Artificial Intelligence Solution Architecting for the Solar Gravity Lens Mission

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Abstract

Solar Gravity Lens is a daring, breakthrough mission concept to image Earth-like exoplanets with high resolution using an optical telescope more than 550 Astronomical Units (AU) from the Sun. At this distance it is possible to use the Sun as a gravity lens to focus light from distant planets. A joint team from The Aerospace Corporation and the Jet Propulsion Laboratory (JPL) developed a mission design involving a small fleet of nanosatellites that use solar sails to reach the mission destination. This mission presents unprecedented challenges in navigation, communication, onboard processing and vehicle health management that will require advances in spacecraft autonomy. This paper presents an overview of the artificial intelligence (AI) use cases to enable this groundbreaking mission. In most use cases, AI needs can be met with existing technology. However, fault detection and correction will require new advances in AI and autonomy.

1 Introduction

For the past four years, NASA has sponsored an audacious mission to send an imaging satellite to 550 AU and beyond. The mission is motivated by an equally audacious goal; to take images of an exoplanet and its solar system, 100 light-year distant, at spatial resolution of 1- 10 km. The mission is called the Solar Gravity Lens (SGL) and is currently in the conceptual design phase and a collaboration between JPL, The Aerospace Corporation, University of California Los Angeles (UCLA) and Xplore Inc. The project is a NASA Innovative Advanced Concepts (NIAC) Phase 3 effort within the Space Technology Mission Directorate (STMD). Einstein's equations for general relativity show that a light ray bends when travelling near a massive object. Calculations that are supported by simulations show that for the mass and shape of the Sun, light rays originating from a distant source from behind the Sun, will bend and come to a focus approximately at 547 AU. The gravitational bending does not produce a single focal point, but a focal line that extends from 547 AU to well past 900 AU. What is unique about this "lens" is the optical magnification which is calculated to be on the order of 10^{11}. Consequently, surface features from an exo-sun or an exo-planet illuminated by its exo-sun can be imaged to identify both global and local features on a several km scale. To acquire that kind of imaging capability by way of a traditional telescope requires an aperture 90 km in diameter and this would produce one-pixel worth of data. The SGL mission attempts to collect a multi-pixel (e.g., 1000 x 1000) image of an exo-planet, 30-100 light-year (9-30 parsec) distant by carrying an imaging telescope having an aperture 1-2 m in diameter. While challenges in the science segment of the mission exist, it is dwarfed by the challenges of getting there quickly (< 40 years), navigating to the SGL focal point (~0.02 nrad) and communicating back the results (from as far back as 800-900 AU).

2 Mission Architecture

Figure 1 presents the SGL mission architecture. Rideshare services are used to launch spacecraft with solar sails (sailcraft) stowed in containerized structures into parking orbits. On command, containers leave the parking-orbit using electric propulsion (EP) and tack toward the Sun deploying sailcraft. The cluster of thirty-five sailcraft (the Pearl) is propelled to the SGL location via solar perihelion transit. The sailcraft communicate with Earth using radio frequency (RF) communications and navigate using NASA's Deep Space Network (DSN). On reaching solar perihelion, each sailcraft does an attitude change rotating the sail to face the Sun. The result is a set of formation flying sailcraft on a hyperbolic trajectory to the SGL focal line that will come to "meet" it many years hence. Starting at 1 AU, the sailcraft eject a 3-axis stabilized proto-Mission Capable Satellite (pMCS) which is a 10 kg, ~1 m diameter disk. The pMCSs maneuver and dock to form 5 mission capable satellites (MCs).

A twenty-eight year cruise phase begins with navigation via DSN until 200 AU and then via star tracker. Communications to Earth is via laser communications but among the MCSs it is via low power, radio frequency (RF) communications. Minor trajectory adjustments are done using onboard EP thrusters. At 550AU the imaging payload on the MCSs sense the appearance of the SGL light of the exo-sun. The distribution of this light on the imager CCD, after passing through the coronagraph, serves as a navigation tool to center the spacecraft trajectory on the exo-sun focal line. When centered on any SGL focal line, the image is a ring with uniform intensity distribution [Toth and Turyshev, 2021].

