A LABORATORY EVALUATION OF TWO GRAPHICAL DISPLAYS FOR SPACE MANIPULATOR POSITIONING TASKS

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Abstract: A space manipulator is a lightweight robotic arm mounted on a space station or a spacecraft. If the manipulator is manually controlled from a remote site (teleoperation), the pictures from cameras in the neighbourhood of the manipulator are the only aids the human operator can use. Besides, manipulator dynamics and the possible presence of time delays in the control loop also complicate manual control.
In space manipulator positioning tasks, the manipulator hand (the end-effector) has to be positioned accurately in front of a known (physical) target. Here, the human operator can only use the camera picture from a camera attached to the end-effector. In that picture, hardly any spatial cues are present. Therefore, it is difficult to assess the attitude of the end-effector relative to the target. This paper evaluates two graphical camera overlays that visualise the actual end-effector attitude. The first overlay, the *Indicator Display,* shows the exact position and orientation of the end-effector with a set of smart two-dimensional display indicators. In the second overlay, the spatial *Pyramid Display,* spatial information is presented by means of the intersections of three spatial graphical objects. The results of man-machine experiments show that the positioning task can be performed remarkably fast with *both* displays. Also, it appears that at the end of the task, the 'Pyramid operator' is more aware of the actual manipulator environment than the 'Indicator operator'.

Keywords: Teleoperation, Manual Control, Evaluation, Graphical Displays

1. INTRODUCTION

1.1 The manual control of a space manipulator

At Delft University of Technology (DUT), Department of Mechanical Engineering and Marine Technology, manual control of a space manipulator is an object of study (Bos, 1991). A space manipulator is a lightweight robotic arm mounted on a space station or a spacecraft. There, it performs inspection and maintenance tasks, e.g. the repair of a damaged satellite. Figure 1 shows an example of such a manipulator: the new European Robot Arm ERA[1] (van Woerkom *et al*, 1994). The ERA is ten metres long and has six Degrees-of-freedom (Dof's). At the end of the 20th century, it might become operational on the new global space station Alpha.

Recurrent tasks of a space manipulator (e.g. the replacement of Orbital Replaceable Units containing scientific experiments) may well be automated and performed under supervisory control. This does not seem plausible for tasks that are not well defined in advance (e.g. repair tasks). Here, the inventiveness of the human operator is required more often. Then, *teleoperation* (Sheridan, 1992) seems a suitable control method. With this method, the human operator controls the manipulator by hand

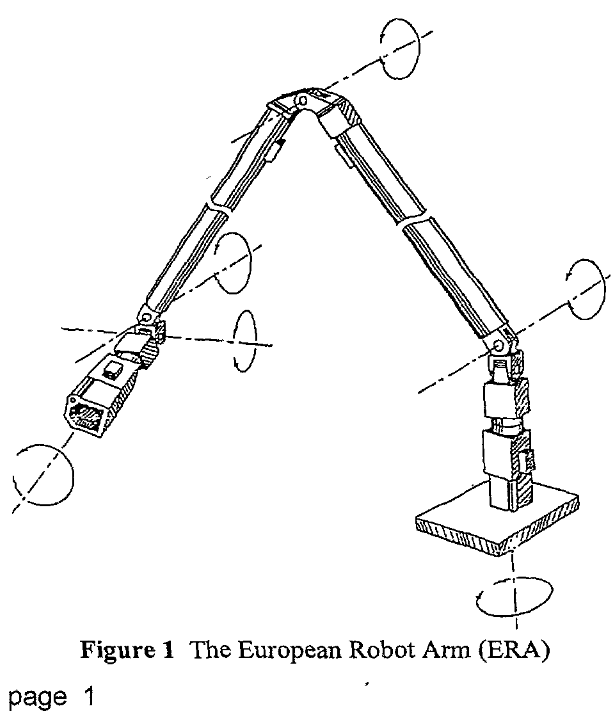


Figure 1 The European Robot Arm (ERA)

[1] The European Robot Arm is developed at Fokker Space and Systems B.V. in Leiden, The Netherlands.

from a remote location (e.g. a space station's manned module or a ground station on earth). Astronauts do not have to go outside their spacecraft to control the manipulator; the manipulator movements are controlled with the help of the pictures from cameras installed in the neighbourhood of the manipulator.

The mentioned teleoperation task is a hard job for the human operator. First, task execution suffers from the manipulator dynamics: because of the lightly constructed limbs, the manipulator will be flexible. Besides, when the operator controls the manipulator on earth, time delays are introduced in the control loop. These delays are caused by the transmission of control signals from earth to space, and back again. Finally, the lack of spatial information in the camera pictures complicates manual control. This paper focuses on that specific problem: because of the loss of the third dimension, it can be difficult to detect whether the moving manipulator may soon collide with one of the objects in its environment. Also, it can be difficult to assess the orientation of the manipulator-hand (the *end-effector*) relative to an object that has to be grasped and displaced.

