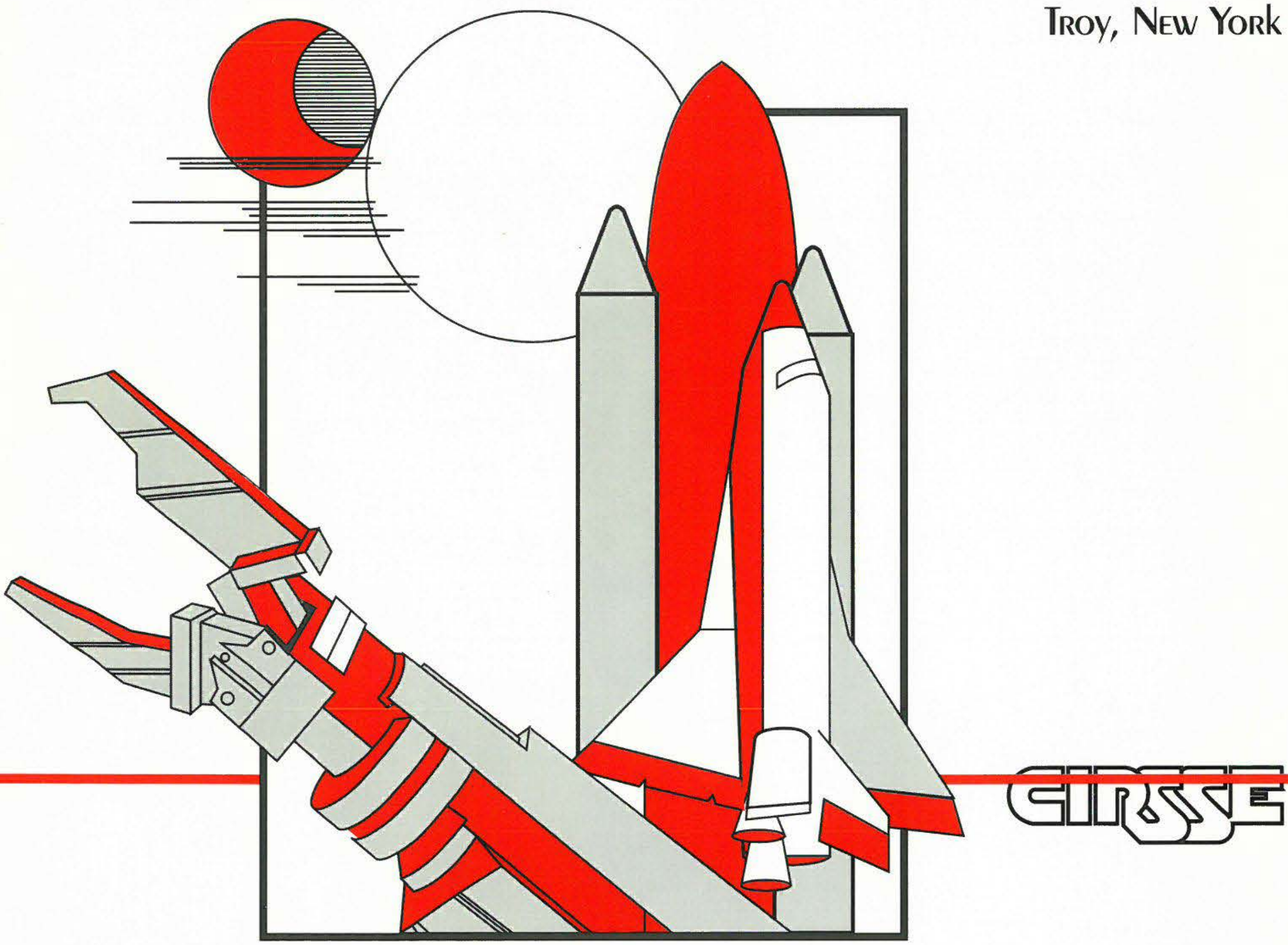
Proceedings

Third Annual Conference on Intelligent Robotic Systems for Space Exploration

November 18-19, 1991
Troy, New York



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The Institute of Electrical and Electronics Engineers, Inc.

