of the mobile-robot to pass through those gaps. The human tele-operators had to rely more and more on the sensor systems and figures 12 to 14 show some examples of the general average improvement.

Human tele-operators consistently passed through smaller gaps when being assisted by the sensors and computer systems. Different surfaces, slopes and boundaries tended to turn robots and that was when the sensors became most useful. The automated systems managed to consistently correct the trajectory of the mobile-robot to a repeatable standard.

Results became more pronounced as human operators were removed from immersion within the situation and environment. Human operators performed best when they could see the mobile-robot and could move around the environment or move with the robot. When human tele-operators were restricted to using a camera mounted on the mobile-robot and observing via a computer screen then results were significantly slower without the assistance of sensor systems. With their assistance the results were more similar (although still worse as human tele-operators were more cautious with the joystick).

When human tele-operators were made to control the mobile-robot via a camera watching both the robot and environment then they found passing though gaps more difficult. With the assistance of sensor systems then mobile-robots could successfully pass through smaller gaps faster (providing the human tele-operator had lined up the mobile-robot sufficiently).

In the environments tested, tele-operators tended to perform better with the radio link compared to the umbilical cable. Figures 12 to 14 show some examples of the results from testing in the various environments (with and without the assistance of the computer and sensor systems). In almost every case, tele-operators performed better with the computer systems.

Figure 12 *Results from testing in the laboratory as the robot passed through smaller and smaller gaps (in cm). The bars on the left are using an umbilical cable (without sensors on the left) and the bars on the right are using a radio link (without the sensor system on the left and with the sensors on the far right). The group of bars on the left were observing the robot, the group in the middle was with a camera mounted on the robot, and the group on the right was with a camera mounted to observe the robot and the environment.*

Figure 13 *Results from testing in complicated corridor 2 as the robot passed through smaller and smaller gaps (in cm). The results were recorded when using an umbilical cable (without sensors on the left and with the sensors on the right). (NB – only one set of results was available here as the radio system was not repeatable)*

Figure 14 *Results from testing in a complicated corridor as the robot passed through smaller and smaller gaps (in cm). The bars on the left are using an umbilical cable (without sensors on the left) and the bars on the right are using a radio link (without the sensor system on the left and with the sensors on the far right). The group of bars on the left were observing the robot and the group on the right was with a camera mounted to observe the robot and the environment.*
(NB –results were not available for the camera mounted n the robot as the radio system was not repeatable)

5.2 Average times taken to complete courses with the narrowest gaps

As the gaps between obstacles on the courses were reduced, the fastest times taken to complete the courses were recorded for each tele-operator.

Figures 15 to 19 show some of the average times taken to complete the courses with the smallest gap width (both with and without the sensor systems). Lines marked with crosses are with the sensor systems engaged and the lines marked with diamonds are without any sensor systems.

In this case, as the gaps were reduced in width, then initially the tele-operators completed the courses more quickly without the sensor systems engaged and as the gaps became smaller then the tele-operators competed the tests more quickly with the sensor systems engaged.

Figures 15 and 16 show some times taken in the laboratory. Figures 17 and 18 show some average times taken in the first simple corridor and figure 19 shows some average times taken in the second simple corridor.

Figure 15 *Times taken in the laboratory (in seconds) for a tele-operator watching the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.*

Figure 16 *Times taken in the laboratory for a tele-operator with a camera viewing the environment and the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.*

__Figure 17__ Times taken in Simple Corridor 1 for a tele-operator watching the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.
(NB – only one set of results was available here as the radio system was not repeatable)

__Figure 18__ Times taken in Simple Corridor 1 for a tele-operator with a camera viewing the environment and the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.

__Figure 19__ Times taken in Simple Corridor 2 for a tele-operator with a camera mounted on the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.

6. DISCUSSION AND CONCLUSIONS

Hardware and software performed adequately for the mobile-robot tests but some technical discussion is included in [49]. The joystick interface and simulation worked well and provided no problems during the tests. The radio link caused problems when a mobile transmitter was used.

The Student's t-test was used to compare means of samples. From each sample, the average (mean) $\bar{x}$ was calculated with a measure of dispersion (range of variation) of data around the sample mean (variance S^2) and thence the standard deviation (S). Having obtained those values, they were then used to estimate population mean μ and variance σ^2.

Not all of the individual sets of tests were statistically significant so that caution was required before generalising the results.

Because pairs of tests and results took place, then it was possible to use a paired-samples statistical test. Results were arranged into two sets of replicate data; pairs of results with and without sensor assistance for each tele-operator. The paired samples test was used because people (tele-operators) were inherently variable. Pairing removed much of that random variability. When results were analysed using a paired-samples statistical test then results were statistically significant. The paired-samples statistical test shows the use without a sensor system and with a sensor system to be significantly different at $p < 0.05$ (95% probability that this result would not occur by chance alone).

A main conclusion is that in simple environments, tele-operators performed faster without a sensor system to assist them but in more complicated environments then tele-operators performed faster with a sensor system to assist them. In these cases, human tele-operators drove robots quickly through wide gaps and observed the situation and made adjustments in plenty of time, without reducing speed. As that was not a finding that was originally being directly tested, tests were effectively 'blind'; investigator(s) and tele-operators did not know the effect being observed before data were analysed.

Results show that with wide gaps between obstacles or in simple environments then human tele-operators consistently performed set tasks more quickly without any assistance from the computer systems and sensors. As gaps between obstacles were reduced or environments became more complicated then human operators could not judge gap widths or the successful trajectory of the mobile-robot to pass through those gaps. Tele-operators often had to slow the robot or stop the mobile-robot and reverse it to avoid collision. When the environment became more complicated then tele-operators consistently performed better with the assistance of the sensors and computer systems. Results tended to become more pronounced as human operators were removed from immersion within the situation and viewed the situation on display screens.

A secondary conclusion is that tele-operators tended to perform better with a radio link than with an umbilical connection because the umbilical connection sometimes affected mobile-robot steering (especially when reversing or when mobile-robots turned back on themselves). These results were not always statistically significant because the difference was sometimes small and not enough testing was completed but the difference did occur in almost all data pairs. Radio connection had the advantage of being more manoeuvrable but electronics in a mobile-robot working in a nuclear plant need to survive in radiation. An umbilical cable can have advantages over a radio connection in a radiation environment as it can also be used to assist in extracting a mobile-robot if key electronic components fail.

