AUTONOMY TECHNOLOGY CHALLENGES OF EUROPA AND TITAN EXPLORATION MISSIONS

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ABSTRACT

This paper discusses requirements for autonomy technology that arise from the unique attributes of proposed exploration missions to Titan, a moon of Saturn, and Europa, an ice-encrusted moon of Jupiter. Recently, the Project Design Center[1] at NASA Jet Propulsion Laboratory was the focal point for an intensive study of these missions. The mission to Europa tentatively includes a communications station on the surface of the ice, a "cryobot" which will melt through the ice to the ice/water interface, and a "hydrobot" which would free-swim under the water in a scientific search for hydrothermal vents. Autonomous commanding and fault protection technologies are key requirements of this mission, as well as the ability to conduct a science mission with very limited communication to other spacecraft or Earth. The proposed Titan mission includes an "Aerobot", a robotically controlled lighter-than-air vehicle. Part of the mission for the Titan Aerobot includes sampling and scientific analysis of surface materials. Some of the significant drivers of autonomy requirements on a Titan mission include the difficulty in selecting sampling sites, the consequences of long round trip light time delays for commanding, and exogenous events such as weather. Autonomous site selection, commanding, science operations, and robust fault detection, isolation and recovery are a few of the mission critical areas that are discussed in the paper.

INTRODUCTION

Europa is one of the highest priority targets in outer Solar System exploration. Liquid water is believed to exist beneath its highly fractured icy crust, perhaps forming a global ocean. At the bottom of this ocean there may be active volcanoes just as there are today on Europa's neighboring satellite Io. Most intriguing, life may exist near those volcanic vents, just as it is found on Earth: at great depths in the ocean, beyond the penetration of sunlight, thriving on upwelling chemical nutrients from the interior of the planet.[2] The driver for exploration of Europa is the discovery and description of its life.

Titan, the largest satellite of Saturn, is the only moon in the solar system with a substantial atmosphere. A dense nitrogen atmosphere, a haze of organic photochemical aerosols, liquid methane oceans, and potential volcanic activity make Titan a cauldron of activity. In remarkable environments like this, complex organic molecules are known to have formed, and these are the precursors of life. Among other goals, the search for these pre-biotic molecules is a priority for a Titan Aerobot mission.

These two missions present some of the most challenging requirements for autonomy technology in future space exploration. They represent several major shifts in what will be required by numerous future missions: Reactive planning in complex, dynamic environments, and; closed-loop interaction and decision-making in science data analysis.

EUROPA MISSION

The major goals of exploring Europa are:

1. Locate and describe the life forms in the Europa Ocean and ice crust

2. Evaluate the Europa Ocean, including its water, bottom, and ice cover, as a habitat for life. It is usually true that life is found at interfaces, and the bottom of the ice as well as the top of the sediment will both be key areas to explore.

3. Determine the long-term history of the Europan habitats and niches for unusual life forms. The discovery of so-called extremophile bacteria (bacteria that live where there are few of the normal food and other requirements for life) lead us to believe that truly novel life can evolve to be successful in a wide variety of niches.

The task of conducting exploration under the ice of Europa is vastly complex in every aspect including scientific strategy, space component, radiation environment, robotic systems for ice and ocean transportation, planetary protection, instrumentation, autonomy, and communications.

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The mission scenario developed in JPL's Project Design Center includes major components that would be landed on Europa: The *lander* which would deliver the science payload to the surface and serve as a communication relay (direct to Earth or to a relay satellite in Europa or Jupiter orbit), a penetrator called a "*cryobot*" which would melt through the Europan ice sheet and deliver the third component, a submarine "*hydrobot*" to the Europan ocean for exploration.

Figure 1: Europa Submarine, Artist's Conception[3]

The Europan environment itself embodies many challenges to exploration. High radiation at the surface, about 14 Mrads per year, indicates that a lander must not only be highly radiation resistant, but should burrow under the surface for additional shielding by the ice if it is to survive the prospective two year duration of the mission. According to Galileo gravity data, the cryobot delivery system must penetrate approximately 10 kilometers of ice. The hydrobot must travel to the bottom of the ocean to a potential depth of 200 kilometers (the upper limit on depth). The pressure at the bottom is around 3 kilobars, roughly three times the pressure at the bottom of Earth's Mariana Trench. The ambient water temperature is around 260 Kelvin, although temperatures will be significantly higher near hydrothermal vents. It will be very dark, so lights for imaging are required. Strong tidal or other currents may be present.

