THE DEVELOPMENT OF A MAN-MACHINE INTERFACE FOR SPACE MANIPULATOR DISPLACEMENT 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 location (teleoperation), the human operator can only see its movements in the pictures from the cameras mounted on the manipulator and the pictures from the cameras installed in the neighbourhood of the manipulator. Typical tasks of space manipulators are transportation tasks and inspection tasks. During the execution of these displacement tasks, the human operator has to be alert not to cause a collision between the manipulator limbs and objects in the environment. This is not an easy job, because the distances between the manipulator and the objects can hardly be estimated from the available camera pictures.

Recently, at our laboratory, a conceptual man-machine interface has been developed for space manipulator displacement tasks. The new anthropomorphic European Robot Arm (ERA) served as a reference in this project. At the control-side of the interface, a force-activated control device with six degrees-of-freedom (the Spaceball) is applied to control the movements of the ERA end-effector (the hand of the manipulator). At the display-side of the interface, a single camera picture is shown: the picture from the camera, that is mounted near the ERA elbow joint. To assist the operator in deriving spatial information from the elbow camera picture, a graphical camera overlay is added: the Raindrop Overlay. In this graphical overlay, the actual distances between the manipulator and the objects in the environment are visualised by means of raindrop-shaped distance lines.

Keywords: Teleoperation, Manual Control, Collision Avoidance, Graphical Displays

1. INTRODUCTION

1.1 The manual control of a space manipulator

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 a space manipulator: the European Robot Arm ERA¹ (van Woerkom et al., 1994; Traa, 1995). This fully symmetric manipulator with two grapples (the end-effectors) is meant for the new International Space Station (ISS; Dooling, 1995). It is approximately ten metres long and will be able to walk across the station by moving an end-effector from its actual base point to a new one; alternately with the first and the second end-effector.

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

¹ The European Robot Arm is developed at Fokker Space B.V. in Leiden, The Netherlands.
required more often. Then, teleoperation (Sheridan, 1992) seems a suitable control method. With this method, the human operator controls the manipulator by hand 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 the cameras installed in the neighbourhood of the manipulator and the pictures from the cameras mounted on the manipulator itself.

The mentioned teleoperation task is a hard job for the human operator. First, the lack of spatial information in the available camera pictures complicates manual control. Besides, task execution suffers from the manipulator dynamics: because of the lightly constructed limbs, the manipulator will be flexible. Finally, 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.

At the Delft University of Technology (DUT), the manual control of a space manipulator at a remote location is an object of study (Bos, 1991). The research is aimed at the development of a conceptual man-machine interface (MMI), that can diminish the three problems mentioned above as much as possible. Elements of the interface are implemented and tested in a simulator (see Figure 2). In this simulator, the movements of the European Robot Arm ERA are simulated by means of a Silicon Graphics graphical workstation (©). This computer animates simplified camera pictures of the ERA movements and additional information displays (©) in real time. Subjects control the movements with a Spaceball® control device (©): a force activated control device with six degrees-of-freedom (DOF’s).

Generally spoken, the activities of a space manipulator can be subdivided in two elemental tasks: the positioning task and the displacement task. Breedveld (1995a and 1995b) has developed the DUT interface for the positioning task. This paper will focus on the development of the DUT interface for the displacement task.

1.2 The space manipulator displacement task

Transportation tasks and inspection tasks are typical displacement tasks. During the execution of these tasks, the manipulator covers large distances. Then, the human operator has to be alert not to cause a collision between the manipulator limbs and objects in the environment. This is not an easy job, because the distances between the manipulator and these objects can hardly be estimated from the available camera pictures. Even worse, sometimes a dangerous object isn't even visible in the camera picture currently observed by the operator.

1.3 The MMI for the displacement task

If we want the human operator to avoid collisions, the MMI for the displacement task has to provide the operator all the information he needs to be able to estimate and control the actual risk of a collision for all parts of the manipulator. Two instruments can provide the necessary information: sensors measuring the current manipulator position, and (obviously) the available cameras. In the case of the European Robot Arm, a number of cameras are located on the ISS (environment cameras), and others are mounted on the ERA itself (four robot cameras; see Figure 1). Besides, the actual joint angles are measured by angle sensors, and the locations of the elements of the ISS are registered in a geometry database (the world model).

