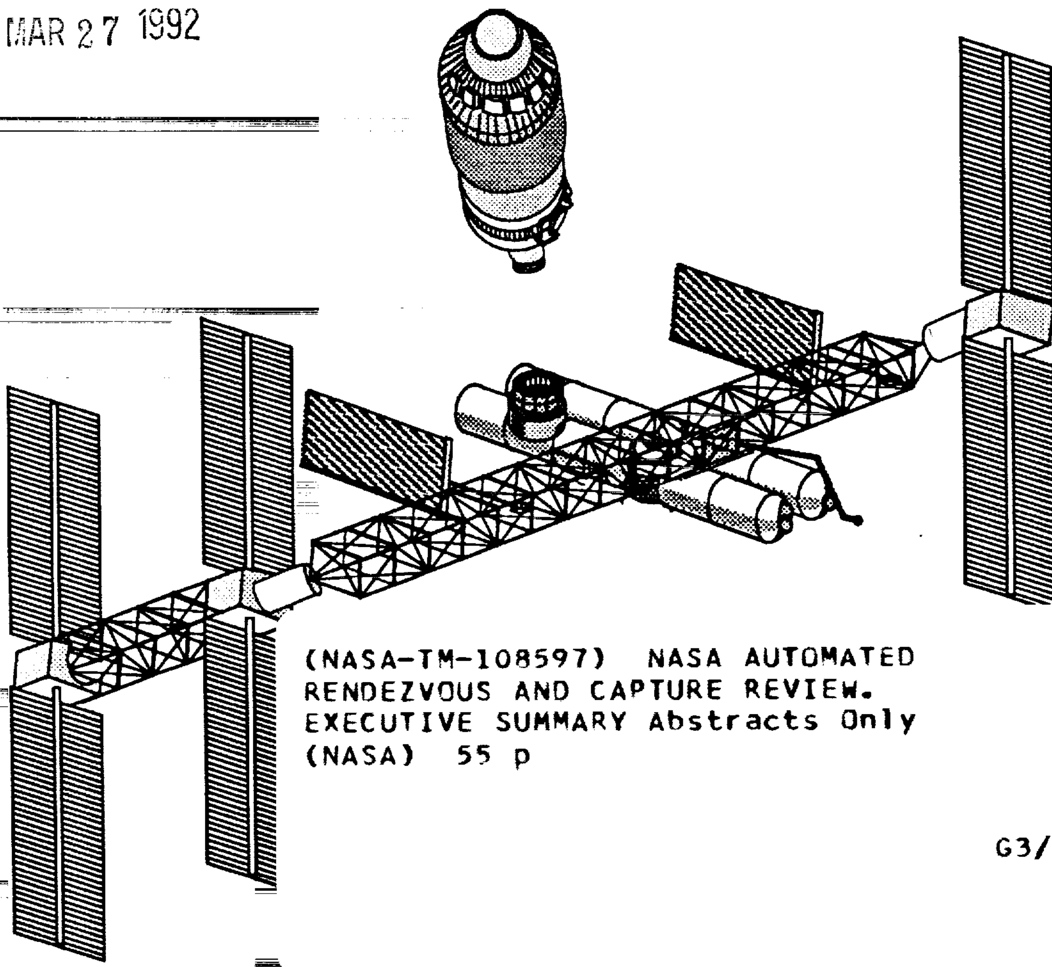
NASA-TM-108597

# NASA Automated Rendezvous And Capture Review

## Executive Summary





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Williamsburg, VA
November 19-21, 1991

## Acknowledgement

*The Automated Rendezvous and Capture Review Executive Summary* presents a compilation of technical summaries, as well as findings and conclusions from the Automated Rendezvous and Capture (AR&C) Review held in Williamsburg, Virginia on November 19-21, 1991. It was prepared through the efforts of technical reporters, Organizing Committee members, and personnel at SRS Technologies in Arlington, VA (under contract NASW-4341) at the direction of Ms. Barbara Askins, Advanced Program Development Division, NASA Headquarters.

# Automated Rendezvous & Capture Review Executive Summary



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# Table Of Contents

## CATEGORY 2: SOFTWARE SYSTEMS



## CATEGORY 3: INTEGRATED SYSTEMS



## CATEGORY 4: OPERATIONS

## Acronyms

| | |
|---|---|
| AR&C | Automated Rendezvous and Capture |
| CAM | Collision Avoidance Maneuver |
| CCZ | Command and Control Zone |
| COMET | Commercial Experiment Transporters |
| CSM | Command / Service Module |
| CTV | Cargo Transfer Vehicle |
| DARPA | Defense Advanced Research Projects Agency |
| DDTF | Dynamic Docking Test Facility |
| DOF | Degree of Freedom |
| DOTS | Dynamic Overhead Target Simulator |
| DTO | Detailed Test Objective |
| DTS | Dynamic Test System |
| EPOS | European Proximity Operations Simulator |
| FDT | Flash during transfer |
| FPM | Forward Propulsion Module |
| GPS | Global Positioning System |
| GSFC | Goddard Space Flight Center |
| IMU | Inertial Measurement Unit |
| INS | Inertial Navigation System |
| IPA | Image Processor Assembly |
| JSC | Johnson Space Center |
| LED | Light Emitting Diode |
| LEM | Lunar Excursion Module |
| LQG | Linear Quadratic Gain |
| LVLH | Local Vertical/Local Horizontal |
| MMU | Manned Maneuvering Unit |
| MPESS | Multiple Payload Experiment Structural System |
| MPRAS | Multipath Redundant Avionics Suite |
| MSFC | Marshall Space Flight Center |
| NLS | National Launch System |
| OAS | Orbital Adjust System |
| OMM | Onboard Mission Manager |
| OMV | Orbital Maneuvering Vehicle |
| OSF | Office of Space Flight |
| PABF | Precision Air Breathing Facility |
| POS | Proximity Operations Simulator |
| RMS | Remote Manipulator System |
| RRS | Rendezvous Radar Set |
| RVU | Remote Voter Unit |
| SES | Systems Engineering Simulator |
| SEU | Single Event Upset |
| SIREN | Search, Intercept, Retrieve, Expulsion Nuclear |
| SNR | Signal to noise ratio |
| SOR | Shuttle Operational Rendezvous |
| SOS | Space Operations Simulation |
| SSF | Space Station Freedom |
| TCS | Trajectory Control Sensor |
| TDRSS | Tracking Data Relay Satellite System |
| TMS | Translation Maneuvering System |
| TPAD | Trunnion Pin Attachment Device |
| TRAC | Targeting Reflective Alignment Concept |

# Automated Rendezvous and Capture Review
# November 19-21, 1991
# Williamsburg, VA

## Executive Summary

PRIMARY

# Automated Rendezvous and Capture Review

## November 19-21, 1991
## Williamsburg, VA

## INTRODUCTION

In support of the Cargo Transfer Vehicle (CTV) Definition Studies in FY92, the Advanced Program Development Division of the Office of Space Flight at NASA Headquarters conducted an evaluation and review of the United States capabilities and state-of-the-art in Automated Rendezvous and Capture (AR&C). This review was held in Williamsburg, Virginia on November 19-21, 1991 and included over 120 attendees from U.S. government organizations, industries and universities.

The review was organized through the efforts of Barbara Askins and Michael Card, NASA Headquarters, Advanced Programs. The organizing committee consisted of representatives from Johnson Space Center, Marshall Space Flight Center, and NASA Headquarters. James Odom, Applied Research Inc. served as the General Chairman of the review.

The Review was initiated in September 1991 by a call for abstracts; those who submitted abstracts were invited to participate. To promote consistency in abstract submissions, the authors were required to include certain types of information. The requirements included a degree of specificity with regard to technical details of the capability being developed, the origins and evolution of the capability, and its level of maturity today. Test experience and/or experimental results, and source/sponsorship were also to be included.

One hundred abstracts were submitted to the organizing committee for consideration. 42 were selected for presentation. The review was structured to include five technical sessions. 42 papers addressed topics in the five categories below.

**Category 1** - Hardware systems and components: sensors, targets, GPS differential measurements, end effectors, capture mechanisms, communications and tracking, propulsion systems, data systems (including data processing), up/down links, sensor interfaces, and computer systems (point design considerations acceptable).

**Category 2**- Software systems: expert systems/artificial intelligence, algorithms/functions, guidance/navigation and controls.

**Category 3** - Integrated systems: automated spacecraft architectures, docking and berthing systems, simulation, real time replanning, and certification/validation.

**Category 4** - Operations: manned/unmanned/vicinity of manned systems, phasing and rendezvous strategies, certification/validation with discussion of ground testing and flight demonstrations, vehicle health maintenance, Space Station Freedom compatibility, collision avoidance, safety and reliability, simulation, and crew systems

**Category 5** - Supporting infrastructure; skills and skill mix, facility capabilities, funding support/requirements, and data base/information management of both existing and new data bases.

At the conclusion of each technical session, a short feedback session was provided to the audience. Technical personnel, designated as reporters, were responsible for summarizing the information presented and the audience's reaction to this information. This resulting compilation has a summary of each session. These summaries include a general overview of the presentation as well as any issues or questions addressed during the presentation.

At the conclusion of the review, an integrated summary session was held. The intent of the session was to provide to NASA management a brief summary of the review. At the summary session, NASA management also presented their views on the review. These results are presented in this volume.

The intent of this executive summary is to provide the reader with an overview of the Review, the observations and insight of the technical specialists working within the AR&C community, and some perspective on the technology available for consideration in the CTV definition studies.

## BACKGROUND

### Historical Perspective on AR&C Capabilities

Rendezvous and capture/docking systems experience has a long and successful history in both the U.S. and Russian space programs. However, these two programs, which have provided essentially all of the world's experience and data, have matured along distinctly different paths. This is due to basic philosophical differences in design, the state of development of the technologies, and differences in expectations, and responsibilities assigned to, control systems with and without man-in-the-loop capability.

The U.S. program explored rendezvous and docking techniques in the early phases of the Gemini program, rendezvousing and docking of the Gemini vehicle with modified Agena target vehicles. The Apollo program flight plan included several mission-critical rendezvous, dock/undock and transfer maneuvers; the first in LEO to separate the Command/Service Module (CSM) from the stack, rotate it 180 degrees, and dock to the airlock docking ring on the Lunar Excursion Module (LEM). After transit to Lunar orbit, the descent crew entered the LEM through the airlock, separated from the CSM, and descended to the Lunar surface. The second rendezvous and capture occurred when the Lunar Ascent Stage ultimately returned to Lunar orbit to rendezvous, dock, and again transfer the crew through the airlock to the CSM.

The Shuttle design includes a remotely controlled manipulator arm for capture, control, berthing, and deployment of payloads. Rendezvous, capture, repair, redeployment, and return have all been demonstrated in Shuttle rendezvous operations over the last 10 years. Additional capability for proximity operations near the Shuttle have been demonstrated using the Manned Maneuvering Unit (MMU). The dominant feature of every U.S. program or mission that has involved rendezvous and capture has been the strong influence of man-in-the-loop for primary control and operation of the vehicle. The U.S. mission experience in rendezvous and capture also can be characterized as mission peculiar/mission unique, in that the rendezvous and capture scenario, the crew and controller training, and the timelines are tailored to specific mission parameters.

By comparison, the Russian program has moved to standardized operations, primarily automated with the crew relegated to over-ride and monitoring functions. The Russian experience has demonstrated continually improving capabilities by using new technologies and block changes on both the Mir and Zenit families; thus providing capability for crew exchange, repair and even reactivation, and resupply of consumables including food, water, supplies, propellants, and gases. The U.S. approach is inherently more labor intensive and considerably more expensive requiring extensive crew training, equipment and control redundancy, and ground backup to assure mission success. The Russian system experience has demonstrated that automated systems do work, can be reliable, and with standardization can provide significant cost benefits in repetitive routine operations typical of those required for SSF resupply missions.

While existing system capabilities are quite dramatic, these designs are now outdated and are not truly representative of the current state of the art. Technologies have evolved in all areas at a very high rate and concurrently, vehicle capabilities and the space infrastructure have been altered by significant technological changes. Onboard digital computational and guidance systems provide high levels of automation and possibly consideration of fully autonomous operations in the near future. The Tracking Data Relay Satellite System (TDRSS) provides nearly continuous and complete data and communications between all spacecraft and ground stations independent of the location. The Global Positioning System (GPS) provides both absolute and relative positioning to in-space assets, at a rate and with a precision superior to the ground station capabilities of just a few years ago. Video and laser technologies and improvements in pattern recognition capabilities have been incorporated into complex military systems and cruise missiles and therefore are available for AR&C applications. Hardware and software now are available with capabilities based on expert systems, robotics, and artificial intelligence.

The Cargo Transfer Vehicle is conceptualized as an unmanned, orbital transfer stage for the Joint NASA/DOD - National Launch System (NLS) with a primary mission of transferring payloads from NLS for resupply of Space Station Freedom (SSF). The CTV is planned to have automated rendezvous and capture systems and controls fully compatible with all aspects of the SSF. For the first time in U.S. space flight experience, an automated, active space vehicle will be required to operate in the specific vicinity, and dock with an essentially passive, manned vehicle system. These missions will be repetitive and will be performed on a routine basis.

Aspects of autonomous rendezvous and capture technology have been under development in various programs throughout NASA. However, no efforts have been integrated sufficiently to enable a flight system. Advanced development technologies are required to define and demonstrate AR&C technology for support of the CTV and SSF operations.

The technology flight demonstrations are required to demonstrate system capabilities for AR&C. The CTV will operate in the SSF Command and Control Zone (CCZ). Operating within the CCZ places stringent requirements on a vehicle in areas of redundancy, system monitoring and command capability, and safing of the vehicle. Thus the CTV requires precise guidance and navigation systems for its missions. It must have the capability to rendezvous and carry out proximity flight with another orbiting spacecraft (the SSF), it must interface with a manned orbiting vehicle, and it must return to ground onboard another manned system (the STS Orbiter).

## PURPOSE AND ORGANIZATION OF THE AR&C REVIEW

In this rich historical environment of well established AR&C capabilities in both the U.S. and Russian space programs, beginning in FY92 NASA's Office of Space Systems Development (previously the Office of Space Flight) initiated the formal process of system definition for the CTV, including design/definition studies of the major AR&C subsystems. An obvious first step in the definition process was to clearly define the state-of-the-art for technologies that could be considered, and to assure the understanding of the application and limitations of these technologies within the constraints of the primary SSF resupply mission requirements.

In August 1991, an inter-center organizing committee for the AR&C Review was established. Ms. Barbara Askins, the CTV Program Manager for the CTV System Definition Studies in NASA Headquarters has served as the Chairperson of the Organizing Committee for the duration of the activities. Other members of the committee are shown in Figure 1. Following submission and selection of an appropriate mix of papers -- papers that were representative of capabilities and technologies of the federal and industrial sectors of the United States -- the committee defined the Agenda for the AR&C Review (shown in the Appendix).

From the outset of the planning, the intent of the organizing committee was to restrict the attendance to active technical personnel only, to facilitate the interchange of ideas and accomplish a constructive/critical peer review of technologies under discussion. To further facilitate this interchange, the organizing committee included an independent and separate "instant replay" of each of the five technical sessions as shown in the Agenda. Following each session, an independent 2 or 3 person team of reporters would overview the content of each paper, critically assess its conclusions and findings, and stand for questions and answers from the audience and the authors/presenters. For the body of this Executive Summary Report, the comments and discussion pertaining to each paper, as prepared by the "reporters," have been distributed to the five appropriate technology categories identified earlier. The major technical comments and opinions included in this Executive Summary are, therefore, representative of the considered opinion of the technical (discipline) specialists attending the review.