The most interesting, and challenging, aspect of the mission involves exploring the sediment in search of volcanic activity and life.

EUROPA: AUTONOMY SCENARIOS

There are significant autonomy challenges for all three vehicles, the lander, the cryobot, and the hydrobot. In this section we identify these challenges in the context of likely mission scenarios.

Arrival and Landing at Europa

Our data on Europa will be more complete by 2015 when this mission is to launch. Nevertheless, some key decisions may need to be made upon arrival at Europa. Choosing a landing target area will be accomplished before launch. However, as the lander approaches the surface, it will be important to choose a location on solid and level ice from which to launch the cryobot into the ice. With the highly variable Europa ice terrain, this is likely to be a significant challenge. The significant light-time delay dictates that this operation must be accomplished using on-board autonomous capabilities.

The Descent of the cryobot

Upon release from the lander, the cryobot will be propelled downward by gravity as it melts through the ice (see Figure 2). The cryobot must penetrate approximately 10 km of ice. The speed of descent is on the order of 1 km per month. There are likely to be many hazards in the ice to be avoided. Large rocks or heavy concentrations of smaller rocks and dust can block the path of the cryobot. Pockets of water embedded in the crust could lead to the cryobot being stopped or to the hydrobot being released into a closed bubble. The path of the cryobot can be altered slightly using differential heating of the skin of the cryobot. Sonar and other sensors can be used to gather information about the surrounding ice and to aid in navigation of the cryobot.

The cryobot will trail a communication link to the lander, either fiber optic micro cable or multiple deployed relay repeaters. With its slow descent, it may be possible to teleoperate the cryobot to a certain degree from Earth even with significant light-time delay. However, once the cryobot nears the water-ice boundary, it must quickly detect and anchor itself in competent ice a few meters above the water-ice boundry in order to provide a base of operation for the hydrobot. This operation must be largely autonomous. Accidentally bypassing the competent ice into the water could mean a catastophic loss of the mission.

The mission gets really interesting when we examine three key operational scenarios involving the hydrobot: Exploring the ice/water interface, descending to the sediment, and exploring the ocean floor.

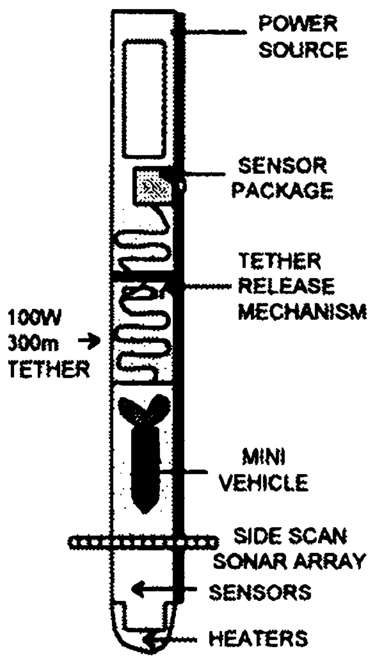

Figure 2: Early Crybot Concept[4]

Exploring the Ice/Water Interface

Life on Earth is often found at the boundaries of different environments. Exploring the immediate area around the cryobot when it first encounters the liquid Europan ocean is therefore an important scientific goal of the mission. The cryobot may use sonar to characterize the general shape of the ice/water interface. The hydrobot will then explore nooks and crannies in search of interesting chemistry and biosignatures. High bandwidth communication between cryobot and hydrobot in this realm are possible, which will facilitate coordination between cryobot and hydrobot as well as reduce the immediate requirements for hydrobot autonomy.

Descending to the Sediment

The descent to the Europa ocean floor is more than just a drop through the water. The mission study anticipated that no more than 72 bps may be available to the hydrobot for communication with the cryobot. These communications limitations will initially force the hydrobot to stay directly underneath the cryobot until reaching the sediment. Scientists would also like to study the environment at different depths in the water column below the cryobot.

