Rascal: A Demonstration of Rendezvous and Proximity Operations within a Small Spacecraft Architecture

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The Rascal mission consists of the demonstration of rendezvous and proximity operations within small spacecraft architecture. Spacecraft RPO missions are defined as those that demonstrate the performance of orbital maneuvers near and around resident space objects (RSO), such as rocket bodies, orbital debris, or other spacecraft, while a small spacecraft architecture is defined as one that utilizes a standard satellite configuration and size that allow for rapid development and launch vehicle integration. In recent years, many RPO missions have been conducted, such as NASA's DART, DARPA's MiTEx, and Orbital's Orbital Express, each to varying degrees of success. Regardless of the program, each of these RPO missions consisted of large spacecraft (100 kilograms and up) that were developed with an equally large amount of capital, resources, and effort. Rascal, on the other hand, seeks to demonstrate similar RPO missions within an architecture that can be developed at a university-level while still capable of demonstrating key RPO capabilities, such as stationkeeping (maintaining a set distance between two RSO's), collision avoidance (rapidly increasing the distance between two RSO's), and rendezvous (moving two RSO's within a set distance of each other). Furthermore, these types of demonstrations have been recently highlighted by NASA as key areas of interest in the future development of intelligent spacecraft systems, meaning that the systems developed to make the Rascal mission possible can be easily transitioned to the greater aerospace community as a whole for use in future commercial or academic RPO missions. As such, the Rascal mission is critical to the further refinement and understanding of spacecraft RPO capabilities within the ever-changing small spacecraft landscape.

Nomenclature

RPO	=	Rendezvous and Proximity Operations
RSO	=	Resident Space Object
P-POD	=	Poly-Picosatellite Orbital Deployer
NLAS	=	Nanosatellite Launch Adapter System
CSD	=	Canisterized Satellite Dispenser
NASA	=	National Aeronautics and Space Administration
ELaNa	=	Educational Launch of Nanosatellites
AFRL	=	Air Force Research Lab
UNP	=	University Nanosat Program
AS&IS	=	Advanced Space & Intelligence Systems
DART	=	Demonstration for Autonomous Rendezvous Technology
DARPA	=	Defense Advanced Research Projects Agency
MiTEx	=	Micro-satellite Technology Experiment
DOF	=	degrees of freedom
ADC	=	attitude determination and control
km	=	kilometers

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km/s	=	kilometers per second
PWR	=	power
UHF	=	ultra high frequency
dB	=	decibel
MHz	=	megahertz
kbps	=	kilobits per second
GHz	=	gigahertz
Mbps	=	megabits per second
*W*hr*	=	Watt hours

I. Introduction

THE Rascal mission consists of the demonstration of rendezvous and proximity operations (RPO) within a small spacecraft architecture.

Spacecraft RPO missions are defined as those that demonstrate the performance of orbital maneuvers near and around resident space objects (RSO), such as rocket bodies, orbital debris, or other spacecraft. Examples of such orbital maneuvers consist of stationkeeping, collision avoidance, and rendezvous, with stationkeeping defined as a spacecraft remaining within a set relative distance of an RSO, collision avoidance as quickly increasing the relative distance between a spacecraft and an RSO, and rendezvous as decreasing the relative distance between a spacecraft and an RSO.

