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The Ultra Survey Mission:
Crafting A Systems Architecture Design Project

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ABSTRACT

Systems Architecture (SA) is a key discipline in Systems Engineering; robust architectures enable success and flawed architectures limit performance. However, SA is challenging to teach students because it is less of a "hard" science. At the University of Detroit Mercy, students in the MS Product Development (MPD) and Advanced Electric Vehicle (AEV) Certificate programs are exposed to a full term of SA. This class stresses the development of heuristics through exposure to mini case studies, class discussions, and several projects (including a field trip to the Henry Ford Museum to study multiple examples of competing historical architectures). The capstone project in this class requires teams of students to create a new architecture for a given set of criteria. One recent final project involved the creation of a space probe architecture that could meet mission objectives given a challenging set of constraints and the creation of DODAF Viewpoints to communicate the architecture.

INTRODUCTION

The Master of Science in Product Development (MPD) program at the University of Detroit Mercy (UDM) was developed in partnership with the Massachusetts Institute of Technology (MIT), the Rochester Institute of Technology, and several industrial partners. It is a cohort-based, tailored version of MIT's System Design and Management Program that meets the needs of the automotive and industrial students typically enrolled. UDM recently created the Advanced Electric Vehicle (AEV) Certificate program to meet emerging demand for electric vehicle expertise; students from the AEV program are blended into select MPD classes.

Systems Architecture (SA) is typically taught as one of the first classes in the curriculum to enable students to understand the importance of clearly defining the intent of a system, exploring the concept space fully, and selecting a robust architecture that will enable successful instantiation of the system through downstream systems engineering, detail design, and other product development processes.

The course uses *The Art of Systems Architecting* by Mark W. Maier and Eberhardt Rechtin [1] and embraces the heuristics emphasis of the text. We stress Edward Crawley's definition of SA: *The mapping of function to form via concept* and Eugene Ferguson's admonition in *Engineering and the Mind's Eye* [2] that "Engineers need to be continually reminded that nearly all engineering failures result from faulty judgments rather than faulty calculations." This course, through its emphasis on case studies of engineering successes and failures and the development of personal heuristics meaningful to the students, attempts to give them a mental framework and set of tools to enable them to be effective systems architects.

CHALLENGES IN OVERCOMING MENTAL INERTIA

Most students who enter the MPD program are mid-career engineers with at least five (and often ten or more) years of experience. Industrial partners usually adopt an internal nomination program to screen candidates; this has ensured a steady stream of excellent students. However, because they are successful in their careers they often have "mental inertia" that limits their ability to fully explore concept spaces and truly understand what they are trying to accomplish. There is a profound tendency to immediately begin designing a system rather than understanding the actual intent and need (and surfacing missing or erroneous requirements and constraints). For example, in one design exercise the students were tasked with building an electric vehicle that met certain given requirements. One student immediately proclaimed that the vehicle would have to be all-wheel drive. It took considerable effort to convey that the requirement was to climb a steep ramp, excel at a speed trial, etc…and that there was no specific requirement to build an AWD vehicle, although that might be one successful solution.

Because many of the students typically design "standard" items (automotive seats or suspension components, for example), they lack experience in "clean sheet" problem solving and experience difficulties in identifying solution-neutral functions. For that reason, several design challenges in the program are designed to give them unusual problems to solve. Students are also typically mentally entrenched in whatever SE tools and processes are used by their organization and are unfamiliar with emerging Model Based Systems Engineering (MBSE) methods.

SYSML AND DODAF

The instructor feels that although SysML has its limitations, students should gain some experience with both SysML and Department of Defense Architecture Framework (DODAF) viewpoints. The benefits of a standard symbology and the "living" nature of SysML models are important concepts; the integration of basic block definition diagrams (BDDs), internal block diagrams (IBDs), and selected DODAF viewpoints into SA and SE classes allows students to experience this emerging modeling language.

MagicDraw (with SysML and UPDM plug-ins) was chosen as the modeling tool for these courses due to the support available from the vendor and the relative user-friendliness of the software's interface.

THE ULTRA SURVEY MISSION

The SA design project has traditionally focused on architecting a non-highway electric vehicle; past assignments have included architecting conveyances for use within gated communities or to haul trash from a metropolis. This year's project was considerably further from the students' "comfort zone": to architect a space probe mission given an unusual set of constraints.