**Automated Rendezvous & Capture Review**
**Organizing Committee**

**NASA Headquarters**
Barbara Askins, Chairperson
Michael Card
Paul Herr
Robert Bristow
John DiBattista

**NASA Marshall Space Flight Center**
Joseph Randall
E.C.Smith
David Schultz
Larry Brandon

**NASA Johnson Space Center**
Ken Cox
William Culpepper
Richard Gavin
William Jackson
Greg Hite

**Applied Research, Inc.**
James Odom,
General Chairman of AR&C Review

**Figure 1. AR&C Review Organizing Committee**

S1-36

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## CATEGORY 1 - HARDWARE SYSTEMS

p. 1

### Coherent Doppler Lidar for Automated Space Vehicle Rendezvous, Stationkeeping and Capture

by James Bilbro, MSFC

The inherent spatial resolution of laser radar makes ladar or lidar an attractive candidate for Automated Rendezvous and Capture application. Previous applications were based on incoherent lidar techniques, requiring retro-reflectors on the target vehicle. Technology improvements (reduced size, no cryogenic cooling requirement) have greatly enhanced the construction of coherent lidar systems. Coherent lidar permits the acquisition of non-cooperative targets at ranges that are limited by the detection capability rather than by the signal-to-noise ratio (SNR) requirements. The sensor can provide translational state information (range, velocity and angle) by direct measurement and, when used with an array detector, also can provide attitude information by doppler imaging techniques. Identification of the target is accomplished by scanning with a high pulse repetition frequency (dependent on the SNR). The system performance is independent of range and should not be constrained by sun angle. An initial effort to characterize a multi-element detection system has resulted in a system that is expected to work to a minimum range of 1 meter. The system size, weight and power requirements are dependent on the operating range; 10 km range requires a diameter of 3 centimeters with overall size at 3x3x15 to 30 cm, while 100 km range requires a 30 cm diameter.

S2-36

N93-21409

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### Video Guidance Sensor

by Richard Howard, MSFC

p. 1

A Martin-Marietta study comparing the application of laser, video, or RF sensors was conducted in 1982. The study concluded that video was the most attractive sensor (the video also could be used for operator monitoring). The Retro-Reflector Field Tracker from the Solar Array Flight Experiment was chosen as a "first generation" sensor and integrated with guidance algorithms for evaluation on the air-bearing vehicle. Results indicated that this sensor was not applicable for the noise environment posed by the multi-layer insulation used on most spacecraft. A "second generation" sensor was developed to be used with a modified RMS target. This sensor utilized two sets of laser diodes to acquire three optically filtered targets. The targets were illuminated first with a 780 nanometer diode, followed by illumination with a 830 nm diode. The second digitized picture was subtracted from the first to get a low-noise image. The centroids of the retroreflectors were used then to uniquely derive target attitude and range. The sensor presently operates to 80 feet and within $\pm$ 40 degrees in pitch and yaw. Sensor operability is a concern if the sun is within a $\pm$40 degree cone angle of the target. The present sensor performance characteristics are less than 1% range error and less than 1 degree angle error. Future sensor development is anticipated to extend the operating range to 150 feet and reduce the cone angle of sensor inoperability to within $\pm$ 10 degrees of direct sunlight. Performance improvements also are anticipated. TRW currently is developing a system that utilizes dual cameras with simultaneous diode illumination. Although further development is being pursued, the basic system has proven sound and the sensor is essentially ready for application.

S3-36

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### Approach Range and Velocity Determination Using Laser Sensors and Retroreflector Targets

by W. J. Donovan, Rockwell International

N93-21410

A laser docking sensor study currently is in the third year of development. The design concept is considered to be validated. The concept is based on using standard radar techniques to provide

p. 2

range, velocity, and bearing information. Multiple targets are utilized to provide relative attitude data. The design requirements were to utilize existing space-qualifiable technology and require low system power, weight, and size yet operate from 0.3 to 150 meters with a range accuracy greater than 3 millimeters and a range rate accuracy greater than 3 mm per second. The field of regard for the system is +/- 20 degrees. The transmitter and receiver design features a diode laser, microlens beam steering, and power control as a function of range. The target design consists of five target sets, each having seven 3-inch retroreflectors, arranged around the docking port. The target map is stored in the sensor memory. Phase detection is used for ranging, with the frequency range-optimized. Coarse bearing measurement is provided by the scanning system (one set of binary optics) angle. Fine bearing measurement is provided by a quad detector. A MIL-STD-1750 A/B computer is used for processing. Initial test results indicate a probability of detection greater than 99% and a probability of false alarm less than 0.0001. The functional system is currently at the MIT / Lincoln Lab for demonstration.

S4-18
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## Contact Dynamics Testing of Automated Three-Point Docking Mechanism

by Kenneth H. Rourke, TRW

An evaluation of an OMV docking mechanism, based on an adaptation of the Shuttle Flight Support System Pallet Berthing Mechanism has been completed. The mechanism uses automatically actuated motorized latches to engage towel bars on the target satellite. LED sensors establish the towel bar position within the capture envelope and the latch capture commands are issued. Then, locking pawls engage the bar, locking and pre-loading the mechanism. Two series of tests were conducted to test nominal and failure mode captures and to evaluate design parameters such as LED sensor locations, automatic closure algorithms, latch closure velocity, position/velocity entry envelopes, and closure method. The first test series involved single latch testing on the Flat Floor Facility, 6 DOF Facility and an analytic simulation model. The intent was to compare results in order to validate the various facilities. Reasonably good agreement was achieved. The second test series repeated the single latch testing on the refurbished 6 DOF Facility to validate the facility modifications. The individual latches were tested under free-drift conditions for functionality and performance. Next, the three-latch configuration underwent parametric testing. Test results validated the improved fidelity of the 6 DOF Facility and verified successful docking at the required entry velocity. The tests determined the "best" design parameter definitions and concluded that the locking pawls should not lock until all three latches completely close.

S5-18
N93-21412
146673

## TRAC Based Sensing For Autonomous Rendezvous

By Louis Everett Texas A&M University, and
Leo Monford, NASA JSC

The Targeting Reflective Alignment Concept (TRAC) sensor is to be used in an effort to support an Autonomous Rendezvous and Docking (AR&D) flight experiment. The TRAC sensor uses a fixed-focus, fixed-iris CCD camera and a target that is a combination of active and passive components. The system experiment is anticipated to fly in 1994 using two Commercial Experiment Transporters (COMETs). The requirements for the sensor are: bearing error less than or equal to 0.075 deg; bearing error rate less than 0.3 deg/sec; attitude error less than 0.5 deg. and; attitude rate error less than 2.0 deg/sec. The range requirement depends on the range and the range rate of the vehicle.

The active component of the target is several "kilo-bright" LEDs that can emit 2500 millicandela with 40 milliwatts of input power. Flashing the lights in a known pattern eliminates background illumination.

The system should be able to rendezvous from 300 meters all the way in to capture.

A question that arose during the presentation: What is the life time of the LEDs and their sensitivity to radiation? The LEDs should be manufactured to Military Specifications, coated with silicon dioxide, and all other space qualified precautions should be taken. The LEDs will not be on all the time so they should easily last the two-year mission.

## Applicability of Relative GPS to Automated Rendezvous between the Space Shuttle and Space Station

by Fred D. Clark and Ann Christofferson
Lockheed Engineering and Sciences Co.

N93-21413
NBS. ONLY
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p. 1

The purpose of this study is to determine the adequacy of the Global Positioning System (GPS) in providing relative navigation for automated rendezvous and proximity operations. The study was performed using the Proximity Operations Simulator (POS), Lockheed's high-fidelity, six-degree-of-freedom simulation of the Space Shuttle and Space Station.

This simulation includes identical models of GPS receivers for each vehicle. The navigation software in each vehicle includes identical Kalman filters. Each vehicle estimates its own state, and the relative state vector is obtained by simply subtracting absolute states.

The GPS model includes errors in the ephemeris and clocks of the GPS satellites. Receiver clock errors and receiver noise are modeled, as well as ionospheric errors. Multipath and obscuration effects are not modeled. The receivers are modeled to provide either the precise positioning service (p-code), or the standard positioning service (C/A code). Both filters include three state vector components for position, velocity, and unmodeled acceleration bias, one component for clock bias, and one component for clock frequency error.

The Shuttle Operational Rendezvous (SOR) profile was simulated with two exceptions. First, the orbiter was targeted to cross the +Rbar below the station and intercept the +Vbar 500 feet in front of the station, rather than targeted directly to the station. Second, when the angle between the line of sight to the station and the +Vbar reached 45 degrees, the orbiter was commanded by the guidance to remain on a 45-degree glideslope for the remainder of the trajectory.

In the simulations, five different dispersions in position and velocity were used to initialize the orbiter at a range of about 100 nautical miles from the Station. Simulations were run with both p-code and C/A code models. Also, in one set of runs, estimated orbiter Reaction Control System (RCS) delta-v was used instead of Inertial Measurement Unit (IMU) data, which has a quantization level of 0.0344 ft/sec. As expected, relative position is estimated better using p-code. Relative velocity estimation is nearly identical regardless of whether p-code or C/A code is used. If delta-v is estimated without IMU, and additional process noise is added during RCS firings, relative velocity errors are halved.

Relative GPS is adequate for controlling the trajectory of the shuttle along a 45-degree glideslope until a few hundred feet from the station. A sensor capable of estimating range, range rate, and bearing would be needed to complete the final phase of an automated rendezvous and capture.

S7-19
ABS. ONLY
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N93-21414

## Trajectory Control Sensor Engineering Model Detailed Test Objective

By Kent Dekome, NASA-JSC, and
Martin Barr, Lockheed Engineering & Sciences Company

P. 1

The concept employed in an existing Trajectory Control Sensor (TCS) breadboard is being developed into an engineering model to be considered for flight on the Shuttle as a Detailed Test Objective (DTO). The sensor design addresses the needs of Shuttle/SSF docking/berthing by providing relative range and range rate to 1500 meters as well as the perceived needs of AR&C by relative attitude measurement over the last 100 meters. Range measurement is determined using a four-tone ranging technique. The doppler shift on the highest frequency tone will be used to provide direct measurement of range rate. Bearing rate and attitude rates will be determined through back differencing of bearing and attitude, respectively. The target consists of an isosceles triangle configuration of three optical retroreflectors, roughly one meter and one-half meter in size. After target acquisition, the sensor continually updates the positions of the three retros at a rate of about one hertz. The engineering model is expected to weigh about 25 pounds, consume 25-30 watts, and have an envelope of about 1.25 cubic feet.

Concerns addressed during the presentation: Are there any concerns with differentiating attitude and bearing to get attitude and bearing rates? Since the docking scenario has low data bandwidth, back differencing is a sufficient approximation of a perfect differentiator for this application. Could range data be obtained if there were no retroreflectors on the target vehicle? Possibly, but only at close range. It would be dependent on target characteristics.

S8-18
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N93-21415

## Thruster Configurations for Maneuvering Heavy Payloads

by Roy K. Tsugawa, Michael E. Draznin, TRW
Richard W. Dabney, NASA MSFC

P. 1

The Cargo Transfer Vehicle (CTV) will be required to perform six degree of freedom (6 DOF) maneuvers while carrying a wide range of payloads varying from 100,000 lbm to no payload. The current baseline design configuration for the CTV uses a forward propulsion module (FPM) mounted in front of the payload with the CTV behind the payload so that the center of gravity (CG) of the combined stack is centered between the thruster sets. This allows for efficient rotations and translations of heavy payloads in all directions; however, the FPM is a costly item, so it is desirable to find design solutions that do not require the FPM. This presentation provides an overview of the analysis of the FPM requirements for the CTV.

In this study, only the reaction control system (RCS) thruster configurations are considered for 6 DOF maneuvers of various CTV cargo configurations. An important output of this study are the viable alternative thruster configurations that eliminate the need for the FPM. Initial results were derived using analytical techniques and simulation analysis tools. Results from the preliminary analysis were validated using our 6 DOF simulation.

Using current baseline thruster locations on a main CTV without the FPM, operations are possible with 75 lbf thruster and 19% fuel efficiency (a 400 lbm fuel penalty) for lateral maneuvers of 100,000 lbm cargo within the final 1000 ft approach. The CTV without its cargo or strongback requires low torque (7.5 lbf thrust), but available 25 lbf thrusters yield 3.4 degrees per square second of rotation acceleration, which implies frequent and fuel-inefficient thruster activity and excessive angular acceleration. An alternative 36-thruster configuration with offset 25 lbf thrusters can achieve 24% efficiency and handle both fully loaded and core CTV operations.

Concerns that were addressed during the presentation: Is there a time penalty? No operational time delay is incurred with lower accelerations used. Is radial center of gravity offset a problem? Not unless it is significantly outside the CTV diameter.

S9-74
N93-21416
146677
p. 2

## Optical Correlators for Automated Rendezvous and Capture
by Richard D. Juday, NASA JSC

The paper begins with a description of optical correlation. In this process, the propagation physics of coherent light are used to process images and extract information. The processed image is operated on as an area, rather than as a collection of points. An essentially instantaneous convolution is performed on that image to provide the sensory data. In this process, an image is sensed and encoded onto a coherent wavefront, and the propagation is arranged to create a bright spot of the image to match a model of the desired object. The brightness of the spot provides an indication of the degree of resemblance of the viewed image to the mode, and the location of the bright spot provides pointing information.

The process can be utilized for AR&C to achieve the capability to identify objects among known reference types, estimate the object's location and orientation and interact with the control system. System characteristics (speed, robustness, accuracy, small form factors) are adequate to meet most requirements. The correlator exploits the fact that Bosons and Fermions pass through each other. Since the image source is input as an electronic data set, conventional imagers can be used. In systems where the image is input directly, the correlating element must be at the sensing location.

Active programs in the development of this technology are already in place within NASA (JSC, JPL, ARC), the military, industry and academia. These programs have developed systems that are essentially ready to be flown in space. The two major elements may be characterized as algorithms/architectures and modulators. Numerous correlator architectures and the associated algorithms already exist and are available in original or modified form. Modulators, while in existence, are not as technologically advanced as the algorithms and architectures. Numerous small business proposals are under consideration to further this technology.

The Johnson Space Center is involved in all aspects of the AR&D activity, including the software and hardware developments. Algorithms such as "Backscratch," estimation filters, pattern recognition, and correlator architectures either are under development or are under influence of JSC personnel. Digital image processors and Spatial Light Modulators are examples of hardware currently being developed under JSC cognizance. According to the author, JSC is at the forefront of Fourier optics pattern recognition.

Some work has been done to estimate the funding required to qualify the hardware to a space environment and to build a flight system. One benefit which may accrue to the program is the ability to piggyback the flight qualification on an ongoing DARPA program. The DARPA correlator will be ready for ground testing in the Fall of 1993. It is estimated that space qualifiable hardware could be available a year later.

At this time, technological challenges are in the areas of developing Spatial Light Modulators to control light, continuing to develop software of filters and noise rejection capability, and improving sensitivity to scale and rotation. Emphasis should be placed on development of the modulators, since the algorithm and architecture development is ahead at this time.

Concerns/questions that arose at the end of the presentation: Existing DARPA program will take hardware through qualification and field testing at levels similar to and often exceeding space needs. What is the range accuracy? Two (2) percent of the range. Can tilt and roll could be determined? Yes, it can, using the Synthetic Estimation Filter.

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P-2

## Office of Spaceflight Standard Spaceborne Global Positioning System (GPS) User Equipment Project

by Penny E. Saunders, NASA, JSC

The Global Positioning System (GPS) provides: 1) position and velocity determination to support vehicle GN&C, precise orbit determination and payload pointing; 2) time reference to support onboard timing systems and data time tagging; 3) relative position and velocity determination to support cooperative vehicle tracking; and 4) attitude determination to support vehicle attitude control and payload pointing.

The expected GPS performance depends on system implementation, hardware design, software design, and GPS service. The standard spaceborne GPS user equipment project was begun by JSC to identify the benefits of a standard GPS receiver development for the STS, SSF, and ACRV and the potential benefits to other NASA programs. The Office of Space Flight then recommended the collection of NASA-wide GPS requirements and preparation of a project plan including cost and schedule estimates. A common GPS system can reduce development, maintenance, and logistics costs.