A small spacecraft architecture is one that utilizes a standard satellite configuration and size that allows for rapid launch vehicle integration, which in turn reduces the costs associated with securing a launch and increases the likelihood of a given mission to reach orbit. Examples of small spacecraft architectures that meet this definition are the CubeSat and Microsatellite-Classes of spacecraft, with the former having a more well-defined and rigorous meaning than the latter. For example, a CubeSat is defined as a spacecraft that consists of some combination of standard unit volumes, with a 1U being a 10cm x 10cm x 10cm cube, 2U being a 10cm x 10cm x 20cm rectangular prism, and so on. This, along with several other well defined specifications, has allowed for the development of standard launch vehicle adapters (such as the P-POD, NLAS, and CSD adapters), as well as the emergence of organizations that are willing to fund CubeSat launch opportunities, such as NASA's Educational Launch of Nanosatellites (ELaNa), the AFRL's University Nanosat Program (UNP), and Boeing's Advanced Space & Intelligence Systems (AS&IS) group. Microsatellites, on the other hand, have little to no standard specifications beyond the fact that they remain under 100 kilograms (though even this specification is disregarded in certain cases). This has prevented the development of standard adapter systems for Microsatellites, meaning that a microsatellite has to be designed with a particular launch vehicle in mind, whereas a CubeSat design is launch vehicle independent. This difference in ease of integration manifests itself in the launch costs for CubeSats versus those of Microsatellites, with the former costing $50 thousand and the latter $2 million on average. Thus, any mission that seeks to use microsatellite architecture, whether for increased payload capacity or extended mission lifetime, will do so at the risk of never actually reaching orbit.

With these definitions in mind, we can now go into greater detail as to what will constitute as a demonstration of an RPO mission within a small spacecraft architecture with respect to the Rascal mission, as well as the way in which Rascal will go about achieving such a demonstration.

II. Mission Overview

With the previous section in mind, as well as the lessons learned from previous RPO missions, the objective of the Rascal mission can be stated as follows: *Rascal is a proof of concept mission demonstrating the capability of two small spacecraft to autonomously perform rendezvous and proximity operations relative to each other*. The reasons for selecting such a mission, as well as for limiting its execution to the realm of small spacecraft, relate to past missions that have attempted to demonstrate RPO missions, with varying success (and cost), as well as current areas of interest in the future of spacecraft mission development and execution, as described in the following sections.

A. RPO Mission History

RPO missions have a long history in human spaceflight, dating back to the first Gemini missions. It was not until the previous decade that interest arose in approaching RPO missions with purely autonomous systems. For the most part, RPO missions have been solely under the purview of NASA and the military; only recently have private companies and universities made inroads in this area. Many previous RPO missions have been large million dollar satellites, each of which approached their mission in many different ways in an attempt to demonstrate many different RPO capabilities. Out of these missions, three were selected for more analysis based on the types of RPO capabilities that they demonstrated.

The first of these spacecraft is the *Demonstration for Autonomous Rendezvous Technology* (DART) mission, developed by the Orbital Sciences Corporation for NASA in 2005, with the mission goal consisting of the demonstration of autonomous navigation and rendezvous capabilities on a microsatellite platform, specifically related to an attempt to dock with an experimental communication satellite. The primary objectives of the mission were to navigate autonomously using GPS and to rendezvous using an Advanced Video Guidance Sensor. Within a few hours of launch, it was able to reach its target, but it experienced a malfunction as it began its approach, resulting in a soft collision between it and the target vehicle, resulting in NASA's termination of the mission. Though not publically released, this soft collision was likely a result of the chaser satellite approaching the target in a manner that the navigation algorithms used to control its propulsion system did not account for. This prevented the Advanced Video Guidance Sensor from switching to its fine tracking mode from its course mode, leading the chaser to think it was further from the target than it actually was, eventually causing the collision. The total cost of the mission was $98 million.

The second of these is *Orbital Express*, which was developed by Boeing and Ball Aerospace and managed by the Defense Advanced Research Projects Agency *(*DARPA*)* and the Marshall Spaceflight Center. The Orbital Express sought to demonstrate several servicing operations, as well as rendezvous and proximity operations. It consisted of two spacecraft, with one being the target and another being the servicing module. The primary spacecraft was able to refuel and replace the batteries of the target spacecraft at a cost of $300 million. The main lesson from this mission is that demonstration of extremely complicated RPO maneuvers is possible, but requires a large amount of resources, development time, and testing, likely more than a university-class spacecraft can achieve.

