New Millennium ST6 Autonomous Rendezvous Experiment (ARX)

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Abstract—This Paper presents an overview of the New Millennium Space Technology 6 (ST6) Autonomous Rendezvous Experiment (ARX) mission and system. ARX is to be hosted as a payload on the United States Air Force Research Laboratory (USAFRL) XSS-11 spacecraft. Launch is currently planned for the fall of 2004. The objective of the experiment is to demonstrate and characterize an autonomous rendezvous system that autonomously locates and rendezvous with a passive object. For this experiment, the object is approximately a sphere of 20 cm diameter and simulates the current concept of the Mars Sample Return mission's Orbiting Sample (OS) Canister. The XSS-11 spacecraft will carry the OS into orbit, and deploy it at the start of the experiment. The Rendezvous System is centered around a light-weight, low-power scanning Laser Mapper (LAMP) sensor, providing high accuracy angle and range information, and a set of rendezvous guidance, navigation and control algorithms that autonomously guide the spacecraft to the desired state with respect to the OS. The experiment will execute a host of different proximity operations, including a number of different transfer maneuvers, approach profiles and fly-arounds of the OS. The demonstrated rendezvous technology is applicable to all future planetary sample return missions, including the Mars Sample Return Mission planned for the next decade. The operational experience gained from this experiment will benefit the design of future autonomous rendezvous and sample capture missions and systems where little or no 'ground-in-the-loop' control may be possible.

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1. INTRODUCTION

In recent years, Autonomous Rendezvous and Capture has received considerable interest because of its broad applicability. It is seen as an enabling technology to a number of applications, including autonomous re-supply missions to the International Space Station (ISS), in-space satellite inspection, servicing and re-fueling, and planetary sample capture and return missions. The need for autonomy is driven by the need to operate cost-effectively and in some cases, such as for sample return missions, by the distance induced signal travel time.

A number of approaches to rendezvous and docking/capture were developed over the years starting with the rendezvous missions performed during the Gemini Program. These ultimately lead to the rendezvous and docking in Lunar orbit during the Apollo Moon landings. Today's US rendezvous activities are centered around rendezvous and docking of the Space Shuttle with the ISS or with the Hubble telescope during servicing mission. While some of the processes involved in rendezvous and docking were automated over the years, the human-in-the-loop both on the ground and in space is still a necessary pre-requisite for safe operations of these missions.

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A first step to automated rendezvous and docking was implemented in the Russian Kurs Rendezvous System currently in use to rendezvous and dock manned Soyuz or unmanned Progress re-supply ships with the ISS. It relies on RF sensors to provide information that guide the spacecraft to the rendezvous and docking, but allows for pilot or operator intervention at any time along the approach trajectory.

A fully autonomous rendezvous system was implemented for the Japanese ETS-VII [1] experiment that flew in July 1998. It successfully performed a number of autonomous rendezvous and docking/berthing operations. The system consisted of two cooperative spacecraft that employed a suite of sensors including GPS navigation and a datalink to accomplish rendezvous and docking.

Presently, a number of different autonomous rendezvous mission and systems are in development. The Demonstration of Autonomous Rendezvous Technology (DART) mission aims at validating the Advanced Video Guidance Sensor (AVGS) developed at NASA's Marshall Space Flight Center for ISS re-supply missions [2]. For the demonstration mission, the DART spacecraft rendezvous with a spacecraft currently in orbit. It relies on relative GPS to get into the vicinity of the target and utilizes the AVGS sensor and retro-reflectors that are mounted on the target vehicle to determine relative attitude and position to the target. The DART mission is scheduled to launch in 2004.

Similarly, the Japanese H-II Transfer Vehicle (HTV) and the European Automatic Transfer Vehicle (ATV) are currently being developed for ISS re-supply missions. They employ a host of rendezvous sensors including relative GPS and a European built Laser Range Finder (LRF). The objective of DARPA's Orbital Express (OE) mission is to demonstrate autonomous in-space re-fueling and servicing of on-orbit assets. The OE mission launches two spacecraft together, the "Astro" and "NextSat" spacecraft. Astro acts as the servicer and NextSat serves as the service vehicle [3]. Launch is scheduled in the 2005 timeframe. While having different objectives, all these missions share a number of important attributes including their vicinity to Earth and their use of the GPS infrastructure.