There are two services provided by GPS, standard and precise. Some commercial applications have achieved centimeter level accuracy using GPS. However, commercial off-the-shelf systems cannot handle the high velocities and Doppler shift. Nevertheless, ACRV, CTV, SSF, and STS can use militarized systems that use Coarse Acquisition, the standard service.

A task team of representatives from JSC, MSFC, GSFC, and JPL was formed to develop a Standard Spaceborne GPS Receiver. The design approach is to maximize the use of available hardware and software, minimize user program integration cost, and provide upgrade options for unique requirements and anticipated future requirements. The design also should reflect: a modularized approach in receiver architecture for incorporation of user-unique requirements, addition of NASA unique command, control and data interfaces, and modified software to accommodate vehicle dynamics; addition of NASA's safety, reliability, and quality standards; and addition of radiation protection.

The project consists of three phases: the definition phase, development phase, and production phase. The definition phase should be completed in September of 1993, the development phase completed in December of 1995, and the production phase starting in January of 1996 and continuing until completion of the last flight unit that is needed.

The GPS application to AR&C consists of placement on both the chaser vehicle and the target vehicle. It includes a communication link between the vehicles so that relative position data can be determined. The expected performance depends on: (1) number of common satellites; (2) receiver measurement accuracy and measurement types; (3) relative state processing algorithms, (4) receiver/processor commonality; and (5) type of GPS service used.

In summary, standard GPS User Equipment development ensures commonality and coordination between user programs, thus providing overall NASA cost reduction and improvement in relative tracking capability. The cost reduction is due to the one-time versus multiple nonrecurring engineering efforts, quantity purchases of flight units, and consolidated engineering supporting development, logistics, operations, and maintenance. The use of a common hardware and software design results in the improvement in relative tracking capability and also improves accuracy and simplifies interfaces.

Concerns discussed following the presentation: When the author mentioned that there is an agreement for scarring SSF for a GPS receiver the audience responded enthusiastically. A question from the floor came up regarding the issue of putting GPS receivers in a vacuum environment and whether the issue was addressed in the standard GPS requirements. It was answered that this issue had not been addressed but the present requirements assume an atmospheric environment. A comment from the floor was that the Explorer platform will fly next year and it will have a GPS receiver onboard operating in a vacuum. A final question was: Are the different accelerations of SSF and the chase vehicle a problem? The answer was that acceleration is generally not a problem. Velocity is the driver because of the Doppler shift.

S11-18

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N93-21418

146647

p. 1

## Autonomous Pre-alignment of a Docking Mechanism

by Monty B. Carroll and John A. Thompson
Lockheed Engineering & Sciences Co.

The subject project can be described as the development and testing of a digitally controlled docking mechanism. The mechanism consists of a 6 DOF parallel manipulator for docking interface pre-alignment, and a machine vision sensor for real-time target tracking. The parallel manipulator also can be used for capture/latching, energy attenuation, and structural rigidization of docking, but the scope of this paper is the proof-of-concept demonstration of autonomous pre-alignment of a docking mechanism using machine vision.

The docking mechanism incorporates 8 linear actuators in tandem attached to a lower and an upper ring. The lower ring is stationary while the upper ring maneuvers the mechanical docking interface in three-dimensional space. Each linear actuator of the manipulator is position controlled by a dedicated digital servo controller and receives actuator length commands from a central IBM PC based master controller. The master controller oversees operation of the linear actuators and receives real-time position and orientation data from either a machine vision processor or a manual 6 DOF input device. The machine vision system, a gray-scale and binary vision system, senses an optical target on the passive docking interface via a CCD camera on the docking mechanism's stationary base. It then provides real-time position and orientation commands to the master controller. The master controller kinematically resolves position lengths of each actuator and moves the docking interface to align with the approaching target. A host or user interface to the master controller provides the start, stop, reset, or mode commands, and displays current manipulator position.

The demonstration of the autonomous prealignment of a docking mechanism was a success, showing a full scale working prototype utilizing machine vision. System response was estimated at 5 hertz. Docking interface alignment was accurate to approximately 20 mm (0.75 inches). It is believed that these system parameters could be considerably enhanced by several minor hardware and software upgrades. The machine vision accuracy was dependent upon the distance of the target from the CCD camera. The positional accuracy obtained for each of target sphere was about one percent of the actual distance. Additionally, it was noted that lighting condition variations greatly influenced vision tracking accuracy. This did not affect the demonstration greatly, since constant lighting could be maintained. However, a more robust tracking algorithm, less sensitive to lighting, was determined possible.

The technology demonstrated in this project has the potential to improve the efficiency and configuration of a docking system. A sensor controlled docking mechanism could have smaller capture guides and shorter attenuator strokes, thereby reducing weight. The capture and attenuation loads would be reduced because of the precise method of alignment. Future work is to include the study of the remaining phases of docking; i.e., capture/latching, attenuation, and structural rigidization. In addition, upgrades to hardware and software are being considered.

S12-32
ABS. ONLY
146680
N93-21419
p. 1

# Rendezvous Radar for the Orbital Maneuvering Vehicle

by John W. Locke, Keith A. Olds, and Thomas Quaid
Motorola, Inc.
Chandler, Arizona

The Rendezvous Radar Set (RRS) was designed at Motorola's Strategic Electronics Division in Chandler, Arizona, to be a key subsystem aboard NASA's Orbital Maneuvering Vehicle (OMV). The unmanned OMV, which was under development at TRW's Federal Systems Division in Redondo Beach, California, was designed to supplement the Shuttle's satellite delivery, retrieval, and maneuvering activities. The RRS was to be used to locate and then provide the OMV with vectoring information to the target satellite (or Shuttle or Space Station) to aid the OMV in making a minimum fuel consumption approach and rendezvous. The OMV development program was halted by NASA in 1990 just as parts were being ordered for the RRS engineering model. The paper presented describes the RRS design and then discusses new technologies, either under development or planned for development at Motorola, that can be applied to radar or alternative sensor solutions for the Automated Rendezvous and Capture problem.

The RRS is an X-Band all solid-state, monopulse tracking, frequency-hopping, pulse-Doppler radar system. One square meter targets are detected at ranges greater than 4.5 nautical miles and larger targets are detected at up to 10 nautical miles. The target is then tracked in angle, range, and range rate to a range of 35 feet from the OMV. Three-sigma measurement performance of <0.1 fps velocity error and <10 ft range error during target track are features of the design. Efficient Gallium Arsenide FET devices for the RF stages and low-power CMOS technology for the digital signal and data processing functions are used extensively to minimize power consumption. To assure mission reliability high-reliability parts are used throughout and the RRS is electrically redundant. Single event upset (SEU) effects have been addressed at both system and circuit levels in the design.

The weight of the electrically redundant system was estimated at 90 pounds, of which 40 pounds was contributed by the antenna, gimbals, motors, etc., leaving 50 pounds for the electronics. Recent progress at Motorola in the infusion of commercial technologies and modern packaging into space systems, promises substantial reductions in size, weight, and cost compared to traditional space hardware designs. Small satellite programs such as Motorola's IRIDIUM space-based personal communications system are developing new packaging approaches for both microwave and digital space-based hardware that could be applied to benefit programs like the RRS. Examples include the use of digital multi-chip modules that would reduce the RRS processor weight by over 70% and MMIC microwave modules that could nearly eliminate critical alignment and tuning procedures (and thus reduce cost and risk) during production.

S13- N93-21420
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146681

# A Berthing and Fastening Strategy for Orbital Replacement Units

by John Vranish and Edward Cheung
Goddard Space Flight Center

A summary of the GSFC applied research effort in robotic berthing is provided. The summary includes several demonstrations and experimental highlights illustrated on video. Two GSFC developments are central to the research, the "Capaciflector" sensor and the "Spline-Locking" Screw fastener.

The Capaciflector is an outstanding close-in complement to vision sensing and is central to collision avoidance, alignment, and precontact and contact control. Its suitability for use in space

p. 2

is described in detail in the presentation showing that this sensor is outstanding for space use. It has, indeed, already gone through most of the space qualification criterion.

The Spine-Locking Screw is central to robotic (and astronaut hand tool) fastening. A fundamental change to the basic machine screw, it permits robots to fasten objects (and themselves in a walking mode) to other objects with high preload forces from small input torques and without any possibility of cross-threading. In addition, this fastener can be slightly modified to provide an outstanding electrical connection along with the mechanical. Like the "Capaciflector," this fastener already has been recognized as an outstanding system for use in space.

Taken together, the "Capaciflector" and the "Spine-Locking" Screw extend the state-of-the-art in automated berthing technology. It is now possible to have smart instrumented payloads with a sensing capability that can easily be fastened by robots with unprecedented control and safety throughout.

S14-32

N93-21421

146682

p. 2

## A Binocular Stereo Approach to AR&C at the Johnson Space Center

by Timothy E. Fisher and Alan T. Smith
Johnson Space Center and Lockheed Engineering and Sciences Company

Automated Rendezvous and Capture requires the determination of the 6 DOF relating two free bodies. Sensor systems that can provide such information have varying sizes, weights, power requirements, complexities, and accuracies. One type of sensor system that can provide several key advantages is a binocular stereo vision system.

Binocular stereo uses two video cameras on the rendezvous vehicle viewing the target vehicle. The target vehicle is equipped with a passive target that allows for easy and robust identification of the target. Range to the target is inferred from the different bearings in the left and right camera views of the target points. When the target has three or more identifiable points in a known geometry, the attitude of the target can be inferred from the bearings and ranges to the three points.

One of the main advantages of such a binocular stereo vision sensor is the simplicity of the hardware. The system uses standard video cameras and digital processing hardware. These items are likely to be present already on the rendezvous vehicle. The other major hardware components required include image digitizing electronics and possibly camera lens and pointing controls. Another advantage of this system is that it uses only passive sensors, limiting the amount of power required. Also, the system requires only a passive target so that rendezvous is possible with non-powered or dysfunctional satellites and systems.

Another advantage of the stereo vision approach is that the system designer has many design trade-offs that can be used to "scale" the system to a particular application (specific baseline, range accuracy, etc.). For example, the field of view of the cameras can be narrowed to increase the operational range of the sensor at the expense of limiting the minimum range at which the system can operate. Other variables that can be altered include camera resolution, baseline distance between the cameras, and vergence angle of the camera pair. Also, the system processor can be replaced with a more powerful one if faster update rates are necessary.

Binocular stereo has some limitations that need to be addressed when considering the sensor requirements. One of the key limitations of this system is the limited operational range of the sensor and the limited range accuracy at longer distances. Range is calculated using a triangle whose vertices are the two cameras and the target point. As the target point moves far away from the cameras, the triangle is elongated, and the errors in measuring the bearing angles dominates the measurement and accuracy suffers. Another reason for the limited operating range of the sensor is that the passive target must subtend several camera pixels before the target identification algorithms can work. These limitations can be counteracted by proper design of the system, but the tradeoffs necessary to achieve the desired results at long ranges may adversely affect performance at shorter ranges.

At JSC, we have developed an engineering development platform to investigate the issues involved in using stereo-based sensors for AR&C. We have successfully demonstrated a binocular stereo based automated rendezvous operation using a mobile robot and a simulated earth background. Preliminary results show range precisions on the order of 0.25% of range at close ranges. Detailed error calculations will be done in the near future.

515-36

N93-21422

146683

## A Comparison of Laser-Based Ranging Systems for AR&C

by Stephen J. Katzberg and Pleasant W. Goode IV
Langley Research Center

The three most common types of laser target ranging (time-of-flight, tone modulated, and FM-CW) are discussed first as far as principle of operation is concerned. The first, time-of-flight, is shown to depend more on the ability of support electronics than the fundamentals of the concept. Examples in the literature are cited to show the remarkably good performance of time-of-flight systems. A system developed in Finland has been shown to have an incremental ranging capability of a few millimeters. The system is not only robust; it does not include additions such as reference legs and the like, which are expected, for improvement in performance.

Though not immediately obvious, the second technique, tone modulated ranging is somewhat of an extension of the time-of-flight technique. Essentially the tone systems use the phase shift of the reflected laser (or LED, for that matter) power to determine the range. Since phase shift is just time shift times the "two PI per period" of the modulation, then this technique is directly analogous to the time-of-flight method already discussed. Limitations on the use of very high modulation frequencies for improved incremental accuracy in this technique arise from the ambiguity in total phase after one period. Tone modulated systems are fairly common, commercial versions have been developed. A simple analysis is presented to show the kind of performance that might be expected from the tone modulated systems.

Third, the FM-CW technique is presented. This is completely different from the tone or time-of-flight techniques, but is a direct translation of the same-named technique used in radar ranging systems. One major advantage for this application that lasers have over the RF version is precise aiming and lack of multipath interference. In this technique, the source must be a rapidly tunable laser source without mode hops of the main oscillating mode. The laser is chirped over its useful tuning range and transmitted to the target. After return from the target, the laser is heterodyne detected and processed. Since the round trip time to the target causes a delayed replica of the transmitted wave, heterodyne detection gives a beat frequency whose value is related to the tuning rate of the laser and the round-trip time. Knowledge of the tuning rate of the laser gives the range through utilization of frequency counters or detectors. It is noted that the FM-CW technique benefits from two factors: high signal-to-noise in heterodyne detection and much higher accuracy from the lack of phase ambiguity limitations. Performance analysis is given for comparison with the other techniques and some typical results are given to show how very accurate the FM-CW laser radar concept can be. As is typically the case, there are competing factors that limit the actual performance possible for FM-CW laser radars can achieve. One of the most important is the effect of lack of coherence length in the types of lasers capable of the wide tuning ranges needed. The effect manifests itself, not only in the loss of signal from coherence loss, but more importantly, the appearance of quantum phase noise associated coherence loss. Quantum phase noise represents a jitter in the phase part of the laser output, and although it is only phase and not amplitude, the effect is the same. Moreover, the phase noise is proportional to laser field amplitude squared, as contrasted to the first power field for the idealized heterodyne quantum noise limited case. The overall effect is to place far more stringent requirements on the type of laser source used than would be otherwise. The magnitude of this problem is illustrated in a simple case to show how much reduction may occur in performance. Laser sources other than the currently used laser diodes may alleviate the problem to a considerable degree with some reduction in performance due to the more limited frequency sweep.

In conclusion, it may be said that the FM-CW laser radar concept has already demonstrated considerable capability, and that limitations on performance stem from characteristics of laser sources which are constantly improving. Given this trend, it seems apparent that the FM-CW laser radar will clearly represent a considerable competitor for the time-of-flight technique and its close cousin, the tone modulated method.

N93-21423

**Demonstration of Automated Proximity and Docking Technologies**

By Robert Anderson, Roy Tsugawa/TRW and
Thomas Bryan, MSFC

146684

P-1

An autodock was demonstrated using straightforward techniques and real sensor hardware. A simulation testbed was established and validated.

The sensor design was refined with improved optical performance and image processing noise mitigation techniques, and is ready for production from off-the-shelf components.

The autonomous spacecraft architecture is defined. The areas of sensors, docking hardware, propulsion, and avionics are included in the design. The Guidance Navigation and Control architecture and requirements are developed. Modular structures suitable for automated control are used.

The spacecraft system manager functions including configuration, resource and redundancy management are defined. The requirements for autonomous spacecraft executive are defined. High level decisionmaking, mission planning, and mission contingency recovery are a part of this. The next step is to do flight demonstrations.

After the presentation the following question was asked. How do you define validation? There are two components to validation definition: software simulation with formal and vigorous validation, and hardware and facility performance validated with respect to software already validated against analytical profile.