The final of these is the *Micro-satellite Technology Experiment* (MiTEx) mission. This mission consisted of three spacecraft working in geostationary orbit, with one serving as an experimental satellite, and the other two as inspection satellites. The inspection satellites, with masses of 225 kg each, were technology demonstration satellites capable of maneuvering in relation to other satellites and providing platforms to inspect other satellites without detection. The satellites demonstrated autonomous operations, maneuvering, and station-keeping capabilities, were designed by Lockheed Martin and Orbital Sciences, and managed by DARPA. They were able to complete their mission with the experimental satellite, and then moved to inspect a failed missile detection satellite to try to find the cause of the failure. The total cost of the mission was $24.6 million.

From these examples, as well as those of numerous other RPO missions that have previously flown, missions of this nature are difficult or next to impossible for universities to successfully develop, so knowing how to limit the scope of university-level RPO missions is important in determining their ultimate success. The requirement that Rascal consist of a demonstration of RPO between two *small* spacecraft stems from this fact. But why do we care about RPO missions at all?

B. Mission Relevance

The Rascal mission relates directly to NASA Strategic Goal 3.3 (As outlined in *NASA's FY 2011 and FY 2012 Annual Performance Plans.*), which states that missions should be pursued that, "Develop and demonstrate the critical technologies that will make NASA's exploration, science, and discovery missions more affordable and more capable."

As a CubeSat RPO mission seeking to demonstrate operations that have not been performed on a system of equal scale, the Racal mission meets both the requirements of a mission that demonstrates critical technologies, while doing so through the use of an affordable spacecraft system. As such, missions such as Rascal's are highly desirable from a NASA development perspective, the reason for this resting in the potential of these types of systems to conduct inspections and maintenance on dying or decommissioned satellites, potentially saving satellite developers millions of dollars in costs associated with replacing such satellites that were previously unrecoverable.

C. Mission Success Criteria

With these factors in mind, the Rascal's mission success criteria were defined such that Rascal could fully demonstrate relevant RPO maneuvers without the risk associated with previously flown RPO mission. Thus, the Rascal mission will be defined in terms of a single "Interceptor" spacecraft performing rendezvous and proximity operations relative to a passive "Target" spacecraft. Thus, mission success can be achieved with only one of the two spacecraft (the Interceptor) executing the criteria defined below.

Rascal shall demonstrate the following RPO capabilities between a target and interceptor spacecraft:

1) Stationkeeping within 10-75 meters.
2) Collision Avoidance by performing an orbital maneuver that intentionally increases the final relative spacecraft displacement to 100 meters in a maximum time of one orbit.
3) Rendezvous by performing an orbital maneuver that intentionally decreases the final relative spacecraft displacement to at least 50 meters for at least 5 orbits.

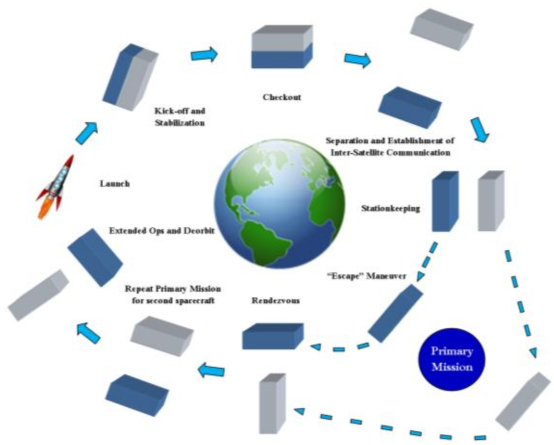

Figure 1. Example Rascal mission concept of operations.

D. Mission Architecture

With mission success defined, as well as the scope of the mission being limited to small spacecraft, it was determined that the Rascal mission could and should be executed through the use of a CubeSat architecture. Based on these success criteria, as well as analyses of spacecraft orbital, power, volume, downlink, and mass requirements (as discussed in the following sections), it was determined that the Rascal mission could be executed through the use of two twin 3U CubeSats (each called Jade and Nephrite). Each of these spacecraft would have their own 6 Degree of Freedom (DOF) propulsion system, active attitude control, image navigation and processing capability, and inter-satellite communication system.