Tele-operators sometimes performed better with a camera mounted on the robot and looking ahead compared with pre-mounted cameras observing robots and environment but that type of result appeared to depend on the specific task.

Although not statistically significant because of a small sample size, it appeared that older tele-operators generally performed tasks more slowly than younger tele-operators and they were less able to direct the mobile-robot through the smaller gaps.

Human operators performed best when they could see the mobile-robot and could move around the environment or move with the robot; results became more pronounced as tele-operators were removed from immersion within the situation. When the human tele-operators used a camera mounted on the mobile-robot and observed via a computer screen then results were worse without the assistance of the sensor systems. With their assistance, results were more similar (although still worse as human tele-operators were more cautious with the joystick).

When a robot turned back on itself during a task (for example changing from coming towards the camera to moving away from the camera) then joystick controls effectively reversed as the camera still viewed the robot and environment from the same place. Tele-operators found that difficult and that effect appears to have accounted for at least some of the difference. At these times then the sensor systems were especially helpful.

7 FUTURE WORK

Results from the work need to be investigated more fully. Further statistical analysis could take place using the existing paired-samples but further testing would make data more accurate. Future work should further test the main conclusion that in simple environments, tele-operators tend to perform faster without a sensor system to assist them. Different robots and sensor systems need to be tested.

The advantages and disadvantages of including safety control strategies need to be further investigated and these (and the sensor systems) could be switched in and out by the tele-operator. Joysticks could be replaced by haptic devices so that tele-operators could feel a back-force generated by the signal from the sensor sub-system. That way distance feedback could be provided through the joystick. These will be investigated with automatic programming [61-64] and Artificial Neural Networks [65].

The secondary conclusion that tele-operators may tend to perform better with a radio link than with an umbilical connection needs to be tested further because results in this study were not always statistically significant.

As human operators performed best when they could see the mobile-robot and move around the environment, future tests might include cameras that could swivel or multiple sets of cameras providing more than one view; for example a view ahead of the mobile-robot and a view of the robot and the environment.

More effective control of the mobile-robot could be achieved if more information about the environment was available, especially in tight spaces. Infra-red could be a simple and suitable medium for a short-range sensor system. With more information available for analysis, the central processor could have tighter control of robot movements.

[**4,300 words reduced from 5,400 words**]

Figure 1 Tele-operator navigating through one of the complicated corridors using the ultrasonic sensor system to assist in steering.

Figure 2 A tele-operator in a laboratory controlling the robot through an umbilical cable with a camera set up to observe the environment and the robot.

Figure 3 Radio controlled robot moving though a complicated corridor assisted by the sensor system on the mobile-robot.

Figure 4 A tele-operator in a laboratory controlling the mobile-robot through a radio link using a camera mounted between the driving wheels.

Figure 5 A tele-operator guiding the robot around a corner at the bottom of a slope at the start of a complicated outdoor environment.

Figure 6 View observed by a tele-operator in a laboratory from an external camera while driving the robot though a complicated outdoor environment using an umbilical cable and assisted by the sensor system.

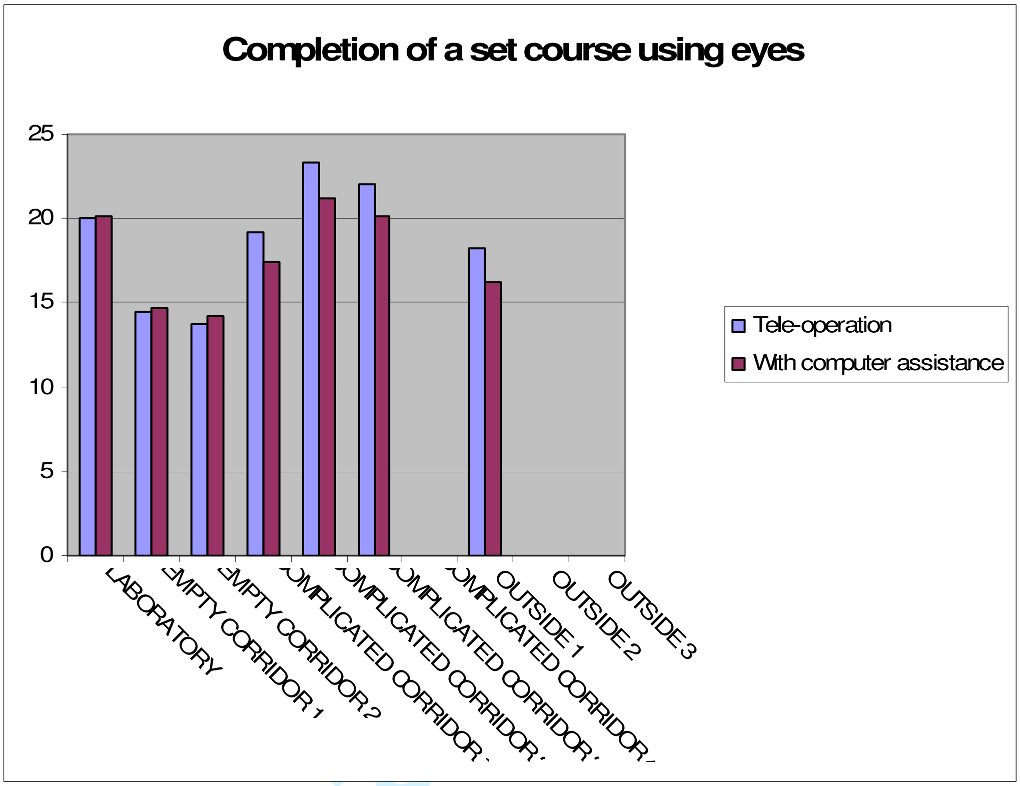

Figure 7 Time taken in seconds to complete tests when the tele-operators were watching the mobile-robot. The bars on the left are without the sensors and the bars on the right are with the sensor system activated.

