Autonomy Requirements Engineering: A Case Study on the BepiColombo Mission

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ABSTRACT

The development of unmanned space exploration missions is closely related to integration and promotion of autonomy in robotic spacecraft. Elicitation and expression of autonomy requirements is one of the most significant challenges the autonomous spacecraft engineers need to overcome. Nowadays, requirements engineering for autonomous systems appears to be a wide open research area with no definitive solution yet. This paper presents an approach to Autonomy Requirements Engineering where Goal-Oriented Requirements Engineering is merged with special Generic Autonomy Requirements. To provide a solution to the domain of space missions, the Generic Autonomy Requirements are put in the context of space missions. Further, the approach is applied to a case study based on the ESA's BepiColombo Mission where mission's autonomy requirements are elicited.

Categories and Subject Descriptors

D.2.1 [**Requirements/Specifications**]: Elicitation methods; Methodologies; I.2.9 [**Robotics**]: Autonomous vehicles;

General Terms

Algorithms, Design, Experimentation, Performance

Keywords

autonomy, requirements engineering, BepiColombo, ESA

1. INTRODUCTION

In their new space exploration initiatives, ESA and NASA emphasize unmanned exploration, often with limited or no human control. The robotics space missions rely on the most recent advances in automation and robotic technologies where autonomy and autonomic computing principles drive the design and implementation of unmanned spacecraft [1]. However, the integration and promotion of autonomy in spacecraft as software-intensive systems is an extremely challenging task. Among the many challenges the engineers must overcome are those related to the elicitation and expression of *autonomy requirements* [1]. To help with these and other related issues, Lero – the Irish Software Engineering Research Center, is currently conducting a joint project with ESA targeting an Autonomy Requirements Engineering (ARE) approach where Goal-Oriented Requirements Engineering (GORE) [2] is used along with a new model for Generic Autonomy Requirements (GAR) [3] put in the context of space missions [1].

In this paper, we present our ARE approach along with a case study where ARE is applied to elicit autonomy requirements for the ESA's BepiColombo Mission [4, 5, 6, 7, 8, 9]. Note that the paper is a follow-up to [1] where we presented our GAR for space missions.

The rest of this paper is organized as follows. Section 2 elaborates on our ARE model. Section 3 presents the BepiColombo Mission. In Section 4, we apply our ARE model to elicit autonomy requirements (self-* objectives) for BepiColombo. Finally, Section 5 presents a brief conclusion and future work.

2. ARE - AUTONOMY REQUIREMENTS ENGINEERING

A comprehensive and efficient ARE approach [1] should take into account all the autonomy aspects of a targeted system and emphasize the so-called *self-* requirements* [3] by taking into consideration the traditional *functional* and *non-functional requirements* of spacecraft systems (e.g., safety requirements). The proposed ARE model 1) relies on GORE [2] to elicit and define the system goals; and then 2) uses GAR [1, 3] put in the specific system's context to derive and define assistive and often alternative goals (objectives) the system may pursue in the presence of factors threatening the achievement of the initial system goals. Once identified, the autonomy requirements might be further specified with languages complying with GAR (e.g., ASSL [10] or KnowLang [11]).

2.1 GAR – Generic Autonomy Requirements

Despite their differences in terms of application domain and functionality, all autonomous systems are capable of autonomous behavior driven by one or more *self-management objectives* [3]. Thus, the development of *autonomous systems* is driven by the self-management objectives (also could be considered as self-adaptive objectives) and attributes, which introduce special requirements termed *self-* requirements* [3]. Note that this requirement automatically involves 1) self-diagnosis (to analyze a problem situation and to determine a diagnosis), and 2) self-adaptation (to repair the discovered faults). The ability to perform adequate self-diagnosis depends largely on the quality and quantity of the system's knowledge of its current state, i.e., on the

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system awareness. Based on the self-* requirements, our GAR model defines a set of generic autonomy requirements [3, 1]:

- **Autonomicity (self-* objectives)** - Autonomicity is one of the essential characteristics of autonomous systems. The self-* objectives provide autonomous behavior (e.g., self-configuring, self-healing, self-optimizing, and self-protecting).
- **Knowledge** – An autonomous system is intended to possess awareness capabilities based on well-structured knowledge and algorithms operating over the same.
- **Awareness** – A product of knowledge representation, reasoning and monitoring.
- **Monitoring** – The process of obtaining raw data through a collection of sensors or events.
- **Adaptability** – The ability to achieve change in observable behavior and/or structure. Adaptability may require changes in functionality, algorithms, system parameters, or structure. The property is amplified by self-adaptation.
- **Dynamicity** – The technical ability to perform a change at runtime. For example, a technical ability to remove, add or exchange services and components.
- **Robustness** – The ability to cope with errors during execution.
- **Resilience** - A quality attribute prerequisite for resilience and system agility. Closely related to safety, resilience enables systems to bounce back from unanticipated disruptions.
- **Mobility** – A property demonstrating what moves in the system at both design time and runtime.

In addition, GAR defines important considerations for building autonomous systems such as:

- Autonomous systems must continuously monitor changes in its context and react accordingly.
- What aspects of the environment should such a system monitor? - Clearly, the system cannot monitor everything.
- Exactly what should the system do if it detects less than optimal conditions in the environment?
- The system needs to maintain a set of high-level goals that should be satisfied regardless of the environmental conditions.
- Eventually, non-critical goals could be not that strict, thus allowing the system a degree of flexibility during operation.

2.2 GORE for ARE

The Goal-Oriented Requirements Engineering (GORE) has extended upstream the software development process by adding a new phase called *Early Requirements Analysis*. The fundamental concepts used to drive the goal-oriented form of analysis are those of *goal* and *actor*. To fulfill a stakeholder goal, GORE [2] helps engineers *analyze the space of alternatives*, which makes the process of generating functional and non-functional (quality) requirements more systematic in the sense that the designer is exploring an *explicitly represented* space of alternatives. GORE produces *goals models* that represent system objectives and their inter-relationships. Goals are generally modeled with *intrinsic features* such as their type, actors and targets, and with *links* to other goals and to other elements of the requirements model (e.g., constraints). Goals can be hierarchically organized and prioritized where high-level goals (e.g., mission objectives) might comprise related, low-level, sub-goals that can be organized to provide different alternatives to achieving the high-level goals.

In our approach, we merge GORE with GAR to arrive at goals models where system goals are supported by self-* objectives promoting autonomicity in system behavior.