This mission, as defined, was presented as a part of Boeing's AS&IS's search for a university satellite program whose mission goals and designs could best transition to wide-scale use in industry satellite systems. Rascal was ultimately selected out of 15 universities as the best candidate for meeting these search criteria. As a result, vast portions of the mission would be provided by Boeing, allowing students at Saint Louis University to focus specifically on making the mission payload perform to its best possible ability. For example, where most satellite programs have to develop and test their own Attitude Determination and Control (ADC) systems, which can involve complex interactions between gyroscopes, reaction wheels, magnetorquers, sun sensors, Earth sensors, star trackers, et cetera, the Saint Louis University team will only have to focus on developing algorithms to orient the spacecraft based on data provided from ADC systems that have been developed and tested by engineers at Boeing. This aid from experienced professionals would add a layer of confidence to the performance of said systems and allows for a greater focus on mission definition and integration.

Table 1. Boeing Colony-II Bus capabilities and constraints.

Parameter	Payload Accommodation/Space Vehicle Performance
Design Life	1 to 3 Years
Payload Mass	Up to 1.83 kg
Payload Power	35 Watts
Payload Size	1U
Pointing Control	0.42 deg
Mass Data Storage	8 GB
Propulsion	150 m/s
Launch Environment	CubeSat GEVS standard

Subsequently, the proposed mission would take the form of developing a payload around the core bus that would be provided by Boeing, whose specifications are defined in Table 1. As such, Rascal mission design by Saint Louis University will be limited to providing a 1U payload that can integrated into the Boeing's Colony-II bus, while simultaneously being capable of providing navigation, guidance, and control of each spacecraft as a whole, with the main focus being the execution of mission requirements defined by Saint Louis University. With this in mind, the layout of the 1U payload allows space for an imaging capturing and processing board (for calculating the relative distance

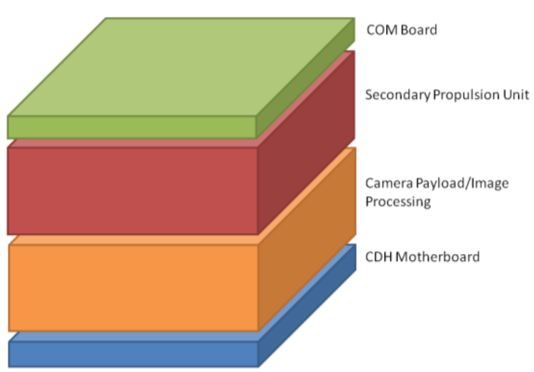

Figure 2. Example Rascal 1U payload layout

and velocity between each spacecraft), interface control board (for independent operation and handling of said image board, as well as for interfacing with the Colony-II bus), inter-satellite communication board (for the sharing of spacecraft orientation and the relaying of satellite health through either spacecraft), and a secondary propulsion unit (in the event that the propulsion unit provided by Boeing does not allow for the type of maneuvers necessary for the successful execution of the mission).

1. Orbital Analysis

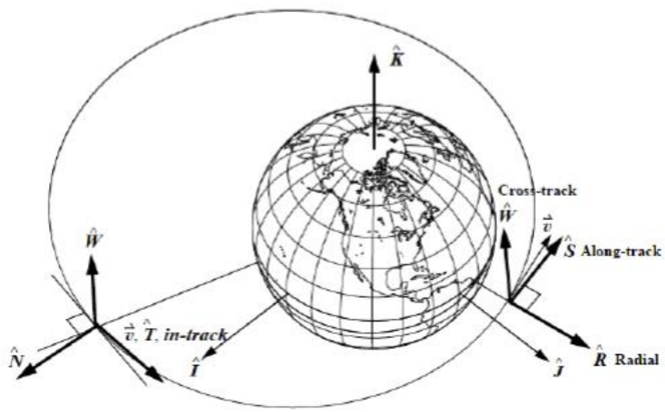

Figure 4. RSW coordinate frame visualization.