Future Planetary Sample Return Missions, on the other hand, have a set of unique challenges not present in previous or existing rendezvous systems in Earth or Moon orbit. Current concepts of a Mars Sample Return mission, for example, envision the collected samples to be stowed in a passive sample canister that is launched into Mars orbit and retrieved by an orbiting spacecraft. The lack of accurate navigation assets, such as the Global Positioning System or ground based radar, in Mars orbit (and other planetary orbits) necessitates the use of novel navigation sensors to search for, track and ultimately approach and capture an Orbiting Sample Canister (OS). As a consequence, a low mass and low-power Laser Mapping Radar (LAMP) is currently being developed at JPL by NASA's Mars Technology program. LAMP provides high-accuracy angle and range measurements for a range of up to 5 km to search for and track an OS during the Terminal Rendezvous Phase.

In addition, the one-way signal travel time to Mars and other future planetary sample retrieval grounds is on the order of several minutes or more, and precludes the level of supervision found in current Earth orbit autonomous rendezvous systems. Thus, a planetary rendezvous system must be designed with a very limited human-in-the-loop element for the terminal rendezvous phase and must include on-board autonomous computations of navigation and maneuver solutions as well as robust fault detection and identification capabilities. To accommodate the lack of full human supervision and, at the same time, increase the probability of mission success and reduce the risk of collision, a rendezvous strategy has to be devised that is both robust to failures and amenable to the limited Ground supervision available. To this end, terminal rendezvous profiles have been developed that provide adequate time for the Ground to verify proper spacecraft and rendezvous sensor performance before proceeding with the rendezvous and that allow for sufficient passive abort margins (i.e. safe unpowered separation) in case of spacecraft failure.

To test and validate some of these technology needs and to pave the way for their use in future Planetary Sample Return Missions, NASA's New Millennium Program is funding the Space Technology 6 (ST6) Autonomous Rendezvous Experiment (ARX). The objectives of the experiment are:

- to demonstrate a rendezvous mission composed of different proximity operations, including a number of different transfer maneuvers, approach profiles and fly-arounds, and leading up to a rendezvous with an OS test article. The proximity operations should serve as the building blocks for future rendezvous and sample capture approach scenarios.

- to validate an Autonomous Rendezvous System (ARS) that autonomously locates and rendezvous with an OS test article. The system consists of a LAMP sensor, Autonomous Rendezvous Guidance, Navigation and Control (ARC) software, a generic interface to the host spacecraft, and an OS test article.

The following sections give an overview of the ST6 mission and system design that is used to meet these objectives. The next section presents the ARX mission, and Section 3 the ARS system. Section 4 discusses the LAMP hardware and software, Section 5 the Autonomous Rendezvous Control software, Section 6 the Orbiting Sample (OS) test article, and Section 7 the operations aspects. Finally, Section 8 presents a summary and conclusions.

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3 In the context of the XSS-11 mission, the OS is also known as Cooperative Space Object (CSO). The term cooperative refers hereby to the retro-reflectors of the OS.
2. MISSION OVERVIEW

ARX is to be hosted as a payload on the United States Air Force Research Laboratory (USAFRL) XSS-11 spacecraft. The XSS-11 spacecraft is "microsat-class" spacecraft with a mass of less than 125 kg. Launch is currently planned for the fall of 2004 atop a Minotaur launch vehicle. The expected orbit altitude is between 600 - 1000 km, the orbit eccentricity is less than 0.01, and the inclination is between 65-89 degrees. The XSS-11 mission duration is one year and the ST6 ARX related mission activities are planned at the beginning of the XSS-11 mission.

In order to meet the aforementioned ARX objectives, two experiment phases have been designed, a LAMP Characterization Phase and an Autonomous Rendezvous Demonstration (ARD) Phase. Both phases use the OS test article, which is deployed from the spacecraft at the outset of the experiment, to rendezvous with or take measurements against. In the LAMP Characterization Phase, the LAMP sensor is characterized across its performance envelope. This serves to validate the proper functional behavior and operating characteristics of LAMP in a space environment.

Once this is accomplished, a host of different proximity operations are performed in the ARD phase. They include a number of different transfer maneuvers, approach profiles and fly-arounds of the OS and are executed under the guidance of the Autonomous Rendezvous System (ARS). Thereby the system is tested end-to-end in closed-loop operations. The ARS uses the LAMP measurements to estimate the host spacecraft's relative position and velocity with respect to the OS. Based on an uploaded list of desired waypoints, the ARX rendezvous guidance algorithms autonomously compute maneuver and attitude requests that guide the spacecraft to the desired state. These maneuver request are then sent to the host spacecraft for execution.

