Orbital Navigation, Docking, and Obstacle Avoidance As A Form Of Three Dimensional Model-Based Image Understanding

J. Beyer, C. Jacobus, B. Mitchell

Environmental Research Institute of Michigan
P.O. Box 8618, Ann Arbor, MI 48107

ABSTRACT

Range imagery from a laser scanner developed at ERIM can be used to provide sufficient information for docking and obstacle avoidance procedures to be performed automatically. Three dimensional model-based computer vision algorithms in development at ERIM can perform these tasks even with targets which may not be cooperative (that is, objects without special targets or markers to provide unambiguous location points). Roll, Pitch, and Yaw of vehicle can be taken into account as image scanning takes place, so that these can be corrected when the image is converted from egocentric to world coordinates. Other attributes of the sensor, such as the registered reflectance and texture channels, provide additional data sources for algorithm robustness.

1. INTRODUCTION

ERIM has been working towards a laser collision avoidance and spacecraft docking system over the last year. Our interest in this project has been motivated by several key events. We have had a long history of using laser radar techniques for precision robotics control for manipulation of parts in jumbled environments, for navigation and obstacle avoidance for vehicle systems (for both factory and natural environments), and for remote data collection for mapping. We recently (October 1987) were selected by NASA Code IC to be the second Center for Commercial Development of Space Automation and Robotics, and have been tasked with developing the sensing systems component of the Fairchild Space Company Team's Flight Telerobotic Servicer (for NASA Goddard).

To support these activities we began working on the design of a system which will allow imaging and docking with uncooperative spacecraft (or other material). By uncooperative, we mean craft which may not have special reflectors or patterns to facilitate the docking operation. This is in contrast to the work currently underway at Johnson Space Center to demonstrate a system which requires designed targets mounted on the spacecraft (i.e. works with cooperative craft). The concept is based on forming range images from a sensor mounted on a maneuverable spacecraft (Figure 1). These range images are then processed by a model-based image processing system to find distinct object locations which can be used to drive a docking/tracking algorithm.

We discuss how this technology, in two different forms, is applicable to both the obstacle avoidance and the precision inspection (and robot control) problems in a Flight Telerobotic Servicer system, and can be used to validate and analyse large space structures, like the Space Station.

2. THE THEORY OF DOCKING

Figure 1 shows a schematic form of the basic docking problem. To be able to maneuver to a given spacecraft, it is necessary to be able to measure its orientation and motion relative to the maneuverable platform precisely. In open space (free from other significant gravitational forces), docking can be directly computed from the relative orientation and motion parameters. In an orbital environment, the computations are more complicated, and also require description of the orbital parameters of one of the spacecrafts.

To determine the relative orientation of a craft, the radial measurements from a sensor on the maneuvering platform to three or more known points (P1, P2, P3) on the craft are sufficient. Figure 2 shows three such measurements, R1, R2, and R3. To calculate the satellite coordinate system's unit vectors, U, V, W, as a function of the maneuvering platform's, X, Y, Z (centered at the sensor):

$$U = (R3 - R2)/\mathrm{abs}(R3 - R2)$$
$$V = (R1 - R3)/\mathrm{abs}(R1 - R3)$$
$$W = U \times V$$

The direction cosine matrix, D, can be converted into any equivalent form, such as pitch, roll, yaw, and is computed as follows:

$$D = \begin{vmatrix} \mathrm{transpose}(U) \\ \mathrm{transpose}(V) \\ \mathrm{transpose}(W) \end{vmatrix}$$

The difference in D from measurement to measurement can be used to estimate changes in orientation (pitch, roll, and yaw) and position for motion estimation. These calculations can be made for any three locations P1, P2, and P3 as long as they are not colinear.

Because of errors in measurement, and because of the possibility of missing measurements (due to loosing identification of P1, P2, P3), it is advisable to feed the the measurements into a Kalman filter. This provides for continuous prediction of spacecraft motion and estimation of probable errors in location.

