A STUDY OF AUTONOMOUS RENDEZVOUS AND DOCKING SYSTEMS

J. D. Micheal
Marshall Space Flight Center
Huntsville, AL

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INTRODUCTION

The problem of automatically docking two spacecraft has received little attention in this country since a pilot has always been available. The Soviet Union has demonstrated a system for automatically docking two controlled, fully active vehicles (ref. 1). To date, no one has developed and flight-tested an automatic scheme in which one vehicle is completely inactive. There is a recognized need for this capability which is associated with satellite retrieval and space construction (ref. 2).

This paper presents an overview of our activities in the automatic rendezvous and docking area. Our interest first began as a result of our involvement with the Teleoperator Retrieval System (TRS) Project whose primary and initial mission was to reboost the Skylab to a higher orbit to extend its lifetime in space. During the course of our work on TRS, we conducted full six degree-of-freedom, man-in-the-loop, hybrid simulations of the TRS/Skylab docking problem. Witnessing the training time required along with the challenge this problem presented to experienced astronauts strongly influenced our decision to begin investigations of autonomous rendezvous and docking systems.

We will begin by covering briefly a representative mission scenario. We will continue our discussion with a statement of the problem which we have addressed and delineate the requirements for the extraction of relative attitude and position data. We have also included a systems block diagram and will describe the integral functions which go to make up an autonomous docking system. Such a system has been simulated, and the digital simulation will be described along with some representative results of a system based on a laser ranging device as the sensor. A television camera as the ranging sensor was also considered and we will discuss one such video based automatic docking scheme along with some representative results as well. Finally, we will briefly cover our current and ongoing efforts in the autonomous video rendezvous and docking area (fig. 1).

- MISSION SCENARIO
- STATEMENT OF PROBLEM
- SYSTEMS DESCRIPTION/BLOCK DIAGRAM
- SIMULATION RESULTS/RADAR
- VIDEO SYSTEMS DESCRIPTION
- CONCLUSION/PLANNED ACTIVITIES

FIGURE 1

MISSION SCENARIO

A typical mission scenario for an automatic rendezvous and docking mission is shown in figure 2. The chase vehicle will be launched from the ground into a coplanar parking orbit either just above and in front of the target vehicle or just below and trailing to minimize the plane change required to rendezvous. The long range rendezvous maneuvers will follow. The target and the chase vehicles have heretofore been tracked from the ground, but, with the advent of systems such as the Global Positioning System (GPS) and the Space Sextant, the tracking as well as the long range rendezvous in general may be done autonomously by the chase vehicle. During this phase, the chase vehicle is placed within the docking sensor's operational range and the target vehicle is acquired. In the approach phase, the chase vehicle's docking sensor output allows for the determination of relative attitude and position. These error signals input the chase vehicle control system which guides the chaser along a prescribed trajectory (one which would be optimized according to mission) to a predetermined standoff range. The station-keeping phase may call for the chase vehicle to circumnavigate the target vehicle for purposes of inspection or, in the event of a tumbling target, may require the chase vehicle to null the relative attitude rate errors in preparation for the docking phase. Final closure through the last 10-20 feet makes up the docking phase which will be the most critical time of the mission. Depending on the respective docking interfaces (chase to target), there may be a soft dock period where all systems are checked prior to rigidization of the docking hardware and completion of the task.

- LAUNCH
- LONG RANGE RENDEZVOUS
- TARGET ACQUISITION/APPROACH
- STATION KEEPING
- DOCK

FIGURE 2

STATEMENT OF PROBLEM

The primary focus of our studies has been on the last three phases of the mission scenario just described with emphasis on the approach phase. One of the first problems to be addressed in this study was deciding on the nature of the system to be studied and to baseline certain systems data such as chase and target vehicle configuration, reaction control system, sensor requirements, etc. Because of the available simulation data showing man's ability to pilot the Teleoperator Retrieval System (TRS) to a soft dock with the uncontrolled Skylab, this was the physical system selected for modeling.

The specific objectives of our studies have been to develop schemes for accomplishing automatic docking between two such spacecraft using a device on the chase vehicle to sense the relative position and attitude of the passive target. A number of devices are under development and one of the more promising ones is a laser ranging radar which we chose to model. In this technique (see fig. 3), the sensor scans a known pattern of reflectors on the target, thus generating a system of vectors between the two bodies which in turn is used to derive the chase to target vehicle relative position and attitude. A minimum of three measurements (reflectors) are required though additional measurements do provide a basis for manipulation to improve attitude position accuracy. In fact, the attitude/position error varies inversely with the square root of the number of reflectors and inversely with pattern size as well. However, assuming minimum requirements are met, the resulting relative position and attitude data would be used to drive a conventional reaction jet control system.