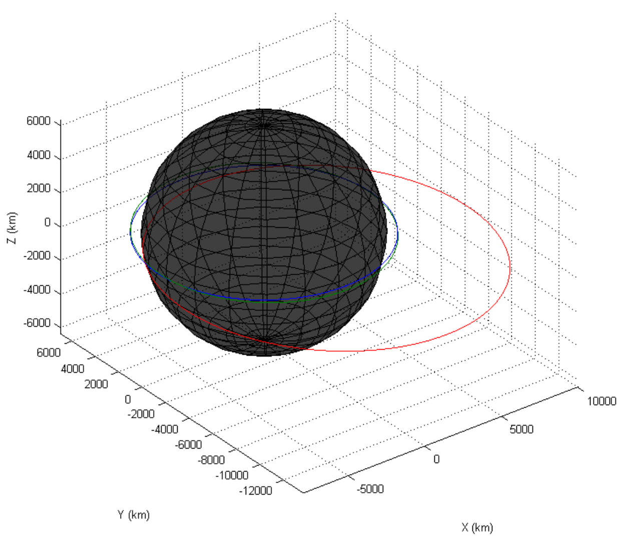

Figure 3. Example transfer orbit from an interceptor spacecraft to a target spacecraft for rendezvous. *The transfer orbit is shown in red, the interceptor orbit in blue, and the target orbit in green.*

Based on the orbital maneuvers described in the mission success criteria, as well as the upper delta-V bound imposed by the Colony-II bus, an orbital analysis of the Rascal mission was performed. This analysis assumed that the initial relative position and velocity of the interceptor spacecraft to the target spacecraft, as well as the local orientation of each, were known, each of which would be provided by a combination of inputs from the image capture and processing board and the ADC sensors already present on the Colony-II bus. Based on this information, these local position and velocity values (defined relative to the target spacecraft's RSW coordinate frame, as shown in Figure 3[6]) could then be translated to an Earth-Fixed Inertial reference frame. From this information, both Kepler's and Lambert's problems were solved, with the initial conditions being the initial inertial positions and velocities of each spacecraft, the final conditions requiring that each spacecraft have the same inertial positions and velocities, and for various delay and transfer times between when the maneuver was actually performed and when the two spacecraft actually achieved rendezvous. Algorithms for accomplishing this were executed in MatLab. A test case with initial target and interceptor positions and velocities of [6697.4756, 1794.5831, 0.000] km, [-1.962372, 7.323674, 0.000] km/s, [5328.7862, 4436.1273, 101.4720] km, and [-4.864779, 5.816486, 0.240163] km/s respectively was run for transfer and delay times ranging between 0 and 250 minutes. The results of this process consist of an example transfer orbit track, as well as the total delta-V required for a given delay and transfer time, as shown in Figures 4 and 5. From Figure 5, it is possible to determine the point at which the minimum delta-V is necessary to perform a given orbital maneuver. In the case of the Rascal mission, initial relative velocities and positions will be small (on the order of meters, not kilometers).

[6] Image courtesy of: Vallado, David A. *Fundamentals of Astrodynamics and Applications*. Dordrecht: Kluwer Academic, 2001. Print.

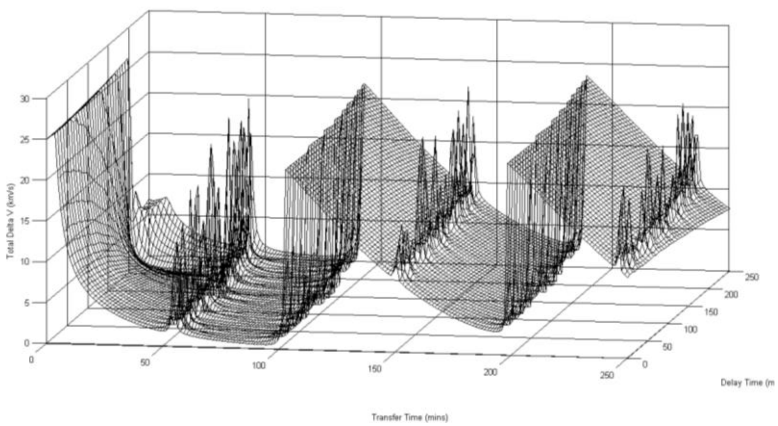

Figure 5. Example delta-V required for rendezvous maneuver given different transfer and delay times.