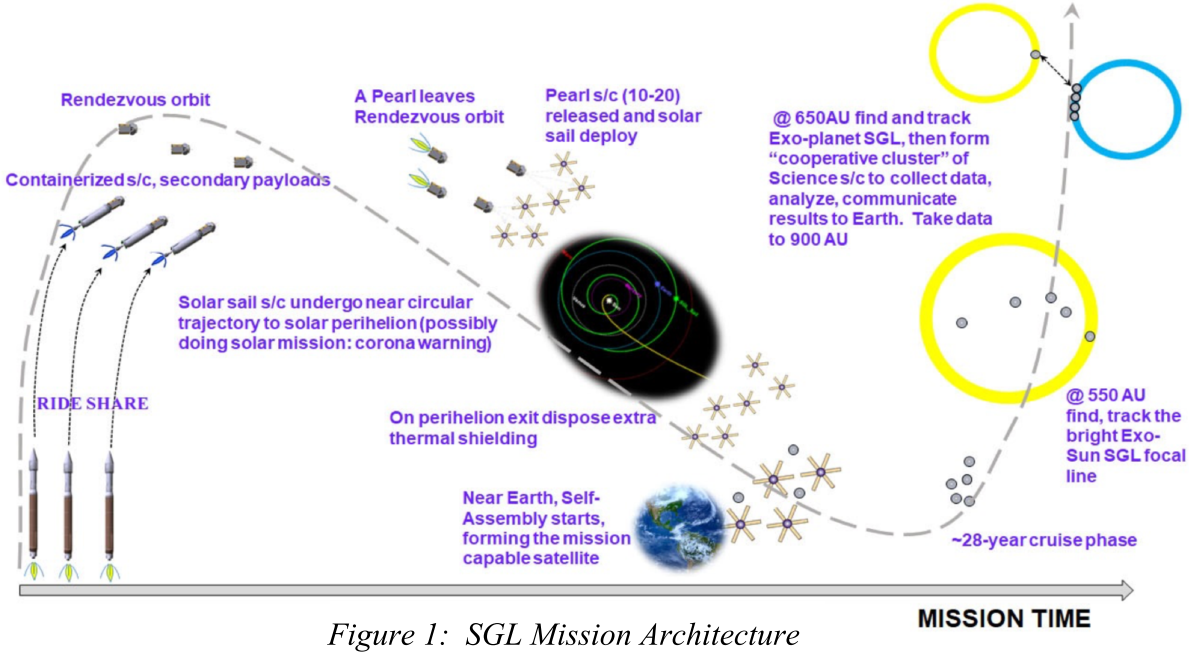
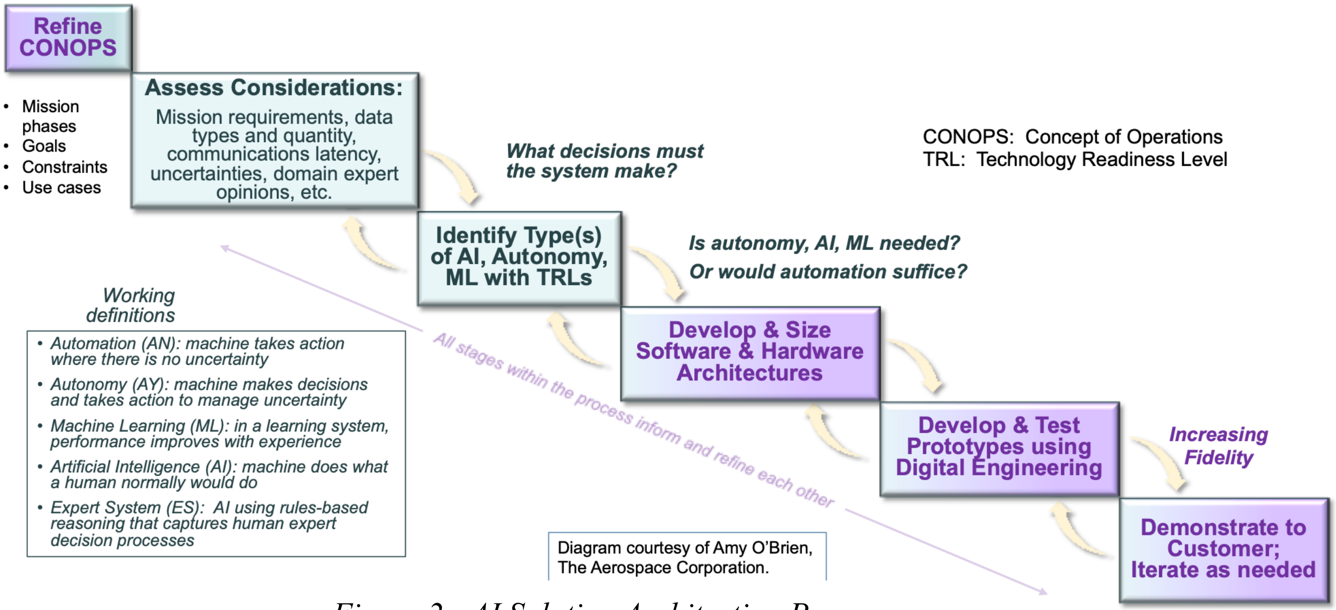