3. BEPICOLOMBO MISSION

BepiColombo is an ESA mission to Mercury [4, 5, 6, 7, 8, 9, 12] (see Figure 1) scheduled for launching in 2015. BepiColombo will perform a series of scientific experiments, tests and measures. For example, BepiColombo will make a complete map of Mercury at different wavelengths. Such a map, will chart the planet's mineralogy and elemental composition. Other experiments will be to determine whether the interior of the planet is molten or not and to investigate the extent and origin of Mercury's magnetic field.

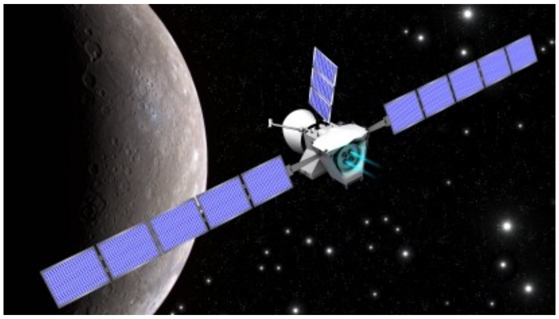

Figure 1. BepiColombo Arriving at Mercury [12]

The space segment of the BepiColombo Mission consists of two orbiters: a *Mercury Planetary Orbiter (MPO)* and a *Mercury Magnetospheric Orbiter (MMO)*. Initially, these two orbiters will be packed together into a special *composite module* used to bring both orbiters into their proper orbits. Moreover, in order to transfer the orbiters to Mercury, the composite module is equipped with an extra electric propulsion module both forming a *transfer module*. The transfer module is intended to do the long cruise from Erath to Mercury by using the electric propulsion engine and the gravity assists of Moon, Venus and Mercury. The transfer module spacecraft will have a 6 year interplanetary cruise to Mercury using solar-electric propulsion and Moon, Venus, and Mercury gravity assists. On arrival in January 2022, the MPO and MMO will be captured into polar orbits. When approaching Mercury in 2022, the *transfer module* will be separated and the *composite module* will use rocket engines and a technique called *weak stability boundary capture* to bring itself into polar orbit around the planet. When the MMO orbit is reached, the MPO will separate and lower its altitude to its own operational orbit. Note that the environment around Mercury imposes strong requirements on the spacecraft design, particularly to the parts exposed to Sun and Mercury: solar array mechanisms, antennas, multi-layer insulation, thermal coatings and radiators.

The Mercury Planetary Orbiter (MPO) is a three-axis-stabilized spacecraft pointing at nadir. The spacecraft shall revolve around Mercury at a relatively low altitude and will perform a series of experiments related to planet-wide remote sensing and radio science. MPO will be equipped with two rocket engines nested in two propulsion modules respectively: a *solar electric propulsion module* (SEPM) and a *chemical propulsion module* (CPM). Moreover, to perform scientific experiments, the spacecraft will carry a highly sophisticated suit of eleven instruments [13].

The Mercury Magnetospheric Orbiter (MMO) is a spin-stabilized spacecraft in a relatively eccentric orbit carrying instruments to perform scientific experiments mostly with fields (e.g., Mercury magnetic field), waves and particles. Similar to MPO, MMO is also equipped with two propulsion modules: a *solar electric propulsion module* (SEPM) and a *chemical propulsion module* (CPM). MMO has altitude control functions, but no orbit control functions. MMO's main structure consists of: *two decks* (upper and lower), a *central cylinder* (thrust tube) and four *bulkheads* [7]. The instruments are located on both decks. The MMO spacecraft will carry five advanced scientific experiments [13].

4. ARE FOR BEPICOLOMBO

4.1 GORE for BepiColombo

By applying GORE, we build *goals models* that can help us consecutively derive and organize the *autonomy requirements* for BepiColombo. In our approach, the models provide the starting point for ARE (Autonomy Requirements Engineering) for BepiColombo by defining 1) *the objectives of the mission* that must be realized in 2) *the system's operational environment* (space, Mercury, proximity to the Sun, etc.), and by identifying the 3) *problems that exist in this environment* as well as 4) *the immediate targets supporting the mission objectives* and 5) *constraints* the system needs to address. Moreover, GORE helps us identify the *mission actors* (mission spacecraft, spacecraft components, environmental elements, base station, etc.). In this exercise, we do not categorize the objectives' actors, but for more comprehensive requirements engineering, actors might be categorized by role or by importance (e.g., main, supporting and offstage actors). Further, the requirements goals models can be used as a *baseline for validating the system*.

BepiColombo's main objective is to explore Mercury and its environment. In addition, the BepiColombo mission is going to addresses fundamental science and minor-body issues as described in [4].

4.1.1 High-level Mission Objectives

ESA imposes to BepiColombo three high-level objectives [4]:

- *Study Mercury*: Gather complimentary data about planetary formation in the hottest part of the proto-solar nebula:
    - **Actors:** *MPO Spacecraft* (Mercury Planetary Orbiter), *MMO Spacecraft* (Mercury Magnetospheric Orbiter), *the Sun*, *Base on Earth*.
    - **Targets:** *Mercury*
- *Study relativity*: Gather data for testing general relativity and exploring the limits of other metric theories of gravitation with unprecedented accuracy:
    - **Rationale**: The discovery of any violation of general relativity would have profound consequences to theoretical physics and cosmology.
    - **Actors:** *MPO Spacecraft* (Mercury Planetary Orbiter), *MMO Spacecraft* (Mercury Magnetospheric Orbiter), *the Sun*, *Base on Earth*.
- *Possible impacts*: Observe minor bodies with semi-major axes of less than 1 AU (the so-called Atens and Inner-Earth Objects), which may possibly impact Earth:
    - **Actors:** *MPO Spacecraft* (Mercury Planetary Orbiter), *MMO Spacecraft* (Mercury Magnetospheric Orbiter), *Base on Earth*.
    - **Targets:** *minor bodies with semi-major axes of less than 1 AU.*

4.1.2 Middle-level Mission Objectives

The middle-level mission objectives provide a detailed realization of the high-level mission objectives (see Section 1.1.1). Thus, a high-level mission objective can be broken down into a few middle-level mission objectives, inheriting the properties of that high-level objective. The following elaborates on the middle-level objectives:

- *Unseen hemisphere*: Discover (photograph and analyze) the unseen hemisphere of Mercury:
    - **Rationale**: The Mercury's unknown hemisphere might appear to be quite different than the known one (similar to the Moon).
    - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
    - **Targets**: Along with photographing the *unseen hemisphere* a supplementary target is a *gigantic dome* on that hemisphere (a ground-based radar observations suggest the presence of a lineament).
- *Geological evolution*: Gather data about the planet's geological evolution. Investigate inter-crater plains, scarps, faults and lineaments:
    - **Rationale**: The planet's surface has traces of various exogenic (bombardment) and endogenic processes.
    - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
    - **Targets**: *large scarps*, *faults* and *lineaments* (such can be induced by phenomenons like the relaxation of the *equatorial bulge*, the contraction due to the cooling of the *mantle*, and the tidal stresses caused by the highly eccentric *planet's orbit*.
- *Tectonic activity*: Explore if Mercury is tectonically active.
    - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
    - **Targets**: *planet's crust.*
- *Chemical analysis*: Perform chemical composition analysis of the planet's surface. Build a mineralogical and elemental composition map of the surface.
    - **Rationale**: This will provide the means of distinguishing between various models of the origin and evolution of the planet.
    - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
    - **Targets**: the *ironoxide content of silicates* (an indicator of the condensation temperature of the solar nebula during the accretion of the planet); the *concentration ratio* of key elements such as *potassium*, *uranium*, and *thorium* (an indicator of the temperature scale of the feeding zone where the body was accreted).
- *Mercury's density*: Investigate the anomaly of the high Mercury's density.

  - **Rationale:** The density of Mercury does not line up with those of the other terrestrial planets, including the Moon. When corrected for compression due to size, it is the largest of all.
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
  - **Targets**: *the iron concentration* in the different regions on the *planet's surface* (supposedly, it was larger in the feeding zone where the planet accreted); *metal oxides* (supposedly, oxides were reduced to metallic form due to the proximity of the Sun); the concentration *of materials with high condensation temperature* (supposedly, the temperature of the young Sun was sufficient to sublimate and blow off silicates, thereby leaving only materials with higher condensation temperatures; *traces of gigantic impacts* (supposedly, the initial composition of the planet has been significantly altered by gigantic impacts, which may have removed a substantial part of the mantle).
- *Internal structure*: Analyze the Mercury's internal structure and find out if there is a liquid outer core.
  - **Rationale:** The high density suggests a relatively *large iron core* in which 70 to 80% of the planetary mass is concentrated, and implies a low moment of inertia factor.
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
  - **Targets:** *concentration of sulphur* on the *planet's surface* (the presence of a small percentage of this element - 1 to 5%, could account for the molten shell, because this element would depress the freezing point of the core alloy); *global shape*, *gravity field* and *rotational state* (these parameters are required to estimate the radius and the mass of the core);
- *Magnetic field*: Investigate the origin of the Mercury's magnetic field.
  - **Rationale:** The existence of the Mercury's magnetic field was discovered by Mariner-10 [1] The field is relatively weak (a few 100 nT at the equator equivalent to about one hundredth of that of the Earth) and could be generated by an internal hydro-magnetic dynamo driven by a liquid shell, perhaps 500 km thick, in the outer core [1].
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
  - **Targets:** *magnetic field, internal dynamo* (detailed mapping of the magnetic field will provide the necessary constraints on the structure and mechanism of the *internal dynamo*).
- *Solar wind*: Investigate the impact of the solar wind on the planetary magnetic field in the absence of any ionosphere.
  - **Rationale:** The *magnetosphere of Mercury* (the Hermean magnetosphere) is exposed to a *solar-wind density* and an *interplanetary magnetic field* (IMF) which are 4 to 9 times larger than at 1 AU.
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *the Sun, Base on Earth*.
  - **Targets:** *solar wind, magnetosphere of Mercury*, *magnetospheric currents* (the topology of the currents might differ significantly from that observed at the Earth, due to the absence of an ionosphere and the massive emission of photoelectrons on the dayside); *magnetospheric sub-storms* (could be triggered by the IMF reversals or internal instabilities); *IMF reversals and IMF variations*; *possible radiation belts* (could cause perturbations in planetary magnetic field); *field-line resonances; reflection properties of the planetary surface* (could cause field-line resonances).
- *Water ice*: Look for water ice in the permanently shadowed craters of the Polar Regions.
  - **Rationale:** Mercury is a world of extreme temperatures. The surface temperature at the sub-solar point reaches 700 K (427°C), but it can be as low as 100 K (-173°C) in shadowed areas.
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
  - **Targets:** *Mercury's Polar Regions, water ice, sulphur* (a major discovery was made by radar observations in 1992 about the a possibility that water ice or sulphur may be present in permanently shadowed craters near the poles, deposited there by meteorites or diffused and trapped from the planet's crust).
- *Exosphere*: Find out the volatiles composing the exosphere of Mercury.
  - **Rationale:** Mercury has no stable atmosphere. The gaseous environment of the planet is best described as *exosphere*, i.e., a medium so rarefied that its neutral constituents never collide.
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Base on Earth*.
  - **Targets:** *the elements O, H, Ne, Na and K* (discovered in the exosphere of Mercury by Mariner-10 and by ground-based observations); *other elements and possible ice near the poles* (may be detected using UV spectroscopic observations of the limb); *in-falling micrometeorites* (solar photo and ion sputtering, and impact vaporization may be used to study such meteorites).
- *Test relativity*: Use the proximity of the Sun to test general relativity with improved accuracy.
  - **Rationale:** A Mercury orbiter offers a unique opportunity to test general relativity and alternative theories of gravity.
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, the *Sun*, *Mercury*, *Base on Earth*.
  - **Targets:** *solar occultations* (solar occultations can provide for classical tests that can be repeated with improved accuracy; new experiments based upon different observable quantities can be performed due to the proximity of the Sun and the high eccentricity of Mercury's orbit); *deflection of radio waves by the Sun*, *time delay of radio signals* (can be used for classical test when Mercury is in its perihelion); *perihelion of Mercury* (the best time to perform relativity tests); *position tracking, gravity field of Mercury, non-gravitational accelerations due to radiation pressure* (these factors influence the gravity experiments, e.g., a precision spacecraft tracking is required along with accurate measurement of non-gravitational accelerations, in particular the radiation pressure and the gravity field of Mercury).
- *Cosmic impactors*: Investigate the possible threats for the Earth coming from cosmic impactors.

  - **Rationale:** BepiColombo has the potential to observe cosmic impactors at distances from the Sun as small as 0.4 AU.
  - **Actors:** *MPO Spacecraft*, *MMO Spacecraft*, *Mercury*, *Earth*, *Base on Earth*.
  - **Targets:** *small space objects between Mercury and Earth*

4.1.3 Low-level Mission Objectives

This level covers preliminary-stage or supporting objectives. Such objectives support the middle-level objectives.