A solution for the mentioned problem is available when position sensors are installed that measure the position of the manipulator relative to the objects in its environment. Then, the measured data can be presented in a graphical display shown on the man-machine interface console at the remote site. At DUT, new concepts for such displays are being developed. Current research is aimed at the development of a graphical display for an elementary subtask of a space manipulator: the *positioning task.*

1.2 The space manipulator positioning task

Before a space manipulator is able to grasp and displace an object, the end-effector must be positioned accurately in front of the object without damaging it. If this positioning task is performed in teleoperation, all end-effector Dof's (three translations and three rotations) have to be controlled manually. When the distance between the end-effector and the object has decreased to less than a few centimetres, it is difficult to detect whether the end-effector and the object collide.

Figure 2 shows an outline of the generalised positioning task currently investigated at DUT. In this task, the end-effector has to be accurately positioned upon a generic object. Here, the human operator can only use the information in the picture from the camera attached to the end-effector. If the end-effector is approaching the object that has to be grasped, this picture contains three characteristic elements: the top-side of the end-effector, the target and the vision-target. The target marks the area in which the front side of the end-effector must be placed to be able to grasp the object safely. The vision target consists of three cylinders in one line (the cylinder in the middle is taller than the others). From the position and size of each cylinder in the camera picture, a computer calculates the actual position and orientation of the target relative to the end-effector. These measures are used in the graphical display for the positioning task.

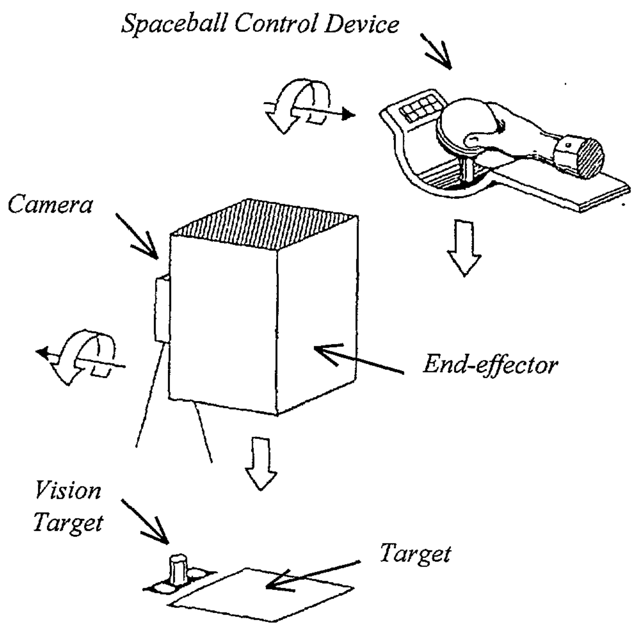


Figure 2 The space manipulator positioning task

In the investigated positioning task, the human operator controls the translational and angular velocity of the end-effector with a commercially available, force activated input device with six Dof's: the Spaceball®. If the operator grasps the Spaceball as if he grasps a car's gear lever, he might feel it as if he grasps the end-effector (*virtual grasping*; see also (Buiël and Breedveld, 1995)).

1.3 The graphical display for the positioning task

In fact, a conventional graphical display that simply shows the actual values of the position and orientation misfits might well suffice for fulfilling the task considered here. Then, to finish the task, the human operator only needs to drag six position and orientation indicators to zero one by one. However, the mentioned 'one-sensor-one-indicator interface' (Goodstein, 1981) enlarges the distance between the operator and the system to be controlled figuratively. With the introduction of the display, the operator acts like an automatic controller in a sense. If the end-effector positioning task is considered as a subtask in a much more comprehensive task, it seems wiser to develop a display that assists the operator in maintaining his spatial awareness of the manipulator environment. This *spatial display* can either be a spatial graphical camera overlay that visualises spatial cues that are missing in the end-effector camera picture, or a synthetic computer-generated image of the actual manipulator environment (an artificial camera picture). If it is well designed, the operator might feel it as if he is actually present in a three-dimensional environment (telepresence, (Sheridan, 1992)).

Currently, the pros and cons of the usage of a spatial display for the end-effector positioning task are investigated at DUT. This paper presents the outcomes of a laboratory man-machine experiment with two graphical displays. The first one is a typical example of a non-spatial, two-dimensional graphical camera overlay: the

