The Successful Development of an Automated Rendezvous and Capture (AR&C) System for the National Aeronautics and Space Administration

Fred D. Roe and Richard T. Howard

Simulation Group, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
256-544-3512, fred.roe@msfc.nasa.gov

Abstract. During the 1990's, the Marshall Space Flight Center (MSFC) conducted pioneering research in the development of an automated rendezvous and capture/docking (AR&C) system for U.S. space vehicles. Development and demonstration of a rendezvous sensor was identified early in the AR&C Program as the critical enabling technology that allows automated proximity operations and docking. A first generation rendezvous sensor, the Video Guidance Sensor (VGS), was developed and successfully flown on STS-87 and STS-95, proving the concept of a video- based sensor. A ground demonstration of the entire system and software was successfully tested. Advances in both video and signal processing technologies and the lessons learned from the two successful flight experiments provided a baseline for the development, by the MSFC, of a new generation of video based rendezvous sensor. The Advanced Video Guidance Sensor (AGS) has greatly increased performance and additional capability for longer-range operation with a new target designed as a direct replacement for existing ISS hemispherical reflectors.

INTRODUCTION

The United States does not have an Automated Rendezvous and Capture/Docking (AR&C) capability and is reliant on manned control for rendezvous and docking of orbiting spacecraft. This reliance on the labor intensive manned interface for control of rendezvous and docking vehicles has a significant impact on the cost of the operation of the International Space Station (ISS) and precludes the use of any U.S. expendable launch capabilities for Space Station resupply. The Soviets have the capability to autonomously dock in space, but their system produces a hard docking with excessive velocity (and therefore force) at contact.

Automated Rendezvous and Capture/Docking has been identified as a key enabling technology for the Space Launch Initiative (SLI) Program, Alternate Access to Station, DARPA Orbital Express and other DOD Programs. The development and implementation of an AR&C capability can significantly enhance system flexibility, improve safety, and lower the cost of maintaining, supplying, and operating the International Space Station.

During the 90's, the Marshall Space Flight Center (MSFC) conducted pioneering research in the development of an automated rendezvous and capture/docking system for U.S. space vehicles. Development and demonstration of a rendezvous sensor was identified early in the AR&C Program as the critical enabling technology that allows automated proximity operations and docking. A first generation rendezvous sensor, the Video Guidance Sensor (VGS) was developed and successfully flown on STS 87 and again on STS 95, proving the concept of a video-based sensor. Advances in both video and signal processing technologies and the lessons learned from the two successful flight experiments provided a baseline for the development, by the MSFC, of a new generation of video based rendezvous sensor. The Advanced Video Guidance Sensor (AVGS) has greatly increased performance and additional capability for longer-range operation with a new Target designed as a direct replacement for existing ISS hemispherical reflectors.

A ground demonstration system for automated guidance, navigation and control (GN&C) and proximity operations (prox ops) software (orbital operations) functional verification was developed. The GN&C, Prox Ops/docking, and collision avoidance maneuver (CAM) software were successfully tested in ground-based simulations.

The MSFC also developed "World Class" Agency unique test facilities that allow for the evaluation of rendezvous sensors and automated rendezvous and docking systems. The facilities allow for software simulations as well as hardware-in-the-loop simulation, and the facilities include the capability of orbital lighting simulation.

SENSOR DEVELOPMENT

The rendezvous and docking sensors were quickly determined to be crucial to the success of any AR&C system. This led to the development and refinement of a series of video-based sensors. Video was chosen as a simple method of viewing an entire field-of-view at one time while getting fast updates. The VGS was the first sensor that was developed under the AR&C program for a flight experiment. After the flight experiment, technology advancements, lessons learned, and changing requirements led to the development of the Advanced Video Guidance Sensor.

