COMPETITION SPACE BOT

HANDBOOK

A REFERENCE GUIDE

SDL/23-3169 Rev.-

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ACRONYM LIST

ADCS	Attitude Determination & Control System
ASME	American Society of Mechanical Engineers
C&DH	Command & Data Handling
CDR	Critical Design Review
CONOPS	Concept of Operations
COPS	Calibration Operations
EOL	End-Of-Life
EPS	Electrical Power System
GEO	Geosynchronous Orbit
GPS	Global Positioning System
ICD	Interface Control Document
LEO	Low Earth Orbit
LEOPS	Launch & Early Operations
MEO	Medium Earth Orbit
MESS	Modular Earth Sensing Surveyor
MT	Mountain Time
NOMOPS	Nominal Operations
OBC	Onboard Computer
OSIRIS-Rex	Origins, Spectral Interpretation, Resource Identification, Security Regolith Explorer
PDR	Preliminary Design Review
PROP	Propulsion
RF	Radio Frequency
RFP	Request For Proposal
RPOD	Rendezvous, Proximity Operations & Docking
RVM	Requirement Verification Matrix
SDL	Space Dynamics Laboratory
SEBoK	Systems Engineering Body of Knowledge
SSO	Sun-synchronous Orbit
STR	Structure
TT&C	Telemetry, Tracking & Control
UNP	University Nanosatellite Program
USU	Utah State University

Welcome to the SpaceBot Competition! This handbook includes official competition rules and guidelines for team participation.

1. COMPETITION OVERVIEW

The SpaceBot Competition is a university robotics competition sponsored by Utah State University (USU) Space Dynamics Laboratory (SDL) and USU's section of the American Society of Mechanical Engineers (ASME).Each university team will be tasked with manufacturing and developing a robotic payload for a theoretical on-orbit spacecraft servicing mission, referred to as "SpaceBot spacecraft." Teams will use systems engineering practices to fully design, assemble, and test their SpaceBot spacecraft system, with guidance from their faculty advisor and other SpaceBot points of contact. Each team will participate in a live demonstration of their SpaceBot spacecraft's system functionality, which a panel of professional judges will rate and score.

1.1 OBJECTIVES

SpaceBot Competition objectives include:

1) Outreach & Education

The competition provides university students with hands-on project application, an introduction to industry practices, connection with subject matter experts, and practice with team collaboration. The intent of this competition is that the SpaceBot spacecraft development will act as an extension of each participant's educational experience, providing additional options for capstone projects or extracurricular activities.

2) Technology Development

Space technology is quickly evolving, requiring constant innovation to fulfill demand. The ideas behind each SpaceBot spacecraft may stimulate creative solutions to aerospace challenges and lead to development and testing of new concepts that advance the state of the art in space robotics.

1.2 RESPONSIBILITIES & EXPECTATIONS

This section describes the responsibilities and expectations for both SDL and university teams throughout the SpaceBot Competition.

1.2.1 SDL Responsibilities & Expectations

SDL commits to providing high-level engineering support and guidance to teams throughout the competition. University teams can expect SDL to provide engineering support via technical points of contact and lists of useful resources. SDL is aware that technical complications or roadblocks arise during development. When these occur, university teams can expect SDL to offer appropriate high-level guidance to overcome the issues, but SDL will not solve the problem outright.

1.2.2 University Team Responsibilities & Expectations

University teams are expected to maintain a high level of professionalism since SpaceBot Competition provides a connection between academia and industry. Professionalism includes, but is not limited to, correspondence, meetings, reviews, presentations, deliverables, and demeanor.

Teams are expected to provide their own on-site testing and hardware for the SpaceBot spacecraft. Teams must have ample student participation and engagement throughout the competition. Each SpaceBot spacecraft should be student designed, maintained, and operated under the guidance of a university faculty advisor.

2. COMPETITION DETAILS

This section outlines the scenario, stakeholder requirements, technical reviews, deliverables, specifications, and the event environment of the SpaceBot Competition. Teams are responsible for their own manufacturing. Contact spacebot@sdl.usu.edu for more information.

2.1 2023-24 SCENARIO

> *You are a private on-orbit satellite servicing company. SDL has contracted with you to develop a robotic payload for an upcoming repair mission.*
>
> *In early 2023, an aerospace start-up firm called Satellites Incorporated launched its newest flagship satellite platform as part of the mission called Modular Earth Sensing Surveyor (MESS). This satellite is a ½ ESPA-sized satellite platform that hosts a complex, high-cost payload performing remote sensing from low Earth orbit (LEO). The spacecraft successfully launched, deployed, initialized, and began nominal operations with few problems and many cheers from the Satellites Incorporated crew.*

> *A few weeks into the spacecraft's voyage, ground operators began receiving abnormal telemetry from the satellite indicating problems. The state-of-health and payload data showed results that did not align with the expected information defined in the mission concept of operations (CONOPS). Ground operators eventually determined that a component onboard the spacecraft was damaged, either during launch or deployment, and would prove fatal for the MESS mission if not resolved.*
>
> *Satellites Incorporated put SDL on contract to repair the damaged MESS spacecraft and help it resume its mission in LEO. The SDL team determined which component on MESS was damaged and used their experience in satellite technology to develop an on-orbit servicing mission to repair the MESS spacecraft. While the SDL team's expertise enabled them to quickly design and procure a rendezvous, proximity operations, and docking (RPOD) spacecraft, they have little time to create the robotic system that will perform the on-orbit repairs.*
>
> *This time crunch led the SDL team to turn to the private sector to help them develop the robotic platform, which will serve as the payload on the MESS repair mission. SDL drafted a Request for Proposal (RFP) that includes a description of the scenario and the requirements for the robotic payload. This RFP was distributed to multiple private on-orbit repair companies, whose systems will be thoroughly evaluated via in-depth technical reviews, documentation, and a final testing campaign at SDL facilities. The company that shows the most technical maturity and creativity in their solution will be awarded a contract for a flight version of their payload.*