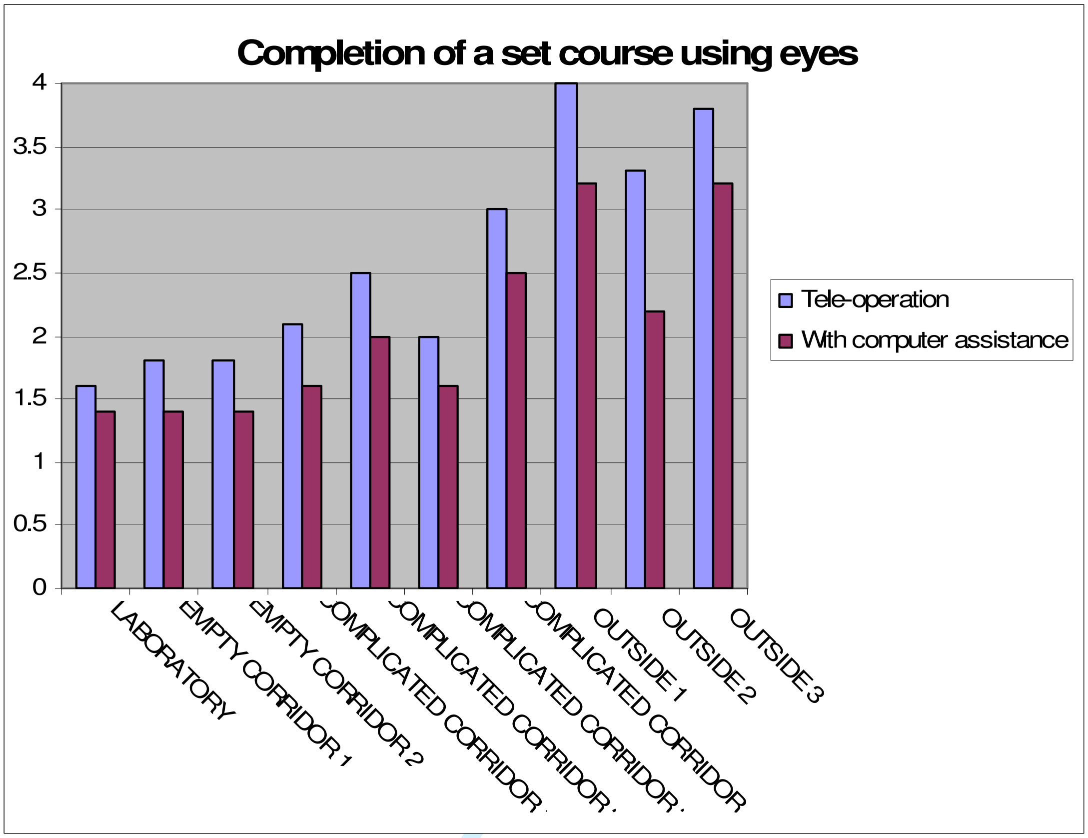

Figure 8 Results from tests with the umbilical cable when the tele-operator was watching the mobile robot pass through smaller and smaller gaps (Y axis in cm). The bars on the left are without the sensors and the bars on the right are with the sensor system activated.

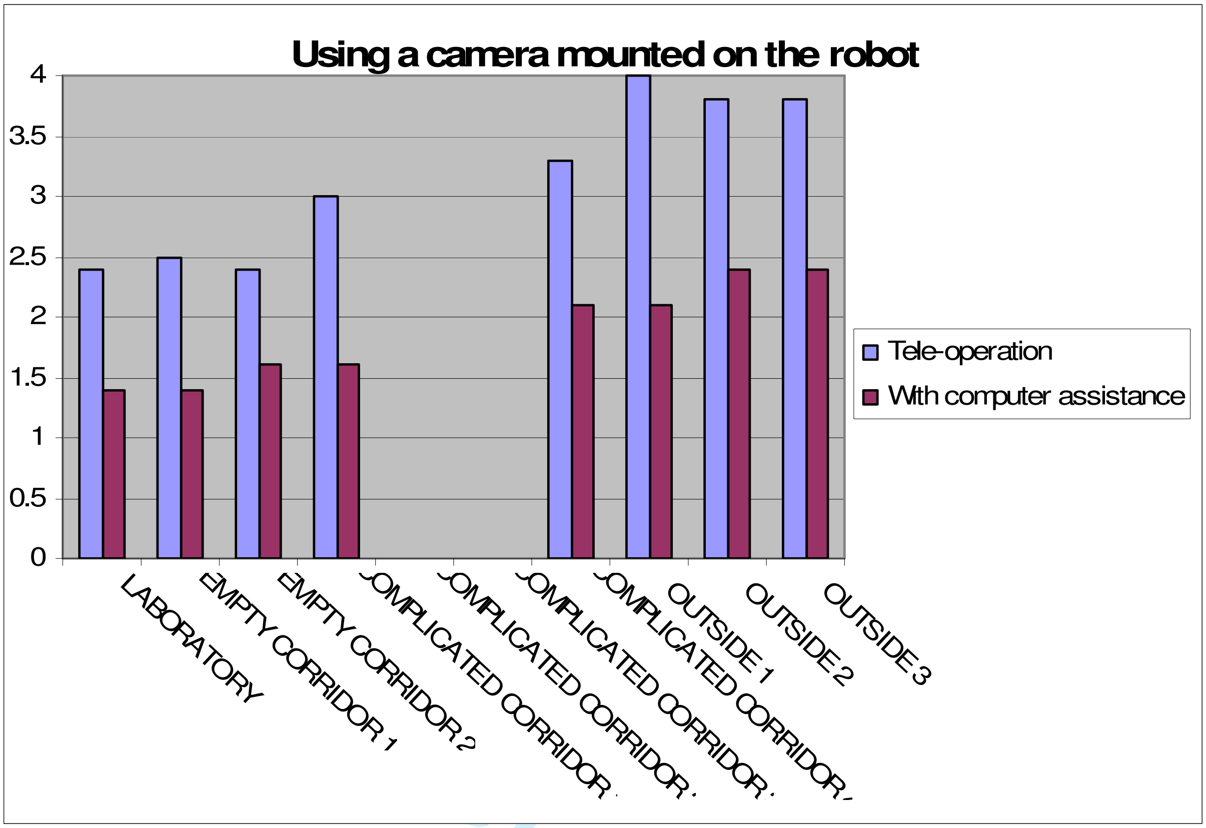

Figure 9 Results from tests with the umbilical cable when the camera was mounted on the mobile-robot and the robot was passing through smaller and smaller gaps (in cm). The bars on the left are without the sensors and the bars on the right are with the sensor system activated.