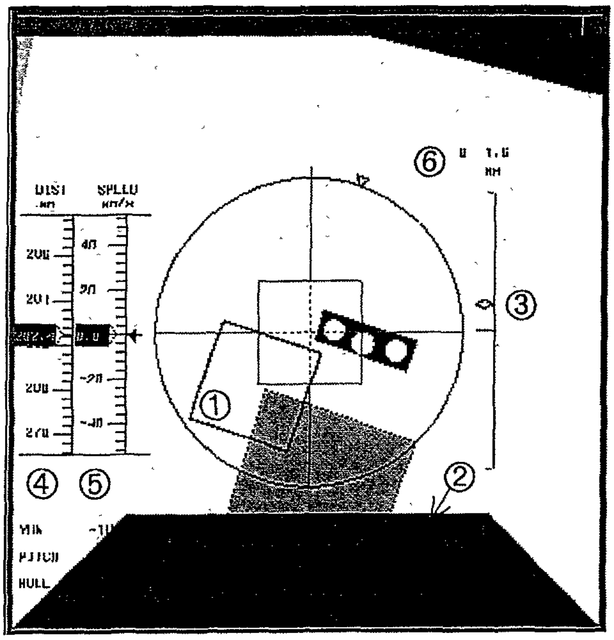


Figure 3 The Indicator Display
(① moving square, ② lateral position misfit, ③ vertical position misfit, ④ distance indicator, ⑤ speed indicator, ⑥ example of a digital misfit meter)

Indicator Display. The second display is a spatial display developed at DUT: the *Pyramid Display*. Detailed information about the work presented here can be found in Buiël (1995).

2. TWO GRAPHICAL DISPLAYS FOR SPACE MANIPULATOR POSITIONING TASKS

2.1 The Indicator Display

Figure 3 shows the Indicator Display in the end-effector camera picture. For this display, display technology that is quite conventional in current Aerospace Engineering has been applied to visualise the actual position and orientation of the end-effector.[2] Just like the artificial horizon in an aeroplane's primary flight display, a moving square near the middle of the Indicator Display (①: the 'horizon') represents the target's orientation relative to the end-effector. For the lateral and vertical position misfit resp., two moving pointers are displayed along the sides of the display (② and ③). A fixed pointer or moving scale altimeter visualises the distance between the end-effector and the plane the target is attached to (④). Next to that indicator, the end-effector velocity can be read from a second moving scale indicator (⑤). Finally, the exact value of each position- and rotation misfit can be read from digital meters (⑥).

All moving elements in the various misfit indicators of the Indicator Display move 'inside-out' (Wickens, 1992). This means that, the movements of those elements in the camera overlay correspond to the movements of the target in the end-effector camera picture. Each moving element changes colour at the moment it moves into (or out of) the safe region for the indicated misfit. At the moment all elements are coloured green (the 'safe' colour), the middle cylinder of the vision target is exactly in the middle of the display. Then, the operator can reduce the remaining distance between the end-effector and the target cautiously, and finally he can place the end-effector upon the target.

2.2 The Pyramid Display

The Pyramid Display (Breedveld, 1994 and 1995) emphasises the spatial cues that were hardly perceivable in the original end-effector camera picture (see Figure 4). First, to improve the sensation of depth, rectangular grids are projected on objects in the manipulator environment (①). Second, three spatial graphical objects are introduced to simplify the perception of the actual end-effector attitude: the frosted glass (②), the insert-box (③) and the pyramid (④). To the operator, each of these objects seems to be present in the manipulator environment. The insert-box and the pyramid seem to be attached to the vision-target; the frosted glass seems to be attached to the end-effector, just like the sight of a gun. To finish the positioning task, the human operator has to move the frosted glass towards the insert-box and the pyramid. When the end-effector approaches the target closely, the frosted glass intersects the insert-box and the pyramid successively. Then, the end-effector position and orientation can be perceived from these intersections.

Figure 5 shows the Pyramid Display at the moment the frosted glass intersects the pyramid. The size of this intersection is an accurate measure for the remaining distance between the end-effector and the target. The shape of the intersection visualises the orientation of the end-effector relative to the target. If a small orientation-misfit is present, the shape will be an irregular quadran-

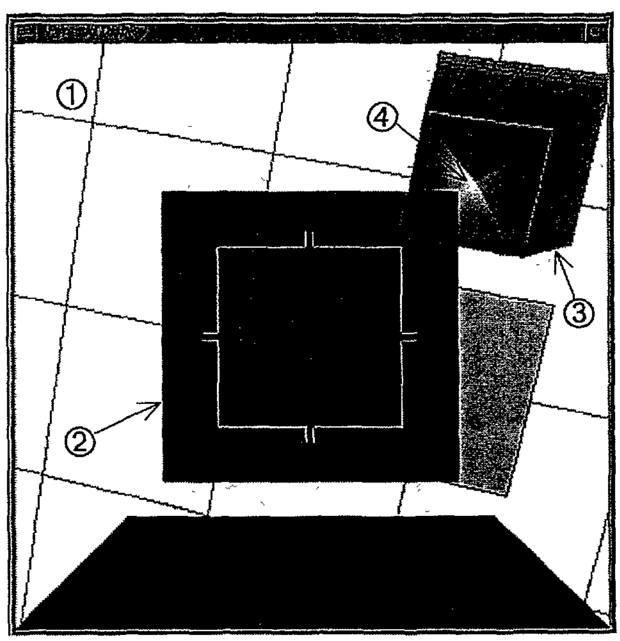


Figure 4 The Pyramid Display (① rectangular grid, ② frosted glass, ③ insert-box, ④ pyramid)

[2] The general design ideas for the Indicator Display came from the U.S. patented graphical display for remotely controlling an assembly of two objects, as developed at Aerospatiale Societe Nationale Indust., Paris, France (U.S. Patent Number 5.119.305, dated June 2, 1992).