Figure 1: SGL Mission Architecture

Simulations show that the change in the intensity distribution of the ring along with its shape can be used as a navigation tool to conduct a local search of the SGL light [Turyshev and Toth, 2020]. At 650 AU, one the MCs is left on the exo-sun SGL focal line, while the others move toward the exo-planet SGL focal line. The MCs that remains behind serves as the center of a local coordinate system based on the exo-sun. Data acquisition begins when the MCs center on the exo-planet focal line. They operate as a cooperative cluster collecting SGL photons with time stamp and spectral analysis. The integrated signals are then deconvoluted and sent back to Earth [Turyshev and Toth, 2020]. Our analysis shows that telemetry can be conducted from 900AU allowing the science phase of the mission to proceed for ~12 years, permitting the capture of images of a single exo-planet over multiple years or images from multiple exo-planets within that solar system.

3 AI Solution Architecting Process

Our AI solution architecting approach is to parse the mission into several critical use cases to help define where and what type of autonomy, AI, or machine learning (ML) might be needed. The purpose of this approach is to ensure that AI and autonomy are directly tied to mission objectives and used only where necessary. Our process is summarized in Figure 2. A high-level software architecture was developed as part of this process, but not shown in this paper.



- *Automation (AN): machine takes action where there is no uncertainty*
- *Autonomy (AY): machine makes decisions and takes action to manage uncertainty*
- *Machine Learning (ML): in a learning system, performance improves with experience*
- *Artificial Intelligence (AI): machine does what a human normally would do*
- *Expert System (ES): AI using rules-based reasoning that captures human expert decision processes*

Diagram courtesy of Amy O'Brien, The Aerospace Corporation.

Figure 2: AI Solution Architecting Process

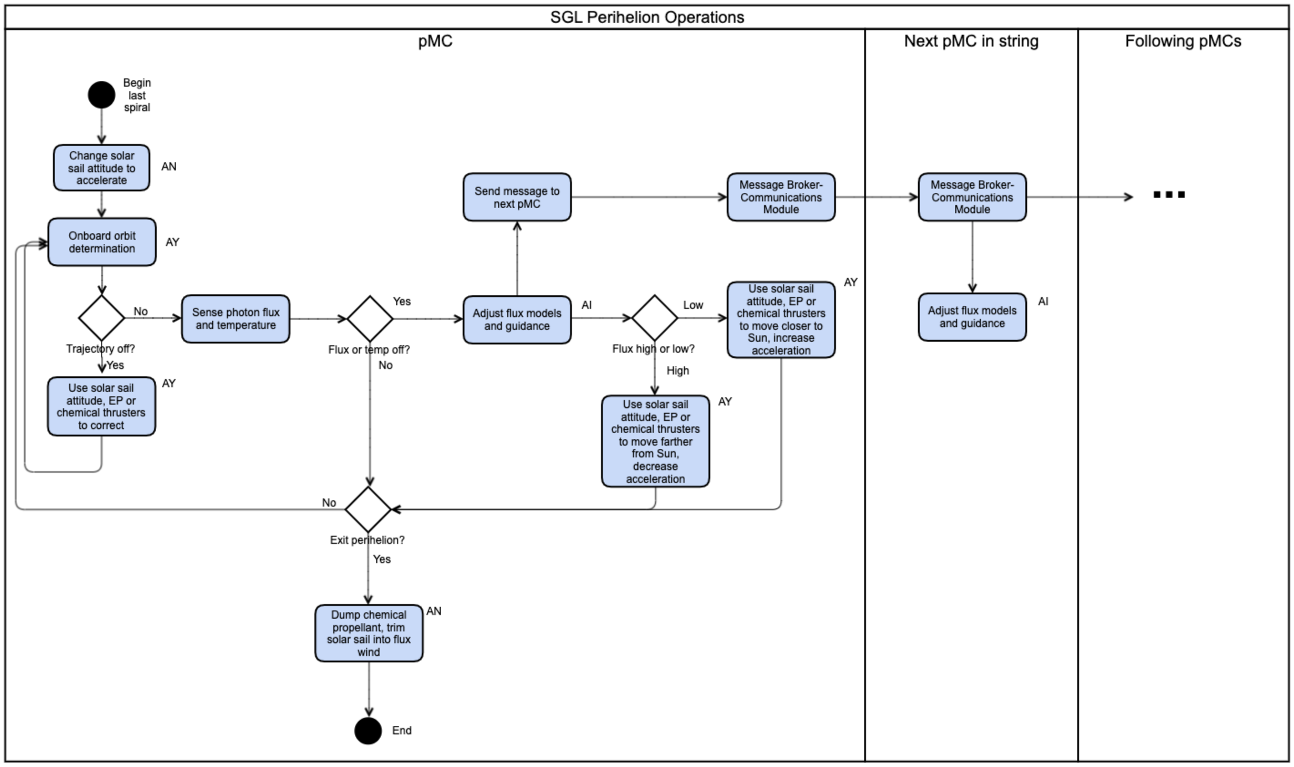


Figure 3: Perihelion Operations Activity Diagram.