- *Launch*: Bring the spacecraft out of Earth's orbit.
  - **Rationale:** Launch opportunities of typically one-month duration for BepiColombo are dictated by positions of the *Earth*, *Venus*, and *Mercury*, allowing the spacecraft to follow its intricate interplanetary trajectory. The next launch opportunity to Mercury occurs in August 2015 and is consistent with the projected completion date of the spacecraft, including margins
  - **Actors:** *launch rocket* (Ariane 5), *BepiColombo spacecraft (transfer module, MPO and MMO), Earth, Venus, Mercury, Base on Earth*.
  - **Targets:** *start-journey orbit* (the Earth orbit where the BepiColombo spacecraft can separate from the launch rocket and start its journey to Mercury).
- *Transfer*: Transport the BepiColombo Spacecraft to Mercury.
  - **Rationale:** Involves the long cruise phase including a combination of electric propulsion and gravity-assist maneuvers (once by Earth, twice by Venus, and four times by Mercury [9]). During the voyage to Mercury, the *two orbiters* and the *carrier spacecraft*, consisting of electric propulsion and traditional chemical rocket units, will form one single composite spacecraft.
  - **Actors:** *BepiColombo transfer module, chemical rocket engines, electric propulsion rocket engines, Earth, Venus, Mercury, the Sun, Base on Earth, BepiColombo composite module (MPO and MMO)*.
  - **Targets:** *interplanetary trajectory*.
- *Orbit-placement*: Both MPO and MMO must be placed in orbit around Mercury to fulfill the mission objectives.
  - **Rationale:** When approaching Mercury in, the carrier spacecraft will be separated and the composite spacecraft will use rocket engines and a technique called *weak stability boundary capture* to bring it into polar orbit around the planet. When the MMO orbit is reached, the MPO will separate and lower its altitude to its own operational orbit. Observations from orbit will be taken for at least one Earth year.
  - **Actors:** *BepiColombo transfer module, electric propulsion rocket engines, chemical rocket engines, Mercury, the Sun, Base on Earth, BepiColombo composite module (MPO and MMO), MPO, MMO.*
  - **Targets:** *MPO orbit, MMO orbit*

Figure 2 depicts the *GORE goals model* for the BepiColombo mission. This figure puts together all the goals specified above by relating them via particular relationships such as *inheritance* and *dependency*. Goals are depicted as boxes listing both goal *actors* and *targets* (note that targets might be considered as a distinct class of actors). As shown, the *low-level objectives* (see Section 4.1.3) are preliminary objectives that need to be achieved before proceeding with the *middle-level objectives* (see Section 4.1.2). Furthermore, the middle-level *objectives* are *concrete descendants* of the *high-level generic objectives* (see Section 4.1.1). The BepiColombo Goals Model provides the traceability mechanism for autonomy requirements. When a change in requirements is detected at runtime (e.g., a major change in the global mission goal), the goals model can be used to re-evaluate the system behavior with respect to the new requirements and to determine if system reconfiguration is needed. Moreover, the presented goals model provides *a unifying intentional view of the system* by relating goals assigned to actors and involving targets. Some of the actors can be eventually identified as the autonomy components providing a self-adaptive behavior when necessary to keep up with the high-level system objectives.

Note that this is an initial GORE model for BepiColombo, and it does not include the self-* objectives and other objectives stemming from the autonomy requirements. The latter shall be integrated in the model after applying the GAR (Generic Autonomy Requirements) for space missions to BepiColombo.

4.2 Constraints for BepiColombo

The following elements express major *gravitational*, *thermal, radiation, orbital, and launch constrains* imposed by the BepiColombo's operational environment:

- *Sun gravity*: Both Orbiters must take into account the gravitational potential of the Sun.
- *Eccentric orbit*: Both Orbiters must take into account the highly-eccentric planet's orbit around the Sun.
- *Temperature*: Both Orbiters must take into account the large temperature amplitude during the complete orbiting cycle. Large heat flux increased above the dayside due to reflected sunlight and infrared emission.
- *Irradiation*: The solar irradiation[1] [14] is about 10 times larger at Mercury than at Earth.
- *Polar orbit*: The orbits need to be polar in order to ensure global coverage of the planet.
- *Launch*: Launch opportunities of typically one-month duration for BepiColombo are dictated by positions of the Earth, Venus, and Mercury, allowing the spacecraft to follow its intricate interplanetary trajectory.

More constraints can be eventually derived from both the mission and environment specifics. Next, the constraints need to be associated with the mission goals to prevent mission failures. Further, constraints shall be considered by the self-* objectives providing assistive behavior to the main mission goals. In the system goals model (see Figure 2), constraints are depicted as gray ellipses linked via a *Restricts link* to objectives.

As shown in Figure 2, the *Launch* constraint adds on the Launch objective. The constraints *Sun gravity*, *Eccentric orbit* and *Polar orbit* restrict the Orbit-placement objective. Both the *Temperature* and *Irradiation* constraints restrict the three high-level mission objectives (see Section 4.1.1): *Study Mercury*, *Study Relativity* and *Possible Impacts*. Note that due to the "inheritance" relationship, these constraints are propagated to all the Middle-level Mission Objectives (see Section 4.1.2).

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[1] Total amount of solar radiation transmitted to the surface of the Earth's atmosphere in a given unit of time [14].