Table 1. summarizes the design goals for the Johnson Space Center cooperative docking experiment. These have been taken by us as reasonable specifications for the docking sensor, with the exception of the maximum bearing angle, which we believe should be as close to 180 degrees as possible (to allow docking and obstacle avoidance over an entire hemisphere), and pitch/yaw which should allow for +/-180 degrees of rotation.

Table 1. Docking Sensor Requirements and Accuracy

Quantity	Measurement Range	Measurement Accuracy
Range	0-5 mi	1% of range to 0.016 ft
Range Rate	+/-20 ft/s	0.7% of range**1/3 to 0.01 ft/s
Bearing Angle	+/-10 deg	0.05 deg nominally
Bearing Angle Rate	+/-1 deg/s	0.003 deg/s nominally
Pitch and Yaw	+/-45 deg	0.3 deg within 100 ft
Roll	+/-180 deg	0.3 deg within 100 ft
Attitude Rate	+/-6 deg/s	0.01 deg/s within 100 ft

3. THE SENSOR

ERIM's approach to performing the ranging task involves using a three dimensional laser ranger. This technique and the associated technology has been developed and used for obstacle avoidance, robotics applications, and mapping for over ten years. The three dimensional ranger is essentially an optical radar, and is shown in functional form in Figure 3. The laser ranger uses a laser diode operating at 820nm as its source. This diode is amplitude modulated and scanned across the field of view using moving mirrors. The beam is reflected off of the target satellite, and the reflected light is gathered by the receive optics and focused on an avalanche photodiode. The signal from the detector has the same frequency as the laser diode modulation, but displaced in phase. This phase shift is proportional to range.

To measure the phase precisely, a lower frequency waveform is mixed with limiter amplified transmitted and received signals, and the resulting lower frequencies are phase compared digitally. This technique allows range measurement to be made real time, without post processing, except for sensor model correction. By taking measurements in an array, two dimensional images of range data (along with registered reflectance data) are formed. Figures 4 and 5 show representative reflectance and range images of part of a shuttle model (on a non-reflective background to simulated space). Note that range data is indeterminate where reflectance values are zero (black in the reflectance data). Figure 6 shows the range data plotted as a three dimensional surface, after the reflectance channel data is used to gate accurate range values only.

There are two key issues which make the ranging system required for this application somewhat different from those previously designed for vehicle guidance and robotics. The first is the necessity to achieve prescribed ranging accuracies. The basic signal to noise relation is:

$$S/N = Isg^2/(Ishl^2 + Iss^2 + Inep^2)$$

Where Isg is the signal current from the reflected beam, Ishl is the shot noise in the detector due to this signal current, Iss is the shot noise due to solar illumination, and Inep is the detector noise equivalent power current. The range measurement accuracy is limited by this S/N ratio. Figure 7 shows a set of design curves relating range error to S/N for targets at several ranges, and demonstrated some nominal values for an achievable docking system using this technology.

Another issue is the likely necessity for measuring range over progressively shorter range distances to higher accuracies. The basic phase detection-based ranging scheme is limited to range measurement over fixed ambiguity distances which are determined by the laser modulation frequency, f, (and the speed of light, c):

$$Ra = \text{Ambiguity Interval} = c/2f$$

Measurement over varying ambiguity ranges can either be handled by having programmable modulation sources, or by mixing two frequencies, f(1) and f(2). If the ambiguity intervals of each are:

$$Ra(1) = c/2f(1) \qquad Ra(2) = c/2f(2)$$

Then there will be a beat frequency of f(B) and a corresponding ambiguity interval, Ra(B):

$$Ra(B) = Ra(1)Ra(2)/(Ra(1) - Ra(2))$$

4. MODEL-BASED IMAGE PROCESSING

After acquisition of sufficiently accurate range imagery, the problem of docking becomes one of finding usable (accurately locatable, non-colinear) satellite locating points. In the case of the JSC demonstration system, the problem is simplified by mounting highly reflective, coded targets on the satellite in known configurations. In this way, each reflector point can be located and identified without significant image processing being done.