To emphasize the lessons taught in class, several requirements given to the students were wrong, ambiguous, or misstated. A significant, potentially mission-ending failure mode was also crafted to demonstrate the need for redundancy (the author asserted multiple times in class that many NASA missions were unsuccessful due to single points of failure). To continue the students' exposure to MBSE methods, several DODAF diagrams were required as project deliverables.

After the author briefed the students on the project, a question-and-answer session was held with the author role-playing both the NASA client and the "BuildTech" engineering representative in charge of executing each architecture. The author was also available outside of class for private discussions with student teams to answer in-depth questions related to their concepts. This enabled students to maintain some level of secrecy if they were more rigorous in their inquiries.

Planet Ultra

Conditions on the planet to be surveyed were carefully crafted to make most obvious solutions impossible and force the students to explore the solution space to develop a suitable concept. To simplify their calculations, the planet was Earth-sized, with 1g gravity, surface temperature: 75 °F (day), -5 °F (night), 1 atm pressure, a 100% nitrogen atmosphere (precluding combustion), and a solar flux that was 80% of Earth's. Students discovered that the temperatures given were for the summer; winter temperatures were significantly colder (this would have a negative impact on battery chemistry).

Atmospheric Irregularities

Irregularities in the atmosphere added a layer of complexity and difficulty for the students. Wind speed at the surface was given as 0-1 mph; wind speed at 100' gusted from 0-120 mph. The greatest challenge was caused by a 6' thick layer of Vallium (a previously unknown nitrogen isotope); it is a 100% absorber of electromagnetic radiation. This barrier layer is 100' above the surface at the boundary of the wind gust zone. Students quickly realized that this constraint meant that the surface was dark, rendering solar panels ineffective and making radio communications from below the layer impossible.

The Plateau

The region to be surveyed was a 100 km x 20 km plateau with a surface similar to the Bonneville Salt Flats; it was crisscrossed with irregular trapezoidal rills 6 feet wide and 4 feet deep. There was also a liquid lead lake in one corner and a "mountain range" 20 ft. tall, 50 ft. wide, with a 15° slope, across the plateau. One week into the project, "NASA" announced that a comet impact had created a water lake. Students, via interviews, also learned that the mineral deposits of interest scramble the local magnetic field, making the use of magnetic compasses impossible. The cumulative intent of the constraints was to prevent a direct copy of the "Mars rovers" as well as to provide a source of effectively unlimited heat and water.

The Survey

The students were directed to survey every square kilometer of the plateau (sampling from the center of a grid within 10 m); no time limit was established. They were given two options: Self-contained, single-use survey units (80 mm diameter, 100 mm tall, resistant to 10,000 g, massing 2 kg) with built-in transmitters or a larger, reusable portable survey unit (100 kg, 0.25 kw-H consumed per survey sample). Regardless of survey method, each sample generates 10 Mb of data. The intent of these options was to give the students a fairly open solution space (for example, launching the disposable units from a vehicle or dropping them from the air). No group chose to request an alternate survey mechanism; the students did discover via the question and answer session that the single-use units were explosive with a significant blast radius. This emphasized the need to not make assumptions about technologies, since any design that simply dropped and triggered a survey unit near a vehicle would be rendered inoperative after the first sample was taken.

Other Resources

The students were told that NASA would deliver their systems to Ultra via an Orion (nuclear-pulse propulsion) transport. There was no weight limit and no cost limit, although the system was required to fit into one or more standard Conex or air freight containers. No fissionables were allowed (to prevent nuclear-powered solutions). The voyage would take a year and NASA would guarantee a relatively soft (2 g) landing on the surface within a 500 m radius of their chosen landing site. To relay survey information, NASA offered the use of two satellites: the Ultra Reconnaissance Orbiter (already in orbit) and the Ultra Climate Orbiter (arriving 6 months before the students' mission). Off-the-shelf transmitters were available; the Climate Orbiter transmitter was smaller and consumed less power. This represented the "bait" for the mission-killing failure mode: The Climate Orbiter would fail upon orbital insertion and not be available for the students to use as a relay; unless their architecture was redundant and could transmit to both orbiters it would not be able to send data to NASA.

INSTRUCTOR INTENT

The instructor felt that several architectures would be viable; wheeled or tracked vehicles (suitably designed to traverse the rills), lighter-than air craft, and heavier-than-air craft could all succeed. Some sort of navigation beacon array (with line-of-sight radio possible, up to the 100' high barrier layer) would be necessary due to the lack of orbital (GPS-type) or magnetic navigation. Power for the probe could be provided by a solar array lifted above the barrier layer, charged batteries landed from orbit, or by using the liquid lead lake. For example, a phase-change "heat battery" of tin could be immersed in the lead and provide a significant source of heat to run a steam generator on a rover.