4 Perihelion Operations Use Case

Perihelion passage is critical for establishing the correct outbound trajectory. Communication with the ground may be limited, and the attitude change actions are quick (after 1 hour of angular acceleration reaching a rotational rate of ~8 degrees/sec). For the operational mission, each launch will have up to 35 sailcraft (i.e., 35 pMCSs)

The pMCSs have solar sails and will approach the Sun in a formation flying cluster with about 5-10 km separation. DSN should have good orbit data on the pMCSs up until perihelion. There is likely no communication with the ground but there could be communication within the cluster. The inbound trajectory consists of 5 or 6 spirals with a change in sail attitude whereupon during the last spiral there is a transition from deceleration to acceleration. Using skiing analogy, pMCSs "snowplow" into the Sun, then change orientation of the sail to pick up velocity. Peak change in velocity (delta-v) could be up to 30 AU/year.

The activity diagram in Figure 3 is a Unified Modeling Language (UML) diagram, similar to a flowchart. The pMCS continuously performs orbit determination using available sensors to estimate deviation from its planned trajectory. If the trajectory is significantly off, it initiates a thrusting maneuver (using solar sail, electric propulsion or chemical thrusters) to get back on course. Even if the pMCS stays on the planned trajectory, it must sense photon flux and temperature and adjust its onboard models if these parameters deviate from expected values. The pMCS communicates the adjusted environment parameters to the following pMCSs and adjusts its acceleration accordingly. These two control loops continue running until the pMCS exits perihelion.

The autonomy needs for this use case are minimal. In general, autonomy will function in a manner very similar to traditional closed-loop guidance, navigation and control (GNC) systems, with some differences in environment, sensors and actuators. Some form of AI may be helpful in adjusting flux models. Technology Readiness Level (TRL) is low for this use case, but could be advanced quickly through ground simulations.

5 Self-Assembly Use Case

This use case covers the in orbit self-assembly of the mission capable (MCS) satellites. Each pMCS spacecraft has a solar sail with 1-2 square meter thin film solar cells which provide power to charge batteries. About twenty days after perihelion