Using Capaciflectors for ORU Docking

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Abstract

On-orbit servicing of spacecraft will require the changeout of their components in space. These components are usually configured into Orbital Replacement Units (ORUs) so that they can be handled by astronauts performing Extra-Vehicular Activity (EVA). Current research in robotics concerning supplementing or replacing EVA use vision and force feedback. Unfortunately, these sensor modalities do not offer a simple way of sensing proximity and avoiding collisions between the ORU and the environment. We propose to use a capacitive sensor for the detection of proximity of the ORU to objects. This sensor provides position and orientation feedback, which can be useful in the positioning and alignment of the ORU with respect to the docking fixture. In this paper we describe an algorithm that has successfully docked and undocked an ORU in a space allowing less than 1" clearance without touching. The resulting algorithm is simple to implement, has modest computational requirements, and is able to continuously prevent collisions of the ORU with the environment.

1. Introduction

Long term science missions proposed for Space Station Freedom (SSF) and Earth Observation System (EOS), have provided a major stimulus for developing subsystems that can be serviced on-orbit. These modules are usually packaged into Orbital Replacement Units (ORUs) that can be handled by astronauts performing Extra-Vehicular Activity (EVA). However, a recent NASA report indicated that EVA effort alone will not be sufficient to support all ORU replacement activity required for the external maintenance of SSF [3]. In addition, other spacecraft such as EOS will be unmanned. Therefore, the utilization of robotics will be essential in the on-orbit servicing of spacecraft.

Our emphasis in research is the investigation of the role of a capacitive sensor [1] in the task of robotic changeout of ORUs. Traditionally, information on the task site is provided by vision and force feedback [4]. Unfortunately, these modes do not allow a simple means of sensing proximity and avoiding collisions between the ORU and the environment. In addition, we feel that proximity sensing capability will provide valuable data on the position and orientation of the ORU with respect to the fixture we wish to dock into. The sensor being used in our testbed relies on the capacitive effect to detect objects. The sensor output provides analog range information and it has a range of approximately 18". The sensor characteristics are described below in further detail.

In the following section, the experimental setup and sensors will be presented. Afterwards, the docking algorithm using the capacitive sensors will be explained in Section 3. In Section 4, experimental results are discussed, followed by the conclusion in Section 5.

2. Experimental setup

A simple setup was chosen as our initial test bed for ORU docking. All contacts between the ORU and the environment are avoided since our current hardware setup does not have any compliance to relieve contact forces that can build up. The task consists of docking the ORU into a fixture that is fastened to an aluminum sheet, Figure 1. Here, docking is defined as positioning the ORU into the fixture while maintaining equal clearance on all sides. We desire to perform this task using only four capacitive sensors mounted on the bottom corners of the ORU and to use no prior knowledge of the position and orientation of the fixture. It is assumed that the operator will have some limited view of the task site in order to direct the overall motion of the ORU. However, collision avoidance and alignment of the ORU in the fixture is automatically handled by the docking algorithm using the four sensors.

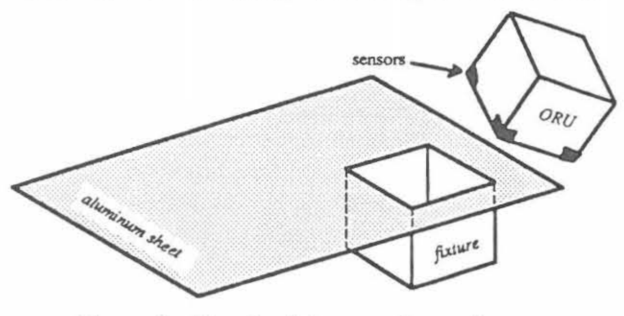

Figure 1. Sketch of the experimental setup.

The ORU is constructed out of aluminum and measures 13"x13.5"x9", while the fixture is constructed out of fiberglass covered by a layer of aluminum foil and

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measures 15"x15"x10". The overall clearance on the sides of the ORU while it is inserted into the fixture is thus between 3/4" and 1". The aluminum sheet measures 32"x50".