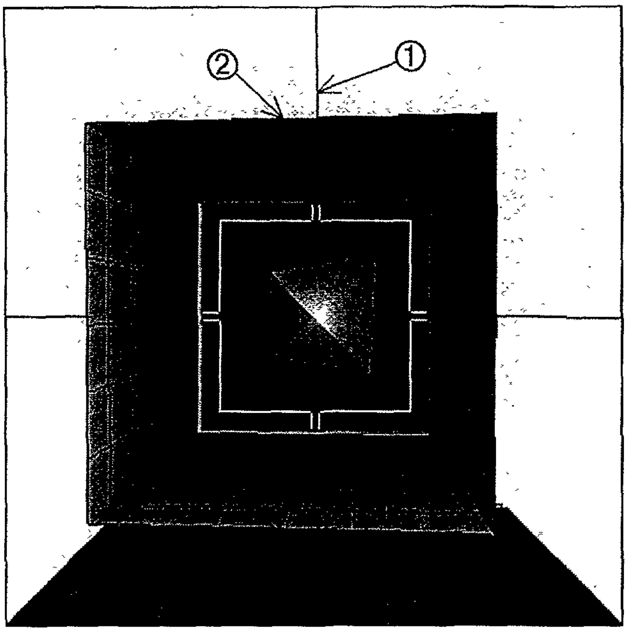


Figure 5 The frosted glass intersects the pyramid (① vertical gridline in the environment, ② longitudinal gridline upon the insert-box; see 4.1)

gle. When the intersection is almost square, orientation and position misfits are all within the desired accuracy. Then, the pyramid changes colour and the operator can place the end-effector upon the target.

2.3 Discussion

Without doubt, an operator using the Pyramid Display will be more aware of the three-dimensional environment the space manipulator is moving in than an operator using the Indicator Display. According to Gibson (1979), the optic flow patterns in the retinal picture of the human eye form an essential cue for spatial perception in daily life. To obtain a spatial impression of the space manipulator environment, the operator should utilise the flow patterns in the end-effector camera picture (i.e. the movements of the target and the other objects visible in that picture) in a similar way. This is more difficult for the operator using the Indicator Display, than for the operator using the Pyramid Display. In the display mentioned last, the presence of textured spatial objects results in a clearer motion perspective. Consider the insert-box to explain this. This box is much longer and bigger than the vision-target. Also, rectangular grids are projected on its sides. Because of this, it is easier to estimate changes in the attitude and position of the insert-box, than to do this for the vision-target. In this way, the insert-box acts more or less like an enhanced vision-target.

Despite the increased spatial awareness of the operator, the usefulness of the Pyramid Display for the end-effector positioning task is not known beforehand. To finish the task with this display, an operator can rely on spatial information only. No additional exact information about the actual end-effector velocity or the translation and rotation misfits in specific directions is provided; the 'Pyramid operator' is forced to *estimate* these quantities from the end-effector camera picture. Here, the 'Indicator operator' is in favour. This operator can always use the exact information in the Indicator Display. All the time, he can find the current velocity of the end-effector, and see which misfits are too large.

However, the question is whether the Pyramid operator really needs additional exact information like that provided by the Indicator Display. By nature, humans are very well capable to perceive spatial information from the outside world. The Pyramid Display capitalises on these capabilities. Here, the intersections of the frosted glass with the insert-box and the pyramid resp. may well provide sufficient information to be able to estimate the actual position and rotation misfits enough accurately. Also, the actual end-effector velocity may well be estimated from the optic flow in the camera picture. To verify this, in a laboratory experiment, the task performance with the Indicator Display has been compared to the task performance with the Pyramid Display.

3. A LABORATORY EXPERIMENT WITH THE TWO GRAPHICAL DISPLAYS

To measure the task performance with both displays, the members of two groups of six subjects have all been trained for a *simulated* space manipulator positioning task. The first group has been trained to perform this task with the Indicator Display; the second group has been trained to do this with the Pyramid Display. All subjects were students in Mechanical Engineering, without any experience in tasks like the simulated positioning task.

3.1 The simulation facility

Figure 6 shows the simulator that was used in the experiment. In this simulator, the movements of the European Robot Arm ERA (see the introduction to this paper) are simulated by means of a Silicon Graphics graphical workstation (①). This computer animates a simplified end-effector camera picture in real time (②); Figure 3 through Figure 5 show examples of that picture). At the start of the simulated positioning task, the end-effector is at one metre distance from the target. To finish the task correctly, the subject has to position the front side of the end-effector straight in front of this target, without coming into collision with the target itself. Here, position-misfits have to be reduced to less than 3.0 millimetres; orientation-misfits have to be reduced to less than 1.5°. The end-effector movements are controlled with a Spaceball (③).