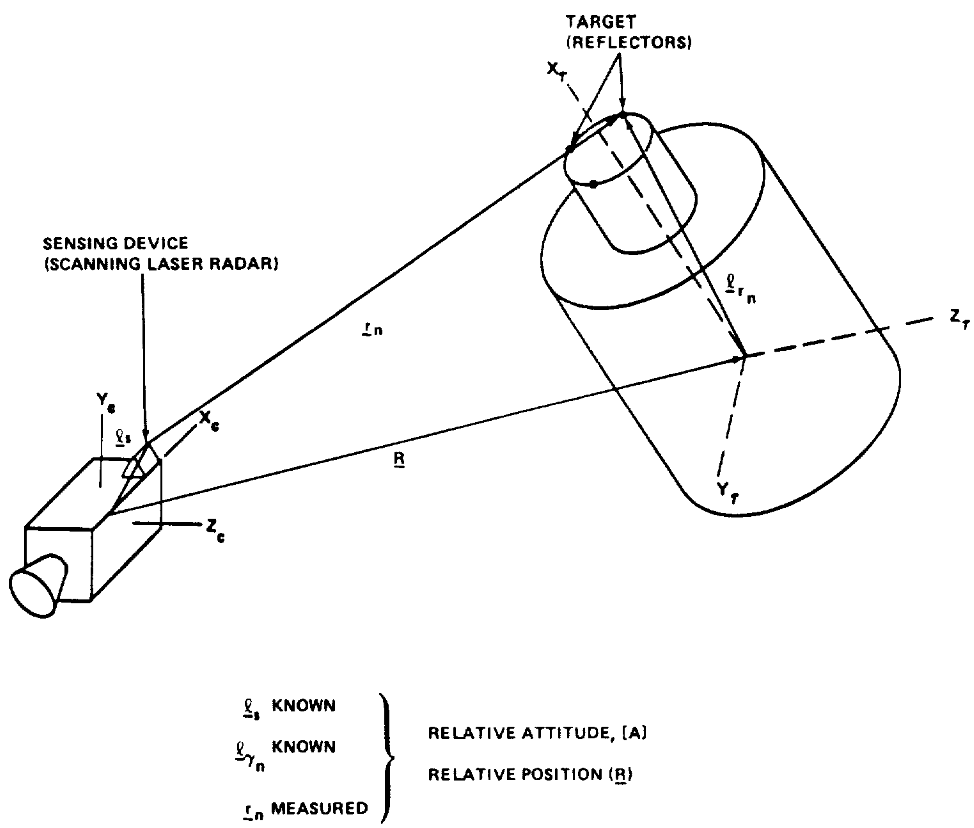


FIGURE 3

SYSTEM DESCRIPTION/BLOCK DIAGRAM

To evaluate the merits of this concept as well as others and to determine how inaccuracies in the data might degrade system performance, the dynamics of an active chase vehicle carrying the sensor and uncontrolled target vehicle carrying the reflector pattern were modeled using the data base described earlier.

A functional block diagram of the resulting digital simulation is presented in figure 4. The block labeled "Signal Processor" contains the algorithms for deriving relative position and attitude information from sensor output. A noise model for the sensor was derived based on sensor accuracies specified in reference 3. The vehicle dynamics block represents rigid body dynamic models of either the chase or target vehicles. The target vehicle motion is governed by orbital mechanics effects as well as being subject to programmed initial conditions which simulate a tumbling target. The chase vehicle motion is the result of orbital mechanics effects and firings from the Reaction Control System (RCS) engines. Signals to fire the RCS engines are generated within the Digital Auto Pilot (DAP), which uses quadratic switching lines determined by the rotational and translational acceleration capability of each chase vehicle axis. The manner in which the required commands are generated and nature of the commands themselves depend on the particular mission phase selected. The functional block(s) labeled mode/logic control contain the control laws for each of three mission phases: (1) Rendezvous Phase, (2) Stationkeeping Phase, and (3) Closure and Dock Phase. This block represents the heart of the autonomous process where based on mission circumstance appropriate reference frames are selected and control priorities are set.