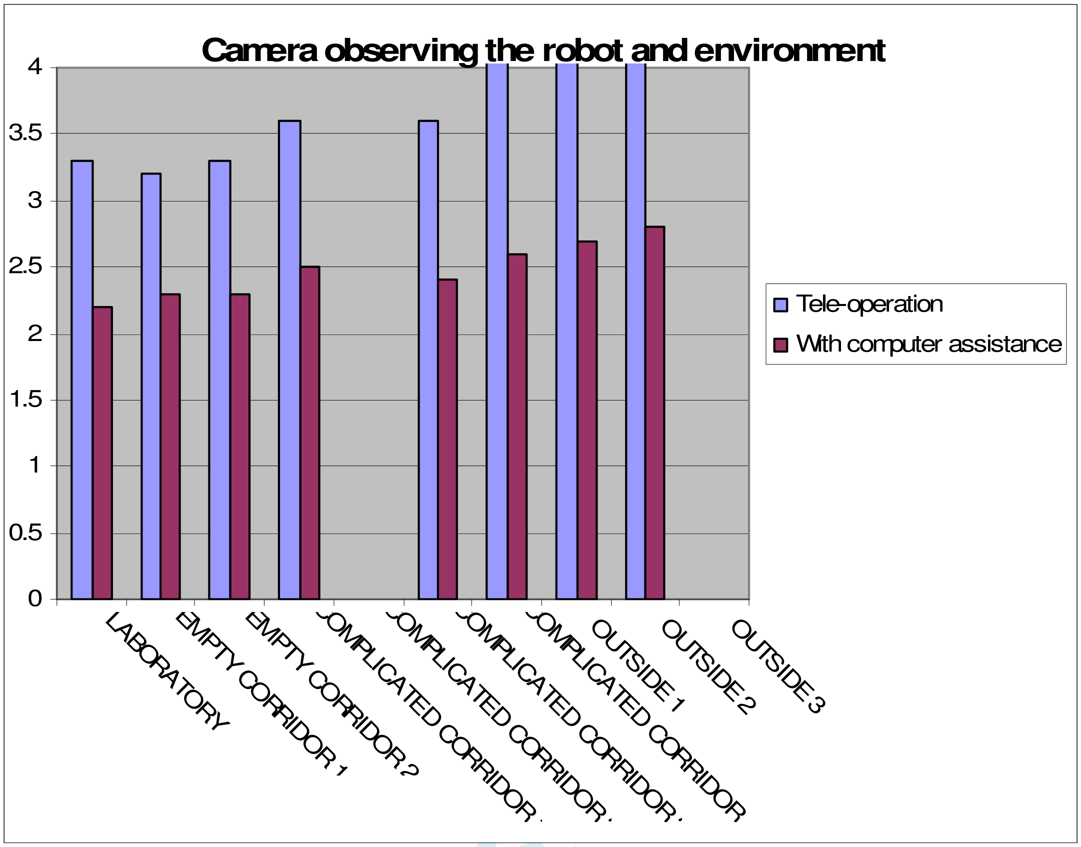

Figure 10 Results from tests with the umbilical cable when the camera was viewing the mobile-robot and the robot was passing through smaller and smaller gaps (Y axis in cm). The bars on the left are without the sensors and the bars on the right are with the sensor system activated.

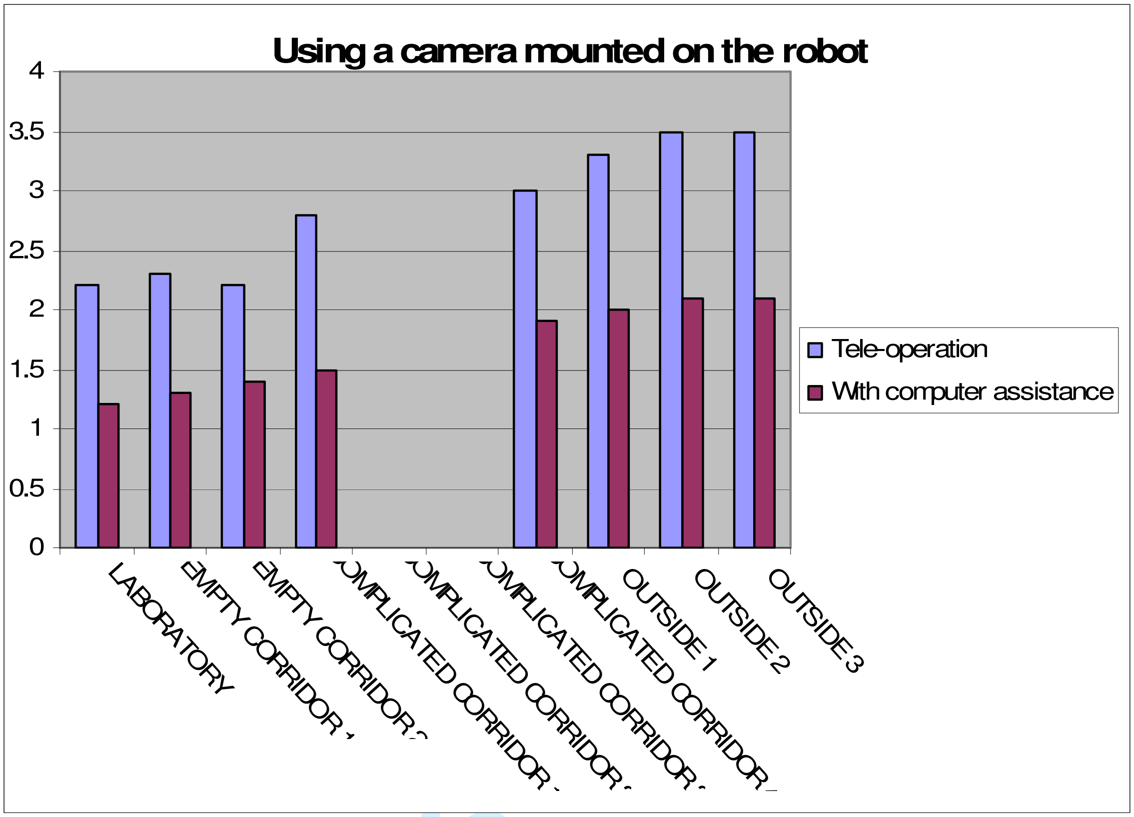

Figure 11 Results from tests with the radio link passing through smaller and smaller gaps (in cm) when the camera was mounted on the mobile-robot. The bars on the left are without the sensors and the bars on the right are with the sensor system activated.