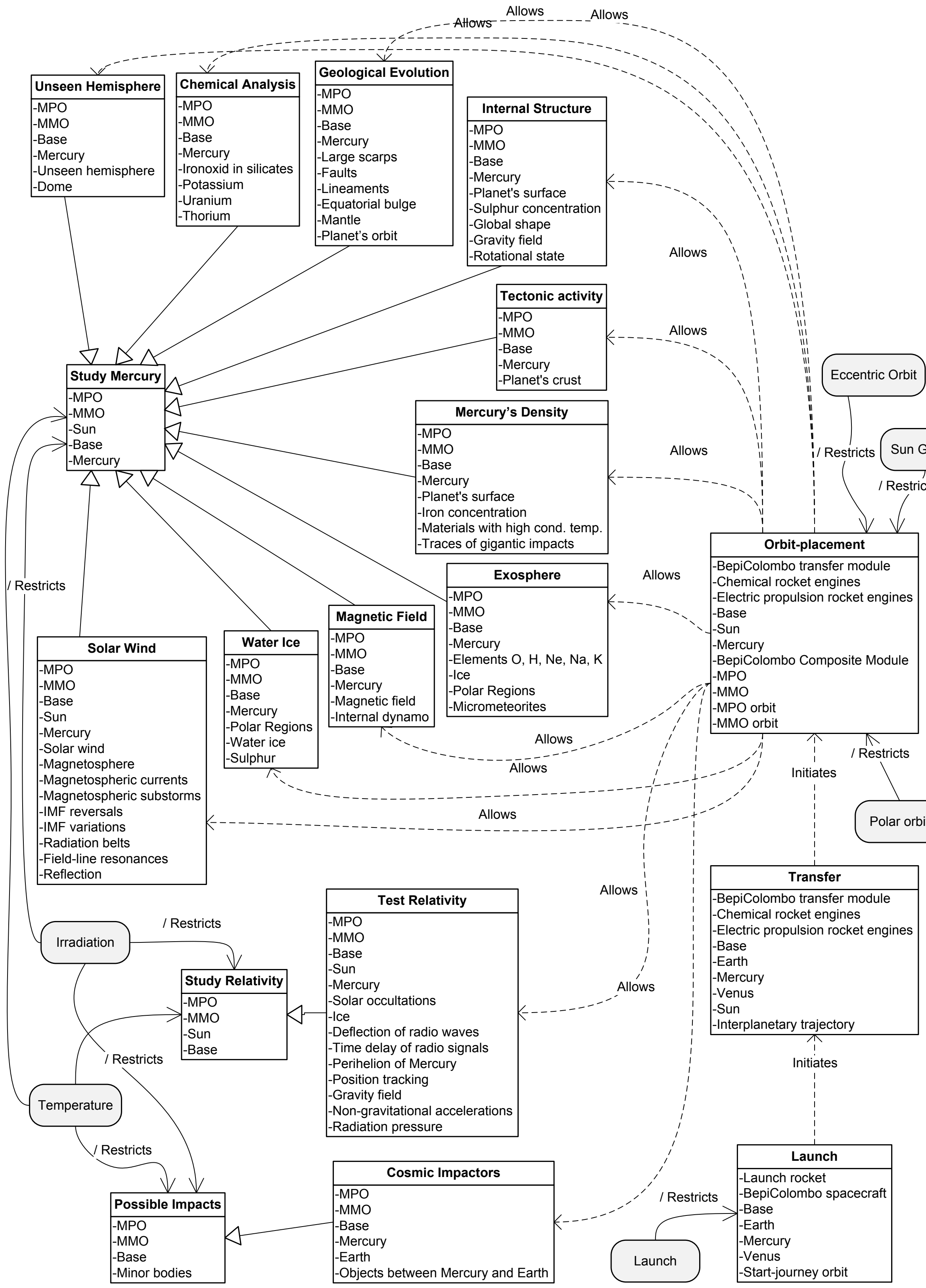

Figure 2. GORE Coals Model for BepiColombo

4.3 GAR for BepiColombo

The BepiColombo Mission falls in the category of *Interplanetary Missions* [1] and consecutively inherits the Generic Autonomy Requirements (GAR) for such missions [1]. Considering the hierarchical structure of the mission objectives (see Figure 2), a good practice will be to associate the autonomy requirements with each level of objectives. Thus, we may have autonomy requirements (including self-* objectives) associated with the *Transfer Objective*, the *Orbit-placement Objective* (see Section 4.1.3), and with the *Scientific Objectives*, grouping all the middle-level objectives (see Section 4.1.2).

In this exercise, we applied GAR for Interplanetary Missions [1] to BepiColombo to derive the following autonomy requirements. Note that due to space limitations, in this paper we present only the autonomy requirements associated with the *Transfer Objective* and those associated with the *Orbit-placement Objective*.

4.3.1 Transfer Objective Autonomy Requirements

The Interplanetary Missions involve more than one space object (planets, the Sun or satellites). Consecutively, the BepiColombo's Transfer Objective involves the planets Earth, Venus and Mercury, the Moon, and the Sun (see Section 4.1.3). Hence, the transfer trajectory needs to be developed with concerns about possible perturbations caused by the gravitational influence of the Sun and the near planetary bodies. By considering the Transfer Objective specifics, we derive the autonomy requirements for that objective, by applying the GAR for Interplanetary Missions [1]:

- **self-* requirements (autonomicity)**:
  - ○ *self-trajectory*:
    - ▪ autonomously acquire the most optimal trajectory to reach Mercury;
    - ▪ adapt to trajectory perturbations due to gravitational influence of the Sun, the Moon, Earth, Venus and Mercury.
  - ○ *self-protection*:
    - ▪ autonomously detect the presence of high solar irradiation and: 1) protect the electronics on board and instruments; 2) get away if possible by using electric propulsion and/or chemical propulsion.
    - ▪ the altitude of the Transfer Module during the interplanetary cruise should be kept without solar input to the MMO's and MPO's upper surface.
  - ○ *self-scheduling*:
    - ▪ autonomously determine the need of a gravity-assist maneuver: 1) near Earth; 2) near Venues (twice); and 3) near Mercury (4 times).
  - ○ *self-reparation*:
    - ▪ autonomously restore broken communication links;
    - ▪ when malfunctioning, components should be fixed autonomously where possible.
- **knowledge:** *mission objectives* (Transfer Objective); *payload operational requirements*; *instruments onboard together with their characteristics* (acceptable levels of radiation); *Base on Earth*; *propulsion system* (electric propulsion rockets, chemical propulsion rockets)*; communication links*; *data transmission format*; *eclipse period*; *altitude*; *communication mechanisms onboard*; *gravitational forces* (Earth gravity, Moon gravity, Venus gravity, Sun gravity and Mercury gravity);
- **awareness:** *trajectory awareness; radiation awareness; instrument awareness; sensitive to thermal stimuli; gravitational forces awareness; data-transfer awareness; speed awareness; communication awareness*.
- **monitoring:** *electronic components onboard*; *surrounding environment* (e.g., radiation level, planets, the Sun and other space objects); *planned operations* (status, progress, feasibility, etc.).
- **adaptability:** *adaptable mission parameters* concerning the Transfer Objective (e.g., what can be adapted in pursing the Transfer Objective); *possibility for re-planning (adaptation) of operations*; *adapt to loss of energy*; *adapt to high radiation*; *adapt to weak a satellite-ground station communication link*; *adapt to low energy*.
- **dynamicity:** *dynamic communication links*;
- **robustness:** *robust to temperature changes; robust to cruise trajectory perturbations; robust to communication losses;*
- **resilience:** *loss of energy is recoverable*; *resilient to radiation*.
- **mobility:** *information goes in and out; changing trajectory.*

4.3.2 Orbit-placement Obj. Autonomy Requrements

The Orbit-placement Objective is to place both MMO and MPO into their operational orbits around Mercury. When approaching Mercury, the BepiColombo Transfer Module will be separated by releasing the module's SEPM. Then, the BepiColombo Composite Module will use the MMO's rocket engines (mainly the CPM) and the weak stability boundary capture mechanism to move the spacecraft into polar orbit around Mercury (see Section 3). When the MMO orbit is reached, the MPO will separate and lower its altitude to its own operational orbit.

