FAA Center of Excellence for Commercial Space Transportation Research

Task 244: Autonomous Rendezvous & Docking

Framework for autonomous rendezvous and docking in low Earth orbit

Background Summary Report

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June 17, 2013

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1 Introduction

The purpose of this study is to provide the Federal Aviation Administration (FAA) with information to support the development of a common process, architecture, and requirements for performing Autonomous Rendezvous & Docking (ARD) missions for spacecraft in Low Earth Orbit (LEO).

With space missions becoming more popular for commercial applications, such as communication, television, and radio, the number of active satellites in orbit is growing. When these satellites fail unexpectedly, they remain in their orbits as obstacles that other satellites must avoid. Thus there is considerable interest in ARD missions that could repair or deorbit failed satellites. ARD missions are also under consideration to extend satellite life by refueling or replacing parts nearing the end of life.

ARD missions cannot be made commonplace using current technology and methods. Today most rendezvous and docking missions are used to resupply the International Space Station (ISS), so there is a significant manual aspect of the mission, with a crew required to assist with the docking. Each mission is individually tailored so there are high non-recurring costs associated with ARD missions. Furthermore, the outdated technology on most current missions limits the potential for increased automation or autonomy. Commercial ISS resupply spacecraft are entering the market that use newer sensor and robotic technology, but the spacecraft are being built specifically for the ISS, so it is expected that a crew will be available to assist with the ARD mission. This study intends to address the issues with current ARD missions and propose methods to resolve these issues.

This report provides a summary of past, present, and future ARD missions in order to outline proven methods and technologies, as well as problems that have been encountered. The ARD mission is defined, which includes a definition of the target configurations and the ARD mission phases.

2 Existing Rendezvous & Docking Missions

2.1 Past Rendezvous & Docking Missions

Rendezvous and docking space missions date back to the 1960s, when the Gemini program tested rendezvous and docking in preparation for the lunar landing. These early missions were highly manual. Although there was autonomy involved in detecting and maneuvering towards the target, a crew was required onboard the vehicle to complete the docking. While American rendezvous and docking missions remained manual until the early 2000’s, the Russians accomplished the first fully autonomous rendezvous and docking in 1967 [5]. This section provides an overview of the missions that introduced rendezvous and docking to the space community.

2.1.1 Gemini

NASA ran the Gemini program from 1962 to 1966, and it served as a method for testing technology that would be used to accomplish a crewed lunar landing. Since the intent was to have a crew available to assist with the docking procedure, an automated process was not considered. The first rendezvous, where two spacecraft achieved docking range, occurred in 1965 between Gemini VI and Gemini VII. The following year, in March of 1966, the Gemini VII docked with an Agena Target Vehicle (ATV), which was launched to serve as the target. The Gemini VII used radar to detect the ATV from within 450 kilometers, and the results were provided to an onboard computer for maneuvering and displayed to the crew [5]. When the ATV was in sight, the crew performed manual maneuvers to achieve the docking. The ATV had both lights and markings to assist with the docking process. The ATV also amplified the radar to ease detection by Gemini, and the ground could command the ATV to maneuver the vehicle into an easily docked position. Not only were early American missions designed to work with a crew, they were designed to work with highly cooperative target vehicles.

The Gemini VII successfully docked with the ATV, but a stuck Gemini thruster resulted in an uncontrolled spin of the combined spacecraft. The Gemini crew was able to successfully mitigate the problem, and the crew undocked and returned to Earth safely. This situation reinforced the belief that a crew was needed to complete a rendezvous and docking mission. The Gemini program ended in 1966, when it was no longer needed as an Apollo “test bed”.

2.1.2 Apollo

NASA ran the Apollo program from 1961 to 1972, and this was the program that inspired rendezvous and docking. The program goal was to achieve a crewed lunar landing, and the Lunar Orbit Rendezvous (LOR) method was selected to achieve the mission. The rendezvous and docking was needed to return the crew to Earth. The Command Service Module (CSM) orbited the moon while the Lunar Excursion Module (LEM) visited the surface. The LEM returned to the lunar orbit and docked with the CSM [5]. The equipment and process was similar to that of the Gemini mission.