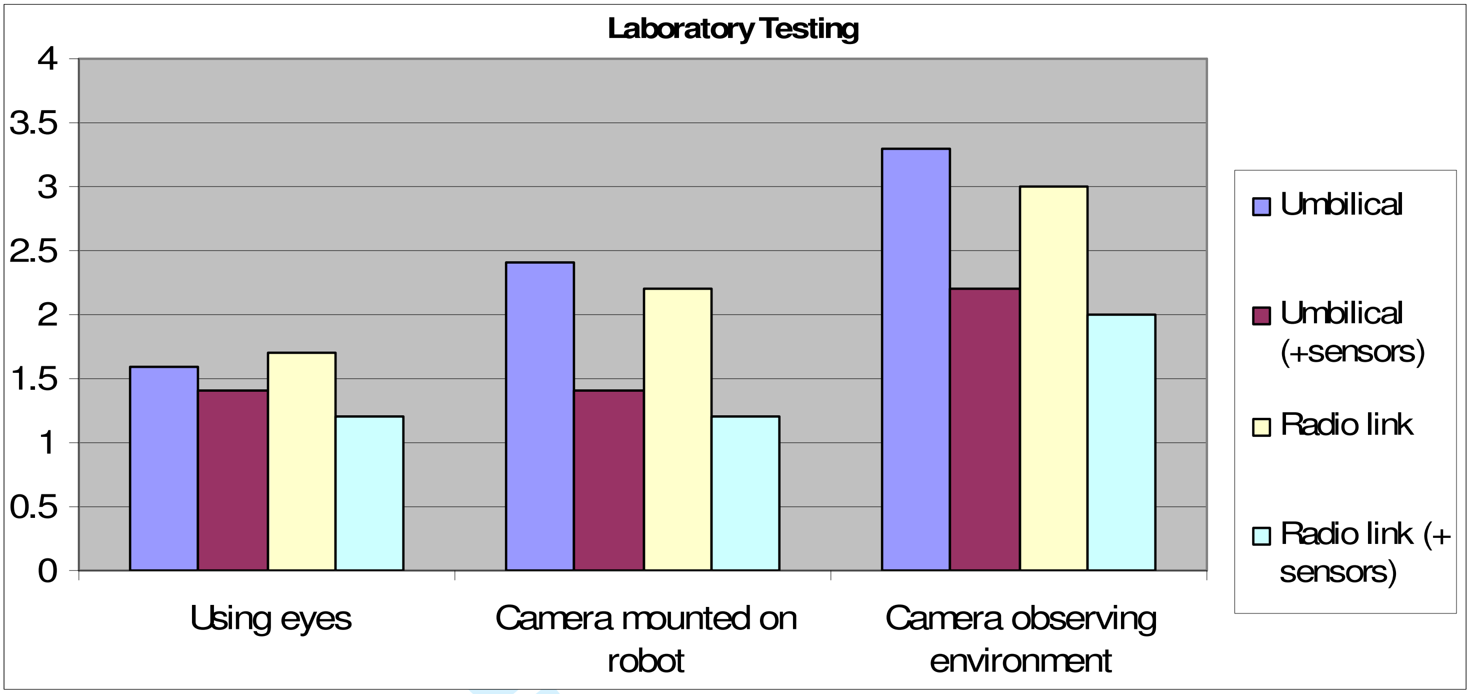

Figure 12 Results from testing in the laboratory as the robot passed through smaller and smaller gaps (in cm). The bars on the left are using an umbilical cable (without sensors on the left) and the bars on the right are using a radio link (without the sensor system on the left and with the sensors on the far right). The group of bars on the left were observing the robot, the group in the middle was with a camera mounted on the robot, and the group on the right was with a camera mounted to observe the robot and the environment.