STUDENT SOLUTIONS

The Blimps

One group proposed to complete the survey with four hydrogen-filled blimps. Each would carry 525 self-contained survey units and use electric motors for propulsion; several containers landed on the surface would provide battery power to recharge the blimps. Each airship would have to contain 1.2 million liters of hydrogen just to lift the survey units; in addition, the team chose to use a rocket to carry the data above the barrier layer. Unfortunately, they chose to specify a transmitter that only could communicate with the doomed Climate Orbiter.

The Blimp + Power Station

Another group proposed the use of a single blimp, also dropping disposable survey units. They chose to capitalize on the potential of the liquid lead pool and included a power station that could crawl a short distance (given the uncertainty in the landing location) and interface with the provided heat source. The blimp would recharge at the station and transmit data by climbing above the boundary layer. Of all the proposals, this architecture has the greatest potential for follow-on exploration (not explicitly requested but a common outcome of NASA missions) due to its effectively unlimited energy availability. (See Figures 1-2)

The Helicopter

The most surprising architecture was that of a Li-ion powered helicopter. Based on the Sikorsky Firefly, the proposed probe would fly around the plateau dropping survey units and recharging at multiple energy depots set up on the plateau. An extendable antenna allowed the probe to communicate with the orbiters. The instructor had not considered a helicopter (given its extreme energy inefficiency compared with other flying solutions). (See Figure 3)

The Brute Force Approach

The most original solution was that of dropping five survey pods (nicknamed "Honey Badgers") on the surface. This team took advantage of the unlimited payload and specified that these pods would be dropped from orbit sequentially (to ensure complete coverage by relaying each container's position before landing the subsequent Honey Badger). They would survey the surface by firing the disposable survey units from mortars. The pods could erect 100' masts with retractable extensions (to avoid the wind gust problem) and established a line-of-sight communications network for redundancy and triangulation. The team specified lead-acid batteries for power and was the only group to specify transmitting the data multiple times to ensure receipt.

This solution is the most limited in that it cannot do any follow-on experimentation; however, it is highly suitable for the stated problem and the team has successfully avoided all the anticipated failure modes. (See Figures 4-5)

OUTCOMES

When this assignment was developed, the instructor expected the solutions to be derived from the following:

Ground Architectures:

- Static
- Wheeled
- Tracked
- Screw drive

Heavier-Than-Air Architectures:

- Flying wing
- Conventional fuselage
- Helicopter

Lighter-Than-Air Architectures:

- Rigid airship
- Semi-rigid airship
- Blimp

Some unanticipated results were also obtained. No team chose to use the liquid lead lake to "charge" a liquid tin "heat battery" (0.21 kJ/kg specific heat + 59 kJ/kg heat of fusion). All teams avoided ground vehicles (apparently the rills and terrain were more intimidating than intended). No team asked "BuildTech" (the construction firm) to develop alternate survey or communications technologies and some groups had very limited interaction with NASA and BuildTech to clarify aspects of the assignment.

The instructor prepared briefings to show the outcome of each mission as if it had been selected by NASA.

The Blimps: Outcome

NASA released the following statement:

"The Ultra Reconnaissance Orbiter detected the launch of the Ultra Probe's data relay rocket. This is the final footnote to this failed mission. The lack of redundant communication doomed this survey as soon as the Ultra Climate Orbiter burned up six months ago."

Failure: Lack of redundant communication

The Blimp + Power Station: Outcome

NASA released the following statement:

"We are delighted to report that the Ultra Probe mission continues to send back high-quality scientific data. The long-term success of the mission is due to the team's novel exploitation of energy sources on the planet and has enabled us to deliver follow-on mission packages that draw power from the recharging station."

This team won extra credit for satisfying an unstated objective; their architecture was deemed to be the most extensible. NASA often extends missions (Voyager, Mars rovers, etc.) and the ability to live on and continue to conduct experiments was rewarded.

The Helicopter

NASA released the following statement:

"The final set of data from the Ultra Probe was transmitted today. Complications due to navigation limited the amount of data we were able to collect. A follow-on mission will have to be undertaken."

Assessment: Likely partial success

The Brute Force Approach: Outcome

NASA released the following statement today:

"The Ultra Probe (nicknamed the "Honey Badger" by its designers) completed its survey of the Ultra plateau today. The survey was completed rapidly and the data received so far is extremely promising."