The problem with this approach is that every object may not have these reflectors mounted on it. For instance, every strut used to construct Space Station space frames will probably not be marked this way. If the strut is dropped by either a construction robot or an EVA astronaut, and retrieval is required, features inherent to the strut will have to be used to determine its position and orientation for docking.

To provide this more general capability ERIM has applied a newly developed model-based vision system, VISTA, developed around the Cytocomputer highspeed flight qualified image processing system, a Symbolics 3600 Lisp machine, and algorithms developed for three dimensional surface identification. VISTA (Figure 8) contains three phases: 1) transformations of images into state-labeled feature maps using conventional image processing (for instance to group co-planar adjacent points), 2) transformation of state-labeled maps into composite symbolic feature maps (in Lisp list form) which describe features (such as lines, surfaces, and vertices) and the relationships between them, and 3) identification by matching prototypical feature-based object models with portions of composite feature symbolic feature maps. VISTA system software is comprised of the image processing language C4PL, which supports conventional and morphological image processing on the Cytocomputer and the VISTA-WORKBENCH which defines object structures, relations between features, and the VISTA model matching language (and matcher), for defining object (in this case satellite) libraries to drive recognition.

To find and match satellite features, satellite surfaces, and then surface junctions (or edges and vertices) must be found, grouped and coded symbolically. These symbolic quantities can then be matched against pre-coded satellite models in VISTA's library of known objects. The satellite encoded models are currently hand built, but will be build from symbolic input constructed from the range data taken under controlled conditions in the future. The method for aggregating surfaces is also under development, however two methods have been implemented previously. The first finds co-planar points by using local plane estimates, and then the degree of fit of each neighborhood range point to the estimated planes. If the individual range points fit the estimated plane well, then the local area is marked as flat (the flat state). If the points do not fit the plane well, then the areas is marked as discontinuous. If the range points jump discontinuously, then the region is marked as a step discontinuity, otherwise it is left as a roof discontinuity. These states are then used to extract a composite feature map, and matched against models for object segmentation, and then satellite (and therefore, satellite feature point) identification.

A similar surface aggregation algorithm developed by Besl and Jain is being coded to allow generalization from planar surfaces to surfaces which are described by more general polynomials. This enhancement may not be required for satellite docking, because for the large number of planar surface typically found in man constructed objects.

5. APPLICATIONS AND FURTHER WORK

This approach to docking is actually a direct application of three dimensional imaging and model-based image processing to the satellite location and orientation finding problem. This problem is also part of the solution to the collision avoidance problem between controlled multiple robots, between the robots and their workspaces, and between free-flying objects. These problems are all important for the Flight Telerobotic Servicer system, and will be addressed as this project continues.

The automatic generation of VISTA object models is related to the problem of making a consistent CAD database (composed of high-level graphical entities, as opposed to simple collections of range points) from range measurements. We have solved this problem for encoding complex surfaces as meshes, but must do more work to reliably convert these meshes into simpler, and more general graphical entities. This capability allows the accurate capture of solid objects, and can be used as input to solids modelling system to verify accurate object mating, without building and fitting mock-ups. As structures in space become more complex, this capability will be routinely required as part of subsystem physical checkout.

6. REFERENCES

1. Besl, P. and Jain, R. 1985. Intrinsic and extrinsic surface characteristics. Proceedings of Computer Vision and Pattern Recognition Conference (San Francisco, CA, June 9-13), pp. 226-233.

2. Sampson, R., Swonger, C. W., VanAtta, P. 1984. Real Time 3 Dimensional Image Processing for Robot Applications. SME Robots 8, (Detroit, June).

3. Crimmins, T. R., W. M. Brown, 1985. Image Algebra and Automatic Shape Recognition. IEEE Transactions on Aerospace and Electronic Systems.

4. Jacobus, C., 1986. Autonomous Delivery Vehicle Systems. USPS Advanced Technology Conference, (Washington, D.C., September).