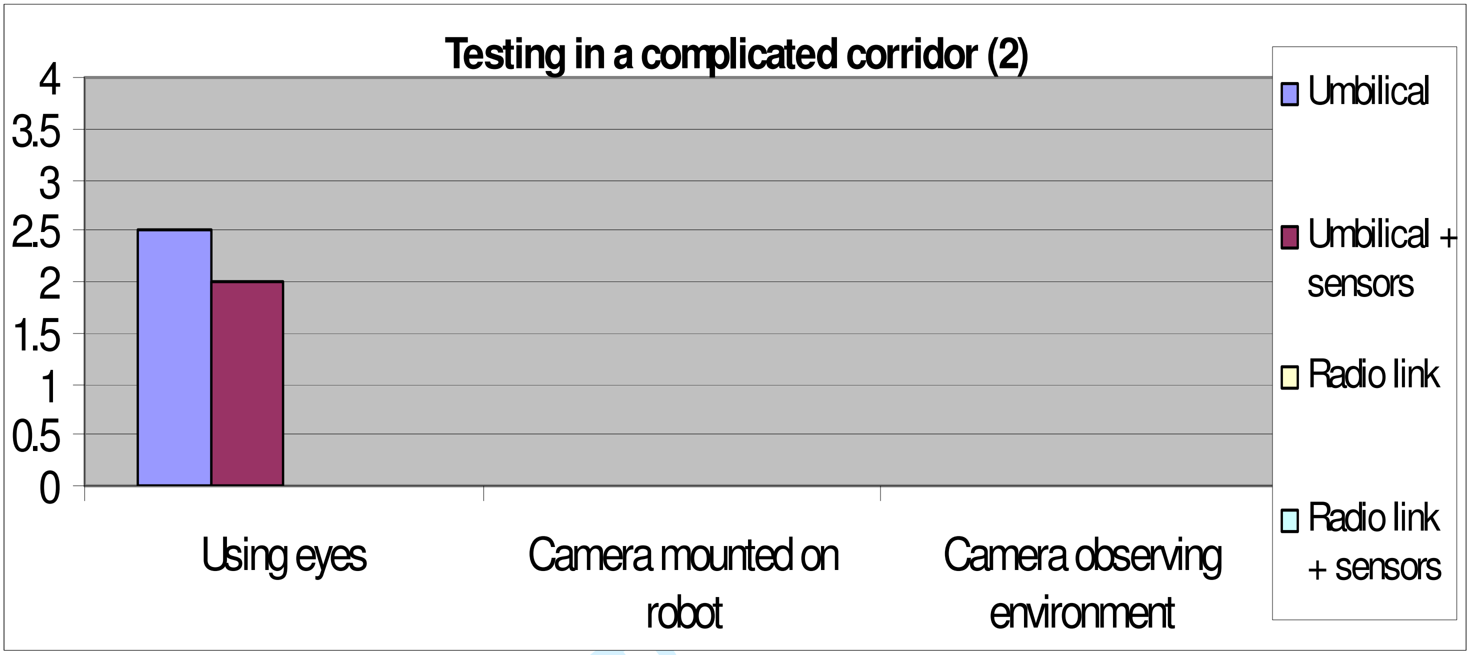

Figure 13 Results from testing in complicated corridor 2 as the robot passed through smaller and smaller gaps (in cm). The results were recorded when using an umbilical cable (without sensors on the left and with the sensors on the right).

(NB – only one set of results was available here as the radio system was not repeatable)

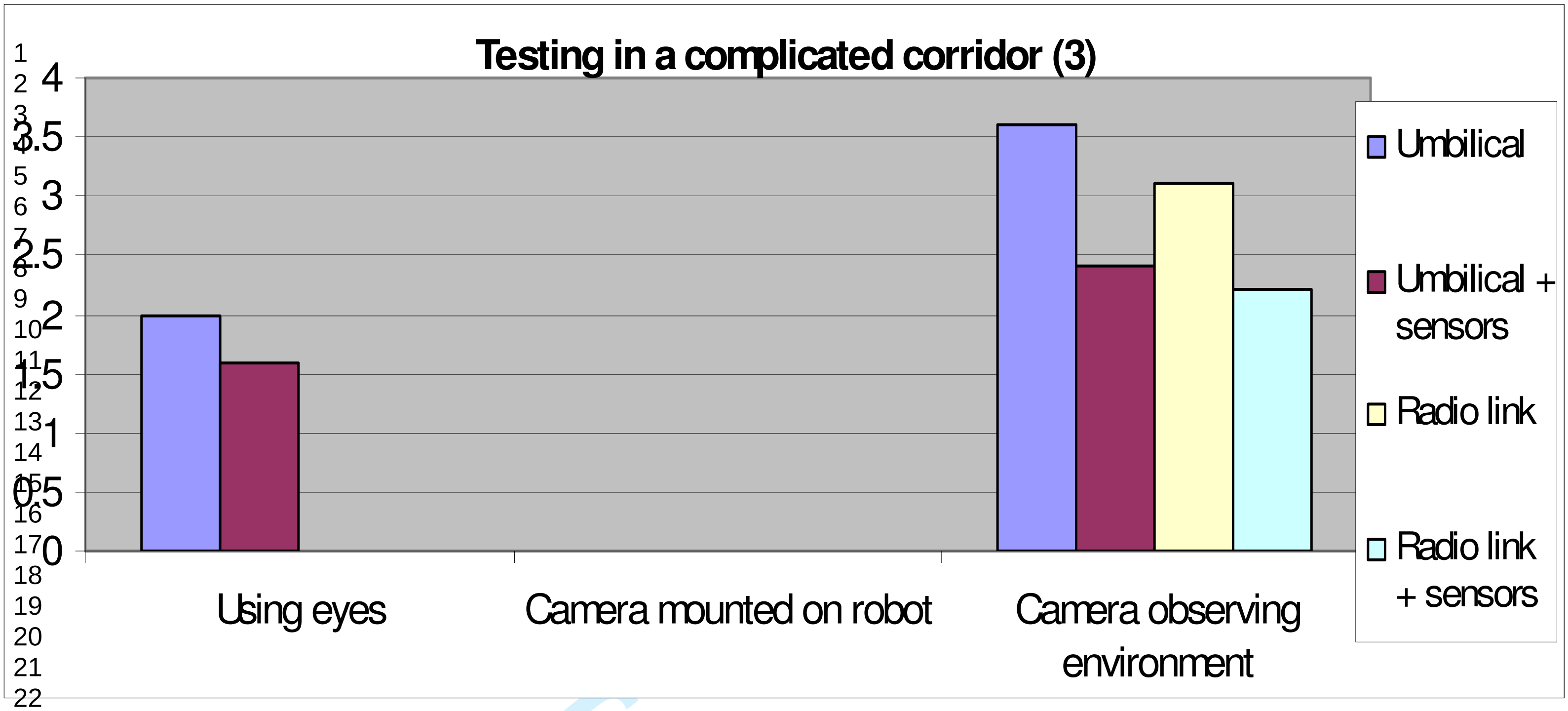

Figure 14 Results from testing in a complicated corridor as the robot passed through smaller and smaller gaps (in cm). The bars on the left are using an umbilical cable (without sensors on the left) and the bars on the right are using a radio link (without the sensor system on the left and with the sensors on the far right). The group of bars on the left were observing the robot and the group on the right was with a camera mounted to observe the robot and the environment.

