Partial autonomy of space systems enhances safety, reliability, productivity, adaptability, and reduction of overall cost. One of the most important features of a robotic system is its ability to acquire, integrate, and interpret multisensory data to generate appropriate actions to perform a given task. In this paper, we show the feasibility of realistic autonomous space manipulation tasks using multisensory information from a vision, force/torque, and touch sensor. We describe the basic functions of the robotic system including the design, implementation, and integration of each of the sensors mentioned above. The cooperative use of sensors is shown through mating/demating of Module Interchange System (MIS). Autonomous location of the mating element, autonomous location of a guiding light target, mating, and demating of the system are successfully performed.

1 Introduction

Robots are beneficial in replacing humans in tasks which are strenuous, boring, difficult, hazardous, or simply more expensive when performed by humans. Robotics is being used currently in hazardous environments such as those encountered in chemical, nuclear, military, underwater, and spaces applications. A prominent example may be found in space applications such as on-orbit laboratories, servicing and repair facilities for spacecraft, and manufacturing and assembling laboratories. Space applications can be greatly enhanced by the use of robotics and automation.

Because of the complexity of the tasks undertaken by robotic systems in space, as well as the associated risk for humans and valuable cargo, fully autonomous robots in space are still unrealistic. Therefore, a framework in which a robotic system capable of performing a well-defined list of tasks autonomously as a "slave" to a human operator is envisioned. The notion of slave is radically different from the concepts used in teleoperation where a manipulator duplicates the operator's motion or executes preprogrammed commands. In teleoperation, only a robust man–machine interface is required. Instead, the notion of slave in this framework embodies the autonomous execution of predefined tasks using local sensory feedback and intelligence.

Consider a robotic system that can operate in teleoperation mode, which is its main mode. By added sensory feedback and intelligence, the system can be set up by a human operator, then put in autonomous mode to perform a well-defined task, after which it reports a success/failure status of the task and then resumes its teleoperation mode, until the next autonomous task is to be executed. In this configuration, teleoperation is the norm: the robotic system acts as a slave to the operator.

As more sensory feedback and intelligence capabilities are added to the robotic system, autonomy becomes the norm with the human operator acting as a "slave" called upon only when needed to check and/or validate sensory data and authorize/execute the execution of a particular task. As mentioned earlier, neither sole teleoperation nor full autonomy is adequate for safe, reliable, efficient, and cost-effective robotic applications. The tasks described in this report are performed within the scope of partial autonomy. In a teleoperation mode, the human operator sets up the robotic system which is then released to perform a fully autonomous task, and then reports back to the human operator.

The intent here is to demonstrate the feasibility of realistic autonomous robotic manipulation using multisensory information. The environment is fully structured and stationary. Only the relative position of the manipulator/end-effector with respect to the objects being manipulated is unknown. The relative position is recovered using sensors (primarily vision). We will autonomously identify, remove, and replace a faulty or spent module (from orbiter) by a new module (from servicer). A mock-up of the MIS system was designed and built. It is composed of a mating module element, a mounting rack, and a light target. The system will be vision-driven with the force/torque and torque sensors used as safety devices.

In Section 2, the different components of the robotic system are described, namely, the vision, force/torque, and touch modules. In Section 3, the MIS mating/demating operations are detailed with pictorial illustration of each phase. Summary and conclusions are given in Section 4.

2 System Integration

In this section, we describe the robotic system used in the illustration of the cooperative use of sensors to perform a mating/demating operation on the Module Interchange System. First we address the overall structure of the system, then briefly discuss the individual sensing modules: vision, force/torque, and touch.

The general constraints on the MIS experiment are as follows. The initial 2-D position and orientation of the module are unknown. Its height, however, is known. The 3-D position and orientation of the mounting rack where the module is to be inserted, which also holds the light targets, are unknown. The only constraint in this experiment is that the MIS be positioned in the field of view of the camera and be within reach of the end-effector. The world coordinate system is defined with respect to the robotic workstation table and is divided into 2 areas: the mating element area and the target area. This means that the robotic system is expected to find the mating element anywhere in the mating area and locate the light target anywhere in the target area. All the dimensions mentioned above along with the information corresponding to the relative positions of the objects being manipulated in this experiment are stored in a database easily updatable by the operator and directly accessible by each sensor module during the running of the operation.
The MIS experiment illustrating the cooperative use of multisensory information for autonomous operations is performed using the following [Fig. 1].