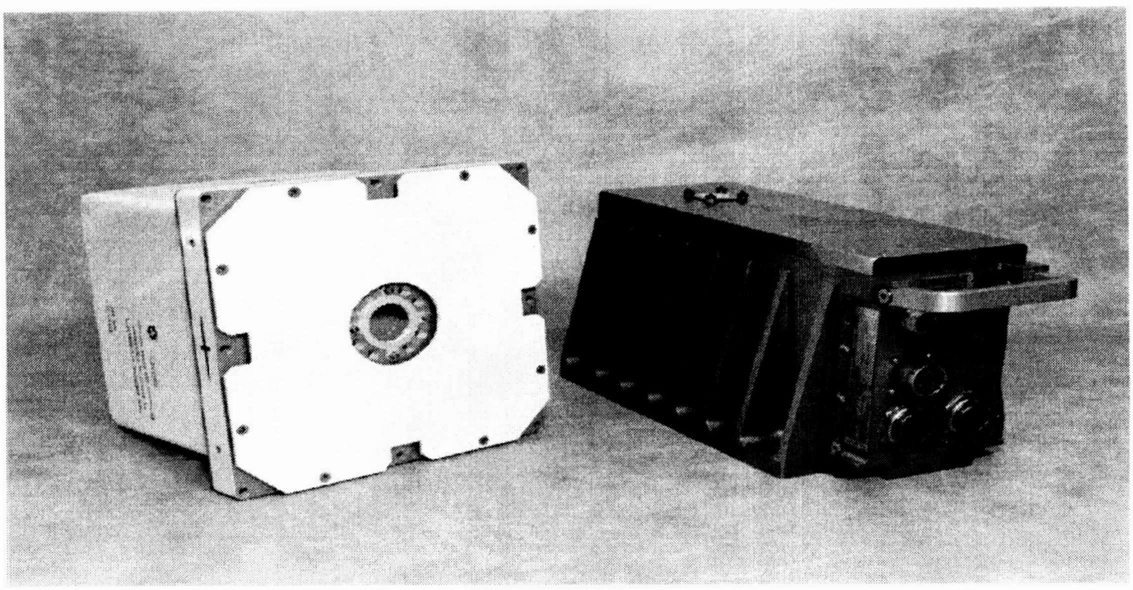

Figure 1. Video Guidance Sensor – sensor head and electronics module

Video Guidance Sensor (VGS)

The VGS was designed to provide near-range (from 110 meters in to dock) sensor data as part of an automatic rendezvous and docking system. The sensor determines the relative positions and attitudes between the active sensor and the passive target. The VGS uses laser diodes to illuminate retro-reflectors in the target, a solid-state camera to detect the return from the target, and a frame grabber and digital signal processor to convert the video information into the relative positions and attitudes.

The system was designed to operate with the target within a relative azimuth of ± 9.5 degrees and a relative elevation of ± 7.5 degrees. The system will acquire and track the VGS target within the defined field-of-view between 1 meter and 110 meters range, and the VGS was designed to acquire and track the target at relative attitudes of ± 10 degrees in pitch and yaw and at any roll angle. The sensor outputs the data at 5 Hz, and the target and sensor software and hardware have been designed to permit two independent sensors to operate simultaneously. This allows for redundant sensors using a common target.

The on orbit performance of the VGS was exceptional with all the design goals met. The sensor design proved robust with a range of target acquisition and tracking of 150meters + (exceeding the specifications by more than 50%). The sensor was also able to track in all orbital lighting conditions, an important capability to demonstrate for a vision-based system.

Detailed technical papers describing the operation of the sensor and the results of the two flight experiments are available from the referenced Web site at the end of this paper and from references 1-3.

Advanced Video Guidance Sensor (AVGS)

The Advanced Video Guidance Sensor builds upon the successes of the VGS to provide an updated sensor design with increased performance and additional capabilities. The new sensor design incorporates the capability of using an updated target that reduces the area required for target mounting to the equivalent area of the standard ISS hemispherical reflector assembly. In fact, the new target is a direct replacement for the existing ISS hemispherical reflector and provides all the existing capability plus 6 degree of freedom (6 DOF) information for docking when used with the AVGS. With a short-range target and a full sized target (1 meter long) that has three 1.5-inch (3.8 cm)