Thus, when performing this analysis for the Rascal mission specifically, it was found that the delta-V required to perform the mission is well below the 150 m/s delta-V limit, thus ensuring that the mission is feasible within a 3U architecture.

2. Power Analysis

The Power Subsystem (PWR) is responsible for the generation, distribution, and regulation of power throughout the spacecraft. A power generation analysis examining a best case scenario (where the surface with the most solar panels is fully exposed) and a worst case (where the surface with the least solar panels is fully exposed) was performed considering several solar panel configurations. The analysis assumed an average solar intensity of 1350 W/m^2, a loaded circuit voltage of 2.31 V per cell, and a solar cell efficiency of 27%. The cells were connected in series with seven cells per panel. Four solar panel configurations were considered.

Configuration 1 had six body mounted solar arrays with a maximum power generation of 5.1 W*hr / orbit, though the lack of deployable panels significantly reduces integration and maneuver complexity.

Configuration 2 had six body mounted solar arrays with four deployable panels such that two panels would be incident to sunlight on four of the six sides. This configuration generated a maximum of 10.2 W*hr / orbit.

Configuration 3 had six body mounted solar arrays and two deployable arrays such that three panels would be incident to sunlight on one side of the spacecraft. Configuration 3 was less complex than Configuration 2 and generated 17.2 W*hr / orbit, though it would require active attitude control to keep the arrays pointed at the sun for the best case scenario.

Configuration 4 assumed one body mounted array with five deployable arrays such that all six panels could be incident to the sun at the same time. This configuration would require sun-tracking and be the most complex for integration and maneuvering, though it also generated the most power with 30.6 W*hr / orbit in a best case scenario.

Based on each of these different configurations, it was determined that the spacecraft will produce sufficient power to meet the 35 Watt limit imposed by the Colony-II bus.

3. Communications Analysis

Communicating with the two spacecraft is needed to determine if each mission criteria has been reached. An analysis was performed on uplink and downlink communication with the spacecraft to determine which type of radio would work for Rascal. A UHF radio and an S-band radio were considered. The orbit used for the analysis was a 300 kilometer altitude orbit and the spacecraft was at 5º elevation with respect to the ground station at Saint Louis University. To determine which radio would work best for Rascal the signal-to-noise ratios had to be calculated for uplink and downlink. To have a good signal-to-noise ratio, it must be 0 or greater; this means the link was closed. The higher the ratio the less chance there is for bit flips. Finding the signal-to-noise ratio is just the sum of the gains added by the radio and antennas and the losses caused by the propagation of the radio waves through the atmosphere as well as any inefficiency the radio introduces. The ground station at Saint Louis has 100 Watt transmit power and the ground station antenna has 15 dB of gain. The UHF radio was assumed to be operating at 440 MHz with 5 Watt transmit power, 100 kbps downlink, and 4 kbps uplink and the antenna has 5 dB gain. The S-band radio was assumed to be operating at 2.4 GHz with 5 Watt transmit power, 1 Mbps downlink, and 4 kbps uplink and the antenna has 5 dB gain. The analysis found the uplink to be positive for both radios, so uplink is not a concern. The downlink ratio for the UHF radio was also positive, meaning Rascal could communicate with the ground with no problem. However, the downlink ratio for the S-band radio was found to be negative with the current assumptions. While this does not mean the S-band cannot be used, it does shorten downlink time.