2.2 STAKEHOLDER REQUIREMENTS & DELIVERABLES

Stakeholder requirements and deliverables are given to company system developers (in this case, university teams) by mission authors/users (in this case, SDL). Requirements define the environment in which the system will be used and/or constraining interfaces between external systems and the developer's system.

Table 1 lists all SpaceBot Competition stakeholder requirements and deliverables. Teams must meet all stakeholder requirements and deliverables or risk point deductions in corresponding judging criteria.

TABLE 1. STAKEHOLDER REQUIREMENTS & DELIVERABLES

REQ. ID	TYPE	NAME	TEXT
D001	Deliverables	Deliverables	The team shall deliver all documents shown in the Deliverables List prior to the start of the challenge.
P001	Performance	Competition repair time	The SpaceBot spacecraft shall complete its repairs on MESS within 30 minutes (from RPOD to egress).
P002	Performance	Remote operation	The team shall operate the SpaceBot spacecraft remotely (without line-of-sight) while repairing MESS.
P003	Performance	Diagnostics	The SpaceBot spacecraft operators shall receive diagnostic telemetry from the spacecraft during operations. The diagnostics shall include position and power usage data.
PR01	Programmatic	Transportation	University teams shall be responsible for the transportation of the SpaceBot spacecraft to SDL facilities.
PR02	Programmatic	Team size	University teams shall consist of no more than 10 members.
PR03	Programmatic	Team education	University teams shall consist of at least 75% undergraduate students.
PR04	Programmatic	Team Advisor	University teams shall be aided by at least one faculty advisor at their university.
PR05	Programmatic	Maximum spending	University teams shall not expend more than $15,000 for the entire SpaceBot Competition project, including hardware, travel, test equipment, etc.
R001	Repair payload	Main mission	The SpaceBot spacecraft shall perform repairs on MESS until it is working properly.
R002	Repair payload	Vehicle damage	The SpaceBot spacecraft shall refrain from causing additional damage to MESS.
R003	Repair payload	Mass	The SpaceBot spacecraft shall have a total mass of no larger than 25 kg.
R004	Repair payload	Size/Stowing	The SpaceBot spacecraft shall have a stowed volume of no more than 15 x 30 x 15 x 30 in.
R005	Repair payload	Assembly reversibility	The team shall assemble the SpaceBot spacecraft using only reversible (non-permanent) methods.
R006	Repair payload	Emergency stop availability	The SpaceBot spacecraft controls shall include easily accessible e-stop buttons for the operator and judges to cease all spacecraft motor function.
R007	Repair payload	Mechanical interface	The SpaceBot spacecraft shall mechanically interface with the host bus in accordance with an ICD.
R008	Repair payload	Electrical interface	The SpaceBot spacecraft shall electrically interface with the host bus in accordance with an ICD.
R009	Repair payload	Flying parts	The SpaceBot spacecraft and all its appendages shall be mechanically secured to the host bus throughout the mission lifetime.
R010	Repair payload	Power type	The SpaceBot spacecraft shall support conventional 120 V wall power during operation.

2.3 TECHNICAL REVIEW REQUIREMENTS

A technical review is an in-depth presentation and assessment of a system's technical development. Reviews occur periodically throughout a system development lifecycle and correlate with progress made.

SpaceBot Competition teams are required to complete two technical reviews prior to the live demo day:

1. Preliminary Design Review
2. Critical Design Review

Technical review presentations should facilitate discussions between the team and their reviewers, offering teams the chance to receive feedback or ask questions about their development progress or any issues.

Teams must convey progress through programmatic and system documentation materials and prepare a presentation, which will provide a high-level summary of the information contained in the correlating documentation. Team faculty advisors may not present with the team but should attend the review for support. Teams should deliver a copy of their review presentation to each reviewer by 11:59 p.m. (MT) on the day preceding the review.

2.3.1 About Reviews

Team technical reviewers should provide feedback on all deliverables during or following each technical review presentation. There is no limit to the number of reviewers, nor a requirement concerning their qualifications, but teams should select reviewers who will help them perform at their best at the live demo day. Reviewers may be faculty advisors, peers, professors, subject matter experts, or anyone who can provide useful feedback on a team's progress. The individuals in each team's technical review panel may differ for each review.

2.3.2 PRELIMINARY DESIGN REVIEW (PDR) BASICS

A successful PDR establishes the basis for proceeding with the detailed design. At this point in the development process, each SpaceBot spacecraft should have high-level details solidified. A general plan to complete outstanding design tasks has been created and some documentation has begun. The purpose of the PDR is to convince your reviewers that your preliminary SpaceBot spacecraft design will have a high probability of meeting competition technical requirements, and that it can be constructed and demonstrated safely.

Present your PDR to selected reviewers (see reviewer requirements in Section 2.3.1). Send your review package and completed review forms to spacebot@sdl.usu.edu by the specified date. If the files are too large to email, they may be submitted separately. All late submissions shall incur an overall penalty.