2.1.3 Soyuz/Kosmos

The Russians took a different approach to rendezvous and docking. They decided to pursue an unmanned docking mission due to a fatal accident with an early manned mission. This unmanned rendezvous and docking would require some level of automation and autonomy. The Soyuz program achieved the first ARD mission. For the Soyuz ARD mission, the chaser was launched first, and then the target was inserted into the orbit the following day. Both the target and chaser had five antennas as part of the Igla rendezvous navigation system [5]. The target was inserted into the orbit within the acquisition range of the chaser. The target and the chaser used their antennas to communicate position information that allowed the vehicles to autonomously position themselves for docking. The successful docking of the Kosmos 186 and 188 was the predecessor to the current vehicle, Progress, which is still used for ISS resupply missions.

2.1.4 Space Shuttle

NASA ran the Space Shuttle program from 1981 to 2011. The Space Shuttle had multiple objectives that required rendezvous and docking capabilities. The Space Shuttle performed “satellite servicing missions, deployment and retrieval of scientific payloads, missions retrieving and returning satellites back to Earth, flights to the Russian space station Mir, and the assembly, crew exchange, and resupply missions to the International Space Station (ISS)” [5]. The Space Shuttle added improved technology in the form of laser ranging and an optical camera, but a crew was still required to perform the docking. Due to the extensive list of missions served by the Space Shuttle, the docking mechanism and trajectories were flexible and adaptable to the different targets the shuttle would acquire. The process for Space Shuttle rendezvous and docking was similar to that of the Gemini and Apollo programs, where the vehicle would maneuver within docking range, and then the crew would handle the docking process. Space Shuttle missions were used to test new rendezvous and docking technologies, from robotic arms to sensors. A significant mission was STS-134, which demonstrated the capabilities of the STORRM system, which is the Ball Aerospace “next generation docking camera and navigation system” [16]. The Space Shuttle program was terminated in 2011. Since then, commercial companies have been focusing their efforts on developing unmanned missions to resupply the ISS.

2.1.5 Demonstration of Autonomous Rendezvous Technology (DART)

The DART program was a NASA ARD demonstration program that was active from 2001 to 2005. The NASA demonstration was intended to rendezvous with the Multiple Paths Beyond-Line-of-Sight Communications (MUBLCOM) satellite. The DART mission was designed to be entirely autonomous with preplanned maneuver sequences and a bevy of onboard equipment for attitude determination and control, target acquisition and relative position measurements. The DART vehicle used the Advanced Video Guidance Sensor (AVGS), which was compatible with the retro-reflectors onboard the MUBLCOM satellite [5]. Both the DART and MUBLCOM vehicles had GPS receivers, which were used to aid the relative position and navigation calculations. The mission used a phasing approach and two-way communications so the chaser and target could share position information. The DART vehicle was successfully launched into its initial orbit. Navigation system anomalies identified during the initial phases were a precursor to the mission fatal anomaly that occurred during proximity operations. The DART vehicle depleted its fuel supply during the proximity maneuvers and collided with the MUBLCOM satellite before achieving its escape trajectory. Post mission analysis determined that the anomaly resulted from a software error, where the GPS receiver bias was not included in the position and velocity calculations. The DART vehicle was not designed to accept commands from the ground, so mission operators could not intervene even after they realized the mission was in trouble. [6]

2.1.6 Experimental Satellite System-11 (XSS-11)

The XSS-11 program was an Air Force ARD demonstration program that was active in 2005. The Air Force was attempting to develop the capability to launch a micro satellite into orbit that could capture multiple inactive targets for return to Earth/disposal. The XSS-11 was intended for autonomous operations, so it included technology not used on previous American rendezvous missions. The vehicle incorporated LIDAR to assist with target detection and relative position calculations. The rendezvous operations used a phasing approach, where the chaser started from an initial orbit below the target, and then a series of velocity change maneuvers placed the chaser within target detection range. The XSS-11 was launched in April 2005 to test its ability to rendezvous with the fourth stage of the launch vehicle, and before being retired, the vehicle completed over 20 successful rendezvous activities [5].