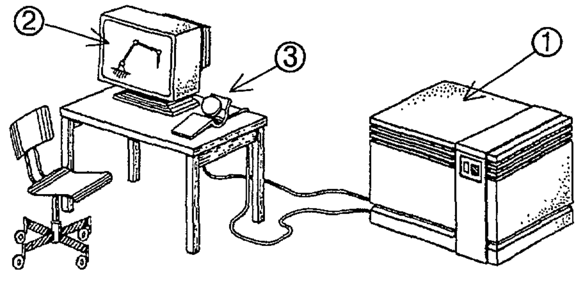


Figure 6 The simulation facility (① graphical workstation, ② end-effector camera picture, ③ Spaceball control device)

In the experiment discussed here, a simple mathematical model was used for the computation of the ERA movements. The model describes the ERA end-effector as an object with six Dof's, of which the movements are constrained by the upper limits for its translational and angular velocities only (0.1 m/s and 10°/s resp.). The end-effector movements are *not* hindered by the manipulator dynamics. In this way, the outcomes of the experiments do not only demonstrate the usefulness of both display concepts for ERA; they are also valid for other situations in which an object has to be positioned accurately in front of another object in teleoperation (e.g. in dredge technology (Jonkhof, 1995), or in laparoscopic surgery). Of course, for the ERA case, after this experiment more experiments will be needed to determine the influence of the slow ERA dynamics on operator performance with both displays.

3.2 The task training

At the start of the training for the simulated positioning task, each subject read the fundamentals of one of the displays in a manual first. After that, a large number of task runs had to be performed with the help of that display (at least 25 runs). Here, the subject was asked to search for a control strategy that results in *fast* task execution, but that guarantees *safe* task execution above all. Here, 'safe' means that no collisions between the end-effector and the object to be grasped were allowed to take place, except for the final intended contact between end-effector and target at the moment the end-effector is correctly positioned. The task had to be practised until the subject was able to perform it with sufficient and almost constant performance. This performance level had been attained at the moment the subject was able to perform eight successive task runs without any hazardous collisions between the end-effector and the target taking place. Also, the standard deviation of the completion times of these eight task runs had to be less than 3.5 seconds. To prevent the subject from becoming tired, a break was taken after each cluster of 25 practice runs.

3.3 Measurements

The task performance finally attained by every subject has been measured in a concluding experiment. In this experiment, each subject was asked to perform 24 task runs with the graphical display he or she had been trained for. Task demands were exactly the same as those in the training sessions.

After the experiment, the first part of a questionnaire was handed out. In this part, the subject was asked to express his or her opinion about the graphical display he or she had been trained for. Other questions dealt with the subject's control strategy for the end-effector positioning task and the mental load the subject experienced while erforming the task. At last, the subject was confronted with the display he had not been trained for. After he had erformed a large number of test runs with that display, he second part of the questionnaire was handed out. In his part, the subject was asked to draw a comparison etween both display concepts.

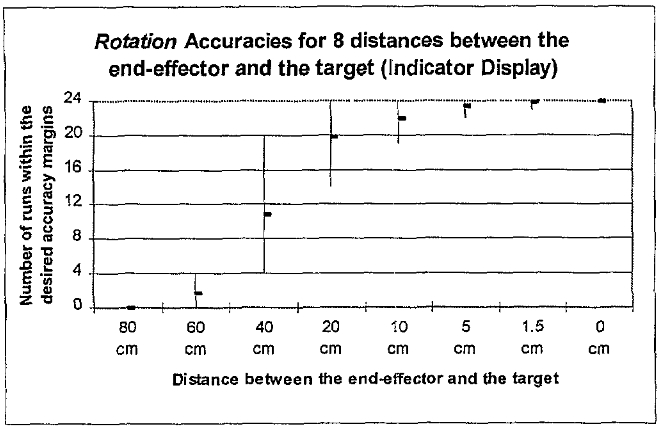
4. THE RESULTS OF THE EXPERIMENT

4.1 Control strategies

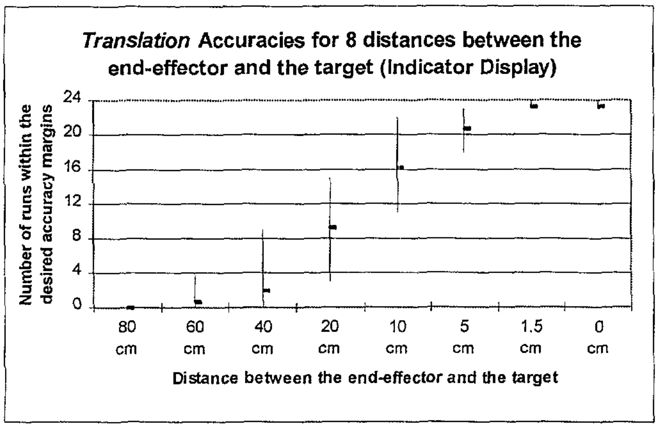
The control strategies with both graphical displays are visualised in Figure 7 and Figure 8 resp. Both Figures show two high-low graphs; one for the rotation misfits and one for the lateral and vertical translation misfits. Each graph shows the number of runs in a single experiment in which the considered misfits are within the requested accuracy at the moment the end-effector is at a specific distance from the target. In each graph, eight values of the distance between end-effector and target are considered. The horizontal dash in each of the eight high-low bars indicates the mean value for the mentioned number of runs (i.e. the mean of the six experiments); the top and bottom of each bar show the extreme values that were found for this number.