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N93-21424

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# CATEGORY 2 - SOFTWARE SYSTEMS

## Intelligent Systems Technology Infrastructure for Integrated Systems

P-1

by Dr. Henry Lum, ARC

A system infrastructure must be properly designed and integrated from the conceptual development phase to accommodate evolutionary intelligent technologies. Several technology development activities were identified that may have application to rendezvous and capture systems. Optical correlators in conjunction with fuzzy logic control might be used for the identification, tracking, and capture of either cooperative or non-cooperative targets without the intensive computational requirements associated with vision processing. A hybrid digital/analog system has been developed and tested with a robotic arm. An aircraft refueling application demonstration is planned within two years. Initially this demonstration will be ground based with a follow-on air based demonstration. System dependability measurement and modeling techniques are being developed for fault management applications. This involves usage of incremental solution/evaluation techniques and modularized systems to facilitate reuse and to take advantage of natural partitions in system models. Though not yet commercially available and currently subject to accuracy limitations, technology is being developed to perform optical matrix operations to enhance computational speed. Optical terrain recognition using camera image sequencing processed with optical correlators is being developed to determine position and velocity in support of lander guidance. The system is planned for testing in conjunction with Dryden Flight Research Facility. Advanced architecture technology is defining open architecture design constraints, test bed concepts (processors, multiple hardware/software and multi-dimensional user support, knowledge/tool sharing infrastructure) and software engineering interface issues.

## Results of Prototype Software Development for Automation of Shuttle Proximity Operations

N93-21425

by H. Hiers, JSC and O. Olszweski, Lockheed Engineering and Sciences Company

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P-1

The effort involves demonstration of expert system technology application to Shuttle rendezvous operations in a high-fidelity, real-time simulation environment. The JSC Systems Engineering Simulator (SES) served as the test bed for the demonstration. Rendezvous applications were focused on crew procedures and monitoring of sensor health and trajectory status. Proximity operations applications were focused on monitoring, crew advisory, and control of the approach trajectory. Guidance, Navigation and Control areas of emphasis included the approach, transition and stationkeeping guidance and laser docking sensor navigation. Operator interface displays for monitor and control functions were developed. A rule-based expert system was developed to manage the relative navigation system/sensors for nominal operations and simple failure contingencies. Testing resulted in the following findings: 1) the developed guidance is applicable for operations with LVLH stabilized targets; 2) closing rates less than 0.05 feet per second are difficult to maintain due to the Shuttle translational/rotational cross-coupling; 3) automated operations result in reduced propellant consumption and plume impingement effects on the target as compared to manual operations; and 4) braking gates are beneficial for trajectory management. A versatile guidance design has been demonstrated. An accurate proximity operations sensor/navigation system to provide relative attitude information within 30 feet is required and redesign of the existing Shuttle digital autopilot should be considered to reduce the cross-coupling effects. This activity has demonstrated the feasibility of automated Shuttle proximity operations with the Space Station Freedom. Indications are that berthing operations as well as docking can be supported.

S19-04
ABS. ONLY
146687

## Autonomous Reconfigurable GPS/INS Navigation and Pointing System for Rendezvous and Docking

N93-21426

by Triveni Upadhyay, Mayflower Communications

P. 1

The briefing describes work using the Global Positioning System to determine position of spacecraft, and development of computer tools to utilize these position determinations to enable autonomous rendezvous. Using GPS data in conjunction with Inertial Navigation Systems (INS) provides the capability for absolute spacecraft navigation, navigation of one spacecraft relative to another, and attitude determination. Some results presented are based on limited observations, though simulation results are documented. A GPS/INS navigation flight experiment could provide a platform for evaluating approaches for autonomous operation and reconfigurability of the navigation and attitude determination subsystem for future space vehicles.

Current emphasis is on the development and demonstration of an Onboard Mission Manager (OMM) and a Multi-Mode Navigation Kalman filter. Sensor data will be handed over to the OMM, which will determine the appropriate response and generate commands for the Kalman filter to use to reconfigure itself. GPS measurements and INS data will be processed in the integrated navigation filter and used to compute errors in position, velocity, and attitude. INS instrument errors (biases, scale factors, etc.) also can be estimated. The OMM then will use a knowledge base to determine appropriate system response. GPS is good for missions that have attitude pointing accuracy requirements within the 100 to 200 arcsecond range.

Several techniques are available for using GPS based data to determine attitude. These techniques include velocity matching, interferometric, and attitude matching. They are used, either singly or in some combination, with either an absolute or a relative GPS/INS navigation mode, to determine the appropriate Kalman Filter configuration. In the report, nine filter configurations were identified to demonstrate the reconfigurability concept.

The Kalman filter software and the OMM software are being developed in the Ada programming language. Emphasis in this development is placed on modularity with a high degree of reconfigurability built into the system. The intent is to support anticipated future expansion requirements and the capability to perform on-board modification of the Kalman filter using a knowledge base. Capability to accept a wide range of sensor input (horizon sensors, sun sensors, star trackers, etc.) also is incorporated in the system.

Preliminary results from the use of both real GPS data and simulations were provided. These results indicate a capability to determine position in a static or benign environment to within 1-2 meters. In a dynamic environment, indications are that position may be determined to within 5-10 meters. These analyses point out the need to develop high fidelity models of ionospheric and multi-path errors to provide improved accuracy.

Some questions arose during the presentation. Did Mayflower incorporated the degradation due to the DoD selective availability (SA) implementation? Mayflower had not incorporated SA in their analysis at this time. What are the GPS limitations in the short range? The multipath effects and obscuration by structures must be closely analyzed. This is especially true for Space Station Freedom due to its size. Finally, a question came up regarding the viability of using receivers from different manufacturers. The use of different receivers should not be a problem as long as they are cooperative and are tracking the same satellites. There may be some degraded performance (on the order of 10 meters) in some mixes of receivers.

S20-18
ABS. ONLY
146688

**Autonomous Rendezvous and Capture System Design**
by Richard Dabney, Marshall Space Flight Center

N93-21427

The presentation addressed the different tradeoffs necessary to get an automated rendezvous and capture system design that meets the requirements. The topics covered are piloted versus autonomous capture design considerations, navigation sensor selection tradeoffs, control algorithm design requirements and concepts, performance evaluation through simulation, system mission readiness verification and validation, and advanced AR&C control system technologies.

In looking at piloted versus autonomous design considerations, the autonomous system has many advantages. The advantages include mission flexibility, potential fault tolerance/redundancy, greater inherent reliability/predictability, reduced mission support/operations cost, reduced fuel consumption, and enhanced mission performance capabilities. The advantages of the piloted system are reduced hardware/software development costs and a reduced development schedule risk. Given the overwhelming advantages of the automated system, it was the one chosen as the baseline for the Cargo Transfer Vehicle Program.

In the area of navigation sensors, several candidate technologies look promising. Scanning laser radars have good accuracy, but higher cost and development risk than other choices. Video scene interpretation methods take advantage of an inexpensive mature technology but have limited acquisition range. Radio frequency techniques offer long acquisition ranges and high accuracy, but pose a high development risk.

In developing a control algorithm, the approach requirements drive what type of algorithm is required. Tumbling or spinning targets require continuous tracking of the docking axis, resulting in a spiral approach trajectory and complex algorithms. Stable target docking can be achieved using simple proportional derivative controllers. The required approach initiation range and position also effect the control algorithm. Approaches along the v-bar from short (< 150 ft) initial distances are simplest. V-bar approaches from greater distances require significant vertical orbital mechanics effects compensation. R-bar approaches require significant orbital mechanics effects compensation at all ranges.

Performance evaluations through simulation are an important element of AR&C. MSFC used AR&C Pathfinder funds to achieve the first known full-scale demonstration of passive target AR&C using MSFC's air-bearing vehicle. The system uses a CCD video sensor to acquire an image of a patented three-point reflective docking target, illuminated by an array of laser diodes. Since the AR&C system was not required to take control until 150 feet, a simple proportional-derivative control loop proved adequate for generating thruster commands. Hundreds of runs have been made and system performance exceeds that of human pilots who have flown the air-bearing vehicle in the past. It is now considered ready for flight qualification and testing.

Requirements for system verification and validation include environmental and dynamic elements. The system should be tested for tolerance of temperature, vibration, vacuum, etc. The dynamics testing should be full scale and continuous from the beginning of rendezvous until final docking is achieved. A flight experiment, either in space or by means of a properly equipped aircraft, is recommended before use of AR&C on high value missions. Collision avoidance capabilities also should be demonstrated along with the planned trajectory.

Two emerging software technologies, neural networks and fuzzy logic, offer significant potential in the area of AR&C. Neural networks are a recently rediscovered computational concept that relies heavily upon parallel architecture and negative feedback to "learn" to solve control, transformation, and pattern recognition problems by correcting its own errors. MSFC has developed a network for computation of relative attitude and position of two spacecraft using video images. Fuzzy logic provides a convenient means of modeling nonlinear functions that are difficult to represent explicitly. This class of algorithms has proven useful for many control tasks normally performed by humans.

S21-18
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146681
p-1

# CATEGORY 3 - INTEGRATED SYSTEMS

## Proximity Operations Considerations Affecting Spacecraft Design

by Steven K. Staas, McDonnell Douglas Space Systems Company

Proximity operations can be defined as the maneuvering of two or more spacecraft within 1 nautical mile range, with relative velocity less than 10 feet per second. The passive vehicle is non-translating and should provide for maintenance of the desired approach attitude. It must accommodate the active (translating) vehicle induced structural loads and performance characteristics (mating hardware tolerances), and support sensor compatibility (transponder, visual targets, etc). The active vehicle must provide adequate sensor systems (relative state information, field-of-view, redundancy), flight control hardware (thruster sizing, minimal cross-coupling, performance margins, redundancy) and software (reconfigurable, attitude/rate modes, translation and rotation fine control authority) characteristics, and adequate non-propulsive consumables such as power. Operational concerns must be considered. These include: (1) the desired approach trajectory and relative orientation; (2) the active vehicle thruster plume effects (forces, torques, contamination) on the passive vehicle; and (3) procedures for contingencies such as loss of communications, sensor or propulsion failures, and target vehicle loss of control.

S22-18
ABS. ONLY
146690

## Guideline Requirements for Serviceable Spacecraft Grasping/Berthing/Docking Interfaces Based on Simulations and Flight Experience

by A. B. Thompson, Martin-Marietta

N93-21429

The described efforts support a NASA Space Assembly and Servicing Working Group activity to draft guideline interface standards. The general requirements are to provide a simple, reliable, and durable system. Interface requirements developed include lateral position offset, axial and lateral velocities, and angular misalignment. A survey of concepts and simulation studies of spacecraft docking, existing docking/end effector performance criteria, and space proven, qualified docking data was conducted and evaluated, in order to provide recommended mechanical interface guidelines and interface tolerances for manual and autonomous capture operations. The criterion for the selection of the guidelines was maximum capability to handle malfunctions. Originally the guidelines for a zero velocity docking were considered to be covered within the grasping/berthing definition. It is acknowledged that perhaps a separate category needs to be established for this option. The draft standard has been delivered to the AIAA for review, revision, and issuance as the first U.S. national standard guideline on interfaces. The intent is to develop the guidelines into an International Standards Organization standard.

S23-18
ABS. ONLY

## Autonomous Docking Ground Demonstration

By S.L. Lamkin, T.Quan Le, L.T. Othon, and J.L. Prather/NASA JSC
R.E. Eick, J.M. Baxter/TRW;
M.G. Boyd, F.D Clark, P.T. Spehar, R.J. Teters/LESC

146691
N93-21430

The Autonomous Docking Ground Demonstration is an evaluation of the laser sensor system to support the docking phase (12 ft to contact) when operated in conjunction with the guidance, navigation and control software. The docking mechanism being used was developed for the Apollo/Soyuz Test Program. This demonstration will be conducted using the 6-DOF Dynamic Test System (DTS). The DTS simulates the Space Station Freedom as the stationary or target vehicle and the Orbiter as the active or chase vehicle. For this demonstration, the laser sensor will be mounted on the target vehicle and the retroflectors will be on the chase Vehicle. This arrangement was chosen to prevent potential damage to the laser. The laser sensor system, GN&C, and 6-DOF DTS will be operated closed-loop. Initial conditions to simulate vehicle misalignments, translational and rotational, will be introduced within the constraints of the systems involved.

The laser sensor system being used is a brassboard version of the Laser Docking Sensor that was being developed for application in the Lunar/Mars Programs. The laser sensor being used has been tested in the 6 DOF Sensor Test Bed (Granite Rail) in Building 14 at NASA/JSC. The Shuttle and Station models are pared down from existing models and will be validated from existing test cases. The integrated test runs currently are delayed by DTS controller hardware problems. Difficulties have been encountered thus far, but progress is continuing.

S34-18
ABS. ONLY

N93-21431

## An Overview of Autonomous Rendezvous & Docking System Technology Development

by Kurt D. Nelson, General Dynamics

The Centaur upper stage was selected for an airborne avionics modernization program for many reasons. The parts used in the existing avionics units were obsolete and continued use of existing hardware would require substantial redesign yet result in the use outdated hardware. Manufacturing processes also were out of date with very expensive and labor intensive technologies being used for manufacturing. The Atlas/Centaur avionics were to be procured at a fairly high rate that demanded the use of modern components. The new avionics also reduce size, weight, power, and parts counts with a dramatic improvement in reliability. Finally, the cost leverage derived from upgrading the avionics as opposed to any other subsystem for the existing Atlas/Centaur was a very large consideration in the upgrade decision. The upgrade program is a multiyear effort begun in 1989. It includes telemetry, guidance and navigation, control electronics, thrust vector control, and redundancy levels.

The new INU combines the inertial measurement system with the flight control system into a single radiation hardened package including ring laser gyros, accelerometers, processors, and electronics. This new system resulted in a weight savings of over 100 pounds and a four-to-one cost reduction. The new Remote Voter Unit (RVU) receives commands and performs a 2 out of 3 vote on the discrete commands with a center select on the analog signals. The RVU is fully internally redundant, has been developed, breadboarded, and demonstrated. The integration of a Global Positioning System receiver into the inertial navigation system has been accomplished for both the advanced Centaur and the cruise missile programs. The capability provided by this system will meet the accuracy requirements for low earth operations independent of mission duration time. It provides precision position and velocity measurements and it can be configured to provide attitude information.

An Image Processor Assembly (IPA) is in flight test and an earlier model IPA was used in a successful proof of concept AR&D ground demonstration in November 1990. This adaptable embedded processor (of Cruise Missile heritage) is modular and can be reconfigured in real-time to perform a variety of mission functions. A unit is being built for the Autonomous Rendezvous, Docking and Landing System Test Program. A typical submodule contains a 32-bit microprocessor with four megabytes of memory. Each board can accept up to eight submodules providing processor capability of eighty 32-bit microprocessors and 320 megabytes of memory with a throughput of 800 MIPS. Modular functions include frame grabbers, graphics display drivers, interface adapters, video processors, and MIL-STD-1553 and other system interfaces. The modular parallel processor approach provides performance and flexibility to rapidly reconfigure for changes in the application environment.

The Centaur modern avionics components can be combined with the Cruise Missile image processing system and GPS to provide a fully autonomous rendezvous and docking system using off-the-shelf technology. The autonomous capability provides collision and hazard avoidance in all operational modes. The system is triple modular redundant. The system can be augmented with S-Band or Ku-Band transceivers and command units to provide a manual override capability to meet additional mission safety requirements or to enhance versatility. The Cruise Missile derived image processing system accommodates a variety of sensors. The integration of GPS/IPS/INS provides a robust, scalable and easily reconfigurable architecture. The mature system elements minimize the integration and development costs.

The Multi-Path Redundant Avionics Suite (MPRAS) advanced development program is focusing on the next generation avionics system architecture. This architecture will use standardized electronics modules to provide a scalable, open architecture with commonality across many programs. In this way, technology can easily be inserted as it matures. By leveraging the modules over many programs the cost also is reduced. Ultimately, the goal of MPRAS is to develop space qualified common modules for processors, data busses, power supplies, sensor interfaces, inertial sensors, and GPS receivers.