5. Mitchell, B., Gillies, A. 1987. A System for Feature-Model-Based Image Understanding. ERIM Report.

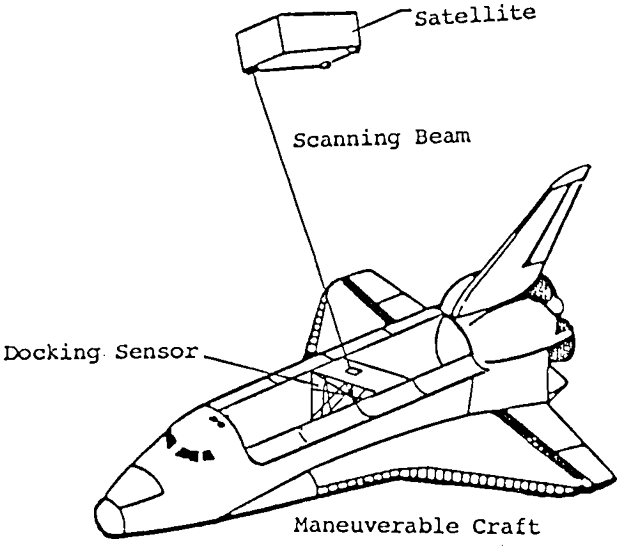

Figure 1. The Laser Docking System Concept

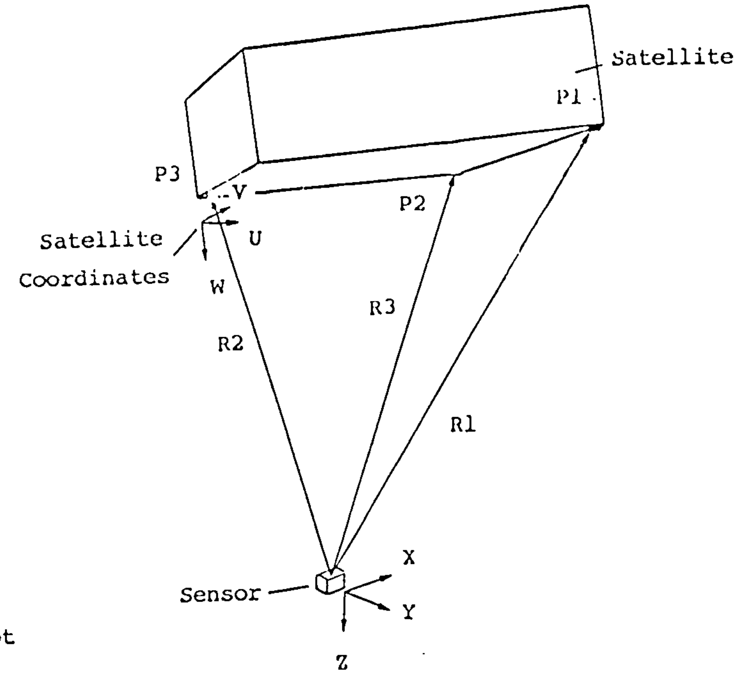

Figure 2. Laser Range Measurements