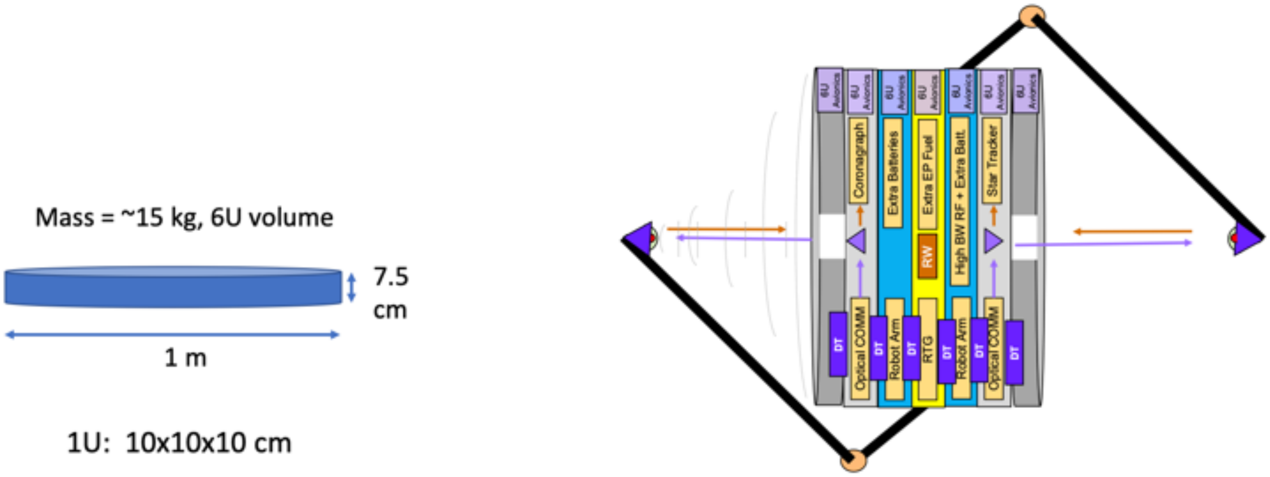


Figure 4: Self-Assembly Before & After

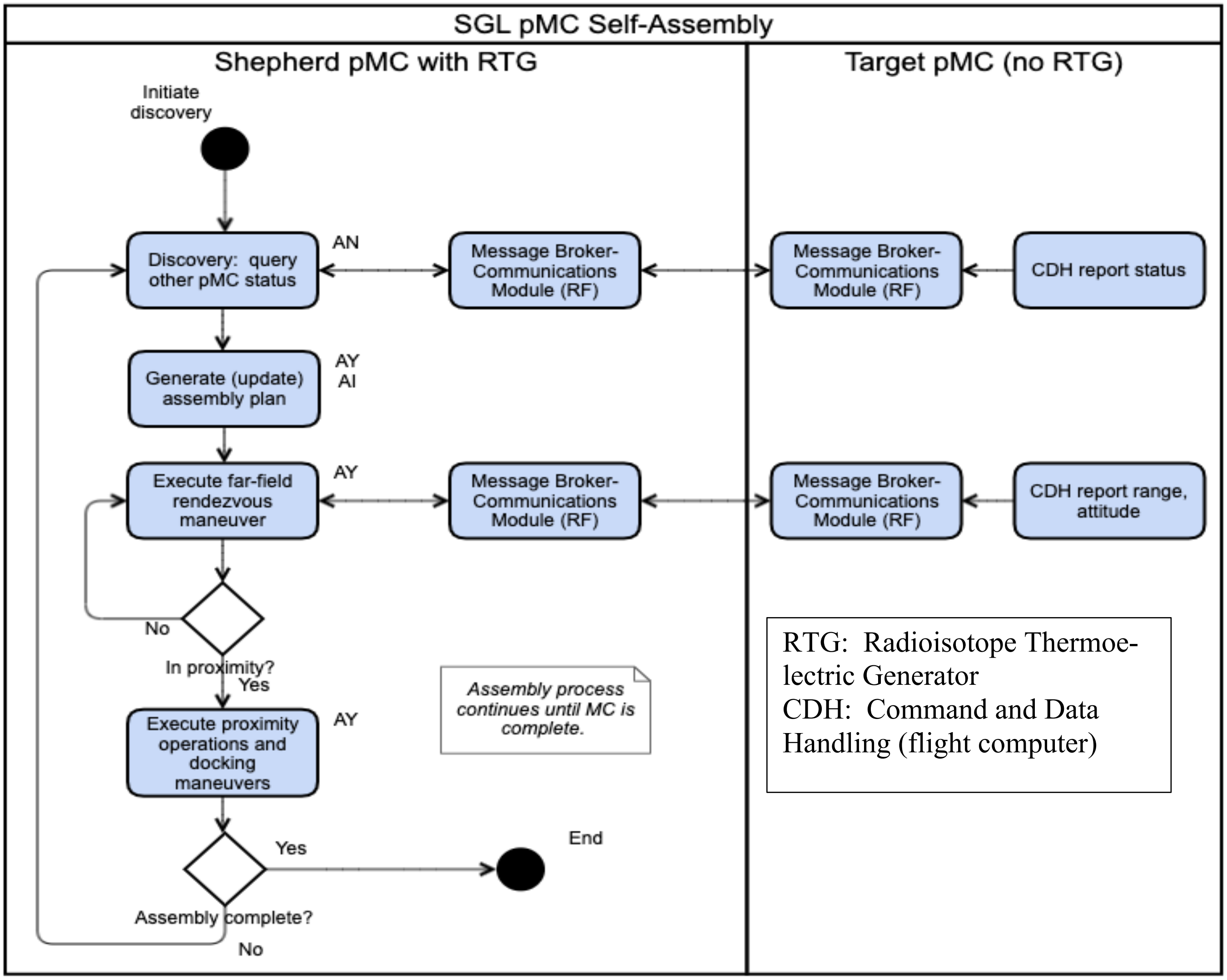


Figure 5: Self-Assembly Activity Diagram

the pMCSs pass 1 AU and solar sails are jettisoned. Time is of the essence since batteries will eventually be depleted and docking with an unpowered spacecraft may be impossible.

Communication to Earth should be relatively prompt but constrained to low data rates of ~10 kbps with higher data rates between pMCSs (~1 Mbps). If the pMCSs are out of the ecliptic, they should also have a continuous line of sight to Earth. DSN is used for the navigation and timing synchronization comes from Earth.

Each pMCS is a "pancake" roughly 1 meter in diameter and 7.5 cm thick, with a mass of about ~10 kg (without sails). (Figure 4). The pMCS has the equivalent avionics volume of a 6U cubesat. All pMCSs have batteries, GNC and propulsion. One out of every seven pMCSs has a radioisotope thermoelectric generator (RTG). Monte Carlo calculations for the rendezvous maneuver show up to 30 days capability for battery life. Seven pMCSs form one MC spacecraft after self-assembly.