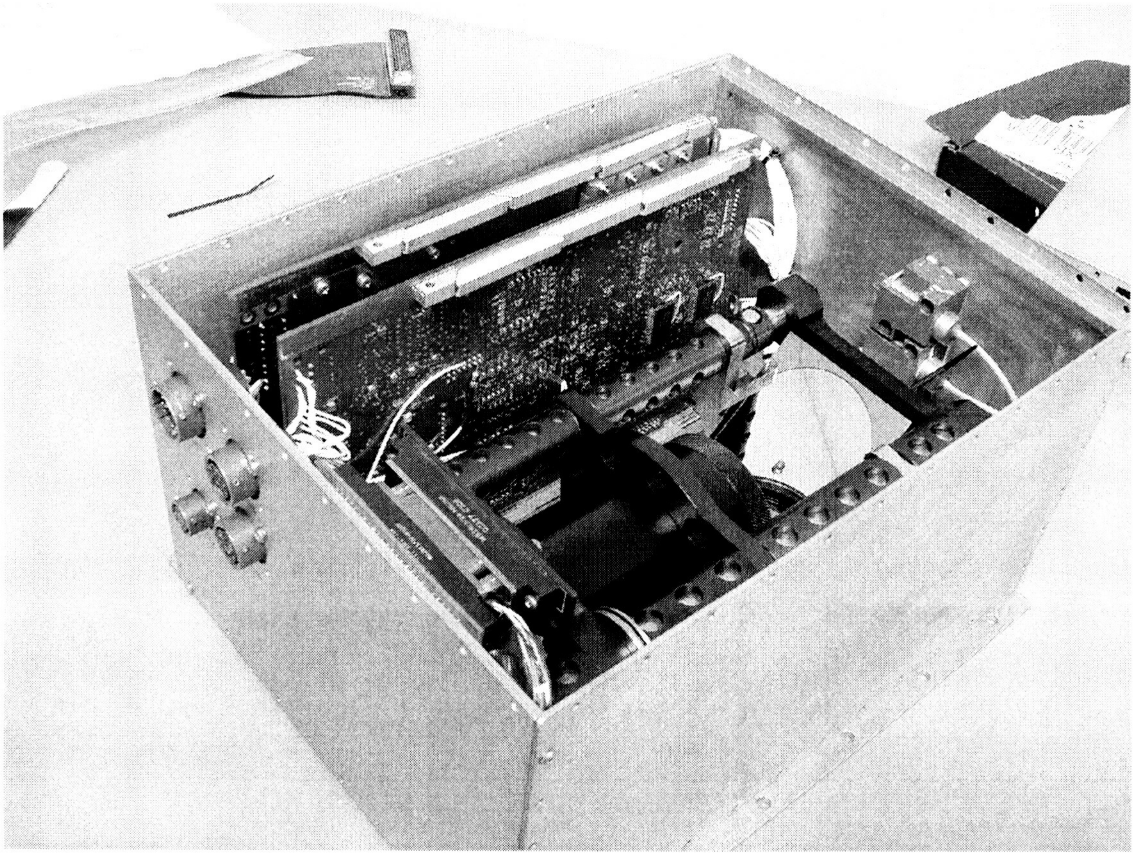

Figure 2. Advanced Video Guidance Sensor – initial prototype interior

diameter retro-reflectors, the AVGS will provide relative positions and attitudes from 300 meters down to 0.5 meters.

The AVGS operates at up to a 25 Hz update rate (and tracks at up to 75 Hz internally) and can detect retro-reflectors at a range greater that 1 km. The AVGS is a single box design, is low power (<50 W absolute worst case, 15 W nominal), light weight (< 20 lbs) and requires only a 10" by 12" mounting footprint (with a height of 6 inches).

AVGS Commercialization

The AVGS design is being manufactured by Orbital Sciences Corporation under the Demonstration of Autonomous Rendezvous Technology (DART) contract and will become an OSC commercial product. Boeing is planning on purchasing an AVGS from Orbital for the DARPA "Orbital Express" flight experiment as their primary rendezvous and docking sensor.

GN&C SOFTWARE DEVELOPMENT FOR AR&C

Engineers at NASA's MSFC have designed and ground tested an AR&C system which, along with the capability to lower mission operation costs, also has a great deal of safety, redundancy and reliability. The MSFC AR&C system incorporates some of the latest innovations in Global Positioning System (GPS) space navigation, video sensor technologies and automated mission planning algorithms as well as the continuous capability for ground and crew monitoring and intervention.

The modular GN&C software that was developed and ground tested includes the capabilities for onboard mission planning, spacecraft automated orbit transfer and rendezvous, proximity operations, station keeping, capture/docking and collision avoidance maneuvers. The developed algorithms provide the capability to dock with 100 percent success in the absence of multiple system failures.