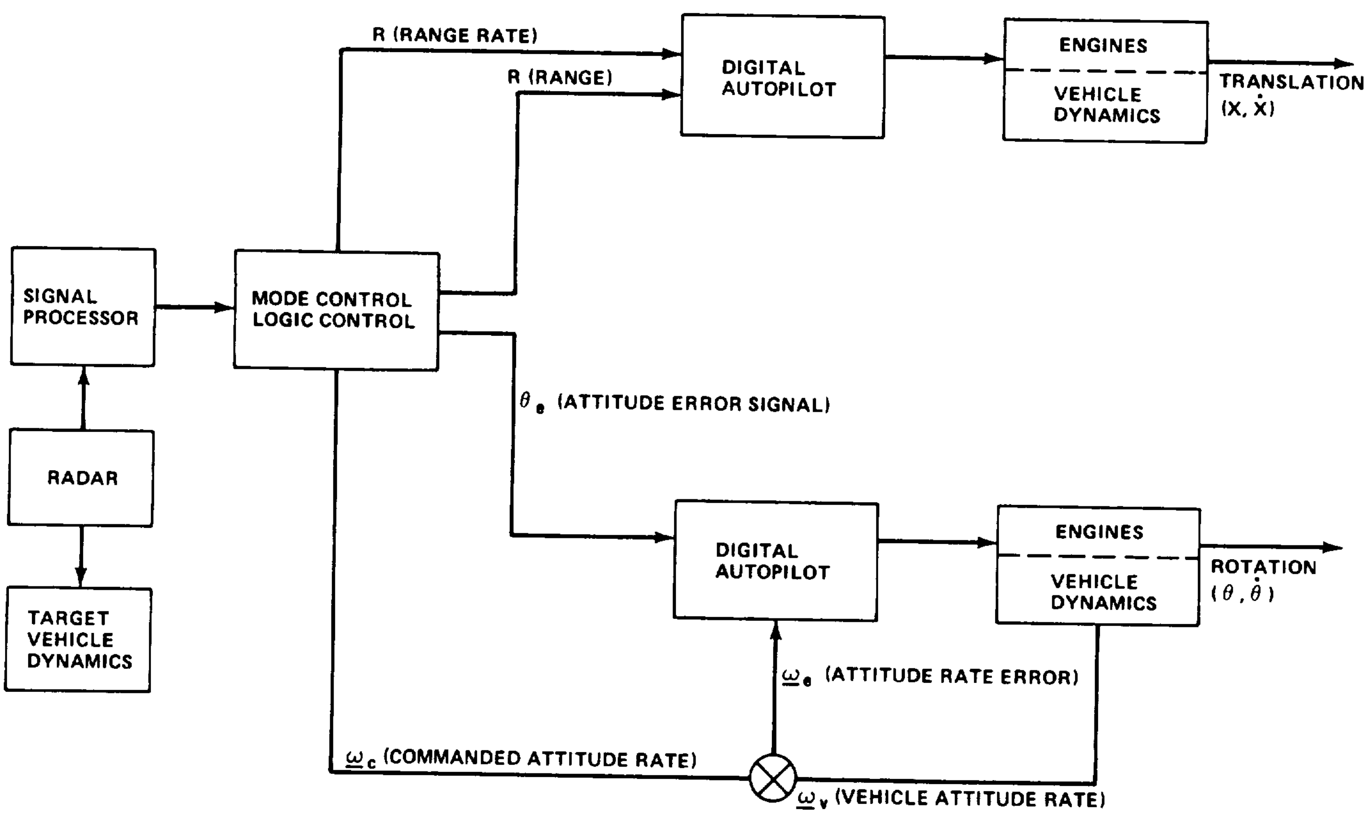


FIGURE 4

SIMULATION RESULTS

Results from the digital simulation program to date are encouraging and support the viability of an automatic rendezvous and docking concept based on the laser ranging radar. Production runs were chosen not only for their challenging nature (that is, high target tumbling rates) but also for initial conditions which would match those already investigated in our 6-DOF man-in-the-loop hybrid simulator. A typical run assumes the target vehicle to be in an arbitrary attitude with an initial angular rate. The chase vehicle begins its final approach from an arbitrary position on the order of 30 m distant.