This team received extra credit for developing the architecture judged most likely to succeed.

The "Hiccup"

The instructor also shared with students the rationale regarding the latent failure mode designed into the project: the failure of Ultra Climate Orbiter (UCO). The off-the-shelf communications system interfacing with the UCO was stated to be smaller and more power efficient to entice students to use it. However, there was no cost, volume, or power limit imposed, so pursuing a non-redundant strategy was driven solely by student assumptions, not the given problem set. This aspect of the project was included to emphasize that in real situations it is often the unstated assumptions that lead to architectural failures.

INSTRUCTOR ASSESSMENT

By constructing the constraints carefully, the instructor intended to drive students away from simple rovers and reward those who fully exploited the available resources. This "clean-sheet" problem set (with interesting constraints) was outside the students' normal experiences and forced them to consider the mission. The biggest issues that would dictate an architecture's success were:

- Navigation/orientation (due to lack of magnetic navigation and the blackout layer)
- Movement (avoiding the rills and climbing the mountain)
- Energy (having enough power to complete the mission)
- Data transmission (through the layer and to the surviving orbiter).

The important constraints and conditions that were withheld included the winter surface temperatures, the explosive nature of the disposable sampling technology, the lack of a usable magnetic field to aid navigation, and the failure of the Ultra Climate Orbiter.

At least one ground vehicle (equipped with some sort of bridging apparatus) was expected; instead, the students uniformly avoided surface solutions. Several of the architectures had minor flaws (the blimps carrying hundreds of survey units and the helicopter) while others were extremely innovative (the Honey Badger, in particular). One group's efforts relied solely on communicating with the Climate Orbiter; their inability to complete the mission emphasized the single-point-of-failure lessons hammered home in class.

Overall, the students rose to the challenge well and are successfully using DODAF viewpoints to communicate their intent. It is the instructor's belief that this exercise has emphasized the following heuristics:

1. Initial constraints/requirements may be wrong.
2. Robust exploration of the concept and solution spaces increases the likelihood of success.
3. Some architectures are doomed from the start; learn to identify them early.
4. Document assumptions fully and confirm they are correct.

REFERENCES

[1] M. Maier and E. Rechtin, The Art of Systems Architecting, Third Edition, CRC Press, 2009.