1. A Cincinnati Milacron 73 – 726 six-degree-of-freedom industrial robot
2. A PERCEPTICS-9200E image processor (CCD camera)
3. Force/torque sensor programmable by the main processor
4. Touch sensor accessible by the main processor

The control of all components of this system is under a VAX 11/785-VMS computer.

The MIS experiment can be summarized as follows. A mating element appears anywhere in the mating area. Its 2-dimensional position and orientation on the table are unknown. The mating element is within the field of view of a camera rigidly mounted on the arm and is within reach of the robot end-effector. The light targets are within the field of view of the camera when the robot is in an arbitrary position within a predetermined area. The paradigm described in the previous section is followed here for the execution of the experiment. The robot is moved by the human operator such that the light target is visible, then the robot is put in autonomous mode. The robot determines the approximate position of the mounting rack using the vision sensor. This measurement is later refined once the robot knows the approximate position of the target. Afterwards, the robot positions itself so that the mating area is within the field of view of the camera and uses its vision sensor to determine (approximately) the 2-dimensional position of the mating element. This measurement is later refined by moving the robot arm closer to the mating element. The robot then picks up the mating element after checking for its presence using the touch sensor. The robot then proceeds to insert the exchange module into the mounting rack.

2.1 Vision Module

In this experiment, the vision sensor (solid-state camera) is rigidly fixed to the robot end-effector in order to simplify the coordinate transformation between world system and camera system. Because solid-state cameras are more rugged and of smaller size they are a better choice for robotics applications. The output of the camera is directly connected to a general-purpose image processor for processing and interpretation. Vision may be used as a substitute for and in conjunction with many of the other types of sensors for the purposes of object detection, recognition, location, and inspection.

During the MIS experiment, the vision system performs the following tasks.

- Identification of 2-dimensional position and orientation of the MIS mating element: Images of the mating element are acquired and processed in order to extract the silhouette of the attachment handle of the mating element. From the zeroth, first, and second moments of this image, the position and orientation of the attachment handle are computed; the technique is detailed in [1].

- Identification of 3-dimensional position and orientation of the mounting element for the MIS: As mentioned earlier, the mounting rack holds 4 guiding lights on which the end-effector locks. The system uses the known relative positions of the targets, their rigidity, as well as the perspective transformation in a pinhole camera model to derive a set of equations from which a unique solution of the calibration matrix relating points in the real world to their images in the camera in question can be obtained. This method has been detailed in [1].

In the next section, we will describe how these two approaches are used to successfully accomplish the mating and demating operations of the MIS.

2.2 Force/Torque Module

Force and torque sensing generally refer to the measurement of the global forces and torques applied on a workpiece by a robot manipulator. In force and torque measurement, we distinguish between active [2] and passive sensing [3,4]. Active and passive force/torque sensors are capable of enhancing the manipulation capabilities of a robot in a variety of tasks such as contact detection, contour following, tool insertion, and mechanical assembly. Force and torque sensors provide a safety device which can interrupt the robot motion when an unexpected obstacle is encountered. In dynamically constrained operations, excessive levels of local force and torque are very common. These sensors can be used as feedback devices that clip or eliminate excessive forces and/or torques.

The force/torque sensor used in this work is the Lord FT-30/100. The sensor is designed for wrist mounting. It uses 8 piezoresistive strain gauges that provide real-time feedback of the location, magnitude, and the orientation of forces and moments. The system is equipped with a processor that resolves the eight raw pieces of data into six cartesian forces and torques at a rate of 83 Hz. During the entire experiment including camera positioning and activation, data acquisition and processing, recognition and manipulation of the mating element, mating and demating of the MIS, the force/torque sensor is active. When the robot encounters excessive force (torque), it stops, waits for a preset time (5 seconds), then proceeds to complete the task where it was left. If these interrupts persist, the system attempts indefinitely to resume its task, until it is manually reset.

2.3 Touch Module

A touch sensor can provide a robot with valuable information that can be crucial in many applications requiring recognition, acquisition, and manipulation of complex workpieces. Obviously, for most general-purpose robotic systems operating in
semi-structured or unstructured environments, the state-of-the-art of vision sensing and scene understanding points towards a need for added sensory capability. Processing of tactile data is generally less complicated because it is not affected by the many variables that affect vision, e.g., shadows, reflections, and variations in illumination [5,6]. The amount of processed data and the complexity of the interpretation methods are much higher in vision than in touch. Intrinsic shape and texture information is readily present in raw touch data; whereas complex and approximate algorithms are required to extract these features from vision data. Touch sensors as presently used in robotics vary from a single-point ON/OFF microswitch to arrays of gray-scale-responsive elements which measure the magnitude of forces applied at each point. Tactile information is often inferred from force measurements [7].