The results from such runs do evidence a chaser vehicle capable of performing a rendezvous and soft dock with an uncontrolled target for a variety of initial conditions. Salient aspects of a representative case are revealed in the plot of range vs range rate (sensed data) in figure 5. The total target spin rate for the case was 1.7 deg/sec and the chaser vehicle was positioned initially at a probe to port range of 23 m and given a small initial closing velocity. The chaser vehicle accelerates to a closing velocity of .6 m/s at a range of 15 m and then decelerates to a velocity of .08 m/s at soft dock. Time of flight is specified at every 5 m range decrement with a total elapsed time for the flight of 56.3 secs. Characteristic data uncertainties (noise), such as those resulting from radar measurement errors, produce some degradations in results such as increased mission times and increased fuel requirements. Though the presence of noise, which can be seen in the comparison plots of range vs range rate in figure 5, does degrade system performance, the overall range/range rate profile remains essentially the same as the no noise case and similarly converges to the soft dock condition. A further example of this convergence is illustrated in figure 6 which is a plot of the root-sum squared (RSS) of the chase to target vehicle attitude errors vs time of flight. After 20 secs of elapsed time, a comparatively high attitude error has been nulled to within deadband limits and remains there for the duration of the flight.

TARGET SPIN RATES 1.7 DEG/SEC

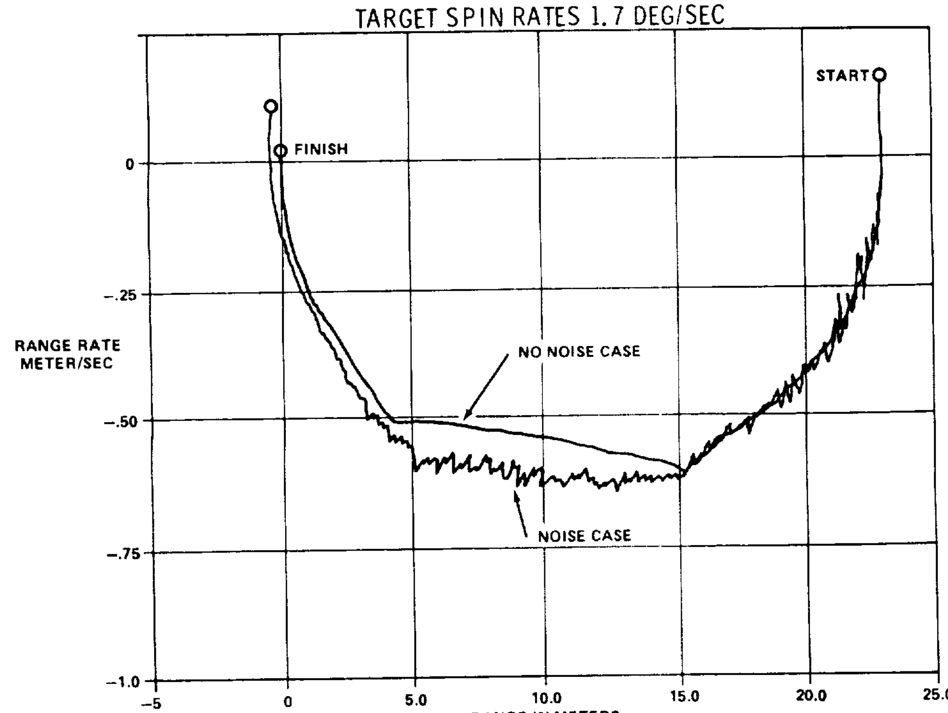


FIGURE 5

DIGITAL SIMULATION RESULTS
TARGET SPIN RATE - 1.7 DEG/SEC

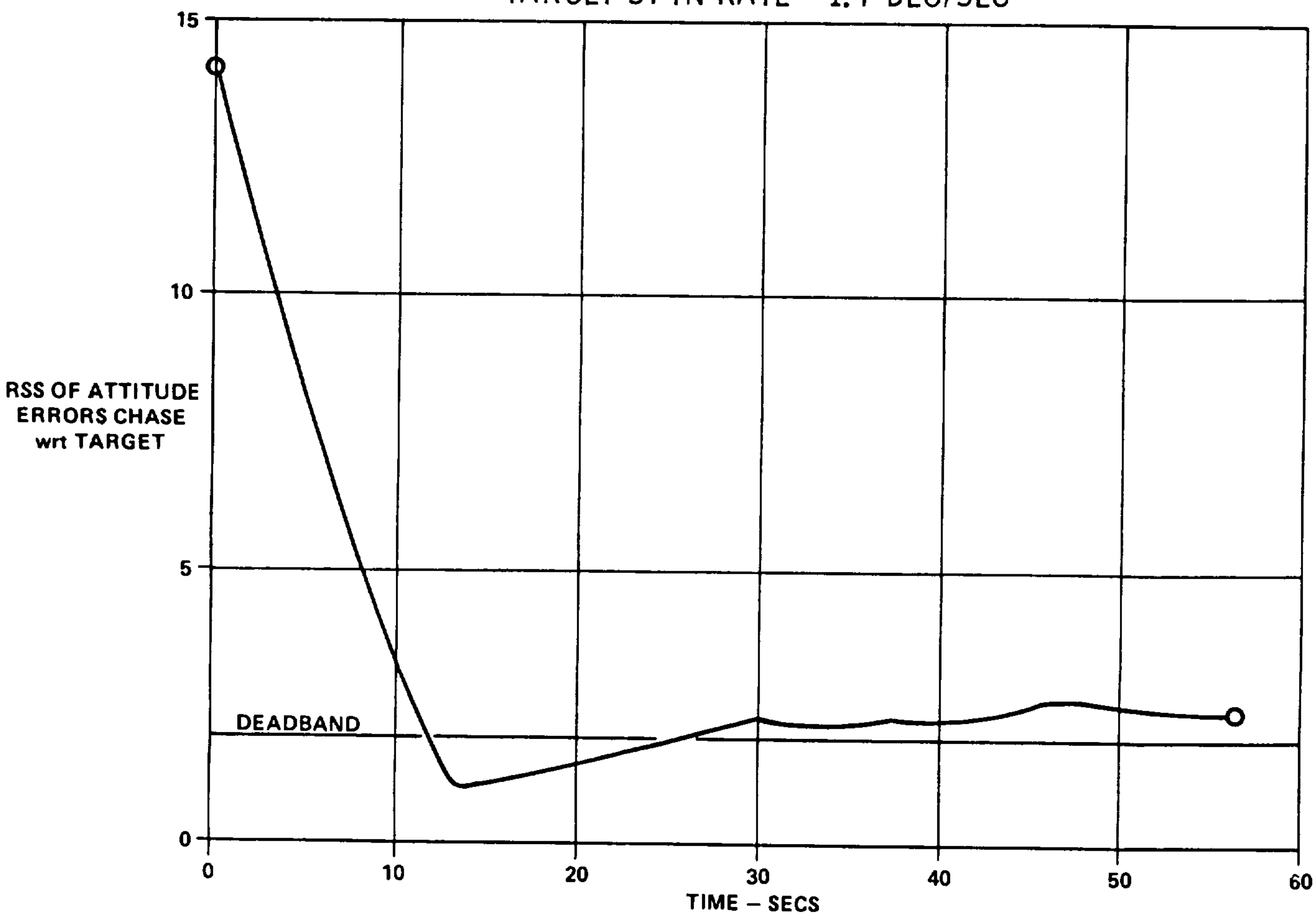
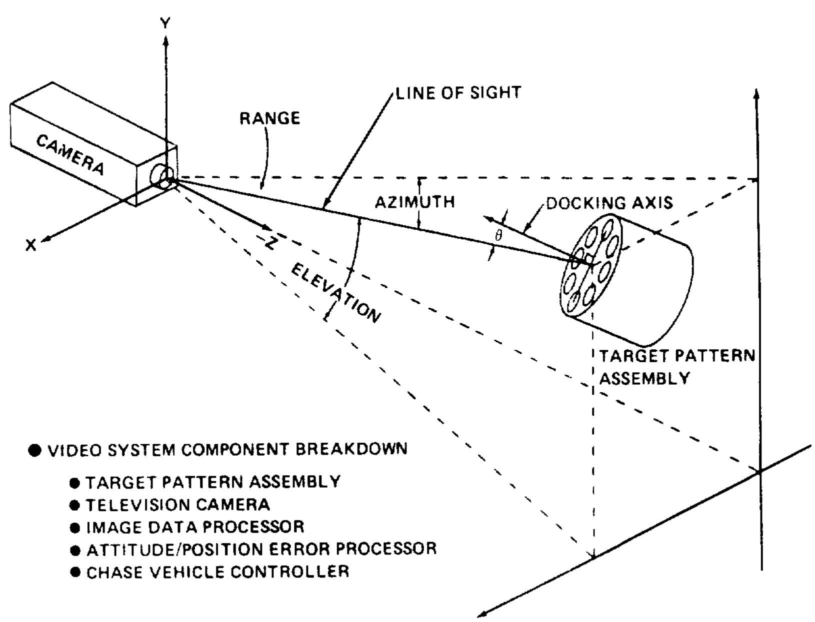