[2] E. Ferguson, Engineering and the Mind's Eye, MIT Press, Cambridge, 1992

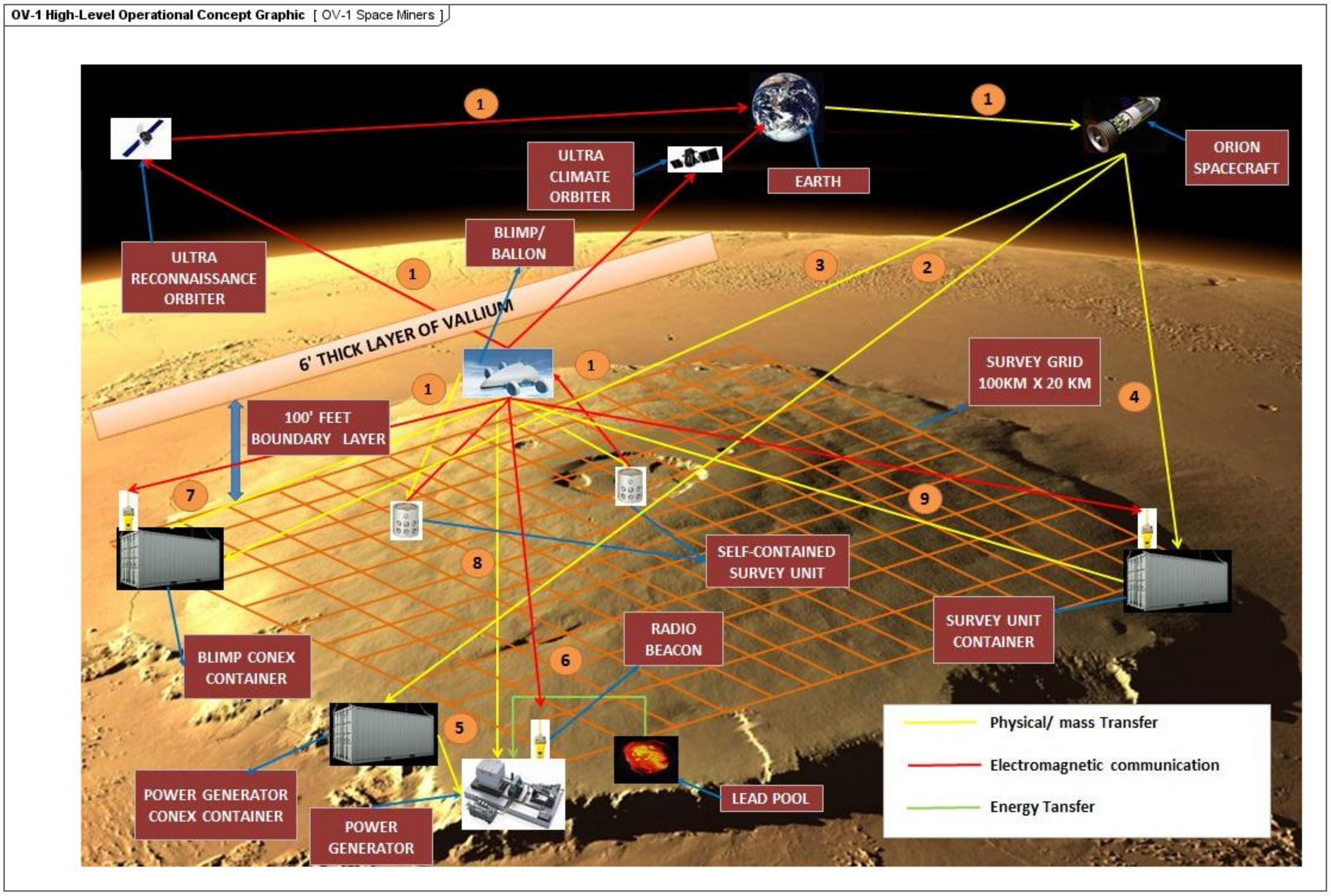

Figure 1: OV-1 for the single-blimp solution.