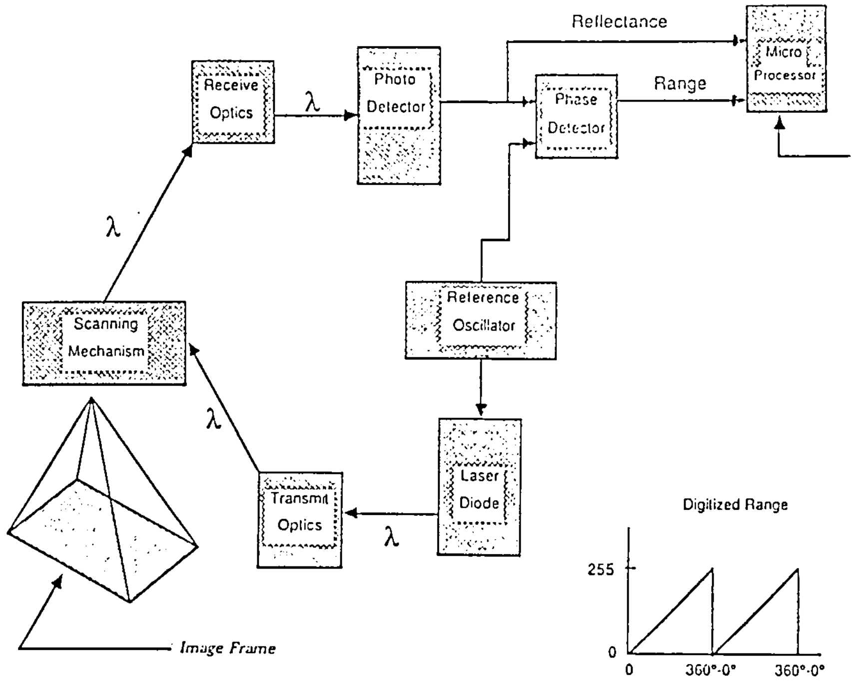

Figure 3. 3D Scanner Block Diagram

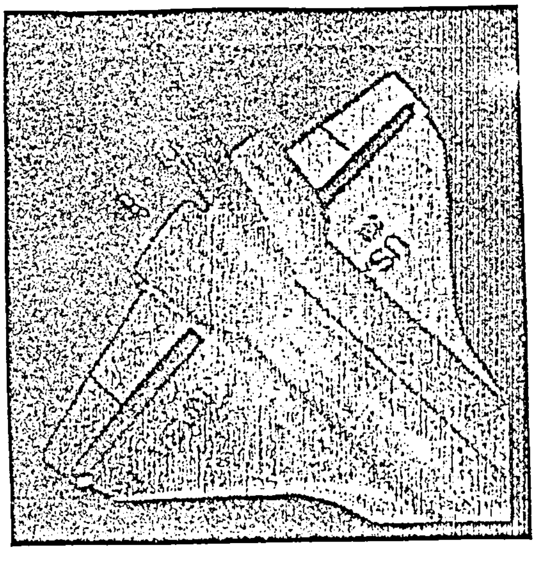

Figure 4. Shuttle Reflectance Image

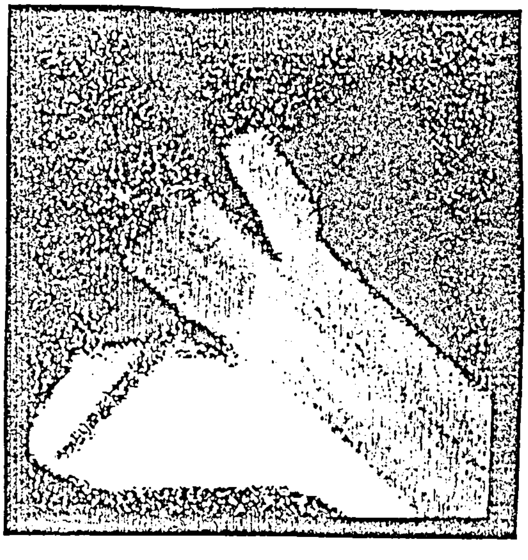

Figure 5. Shuttle Range Image