The mission design for both phases is driven by a number of spacecraft, mission and operations resource constraints, including:

- Delta-v: The LAMP Characterization and ARD Phase have a delta-v allocation of 14 m/s and 25 m/s, respectively.
- Power: Frequent sun pointing is required to maintain the battery state of charge. Since the solar panel orientation is fixed with respect to the spacecraft, the spacecraft has to turn in order to point the active side of the panels towards the sun, thereby removing the OS from the LAMP field of regard (FOR). The ARS maintains and propagates OS knowledge during this time in its state estimator and upon completion of the sun pointing, the spacecraft turns back to where ARS believes the OS to be. If the knowledge degraded to the point where the OS is not in the FOR, a limited search covering the position uncertainty ellipsoid will be performed.
- Up-/downlink opportunities: A limited set of short up-/downlink opportunities per day require real-time decision making during critical operations. It also requires that important mission events are timed to coincide with available ground coverage.

The LAMP Characterization and ARD phases are discussed below in more detail.

**LAMP Characterization Phase**

The objectives of the LAMP characterization phase is to test the LAMP sensor across its entire performance envelope, including evaluation of noise, acquisition and tracking performance characteristics. To this end, a sequence has been designed that exercises the LAMP through its projected range capability of up to 5 km. in a fuel-efficient manner.

The LAMP characterization is shown in Figure 1.

![Figure 1 - LAMP Characterization Phase](image)

For vehicle safety purposes, the LAMP Characterization Phase will be executed using the XSS-11 rendezvous guidance and control software.
stays there for more than 5 minutes before it would drift out of the FOR again. During this time the LAMP will acquire the OS and downlink raw images and as well as processed centroid measurements of the OS. The Ground will assess the proper functioning of LAMP and enable the spacecraft pointing control loop. Once enabled, the spacecraft will track and maintain the OS in the center of LAMP's FOR.

The Ground will also assess that all spacecraft functions are nominal and, once a safe distance is attained, enable the position control loop and command a station keeping at approximately 30m from the OS. Next, the spacecraft is transferred to 120m to further increase a safe distance to the OS. During the entire time the LAMP is tracking the OS and collecting measurements. The center piece of the LAMP characterization phase is a 3880m x 1940m "football orbit" that has its perigee 120m from the OS and its apogee at 4000m. This orbit is flown twice and provides a number of LAMP measurement opportunities in the range of 120m to 4km. Upon exit of football orbit an additional two-impulse transfer to 30m is performed to provide an additional opportunity for close-in measurements. Finally, the spacecraft is taken to safe distance of 500m. Figure 1 shows the proposed sequence.

**Autonomous Rendezvous Demonstration (ARD)**

The objectives of the ARD phase are to demonstrate a rendezvous mission composed of different proximity operations and to exercise the ARS system in an end-to-end manner. The proximity operations include (see Figure 2):

- **Station Keeping**: Maintaining a stationary position with respect to the Orbiting Sample (OS). Because it is fuel efficient, most of the time station keeping is performed in the same orbit as the OS at a point in front or behind of the OS, i.e. on the +/V-bar. Station keeping is useful to keep the spacecraft in the OS' vicinity during ground-interaction (e.g. Go No-Go) and during trouble shooting.

- **Rendezvous Approach**: The process of approaching the OS for a rendezvous to within the allowable minimum distance under controlled conditions (e.g. speed and approach angle).

- **Football Orbit**: An apparent circumnavigation of the OS by the spacecraft in the course of one orbit as seen from the OS. This is a natural motion and thus fuel-efficient. It is accomplished by adjusting the chase orbit to have the same semi-major axis but a slightly different eccentricity as the OS orbit. The football orbit
is useful for OS observation and to perform sensor handovers.

- **Two-Impulse Transfer**: A two-burn transfer from an initial position vector with respect to the OS to a final position vector with respect to the OS in a given amount of time.

- **Co-elliptic Orbit Transfer**: Transferring the spacecraft into an orbit that is "parallel" to and either above or below of the OS orbit as seen from Earth. This results in a fixed separation or approach rate of the spacecraft with respect to the OS with little fuel expense.