This paper will guide you through three stages in the design of the DUT interface for the displacement task. In the first stage, the information to be presented at the display-side of the interface has been selected. Here, one of the available camera pictures has been chosen to be the central camera picture on the interface console. In the second stage, the six Spaceball DOF’s have been mapped consciously to the movements of the manipulator in that picture (design of the control method). Third, a graphical overlay has been designed. This overlay emphasises the spatial information in the central camera picture, and presents additional information about the collision risk at the locations that are invisible in it.

2. THE DISPLAY–SIDE OF THE INTERFACE

2.1 Introduction

In current teleoperation testbeds (e.g. Pauly and Kraiss, 1995; Blackmon and Stark, 1995; Silva and Gonçalves, 1993; Bejczy, 1996) all of the available camera pictures and position information are often integrated in a small number of spatial information displays. Each of these displays presents a different view of the remote environment to the operator. This view can either be an existing camera picture with a spatial graphical overlay, or a synthetic spatial image of the environment (an artificial camera picture). In both cases, 3D computer graphics are used to visualise the available position information.

2.2 Two subtasks in the displacement task

The availability of multiple viewpoints of the remote site is important for planning the rough collision-free path to the desired location of the manipulator; in this planning subtask, information about the whole working environment is of major importance. But while moving along a chosen path, that is not the case anymore. For this...
control subtask, the operator requires detailed information about the collision-risk at the current manipulator location only. If he is expected to extract this information from the same information displays as the ones used for the planning subtask, the operator may find difficulties, especially if the manipulator has to cover large distances. Then, multiple (artificial) camera pictures can show valid information at the same time. E.g. one picture might show the current position of the end-effector, and another one might show a hazardous object at short distance from the manipulator base. Then, it can be difficult to decide on future control actions.

Until now, relatively small attention has been paid to the operator's information needs in the control subtask. In most of the current teleoperation testbeds, the above mentioned planning-oriented displays are applied to pre-program the desired displacement (e.g. Blackmon and Stark, 1995), or to perform the job in (semi-)supervisory control (e.g. Park, 1991). Generally, fully manual control of gross motions is only a redundant control method meant for extraordinary situations in which the normal control method is malfunctioning. Consequently, there is no proper display concept for the control subtask. For this reason the development of the DUT interface for the displacement task has mainly been focused on that part of the job. It is assumed that suitable planning-oriented displays are available, and that the operator already knows the rough collision-free path to the desired location while using the information display for the control subtask.

2.3 The information display for the control subtask

In the ideal situation, all the information the operator needs for the control subtask is visualised in one single spatial image of the current manipulator location. To ensure that this image will always show valid information, the viewpoint of the image has to move simultaneously with the manipulator movements. In the ERA case, the viewpoint for a synthetic 'best view' of the current manipulator environment can always be computed from the actual manipulator position and the ISS world model. For a teleoperator with moving base, Das (1989) proposed to calculate the viewpoint from which the operator can see the end-effector, and the two objects at the shortest distance from the manipulator. Then, the operator always controls the movements of the end-effector in the best view of the area with the largest danger of a collision. Unfortunately, with this method, the automatic movements of the artificial camera are tied up with the locations of objects in the actual environment of the manipulator. Then, it is difficult for the operator to predict the camera movement that will result from his intended manipulator movements. Therefore, he must check in which way he looks at the remote environment after each control action. This 'mental displacement' of the viewpoint will take more time in case the viewpoint change is large (experiments carried out by Kleinhans (1992) confirm this theory).

A more intuitive way to move the camera viewpoint simultaneously with the manipulator movements can be realised by using the picture from an (artificial) robot camera. If the control method is consciously designed, the operator will know exactly in which direction the 'home limb' of the camera will move for each elemental movement of the manipulator. Then, the mental viewpoint displacement will hardly take any time. Ultimately, the mapping between the movements of the control device and the camera movements results in a feeling of telepresence (Sheridan, 1992): the operator feels as if he controls the movements of his own eyes in the remote environment and flies along with the manipulator. In that case, he might well be able to perceive spatial information in the camera picture in a similar way as in daily life. According to Gibson (1979), the flow patterns in the retinal picture of the human eye (optic flow) form an essential cue for body motion perception in daily life. While displacing a space manipulator, the home limb of a robot camera will never move in the accompanying camera picture. The operator must perceive the manipulator motion from the resulting movements of the objects visible in the background of the picture. This continuous flow of objects might well be an analogue cue for manipulator motion perception as optic flow is for body motion perception in daily life.