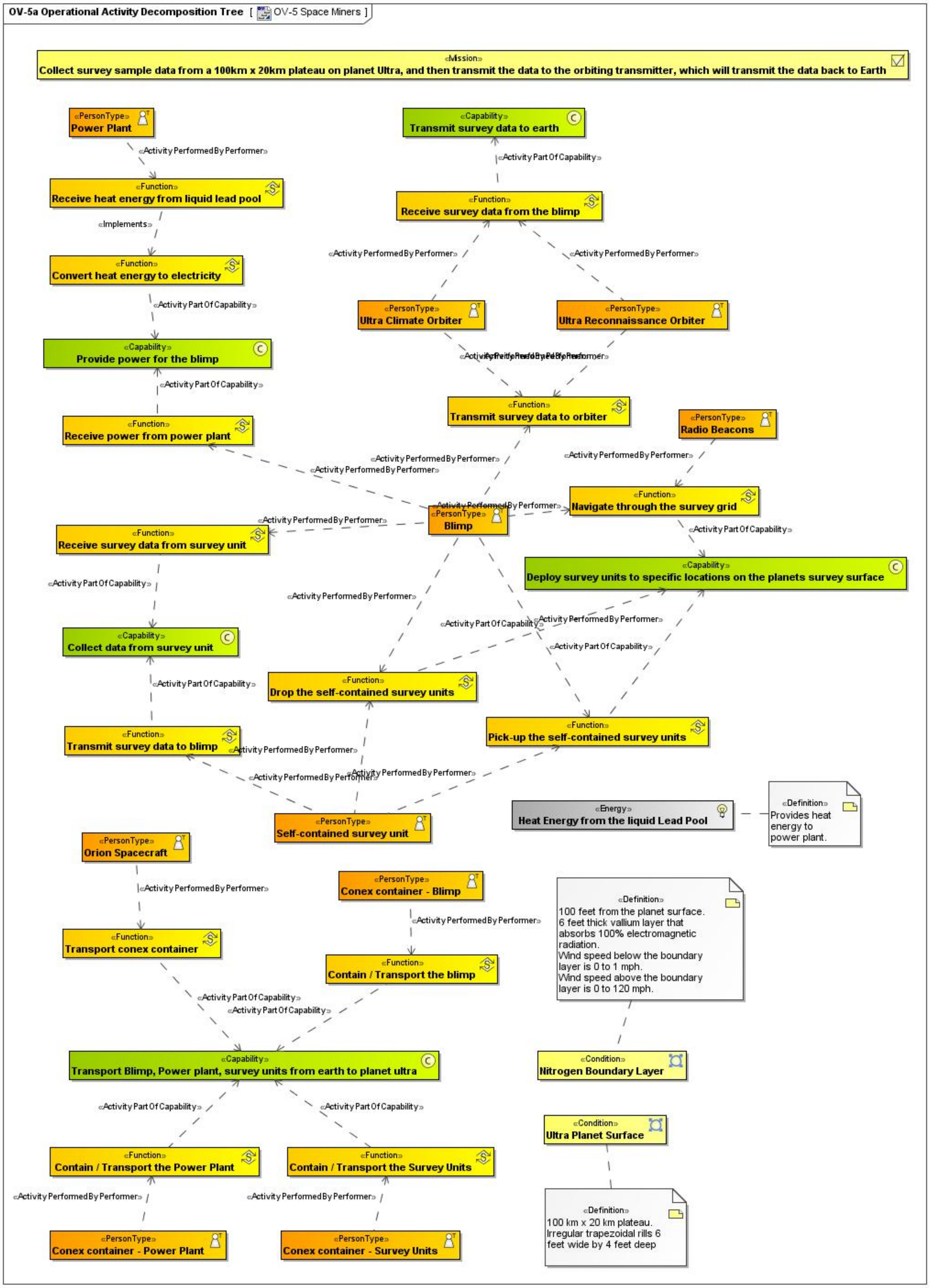

Figure 2: OV-5 for the single-blimp solution.