2.1.7 Orbital Express

Orbital Express was a DARPA/NASA cooperative mission in 2007. The program was attempting to test autonomous on-orbit servicing of a target vehicle. The Orbital Express program built the chaser, the Autonomous Space Transfer and Robotic Orbiter (ASTRO), and the target, NEXTSat. ASTRO used the Autonomous Rendezvous and Capture Sensor System (ARCSS), which consisted of two imaging sensors for use at near to mid-range, an infrared sensor, and a laser range finder. Sensor data were processed using specialized imaging software to gain knowledge of the target position. [5] The mission demonstrated a successful ARD, and multiple successful servicing activities, including a propellant transfer and a battery transfer. The mission demonstrated multiple mating and de-mating operations, using a variety of approach trajectories and autonomy levels. The mission experienced anomalies, including a malfunctioning robotic arm, but both vehicles were recovered. The mission was deemed complete on July 22, 2007, and both vehicles were retired. [7]

2.2 Current ARD Missions

Despite the past demonstration missions of autonomous operations, all the current rendezvous missions are used to resupply the ISS, so a crew is used for the docking phase. This section provides an overview of the current activities.

2.2.1 Soyuz/Progress

The Russians expanded their Soyuz manned vehicle to include an unmanned cargo section, Progress, in the 1970s. This spacecraft was used to supply the Salyut 6 space station, and to build and supply the Mir space station. The Progress has been used to resupply the ISS since 2000, and it has performed the most resupply missions to date. The initial vehicles used the same Igla sensing system used by the Kosmos missions, but the Progress vehicles were updated in the 1980s to use the Kurs sensing system. The Kurs system uses antennas like the Igla system, but Kurs was an improvement in that it allowed for acquisition at larger distances and rendezvous with space stations [5]. The Progress uses direct orbit insertion to place the vehicle within acquisition range of the target, and then performs small maneuvers to attain docking range. The crew assists with the docking procedure.

2.2.2 Automated Transfer Vehicle (ATV)

The European Space Agency (ESA) built the ATV to serve as an ISS resupply vehicle. The ISS resupplies started in 2008, and there have been three launched to date, with two more planned through 2014, after which the program will end. The ATV is a very large vehicle, with ATV-003 (Edoardo Amaldi) being the largest operational vehicle at the time of launch in 2012 [8]. The ATV uses a phasing approach to rendezvous and docking. The ATV is launched into an orbit below the ISS, and a series of maneuvers places the ATV within docking range of the ISS. Each phase requires approval before the ATV is commanded to continue with the mission. The ATV uses GPS data to obtain relative position and velocity data. A two-way communications link is established with the ISS, so the position and velocity data are shared between ATV and ISS. The ATV uses an optical camera and antenna measurements to dock with the ISS. The ATV is capable of performing a fully autonomous docking; however, this has not been necessary to this date, since the ISS remains manned. Once the ATV is docked, the ISS crew unloads the ATV. The ATV is then used to reposition the ISS, and the crew fills the ATV with waste. After about six months, the ATV is closed, undocked, and maneuvered into the Earth atmosphere to decay. [9]

2.2.3 H-II Transfer Vehicle (HTV)

The Japan Aerospace Exploration Agency (JAXA) built the H-II Transfer Vehicle (HTV), aka Kounotori, to perform unmanned resupplies to ISS, including the Kibo Japanese Experiment Module (JEM). The HTV design was started in the 1990s, and the first mission to the ISS was in 2009. Three have been launched to date with the fourth, fifth, sixth, seventh planned for 2013, 2014, 2015, and 2016. The HTV is similar to the ATV in that it uses a phasing approach to reach the ISS from below, and approval is needed before the next phase is commanded. The HTV is docked to the ISS using the ISS robotic arm. The HTV can carry cargo in both pressurized and unpressurized cabins, but it cannot maneuver the ISS to adjust the altitude. The HTV uses data from the Proximity Communication System (PROX) and laser reflectors installed on the Kibo JEM ISS module to maneuver within docking range of the ISS. HTV communicates its own position and velocity data to the ISS to assist with the docking operation [11]. The HTV is operated in a similar fashion to the ATV where the crew unloads the cargo, loads the HTV with waste, and the HTV decays upon reentry into the Earth atmosphere.

2.2.4 Dragon

The Dragon is an interesting newcomer to ISS resupply missions because the Dragon has a reusable capsule that is retrieved after Earth reentry and used in the next resupply mission, thus reducing the wasteful practices of one-time use resupply vehicles. This capsule that survives reentry can also deliver important scientific samples to Earth without use of a manned vehicle, such as the Space Shuttle. The Dragon was developed by SpaceX as a response to the demand for resupply vehicles from commercial entities. The Dragon currently resupplies the ISS, but the vehicle was designed to support Earth reentries from lunar and Martian missions as well. The Dragon program is not only responding to the current mission needs, but it is also thinking ahead to future needs for ARD missions.