Figure 5 shows the activity diagram for this use case. It is possible, perhaps even likely, that not all pMCSs will make it to 1 AU and some may not have full functionality. Therefore, we need a discovery method to communicate with the available pMCSs and determine what systems survived. We also need a planning and scheduling capability onboard that is integrated with autonomous navigation, rendezvous, and docking. An initial assembly plan could be developed on the ground, but the system needs to respond quickly to anomalies. Both far-field rendezvous and proximity operations and docking are autonomous and will need careful testing.

Autonomous scheduling is a “traditional” AI problem and has been studied and implemented extensively in robotics. [Ghallab, 2016]. Autonomous rendezvous and docking was demonstrated in space on DARPA's Orbital Express mission in 2007 [Friend, 2008]. The Cubesat Proximity Operations (CPOD) mission developed miniaturized components for autonomous rendezvous and docking that fit into a cubesat form factor [Roscoe et al, 2018]. The AI and autonomy needs for this use case can be satisfied with known techniques which are fairly mature, with estimated TRL of 7.

6 Exo-Sun Acquisition Use Case

This use case covers the acquisition of the exo-planet Solar Gravity Lens (exo-pSGL) by first aligning with the exo-sun Solar Gravity lens (es-SGL). The width of the es-SGL is ~ 100 km while that of the exo-pSGL is 1.3 km (for an exo-solar system 100 light-year distant). After centering all the MC spacecraft on the es-SGL, one MC spacecraft serves as coordinate reference allowing the other MC spacecraft to search for the exo-pSGL. The search for the exo-pSGL uses a simulation as guide which describes how the intensity pattern of ring-shaped image should change until the exo-pSGL light begins to hit the detector [Turyshev and Toth, 2020]. However, if the navigation has failed and we do not see the es-SGL or later the exo-pSGL, the MC spacecraft initiate a search.

Figure 6 shows a search approach for the es-SGL using 4 MC spacecraft and Figure 7 shows the activity diagram. An MC spacecraft starts in doughnut formation at the predicted location of the es-SGL. The observer MCs will do a maneuver to start a search pattern to look for increasing light. The search pattern follows a spiral out (or in) with MCs 1, 2 and 3 moving. MC4 in the center stays in place. It is not known in advance which MC will detect the SGL light first. Once one of the MCs has detected the light, the appearance of the image on the CCD (e.g. a spot on left, right) does provide a guide of the general direction of travel to capture the whole SGL ring