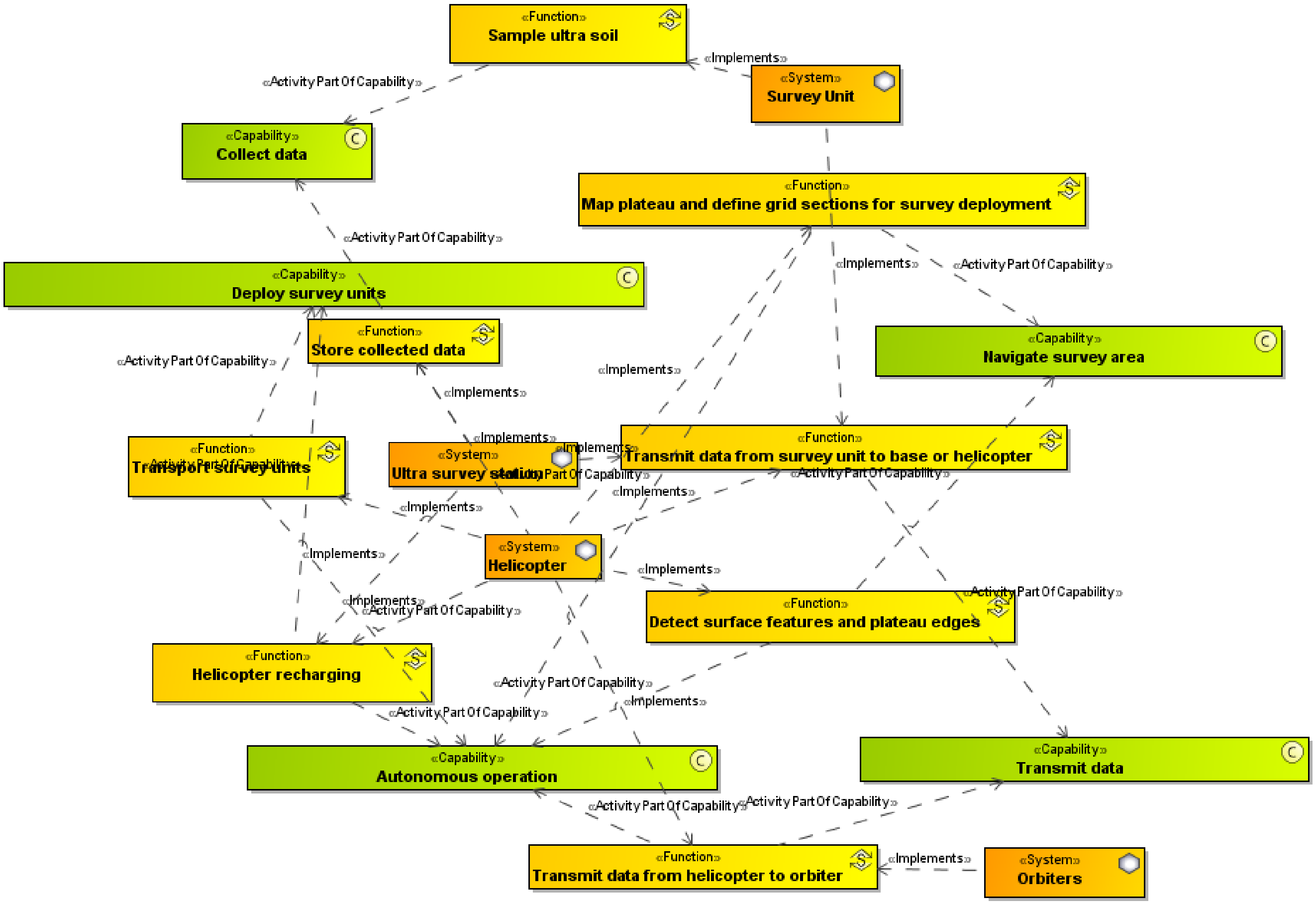

Figure 3: OV-5 for the Helicopter Proposal.

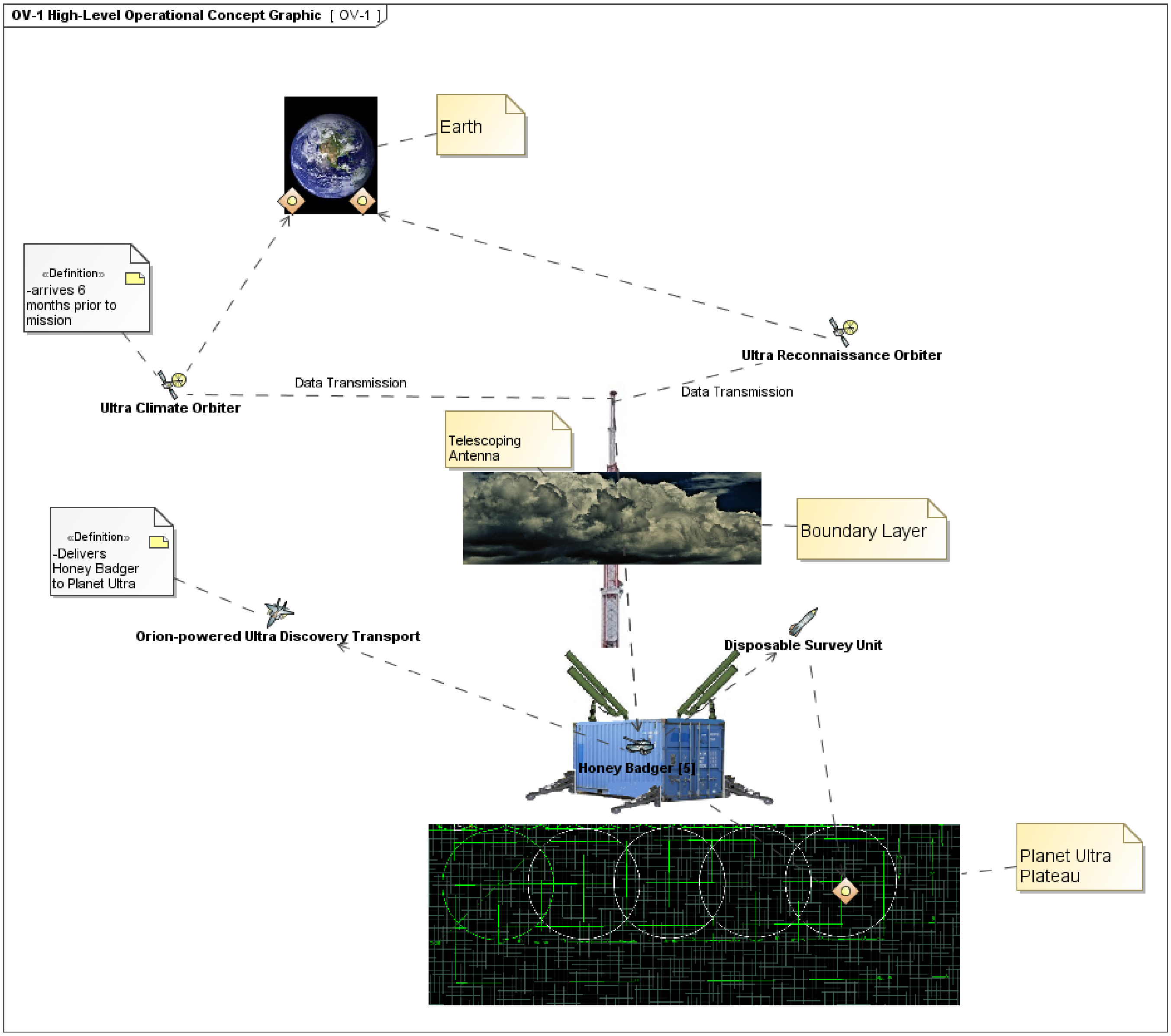

Figure 4: OV-1 for the Honey Badger Proposal.