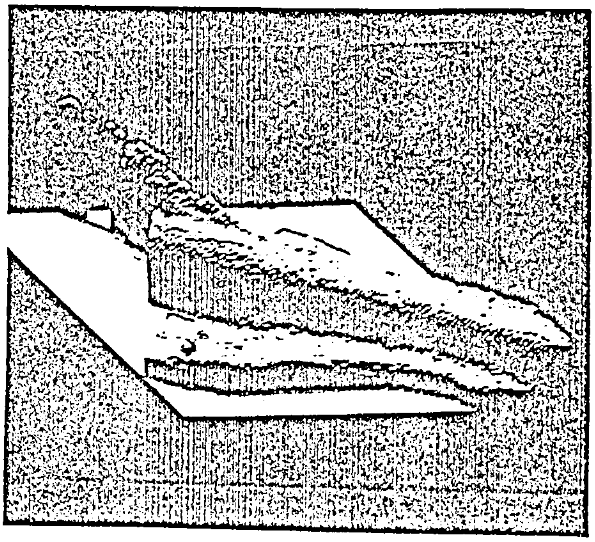

Figure 6. Shuttle Range Image Plotted From Perspective

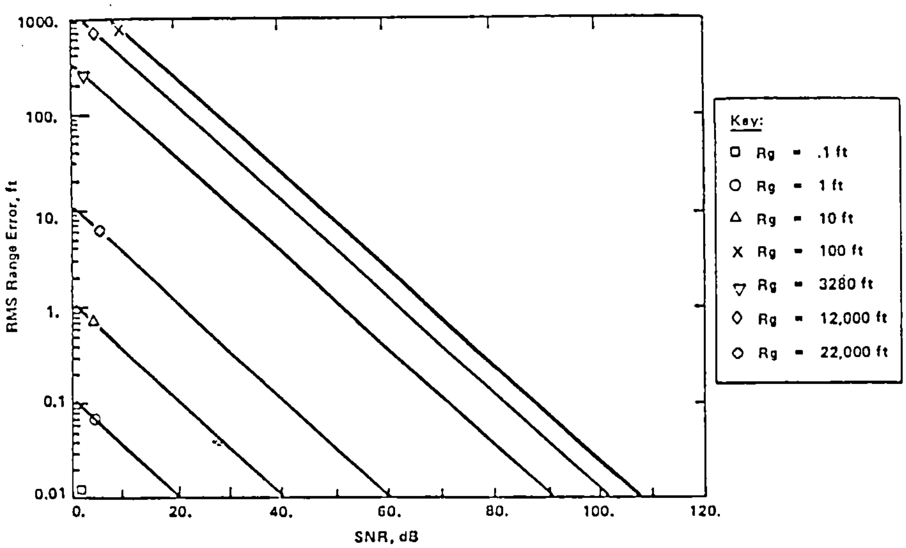

Figure 7. RMS Range Error versus SNR For a Typical Design

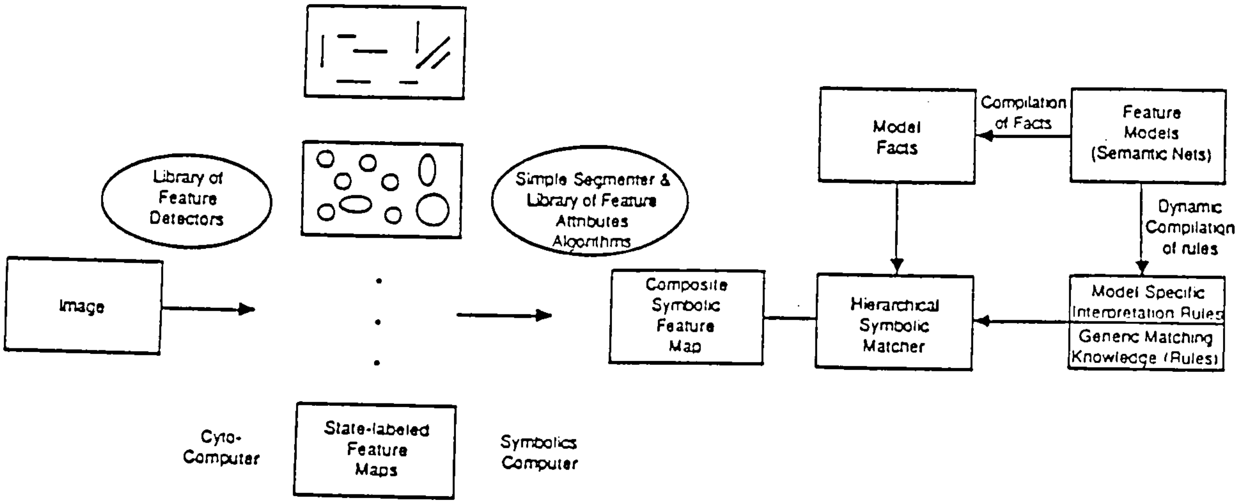

FIGURE 8: VISTA System Overview