The Centaur modern avionics suite combined with existing Cruise Missile technology provides a very viable approach to a fully autonomous rendezvous and docking system. The image processing system also provides the added benefit of performing terrain mapping and object recognition. This capability allows the same system to be used for autonomous landing support. A fully integrated system approach provides a versatile control system with several applications. This system is being evaluated for application to the Cargo Transfer Vehicle, Space Station Resupply, Advanced Manned Launch System, High Speed Civil Transport, Common Lunar Lander, and other planetary landers. The Laboratory facilities at JSC, MSFC, LaRC, and ARC will provide the key testbed accommodations for the evaluation of this system.

Concerns / questions that arose during the presentation include: What is the probability of qualifying the super computer from the cruise missile? It is undergoing MIL qualification. Space qualification would depend on interest and funding. How much memory is in the 1750 processors? Up to 256 K bytes (16-20 bit), with present operation at 128 Kb. Is there planning to go to a four string system to meet two fault tolerance? Yes, an evolutionary system such as MPRAS would meet a FO/FO requirement whereas the TMR does not.

S25-18
N93-21432

**An Autonomous Rendezvous & Docking System using Cruise Missile Technology**

by Ed Jones and Bruce Nicholson - General Dynamics

146623
p/2

In November 1990 General Dynamics demonstrated an AR&D system for members of the Strategic Avionics Technology Working Group. This simulation utilized prototype hardware derived from the Cruise Missile and Centaur avionics systems. The object of this proof of concept demonstration was to show that all the accuracy, reliability, and operational requirements established for a spacecraft to dock with Space Station Freedom could be met by the proposed AR&D system.

The AR&D system originally was designed to support Expendable Launch Vehicle (ELV) logistic support of SSF; integrating the best features of two mature avionics systems in meeting the stringent requirements associated with docking/berthing with the SSF. The advanced Centaur avionics system has a scalable architecture and combines a three-string INS with a redundant Global Positioning System (GPS). The communications system can be configured to support teleoperated, supervised automatic and/or autonomous operations. The Image Processing Assembly (IPA) is derived from the units currently being evaluated in the Cruise Missile flight test program. The IPA accommodates a variety of sensor inputs, has a proven record of target recognition and accurate tracking capabilities, is programmable in several computer languages including Ada, and provides performance and flexibility to rapidly reconfigure for changes in the application environment. Circuit boards are constructed with submodules that allow the designer to tailor the hardware to the target applications. A typical submodule contains a 32-bit microprocessor and four megabytes of memory. Each board can accept up to eight submodules. Available processor modular functions include video frame grabbers, graphics display drivers, interface adapters, video processors, and MIL-STD-1553 and other system interfaces. Sensors accommodated include video, forward looking infra-red, and laser sensors.

The AR&D proof of concept demonstration simulation included as much hardware as possible and required real-time system operational capabilities that were provided by the Advanced Avionics System Development Lab. The docking vehicle and SSF dynamic models were contained in the main processor where the relative positions of the vehicles also were calculated as they orbit the earth. A docking vehicle view of the SSF is generated on a graphics monitor, which is viewed by a video sensor/IPA; an INU is mounted on a three-axis table to emulate the system's inertial sensors; and the loop is closed through the autopilot and dynamic model. System performance and status is monitored on graphic monitors or workstations. Three real-time parameters can be monitored on individual, autoranged graphs. Overall system performance is evaluated by freezing and displaying the velocity and displacement parameters at the instant of contact. A dedicated window displays the simulator's operational mode and configuration. Other windows display the orbital position and firings of the RCS jets. When docking with SSF, the docking vehicle must follow specific approach procedures. The simulated ELV approach started at a range of 300 meters behind the SSF, along its velocity vector, with approach to this point based on inertial and GPS references. Though the IPS can acquire and track the SSF from more than a kilometer, it is not the primary sensor until about the 20-meter range. Initially, the target was SSF. The target transition to the SSF docking module, then to the target on the docking module, and finally to the small target on the hatch of the docking module.

Expanded use of the simulator is planned for 1992. Areas to be explored will include sensor suite mix to add robustness, optimization of IPA configuration to support terminal guidance with collision avoidance, and evaluation of autolanding capabilities for terrestrial and planetary applications. The simulation facility will be used to help integrate the AR&D system into the NASA test facilities participating in the ARD&L System Test Program. The test program potentially will involve test facilities at JSC, MSFC, and LaRC to independently test and validate the performance of key elements of this pathfinder AR&D system.

Concerns addressed during the presentation: Is the use of the image processor discussed an overkill since only four dots were being viewed? Yes, for only that function. When growth considerations such as handling multiple targets, performing docking and supporting landing are considered, there is no overkill. What are the power requirements? 80 watts, but the system is flexible and can be reconfigured according to need.

S26-18
ABS ONLY
14/6/94

## On-Orbit Demonstrations of Automated Closure and Capture Using ESA-Developed Proximity Operations Technologies and an Existing Serviceable NASA Explorer Platform Spacecraft

N93-21433

by Bill Hohweisner, Fairchild and
Jean-Michel Pairot, Matra Marconi Space

Since 1984 the European Space Agency (ESA) has been working to develop an autonomous rendezvous and docking capability to enable Hermes to dock automatically with Columbus. As a result, ESA (with Matra, MBB, and other space companies) have developed technologies that are directly supportive of the current NASA initiative for Automated Rendezvous and Capture. Fairchild and Matra would like to discuss the results of the applicable ESA/Matra rendezvous and capture developments and suggest how these capabilities could be used together with an existing

NASA Explorer Platform satellite to minimize new development and accomplish a cost-effective automatic closure and capture demonstration program.

Several RV sensors have been developed at breadboard level for the Hermes/Columbus program by Matra, MBB, and SAAB. For example, the Matra laser proximity operation sensor, developed with Matra and CNES funding is based upon a flight qualified CCD sensor working together with a pulsed laser to illuminate retroreflectors mounted on the target docking side. The CCD operates in a Flash-During-Transfer (FDT) mode, enabling operation even with sunlight in the sensor FOV. The sensor has demonstrated good results at ranges out to 1 km and at proximity operation relative velocities, even with the sun in the FOV. The sensor demonstrated recently at 10 m: range accuracy to 0.8% of range (3 sigma); elevation/azimuth accuracy better than 0.02° (3 sigma); and attitude angles of the target to better than 0.25° (3 sigma) using five optical retroreflectors in a 15 cm wide pattern.

Detailed algorithms for automatic rendezvous, closure, and capture have been developed by ESA and CNES for application with Hermes to Columbus rendezvous and docking. They currently are being verified with closed-loop software simulation. The algorithms have multiple closed-loop control modes and phases starting at long range using GPS navigation. Differential navigation is used for coast/continuous thrust homing, holdpoint acquisition, v-bar hopping, and station point acquisition. The proximity operation sensor is used for final closure and capture. A subset of these algorithms, comprising the proximity operations algorithms, could easily be extracted and tailored to a limited objective closure and capture flight demonstration.

The software to implement the automatic operations has been written in C and Ada. Closed loop performance tests are in progress. These tests include the software for final approach operations (100 m to a few cm), and testing is to be complete by January 1992.

Fairchild and Matra suggest that by combining ESA and NASA resources, a complementary, cost effective flight demonstration program to demonstrate automated closure and capture could be readily structured. This joint, cooperative program would use the automated guidance and proximity operations system developed by Matra for ESA and the existing, on-orbit Explorer Platform (EP) spacecraft developed by Fairchild for NASA. These two system elements would be integrated by Fairchild with an EP-mounted docking module receiver and a maneuvering payload module (PLM) to close with and dock to the EP docking module receiver.

The proposed program would have Fairchild build the docking module to be attached on-orbit to the EP, build the payload module with a maneuvering capability that performs the docking with the EP-attached docking module (using the Fairchild-developed resupply interface mechanism), complete development of the STS procedures for on-orbit EP payload changeout to remove the current EUVE payload and attach the docking module; and accomplish the overall system integration. European Space Agency and Matra would provide the proximity operations sensor and the guidance software as well as verify the satisfactory flight hardware closure and capture on the European Proximity Operations (EPOS) simulator and/or on the CNES 6 DOF Dynamic Docking Test Facility (DDTF).

37-37

N93-21424

## A Method for Modeling Contact Dynamics for Automated Capture Mechanisms

by Philip J. Williams, Logicon Control Dynamics Inc.

Logicon Control Dynamics develops contact dynamics models for space-based docking and berthing vehicles. The models compute contact forces for the physical contact between mating capture mechanism surfaces. Realistic simulation requires proportionality constants, for calculating contact forces, to approximate surface stiffness of contacting bodies. Proportionality for rigid metallic bodies becomes quite large. Small penetrations of surface boundaries can produce large contact forces.

The Method of Soft Constraints is a contact dynamic modeling technique in which surface boundary constraints of contacting bodies are enforced through application of restoring forces to the bodies when contact is detected. This technique allows small violations of the constraints. The advantages of the method are that it is relatively easy to implement and the number of constraints is unlimited.

A disadvantage of the method is that simulation run times are relatively long on most affordable computers. Usually, results are saved from a simulation and then processed by a graphics program to generate an animation. What makes the simulation take a long time? When this type of contact model is used for "force" with the system equations of motion run in a time domain simulation, the integration step must be chosen carefully. Often a very small integration time step is selected to avoid numerical instability even though this makes the simulation run time longer.

Contact force models using the Method of Soft Constraints can help evaluate capture mechanism performance, both before and after hardware production. Engineers can use simulation results in examining loads, and dynamic response characteristics as well as in stress analysis. Data can help determine size and shape of capture envelopes and can evaluate mechanisms and their controllers.

Contact force models were used to validate hardware-in-the-loop tests at MSFC's 6-DOF motion facility. Models included were: OMV, SSF docking, SSF berthing, and Apollo/Skylab. These models were incorporated in time-domain contact dynamics simulations. They were used to generate contact loads and dynamic response data.

The contact force model for Space Station Freedom contains component models for all parts of the berthing system, thus facilitating accurate simulations. Mass properties and initial conditions are given to the contact force models and the hardware in-the-loop simulation. Computer dynamic responses and contact characteristics closely match the actual results. In 1992, this model will support hardware in the loop berthing tests.

After the presentation, two questions were asked. Does the model deal with compliance between the payload and the Remote Manipulator System (RMS)? Flexibility terms were incorporated. Could berthing or docking with Space Station Freedom be accomplished without force feedback? The force feedback discussed in the presentation was only for simulation implementation and the actual docking does not require force feedback.



## A Phase One AR&C System Design

By Peter Kachmar, Robert Polutchko, Marty Matusky, and William Chu/C.S. Draper Laboratory
William Jackson and Moises Montez/JSC

The Phase One AR&C System Design integrates an evolutionary design based on the legacy of previous mission successes, flight tested components from manned Rendezvous and Proximity Operations (RPO) space programs and additional AR&C components validated using proven methods.

The Phase One system has a modular, open architecture with the standardized interfaces proposed for Space Station Freedom system architecture.

As of today, the "Phase One" AR&C integrated GN&C system design is complete. The new subsystems are an integrated system executive; laser sensor and laser navigation capability for relative position, velocity, and attitude; auto maneuver execution; and trajectory controller. The hardware requirements are specified, and essential components were validated with proven tools which were themselves proven through flight design support.

The next step is to define and execute flight demonstrations of the Phase One system and its components.

After the presentation, concerns were addressed: What are the additional laser requirements? The response: A report to NASA is planned in about 4 weeks. The plan is to look at expanding the envelope to include manned and unmanned operations and to look at performance degradation. A trade comparing the Phase One system with respect to laser accuracy specifications will be done.

529-54
ABS. ONLY

## CATEGORY 4 - OPERATIONS

146697
N93-21436

### Operator-Assisted Planning and Execution of Proximity Operations Subject to Operational Constraints

p. 1

by Arthur J. Grunwald and Stephen R. Ellis, Ames

Future multi-vehicle operations will involve multiple scenarios that will require a planning tool for the rapid, interactive creation of fuel-efficient trajectories. The planning process must deal with higher-order, non-linear processes involving dynamics that are often counter-intuitive. The optimization of resulting trajectories can be difficult to envision. An interactive proximity operations planning system is being developed to provide the operator with easily interpreted visual feedback of trajectories and constraints. This system is hosted on an IRIS 4D graphics platform and utilizes the Clohessy-Wiltshire equations. An inverse dynamics algorithm is used to remove non-linearities while the trajectory maneuvers are decoupled and separated in a geometric spreadsheet. The operator has direct control of the position and time of trajectory waypoints to achieve the desired end conditions. Graphics provide the operator with visualization of satisfying operational constraints such as structural clearance, plume impingement, approach velocity limits, and arrival or departure corridors. Primer vector theory is combined with graphical presentation to improve operator understanding of suggested automated system solutions and to allow the operator to review, edit, or provide corrective action to the trajectory plan.

530-18
ABS. ONLY

### Collision Avoidance for CTV: Requirements and Capabilities

by Thomas Nosek, TRW
Presented by Ken Rourke, TRW

146698
N93-21437

Collision avoidance must be ensured during CTV operations near the space station. The design of the Collision Avoidance Maneuver (CAM) will involve analysis of CTV failure modes during rendezvous and proximity operations as well as analysis of possible problems external to the CTV, but that would require CTV to execute a CAM. In considering the requirements and design of the CAM for the CTV, the CAM design for the Orbital Maneuvering Vehicle (OMV) is a useful reference point from which some lessons can be learned and many CTV design options can be set forth

One design choice, the degree of integration of the CAM with the CTV's primary avionics, will greatly impact the CTV's CAM options. Also, staged CAM options at successive hold distances and times provide options for fault recovery without prematurely terminating the mission.

Questions and issues: Is a dissimilar backup computer required (in spacecraft)? Some people would like to remove the fifth "watchdog" computer unless or until it is shown to be necessary by some requirement or calculation.

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531-18
ABS. ONLY
146699

### MMU Applications for Automated Rendezvous and Capture

by Ed Whitsett, NASA, JSC

p. 3

The Manned Maneuvering Unit (MMU) is a proven free flying platform that can operate in a piloted or unpiloted mode. The MMU is a possible candidate for an on orbit AR&C demonstration. A pilot can transition the system between manual and automated modes, then monitor the automated system for safety.

There is considerable flight experience with the MMUs. In February 1984, two MMUs were used on Challenger (STS 41-B). Astronauts performed translations of 150 and 300 feet to and from the orbiter. With a Trunnion Pin Attachment Device (TPAD) connected to the MMU control arms, docking exercises were performed on the SESA and SPAS pallets.

Another Challenger mission (STS 41-C) carried two MMUs in April 1984. During EVA, an astronaut attempted to capture a Solar MAX Satellite that was rotating and out of control. Unfortunately, the TPAD could not achieve a hard dock with the trunnion pin.

Discovery (STS 51-A) carried the MMUs up to space again in November 1984. Using the MMU, an astronaut rendezvoused with PALAPA B-2. This time, the TPAD affected a hard dock. The astronaut stabilized the satellite using the MMU's Automatic Attitude Hold (AAH). A WESTAR VI was captured two days later, using the same procedure.

Safe, noncontaminating gaseous nitrogen is the MMU propellant. Recharging can occur on-orbit using the Shuttle's large nitrogen tanks. The MMU can achieve 66 feet per second total change in velocity with a full charge and average sized astronaut. Other system characteristics are:

| | |
|---|---|
| MMU weight with full charge: | 339 pounds |
| Operation time on one (1) battery: | 6 hours |
| Distance in daylight: | 450 feet |
| Distance at night with running lights: | 150 feet |
| Translation velocity: | 0.3 ft/sec |
| Rotation acceleration: | 10 deg/sec/sec |
| Height: | 50 inches |
| Width: | 33 inches |
| Length: | 27 inches (arms folded) |

The MMU can fly in either a pilot monitored or unmanned configuration. EVA Retriever programs demonstrated automated systems interfaces using MMU flight hardware.