Figure 3 shows a possible trajectory that encompasses all the aforementioned maneuvers and mission segments. The mission starts at 100m in front of the OS on the V-bar where the handover from XSS-11 to ARS control occurs during a ground contact. Next, the spacecraft approaches the OS in a forced motion approach along the V-bar to its closest approach point of 30m. The closest approach distance is governed by vehicle safety considerations. It then separates using two two-impulse transfers first to 120m and then to 1km, respectively. At this point the spacecraft will station keep for a number of orbits to replenish its batteries. ARS thereby directs the spacecraft to frequently point back to the OS in order to maintain relative position knowledge of the OS. Next, the spacecraft is directed to enter a 4km football orbit and circumnavigates the OS once. Upon crossing the -R-bar, the spacecraft executes a maneuver to insert an out-of-plane (OOP) component. This results in a 250m out-of-plane distance when crossing the -V-bar and serves to demonstrate passive abort capability of OOP football orbits. The OOP component is taken out when the spacecraft passes through the +R-bar. Upon crossing the V-bar, ARS directs the spacecraft to again station keep for a number of orbits to recharge the battery before entering a co-elliptic approach. During the latter, the spacecraft increases its orbit by approx. 200m and establishes a constant approach rate to the OS. Finally, after flying by the OS, the spacecraft is commanded to station keep 500m behind the OS on the V-bar.

The entire trajectory is planned and described by means of waypoints. The waypoints are stored in a Terminal Approach Profile (TAP) file by the mission designers and uplinked to ARS during the operations. The waypoint description includes the time the spacecraft has to arrive at the waypoint, a given velocity at the waypoint, the dwell time at this waypoint, the attitude and position deadband active at this way point, Go/NoGo criteria that have to be met in order to continue to the next way point, and sun point intervals that are scheduled between way points. ARS will autonomously step through the TAP file and guide the spacecraft through the desired waypoint sequence.

### 3. SYSTEM OVERVIEW

**XSS-11 Host Spacecraft and ARS Description**

The XSS-11 spacecraft is three-axis stabilized satellite designed for Earth orbit. Its propulsion system consists of a 22N Orbit Adjust engine, 8 coupled, warm gas ACS thrusters (0.7N each) and 2 Z-axis thrusters (0.9N). The spacecraft avionics is centered around a RAD 750 processor with 512 Mbytes of mass memory storage for recorded data. Its avionics suite includes a LN-200 MU, a star tracker, and sun sensor for attitude determination, and a GPS receiver for on-orbit position and velocity updates. Figure 4 shows the XSS-11 spacecraft with the OS test article still attached.

The XSS-11 telecommunications subsystem has both an S-Band and a TDRSS transceiver on board. The ARX mission has baselined the use of the S-Band communications capability only in its mission and experiment design.

![Figure 3 - Autonomous Rendezvous Demonstration Phase](image1)

![Figure 4 - XSS-11 Spacecraft](image2)
although the TDRSS data links will be used when they are available in flight. Fixed solar panels generate power for the entire spacecraft augmented by a rechargeable on-board battery during eclipse times or peak power utilization, and the thermal subsystem provides temperature control throughout.

The Autonomous Rendezvous System (ARS) is a payload on the XSS-11 spacecraft. It consists of the LAMP sensor, associated processing and interface software, and a suite of Autonomous Rendezvous Guidance, Navigation and Control (ARC) algorithms. These software modules are hosted on the LAMP Mongoose Processor. The spacecraft will also carry the OS Test Article and the OS ejection mechanism.

ARS is operated in two modes: during ARX, ARS is active and in control of the XSS-11 spacecraft. For all other XSS-11 mission phases, the LAMP sensor continues to serve as the primary rendezvous sensor, but ARS disables its rendezvous algorithms and XSS-11 utilizes its own set of rendezvous algorithms instead.

In addition to the LAMP sensor, the XSS-11 spacecraft has a visual camera as a secondary rendezvous sensor. In context of ARX, the camera is used for visual verification of LAMP measurements in close vicinity of the OS test article. Figure 5 gives an overview of the XSS-11 and ARS System Architecture.

**Figure 5 - XSS-11 and ARX System Architecture Overview**

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**XSS-11/ARS Interface**

One of the biggest challenges in the architecture presented is the definition of the interface between XSS-11 and ARS. For typical payloads, such as science instruments or sensors the data acquisition is the primary driver for the interface definition. In case of ARS, it functions not only as a sensor, but also acts as an integral part of a tightly coupled rendezvous control loop system and, thus, has to seamlessly integrate with the spacecraft’s GNC functions.