In the DUT spatial information display for the control subtask, the above mentioned idea has been adopted. The picture of the elbow camera mounted on the ERA forearm (camera 3 in Figure 1) is the central spatial image in the display. Figure 3 shows the elbow camera picture as it is animated in the experimental facility. The picture will always show the movements of the end-effector, and two other parts of the manipulator often in danger of a collision: the wrist and the forearm. Since the elbow camera is mounted near the elbow, the forearm will partially cover the operator's view of the actual environment at any time.

![Figure 3 The ERA elbow camera picture](image-url)
The usage of the elbow camera picture makes two demands on the further design of the MMI for the control subtask. First, a control method has to be found, that enables the operator to predict the camera movements that will result from his intended control actions. Second, the graphical camera overlay has to provide information about the danger of a collision for the invisible parts of the manipulator: the upper arm and the backside of the forearm. In an ideal situation, the visualisation of the collision risk in the overlay suggests the control actions required to minimise this danger simultaneously. The graphical overlay has to be adapted to the applied control method to achieve this aim. Therefore, the choice of the control method preceded the development of the graphical overlay.

3. THE CONTROL–SIDE OF THE INTERFACE

3.1 Introduction

With the force-activated Spaceball, the translational and angular velocity of a spatial object in a three-dimensional workspace can be controlled intuitively. The magnitude of the force (torque) applied to the Spaceball determines the magnitude of the object’s translational (angular) velocity. The direction of the applied force (torque) determines the direction of the object’s translational (angular) velocity. So, if the user grasps the Spaceball as if he grasps a car’s gear lever, he might feel it as if he grasps the controlled object (virtual grasping). Normally, if a Spaceball is used to control the movements of a robot, the principle of kinematic control is applied. With this method, the operator virtually grasps the end-effector. After he has defined a desired end-effector pose change, the joint velocities necessary to attain the desired pose change are automatically computed from the manipulator’s inverse kinematics. The implementation of kinematic control requires the choice of a control base frame. This is the coordinate frame in which the operator specifies the desired end-effector pose changes. After the control base frame has been chosen, the mapping method must be selected. This method defines in which way the six Spaceball DOF’s are mapped to changes of the end-effector pose in the control base frame.

3.2 The choice of the control base frame

The origin of the control base frame (the control origin) is imaginarily and inseparably linked to a part of the space manipulator. The orientation of the frame defines the principal movements of the end-effector. The operator can define a desired translation of the end-effector as a combination of three orthogonal translations in the directions of the frame axes. A desired change in orientation can be defined with a rotation vector. The direction of this vector defines the direction of the rotation axis; the vector length defines the rotation angle. Position and orientation of the control base frame have to be chosen carefully. To avoid mental rotation problems, the orientation of the frame in the elbow camera picture should never change. Therefore, the orientation of the control base frame has been equated to the orientation of a frame imaginarily linked to the elbow camera (the camera frame; see Figure 5). The frame position (as defined by the control origin) determines the point that is insensitive for rotation commands. At first sight, it seems wise to place the control base frame upon the end-effector (the end-effector frame; see Figure 5). In this case, the end-effector position and orientation can be controlled separately. E.g. if the control origin is located at the end-effector tip, the operator can first move the tip to the desired location. After that, the orientation of the end-effector can be corrected without changing the tip position. Unfortunately, in the case of the ERA, the usage of an end-effector frame has a major drawback. In almost all poses of the manipulator, a movement of the end-effector in one of the principal movement directions will require rotations of all six ERA joints. Because of this, all manipulator limbs will move in different directions during the change of the end-effector pose. Then it will be difficult for the operator to predict the resulting limb and camera movements. As a result, he can hardly control the collision risk around the limbs.