In principle, we can imagine the aluminum sheet to be part of the space craft, or the top face of other ORUs that are docked; their sides make up the sides of the fixture. In addition, there may be multiple open fixtures ready to accept ORUs. During the docking maneuver, there will be opportunity for the operator to specify which fixture he intends to use.

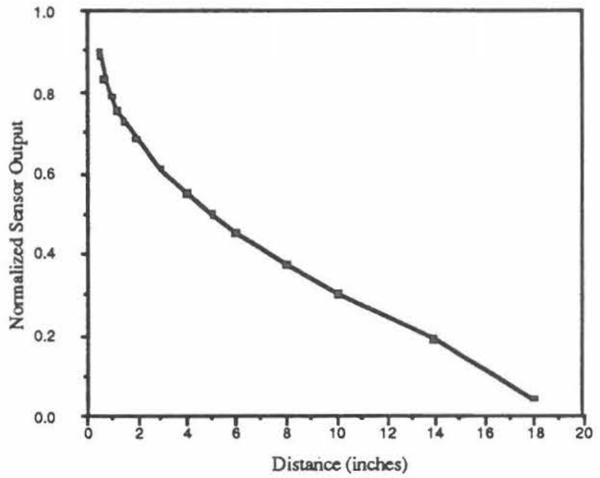

Figure 2. Plot of the normalized sensor output versus distance to test object.

The capacitive sensors were developed at the NASA Goddard Space Flight Center [1]. They are sensitive to all conductive and dielectric objects including metal objects and humans. As the plot in Figure 2 shows, their range is about 18". Four capacitive sensors are mounted on the bottom in the corners of the ORU. They are placed so that in addition to being sensitive to objects on the bottom of the ORU, they are also able to detect objects that are near the sides of the ORU. In this manner, some feedback on the position of the ORU can be gained while it is being inserted into the fixture. A plot of the data from one of the sensors (normalized to a scale of 0 to 1) versus the distance to a test object is shown in Figure 2. The sensors undergo a calibration procedure to ensure that they possess identical responses to objects. The data is then linearized by using the logarithmic function, and then normalized to a scale of 0 to 1, corresponding to situations with no object, and close contact respectively.

3. The docking algorithm

The algorithm consists of five major steps, performed in the following sequence:

a) Leveling, the ORU is brought near the aluminum sheet until it is detected by at least one of the sensors. The bottom face of the ORU, which contains the sensors, is then automatically leveled against the aluminum sheet, and brought to a distance of 2" to the sheet.

b) Jogging, the operator uses keystrokes (or a joystick) to bring the ORU to the desired fixture (in our case there is only one) until at least one of the sensors is near the edge of the fixture's hole. The motion of the ORU in this step is parallel along the face of the aluminum sheet. The distance to the sheet is adjusted continuously to maintain the 2".

c) Centering, the ORU is then automatically centered above the fixture's hole if at least one sensor detects the hole.

d) Rotating, the ORU is rotated above the fixture, aligning the ORU such that the sensor outputs are minimized.

e) Insertion, lastly the ORU is inserted into the fixture, while maintaining maximum clearance on all sides.

At all times the ORU's distance to the nearest object is monitored and adjusted. If the aluminum sheet moves away, the ORU follows; on the other hand, if there is motion towards the ORU by the aluminum sheet, or if there is an impending contact, the ORU's position is controlled to automatically and continually avoid collisions. Individual parts of the docking algorithm will be discussed in further detail below.

Frames and vectors

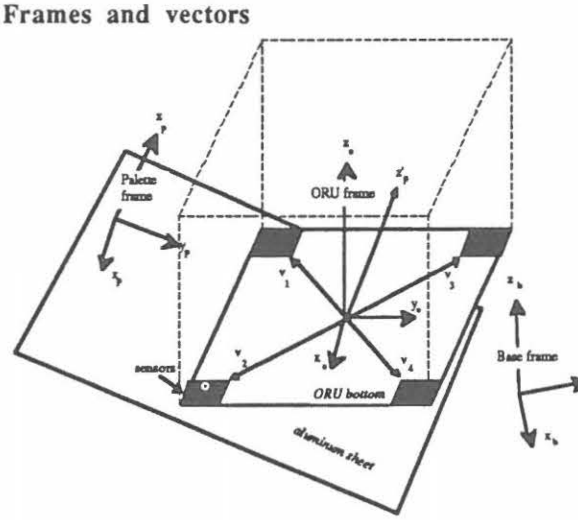

Figure 3. Vectors and frames used in the docking algorithm. The dark rectangles are the sensors, vector v_i identifies sensor i.