2.3.3 Critical Design Review (CDR) Basics

A successful CDR establishes the basis for proceeding with the construction and verification phase of the project. The purpose of a CDR is to prove to reviewers that the final design meets the mission objectives and requirements, and that it has been constructed safely and will be demonstrated safely. All drawings need to be completed for the CDR, or a plan should be in place to complete them. Analyses and critical testing should be complete before your CDR. The CDR presentation should be independent of the PDR presentation; it may have the same basic content and structure but should contain final design information, which may or may not have changed since the PDR.

Present your CDR to selected reviewers (see reviewer requirements in Section 2.3.1). Send your review package and completed review forms to spacebot@sdl.usu.edu by the determined date. If the files are too large to email, they may be submitted separately. All late submissions shall incur an overall penalty.

2.4 DELIVERABLES

Each team is required to submit deliverable packages periodically throughout the design process for their PDR, CDR, and Live Demo Day project milestones. Milestone deliverable packages consist of a specified list of documentation, slide decks, spreadsheets, and posters that convey to the stakeholder how, or how well, the robotic system works.

Each deliverable has varying levels of complexity and describes and keeps record of programmatic information or technical capabilities. Some deliverables, like the CONOPS document, may be started for the PDR and then revisited and refined as the SpaceBot spacecraft's system design matures. Other deliverables, such as the payload Interface Control Document (ICD), are better defined only when the system design is mature. Table 2 lists the documents due for each milestone.

TABLE 2. DELIVERABLES

	PACKAGED FOR		
DOCUMENT	**PDR**	**CDR**	**DEMO DAY**
Project Schedule	X	X	X
Project Budget	X	X	X
Concept of Operations (CONOPS)	X	X	X
Requirement Verification Matrix (RVM)	X	X	X
System Block Diagram	X	X	X
Safety Assessment	X	X	X
Mass Budget	-	X	X
Testing Campaign	-	X	X
Interface Control Document (ICD)	-	X	X
Drawings	-	X	X
Assembly Procedure	-	-	X

2.4.1 Project Schedule

Project schedules convey task decomposition and timelines to team members and the stakeholder (SDL). Schedules depict a sequential view of each task of the overarching project from start to finish. Tasks are typically decomposed from high-level tasks (like "Build a SpaceBot spacecraft") down to low-level tasks (like "Design mounting bracket for camera") with established start and end dates and task durations. Project schedules are not always perfect, all-encompassing, or concrete; they tend to change over time as a project matures.

Each team's SpaceBot Competition project schedule should be in Gantt chart format, with bars that stretch from month to month indicating task length and a detailed list of project tasking. SDL advises teams to use Microsoft Project as a Gantt chart tool, or

Excel or Google Sheets if Microsoft Project is not available. Teams should select a team member to establish and regularly maintain their schedule.

2.4.2 Project Budget

Project budgets predict and record how teams plan to spend and how they actually spend their money. Project teams initially establish budgets using research and well-educated estimates, but budgets mature over time as the system design solidifies.

Each team's SpaceBot Competition project budget must contain the following information:

- Source of all awarded funding (your university, other sources, etc.)
- Allocation of funding within the project (how much will be spent on hardware, travel, test equipment, etc.)
- Up-to-date spending amounts

Final budgets must indicate the exact amount expended for the entire SpaceBot Competition project. Budgets will verify that teams met the maximum spending requirement.

2.4.3 Concept of Operations (CONOPS)

A mission CONOPS facilitates a common understanding of the characteristics of a system. A CONOPS document describes the system concept and how that concept will operate in its intended environment. CONOPS communicate the system vision to the stakeholder.

SpaceBot Competition teams are responsible for thinking through exactly how the mission will be executed and how the team will interact with the payload during the mission. This exercise will help establish a CONOPS. The outline of the mission CONOPS should include major, high-level stages of each team's mission, including details on which specific component will be replaced. SpaceBot Competition teams should use verbiage and organization similar to that used in full satellite CONOPS documentations. Typical CONOPS stages include the following:

- Initialization (deploy from launch vehicle and turn on)
- Calibration (make contact with the ground and ensure the payload is ready)
- Conduct mission (let the payload perform)
- Transition to end-of-life (turn the satellite off and let it float away)

Additional information that could help teams define their SpaceBot spacecraft's CONOPS are available at https://universitynanosat.org/resources/nanosatellite-program-expert-area-telecons.

Teams can assume SDL has taken care of all RPOD tasks, so the host satellite will already be docked with the malfunctioning satellite. Each team's SpaceBot spacecraft CONOPS should begin with the payload stowed and powered off within the host satellite, detailing everything else that needs to occur to repair the malfunctioning spacecraft after that point.

CONOPS documents should also list the different phases of the mission and detail key objectives of each phase. Phase descriptions should answer questions such as:

- "What will the robot operators be doing during this time?"
- "What will the configuration of the robot be during each phase?"
- "What is the entrance/exit criteria for entering/exiting each phase of the CONOPS?"

Teams are required to use a high-level diagram to aid in conveying their mission CONOPS description. Diagrams provide a concise, visual method for decomposing the mission. High-level "OV-1"-type diagrams are particularly useful for seeing how different mission segments interact with each other, while context diagrams help establish the inputs, outputs, and constraints that a system may experience.