To avoid the mentioned problems, the control base frame has been placed at the end of the forearm: the wrist (see Figure 5). Now, a translation in the direction of one of the frame axes requires rotations of the two shoulder joints and/or the elbow joint only (see Figure 6). Generally, an end-effector rotation defined by a rotation vector located at the control origin will still require movements of all joints. But this number of joint rotations can now be decreased if the desired orientation changes are no longer specified with rotation vectors.
3.3 The choice of the mapping method

Just like the six principal movements of the end-effector are defined by the control base frame, the six principal movements of the Spaceball are defined by the Spaceball frame. The origin of this frame is imaginarily linked to the centre of the Spaceball sphere. The orientation of the frame defines the mapping method: a translation or rotation of the Spaceball in the direction of one of the frame axes results in an analogous displacement of the end-effector in the control base frame.

Earlier man-machine experiments with the DUT interface for space manipulator positioning tasks have shown the benefits of the downward mapping of translations (Buiël and Breedveld, 1995). With this method, the operator must push the Spaceball downward in the elbow camera picture to translate the end-effector parallel to the elbow camera lens (the movement reference plane). Because of the demonstrated advantages of this mapping method, it has also been implemented in the DUT interface for the displacement task. In accordance with the downward mapping of translations, the Spaceball x- and y-rotation have been mapped to the yaw- and pitch-rotation of the end-effector resp. Finally, the Spaceball z-rotation has been mapped to the end-effector roll-rotation.

4. THE GRAPHICAL CAMERA OVERLAY

4.1 Introduction

The chosen control method ensures that the operator can predict the resulting limb movements for every displacement of the end-effector. If a limb is in danger of a collision, the graphical overlay for the elbow camera picture can now assist the operator in avoiding the collision by suggesting the limb displacement that’s needed to decrease the collision danger. An intuitive way to do this is to visualise the shortest distance between the limb and the hazardous object in the environment. At DUT, de Beurs (1995) developed a computer algorithm for computing distances between objects in the ISS world model. For each pair of objects, the two object nodes at closest distance are calculated by the algorithm in very little computing time. If both nodes are visible in the camera picture, the distance can be visualised by means of a cleverly shaped distance line (see 4.2). If they’re not visible, the control actions required to decrease the collision risk have to be visualised in a different way (see 4.3).

4.2 Visualisation of distances with distance lines

Figure 7 shows the basic idea for the graphical overlay with distance lines (de Beurs, 1995). Three dashed lines visualise the closest distances between the space manipulator and the elements of a central truss at the ISS. To the operator, it seems as if each of the lines is...
Figure 7 Elbow camera picture with basic distance lines

actually present in the remote environment. Pilot experiments with this distance line overlay demonstrated the usefulness of the added distance information. But they also indicated two problems inherent to the shape of the distance lines. First, if both the environment-end and the manipulator-end of a distance line are (almost) in one line with the viewing direction of the elbow camera, the operator can hardly estimate the length of the line. Second, the danger of a collision increases at the moment the length of the distance line decreases. This is a major drawback from an ergonomic point of view: at the moment the danger grows, its display indicator becomes less eye-catching. Ultimately, at the moment a collision occurs, it isn't even visible.

Next to the shape of the basic distance line, Figure 8 shows three alternative shapes for this line that (partially) come up to the observed problems. The first option, the elastic line, solves the first problem only. The cross-section of this line increases after a decline of the line's length. Indeed, if it is observed from one of its ends, the line becomes more distinctive at the moment its length decreases. But if it is observed from the side, the line will still be flattened. The second option, the sphere, solves this problem. Here, a sphere marks the environment-end of the original distance line. The sphere radius increases while the indicated distance decreases. Since its size now grows in all directions, the distance indication will be clearly visible from any side. Note that at the moment the sphere radius equals the remaining distance, the manipulator will intersect the sphere (distance < 5 cm in Figure 8). At this moment, the maximum amplitude of the limb vibrations due to the limb flexibility roughly equals the remaining distance, and major attention is needed from the operator. To indicate this, the sphere changes color (green turns red).