Consequently, in defining the interface two important aspects have to be taken into account:

- The interface should be simple to account for the fact that a number of organizations at different geographic locations contribute to the closed-loop rendezvous system and to facilitate the integration of ARS.
- The interface should be generic to enable future missions to use ARS as an "add-on" payload on any host spacecraft, with only minor adjustments (e.g. gains) to accommodate different spacecraft properties.

It is thus important to exactly define roles and responsibilities between the two systems and organizations. Much of the groundwork to address these aspects has been done in context of the Mars Sample Return (MSR) Rendezvous Technology development and is being used in the current context.
During ARX, the responsibilities of ARS include:
- measuring relative state of the spacecraft with respect to the OS test article.
- determining the required pointing of the spacecraft in order to maintain the OS in the LAMP FOR and
- issuing the corresponding pointing requests to the host spacecraft
- determining the delta-v maneuvers to insert in and maintain the spacecraft on the desired trajectory. The desired trajectory is hereby stored in the ARS system
- issuing the corresponding delta-v requests to the host spacecraft for execution.
- issuing sun pointing requests in order to maintain battery state of charge

Besides housekeeping and telecom responsibilities, the spacecraft's responsibilities during ARX include:
- measuring and providing inertial spacecraft attitude and rate to ARS
- relaying ground uplinks of the XSS-11 spacecraft ephemeris to ARS, when available
- executing pointing and delta-v requests received from ARS
- providing feedback on measured delta-v to ARS
- relaying all uplinked ground commands and TAP files to ARS
- managing power and sun pointing including turning to and from the sun and recharging of the batteries.

In addition, ARS and XSS-11 exchange timing, status and health information. XSS-11 also maintains overall responsibility for vehicle safety, fault protection, and, if necessary, performs the execution of an abort maneuver. The update rate for all the information exchanged over the interface is 2 Hz. Figure 5 shows the data interface.

The physical interface between the XSS-11 spacecraft and ARS is via an RS-422 serial bus provided by the LAMP hardware and the protocol is based on a semi-custom synchronous/asynchronous design. Incoming data to the LAMP arrives at the rate of 460.8 kbit/sec asynchronous. Outgoing data from the LAMP is sent at 1.25 Mbits/sec synchronous.

**ARS Software System Architecture**

The ARS software architecture consists of 4 primary modules:
- LAMP Operating System (LAMPOS)
- Command and Data Handling (C&DH)
- LAMP Rendezvous Software (LRS)
- Autonomous Rendezvous Control (ARC)

The LAMPOS provides a communication layer on top of a version of WindRiver's VxWorks operating system executing on the LAMP "Mongoose" processor. It serves as the primary communications layer across the XSS-11/ARS interface and provides some allocation and clean-up utilities as various tasks are started and halted. Additionally, LAMPOS communicates directly with all of the drivers for the various sensors and actuators within LAMP. Clock synchronization between the LAMP oscillator and the spacecraft internal time is maintained by LAMPOS.

The ARS Command & Data Handling (C&DH) software distributes all incoming commands to the various tasks (e.g. LRS, ARC) as well as collects and packages all outgoing data from the same tasks. Its primary function is to serve as the system "point of contact" for all incoming and outgoing data. It also serves to route data from one task to another.

The LAMP Rendezvous Software (LRS) is the application-specific software that controls the scanning in LAMP's Field of Regard (FOR), processes raw measurements, and determines the range and bearing information to the OS test article or other objects in the LAMP FOR. In addition, it provides the status of the hardware such as measured temperatures and voltages as well as any faults detected during the reporting period. LRS is discussed in Section 4 in more detail.

The Autonomous Rendezvous Control (ARC) Software is responsible for executing the autonomous rendezvous operations in ARS. It estimates and maintains the spacecraft relative state (i.e. position and velocity) with respect to the OS test vehicle, calculates pointing commands to maintain the OS in the LAMP FOR, and determines trajectory commands to guide the spacecraft along the desired trajectory. ARC is discussed in Section 5 in more detail.

**4. LAMP Sensor Description**

**LAMP Hardware Architecture**

The LAMP (Laser Mapper) sensor is a laser radar. It operates by emitting short high power laser pulses, which bounce off an internal gimbaled mirror that determines the azimuth and elevation of the outgoing beam. When the laser pulses hits a target, a small amount of the light is reflected back to the instrument. The returned laser pulse bounces off the internal mirror and is collected by a telescope. On the way out, the laser actuated trigger starts a counter that is stopped by the return pulse. The counter value (time of flight) is proportional to the distance [4,5], and the instantaneous gimbal angles provide the direction to the object. This principle is sketched in Figure 6. By sweeping the internal gimbaled mirror though a number of angles, it is possible to form a 3-dimensional image of the space in front of LAMP.