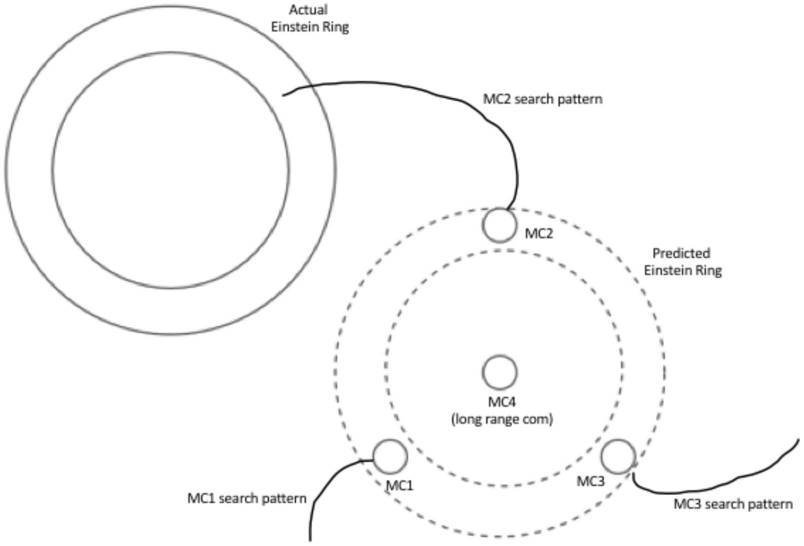


Figure 6: Exo-Sun Search Pattern

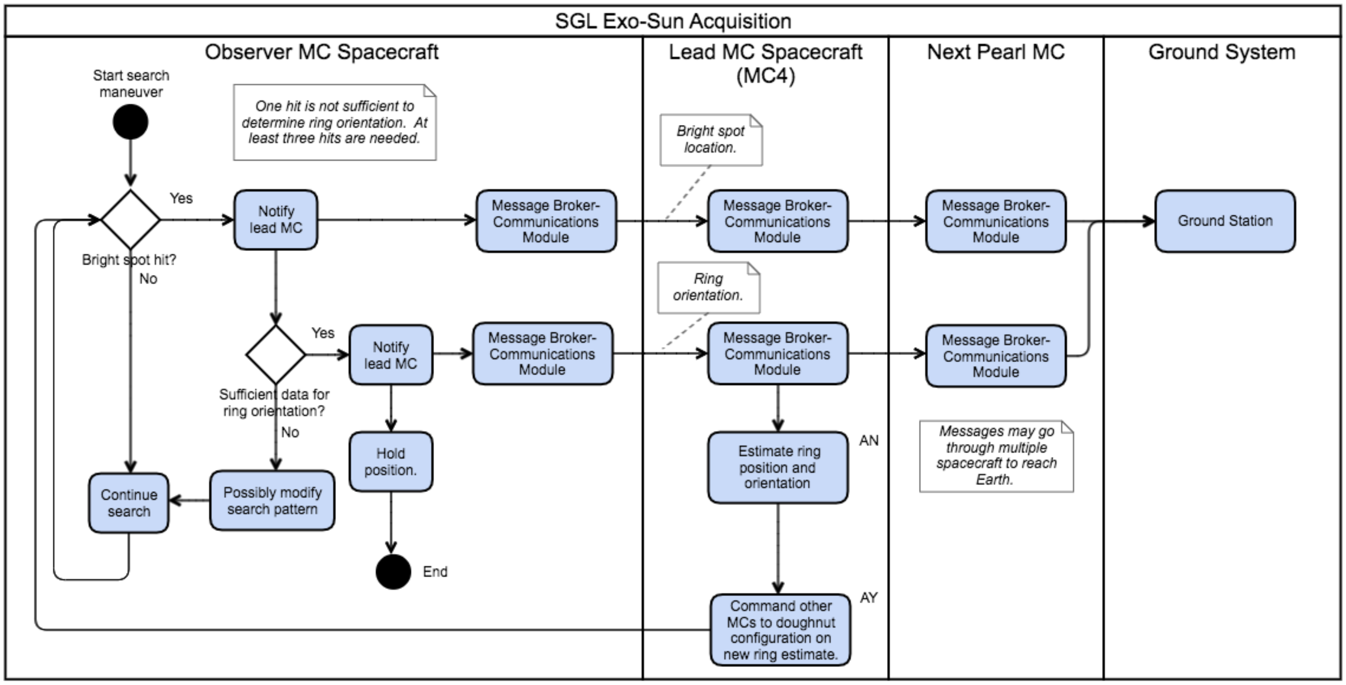


Figure 7: Exo-Sun Acquisition Activity Diagram

(i.e., centered). The same concept applies for the search of the exo-pSGL [Turyshev and Toth, 2020].

Assuming no spacecraft failures, AI, ML and autonomy needs are minimal for this use case. Autonomous navigation and ring location estimation algorithms should suffice to achieve exo-sun acquisition. There is simply not enough information to warrant more advanced methods. Estimated TRL level is low but could be advanced quickly through simulation.

7 Onboard Fault Detection and Correction Use Case

This use case covers Fault Detection and Correction (FDC). FDC monitors vehicle health and resolves issues to keep spacecraft functioning. SGL spacecraft will operate for decades in deep space and the probability of significant anomalies and failures is high, even with very reliable electronics and mechanisms. The round trip light time to 550 AU and back (the location of the absolute beginning of science operations) is on the order of 6.3 days. For this reason, most anomalies and failures must be resolved onboard.

FDC consists of an onboard intelligent system that monitors spacecraft telemetry, as shown in Figure 8. In the event of an anomaly, it attributes the fault to a root cause and chooses a course of action (COA) to resolve the anomaly. FDC is effectively an autonomous data-driven application that does what human operators would normally do in response to known failure modes. It makes extensive use of Failure Modes Effect Analysis and Fault Tree Analysis.

The AI, ML and autonomy needs for this use case will be significant. Two types of intelligent systems exist in this use case: short-term onboard systems that react quickly to ensure spacecraft health and long-term ground systems that can handle more challenging issues in cooperation with human operators. Multiple types of AI may be needed to maintain spacecraft health, including expert systems, multi-agent autonomy, and anomaly detection techniques. Basically, the equivalent of spacecraft operators and a spacecraft engineering team must be brought into space to keep the mission operating through faults that cannot wait for a 1 week round trip light time.