2.4.4 Requirement Verification Matrix (RVM)

System designers use RVMs to clearly show each requirement and which methods will be used to verify those requirements over the duration of the project. RVMs depict requirements made at the beginning of the mission and how they apply to the physical product that is created (also known as traceability). Once a product is designed and fabricated, it is sent through a meticulous testing campaign to verify that it meets all the defined requirements.

RVMs are typically stored in a spreadsheet format with each requirement in its own row. Each team's SpaceBot Competition RVM should capture all requirements levied on the system, either by the stakeholder or the system designers. The column headers of the spreadsheet should include the following:

- Requirement ID
- Name
- Text
- Author
- Verification method
- Verification artifact
- Verification status

See Table 3 or NASA Systems Engineering Handbook Appendix D for a RVM example.

TABLE 3. RVM FORMAT EXAMPLE

ID	NAME	TEXT	AUTHOR	VERIFICATION METHOD	VERIFICATION ARTIFACT	VERIFICATION STATUS
SB-01	Requirement 1	The SpaceBot shall…	SDL	Test	SpaceBot Spacecraft Full System Test	Open
SB-02	Requirement 2	The vision system shall…	SDL	Test	Vision Full System Test	Open
SB-03	Requirement 3	The camera shall…	SDL	Inspection	Vision Full System Test	Verified

2.4.5 System Block Diagram

Block diagrams graphically represent a system and its internals in a series of blocks. The purpose of system block diagrams is to capture the decomposition of the system into its subsystems, as well as the interfaces between those subsystems via lines and arrows.

SpaceBot Competition teams are required to provide block diagrams for both the system and each of the identified subsystems. Diagrams should convey the structure of the system to the stakeholder and other external parties, making it easy for them to understand how the system is internally organized. At a minimum, block diagrams must show interface connections such as power and data throughput. Blocks within the diagrams should correspond to components that physically comprise each team's SpaceBot spacecraft.

2.4.6 Safety Assessment

Safety assessments document all hazards that may be present when assembling, handling, or operating a system.

SpaceBot Competition teams are required to provide a thorough safety assessment to ensure that all potential hazards are identified and addressed. Inherently, the SpaceBot Competition requires that teams interact with hardware that could potentially cause harm if not properly handled, such as robotic collisions or contact with active electrical connections.

Team safety assessments must identify the hazards associated with each SpaceBot spacecraft system and list strategies for how those hazards will be mitigated. Mitigation strategies can take the form of guarding/cages around the robot system, e-stop buttons, protective gear, software, etc.

2.4.7 Mass Budget

A mass budget tracks the as-designed mass of the system and compares it to the mass allowed by the stakeholder. Mass budgets are organized by subsystem, showing mass values at the system, subsystem, and component levels.

SpaceBot Competition teams are required to submit a mass budget document. This document will help teams monitor their SpaceBot spacecraft's mass over time to be compliant with the levied mass requirement. Each team's SpaceBot spacecraft mass will be verified via weigh-ins on Live Demo Day.

2.4.8 Testing Campaign

Testing is a vital part of system design, preparing both the system and the team for operation in a live environment. All space systems must undergo testing to verify requirements and overall functionality. System testing proves that the system will perform as designed and helps identify potential points of failure in a controlled environment. Failures during testing often warrant revisiting prior design decisions, refactoring requirements, or even modifying/descoping the original mission details.

Testing is also used to verify requirements defined at the beginning of the product's lifecycle. Systems may be designed to meet a requirement, but the requirement may not be fully verified until that function of the system has been tested. Therefore, each system's testing campaign should be well planned and meticulous to ensure that all system functions are properly verified. A common phrase used in this part of system development is "Test as you fly," meaning that all tests should be accurate and representative of how the system will operate. Test planning should begin early (if not done alongside the requirements) to capture every function that the system will exhibit.

Testing often occurs at various levels, such as component/unit testing, subsystem testing, and full system testing. These correspond with the right side of the Systems Development V-Model, ensuring each level of the system functions as tested and is verified before moving to a higher level. Each test should have a specified overarching goal that is well understood by all parties performing the test. For example, the goal of the Camera Acceptance Test may be to ensure that the purchased camera functions exactly as the vendor advertised; the objective of the Full Functional Test may be to ensure that all subsystems function nominally following a full assembly. Objectives must be established for all tests before any testing commences.

SpaceBot Competition teams must submit a detailed plan for each test they will perform on their SpaceBot spacecraft. This plan should detail the following:

- All scheduled tests
- The objective for each test
- The components that will be tested
- The pass/fail criteria for each test

In addition to the plan, each team must submit procedures for each test that provide step-by-step instructions on how to complete said test. Test procedures should be clear and unambiguous, leaving no room for misinterpretation while the test is being conducted. Expected outcomes should be listed for the overall test and for each step of the test itself. Test procedures should list the requirements that the test satisfies, while tests should also be referenced from the RVM as verification artifacts.

2.4.9 Payload Interface Control Document (ICD)

Interface Control Documents (ICDs) define the interfaces between the system and all external elements that interact with the system. The system is documented as a black box, defining external features only. ICDs typically control mechanical (physical interactions), electrical (electrical/power interactions), and software (data and messaging interactions) interfaces between the stakeholder's system and the contractor's system. Stakeholders need ICDs to understand how to interact with the system, versus understanding how the entire system works. Stakeholders use ICDs to design other systems to meet the interfaces described in the designer's ICD or verify that the designer is meeting their interface designs.