These requirements indicate that the hydrobot cannot afford to send engineering data after starting its descent to the ocean floor. The hydrobot must reason about its own internal state, including analysis of its own engineering data to detect faults and appropiately modify its behavior to maximize science return.

Safely navigating a direct descent with uncertain tides and currents is an autonomy challenge. While descending, the hydrobot needs to reason about descent and lateral velocities in order to stay in acoustic contact with the cryobot and avoid crashing into the bottom.

Exploring the Europan Ocean Floor

In its travels through the Europan ocean, the hydrobot will use a combination of dead reckoning, inertial sensing, and the analysis of its surroundings to navigate. These, and imagery from side-scan sonar and other sensors, can be used to allow the hydrobot to maintain an estimate of its location relative to the cryobot.

Given the low communications bandwidth, the hydrobot will have to detect and pursue science opportunities with minimal interaction from Earth. This involves generating its own map of the bottom while out of communications, identifying potential targets for further study, performing the studies, and then returning to a place below the cryobot where it can uplink results.

A number of exploration patterns have been suggested. Owing to the limitations of telecommunications through seawater, the hydrobot must return to the vicinity beneath the cryobot in order to uplink data collected on its surveys. Even directly beneath the cryobot, communications capabilities are likely to be very limited. The most likely exploration patterns include "out and back" features, with multiple lobes in different directions centered on the spot immediately below the cryobot.

These mission attributes indicate that the hydrobot must have the ability to reason about when it can communicate, carefully select what to say, and maintain a coherent dialog with the cryobot over the course of the mission.

As the hydrobot explores the ocean floor it will search for hydrothermal vents using side-scan sonar, flash photography, and chemical and thermal sensors. The chemical and thermal sensors will most likely be used to simply follow gradients to their source. When in the vicinity of a vent, side-scan sonar maps of the area will allow the hydrobot to pin-point the vent. Once the vent has been located precisely, flash photographs of the vent will then be used to guide the taking of samples from the vent and its environs. This will include scraping the vent and bringing the sampled material closer to on-board sensors.

It will not be possible for the hydrobot to transmit all the collected scientific data to Earth due to both restricted communication opportunities and on-board data storage capacity. Priorities concerning data taken to support the science objectives will be established before launch. However, the data collected in each phase of the mission will need to be prioritized autonomously by the hydrobot for relay to Earth based on quality, information content, and relevance to mission objectives.

CORE AUTONOMY FOR THE EUROPA MISSION

There are clearly many technical challenges present in a mission to Europa. A few of the most central core autonomy technologies required for the Europa mission vehicles include reactive planning, data fusion and interpretation, and scalable computing.

Since the hydrobot will be out of touch with human controllers for extended periods, the effects of uncertainty and incomplete knowledge about the environment will make it infeasible to execute detailed plans generated on Earth. Such detailed plans might work reasonably well for short range missions at the ice/water interface, but hydrobot missions any significant distance away from the cryobot will need a planner to continuously adapt an abstract mission plan to the current context as it unfolds. Unexpected events are likely in a mission of this complexity in an uncertain, dynamic environment. Reactivity will also help make the most of scientific opportunities, such as the detection of a hydrothermal vent. Survivability is enhanced by reactivity and continuous planning as well. There is no static "safe" mode in which the hydrobot can stop and wait for instructions from Earth. The hydrobot must return to a point below the cryobot before it can communicate with Earth-based controllers. An appropriate response to engineering anomalies will require the vehicle to remain "fail operational" so that it can contact Earth if necessary and continue the mission. An approach to these continuous reactive planning requirements called "Iterative Repair Planning" is currently being pursued at JPL.[5]

In order to allow the cryobot and hydrobot to navigate, a number of different sensor modalities will have to be combined through data fusion. Using input from the sonar and chemical and thermal sensors, both the cryobot and hydrobot will have to form models of the world around them. The fusion of this data must result in a consistent stable model of the world which can be used both for navigation over thousand kilometer traverses and planning to achieve mission goals.

With a largely unknown environment, there will be much uncertainty in the vehicles' reasoning about its location in the world and in the data that it receive from the sensors. Missing and anomalous data will occur in many circumstances. For example, an area may be shadowed by an underwater obstacle, a fault may have caused a loss or corruption of data, or a damaged or faulty sensor may leave the robot partially blinded. This missing or anomalous data must be accommodated seamlessly without paralyzing the vehicles' ability to navigate autonomously.