(NB –results were not available for the camera mounted n the robot as the radio system was not repeatable)

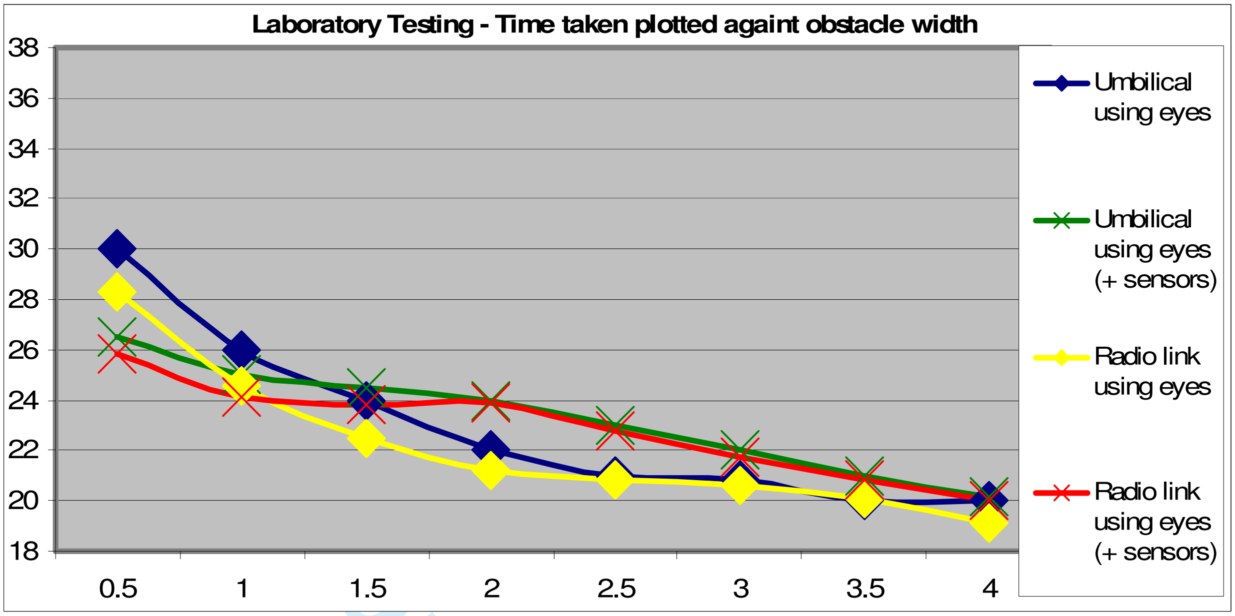

Figure 15 Times taken in the laboratory (in seconds) for a tele-operator watching the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.

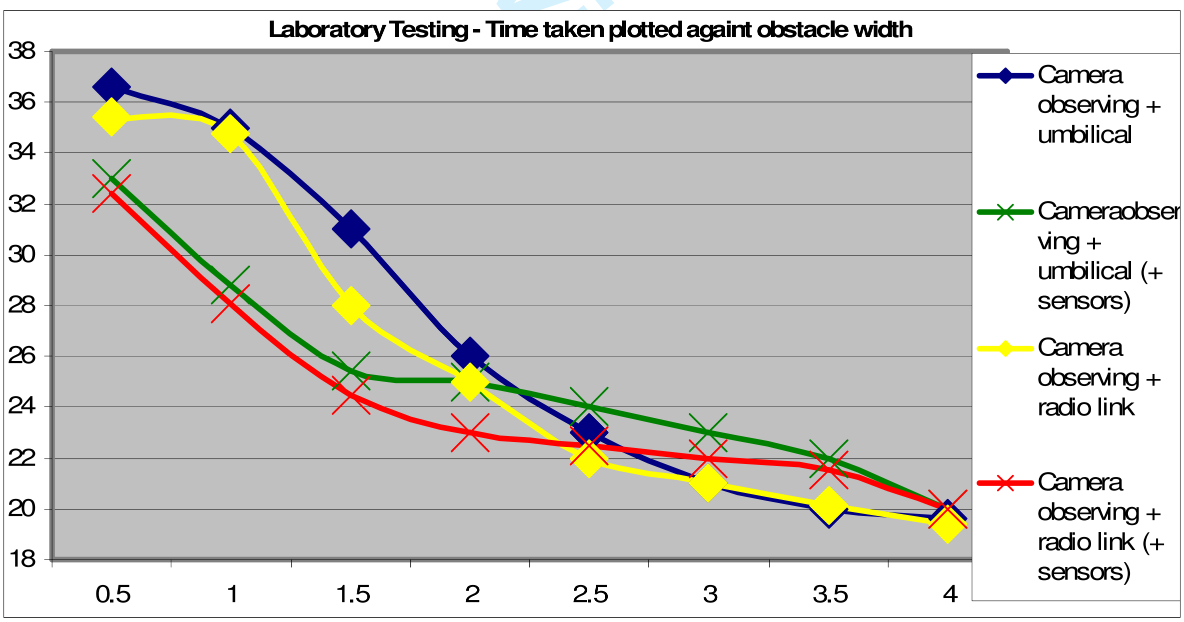

Figure 16 Times taken in the laboratory for a tele-operator with a camera viewing the environment and the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.