LAMP is based on a passively Q-switched Nd-YAG microchip laser. The pulse repetition frequency is ~10 KHz and the pulse energy is ~10 mJ with a wavelength of 1064 nm. The laser beam has been shaped to have a 0.02° (0.35 mrad) divergence. The Nd-YAG microchip laser is pumped by an external 808 nm pump diode laser that constantly outputs 2.5 W. In order to maintain the laser diode's required temperature range of 19°C - 21°C, it is housed in a separate temperature controlled Pump Laser Enclosure and is connected to the microchip laser though an optical fiber.
The laser pulse going out of LAMP contains \(4 \times 10^{13}\) photons. A 7mm retro reflector, such as the ones mounted on the surface of the OS test article, at 5 km intercepts \(6 \times 10^{6}\) photons. 3\(\times 10^5\) of these photons return to LAMP's 5 cm aperture telescope and are sufficient to yield a reliable detection. The photon budget is less favorable when a Lambertian surface is being ranged. Here, most of the photons that hit the target area are irradiated in all directions. For a target surface with a \(0.1 \text{ m}^2 \text{ area} \times \text{albedo product, the detection range is 2.5 km. The LAMP telescope itself has a 5 cm aperture and is a classical Cassegrain type. Table 1 shows key parameters of LAMP.}

When a laser pulse is emitted from the Nd:YAG microchip laser a small part of the signal is routed to a fast Si-PIN detector. This detector starts a timer. A very fast Avalanche Photo Diode (APD) is mounted behind the Cassegrain telescope with a series of high bandwidths amplifiers. When the light pulse returns, it will generate a signal in the amplifiers that will stop the timer when the signal reaches a threshold. Since the dynamic range of the returned signal spans many orders of magnitude, there are a number of different stop channels (corresponding to different amplification levels). At close range, the signal will completely saturate the APD/amplifiers and at distant ranges only the most sensitive channel will detect a signal. The timing chip uses a clock frequency of 70 MHz, but is able to interpolate to a resolution of 0.4 nS, equivalent to 2.5 GHz [6]. The timing circuitry is mounted on a dedicated timing board housed in a separate Electronics Assembly.

The scan mechanism consists of a two-axis gimbal (azimuth and elevation) with a 5 cm diameter beryllium mirror. It allows for angular movements of +/-5° in both azimuth and elevation axes. The elevation and azimuth axes have a maximum sweep rate of 10°/sec and 10,000°/sec, respectively, and allow for a maximum scan rate of 1 second for the entire field of regard (10000 measurements). The gimbal is driven by software controllable scan drive electronics. A small laser beam is directed to the back of the gimbal mirror and reflected onto a position sensitive detector thereby providing the processor with the current angle of the gimbal. The microchip laser, optics, gimbal and detectors are housed in the Optical Head Assembly. Figure 7 shows an image of the LAMP optical head without top panel.

The LAMP processor is a 12.5 MHz, 32-bit MIPS R3000 Synova "Mongoose" Processor with 4 Mbytes of EEPROM, 64 Mbytes of SDRAM and a RS-422 interface. It is sized to host the entire ARS software. The processor board, Input/Output, power and current supply boards as
well as the timing and scanner boards are housed in a separate Electronics Assembly chassis. The entire LAMP sensor including cables and fiber optics weighs 5.9kg and consumes an average of 35W of power (heaters excluded).

**LAMP Rendezvous Software**

The objective of LAMP Rendezvous Software (LRS) is to acquire an object in its field of regard (FOR) and then track it in order to provide range and bearing estimates (azimuth and elevation). It accomplished this, by controlling the scan pattern (i.e. gimbal movements) and processing the timing and angle measurements obtained. For the ARX mission, the space object is the OS test article, i.e. a sphere of 20 cm diameter (described in Section 7). However, LRS can also acquire and track other arbitrary shaped space objects. For the purpose of this paper, these objects are referred to as Resident Space Objects (RSO).