For the MIS experiment, 2 microswitches are mounted inside the end-effector textured compliant surfaces. They are used primarily for inspecting the presence/absence of a workpiece (here, the mating element) between the end-effector jaws. The manipulation experiment is halted whenever the actual reading is different from that expected.

3 Mating/Demating System

In this section, we describe the autonomous insertion and removal of the Module Interchange System (MIS) using the concepts briefly discussed in Sections 2.

3.1 The MIS: Set-Up

The goal here is to autonomously identify, remove, and replace a faulty or spent module by a new module from a tool rack. A mock-up of the MIS has been designed and built [Fig 2]. The system is vision-driven with the force/torque and touch sensors used as safety devices. The MIS hardware consists of a rack located at the corners of the rack’s front surface. These lights are used by the vision system to determine the position and orientation of the rack. The light positions, with respect to the lower left-hand corner of the receptacle, are (1.25, 1.50), (1.50, 7.50), (4.75, 7.50), and (4.75, 1.25). The first dimension is the distance across and the second dimension is the height, both in inches. The initial position and orientation of the exchange module are unknown. Its height, however, is known. The position and orientation of the mounting rack which houses the used module and holds the light the target are unknown. The only constraint in this experiment is that the MIS (exchange module, mounting rack, and target) be positioned in the field of view of the camera and be within reach of the end-effector. All the dimensions mentioned in this section relative to the physical properties of the MIS are stored in a database (MIS database).

3.2 The MIS: Experiment

The MIS experiment involves determining the 2-D position and orientation of the interchange module as well as the 3-D position and orientation of the 4-light target attached to the mounting rack, then performing insertion and removal of the interchange module.

First, in order to locate the mounting rack, the robot moves the camera to a predefined position so that the target area is within the field of view of the camera [Fig 3]. It turns on the 4 indicator lights on the mounting rack, acquires an image of the scene [Fig 4(a)], and then acquires another image [Fig 4(b)] after it turns off the MIS target. The difference image is computed [Fig 4(c)] and the resulting patterns are thinned [2] to find the position of the 4 lights (target) in the image. Their respective pixel coordinates are:

<table>
<thead>
<tr>
<th>Point</th>
<th>i</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td>46</td>
<td>28</td>
</tr>
<tr>
<td>P1</td>
<td>81</td>
<td>39</td>
</tr>
<tr>
<td>P2</td>
<td>45</td>
<td>46</td>
</tr>
<tr>
<td>P3</td>
<td>81</td>
<td>47</td>
</tr>
</tbody>
</table>

Using the camera positioning technique briefly in Section 2.1, we find the 3-D position and orientation of the mounting rack. The resulting position vector in this experiment is:

\[(X_0^p, Y_0^p, Z_0^p, \theta_1, \beta_1, \alpha_1) = (23.36, -19.41, 10.11, 54.6, 104.5, 84.5)\, .\]

The parameters \(X_0^p, Y_0^p, \) and \(Z_0^p\) are in inches; \(\theta_1, \beta_1, \) and \(\alpha_1\) are in degrees. After this experiment, the robot has an approximate idea about the position of the mounting rack. To refine its
measurement, the robot moves the camera closer to and directly in front of the MIS target and then repeats the measurement of the 3-D position and orientation [Fig. 5(a) through (c)]. The resulting pixel coordinates for the 4-light target are:

<table>
<thead>
<tr>
<th>Points</th>
<th>i</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₀</td>
<td>113</td>
<td>86</td>
</tr>
<tr>
<td>P₁</td>
<td>111</td>
<td>46</td>
</tr>
<tr>
<td>P₂</td>
<td>30</td>
<td>86</td>
</tr>
<tr>
<td>P₃</td>
<td>31</td>
<td>43</td>
</tr>
</tbody>
</table>

The corresponding position and orientation of the mounting rack are calculated as:

\[(X_r^0, Y_r^0, Z_r^0, \theta_2, \beta, \alpha_2) = (23.23, -19.62, 9.35, 66.4, 93.0, 90.1)\].