SpaceBot Competition teams need to produce a payload ICD to document how each SpaceBot spacecraft will interact with the host satellite mechanically, electrically, and digitally. Teams should include a mechanical drawing of the payload system to verify that the dimensions of the payload's mounting pattern match that of the host satellite.

Teams should also document external electrical and software connections as if the payload were to be connected to a spacecraft. The electrical connection should specify the following:

- Connector locations
- Pinouts
- Signal names/values

Software details should convey:

- The type of data protocol used
- Package structure
- Anything else needed to communicate with the payload

2.4.10 Assembly Procedure

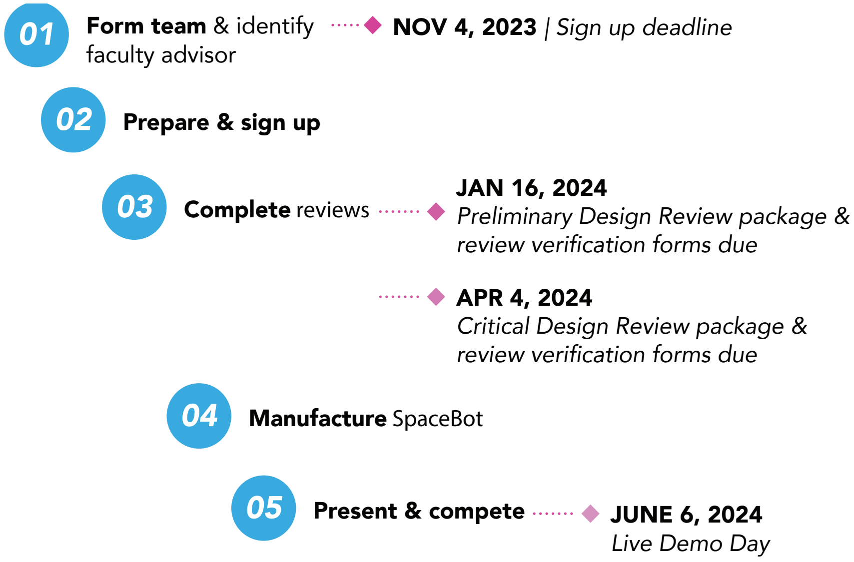
Assembly procedures are detailed, step-by-step instructions on how to assembly system hardware. The purpose of assembly procedures is to clearly specify all tools, parts, and personnel needed to completely assemble a system. Assembly procedures contain images, diagrams, and clear language to avoid ambiguity.

SpaceBot Competition teams are required to submit a full system assembly procedure in their Live Demo Day deliverable package. The purpose of this requirement is to ensure that each team member present for the live demonstration has clear instructions for how to assemble the SpaceBot spacecraft.

2.5 COMPETITION TIMELINE

Figure 1 depicts the timeline of events for the entire competition. SDL reserves the right to make changes to the timeline but will communicate any changes to team leads as soon as possible. Document packages or review materials will be due by 8:00 AM (MT) on the specified dates.

Figure 1. Competition Timeline



2.6 LIVE DEMO DAY EXPECTATIONS

SpaceBot Competition teams can select up to five team members to travel to SDL's headquarters in North Logan, Utah, to present a poster, give a 15- to 20-minute presentation, and demonstrate the capability of their SpaceBot spacecraft to a panel of judges.

Each team must submit the Live Demo Day Attendance Form by the date specified.

Each team will:

- Receive a 10′ x 10′ staging area with a 6′ table where they can unpack their hardware
- Weigh their SpaceBot spacecraft on site
- Select two team members to participate in the poster session while the rest of the team members unpack
- Bring a 24″ x 36″ poster describing the team's SpaceBot Competition project and prepare to speak informally about it during the one-hour poster session
- Develop a presentation, no longer than 20 minutes, for SDL judges (and the other competitors). Presentation content should be appropriate to a Flight Readiness Review, as described below:
  - Present and defend the as-built SpaceBot spacecraft
  - Share results of tests, demonstrations, inspections, and analyses to prove the system meets all requirements and mission objectives
  - Show how personnel and all final hardware, software, and procedures are operationally ready and/or can be safely launched and deployed (or that teams are aware of what changes would be needed for a flight version)
  - Share risk assessment and mitigation strategies
  - Provide requirements verification
  - Include cost estimate, timeline, project schedule

2.6.1 Agenda

Table 3 lists the preliminary agenda for the live demo day.

TABLE 4. PRELIMINARY LIVE DEMO DAY AGENDA

TIME (MT)	EVENT
800	Competition starts
0800 - 0900	· Teams check in · Teams unpack and weigh SpaceBot spacecraft · Poster Session
0900 - 1030	Team presentations
1030 - 1045	Break
1045 - 1215	Demo Session 1 (2 Teams)
1215 - 1315	Lunch (provided)
1315 - 1445	Demo Session 2 (2 Teams)
1445 - 1630	Tour of SDL facilities; Judges confer
1630 - 1700	Awards ceremony
1700	Competition concludes

2.6.2 Judging Criteria

Table 4 lists the criteria that judges will use to score each team and their SpaceBot spacecraft.