<u>Control strategy for the Indicator Display</u>
Generally, task execution with the Indicator Display can be split up in four stages. In the first stage, the subjects moved the end-effector towards the target at maximum speed. While the end-effector moved towards the target, the end-effector orientation was corrected gradually. At the moment the end-effector had approached the target up to about 40 to 60 cm, the subjects corrected the remaining orientation misfits with the help of the moving square in the middle of the display (2^{nd} stage). After the rotation misfits had been reduced to acceptable values, the lateral and vertical position misfits were controlled with the help of the two moving pointers displayed along the sides of the display (3^{rd} stage). Figure 7 confirms that the lateral and vertical position misfits were controlled after the rotation misfits had been corrected: when the distance between the end-effector and the target is in between 40 and 10 cm, the mean number of runs with 'accurate' rotation misfits is always (much) larger than the mean number of runs with 'accurate' lateral and vertical position misfits. When the rotation misfits and the lateral and vertical position misfits were small enough (distance < 5 cm in Figure 7), the end-effector was placed upon the target (4^{th} stage).

Most subjects said that they had found some problems with the arrangement of the indicators in the Indicator Display in the last task stage. Here, a large number of indicators have to be checked sequentially. Of course, the subject has to take care that each misfit indicator indicates a value that is within the desired accuracy margin for that misfit. Also, the distance indicator has to be checked from time to time. Almost all subjects mentioned that it is almost impossible to read out these indicators at a single glance. Here, especially the distance indicator caused problems. If their eyes focused on the centre of the large circle in the middle of the display, subjects were just able to read out the orientation indicator and the lateral and vertical translation misfit indicators. The distance indicator was not clearly visible if the eyes focused on the middle of the display. Since that indicator is placed on the very left side of the display, the subject's eyes had to turn to the left to be

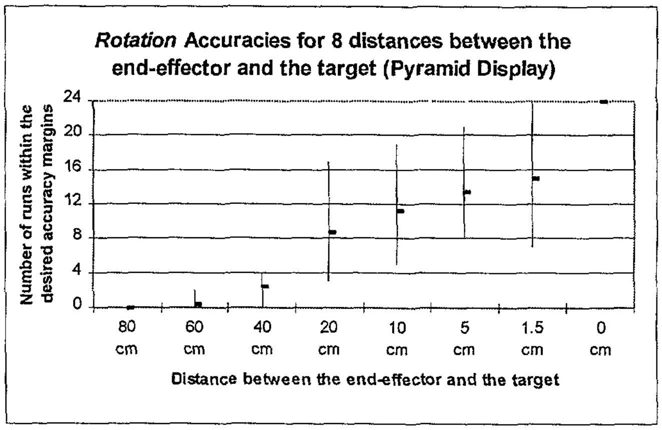


a) Control of rotation misfits

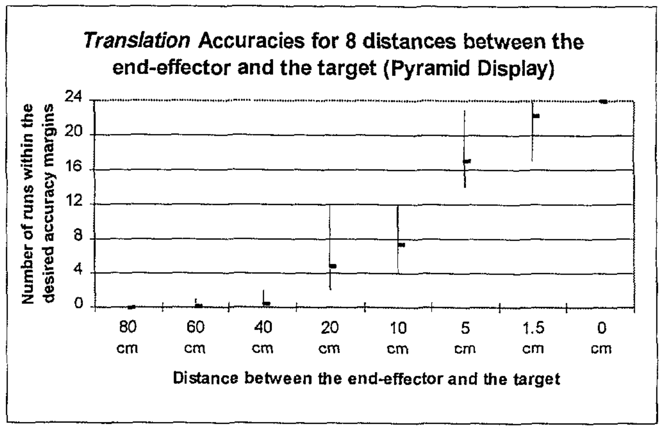


b) Control of translation misfits

Figure 7 Indicator Display control strategy



a) Control of rotation misfits



b) Control of translation misfits

Figure 8 Pyramid Display control strategy
(insert-box height = 10 cm; pyramid height = 1.5 cm)

able to read out the remaining distance between the end-effector and the target.