To derive the autonomy requirements assisting that objective, we need to identify the appropriate category of GAR (Generic Autonomy Requirements) that might be applied. Considering the Orbit-placement Objective, the BepiColombo mission falls in the category of *Interplanetary Missions using Low-thrust Trajectories* [1]. Such missions use spacecraft for orbit control activities in geostationary orbits, drag compensation in low orbits, planetary orbit missions and missions to comets and asteroids. These missions often have a complex mission profile utilizing *ion propulsion* in combination with multiple *gravity-assist manoeuvers* (similar to BepiColombo). Therefore, by considering the Orbit-placement Objective specifics, we derive the autonomy requirements for that objective, by applying GAR for Interplanetary Missions using Low-thrust Trajectories [1]:

- **self-* requirements (autonomicity)**:
  - ○ *self-jettison*:
    - ▪ the Transfer Module shall automatically release its SEPM when the right jettison attitude is reached;
    - ▪ the Composite Module shall automatically release MMO when the polar orbit is reached.
  - ○ *self-capture*:
    - ▪ the Composite Module shall autonomously determine a steering law and use low thrust to achieve capture around Mercury.
  - ○ *self-escape*:
    - ▪ the Composite Module shall autonomously acquire the escape procedure and use it to leave Mercury if necessary;

  - *self-low-thrust-trajectory*:
    - autonomously determine a steering law for a thrust vector and use low thrust to bring the Composite Module into polar orbit;
    - autonomously determine a steering law for a thrust vector and use low thrust to bring MPO into its orbit.
  - *self-protection*:
    - both the Composite Module and MPO shall autonomously detect the presence of high solar irradiation and: 1) protect the electronics on board and instruments; 2) get away if possible by using electric propulsion and/or chemical propulsion.
  - *self-thermal-control*:
    - both MMO and MPO shall maintain the onboard equipment and the spacecraft structure in proper temperature range.
  - *self-scheduling*:
    - both the Composite Module and MPO shall autonomously determine what task to perform next in the course of pursuing the Orbit-placement Objective: 1) jettison; 2) start and stop engines; 3) spin-up by using thrusters; 4) moving by using thrusters.
- **knowledge:**
  - *central force field physics; steering law model for weak stability boundary capture; MMO orbit; MPO orbit; maximum rate of change of orbital energy for MMO and MPO; maximum rate of change of orbital inclination for MMO and MPO; instruments onboard together with their characteristics* (acceptable levels of radiation)*; Base on Earth*; *propulsion system* (chemical propulsion rockets)*; communication links*, *data transmission format*, *communication mechanisms onboard*; *gravitational forces* (Sun gravity and Mercury gravity);
- **awareness** (for both the Composite Module and MPO)**:**
  - *Mercury capture awareness; Mercury escape awareness; trajectory velocity awareness; Mercury's magnetic field awareness; Mercury's gravitational force awareness; Sun's gravitational force awareness; awareness of the spacecraft's position on the projected trajectory perturbations; radiation awareness; instrument awareness; sensitive to thermal stimuli; data-transfer awareness; speed awareness; communication awareness*.
- **monitoring** (for both the Composite Module and MPO)**:**
  - *the environment around Mercury* (e.g., radiation level, Mercury, the Sun); *planned operations* (status, progress, feasibility, etc.).
- **adaptability** (for both the Composite Module and MPO)**:**
  - *adapt the low thrust trajectories to orbit and/or altitude perturbations*.
- **dynamicity** (for both the Composite Module and MPO)**:**
  - *dynamic near-body environment*; *dynamic trajectory following procedure*; *dynamic communication links*.
- **robustness** (for both the Composite Module and MPO)**:**
  - *robust to solar irradiation*; *robust to temperature changes* (high temperature amplitude)*; robust to orbit-placement trajectory perturbations; robust to communication losses.*
- **resilience** (for both the Composite Module and MPO)**:**
  - *resilient to magnetic field changes*.
- **mobility** (for both the Composite Module and MPO)**:**
  - *trajectory maneuvers for avoiding orbit and/or altitude perturbations*.

4.4 GORE and GAR Merged

From the self-* requirements derived in Section 4.3 we can derive self-* objectives providing *mission behavior alternatives* with respect to the BepiColombo Mission Objectives (see Figure 2).

The following elements describe the self-* objectives assisting the BepiColombo's Transfer Objective:

- *Self-trajectory_1*: Autonomously acquire the most optimal trajectory to reach Mercury.
  - **Actors:** *BepiColombo transfer module, chemical rocket engines, electric propulsion rocket engines, Earth, Venus, Mercury, the Sun, Base on Earth, BepiColombo composite module (MPO and MMO).*
  - **Targets:** *optimal interplanetary trajectory*.
- *Self-trajectory_2*: Autonomously adapt to trajectory perturbations due to gravitational influence of the Sun, the Moon, Earth, Venus and Mercury.
  - **Actors:** *BepiColombo transfer module, chemical rocket engines, electric propulsion rocket engines, Earth, Venus, Mercury, the Sun, Base on Earth, BepiColombo composite module (MPO and MMO), trajectory perturbations*, *gravitational influence*.
  - **Targets:** *interplanetary trajectory*.
- *Self-protection_1*: Autonomously detect the presence of high solar irradiation and protect (eventually turn off or shade) the electronics and instruments on board.
  - **Actors:** *BepiColombo transfer module, the Sun, Base on Earth, BepiColombo composite module (MPO and MMO), solar irradiation, shades, power system.*
  - **Targets:** *electronics and instruments*.
- *Self-protection_2*: Autonomously detect the presence of high solar irradiation and get away if possible by using electric propulsion and/or chemical propulsion.
  - **Actors:** *BepiColombo transfer module, chemical rocket engines, electric propulsion rocket engines, Earth, Venus, Mercury, the Sun, Base on Earth, solar irradiation*.
  - **Targets:** *safe position in space*.
- *Self-protection_3*: Autonomously maintain a proper altitude of the Transfer Module during the interplanetary cruise, so no solar input will reach the MMO's and MPO's upper surface.
  - **Actors:** *BepiColombo transfer module, chemical rocket engines, electric propulsion rocket engines, Earth, Venus, Mercury, the Sun, Base on Earth, solar input*.
  - **Targets:** *safe altitude*.
- *Self-scheduling_1*: Autonomously determine when a gravity-assist maneuver is required near Earth.
  - **Actors:** *BepiColombo transfer module, Earth, Earth gravitational influence*.
  - **Targets:** *gravity-assist maneuver*, *interplanetary trajectory*.
- *Self-scheduling_2*: Autonomously determine when a gravity-assist maneuver is required near Venus.
  - **Actors:** *BepiColombo transfer module, Venus, Venus gravitational influence*.
  - **Targets:** *gravity-assist maneuver*, *interplanetary trajectory*.