In this way, the sphere provides information about the manipulator flexibility and solves both of the observed visualisation problems at the same time. But it introduces a new problem also. At the moment the sphere does not intersect the manipulator, it does not visualise the direction of the distance line. The third (and finally preferred) option, the raindrop, solves this problem. Here, the sphere merges with a dashed cone when the indicated distance exceeds the sphere radius. The top of the cone marks the manipulator-end of the original distance line. At the moment the sphere radius exceeds the distance once more, the raindrop turns into a sphere again. Figure 10 shows the resulting elbow camera picture with raindrop-shaped distance lines. Once again, the picture shows three distances to a primary truss of the ISS. At the location of the large sphere, the distance between the manipulator and the truss is almost zero.

<table>
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<th>Distance</th>
<th>Basic line</th>
<th>Elastic line</th>
<th>Sphere</th>
<th>Raindrop</th>
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<td><img src="image6" alt="Sphere" /></td>
<td><img src="image7" alt="Raindrop" /></td>
</tr>
</tbody>
</table>

Figure 8 Four optional shapes of the distance lines
Figure 10 Elbow camera picture with raindrop-shaped distance lines

4.3 Visualisation of the collision danger outside the visible area

Two parts of the ERA are invisible in the elbow camera picture: the upper arm, and the backside of the forearm. The collision danger for the backside of the forearm can be visualised by virtually transforming the forearm into a transparent glass tube. As a result, the raindrops currently located at the backside of the forearm will be visible at the back of the tube. Of course, this strategy cannot be applied to visualise the collision danger around the upper arm. The distance lines located near this manipulator limb will normally be located outside the viewing volume of the elbow camera. For each of these invisible raindrops, the overlay must visualise the size of its sphere and the direction of its dashed cone in a different way.

Figure 9 shows an example of a situation in which the upper arm is in danger of a collision. Here, a hazardous object is located close to the bottom of the upper arm. The direction of the accompanying distance line is visualised in a cross section of the upper arm. Because of the cylindrical shape of the upper arm, this line will always be directed perpendicular to the surface of the upper arm. The radial position of the line (quantified by the angle \(\alpha\)) is an important cue for the determination of future control actions. Since the line is located at the bottom of the upper arm, the operator knows that a collision will occur if he moves the wrist forward. In the same way, if the line would have been located on the left side of the upper arm, a collision would have occurred if he had moved the wrist to the left.

From Figure 9, it can be concluded that the radial position of each invisible distance line implicitly shows the control action that’s needed to decrease the local collision risk. This important observation is utilised in the display indicator for the collision danger around the upper arm (see Figure 11). The main element of this indicator is a large circle. This circle represents the cross section of the upper arm. For each invisible distance line, a sizeable sphere marks the location of its manipulator-end (e.g. the sphere located at the bottom of the circle in Figure 11 represents the location of the hazardous object visible in Figure 9). Just like the raindrops in the elbow camera picture, the sphere radius increases while the indicated distance decreases. From the radial position of a sphere, the operator can read the control action that’s needed to decrease the local collision risk.

5. CONCLUSIONS AND FUTURE RESEARCH

In this paper, most attention has been paid to the problem of collision avoidance during gross motions of a space manipulator. The developed graphical overlay with spherical and raindrop-shaped distance indicators...
clearly visualises the locations currently in danger of a collision, and the control actions that are needed to decrease the danger. As a result, the overlay provides a solution for the first general problem in teleoperation tasks: the lack of spatial information in the available camera picture(s). At the same time, a solution for the second problem - the flexibility of the manipulator limbs - is provided. Raindrops and spheres implicitly show the maximum amplitude of the manipulator limb vibration caused by the flexibility of the limbs. Only the last problem - the introduction of time delays when the operator controls the manipulator on earth - has not been considered yet.

In the near future, man-machine experiments will be carried out to demonstrate the usefulness of the provided distance information. Finally, the time delay problem will be considered. To eliminate this problem, the developed spatial information display will be transformed into a setpoint display (Breedveld, 1995b). A setpoint display visualises the operator's control actions (i.e. the setpoint for the manipulator velocity) immediately after they have been carried out. E.g. the movements of a transparent (phantom) manipulator can visualise the current velocity setpoint. Since he can directly see the results of his control actions, the operator does not have to wait until actual camera pictures arrive at his location.

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