This system may need multiple anomaly detection techniques for high dimensional time series, including neural networks, hierarchical temporal memory, statistical machine learning, and a knowledge base. Anomaly detection algorithms will process onboard telemetry data in near real time, looking for unusual patterns, even before individual mnemonics violate thresholds. Similar anomaly detection algorithms are currently being implemented on the ground [Hundman et al, 2018]. As new anomalies are detected and resolved, the signature pattern and course of action are propagated across the constellation to enable "machine mentoring." This is accomplished through a distributed data service that maintains data replication so that a critical piece of data will not be lost if one node goes down. Unusual patterns and COAs may not

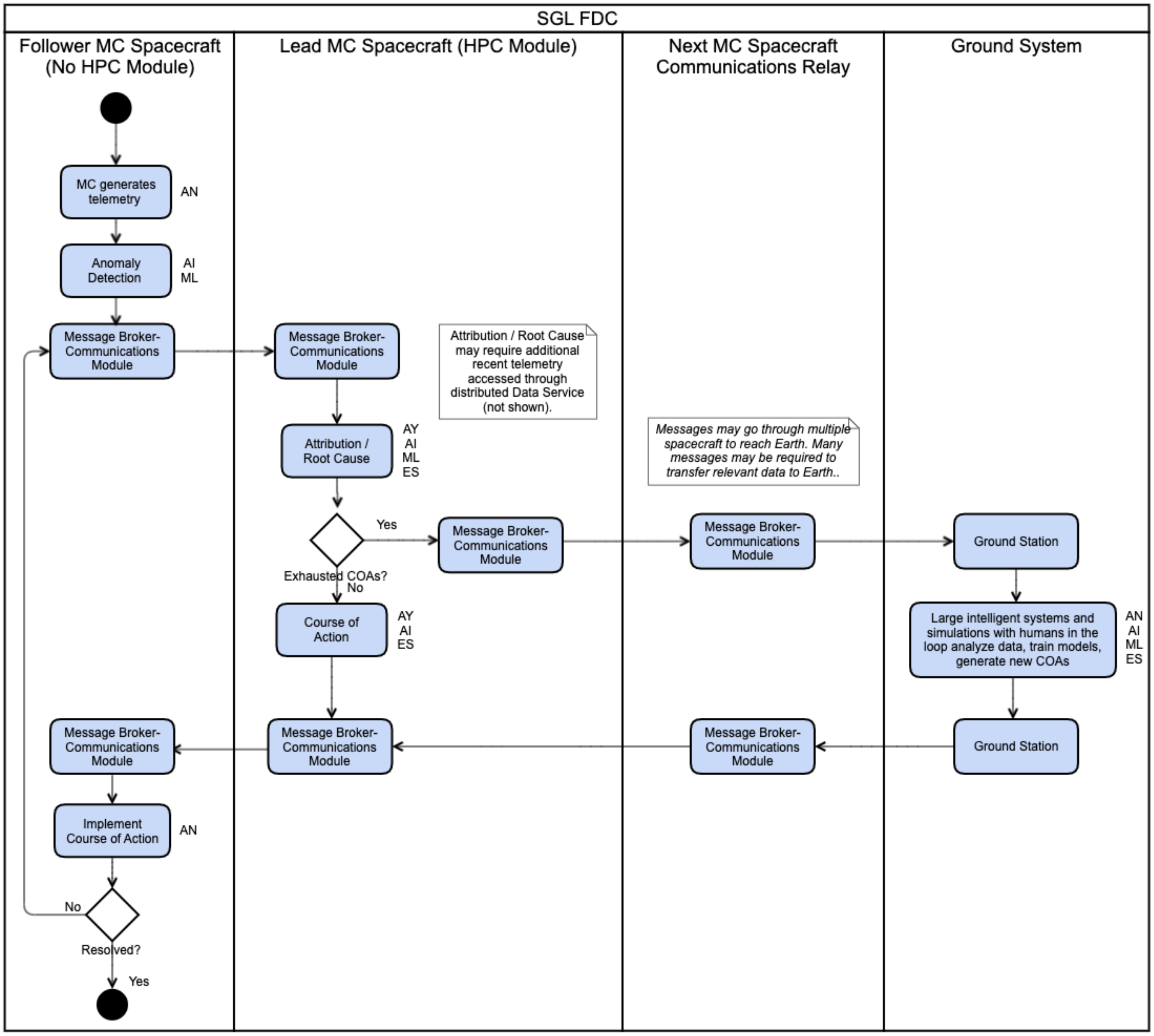


Figure 8: Fault Detection and Correction Activity Diagram

be resident in every spacecraft, but accessible from nearby modules.

TRL for these technologies is low. Autonomous Fault Detection and Correction is an area of heightened interest within the space community and requires significant advancement for this mission to be feasible.

8 Conclusions

A mission to the SGL opens up a unique possibility of direct high-resolution imaging coupled spectroscopic analysis of a habitable Earth-like exoplanet, not technically feasible otherwise. In this paper we have attempted to lay out the SGL concept of operations and significant AI use cases. In most use cases, the AI and autonomy requirements can be satisfied with existing technologies. In some use cases, such as guidance and control for perihelion passage, the technologies may need to be adapted to the unusual environment of the mission. The only exception is onboard fault detection and correction, which will require much more capability than exists in space missions today.

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