TABLE 5. JUDGING CRITERIA

CRITERIA	SCORE
OBJECTIVE COMPLETE • Was the malfunction correctly diagnosed? • Was the malfunctioning spacecraft repaired?	**(150 PTS)**
REQUIREMENTS • Were all requirements met? • Which requirements were violated?	**(200 PTS)**
EXPERIMENTAL APPROACH • Is the approach creative? • Is the approach technically relevant? • Is the approach of high quality? • What is the quality of the physical build?	**(300 PTS)**
DELIVERABLES • Were all deliverables submitted on time and according to milestone requirements? • What is the quality of each deliverable?	**(200 PTS)**
PROFESSIONALISM • How is the overall team image? • Did the team present professionally and with skill? • Did the team respond to correspondence in a timely and professional manner? • Did the team show good sportsmanship?	**(150 PTS)**
TOTAL SPACEBOT COMPETITION SCORE	

3. INTRODUCTION TO SATELLITES

This section introduces the concept of satellite systems at a high level. Understanding core space system functionality will be vital for identifying the malfunction onboard the MESS satellite and for creating the repair plan in the CONOPS. The section will discuss how satellites are used in orbit and describe common subsystems.

3.1 SATELLITE PURPOSE

With the evolution of computers and space technologies in recent decades, satellites have become a necessity for the full operation of Government and commercial organizations. According to the United Nations Office for Outer Space Affairs, there are currently 8,621 satellites orbiting Earth, all serving important global functions. Satellites enable functions in space that would be inefficient or impossible from the ground, including the following:

1) Communication
2) Meteorology/Earth observation
3) Navigation
4) Astronomical studies

From providing GPS to fundamental communication systems on Earth, satellites are necessary and will continue to be a focal point of manufacturing in the space exploration economy.

3.2 SATELLITE ORBITS

Satellite missions vary widely, with each having unique requirements. Some space missions need access only to the very edge of Earth's atmosphere, while others need to reach some of Earth's farthest orbits. Orbits also influence spacecraft design in how much protection the electronics need from the harsh environment of space. There are three Earth orbits that are commonly used by satellite missions: low Earth orbit, medium Earth orbit, and geosynchronous orbit.

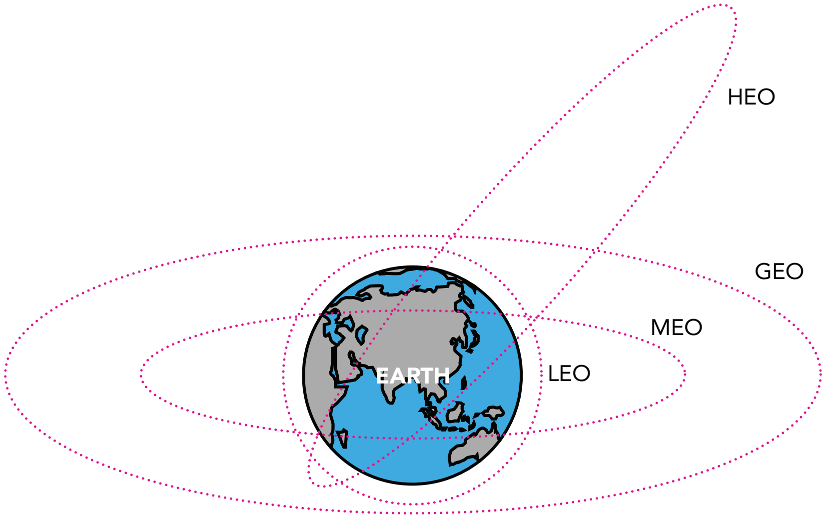


Figure 2. Earth Orbits (not to scale)

Most satellites orbit close to Earth within the thermosphere, also known as low Earth orbit (LEO), anywhere between 160 and 1,500 kilometers above Earth's surface. LEO satellites are ideal for taking images of Earth and performing scientific research such as sensing radiation and atmospheric phenomenon. Sun-synchronous orbit (SSO) satellites also provide these services but travel from the north to south pole of Earth between 600–800 kilometers above Earth.

Medium Earth orbit (MEO) satellites operate at a higher elevation, between 5,000 to 20,000 kilometers. Satellites at this orbit provide GPS navigation and data communication.

Geostationary orbit (GEO) satellites are the farthest from Earth's equatorial surface, at approximately 36,000 kilometers.

GEO satellites have an orbital period consistent with Earth's rotation, making them ideal for communication services like cell phones, as well as meteorology.

3.3 MISSION PHASES

Satellite missions are segmented into distinct phases, each with its own predefined sets of rules, plans, and activities for the satellite. Mission CONOPS are usually organized by mission phase, clearly defining what the spacecraft will do in each phase. This section will introduce some generalized mission phases and describe what occurs in each of them.

3.3.1 Launch & Early Operations (LEOPS)

The LEOPS phase occurs as soon as the satellite's launch vehicle leaves planet Earth. The satellite endures a jarring, high-G ride into orbit as the rocket moves the satellite out to microgravity. This phase of the mission also includes the satellite's deployment from the launch vehicle into its initial orbit. This is when the spacecraft is powered on (initialized) and begins communicating with the ground. The spacecraft downlinks state-of-health data, informing the spacecraft operators that all subsystems are alive and functional. GPS receivers on the spacecraft establish lock, enabling the spacecraft to communicate its actual position to the ground.

3.3.2 Calibration Operations (COPS)

The COPS phase is the commissioning portion of the mission when corrections needed for the payload to function nominally take place. An example for an optical payload may be correcting for mechanical misalignments by comparing against observed and known object alignments in space. A fully calibrated optical payload will enable the mission to collect more accurate data and make the mission more successful overall.