- *Self-scheduling_3*: Autonomously determine when a gravity-assist maneuver is required near Mercury.
    - ○ **Actors:** *BepiColombo transfer module,* Mercury, Mercury *gravitational influence*.
    - ○ **Targets:** *gravity-assist maneuver*, *interplanetary trajectory*.
- *Self-reparation_1:* Autonomously restore broken communication links.
    - ○ **Actors:** *BepiColombo transfer module, BepiColombo composite module (MPO and MMO), communication link (state: broken)*.
    - ○ **Targets:** *communication link (state: operational)*.
- *Self-reparation_2:* Autonomously fix malfunctioning components if possible.
    - ○ **Actors:** *BepiColombo transfer module, BepiColombo composite module (MPO and MMO), component (state: malfunctioning)*.
    - ○ **Targets:** *component (state: operational)*.

Figure 3 depicts a partial goals model showing the relationships between the Transfer Objective and the assisting self-* objectives, providing mission behavior alternatives with respect to the Transfer Objective. As shown, most of the assisting self-* objectives inherit the Transfer Objective and consecutively, the main objective's target (the mission's *interplanetary trajectory*) is kept in all of those self-* objectives. The mission switches to one of the assisting objectives when alternative autonomous behavior is required (e.g., high irradiation emitted by the Sun).

The following elements describe the self-* objectives assisting the BepiColombo's Orbit-placement Objective:

- *Self-jettison_1*: Autonomously release the SEPM when the right jettison attitude is reached:
    - ○ **Actors:** *BepiColombo transfer module, SEPM, Mercury, the Sun, Base on Earth.*
    - ○ **Targets:** *BepiColombo composite module*.
- *Self-jettison_2*: Autonomously release MMO when the polar orbit is reached:
    - ○ **Actors:** *BepiColombo composite module, MMO, Mercury, the Sun, Base on Earth.*
    - ○ **Targets:** *MPO, Polar orbit*.
- *Self-capture*: Autonomously determine a steering law and use low thrust to achieve capture around Mercury:
    - ○ **Actors:** *BepiColombo composite module, CPM, Mercury, the Sun, Base on Earth.*
    - ○ **Targets:** *steering law, Mercury capture*.
- *Self-escape*: Autonomously acquire the escape procedure and use it to leave Mercury if necessary:
    - ○ **Actors:** *BepiColombo composite module, CPM, Mercury, the Sun, Base on Earth.*
    - ○ **Targets:** *escape procedure, Mercury leave*.

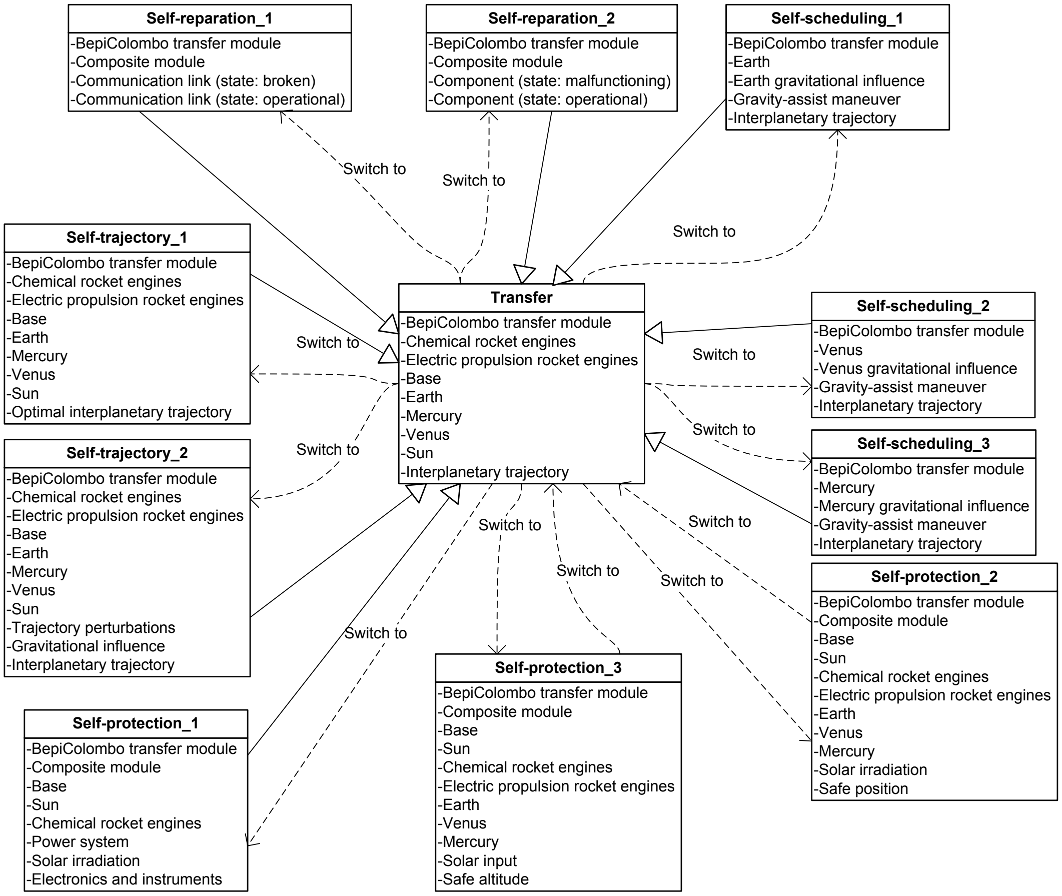

Figure 3. Goals Model for BepiColombo with Self-* Objectives Assisting the Transfer Objective