Primary elements of an MMU based on-orbit AR&C demonstration are the MMU, an avionics package, and the Orbiter Remote Manipulator System (RMS) or Multiple Payload Experiment Structural System (MPESS), for use as a target. An AR&C avionics package can attach to the MMU between the control arms. The avionics container could be based on the IMAX camera design and could be mounted in front of the pilot. The avionics include the docking/capture sensor, GN&C processors, transmitter, additional power, and an optional pilot supervisory display. A docking or berthing mechanism can fit on the exterior of the package. An interface between the avionics package and the MMU would enable the AR&C system to access MMU gyro data and allow control of the MMU propulsion subsystem.

Propulsion system commands can be issued through the handcontroller interface, based on automated control algorithms. Control authority of the CTV can be emulated in a pulsed thruster mode.

Options for the AR&C target are: (1) docking/capture target only; (2) target and docking mechanism; or (3) spacecraft mockup with target and docking mechanism. Either the Orbiter RMS or the MPESS can have a mounted target. The MPESS would be in the Orbiter cargo bay.

A low cost on-orbit demonstration can start in the near term (~1.5 years). Facilities already exist for the design, development, simulation, integration, ground test, and training. The Space Operations Simulation (SOS) Laboratory provides a real-time simulation capability for rapid development, simulation, and system performance evaluation. The JSC Precision Air Bearing

Facility (PABF), using a MMU qualification-unit and EVA Retriever, can support physical integration of the MMU and AR&C systems.

Questions were addressed at the end of the presentation: Can the range of the MMU extend beyond 300 feet? Yes, but at this time a mission rule limits the range to 450 feet. Can an unmanned MMU be considered for an AR&D demonstration flight? Yes, but we want to make sure to provide safety/override capability in the event of an anomaly. What is the astronauts' reaction to the Auto R&D scenario? They do support the effort, but when safety reviews come up, the job of selling the idea gets harder.

S32-16
N93-21439
146700
p. 2

**The Realtime Operations of the Space Shuttle Orbiter during Rendezvous and Proximity Operations**

by Andrew Dougherty, Goddard Space Flight Center

The Shuttle first demonstrated the capability to perform precision proximity flying in 1983 when the SPAS-01 satellite was deployed and subsequently retrieved. This flight was intended to validate the capability of the Shuttle to perform proximity operations with a co-orbiting vehicle in preparation for the Solar Maximum Repair mission of the next year.

STS-39 was flown in April 1991 and contained the most complex relative trajectory flown by the Shuttle yet. Existing onboard targeting algorithms were used to plan and execute the complex flight profile. New techniques for using the software had to be developed to support the trajectory and they proved to be more accurate than the ground software in executing maneuvers.

Shuttle rendezvous operations have two segments: phasing and "the day of rendezvous." Phasing begins at lift-off and ends when the range to the target is approximately 40 nmi. The "day of rendezvous" phase of operations covers the last 40 nmi to the target. The name comes from the fact that most of the maneuvers executed during that last day are computed onboard, providing a functional difference.

Shuttle proximity operations cover the final phase of the rendezvous. The phase is characterized by crew control of the trajectory based on radar data and out-the-window viewing of the target. It begins immediately after the last rendezvous burn and ends with the successful grapple of the target. A subsection of proximity operations involves the deployment and separations. There are two phases of proximity operations, the standardized transition trajectory and the final approach. As the name implies, transition trajectory is a well known and standard trajectory flown by the crew to transition the Shuttle from an interception trajectory to formation flying with the target some 130 meters in front of it on the velocity vector. The approach, however, is not as standard because it depends on the characteristics of the target. Some targets are Local Vertical/Local Horizontal (LVLH) stabilized and some are inertially stabilized. The Shuttle program prefers the target to be in a LVLH stabilized configuration for grapple and places tight restrictions on the attitude and attitude rates of the target for nominal operations via the PIP.

Many significant lessons can be learned from the Shuttle program that can reduce mission planning costs for future vehicles; for examples: unify flight design and real-time operations software, integrate the flight design and real-time operations personnel, provide a control center and flight vehicle that allows for quick software upgrades, and use new state-of-the-art software development tools to reduce configuration control.

Significant benefits to both the Shuttle and Cargo Transfer Vehicle programs could be realized by co-developing rendezvous and proximity operations software because of the commonality of the algorithms.

In summary, any vehicle that is designed to perform rendezvous and proximity operations must consider at least the following conditions in the design of the vehicle: plume impingement and contamination, sensors, visual cues, data transmission times, data presentation to the pilot, flying qualities from jet placement, and grapple operations.

S33-18
ABS. ONLY

## Autonomous Rendezvous and Docking - A Commercial Approach to On-Orbit Technology Validation

P. Tchoryk et. al, Environmental Research Institute of Michigan), Space Automation and Robotic Center and
R.P. Whitten, NASA-HQ (Code CC)

14678/
N93-21440
P. 2

SpARC, in conjunction with its corporate affiliates, is planning an on-orbit validation of autonomous rendezvous and docking (ARD) technology. The emphasis in this program is to utilize existing technology and commercially available components wherever possible. The primary subsystems to be validated by this demonstration include GPS receivers for navigation, a video-based sensor for proximity operations, a fluid connector mechanism to demonstrate fluid resupply capability, and a compliant, single-point docking mechanism.

The focus for this initial experiment will be ELV based and will make use of two residual Commercial Experiment Transporter (COMET) service modules. The first COMET spacecraft will be launched in late 1992 and will serve as the target vehicle. After the second COMET spacecraft has been launched In late 1994, the ARD demonstration will take place. The service module from the second COMET will serve as the chase vehicle.

The ARD mission begins with the validation state, in which the ARD payload is powered up and the payload controller (a 286 running VRTX and the Spacecraft Command Language) starts executing tasks. GPS almanac data is uploaded from the ground station and loaded into the GPS receivers on COMETs 1 and 2, allowing GPS data collection to begin.

In the ready state, COMET 1 is maneuvered into velocity vector mode in preparation for ARD, via commands from the ground station. At this point the RF link is activated and time stamped GPS and ACS data is transmitted through the link. COMET 2 begins monitoring the RF link for COMET 1 transmissions.

In the rendezvous state, ephemeris data for COMETs 1 and 2 (based on ground tracking and on-orbit GPS data) are used to compute the targeting commands required for COMET 2 to rendezvous with COMET 1. The resulting command sequence is then uploaded into COMET 2 from the ground station. The COMET 2 Orbital Adjust System (OAS) begins executing the commands to reach a station keeping state near COMET 1. While still several kilometers away from COMET 1, COMET 2 will be able to receive data through the RF link.

Relative position and velocity can then be used to keep COMET 2 in a station keeping state approximately 1 km from COMET 1.

Upon successful validation of system operations by the ground station, COMETs 1 and 2 are set into the proximity operations state. Using a combination of relative GPS information, a video tracker, and video-based proximity sensor, the Translation Maneuvering System (TMS) on COMET 2 executes commands to place COMET 2 within approximately 1 m from COMET 1.

At this point, the two spacecraft enter the docking state. COMET 2 instructs COMET 1 to shut down its ACS, allowing docking to take place with a stable, yet passive, spacecraft. The docking is essentially a two-step process, consisting of a latched, but loose, coupling between the spacecraft followed very quickly by a braking procedure, hard docking and rigidization.

In the alignment state, the two spacecraft are rotated relative to one another to ensure they will be lined up close enough for the fluid connector halves to mate. Once the two spacecraft are aligned, the fluid connector mechanism draws the two connector halves together in preparation for the fluid exchange experiment. The two spacecraft will undock and dock several times to fully test the system.

The three primary technology areas to be validated by this demonstration are navigation sensors, docking mechanism, and fluid exchange system. The major subsystems of the baselined ARD demonstration include: GPS receivers on both spacecraft for relative position and velocity information during rendezvous and close proximity operations, video-based, closed-loop sensing and processing for position, attitude, and rate information during close proximity/docking operations, a single-point, probe-type docking mechanism with enough compliance for autonomous docking, and a fluid connector interface mechanism to allow efficient transfer of fluid resources.

534-37
N93-21441
146702
p/ 1

## Experimental Validation of Docking and Capture Using Space Robotics Testbeds

by John Spofford, Martin Marietta

Docking concepts include capture, berthing, and docking. Definitions of these terms, consistent with AIAA, are: Capture (Grasping) - the use of a manipulator to make initial contact and attachment between transfer vehicle and a platform. Berthing - positioning of a transfer vehicle or payload into platform restraints using a manipulator. Docking - propulsive mechanical connection between vehicle and platform. The combination of the capture and berthing operations is effectively the same as docking; i.e., Capture(Grasping) + Berthing = Docking.

Accurate estimation of target vehicle position and attitude is critical to successful autonomous rendezvous and capture. Computer vision is a sensing technique that can provide accurate position data at close ranges. With appropriate targets, the required computing power for target feature extraction is minimized. An advantage of using computer vision-type sensors is that human operators also can use the direct video image.

Martin Marietta has a 20 x 30 foot epoxy air bearing floor. Three testbeds, a Free Flying Vehicle, a Large Space Manipulator and a Dexterous Manipulator, provide a three DOF environment that closely approximates zero gravity. The testbed vehicle has three maneuvering DOF: two translational and one rotational. The vehicle has mounting points for additional test mechanisms and interfaces.

There are a few technical challenges to address. First, an integrated simulation of the complete capture and berthing operation, incorporating vehicle, platform and manipulators, should be implemented on a hardware testbed. Second, the control of a manipulator from a free flying vehicle is still an R&D activity. Finally, flight validation of the autonomous capture and berthing method will have to occur before user confidence is complete.

Questions / concerns addressed following the presenting: How does one determine the range, using the video system? With a five point non-planer target of known geometry and based on the viewed image, the range is calculated as well as out of plane parameters. How is the gap between rendezvous and capture bridged? Some other system, perhaps laser based, is needed for range of one kilometer and out.

S35-12
N93-21442
146703
p. 1

# On-Orbit Operational Scenarios, Tools, and Techniques

by Jerry Jennings, James Walker/TRW

A derivation of OMV developed PC-based mission planning tools is described. Preliminary application of these tools has been shown to illustrate that detailed description of events and mission modeling complexity can be accommodated easily. Also, spreadsheet models can be expanded to increase detail.

Refinements are being done to tailor these to CTV and other future applications. Near-term modifications of spreadsheet analysis tools include: a definition of CTV operating states (13 are defined so far), the introduction of CTV power system architecture into models, and a modification of propellant spreadsheets for CTV propulsion definition.

Simulation and test data will replace analytical data in future versions of the spreadsheet tools.

Questions and concerns were addressed: How do you plan to handle CAM in a case where the approach orbit is above or crossing SSF and a failure causes loss of ability for approaching spacecraft to carry out a CAM? This is just now being addressed in CTV panels. One response would be to use only benign approach orbits. Efficiency factors during the final portion of the dock also may affect approach orbit selection.

How is the worst case scenario defined? The data presented in the paper used stacked worst case (3 sigma) estimates. The examples given were long holds and 3 docking attempts from 1000 feet.

Was GPS baselined? The GPS was baselined on CTV, but not on SSF. However, it was assumed that SSF has lights and cameras.

536-18

N93-21443

## CATEGORY 5 - SUPPORTING INFRASTUCTURE

146704

### Six-Degree-of-Freedom Test Facility

by Michelle Bittel, Lockheed Engineering & Sciences Company

p. 1

Shuttle to Space Station docking has become an important issue in the last few years. Docking sensors have been proposed that will provide the high precision measurements required for the fuel efficient rendezvous and docking of space vehicles. These sensors also will be used for satellite servicing and orbital assembly. The performance of the docking sensors must be tested before they are implemented in a space environment. A 6-DOF test facility has been developed at the Tracking and Communications Section, Johnson Space Center, to test the static and dynamic accuracies of docking sensors. A candidate sensor is evaluated by comparing the sensor's static position and velocity measurements to the more accurate 6-DOF system.

The facility comprises very robust hardware. An air-bearing 12-meter granite rail system highlights the system. Five rotary stages provide rotational movement. Additional hardware supporting the facility include a GPS time receiver, a rate meter, and a metrology system. A centralized computer with associated software controls the facility. The 6-DOF facility can provide one degree of translation (range) and five degrees of rotation (bearing angles and attitude). Range accuracies are 10.0 microns/meter while rotational accuracies are $\pm$ 0.001 degrees.

The 6-DOF Test Facility hardware is fully integrated. Software has been developed in-house to support system operation. The system has been tested statically and the operational parameters verified. System accuracies remain to be determined. Dynamic testing of the facility is expected to begin shortly. Several companies (such as McDonnell Douglas, Autonomous Technologies, and General Dynamics) are scheduled to test sensors in the next few months. The 6-DOF facility will be available for use in November 1991.

N93-21444

### Soviet Automated Rendezvous and Docking System Overview

By Elaine M. Hinman and David Bushman/MSFC

NBS ONLY

146705

p. 2

The Soviets have been performing automated rendezvous and docking for many years. Its has been a reliable mode of resupply and reboost for years.

During the course of the Soviet space program, the autodocking system has evolved. The earlier IGLA system has been replaced with the current KURS system. Both systems are radar-based. The variation in strength between antennas is used for computing relative positions and attitudes. The active spacecraft has a transponder. From discussions with Soviet engineers, it seems the docking process can be controlled either from the ground or from the active (docking) spacecraft's onboard computer.

The unmanned Progress resupply ships regularly dock with the current MIR Space Station. The Soyuz T spacecraft incorporated the IGLA system, and the later Soyuz TM and Progress M Series spacecraft incorporated the KURS. The MIR Complex has both systems installed. The rear port and the KVANT docking port have the IGLA system installed to support earlier Progress ships that uses the IGLA. The first Soyuz TM docking occurred In May of 1986, while the first Progress M docked in September of 1989.

Questions addressed during the presentation: How is Attitude Determined? Roll is sensed using directional antennas and both chase vehicle and Station is held in attitude hold.

What optical targets are used for contingency? The MIR optical target appears to be similar to the Apollo docking target.

Is override of automation by Cosmonauts cultural? Seemingly yes, since all unmanned vehicles sent to Mir have successfully docked automatically.

What is the terminal velocity at docking? The terminal velocity is 0.2 m/sec.

S38-18
N93-21445
146706
P.7

## Supervised Autonomous Rendezvous and Docking System Technology Evaluation

by Neville I. Marzwell, NASA JPL

Technology for manned space flight is mature and has an extensive history of the use of man-in-the-loop rendezvous and docking, but there is no history of automated rendezvous and docking. Sensors exist that can operate in the space environment. The Shuttle radar can be used for ranges down to 30 meters, Japan and France are developing laser rangers, and considerable work is ongoing in the U.S. However, there is a need to validate a flight qualified sensor for the range of 30 meters to contact. The number of targets and illumination patterns should be minimized to reduce operation constraints with one or more sensors integrated into a robust system for autonomous operation. To achieve system redundancy, it is worthwhile to follow a parallel development of qualifying and extending the range of the 0 - 12 meter MSFC sensor, and simultaneously qualify the 0 - 30+ meter JPL laser ranging system as an additional sensor with overlapping capabilities. Such an approach offers a redundant sensor suite for autonomous rendezvous and docking. The development should include the optimization of integrated sensory systems, packaging, mission envelopes, and computer image processing to mimic brain perception and real-time response. The benefits of the Global Positioning System in providing real-time positioning data of high accuracy must be incorporated into the design. The use of GPS-derived attitude data should be investigated further and validated.

In the guidance and navigation area, algorithms for the design of homing trajectories for rendezvous and docking include techniques such as proportional navigation and those based on trajectory optimization using the Clohessy-Wiltshire equations. While being more fuel optimal, the latter techniques generally lead to non-intuitive trajectories not suitable for supervised rendezvous. However, a new technique (Olszewski, 1990) which allows optimized trajectory design wherein the trajectory profile can be prescribed, promises to alleviate this shortcoming.