3.3.3 Nominal Operations (NOMOPS)

The NOMOPS phase is the performance of the satellite's mission. This phase can last years, depending on the expected life of the satellite and its mission time. This phase usually includes data collection through the payload and operating in accordance with the CONOPS.

3.3.4 End-of-Life (EOL)

The EOL phase is the conclusion of the mission. This phase considers how the satellite will be discarded once it completes its mission. Once in EOL, satellites in GEO are maneuvered to a "graveyard orbit," so the satellites do not become additional debris in the GEO belt. Satellites in lower orbits, like LEO, will eventually (depending on orbit altitude) fall back into Earth's atmosphere and disintegrate on reentry. When the satellite is in its final orbit (either for reentry to Earth or in a graveyard orbit), it will power down all subsystems and remain there.

3.4 COMMON SATELLITES SUBSYSTEMS

The decomposition of a satellite includes lower-level subsystems. All subsystems must coordinate with each other to have a functioning spacecraft. Subsystems have specific functions within the overall satellite system, making each vital for mission success. Any component failure could significantly hinder a satellite's operations or lead to complete mission failure.

This section introduces common subsystems featured in modern spacecraft and each subsystem's functionality and core components.

3.4.1 Electrical Power Subsystem (EPS)

The role of the EPS is to fulfill the power needs of the rest of the system, enabling it to operate efficiently and effectively. An EPS must generate and store enough power to support the onboard components. Solar panels generate power, which is stored in the battery. Power is then distributed to the rest of the system through either wire harnessing or printed circuit board passthroughs.

Electrical components draw power at differing rates (some significantly more than others). Bigger satellites typically draw more power than smaller ones, thus driving a need for more solar cells and bigger battery banks. Power budgets are used to monitor both the orbit average power (OAP) and the maximum/peak power draw of each component during each mode and CONOPS phase.

3.4.2 Tracking, Telemetry & Control Subsystem

The purpose of the TT&C subsystem is to provide communication between Earth and the satellite. The TT&C subsystem enables operators to communicate with the satellite and send commands to and receive data from the spacecraft. When received, data is often categorized into two sets:

1) Telemetry data
2) Payload data

Telemetry data contains system diagnostics that inform the operators of the spacecraft's current state (subsystem health, spacecraft position and attitude, faults, errors, etc.). Payload data is any science data generated by the payload, and it is heavily mission dependent. For example, optical payloads may downlink images or videos.

The TT&C subsystem solves the following problems:

- "How will we communicate with the satellite?"
- "How will we receive information from the satellite?"

The TT&C subsystem typically comprises two component types:

- Antennas
- Transponders (or radios)

Antennas send and receive raw radio frequency (RF) signals from the satellite and the ground, respectively. Antennas operate in a set frequency range/band, such as S-band, X-band, or UHF, which affects how quickly it can send/receive data. Transponders convert RF signals into digital data that onboard computers (OBCs) can process, and vice versa.

3.4.3 Command & Data Handling (C&DH) Subsystem

The C&DH subsystem of a satellite controls all spacecraft functions and is referred to as the satellite's "brains." The C&DH subsystem performs the following:

- Manages data
- Executes commands
- Processes information
- Performs predefined functions through onboard flight software

The C&DH subsystem solves the following problems:

- "How will the subsystems be controlled?"
- "How will the subsystems be monitored?"
- "How will the commands be processed?"
- "How will data be stored?"
- "How will the satellite 'make decisions'?"

C&DH subsystems often take the physical form of OBCs on satellites. These computers store all the flight software and single points through which information from all subsystems flow. Commands sent from the ground are received by the TT&C antenna, converted to a digital form (demodulated) by the TT&C transceiver, and sent to the OBC. The OBC then uses its preloaded command log to execute instructions issued from the ground. Based on the command, the OBC will then command each subsystem to comply with the ground's request.

3.4.4 Attitude Determination & Control Subsystem (ADCS)

The ADCS has two major roles in a satellite system:

1) Determine the attitude or orientation of the satellite

2) Control the attitude of the satellite

Spacecraft attitude knowledge and correction is vital for the success of any mission. Attitude control is needed for a spacecraft to perform the following:

- Generate power
- Uplink and downlink
- Manage thermals
- Maneuver
- Perform the overall mission

The ADCS uses a series of actuators, mechanisms, and sensors to determine what the satellite's attitude is and help it point to where it needs to go. The ADCS solves the following problems:

- "How will we know which way the satellite is pointing?"
- "How will we make the satellite point in the desired direction?"
- "How accurate does the pointing need to be?"

While an ADCS can consist of many different types of components, the subsystem can be decomposed into three categories:

- Sensors
- Actuators
- Controller

Sensors such as star trackers, Sun sensors, Earth sensors, and magnetometers take data to determine the satellite's attitude. Actuators control the roll, pitch, and yaw of the spacecraft using reaction wheels and torque rods. The controller is a device dedicated to controlling all ADCS hardware; it affects attitude changes based on sensor input and communication with the OBC.

3.4.5 Propulsion (PROP) Subsystem

To remain in a specific orbit, a spacecraft needs some form of PROP to resist Earth's gravitational pull. Propulsion is also important if the satellite needs to move at all, whether in attitude adjustment or rotation. There are different types of satellite propulsion, such as electrical propulsion and chemical thrusters. The PROP subsystem solves the following problems:

- "What is the plan to correct the satellite's orbit should it go off route?"
- "How does the selected propulsion type affect the payload weight?"
- "How will the satellite be kept from deorbiting?"
- "What kinds of maneuvers will the spacecraft need to perform throughout its mission (if any)?"