The above problem clearly shows that subjects really needed the distance indicator in the final stage of the positioning task performed with the Indicator Display; in this task stage, they were not able to assess the remaining distance between the end-effector and the target from the actual end-effector camera picture only. This indicates that with the Indicator Display, subjects are not enough aware of the spatial properties of the environment of the end-effector at the end of the positioning task. Because of this, most subjects assessed the probability of a collision with the Indicator Display to be larger than the probability of a collision with the Pyramid Display.

Control strategy for the Pyramid Display

The subjects that were trained with the Pyramid Display also guided the end-effector towards the target at maximum speed first. At the same time, they roughly corrected the alignment of the insert-box with the frosted glass. At the moment the frosted glass was about to intersect the insert-box for the first time (distance = 10 cm in Figure 8), the subjects considered the remaining position and orientation misfits. Here, two distinct strategies were found. Three subjects applied the 'pyramid strategy'. They moved the frosted-glass slowly towards the pyramid (distance = 1.5 cm in Figure 8), and corrected the remaining position and orientation misfits with the help of the intersection between the frosted glass and the pyramid. The other subjects applied the 'insert-box strategy'. They corrected the remaining misfits by looking consciously at the rectangular grids projected upon the insert-box and the environment of the target. Consider Figure 5 to explain this. Because the intersection of frosted glass and pyramid is not square, the end-effector is not perfectly aligned with the target in this figure. This can also be concluded from the fact that the vertical grid line marked ① (a part of the rectangular grid projected on the target object) is not in one line with the longitudinal grid line marked ② (a part of the rectangular grid projected on the insert-box). At the moment the end-effector is perfectly aligned with the target, both gridlines will be in one line.

The observation of two distinct control strategies for the Pyramid Display influenced the length of the high-low bars in Figure 8 (especially the bars in Figure 8a). At the moment the frosted glass has not intersected the pyramid yet (distance > 1.5 cm), the mean number of runs with 'accurate' misfits is (much) larger for the 'insert-box subjects' than for the 'pyramid subjects'.

4.2 Task performance and mental load

Task performance has been analysed by means of two performance measures: the number of collisions occurring in a single experiment and the mean completion time of the 24 task runs in a single experiment. At the end of this analysis, the attained level of task performance has been related to the mental load the subjects experienced while performing the positioning task. In this way, the suitability of both displays for the end-effector positioning task was investigated.

Number of collisions

The number of collisions occurring in the twelve concluding experiments was very small. In all Pyramid Display experiments, only three collisions occurred (each one was caused by a different subject). In the experiments with the Indicator Display, four collisions occurred (two of these collisions were caused by a single subject; two other subjects caused one collision only).

Task completion time

Figure 9 shows 95% confidence intervals for the mean completion time of the 24 task runs performed by each subject (each set of 24 completion times is assumed to be a sample from a normal distribution). Relatively large performance differences are present between the subjects trained for the Pyramid Display. In (Buiël, 1995) it is shown that these differences may well be explained from the operator's capability to perceive the spatial information in the Pyramid Display. For the Indicator Display, the performance differences between the six subjects are small. Apparently, the control strategy for this display caused almost equal problems to all subjects.

From Figure 9, it can already be concluded that with both graphical displays the positioning task can be performed quite fast. The grand mean run completion time for all subjects trained for the Pyramid Display is 23.9 sec.; for the subjects trained for the Indicator Display this is 24.7 sec. (the minimal time necessary to complete a task run was 10 sec.; this value can be computed from the upper limits for the translational and angular end-effector velocities). A two-sample student's t-test with df = 10 indicates that this difference is far from significant on the 5% significance level ($t_{10} = 0.38$, two-tailed $p = 0.71$).

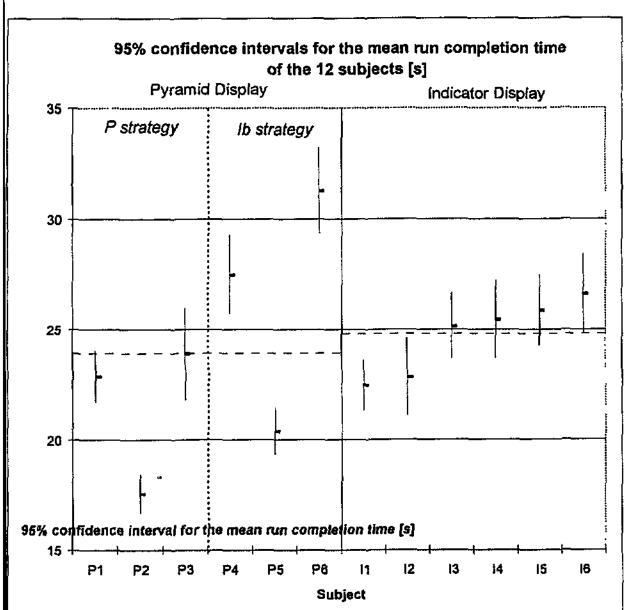


Figure 9 95% Confidence intervals for the mean run completion time of the 12 subjects

Table 1
Mental load experienced by the 12 subjects

Display	Mental load (Large values indicate large mental load)						
	1	2	3	4	5	6	7
Pyramid Display	1	3			2		
Indicator Display		3	1	1	1		

The table shows the number of subjects that experienced a specific level of mental load. Level 1 indicates that the positioning task is *not* mentally fatiguing; level 7 indicates that the task is mentally *very* fatiguing.