There are three frames involved in the docking task. The first frame is the *base frame* of the robot arm in which commands to the robot are given. Its location and orientation will vary depending on the convention decided by the robot manufacturer. The second frame is the *ORU* *frame*; its origin is centered on the bottom face of the ORU, its z-axis being parallel to the normal of the bottom face of the ORU. The pose (position and orientation) of this frame with respect to the base frame can be found by using the forward kinematics of the arm and its current joint angles. The third frame is the aluminum sheet frame, also known as the *palette frame*. Its z-axis is parallel to the normal of the aluminum sheet. The location of this latter frame is not known, but its z_p-axis is estimated (in the form of z'_p) by using the data from the capacitive sensors.

3.1 Leveling

The desired orientation and position of the ORU after it has been leveled is such that the bottom face (with the sensors) is parallel and at a set distance to the aluminum sheet. The orientation of this latter object is represented by its normal vector z_p, which estimate z'_p is found using the data from the four capacitive sensors:

$$z'_p = z_o + K_s (s_1 v_4 + s_2 v_3 + s_3 v_2 + s_4 v_1) \quad (3.1)$$

where: s_i - output from the i^{th} sensor.

v_i - vector describing the location of the i^{th} sensor in the ORU frame.

z_o - normal of the ORU bottom in the ORU frame.

z'_p - estimated normal of the aluminum sheet in the ORU frame.

K_s - sensor gain.

If all four sensors detect the same distance to the aluminum sheet, the second term on the right of equation 3.1 will go to zero, since $v_1 = - v_4$, and $v_2 = - v_3$, causing $z'_p = z_o$. If however, there is an imbalance, the vector z'_p will rotate towards the sensor(s) with the highest reading(s). For example, if $s_1 > s_4$ and $s_2 > s_3$, z'_p will be rotated as shown in Figure 3.

To orient the ORU such that z_o becomes parallel to z'_p, we need to rotate over some axis perpendicular to both z'_p and z_o, by an amount equal to the angle between z'_p and z_o, these are found by:

$$a = z'_p \times z_o \quad (3.2)$$
$$alpha = K_o \operatorname{acos} (z'_p \cdot z_o)$$

where: a - the axis of rotation for the ORU.

x - the vector cross product.

alpha - amount of rotation.

K_o - orientation gain.

acos - inverse cosine.

• - vector dot product.

In addition to the rotation of the ORU, its position is also adjusted so that its distance to the aluminum plate is 2". This is done by moving the ORU along z'_p in response to the sensor data:

$$b = K_p (s_m - s_d)\ z'_p \quad (3.3)$$

where: b - ORU cartesian motion.

K_p - position gain.

s_m - output of sensor with highest reading.

s_d - desired sensor output : 0.67 for a distance of 2".

The ORU is positioned and oriented repeatedly until the angle between z'_p and z_o goes to zero and it is located a certain distance from the aluminum sheet. The ORU is then said to be leveled. Note that the dynamical behavior and convergence characteristics of this procedure is controlled by adjusting K_o, K_s, and K_p. Larger values for these gains will cause faster motion, at a risk of overshoot and other unstable behavior.