In the absence of oversight from Earth, the lander, cryobot, and hydrobot must self-calibrate their instruments so that meaningful analysis can be performed on-board. As the robotic vehicles move through the Europan environment, conditions will change and the sensors and algorithms using sensor outputs will have to recalibrate and track the drift. Furthermore, although we generally assume that the environment will be stable in the short term, we must be prepared for it to change over the course of the mission (the Crybot will descend through the ice for ten months and the hydrobot will explore the ocean for up to twelve months). Both the ice/water boundary and the ocean floor may evolve with time (e.g., hydro thermal vents often appear suddenly) and the model of the world maintained by the robots will have to adapt accordingly.

Underlying many of the autonomy technologies required for the Europa mission is the ability to process images and other sensor data to recognize and classify patterns of interest. Classification is carried out in the presence of noise which is inherent in the environment and the sensor modalities. Robust noise-tolerant algorithms for classification have yet to be developed. Unique classification methods that operate over multiple dynamically-evolving data sets must also be developed. These will be key in the search for underwater hydrothermal vents. For example, combinations of water temperature and concentrations of dissolved gases may be used to help identify the direction and location of underwater vents. Some of the most important classification algorithms that must be developed are in the area of biosignature recognition.

The Europa hydrobot promises to have the most computationally intensive operations of any future mission, and much of this derives from the requirements for autonomy. With many different semi-independent computational subsystems such as the planner, navigator, world modeler, data acquisition, and data analysis all vying for computational resources, parallel processing and intelligent scheduling of tasks will be necessary to get everything done in an efficient and robust way.

TITAN MISSION

Titan, the largest satellite of Saturn, is the only moon in the solar system with a substantial atmosphere. The dense nitrogen atmosphere has twice the surface pressure of that of Earth. This makes it practically ideal for exploration with Aerobots.[6] A ubiquitous haze layer of organic photochemical aerosols obscures the surface from observation from space except with radar. (In the Los Angeles area, we would refer to this as a "class one million smog alert"!) An in situ vehicle penetrating beneath the haze layer may find a remarkable low temperature world in which familiar features of Earth such as oceans, rainfall and volcanic activity appear. The surface may be include liquid oceans, solid features, and slush. The oceans may be composed of liquid methane, the rain made up of drops of methane and liquid nitrogen and the lavas pouring on to the surface formed of liquid water and ammonia. In this remarkable cauldron of activity. complex organic molecules are known to have formed and prebiotic molecules may exist. The highest scientific priority at Titan is the chemical analysis of surface materials.

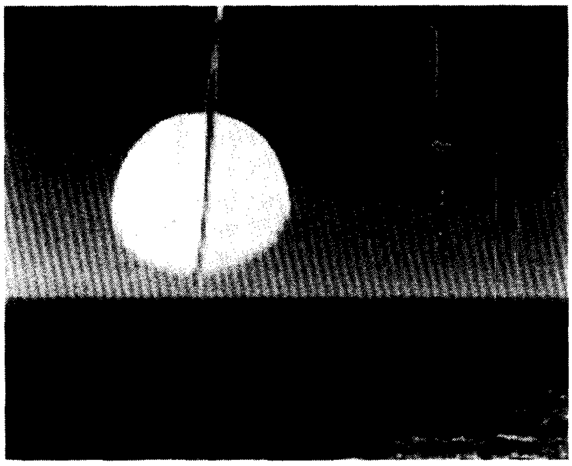

Figure 3: Titan Aerobot, Artists Conception

Some of the high level objectives for a Titan Aerobot mission would include:

- Characterize surface morphology below haze layer.
- Make low atmosphere chemical composition measurements.
- Sample surface (liquid and solid) organic chemistry and "mineralogy" at designated sites.
- Contribute to understanding of global atmosphere dynamics and winds.
- Perform global inventory of surface volatiles.