To have an effective PROP subsystem, payload and specific impulse should be considered in the design. The velocity provided by the PROP subsystem will need to push the spacecraft from Earth's gravity as well as maintain orientation changes once the satellite is in orbit. Most PROP subsystems use chemical propulsion, which produces chemical reactions to create the energy needed to operate efficiently.

3.4.6 Structure (STR) Subsystem

A satellite's STR subsystem is the physical backbone of its system. The STR is the frame comprising the satellite body and surrounding the electrical components. Its primary purpose is to protect the bus avionics and payload from two harsh environments:

- Launch
- Space

A rocket launch is vigorous for everything onboard, so the satellite STR must keep all components in place to prevent the satellite from either damaging itself or other objects in its vicinity. The space environment experiences not only extreme temperatures, but also high amounts of radiation. The STR helps regulate the temperature of all onboard components through conduction and acts as the first layer of protection against radiation in space.

3.5 MISSION EXAMPLE: OSIRIS-REX

In September 2016, NASA's Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) spacecraft launched to collect a sample from the carbonaceous asteroid Bennu. After sample collection, OSIRIS-REx returned to Earth to deliver the sample capsule. From there, OSIRIS-REx took on a new mission to study asteroid Apophis.

The OSIRIS-REx mission was a team collaboration between NASA's Goddard Space Flight Center, the University of Arizona's Lunar and Planetary Laboratory, SDL, and Lockheed Martin. Lockheed Martin built the spacecraft structure and provided mission operations. SDL built the detector assemblies used for the three cameras on the spacecraft. The Lunar and Planetary Laboratory provided principal science operations, and NASA oversaw spacecraft engineering, navigation, and management.

3.5.1 LEOPS

The satellite was carried on the Atlas V launch vehicle from United Launch Alliance. As planned, the OSIRIS-REx satellite detached from Atlas V 55 minutes after engine ignition. The RD-180a engine was a liquid fuel engine with a dual combustion chamber to provide ample thrust to carry the satellite into its necessary orbit through the first stage of launch. A second fuel booster, Centaur, provided thrust during the second stage.

3.5.2 COPS

The COPS phase for OSIRIS-REx began shortly after it separated from the launch vehicle. The solar panels deployed, its own propulsion system was initiated, and the communication link was established between the spacecraft and ground control.

Approximately three months later, OSIRIS-REx used both its ADCS and TT&C subsystems to begin traveling into deep space. Its propulsion subsystem was also used to alter the velocity of the spacecraft. OSIRIS-REx continued traveling toward the asteroid Bennu using these subsystems. There was an unofficial transition into the NOMOPS phase. While traveling to Bennu, OSIRIS-REx was searching for and capturing images of any near-Earth objects. The spacecraft took approximately 135 survey images every day on its journey to Bennu.

3.5.3 NOMOPS

For OSIRIS-REx's mission, the NOMOPS phase was defined by its arrival to Bennu. OSIRIS-REx arrived within Bennu's orbit in December 2018, approximately two years after its initial launch. OSIRIS-REx orbited Bennu to obtain data on its shape, orbit speed, and surface.

All subsystems had to be exercised for the spacecraft to land carefully on Bennu's surface. Mission scheduling was adjusted in reference to when OSIRIS-REx would take a sample. The first sampling phase took place two months past its originally scheduled date. The mission successfully completed collection rehearsals. In October 2020, OSIRIS-REx performed its main operation of taking a real sample. However, rocks from the asteroid became wedged in the mylar flap intended to enclose the sample. The opening of the flap caused the sample to escape. To prevent more of the sample from escaping, various mechanical maneuvers in the ADCS subsystem were halted. The sample from Bennu was officially stowed away a month earlier than planned.

Various TT&C mechanical maneuvers were needed to secure the sample capsule properly and to confirm the parts of the capsule were performing as expected in the pursuit of securing the capsule's capture ring. About six months after the sample collection, OSIRIS-REx prepared to return to Earth. In May 2021, OSIRIS-REx officially left Bennu's orbit.

3.5.4 EOL

OSIRIS-REx entered Earth's orbit and expelled the sample capsule into Earth's atmosphere. Upon the capsule's landing, the sample was analyzed at NASA's Astromaterials Research and Exploration Science Directorate.

Rather than retiring on Earth, OSIRIS-REx was rebranded as OSIRIS-APophis Explorer, or OSIRIS-APEX, and will rendezvous around the Sun. Another asteroid, Apophis, will come close to Earth on April 13, 2029. OSIRIS-APEX will begin orbiting Apophis on April 21, 2029, and will perform a study of the asteroid.

4. ADDITIONAL RESOURCES

Use the following reference links when developing your SpaceBot spacecraft or writing the required deliverables.

- University Nanosatellite Program (UNP)
    - Additional documents, lectures, and resources on space systems engineering from Air Force Research Lab's 20+ year outreach program
- NASA Systems Engineering Handbook
    - NASA's guide to systems engineering
    - SE Book of Knowledge (SEBoK)
    - Wiki-based database on systems engineering concepts and topics

5. CONTACT

Please send competition questions, technical inquiries, or feedback to spacebot@sdl.usu.edu.

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