3.2 Jogging

Once the ORU is leveled, the operator can specify into which of the available fixtures he wishes to dock the ORU. This is done by jogging the ORU parallel to the aluminum sheet until one of the sensors detects the fixture's hole. Note that equation (3.3) is still used to maintain a constant distance between the aluminum sheet and the ORU. In this manner, collisions can be avoided if the aluminum sheet shifts. In addition, if there is a step in the aluminum sheet, due to perhaps a protrusion, the ORU can automatically hover over the obstruction.

$$b = K_p(s_m - s_d)\, z_o + o \quad (3.4)$$

where : b - ORU cartesian motion

o - Operator motion command in ORU frame

K_p - position gain

3.3 Centering

After the ORU is positioned near a fixture, the data from the sensors is used to generate an error signal to center the ORU in the hole. The key element in each of the major steps during docking is the goal to equalize the data from all four sensors. During the 'leveling' portion of the algorithm, the combined data is used to orient the ORU using only rotation to decrease the difference between the output of the sensors. In the case of 'centering', the combined data is used to move the ORU parallel to the aluminum sheet in order to reduce any differences between the sensor outputs. When all sensors are equal, the ORU is centered over the hole, with all four sensors being positioned an equal distance to the walls of the fixture. The control function used during centering is:

$$b = K_p(s_m - s_d)\, z_o + K_c\, (s_1 v_4 + s_2 v_3 + s_3 v_2 + s_4 v_1) \tag{3.5}$$

where : b - ORU cartesian motion
Kc - centering gain
Kp - position gain
s_d - desired sensor output : 0.67 for centering

The term $K_p(s_m - s_d)\, z_o$ on the right hand side of equation (3.5) causes the ORU to 'hover' with a constant sensor reading over the aluminum sheet. The quantity K_p controls the convergence characteristics and speed of the cartesian motion.

The remaining term on the right hand side of equation (3.5) moves the ORU away from the sensors that are detecting the aluminum plate towards those that aren't. In this manner, the ORU will be halted when it is centered over the fixture's hole. Note that the centering gain, K_c, controls the dynamical behavior of the ORU as it centers. If the parameter is chosen too large, the ORU will overshoot while choosing it too small will lead to sluggish convergence.

3.4 Rotating

Once the ORU is centered over the hole, it is aligned with it using this step of the docking algorithm. The ORU is rotated around its z_o-axis until it can be inserted into the fixture. It is important to note that when the data from all four sensors is averaged, we obtain a minimum when the sides of the ORU are parallel with the sides of the fixture. This point is known as a point of maximum clearance. There are four such locations as the ORU is rotated 360°. Figure 4 shows experimental data that was obtained by averaging the four sensor outputs, and rotating the ORU over 135°.

The algorithm proceeds by rotating the ORU a total of 110° in discrete steps while recording the average from the four sensors. This rotation range ensures that at least one minimum point is included. After this sampling process is completed, the data is sorted to find the angle with the minimum sensor reading. This data point along with its two adjacent ones are then used in a parabolic curve fit. The minimum of the resulting parabola is then used to position the ORU at the point of maximum clearance.

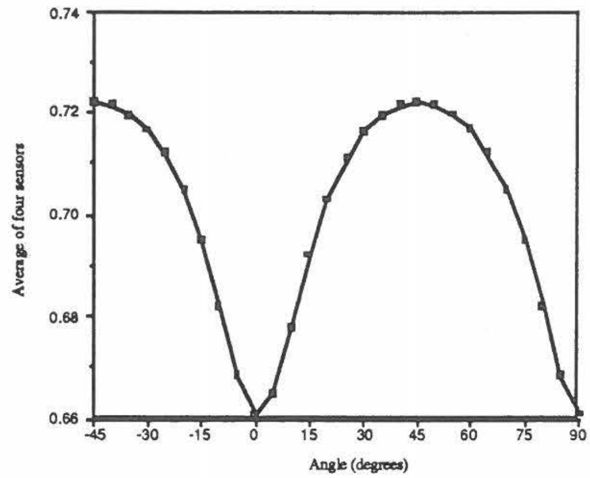

Figure 4. Average sensor data when ORU is rotated while centered over the fixture.

3.5 Insertion

Once the ORU has undergone the previous other steps of the algorithm, it will be ready for insertion into the fixture. In this maneuver, we wish to continue centering the ORU during insertion and move the ORU until the bottom of the fixture is detected. For this step we can simply use equation (3.4), used during the 'centering' part of the algorithm. The only modification will be to raise the desired sensor level so that the ORU will continue to move into the fixture until it detects the bottom. To gain insight into the proper value for the desired sensor output level during insertion, the average sensor value is plotted against the distance between the bottom of the ORU and the aluminum sheet, see Figure 5. Note that the depth of the fixture is 10", negative values for the distance in the figure mean that the ORU is inserted. Using the experimental data as a guide, $s_d = 0.8$ was chosen for the insertion task.