**Table 1 - Key LAMP Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam divergence</td>
<td>0.02 degree</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>10 KHz</td>
</tr>
<tr>
<td>Mass</td>
<td>5.9 kg</td>
</tr>
<tr>
<td>Power consumption</td>
<td>35 Watts</td>
</tr>
<tr>
<td>Detection range (retro reflector)</td>
<td>5 km</td>
</tr>
<tr>
<td>Detection range (Lambertian surface)</td>
<td>2.5 km</td>
</tr>
<tr>
<td>Range Bias (retro reflector)</td>
<td>10 cm</td>
</tr>
<tr>
<td>Range Scale Factor (retro reflector)</td>
<td>0.25%</td>
</tr>
<tr>
<td>Range Random Error (retro reflector)</td>
<td>2.6 cm (3s)</td>
</tr>
<tr>
<td>Angle Random Error (retro reflector)</td>
<td>0.6 mrad (3s)</td>
</tr>
</tbody>
</table>

During acquisition, the outgoing pulse is scanned across the sky so that enough energy lands on the object for a return to be detected. The size of the pulse (0.35 mrad), the pulse repetition rate (10,000 Hz), and the angular extent of the object at the expected range determine the speed of the scan during acquisition. In order to ensure detection, the separation between the pulses can be no larger than the angular size of the object at a given range. As the range of the object is initially unknown, it is assumed that the angular aspect is smaller than the spot size (pulse divergence) resulting in an acquisition scan rate of 3.5 radians/sec for the elevation axis and 3.4 mrad/sec for the azimuth axis.

Once the object is detected during the acquisition scan, the scan mirror is directed to a small sub-window centered on the bearing to the initial acquisition. If the object persists the LAMP Rendezvous Software assumes that the object is located and commences tracking the object. Tracking consists of continually scanning the mirror in a small window around the target. The size of the sub-window is determined by the angular aspect of the object being tracked (the larger the angular extent, the bigger the scan window). After each scan, the centroid of the scan is calculated, and this measurement is then used to adjust the location of the next scan (re-centering the object), and stored for later use in reporting the object's location.

Every 0.5 second (i.e. at 2 Hz), the LRS collects all the centroid measurements made in this cycle (up to 25 depending on the range of the object). For the OS test article, a linear regression is performed over the centroid measurements to determine the mean OS velocity and position over time (see Figure 8). For the RSO, the latest centroid measurement is provided in the report along with the closest and furthest points observed in the most recent scan. This information is then provided to GNC system in control (ARC or XSS-11). The resulting performance capabilities are shown in Table 1.

LRS is also responsible for monitoring and controlling LAMP's temperature and laser levels, as well as performing LAMP fault protection.
5. AUTONOMOUS RENDEZVOUS CONTROL (ARC)

The Autonomous Rendezvous Control (ARC) software estimates relative position and velocities of the OS test article relative to XSS-11 using LAMP measurements, and generates attitude and inertial AV commands at 2 Hz control cycle. The attitude commands maintain the relative LAMP pointing at the OS test article or re-orient the XSS-11 to burn attitude, while delta-V commands steer the XSS-11 along the rendezvous trajectory. These command requests are sent to the XSS-11 guidance, navigation and control (GNC) unit for execution. The XSS-11 GNC system provides attitude and rate estimates, ephemeris, accelerometer data, as well as the controller and thruster firing logics to execute the ARC commands. The ARC architecture indicating the relationship between the ARC components and their environment is shown in Figure 9.

XSS-11 executes the delta-v commands in two possible modes: Vector mode and X-mode. Vector mode uses the Attitude Control System (ACS) thrusters and/or Z-axis thrusters to execute the burns and thereby maintains the spacecraft attitude. It is mostly used for small burns. X-mode utilizes the 22-N Orbit Adjust engine that is aligned with the spacecraft's X-axis. To execute the burn, the spacecraft has to turn to align the spacecraft's X-axis with the desired thrust direction (i.e. "turn and burn").

ARC is driven by a Terminal Approach Profile (TAP) file that defines the desired trajectory. The TAP file has been planned by mission designers beforehand on the Ground and is uplinked to the ARS during operations. In the TAP file, the desired trajectory is defined by means of waypoints the spacecraft has to pass. The waypoints are specified in the TAP file in OS-fixed local-vertical, local-horizontal frame (LVHL). The waypoint description includes the time the spacecraft has to arrive at the waypoint, a given velocity at the waypoint, the dwell time at this waypoint, the attitude and position deadband active at this waypoint, Go/NoGo criteria that have to be met in order to continue to the next waypoint, and sun point intervals that are scheduled between waypoints.