FIGURE 6

VIDEO APPROACH

The large majority of missions dealing with spacecraft placement and retrieval or with space construction envisioned, thus far, involve a propulsive transfer stage equipped with a television system for providing visual feedback to a remote site. A visual system which could also provide tracking data for an autonomous docking system could prove to be quite an advantage to this category of mission. As a result, we have been investigating the feasibility of a video based autonomous rendezvous and docking system. Such a video system (see figure 7) would utilize a television camera that has the capability of digitizing the visual information and transferring this data to an image data processor in real time. Either through the knowledge of the target vehicle geometry or through the knowledge of a known pattern of reflectors on the target, the chase to target vehicle range and relative attitude may be derived. As with the lasar ranging technique, this data is used to drive the chase vehicle attitude control system. Since the practicability of automating the chaser vehicle control system, given the appropriate error signals, was established in our study of the laser ranging technique, the focus of our attention with the video system has been on the first four areas listed in figure 7.

The simulation program developed for these studies includes a model for the television camera which chooses the cluster of pixels to be turned on for each target pattern light or reflector as a function of camera parameters, target pattern, target orientation, and range. This data is the digitized representation of the visual image that is passed to the image data processor (IDP). The IDP in turn calculates the centroids of each of the pixel clusters and it is from the x-y coordinates of these light centroids that the relative attitude and position data may be derived. One target pattern which we have investigated is a circular pattern of eight lights or reflectors. Except when the line of sight is perpendicular or in the same plane of the pattern of reflectors, the pattern will appear as an ellipse to the computer. From the orientation of the ellipse and its eccentricity, relative attitude may be derived; and, from the semi-major axis length an estimation of range is made. This relative attitude and displacement data is less accurate than the technique based on the laser ranging device, but appears to be sufficient for the stable target case.



- VIDEO SYSTEM COMPONENT BREAKDOWN
  - TARGET PATTERN ASSEMBLY
  - TELEVISION CAMERA
  - IMAGE DATA PROCESSOR
  - ATTITUDE/POSITION ERROR PROCESSOR
  - CHASE VEHICLE CONTROLLER

FIGURE 7

CONCLUSIONS/PLANNED ACTIVITIES

The results obtained thus far support the viability of both the laser ranging technique and the video technique as viable approaches for an autonomous docking system. Digital simulation results to date indicate areas of performance comparable to or exceeding that achieved by a trained pilot in our man-in-the-loop simulations. While no fundamental problems have been uncovered, additional work remains to be done, especially on the video system and more work is planned to improve this technique. In FY-82, we received support from OAST to continue this investigation, and a contract with Martin Marietta Corporation is just underway.

The contracted effort will include (see figure 8) the identification and functional description of video techniques, similar to the one described above, which offers a method for deriving relative position and attitude from video sensor output. The necessary extraction equations, algorithms, and associated computational operations will be outlined for each of the viable techniques discovered. Each of the above approaches will then be implemented in a simple docking simulation along with appropriate models for input data errors. Runs will be made against a series of test cases to provide a first level assessment of the approaches.

We will parallel this contracted effort with studies of our own enhanced by projected improvements in our simulation capability. We have recently obtained a television camera and associated interface hardware. This system, nearly complete, will operate in conjunction with a minicomputer to provide a new video system analysis and demonstration tool. This new system along with continuing improvements to our digital simulation programs will help in our efforts to improve on present video techniques and to explore new techniques with promising application to autonomous rendezvous and docking systems.

- STUDY CONTRACT PROGRAM MILESTONES
  - IDENTIFY/DESCRIBE VIDEO TECHNIQUES
  - DEFINE ALGORITHMS FOR DERIVING POSITION/ATTITUDE
  - IMPLEMENT/EXERCISE SIMULATION PROGRAMS
- MSFC'S PLANNED ACTIVITIES
  - HARDWARE DEMONSTRATION OF VIDEO SYSTEM
  - IMPROVE ON PRESENT VIDEO TECHNIQUES
  - EXPLORE NEW TECHNIQUES

FIGURE 8

REFERENCES

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3. Flom, T., and Coombes, H. D., "Construction and Testing of a Scanning Laser Radar (SLR), Phase 2," NASA CR-123530, 1971.