The mission concept includes a Titan orbiter and a planetary aerobot. The orbiter would be used both as a science platform and for data relay, either direct to Earth or possible relay via the Cassini spacecraft in orbit around Saturn. The planetary aerobot would descend into Titan's atmosphere for direct in-situ measurements and exploration. Planetary aerobots are robotically controlled lighter-than-air vehicles. Titan's dense atmosphere, extreme but uniform temperature environments, and challenging surface environment make it a good candidate for exploration with aerobots.

TITAN: AUTONOMY SCENARIOS

After aerocapture and insertion into the Titan atmosphere, the Titan aerobot would drift longitudinally with the Titan winds. Periodically, the aerobot would descend to a targeted point on the surface for sampling and other tests. The concept for the primary mission requires sampling from a minimum of ten separate sites around Titan.

There are several driving challenges for autonomy in the mission concept: The aerobot must select target sites for sampling as it floats over the world. The aerobot must navigate from high altitude to the targeted site, and conduct the sampling operation. The aerobot must respond safely to exogenous events, such as weather. And the aerobot must make the best use of the available bandwidth of the communications relay to send the highest priority data back to Earth. We will discuss each of these in turn.

The selection of sites for surface sampling and analysis poses one of the first challenges. Due to the layers of atmospheric haze, it is impossible for the sampling sites to be pre-selected from orbiter data. Similarly, round trip light time delays of three hours or more prohibit real-time selection of sampling sites by scientists on Earth: By the time a site was selected, the aerobot is likely to have drifted past a point where it can descend from altitude to the target. By integrating data from a variety of instruments onboard the aerobot gondola, the aerobot must be able to autonomously identify a desirable site for sampling when the opportunity arises.

Before the mission, we can provide the aerobot with several heuristics to aid in site selection. For example, the first two or three sampling sites are likely to be "safety" driven, that is, we want to sample from areas where the relevant systems can be exercised and samples collected without substantial risk to the mission. Risks might arise for example, from snagging on rough terrain and this would suggest that a safe site is one with a relatively smooth surface. Other heuristics might include: sample from areas with whose albedo contrasts with nearby areas, sample from a variety of topographic surface types (e.g., shorelines, valleys, cliffs), and sample a certain distance between sites. From aerobot imagery, we may be lucky to see and extract scientific features that could be useful sampling targets, such as geysering. While helpful, these heuristics are not sufficient to help select desirable sampling sites. Although we may have a limited amount of surface topography information of from the Huygens probe on a coarse level, the bottom line is that we won't know the precise characteristics of scientifically desirable sample sites until the aerobot has arrived at the planet and captured and analysed several samples. This consideration suggests that a trainable recognizer for science site selection will be required.

Once a sampling site has been selected, the next challenge is to reach it so that sampling mechanisms can be deployed This need not occur directly at the surface; a variety of sample collection mechanisms from low altitude are under consideration including deployable instrumented snakes, sondes, and other tethered sampling paraphernalia.[7]

Like most balloons, the aerobot has only vertical control for ascent and descent. Otherwise, it is at the mercy of the Titan winds. These winds are estimated to be tens of kilometers per hour at five thousand meters ("cruise") altitude, and about 1 kilometer per hour at the surface. With three hour round trip light time delay from Earth, commanding the descent to a target sampling area must be conducted autonomously on-board the aerobot. As the aerobot descends, it may easily drift laterally and thereby bypass the targeted site. A better approach would be for the aerobot to select several target sites, and then plan a descent trajectory that will give it the highest potential of reaching the highest value sites. The planned trajectory would be monitored and altered as necessary to achieve the goal. To do this, the planning system must have an understanding of the scientific value of the target sites, and use this information to set appropriate goals.

The success of the aerobot's mission is dependent on its ability to plan and execute effective operations in the context of what is likely to be a very dynamic weather environment. Methane rain, storms, winds, lightning and other meteorological phenomena will affect the aerobot's plans on a continuous basis. The aerobot planner will be able to make better plans if it can adapt and correct it's predefined model of Titan weather effects using experiential data. Similarly, over the course of an extended mission lasting several Titan seasons, it is reasonable to expect on-board anomalies and other contingencies to arise, some due to weather effects (e.g., charge build-up, corrosion) and some due to equipment or software malfunctions. The aerobot should have the ability to plan flexibly in the context of a degradation of its capabilities to continue the mission.