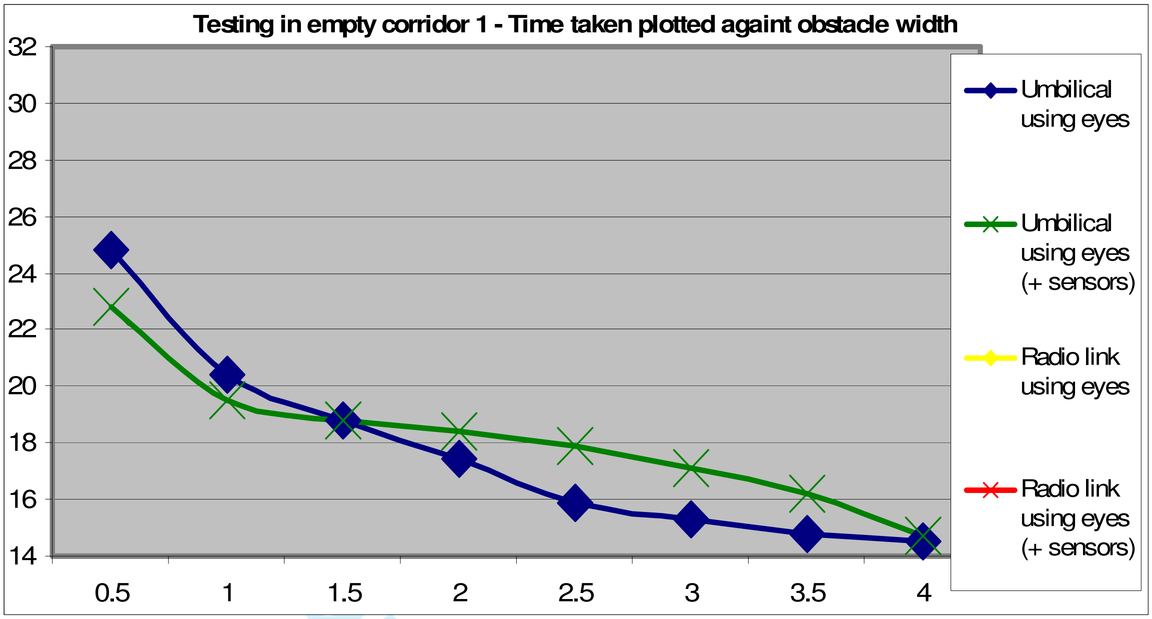

Figure 17 Times taken in Simple Corridor 1 for a tele-operator watching the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.

(NB – only one set of results was available here as the radio system was not repeatable)

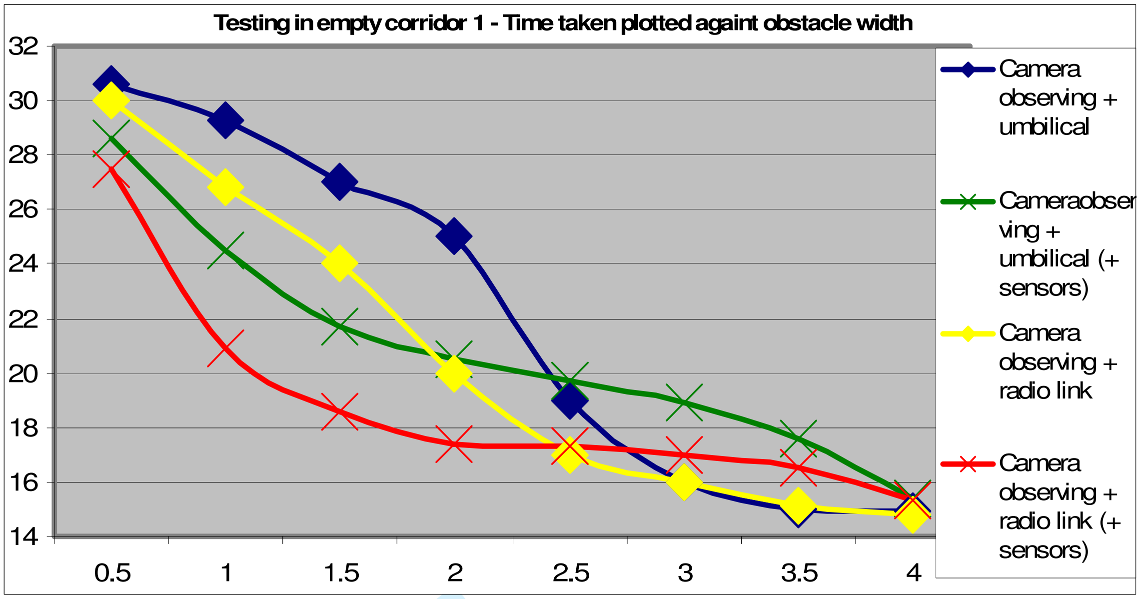

Figure 18 Times taken in Simple Corridor 1 for a tele-operator with a camera viewing the environment and the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.

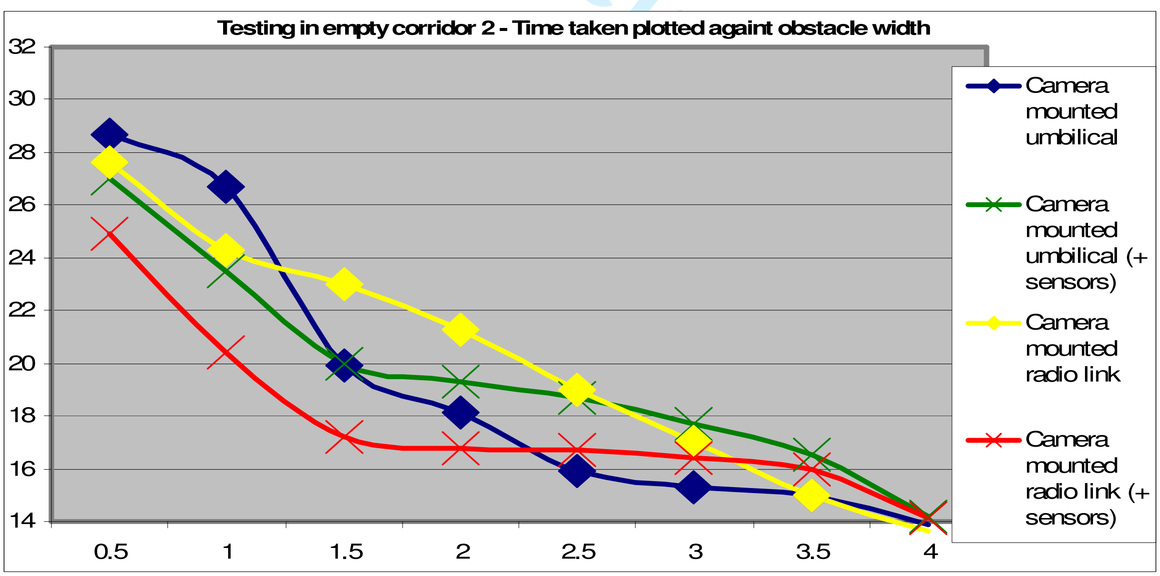

Figure 19 Times taken in Simple Corridor 2 for a tele-operator with a camera mounted on the mobile robot and with reducing gap width between obstacles. The time taken in seconds is on the Y axis and the width in cm is on the X axis.

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