Here also, note the low disparity between the two measurements for \(X^0\), \(Y^0\), and \(Z^0\). By contrast, the correction in the angles is more significant. This was typical of this experiment.

Second, the robot moves the camera to a predefined position high above the mating elements area [Fig. 6] to determine the 2-D position of the mating element. An image is acquired, histogram–equalized, and thresholded [2] to extract the object (module) from the background (table) [Fig. 7(a) and (b)]. The image acquired here is \(128 \times 128\) in size. Using the techniques briefly discussed in Section 2.1, the center of area of the mating module is computed. In the sample MIS experiment profiled here, it was found to be: \((i_1, j_1) = (91, 83)\). The parameters \(i_1\) and \(j_1\) are the row and column pixel coordinates, respectively. Using the camera geometry, the corresponding coordinates with respect to the world coordinate system are:

Figure 4: Image of MIS target with (a) lights on, (b) lights off, (c) difference image.

Figure 5: Close-up image of the MIS target with (a) lights on, (b) lights off, (c) difference image.

Figure 6: The vision system acquires an image of the mating elements area to locate 2-D position of the module to be mated.

Figure 7: Top view of the mating element area: (a) original image, (b) thresholded image. Close-up of the module: (c) original image, (d) thresholded image.

Figure 8: The robot proceeds to pick-up the mating module.
(X_1, Y_1, Z_1) = (11.72, 19.03, 9.50). The Z_1 coordinate, which is the height of the mating module, is known. The dimensions are measured in inches with respect to the word coordinate system.

Third, the robot moves the camera closer and directly above the mating module and acquires another image of the mating module to determine its position and orientation more accurately. This image is similarly processed [Fig. 7(c) and (d)] and the pixel coordinates of the center of area is computed. In this case, they are: (r_2, z_2) = (78, 60).

Using the camera geometry, the corresponding coordinates with respect to the word coordinate system are: (X_2, Y_2, Z_2) = (10.94, 19.22, 9.50). The Z_2 coordinate, which is the height of the mating module, is known. Using the scheme presented in Section 2.1, the orientation is calculated to be -42.9^\circ with respect to the X-axis. Once these values are known, the robot then picks up the module [Fig. 8].

Fourth, the robot proceeds to insert the mating module [Fig. 9]. At this time, the robot has computed the 2-D position and orientation of the mating element. It has also computed the 3-D position and orientation of the mounting rack that will hold the module. The manipulator grasps the module, using the attachment block and inserts it. As the module is inserted, the complement connectors are mated between the end of the rack and the module. At this point, the module has been installed [Fig. 10], and the manipulator releases the attachment block.

The demating operation of the MIS is performed using the same steps to determine the position of the module rack. The manipulation part is simply the reverse action. In this experiment also, it is essential to note that the entire experiment is performed autonomously without any intervention from the human operator. The limitation here is that the mating element, the mounting rack, and the light target are within the field of view of the camera and within reach of the robot arm.

4 Conclusions

In this paper, we described a robotics system that autonomously performs realistic manipulation operations suitable for space applications. This system is capable of acquiring, integrating, and interpreting multisensory data to locate, mate, and demate a Module Interchange System using vision, force/torque, and touch sensors. The experiment was successfully accomplished on a mock-up built for this purpose.

Acknowledgements

The efforts of Dr. R. O. Eason in developing the robotic workstation and documenting the sensor acquisition and interpretation modules are sincerely acknowledged. Mr. B. Bernhard developed the experimental set-up used in this paper; his contributions are sincerely acknowledged also.

References


Dr. M. A. Abidi

Dr. M. A. Abidi was born on December 31, 1955. He received his Principal Engineer (Eq. Master's) in Electrical Engineering in 1981 from the National Engineering School of Tunis, Tunisia. He received his Master's of Engineering (second) in Electrical Engineering in 1985 and the Ph.D. in Electrical Engineering in 1987, both from the University of Tennessee, Knoxville.

In 1986, Dr. Abidi joined the Department of Electrical and Computer Engineering at The University of Tennessee. Specific areas of research include pattern recognition, image processing by computer, and robot vision. He is a member of Tau Beta Pi, Phi Kappa Phi, and Eta Kappa Nu. He received the First State Award in primary graduation, the First State Award in secondary graduation, and the First Presidential Principal Engineer Award. Dr. Abidi is a member in the professional societies of the Institute of Electrical and Electronics Engineering, Computer Society, Pattern Recognition Society, and American Society of Photogrammetry and Remote Sensing.