In the control area, a variety of feedback compensator design techniques are available. While the design issues for the Linear Quadratic Gain (LQG) and H-infinity type controllers are well understood, the specific choice can be determined only on a case by case basis. The tradeoff among the methods is between performance and compensator complexity.

Fuzzy control theory remains an area needing further research, and has the potential of providing simpler controllers.

Neural networks offer tremendous potential but further development is needed. The objective of neural network implementation is to enhance the performance of existing classical model-based and adaptive schemes. Enhancement of system performance will be a result of neural network based identification of nonlinear effects such as actuator saturation and backlash and onboard control correction, including design aids to help control engineers rapidly select optimal control parameters. The neural network program is justified based on the fact that classical model-based and adaptive approaches do not compensate for nonlinear effects for areas such as actuators, contact dynamics, sensor errors, and sensor failure, and therefore system performance is degraded. Recent results indicate that neural nets are excellent nonlinear estimators, with good fault tolerance properties due to the internal redundancy in information storage. Also, since the conventional selection of correct control parameters is a very time intensive process, any updating of control parameters during a mission would be extremely expensive. Neural nets have already been applied to numerous pattern recognition problems, and therefore their application to the gain scheduling problem is relevant. The synthesis of neural networks can lead to better interactions with the unknown environments and responses that can be expected with classical control methods and is ideally suited for the AR&D problem. Neural nets provide an efficient way to implement nonlinear estimators and do not require explicit information about the environment.

As with other elements of AR&D, the recursory capture mechanisms are available or under development, but flight credibility is yet to be established. A number of significant test beds exist in support of AR&D at government-owned foreign and contractor facilities. Full credibility is yet to be earned for ground supervised AR&D flight systems to demonstrate sensors, software, mechanisms, and proximity operations. A flight validation program should be our top priority.in support of validating these test beds and methods.

The presentation and discussion afterwards brought out that there are about 40 sensors applicable to AR&D. On the open market there are many more sensors described in classified documentation.

Questions addressed include: Has a study been conducted on managing the AR&D system during communications blackout and is there onboard software to handle this contingency? There is onboard software, but ground intervention is allowed since unforeseen, unplanned events always occur. The study aspect of the question was not answered.

What type of learning is used with neural networks and where does the data come from? The data comes from computer simulation. The type of data includes the impact of various spacecraft masses, sizes, etc.

The main point of Marzwell's presentation was that the technology is available to develop an AR&D system. However, we need to do the system engineering to integrate it.

N93-27446

**Autonomous Rendezvous and Capture Development Infrastructure**

Thomas Bryan et. al, NASA-MSFC

146707

p. 2

In the development of the technology for autonomous rendezvous and docking, key infrastructure capabilities must be used for effective and economical development. This need involves facility capabilities, both equipment and personnel, to devise, develop, qualify, and integrate ARD elements and subsystems into flight programs. One effective way of reducing technical risks in developing ARD technology is the use of the Low Earth Orbit test facility. Using a reusable free-flying testbed carried in the Shuttle, as a technology demonstration test flight can be structured to include a variety of sensors, control schemes, and operational approaches. This testbed and flight demonstration concept will be used to illustrate how technologies and facilities at MSFC can be used to develop and prove an ARD system.

To maximize on-flight experiment experience and qualified equipment and minimize program risk and agency costs, the concept uses the existing Spacelab Multi Purpose Experiment Support Structure (MPESS), as a deployable/retrievable target vehicle (by adding a cold-gas three-axis stabilization system) with accommodation for assorted sensors and subsystem tests. A small automated chase vehicle can be adapted from a Lightsat to carry ARD equipment and can fly various 6-DOF separations and approaches. The GPS can be used for rendezvous, MSFC video guidance sensor can be used for final approach, the OMV-derived three point docking mechanism for docking, and the Automated Fluid Interface system for umbilical connection. The chase vehicle is docked and locked onto the pallet after testing and integration, allowing the shuttle crew and the ground processors to handle the experiment as a single integrated payload.

Using the flight demonstration concept as a strawman program, the potential utilization of various facility capabilities at MSFC facilities was discussed, namely: the Dynamic Overhead Telerobotic Simulator, Spacecraft Air-bearing Simulator, Flight Robotics Laboratory, Space Operations and Mechanism Test Bed, Optical Instrumentation Facilities, RF System Test Facilities, and Integration and Environmental Testing. Additional facilities exist at Redstone Arsenal.

S40-12
ABS. ONLY

N93-21447

**Automated Technologies Needed to Prevent Radioactive Materials from Reentering the Atmosphere.**

Dave Buden, Idaho National Engineering Laboratory and
Joseph A. Angelo, Jr., Science Applications International Corporations

P. 1

Project SIREN (Search, Intercept, Retrieve, Expulsion Nuclear) was created to identify and evaluate the technologies and operational strategies needed to rendezvous with and capture aerospace radioactive materials (e.g., a distressed or spent space reactor core) before such materials can reenter the terrestrial atmosphere, and then to safely move these captured materials to an acceptable space destination for proper disposal. A major component of the current Project SIREN effort is the development of an interactive technology model (including a computerized data base) that explores, in building-block fashion, the interaction of the technologies and procedures needed to successfully accomplish a SIREN mission. The SIREN model will include appropriate national and international technology elements – both contemporary and projected into the next century. To obtain maximum flexibility and use, the SIREN technology data base is being programmed for use on 286-class PCs.

The major technical elements for a successful SIREN mission include: ground and space-based tracking, launch vehicles of needed payload capacity, telerobotic systems, sensors, capture technologies, and space transport, and disposal. However, Project SIREN also will impose specialized requirements including the use of dextrous aerospace systems capable of properly functioning in intense radiation and thermal environments.

The SIREN data base now being constructed will cover all the principal technology elements needed to successfully accomplish a SIREN mission. Inputs to the building block categories also should provide a valuable stimulus to those now investigating automated rendezvous and capture technology and operational requirements.

The data base provides for descriptive material covering applicable nuclear power systems, payloads, satellite orbits, tracking systems, launch systems, capture technologies, and disposal options. The capture technologies include the vehicles and propulsion stages needed to effect capture. Plans are to add the sensors and robotic arm technologies as the program matures. A list of key references is included to provide traceability.

The Mission options include performance of the entire mission of tracking, capture, and disposal or only certain aspects of the mission. Analysis is included in the program to determine the feasibility of using different components in performing a given mission. The date of the mission is input so one can evaluate the specific availability of various technologies. Analysis can be performed in interactive or in the batch mode.

41-10

ABS ONLY

N93-21448

# NASA MSFC Hardware in the Loop Simulations of Automatic Rendezvous and Capture Systems

p. 2

Patrick Tobbe, and Charles Naumann, Control Dynamics Company
William Sutton and Thomas Bryan, NASA MSFC.

Two complementary hardware-in-the-loop simulation facilities for automatic rendezvous and capture systems at the Marshall Space Flight Center are described. One, the Flight Robotics Laboratory, uses an 8 DOF overhead manipulator with a work volume of 160 by 40 by 23 feet to evaluate automatic rendezvous algorithms and range/rate sensing systems. The other, the Space Station/Space Operations Mechanism Test Bed, uses a 6 DOF hydraulic table to perform docking and berthing dynamics simulations.

The MSFC Flight Robotics Laboratory provides sophisticated real-time simulation capability in the study of human/system interactions of remote systems. The facility consists of a 5800 square foot precision air bearing floor, a teleoperated motion base, an overhead electric manipulator, a remote operator's work station, real time computer system, and various simulation mock-ups. The facility can be used to study the performance of automatic or man-in-the-loop rendezvous systems in a real time environment. Planar hardware demonstrations are performed with the air bearing vehicles, using its pneumatic thrusters for remote control. The overhead manipulator is used for six degree of freedom hardware in the loop simulations. These studies investigate the performance of the automatic rendezvous algorithms, range/rate sensors, and human factor concerns such as light and camera placement, control system sensitivity, and transmission time delays for man in the loop operations. The simulation is best suited for examining the performance of the system up to the point of capture or contact.

The Dynamic Overhead Target Simulator (DOTS) is an 8 DOF, heavy duty electric manipulator capable of traversing over the entire air bearing floor. The system is composed of a precision overhead X-Y crane to which a six degree of freedom robot arm is mounted. A series of micro VAX computers are used in real time to convert arm tip position and orientation commands into crane and arm joint velocity commands. The commands are generated through closed form inverse kinematic relationships and digital control laws housed on the VAX network. An elaborate real-time safety algorithm performs collision avoidance and joint position and rate limiting.

The arm joints, ordered from the X-Y crane, are waist yaw, shoulder pitch, arm extension, wrist pitch, wrist yaw, and wrist roll. The manipulator has a payload capability of 1000 pounds with an 18-inch offset from the roll axis; it has a work volume of approximately 160 by 40 by 23 feet. Each joint on the arm is driven by a rate servo and instrumented with a 12-bit digital encoder and analog tachometer. These sensors are interfaced to the computer and used in real time to generate joint rate commands, monitor arm tip, position for collision avoidance and simulation performance, and limit joint positions and rates.

The micro VAX network currently runs the arm controls and safety software, orbital dynamics simulation, and all input/output data transfer and storage operations in a cycle time less than 50 milliseconds.

The Space Station/Space Operations Mechanism Test Bed consists of a hydraulically driven, computer-controlled 6 DOF force and moment sensor, remote driving stations with computer generated or live TV graphics, and a parallel digital processor that performs calculations to support the real-time simulation.

The function of the mechanism test bed is to test docking and berthing mechanisms for Space Station Freedom and other orbiting space vehicles in a real-time, hardware-in-the-loop simulation environment. Typically, the docking and berthing mechanisms have two mating components, one for each vehicle. In the facility, one component is attached to the motion system, while the other component is mounted to the force/moment sensor fixed in the support structure above the 6 DOF. The six components of the contact forces/moments acting on the test article and its mating component are measured by the force/moment sensor. The force/moment sensor is interfaced to the real-time Alliant computer system.

S42-16
ABS. ONLY
N93-21449
146710

## Space Shuttle Program - Automatic Rendezvous, Proximity Operations, and Capture

by William Jackson et al, NASA JSC

An overview of the current NASA Johnson Space Center capabilities and ongoing activities for the design, development and demonstration of AR&C capabilities was provided. The JSC plans for ground and flight tests/demonstrations of progressive AR&C capabilities, using the Space Shuttle are described. The Space Shuttle could provide an effective "flying test bed" for these demonstrations.

A number of organizations at NASA JSC which responsibilities and capabilities associated with AR&C: the Flight Crew Operations Directorate includes the Astronaut Office, Space Shuttle Support, Office and Space Station Support Office, the Mission Operations Directorate includes the Systems Division provides mission support for Space Shuttle systems, training, operations, flight design and dynamics and Space Shuttle ground systems and the Engineering Directorate which provides engineering support to the Space Shuttle Program. The JSC can provide the following facilities: 6 DOF test facility, GPS test bed, Electro-optics Laboratory, Inertial Systems Laboratory, GN&C Emulator test bed, 6-DOF Docking Dynamic Test System, Robotics and Mechanical Systems Laboratory, Integrated Graphic Operation Analysis Laboratory and Intelligent Systems Laboratory.

The JSC proposes a phased approach to flight demonstrations of AR&C capabilities to minimize impact on the Orbiter and Orbiter operations. The priorities in this phasing are: (1) proximity operations, (2) capture, and (3) rendezvous. Priority is based on a combination of expected return on investment and complexity in integration with the Orbiter.

A four-stage flight demonstration is proposed. The four stages allow for a progressive development, application, integration, and demonstration of AR&C capabilities, that is consistent with the development schedules of the supporting systems and opportunities for Orbiter flight tests. The actual number of sequence of flight demonstrations is still under study and several options are being considered to optimize the costs and complexity of the demonstrations with the benefits. These stages fall into one of three ranges of operations: rendezvous - liftoff to 2 km, proximity operations from 2 km to 15 km; or capture/release - <15 km.

The Stage 1 Flight Demonstration is an open-loop flight test of a laser sensor which provides range, range rate, and bearing information to the Orbiter flight crew via supplemental displays, while the Orbiter is operating in the proximity operations zone of the target (e.g., 2 km to 50 ft). In this region, there is essentially no potential for Orbiter and target vehicle collision, regardless of the performance of the augmented system. Advanced targeting and guidance algorithms would be exercised in a "background," using information from the laser sensor to compute commands as though the loop were closed.

Based on the experience and confidence provided by the Stage 1 Demonstration, the Stage 2 Demonstration would extend the use of the supplemental Orbiter flight crew displays and GN&C algorithms to support manual operations from proximity operations to a capture position. Stage 2 also is an open-loop flight demonstration that moves the Orbiter within the capture range of the target vehicle. It can include flight tests of sensors for active docking mechanisms and/or automatic tracking by a manipulator in this flight envelope.

Stage 3 will be conducted as a two part demonstration. Stage 3a is relatively independent of the other stages since the techniques and systems required for proximity operations and capture do not depend heavily on the rendezvous operations. The automatic rendezvous capabilities to be demonstrated include: extended range tracking via GPS, automatic operations management, and onboard trajectory control, and systems management across the required rendezvous maneuvers. Automatic rendezvous could be initiated from a "standard" parking orbit or it could be comprehensive and include a "ground-up" automatic rendezvous operation.

Stage 3b will use an automatic system to maintain relative position, velocity, and altitude between the Orbiter and target vehicle along a desired relative approach profile (from approximately 2 km to 15 m). The key system elements include a laser radar for relative state measurements; closed-loop translational state targeting algorithms and automated delta-velocity guidance; optimal jet selection for efficient translational and rotational control; collision monitoring and prediction; automatic fault detection, isolation, and recovery for the avionics components; and an orbit maneuver replanner/scheduler/sequencer which accommodates actual flight conditions.

The Stage 4 Demonstration will be the most ambitious flight demonstration; it could include an automatic capture. The key system elements which would be demonstrated include a laser radar for relative state measurements compatible with the required capture accuracies; near vicinity collision avoidance monitoring and prediction; active docking mechanisms or sensors; enhanced SRMS tracking and capture capabilities; and on-orbit maneuver replanner/scheduler.

Successful completion of these objectives will demonstrate an integrated and enhanced operational capability that provides significant benefits for existing and future space flight programs.

## DISCUSSION OF FINDINGS

Omit to end

A careful review of the discussions included in Categories 1 through 5 will show many areas of broad consensus and, likewise, many areas of clearly divergent opinion. These often develop from the subjective and honest differences of opinion that result from the absence of data, incomplete understandings, disagreement on the maturity level of various technology and / or different perceptions as to how well various technologies actually might be integrated into a functional subsystem or system.

There was recognition that some of the findings were in the realm of purely technical considerations, issues that could be resolved by further tests, simulations, and component demonstrations. There were also subjective concerns that are not as easily reconciled, such as rate-of-change in the maturation of a technology under various funding scenarios, availability of a near term demonstration at the subsystem level, and whether or not a software capability would evolve with sufficient capabilities to exploit a particular technology. And finally, there were concerns that were addressed to senior program managers and administrators who will be required to define and conduct a cost-constrained, tightly scheduled CTV/AR&C definition program that captures the viable technologies and provides the capability for the SSF resupply missions.

There was agreement that the technology base for AR&C system design is quite large and many options exist for providing the United States with an AR&C system/capabilities for CTV that is clearly advanced over any current capabilities.

There was agreement that the full breadth of technologies available within the U.S. industry and government infrastructures had not been explored at this review because of military classification. Guidance and control capabilities demonstrated within weapons systems utilized in Desert Storm were not evaluated and clearly have the potential for application within the AR&C system. Subsequent to the review in 1991, NASA Headquarters personnel have initiated actions with the DOD to conduct an assessment of the applicable technologies in the spring of 1992.