Development of Dragon started in 2004, and the first successful ISS resupply mission was performed in October 2012, with a second, using the cargo trunk, occurring in March 2013. The second mission resulted in a successful return of materials to Earth in the reusable capsule. There are future Dragon missions planned for ISS resupply as far as 2016. The Dragon is capable of performing fully autonomous rendezvous and docking operations, but there is an ability to manually override the autonomous process. The Dragon uses a combination LIDAR and thermal imaging sensor called DragonEye to perform proximity operations. The Dragon is berthed to the ISS using the same robotic arm that berths the HTV [13] . The ISS resupply mission performed by Dragon is similar to the HTV and ATV missions, where there are holds between phases of the mission, so the ground crew can confirm the Dragon is operating nominally and the ISS is ready to perform the berthing.

2.3 Potential Future ARD Missions

Manned rendezvous missions are useful for ISS resupply, but they are not feasible for satellite servicing and retiring missions, so there is still a push to develop ARD missions that are cost efficient and/or reusable. The future ARD missions in development today are being developed to resupply the ISS, but the design is forward thinking, such that the vehicles will be capable of supporting future ARD missions unrelated to ISS resupply. Two of the new vehicles support a crew, but the crew is not required to complete the rendezvous and docking activity.

2.3.1 DragonRider

The Dragon vehicle is being expanded to support manned operations, and this manned vehicle is the DragonRider. The design is similar to the Dragon, with the only difference being the presence of up to seven crew members. The DragonRider design is not complete, and there are no currently publicized plans to use the vehicle for ISS resupply, or other missions.

2.3.2 Cygnus

The Cygnus vehicle is being developed by Orbital Sciences Corporation in response to the desire to have commercial companies supporting ISS resupply missions. The first Cygnus mission is currently planned for June 2013, and there are eight vehicles on contract with NASA. The Cygnus vehicle will berth to the ISS using the same robotic arm as the HTV and Dragon. The Cygnus will not have the capability to return material to Earth, but waste can be loaded into the cargo bay for disposal upon Earth atmosphere reentry. The Cygnus vehicle will use TriDAR sensors to perform the ARD mission. TriDAR is a “combination of high-precision, near-field triangulation with a long-range Time-of-Flight (LiDAR) system” [14]. TriDAR consists of thermal imaging and LIDAR sensors, as well as proprietary software that processes the image data to calculate the position and orientation of the target. The use of TriDAR will allow Cygnus to not only be used for ISS resupply missions, but also for ARD missions involving unmarked targets.

2.3.3 Dream Chaser

The Dream Chaser is Sierra Nevada Corporation’s response to new commercial opportunities. Dream Chaser is a manned ISS resupply vehicle, which can also be operated autonomously. The Dream Chaser will carry up to seven crew members and cargo to and from the ISS. The Dream Chaser is launched on a standard launch vehicle, but it is being designed to land on any airport runway. The Dream Chaser is still under development, with testing of the operational capabilities using an Engineering Test Article (ETA) planned for 2013 [15]. There is no currently planned ISS resupply mission.

2.4 ARD Technology Evolution

As can be expected, the technology used for rendezvous and docking missions has improved since the first missions in the 1960s. The earliest American missions were able to use radar for long range measurements, which would allow the vehicle to maneuver towards the target; however, crew observations and manual maneuvers were required for proximity operations. The early Russian missions were able to perform the entire rendezvous and docking mission autonomously, but they relied on heavy antenna systems for position and velocity measurements. Since heavy vehicles are costly to launch, research has been focused on developing lightweight, accurate sensors that can provide data to an onboard processor for autonomous operations. The technology is trending towards using LIDAR for ARD missions. The new vehicles being developed all use a LIDAR camera coupled with image processing software. Ball has developed one of the lightest LIDAR systems, STORRM, which can provide imaging data from the farthest range. STORRM uses a LIDAR Vision Navigation Sensor to obtain target position and velocity measurements and a Docking Camera to provide images of the docking [17]. While STORRM is not used on any current ARD missions, the capabilities were tested on the STS-134 Space Shuttle mission, and it is planned for use on the Orion crew exploration vehicle, which is a vehicle being developed by Lockheed Martin to provide a mechanism for manned interplanetary travel.