Therefore, it has been concluded that a possible performance difference between both displays is so small, that it is not worth mentioning. With the Indicator Display, as well as with the Pyramid Display, the end-effector positioning task can be performed very fast.

Mental load

Immediately after the experiment, each subject was queried for the mental load that he had experienced while performing the positioning task. The mental load was assessed by means of a discrete rating scale with seven levels at equal distances. Table 1 shows the mental load ratings of the twelve subjects. Again, no substantial differences are found between both graphical displays. In both groups, four subjects selected an option that indicates a low level of mental load (i.e. options 1, 2. and 3); the mental load experienced by the others was larger (options 4 or 5).

If the outcomes of the analysis of task performance and mental load are combined, it can be concluded that both graphical displays are suitable for the end-effector positioning task. With both displays, the task can be performed quickly and with small mental effort.

4.3 Subject opinions

After the training with the second display, each subject was asked to choose his favourite graphical display. Finally, eight subjects preferred the Pyramid Display, and three subjects preferred the Indicator Display. One subject liked the Pyramid Display just as much as the Indicator Display. The opinions of the subjects have been influenced by the order in which both displays were presented to them. Five of the six subjects that were first trained with the Pyramid Display preferred that same display in the end. The six subjects that were first trained with the Indicator Display were more divided about the choice of the best display.

Most subjects did not experience large difficulties with *both* graphical displays. This is illustrated in Table 2. This table shows the means and standard deviations resp. of the marks that each subject has assigned to both displays. In the same way as a Dutch school teacher judges his pupils, each mark had to be a whole number between 1 and 10. A number between 1 and 5 indicates that the display is unsatisfactory; other values indicate that it is satisfactory (if a display is marked with a 10, it is perfect). The table shows that both displays are marked

Table 2
The assessment of both displays by the 12 subjects

Graphical display	Training order		Grand
	PD/ID	ID/PD	mean
Pyramid Display	8.3 (sd 0.5)	7.7 (sd 0.7)	8.0 (sd 0.7)
Indicator Display	6.5 (sd 1.5)	7.5 (sd 0.5)	7.0 (sd 1.2)

The table shows the mean and standard deviation resp. of the marks that each subject has assigned to both displays. Each mark had to be a whole number between 1 and 10. A large value indicates that the display was highly appreciated.

as satisfactory. The appreciation for the Pyramid Display is a little larger than the appreciation for the Indicator Display. Again, the final assessments of the displays have been influenced by the order in which both displays were presented to the subjects.

In general, the subjects who preferred the Pyramid Display liked the amount of spatial information in this display. They said that with the help of these spatial cues, the actual attitude of the end-effector and the actual distance between end-effector and target can roughly be estimated in short time. With the Indicator Display, this takes more time, because here, especially at the moment the end-effector is very close to the target, hardly any useful spatial cues are present in the end-effector camera picture. Next to this benefit, those who preferred the Pyramid Display also mentioned that they found the Indicator Display much more crowded than the Pyramid Display. One of them said: "The Pyramid Display is simple, but it is also comprehensible; the Indicator Display is full of different indicators and numbers."

The subjects who preferred the Indicator Display liked the amount of exact information in this display. They said that with the Pyramid Display, it takes some time to find those misfits that are not within the desired accuracy margins at the very end of the positioning task. This is no problem in the Indicator Display, because each misfit value is displayed separately in that display.

5. CONCLUSIONS

The outcomes of the experiment show that with the spatial Pyramid Display, as well as with the two-dimensional Indicator Display, a non-flexible tele-manipulator can be positioned accurately in very short time, and with small mental effort. With the experiment, the pros and cons of the usage of a spatial display in teleoperation tasks have become more clear. With the Pyramid Display, the human operator should be able to perceive spatial information in the same way as he does in daily life. Indeed, most of the subjects that participated in this experiment liked the amount of spatial information in the Pyramid Display. Different strategies were applied to utilise this information. The experiment also shows that to some extent, the task performance with this display depends on the operator's capability to perceive that information. This was indicated by the relatively large performance differences found among the subjects that were first trained with the Pyramid Display.

The experiment also demonstrates the usefulness and vulnerability of conventional display technology for teleoperation tasks. The major benefit of the Indicator Display is that the human operator can always *exactly* see what is wrong (i.e. which position and rotation misfits are not within the desired accuracy margins). The display does not capitalise on the human's natural capabilities to perceive spatial information. Especially at the end of the positioning task, hardly any spatial cues are present in the end-effector camera picture. In the experiments, this resulted in a diminishing spatial awareness: the subject's eyes had to turn to the left of the display from time to time, to find the remaining distance between the end-effector and the target.

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