This same methodology can be used for ORU extraction as well. Choosing a value of s_d smaller than 0.75 will cause the ORU to be backed out of the fixture. The final distance of the ORU away from the aluminum plate after extraction is determined by appropriate choice of s_d. For example, a value of 0.4 causes the ORU to backed about 7.5" away from the aluminum sheet.

Note that safety is preserved even if there is insufficient clearance in the fixture due to it being too small, or because of a failure in the 'rotating' portion of the docking algorithm. If the command to 'insert' is given in the case of insufficient clearance, the ORU will be moved closer and closer to the aluminum plate, but will be halted once the desired sensor level has been achieved, preventing a collision.

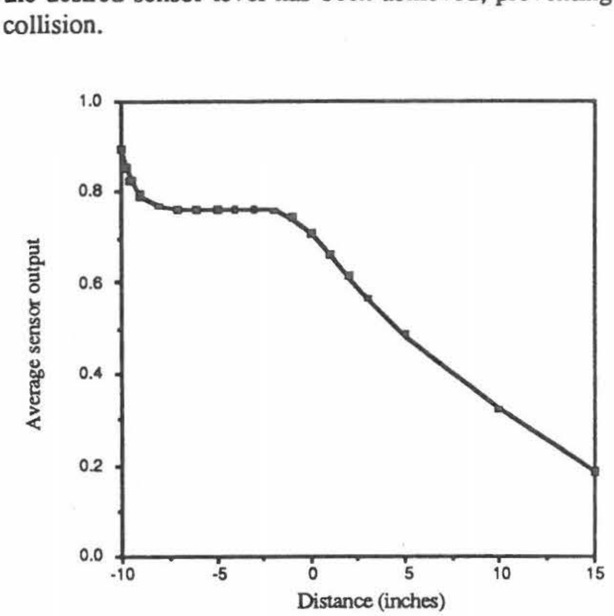

Figure 5. Average sensor data while inserting the ORU into the fixture.

4. Conclusion and further work

The algorithm and experimental results described here concern a procedure for non contact docking of the ORU into its fixture. Once this is accomplished, the ORU can to be mated with the fixture using a device that can tolerate residual misalignments in the position and orientation of the ORU. Such a device is for example the Work Attachment Mechanism/Work Attachment Fixture (WAM/WAF), also developed at Goddard Space Flight Center [5]. In addition to mechanical connection, the WAM/WAF also has the ability to electrically connect the ORU with the fixture. In the future, we intend to equip the ORU with two such WAM/WAFs. One on the top face as connection to the robot, and one on the bottom face for mating with the fixture. By using WAM/WAFs to attach the ORU to the robot, the capacitive sensors on the ORU can be electrically connected.

Our first attempt at docking the ORU into the fixture has been quite successful partly due to the simple setup that was chosen for the test bed. It is desired to remove some of the restrictions that were imposed. This can be for example, not assuming ORUs on all four sides of the fixture, or by having an uneven aluminum sheet around the fixture. In that case, the centering algorithm will have to be modified to account for the missing or lowered side(s).

It is also desirable to combine the 'leveling' and 'centering' move into one. In this manner, it is possible to insert the ORU into its fixture using a technique similar to how a human does the peg-in-hole insertion task. The human is able to detect a force that causes the peg to be inserted upright. For this task to succeed however, more sensors are necessary to enable detection of the position of the top face of the ORUs with respect to the fixture in addition to the current sensors that read the position of the bottom face.

Lastly, it is also desired to have a joystick operator interface. Using this system, the operator can drive the ORU around using a device such as JR3's six degree of freedom force input joystick [2], or Dataglove's six degree of freedom position input system. The operator's command is obeyed whenever the ORU is free to move. If obstructed however, the ORU is moved to best accommodate the operator's commands while avoiding collisions.

Acknowledgement

The authors express their gratitude to John Vranish (NASA Goddard Space Flight Center) for his support for this work.

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