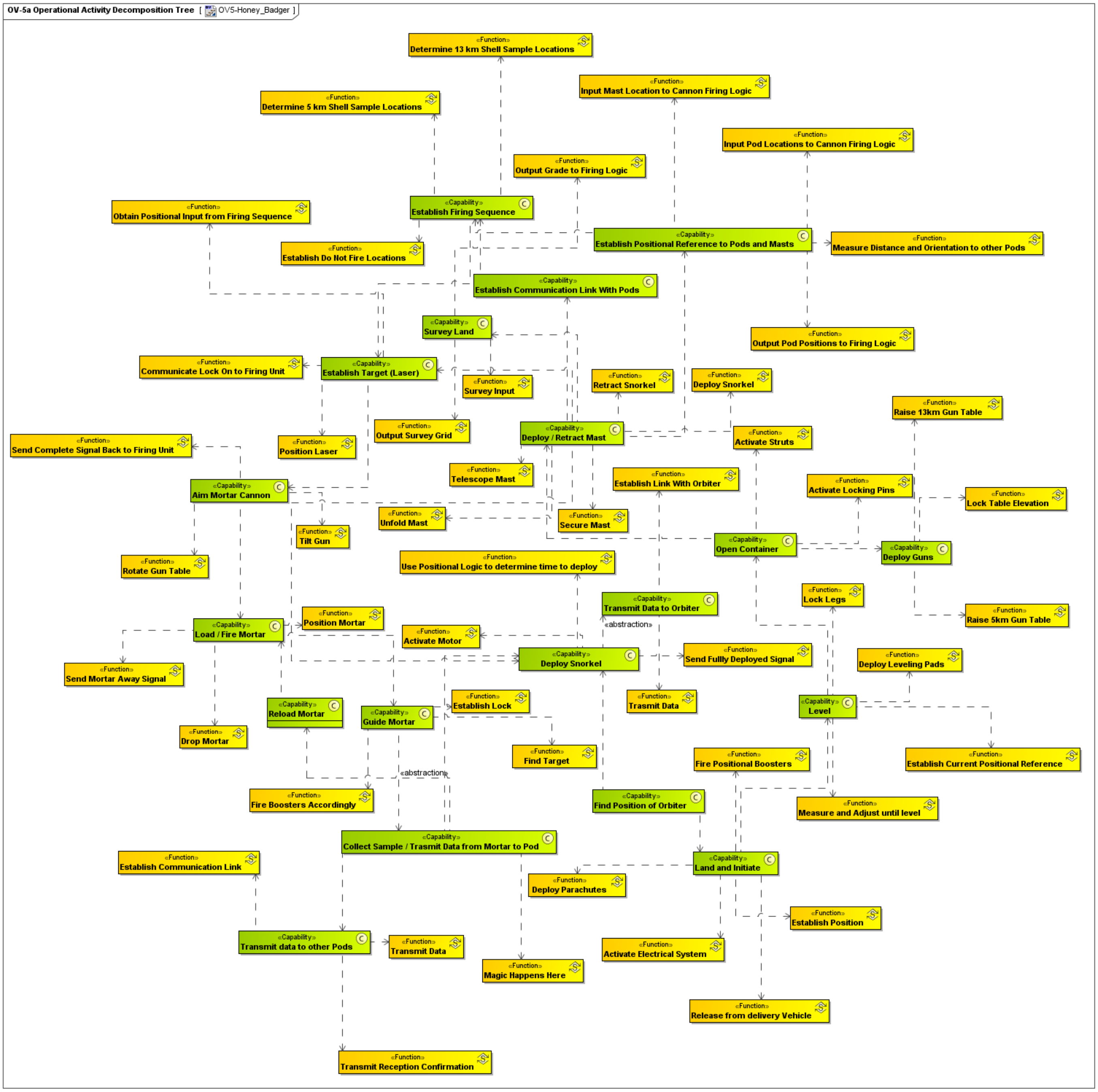

Figure 5: OV-5 for the Honey Badger Proposal.