ARC's mode commander autonomously steps through the TAP file, commands the required mode transitions (e.g. stationkeep, sun point, and OS search), and calls and distributes the relevant TAP file entries to the other ARC functions.

The trajectory commander determines delta-v requests expressed in inertial coordinates that, if executed, traverse the specified waypoints in prescribed order. In calculating the delta-v requests, the trajectory commander considers transfer times specified in the TAP file. While ARC is executed at a rate of 2Hz, delta-v requests are expected to be issued less frequently during the experiment.

The attitude commander issues attitude requests to XSS-11 to keep the OS in LAMP FOV when in track mode or re-orient the XSS-11 to burn attitude. It operates in either 2-axis or 3-axis pointing mode. The former determines the direction a given spacecraft axis has to point to, but lets the XSS-11 spacecraft determine the third axis (the twist angle around this axis) in order to optimize spacecraft
housekeeping and telecom functions. In addition, the attitude commander performs OS search when necessary. In particular, a limited search for the OS may be necessary when the spacecraft turns back to the OS after an extensive sun pointing period.

Finally, the state estimator estimates relative CSO-to-Orbiter position and velocity in inertial frame, absolute CSO position and velocity in inertial frame, and health status from residual tests.

Using computer simulations, the ARC design has demonstrated the capability to maintain station keeping of the XSS-11 position relative to OS to an accuracy of 2 - 5% of the range for range between 30 and 100 meters, and the LAMP to CSO pointing error to within 20 mrad (36) per axis.

6. ORBITING SAMPLE (OS)

The OS Test Article is approximately a sphere of 20 cm diameter and simulates the current concept of the Mars Sample Return mission's Orbiting Sample (OS) Canister. To enhance the return signal from the laser pulse, the OS is equipped with fifty 7 mm retro-reflectors. The reflectors direct the impinging energy back along the incident angle to the LAMP's detectors. The size of the retro-reflectors is limited in order to enable the future accommodation of solar cells or other mechanical features, but is sufficient to detect an impinging laser pulse at greater than 5 km when viewed within a 30 degree angle. Their placement is designed to assure that a pulse from any orientation of the OS would land on at least one of the reflectors. The current layout provides detectable returns at 5 km from over 99.999% of the orientations. The orientations that did not provide detectable returns are the result of destructive interference from multiple cubes. Figure 10 shows the OS layout and the ejection mechanism.

7. MISSION OPERATIONS

Mission Operations for the ARX mission are conducted at Kirtland Air Force Base in Albuquerque, New Mexico collocated with the XSS-11 spacecraft’s Flight Operations Team (FOT) in the fall and winter of 2004.

ARS and spacecraft commands are uplinked and spacecraft telemetry data downlinked through the Air Forces Satellite Control Network (AFSCN). The downlinked telemetry is displayed in real-time on "X-terminal" displays that allow the ARX team to perform real-time evaluation and decision-making. The downlinked telemetry is also stored in the XSS-11 Data Archive and made available to the ARX team to perform mission simulation and non-real-time analysis on a ARX-developed workstation. An overview of the XSS-11/ARX Ground System is shown in Figure 11.

8. SUMMARY AND CONCLUSIONS

This paper presented an overview of the ST6 Autonomous Rendezvous Experiment (ARX). The ARX mission aims at demonstrating a number of different proximity operations leading up to a rendezvous with an OS test article. In addition, it validates the Autonomous Rendezvous System (ARS) including the LAMP sensor and the Autonomous Rendezvous Control (ARC) software. The LAMP sensor has the capability to detect and track the retro-reflector equipped OS up to 5km. The ARC software allows the autonomous execution of rendezvous profiles that are defined by means of waypoints and uplinked to the spacecraft.

The demonstrated rendezvous technologies are applicable to all future planetary sample return missions, including the Mars Sample Return Mission planned for the next decade. The demonstrated proximity operations will serve as the building blocks for future terminal rendezvous approach scenarios. Moreover, these missions will rely heavily on novel sensor technologies and autonomous navigation and guidance capabilities such as the ones demonstrated in the ST6 ARX. A simple but generic interface enables future missions to use ARS as an "add-on" payload on any host spacecraft, with only minor adjustments to accommodate...
different spacecraft properties. Finally, the operational experience gained from this experiment will benefit the design of future autonomous rendezvous and sample capture missions and systems where little or no 'ground-in-the-loop' control may be possible.

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