The vast majority of the volume of Titan aerobot scientific data will consist of imagery. Other instruments in the baseline mission concept include a gas chromatograph mass spectrometer (GCMS), an x-ray flourescence instrument (XRF), an infra-red spectrometer, specialized instruments for study of pre-biotic chemistry, a complete wet chemistry lab, and radar. Although onboard data storage will be prodigious relative to current missions, it will nevertheless be oversubscribed. Scientists will undoubtedly demand certain types of data be returned, and this will pose and additional constraint on the resources. Furthermore, data relay to the orbiter will be intermittent and have limited bandwidth. The aerobot therefore must have the ability to decide what data to keep and what data to transmit back first. For example, imagery (wide angle or narrow-angle) may reveal important scientific features that cannot be reached by the current balloon pass. These features can be flagged and prioritized for later download to Earth.

CORE AUTONOMY FOR THE TITAN MISSION

The Titan aerobot mission requires an unprecedented degree of autonomous decision-making and commanding. Many of the technology needs are shared with other in-situ explorations, such as the Europa Ocean exploration. A few of the most central core autonomy technologies required for the Titan mission include:

- closed-loop sensing, planning, and execution;
- goal-based commanding, resource management, fault detection, fault isolation and fault recovery;
- contingency planning;
- adaptive planning;
- adaptive modeling;
- autonomous science image feature detection;
- on-board science data processing.

Technology development for these capabilities is challenging and a very active area of research. Current research at JPL is pursuing variants on an architecture consisting of four fundamental components: a mission manager, a planner scheduler, a diagnostics executive, and a real-time controller.[8,9] While the real-time controller implements activities by managing feedback control loops, the diagnostics executive determines the internal state and external surroundings by monitoring (and possibly aborting) the feedback loops. Given the context determined by the executive, the planner scheduler reasons about desired future activities and instructs the executive what to do next. Finally, the mission manager determines mission and context dependent goals to motivate future desired activities. These activities are computed and maintained by the planner.

Different technology alternatives implement these components in different ways. In some cases components are even merged into a single rule-based expert system on top of a real-time control system. The main development issue involves how much reasoning is performed at each level, and whether the levels interact continuously or intermittently. For instance, the DS1 remote agent has an executive that continuously interacts with the real-time system, but the planner scheduler only wakes up intermittently to interacts with the executive. The component technologies are described more fully elsewhere.[10]

A key research topic is how to deal with uncertainty in both the world model and the results of the actions of the aerobot robot on the world. For instance, in an aerobot descent, reducing the buoyancy a certain amount for a given time will not necessarily result in the predicted vertical movement unless the atmospheric pressure and winds aloft are taken into account during plan execution. Ideally, the world modeling system would be able to use experiential data to reduce the uncertainty for future descent plans.

One of the key attributes of the algorithms used to provide the autonomy capabilities is that they must produce results in an incremental fashion such that they can be stopped any time and produce the current best answer. Anytime algorithms are needed so that resources can be redistributed quickly if necessary instead of being tied up with lengthy calculations before producing a high quality answer. Also, if more resources are available, the algorithms can be run longer in order to achieve a more precise answer. The algorithms also need to scale with the resources available to them. The resources available may change due to usage by higher priority tasks or partial failure of the computing hardware.

SUMMARY

In this paper, we have outlined the autonomy challenges for two of the next millenia's most exciting and challenging missions: Exploration of the oceans of Europa and the atmosphere and surface of Titan. Some of the component autonomy requirements are common to both missions, such as the ability to make and execute plans in a highly uncertain and dynamic environment, with limited ability to interact with Earth-based mission controllers. Another common attribute of these missions is the need to include science planning, data collection, and data interpretation in a closed-loop with autonomous mission planning.

Current autonomy technology research programs have been occupied for years with developing robust component systems, such as planners, diagnostic systems, and science data analysis systems. Considerable progress has been made and these systems are now entering routine use in ground applications. Only recently have some of these components come together in technology flight experiments, such as the DS1 Remote Executive Experiment (RAX). To achieve the level of readiness required for the Europa and Titan missions, considerable new research effort needs to be made to bring scientific judgement into the autonomous control loop of these systems. Despite the fact that these missions are at least a decade away, the time seems short.

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NOTES

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