There was agreement that the AR&C demonstrations should be directed toward CTV. There is anticipated growth to other missions but technologies will mature rapidly over time and future mission requirements should not influence the CTV activities.

There was a consensus that the evolving capabilities of the GPS should be incorporated into an advanced AR&C system. The TDRSS will continue to serve a vital link for ground-to-space communications. It provides nearly continual and complete data and communications between all spacecraft and the ground support system.

There was consideration that evolving robotic technologies, artificial intelligence, and expert systems technologies should not be included in any of the near term automatic demonstration activities but might be ready for integration with the evolutionary CTV system or future autonomous systems.

There was agreement that a primary goal for the NASA program management is to establish the specific design and functional requirements.

A major area of concern, expressed in a number of ways, by many participants, was directed to demonstration of the advanced AR&C capabilities. These concerns centered on the issues below:

- What constitutes a viable "demonstration" program, does it just provide proof of concept or must it provide parametric design data?
- Are simulations and ground-based facility tests sufficient?
- Does AR&C require a "flight test" demonstration?
    - What does it have to do?
    - What form shall it take?
    - If so, how much will it cost?
    - Can we afford it?

Joint 'international' programs were identified as an option by several speakers.

## SUMMARY

A primary tenet of the organizing committee was to serve as a catalyst for the interchange of technical discussions among the attendees and to provide immediate feedback to the participants in real time. As shown in the Agenda (see Appendix), the organizing committee invited the senior attendees from NASA MSFC (Mr. Joseph Randall, Director, Information & Electronic Systems Laboratory); NASA JSC (Dr. Kenneth Cox, Chief, Avionics System Division); and NASA Headquarters (Mr. Michael Lyons, *now* Deputy Associate Administrator, Office of Space Systems Development) along with the AR&C Review General Chairperson (Mr. James Odom) to provide their own independent overview of the 1991 Review. Speaking extemporaneously, each provided the participants and audience with an assessment of the important topics, technologies, findings, and issues that they personally felt were of significance to the review and discussions of AR&C.

The remarks of the senior technical personnel provide an assessment of the 1991 Review, the state-of-the-art of the technologies, and the elements necessary to achieve an advancement in AR&C capabilities from the vantage point of four different perspectives. The comments of each speaker have been summarized below

Mr. Randall

- Sensors are available.
- Recommendations include:
  - Must address how CTV and Shuttle dock with SSF.
  - MSFC recommends automated CTV using GPS with proximity operations sensor.

- Proximity operations sensors should be reliable, simple.
- A flight demo is required:
  - GPS hand-off to proximity operations sensor.
  - JSC and MSFC need to sit down together and decide how to do it.

Dr. Cox

- Two reasons for a flight demo
  - End-to-end demo in space
  - Demonstrate automatic techniques
- How?
  - Concurrent engineering and operations--fly what we design (no changes)
  - Decrease operational costs.
  - Use existing technology.
  - Accept reasonable and prudent risk.
    - --Engineering integrity
    - --Operational integrity
  - Place emphasis on simplicity, modular approaches.
  - Use system engineering approaches.
  - Place emphasis on flight testing vs. ground testing.
  - Make primary customer CTV; second: SEI.
  - Use in-house development @ MSFC & JSC (not contracted out).
  - Multiple flights (& multiple sensors)
  - Develop a flight test plan (HQ, MSFC, JSC) --involve the CTV program office

Jim Odom

- Adequate facilities exist.
- AI and fuzzy logic provides significant capability.
  - Provides hooks and scars
- Future attention on integrating new systems.
- Develop the real requirements for CTV -- soon!
  - Ranges of masses, sizes
  - Ranges of redundancies
  - Dual propulsion system
- Phased development is required.
- Job is to pick the right suite of sensors, tracking, closure system
  - Redundant systems and
  - Redundancy management
- Use the GPS system.
- Adequate flight demo as soon as possible.
- Many sensors exist.
- Binocular approach looks good.
- The job is defining the real requirements for the AR&C and then engineering them:
  - Baseline AR&C with manned supervision,
  - Major system drivers,
  - Suite of solutions.

Mike Lyons

• Make it an international program,
• Make the hardware long life,
• Make the demo low cost,
• Must learn to share and compromise (NASA),
• Do it in the context of CTV.

## CONCLUSIONS

The 1991 AR&C Review was a successful endeavor. The tenets and goals established for the review have been achieved. The state-of-the-art in AR&C has been evaluated. It is broad and robust and it provides the potential for an AR&C capability superior to existing systems. State-of-the-art technologies were evaluated and assessed in the five categories:

- Hardware Systems and Components;
- Software Systems;
- Integrated Systems;
- Operations; and,
- Supporting Infrastructure.

The fact is that the technology base is even larger than described during the review, because of exclusions from the civil sector that result from military classification. The potentials of these technologies must be explored. The NASA managers have taken an action to accomplish this with their DOD counterparts.

As in any complex technical endeavor, the AR&C Review is but one in a series of iterative activities necessary to define and implement a next generation system capability with significantly improved technologies. The AR&C Review suggests/confirms that a highly competitive technology environment, with a diverse array of options, is present for the conduct of the CTV/AR&C Phase A studies. Because of the advanced nature of these technologies and their low maturity for space applications and the in-space environment as well as over-riding concerns about system integration, demonstration programs of some kind are perceived as necessary. Considerable efforts and time will be involved in defining the depth and content of a viable demonstration program, especially if it is determined that it must be a flight demonstration.

Cautionary comments were provided by a number of people concerning costs. Cost constraints are real; they are likely to continue for at least the next several years. Precursor technology development and the near term "demonstration" activities described during the review will be tested for their frugality. It is incumbent on the technologists and program managers to recognize these limitations and thus define tests, programs, and activities that provide the maximum data return for the dollar.

If international protocols develop within the AR&C community over the next several years, the selection and definition of competing technologies will be even more complex. It will be very hard to offer immature technologies in the international environment. This brings into question which technologies should be selected, prioritized, and matured and how funding is to be provided for the maturation process.

*The purpose of this Executive Summary is to provide a short, terse overview of the planning, implementation, content, findings and conclusions reached at the Automated Rendezvous and Capture Review held at the Fort Magruder Inn in Williamsburg, Virginia from 19-21 November 1991.*

# Appendix

**NASA Automated Rendezvous & Capture Review**
**Tuesday, November 19, 1991**
Agenda

| | |
|---|---|
| 7:00-8:00 am | Registration |
| | **Opening Session** |
| 8:00-8:15 am | Introduction/Announcements<br>- James Odom, Applied Research Inc., General Chairman |
| 8:15-8:40 am | Cargo Transfer Vehicle/New Launch System Status Briefing<br>- Harry Buchanan, NASA Marshall Space Flight Center |
| 8:40-9:00 am | Quality Functional Deployment for AR&D-Summary of Results<br>- Ken Cox & Greg Hite, NASA Johnson Space Center |
| | **Session I**<br>Chairman: William Culpepper, JSC<br>Co-Chairman: Nick Smith, Martin Marietta<br>Reporter: William Jackson, JSC |
| 9:00-9:20 am | Proximity Operations Considerations Affecting Spacecraft Design<br>- Steven Staas, McDonnell Douglas Space Systems Co. |
| 9:20-9:40 am | Coherent Doppler LIDAR for Automated Space Vehicle, Rendezvous, Station-Keeping and Capture<br>- James Bilbro, MSFC |
| 9:40-10:00 am | Video Guidance Sensor for Autonomous Capture<br>- Richard T. Howard, MSFC |
| 10:00-10:20 am | Manned Aspects of Rendezvous<br>-Arthur J. Grunwald, NASA Ames |
| 10:20-10:35 am | Break |
| 10:35-10:55 am | Approach Range and Velocity Determination Using Laser Sensors and Retroreflector Targets<br>- William Donovan, Rockwell International |
| 10:55-11:15 am | Guideline Requirements for Serviceable Spacecraft Grasping/Berthing/Docking Interfaces Based on Simulations and Flight Experience<br>- Allen B. Thompson, Martin Marietta |
| 11:15-11:35 am | Contact Dynamics Testing of Automated Three Point Docking Mechanism<br>- Kenneth H. Rourke, TRW |
| 11:35-11:55 am | Intelligent Systems Technology Infrastructure for Integrated Systems<br>- Dr. Henry Lum, NASA Ames Research Center |
| 11:55-12:15 pm | Results of Prototype Software Development for Automation of Shuttle Proximity Operations<br>- Hal Hiers, NASA /JSC<br>- Oscar Olszweski, Lockheed Engineering & Sciences Co. |
| 12:15-1:15 pm | Lunch |

| | |
|---|---|
| 1:15-1:45 pm | Feedback for Session I |

## Session II

Chairman: E.C. Smith, MSFC
Co-Chairman: Kenneth H. Rourke, TRW
Reporters: Thomas Bryan, Elaine Hinman, Richard Howard, MSFC

| | |
|---|---|
| 1:45-2:05 pm | Demonstration of Automated Proximity and Docking Technology<br>- Robert L. Anderson, TRW |
| 2:05-2:25 pm | Collision Avoidance for CTV: Requirements and Capabilities<br>- Thomas Nosek, TRW |
| 2:25-2:45 pm | Trajectory Control Sensor Engineering Model DTO<br>- Kent Dekome, NASA /JSC |
| 2:45-3:05 pm | TRAC Based Sensing for Autonomous Rendezvous<br>- Louis J. Everett, Texas A&M University |
| 3:05-3:20 pm | Break |
| 3:20-3:40 pm | Autonomous Docking Ground Demonstration<br>- Stephen L. Lamkin, NASA /JSC |
| 3:40-4:00 pm | Soviet Automated Rendezvous and Docking System Overview<br>- Elaine Hinman , NASA/ MSFC |
| 4:00-4:20 pm | Thruster Configurations for Maneuvering Heavy Payloads<br>- Roy Tsugawa, TRW |
| 4:20-4:40 pm | A Phase One AR&C System Design: Development and Validation Results<br>- Peter Kachmar, C.S. Draper Laboratory |
| 4:40-5:00 pm | On-Orbit Operational Scenarios, Tools, and Techniques<br>- James D. Walker, TRW |

## NASA Automated Rendezvous & Capture Review
## Wednesday, November 20, 1991
Agenda

| | |
|---|---|
| 8:15-8:30 am | Announcements |
| 8:30-9:00 am | Feedback for Session II |

### Session III

Chairman: David N. Schultz, MSFC
Co-Chairman: F. Brooks Moore, Logicon Control Dynamics Inc.
Reporters: Larry Brandon, Lee Varnado, Daniel O'Neil, MSFC

| | |
|---|---|
| 9:00-9:20 am | Supervised Autonomous Rendezvous & Docking System Technology Evaluation<br>- Neville Marzwell, NASA JPL |
| 9:20-9:40 am | Office of Space Flight Standard Spaceborne Global Positioning System User Equipment Project<br>- Penny Saunders, NASA JSC |
| 9:40-10:00 am | Autonomous Reconfigurable GPS/INS Navigation and Pointing System for Rendezvous and Docking<br>- Triveni Upadhyay, Mayflower Communications |
| 10:00-10:20 am | Optical Correlators Automated Rendezvous And Capture<br>- Richard Juday, NASA JSC |
| 10:20-10:35 am | Break |
| 10:35-10:55 am | A Method for Modeling Contact Dynamics For Automated Capture Mechanisms<br>- Philip Williams, Logicon Control Dynamics Co. |
| 10:55-11:15 am | Manned Maneuvering Unit Applications for Automated Rendezvous and Capture<br>- C. Edward Whitsett, NASA JSC |
| 11:15-11:35 am | Experimental Validation of Docking and Capture Using Space Robotics Testbeds<br>- John Spofford, Martin Marietta |
| 11:35-11:55 am | An Overview of Autonomous Rendezvous and Docking System Technology Development at General Dynamics<br>- Fred Kuenzel, GDSS<br>- Kurt Nelson, GDSS |
| 11:55-12:15 pm | An Autonomous Rendezvous and Docking System Using Cruise Missile Technology<br>- Ruel Edwin Jones, GDSS<br>- Bruce Nicholson, GDSS |
| 12:15-1:15 pm | Lunch |
| 1:15-1:45 pm | Feedback for Session III |

## Session IV

Chairman: Rick Gavin, JSC
Co-Chairman: Ed Jones, General Dynamics
Reporter: John McNamanem, JSC

| | |
|---|---|
| 1:45-2:05pm | Applicability of Relative GPS to Automated Rendezvous between the Space Shuttle and Space Station<br>- Fred Clark, LESC<br>- Ann Christofferson, LESC |
| 2:05-2:25pm | Autonomous Rendezvous and Capture System Design<br>- Richard W. Dabney, MSFC |
| 2:25-2:45pm | Autonomous Prealignment of a Docking Mechanism<br>- Monty Carroll, LESC<br>- John Thompson, LESC |
| 2:45-3:05pm | Rendezvous Radar for the Orbital Maneuvering Vehicle<br>- John W. Locke, Keith Olds, and Howard Parks, Motorola, |
| 3:05-3:20pm | Break |
| 3:20-3:40pm | A Berthing and Fastening Strategy for Orbital Replacement Units<br>- John Vranish, NASA Goddard Space Flight Center<br>- Edward Chueng, NASA Goddard Space Flight Center |
| 3:40-4:00 pm | A Binocular Stereo Approach to AR&C at the Johnson Space Center<br>- Timothy Fisher, NASA JSC<br>- Alan Smith, LESC |
| 4:00-4:20pm | The Real-Time Operations of the Space Shuttle Orbiter During Rendezvous and Proximity Operations<br>- Andrew Dougherty, NASA Goddard Space Flight Center |
| 4:20-4:40 pm | Six Degree of Freedom Test Facility<br>- Michelle Bittel, LESC |
| 4:40-5:00 pm | A Comparison of Laser Based Ranging Systems For AR&C<br>- Stephen Katzberg, & Pleasant Goode, NASA LaRC |

**NASA Automated Rendezvous & Capture Review**
**Thursday, November 21, 1991**
Agenda

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|---|---|
| 8:00-8:05 am | Announcements |
| 8:05-8:35 am | Feedback for Session IV |
| 8:35-9:00 am | Chairman's Address<br>- James Odom, Applied Research Inc. |

**<u>Session V</u>**
Chairman: Michael Card, HQ
Reporter: Neville Marzwell, JPL

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|---|---|
| 9:00-9:20 am | Autonomous Rendezvous and Capture Development Infrastructure<br>- Thomas Bryan, NASA MSFC |
| 9:20-9:40 am | On-Orbit Demonstration of Automated Closure and Capture Using ESA-Developed Proximity Operations Technologies and an Existing, Serviceable NASA Explorer Platform Spacecraft<br>- Bill Hohwiesner, Fairchild |
| 9:40-10:00 am | Autonomous Rendezvous and Docking - A Commercial Approach to On-Orbit Technology Validation<br>- D.J. Conrad, SpARC |
| 10:00-10:15 am | Break |
| 10:15-10:35 am | Automated Technologies Needed To Prevent Radioactive Materials From Reentering the Atmosphere<br>- David Buden, Idaho National Engineering Lab |
| 10:35-10:55 am | NASA MSFC Hardware In the Loop Simulations of Automatic Rendezvous and Capture Systems<br>- Patrick Tobbe, Logicon Control Dynamics Inc. |
| 10:55-11:15 am | Space Shuttle Program - Automatic Rendezvous, Proximity Operations, and Capture<br>- William Jackson, JSC |
| 11:15-11:45 pm | Feedback Session V |

**<u>Closing Session</u>**
Chairman: James Odom, Applied Research, Inc.

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| 11:45-12:40pm | Integrated Summary Session |
| 12:40-1:15 pm | NASA Management Feedback Comments |
| 1:15 pm | Adjourn |