The operation of the mission is accomplished by stepping through a set of automated maneuvers, or events, through which the Chase Vehicle (CV) moves in a safe and assured way towards the Target Vehicle (TV) to eventual dock. The Event Controller is the function that keeps track of the current mission event, when to switch events and even when to change entire event sequences. Each event has a set of predefined parameters that allow the GN&C system to perform certain tasks or maneuvers. These parameters include guidance targets, expected transfer times, approach corridor limits and approach speed limits. When the Event Controller determines that an event has been completed successfully, it transitions to the next event. One event type, rendezvous, automatically performs numerous orbital transfers and plane changes to take the CV from the orbit insertion point to the proximity zone of the TV. All other event types are executed within the proximity zone and include controlled drift, Clohessy-Wiltshire (CW) transfer, station keeping, forced approach and finally terminal autopilot.

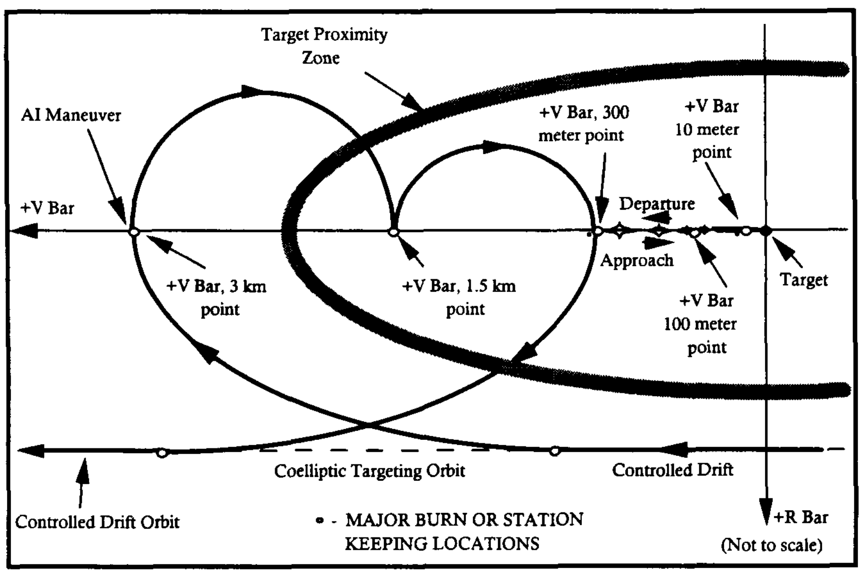

Figure 3. Relative Motion of Chase Vehicle and Target Vehicle during proximity operations

ACRONYMS AND ABBREVIATIONS

AR&C	Automatic Rendezvous & Capture
AR&D	Automatic Rendezvous & Docking
AR&M	Automatic Rendezvous & Mating
AVGS	Advanced Video Guidance System
CAM	Collision Avoidance Maneuver
CV	Chase Vehicle
DARPA	Defense Advance Research Projects Agency
DART	Demonstration Automatic Rendezvous Technology
DOD	Department of Defense
DOF	Degrees of Freedom
DOTS	Dynamic Overhead Target Simulator
FRL	Flight Robotics Laboratory
GN&C	Guidance Navigation and Control
GPS	Global Positioning Satellite
Hz	Hertz
ISS	International Space Station
Km	Kilometer
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
SLI	Space Launch Initiative
STS	Space Transportation System
TV	Target Vehicle
U.S.	United States
VGS	Video Guidance Sensor

ACKNOWLEDGMENTS

The authors wish to thank their management for their support and for the opportunity to work on the systems and facilities described in this paper

REFERENCES

1. Howard, R. T., Bryan, T. C., Book, M. L., and Jackson, J., "Active Sensor System for Automatic Rendezvous and Docking," in *Proceedings of SPIE Laser Radar Technology and Applications II*, pp. 106-115, 1997.
2. Howard, R. T., Bryan, T. C., Book, M. L., "The Video Guidance Sensor – A Flight Proven Technology," in proceedings of *22nd Annual American Astronautical Society Guidance and Control Conference*, 1999.
3. Howard, R. T., Bryan, T. C., and Book, M. L., "On-Orbit Testing of the Video Guidance Sensor," in *Proceedings of SPIE Laser Radar Technology and Applications IV*, 1999.
4. Cruzen, C. A. and Lomas, J. J., "Design of the Automated Rendezvous and Capture Docking System", SOME CONFERENCE, 2000.
5. Cruzen, C. A., Lomas, J. J., and Dabney, R. W., "Test Results for the Automated Rendezvous and Capture System," in proceedings of *23rd Annual American Astronautical Society Guidance and Control Conference*, 2000.