3 ARD Mission Definition

3.1 ARD Mission Statement and Objectives

Spacecraft rendezvous missions are important in order to preserve resources and remove space debris. The current method of performing spacecraft rendezvous missions is time consuming and expensive, since each rendezvous is custom.

A common autonomous rendezvous and docking process is needed such that the missions become routine, saving time and expense in mission design and operations. Maintaining spacecraft safety must be one of the main considerations in autonomous operations.

The objectives for this study are as follows:

a. To understand the requirements for autonomous rendezvous and docking of commercial spacecraft in LEO for the purposes of material transfer, servicing, or retirement.
b. To enable the FAA to establish architecture, requirements, and processes for future ARD operations.
c. To minimize non-recurring engineering costs associated with designing and implementing ARD operations.
d. To identify new technologies for one or more of the main aspects of ARD: 1) GN&C, 2) Sensors, 3) Mission Management, 4) Docking.

3.2 ARD Target Configurations

The prototype ARD mission will involve two spacecraft, a chaser and a target. The chaser is the spacecraft being controlled by mission operations, and being tasked to dock with the target in order to provide the required servicing. The target is the spacecraft, or object, that requires the servicing.

In order to define the ARD mission, the target categories must be identified. There are many different target behaviors, which may require different chaser capabilities. The target configurations are defined for the following categories:

1. Knowledge – the degree to which the target is known by the chaser
    a. Marked – the target has markings that facilitate detection by the chaser
    b. Drawings – the mission designers have drawings of the target, and the chaser can be programmed with *a priori* target specification knowledge
    c. None – there is no knowledge of the target
2. Control – the predictability of the target motion
    a. Active – the target is responding to ground commands, and the motion can be controlled
    b. Passive Stable – the target is not responding to ground commands, but the motion is stable, so it can be accurately predicted
    c. Tumbling – the target is not responding to ground commands, and the motion is unstable, so it cannot be reliably predicted
3. Cooperation – the degree to which the target will take part in the rendezvous mission
    a. Maneuvers – the target can actively perform maneuvers to assist in the rendezvous operation
    b. Measurements/2-way Comm – the target can transmit/receive position data to/from the chaser
    c. 2-way Comm – the target can receive position data from the chaser
    d. None – the target has no active participation in the rendezvous maneuver
    e. Avoidance – the target is actively attempting to avoid the rendezvous operation

All ARD missions will involve a target with one of the configurations identified in each category. Figure 1 shows that the ARD mission becomes more challenging as the knowledge, control, and cooperation of the target decreases.

Increasing Challenge →

Knowledge	Marked	Drawings	None		
Control	Active	Passive Stable	Tumbling		
Cooperation	Maneuvers	Measurements 2-way Comm	2-way Comm	None	Avoidance

Figure 1: Target Categories

Requirements for the ARD mission will vary depending on the target configuration. To avoid designing missions for all target combinations, three cases were identified as a focus of this study. The cases are shown in Table 1. These cases are the most likely target configurations expected to require an ARD mission.

Table 1: Target Configuration Cases

Case	Knowledge	Control	Cooperation
Refuel/Material Delivery	Marked	Active	2-way Comm
	Drawings		None
Repair/Retire	Marked	Passive Stable	None
	Drawings		
Debris Disposal	None	Tumbling	None

3.3 ARD Phases

An ARD mission has multiple phases, each with specific objectives and requirements. In order to design a usable ARD mission, all phases must be understood and taken into consideration [2]. For this study, phases were defined using information from previous research as documented in [1] and [2]. The ARD mission phases are as follows:

0. Launch/Separate Orbits – the chaser is launched into an orbit in the same plane as, but below the target
1. Phasing – the phase angle between the chaser and the target is reduced, so that the chaser becomes closer to the target, but stays below the target; the chaser acquires the initial aimpoint for approach at the end of phasing
2. Far Range/Homing – the chaser achieves position, velocity, and angular rate conditions needed for the close range phases; relative navigation is available between the chaser and the target; the chaser reaches the edge of the approach ellipsoid, but does not enter
3. Close Range
    a. Closing/Prep – the range to the target is reduced, and the chaser enters the approach ellipsoid
    b. Final Approach – the chaser achieves docking/berthing capture conditions, and the interfaces are within docking range
4. Mating – the chaser docking/berthing mechanisms connect with the target mechanisms
5. Joint Maneuvers – the chaser and target are connected, and the chaser and target are exchanging materials, or the chaser is maneuvering the target
6. Departure – the chaser docking/berthing mechanisms disconnect from the target mechanisms, and the chaser departs on a non-returning trajectory

Figure 2 depicts the phases in relation to the range between the chaser and the target. Most of the phases occur when the chaser and target are within five kilometers of eachother, so the mission must consider safety requirements to protect the chaser and target from inadvertent collision.

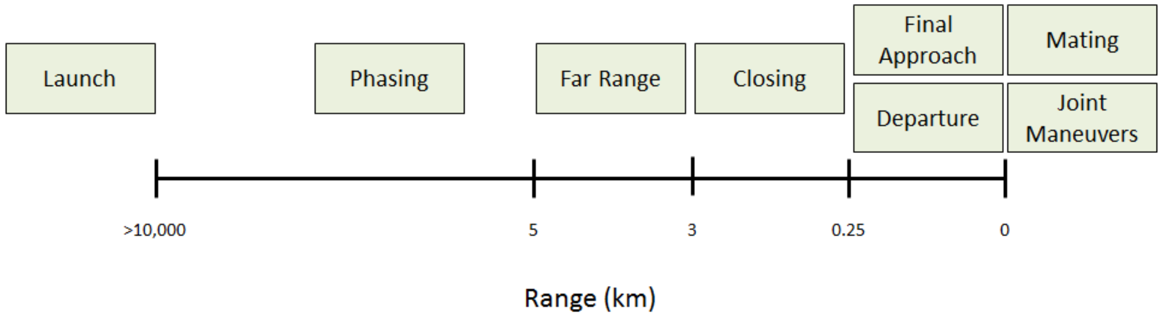

Figure 2: ARD Phases

The phases are primarily identified by the range between the chaser and target and the sensor used to achieve the goals of the phase. Table 2 provides the phases, the range, sensor, and safety considerations that must be taken into account during mission design.

The main safety consideration is to prevent collision between the chaser and the target. When the range is within 0.25 kilometers, it is important to preclude thruster firings from impacting either the chaser or the target.

Table 2: ARD Phase Definitions

ID	Phase	Range (km)	Sensor	Safety Considerations
0.0	Launch/Separate Orbits	> 10,000	Absolute Nav (GPS)	1) Resume mission on nav failure
1.0	Phasing	> 5	Absolute Nav (GPS)	
2.0	Far Range/Homing	3..5	Radar RGPS Lidar	1) Preclude collision 2) Maintain target sensing 3) Hold outside of approach ellipsoid
3.0	Close Range			
3.1	Closing/Prep	0.25..3	Radar Lidar	1) Preclude collision 2) Do not passively enter keep-out zone
3.2	Final Approach	0..0.25	Optical RF Lidar	1) Preclude collision 2) Maintain low velocity 3) Do not passively exit safety approach corridor, do not enter keep-out zone 4) Avoid plume impingement
4.0	Mating	0	Optical Lidar	
5.0	Joint Maneuvers	Joined	Optical	1) Avoid premature departure
6.0	Departure	0..0.25	Optical Lidar	1) Preclude collision 2) Maintain low velocity

4 Conclusion

A common architecture for ARD missions that is highly capable and robust is important to preserve on-orbit resources, which will save time and money. Satellite missions will become more attractive for commercial providers as the associated costs decrease. This study focuses primarily on outlining a common ARD architecture for commercial spacecraft in LEO, however, it has been suggested that a common ARD architecture may benefit spacecraft in GEO as well [4]. Developing an architecture that can be easily expanded to other orbits is advised to minimize cost and risks when companies decide to develop GEO servicing missions.

This report provides the initial steps in establishing a common ARD architecture. The target configurations are selected to focus the architecture on the likely targets instead of applying unneeded effort designing for targets that will never be encountered. The ARD mission phases are identified. The phases provide additional bounding on the architecture requirements. The architecture should be designed to account for the environment, goals, and safety considerations of each phase.

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