- *Self-low-thrust-trajectory_1*: Autonomously determine a steering law for a thrust vector and use low thrust to bring the Composite Module into polar orbit (MMO's orbit):
  - **Actors:** *BepiColombo composite module, CPM, Mercury, the Sun, Base on Earth.*
  - **Targets:** *steering law, thrust vector, MMO's orbit*.
- *Self-low-thrust-trajectory_2*: Autonomously determine a steering law for a thrust vector and use low thrust to bring MPO into its orbit.
  - **Actors:** *MPO, CPM, Mercury, the Sun, Base on Earth.*
  - **Targets:** *steering law, thrust vector, MPO's orbit*.
- *Self-protection_1*: Autonomously detect the presence of high solar irradiation and protect (eventually turn off or shade) the electronics and instruments on board.
  - **Actors:** *BepiColombo composite module, the Sun, Base on Earth, solar irradiation, shades, power system.*
  - **Targets:** *electronics and instruments*.
- *Self-protection_2*: Autonomously detect the presence of high solar irradiation and get away if possible by using chemical propulsion.
  - **Actors:** *BepiColombo composite module, CPM, Mercury, the Sun, Base on Earth, solar irradiation*.
  - **Targets:** *safe position around Mercury*.
- *Self-protection_3*: Autonomously detect the presence of high solar irradiation and protect (eventually turn off or shade) the electronics and instruments on board.
  - **Actors:** *MPO, the Sun, Base on Earth, solar irradiation, shades, power system.*
  - **Targets:** *electronics and instruments*.
- *Self-protection_4*: Autonomously detect the presence of high solar irradiation and get away if possible by using chemical propulsion.
  - **Actors:** *MPO, CPM, Mercury, the Sun, Base on Earth, solar irradiation*.
  - **Targets:** *safe position around Mercury*.
- *Self-thermal-control_1*: Autonomously maintain the onboard equipment and the spacecraft structure in proper temperature range.
  - **Actors:** *MMO, MMO's Thermal Control System, MMO's instruments, the Sun, Base on Earth, Mercury*.
  - **Targets:** *proper temperature*.
- *Self-thermal-control_2*: Autonomously maintain the onboard equipment and the spacecraft structure in proper temperature range.
  - **Actors:** *MPO, MPO's Thermal Control System, MPO's instruments, the Sun, Base on Earth, Mercury*.
  - **Targets:** *proper temperature*.

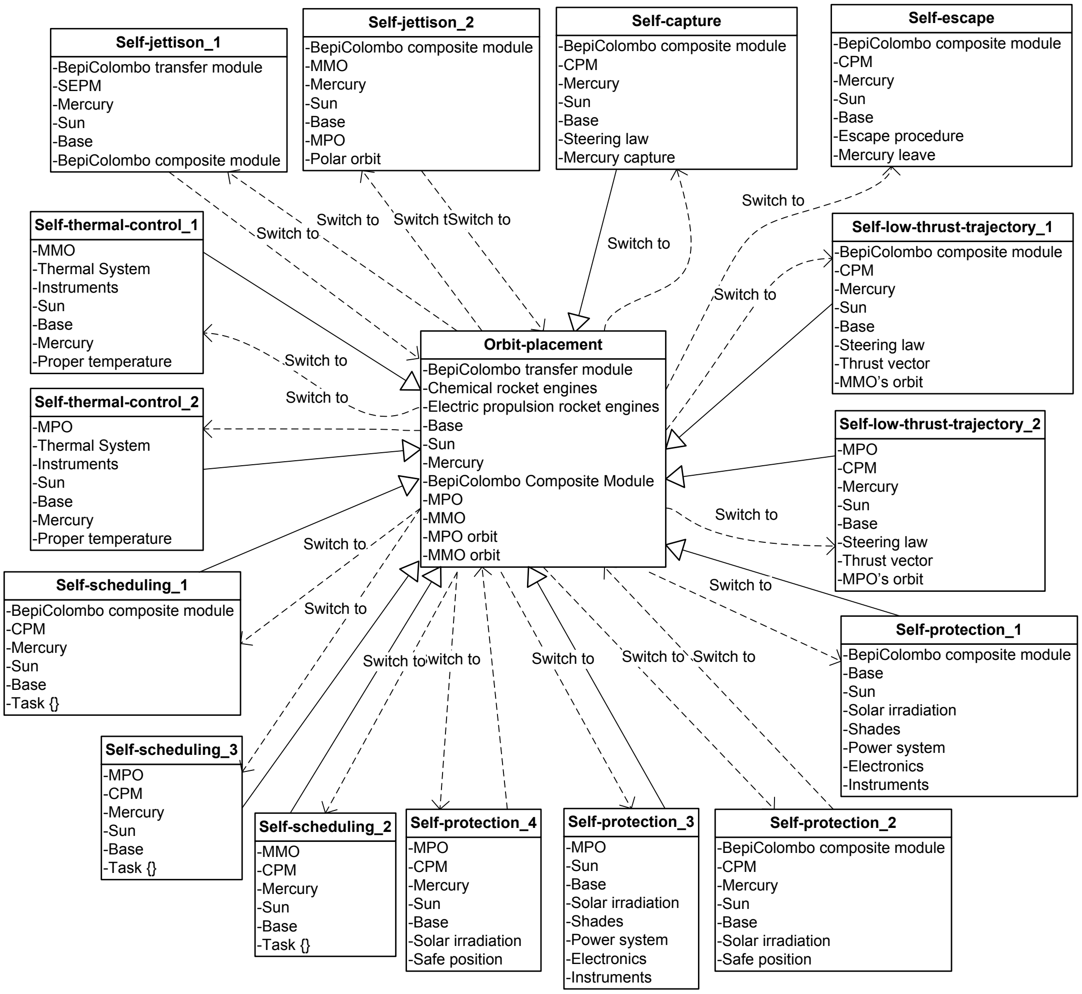

Figure 4. Goals Model for BepiColombo with Self-* Objectives Assisting the Orbit-placement Objective

- *Self-scheduling_1*: Autonomously determine what task to perform next in the course of pursuing the Orbit-placement Objective:
  - **Actors:** *BepiColombo composite module, CPM, Mercury, the Sun, Base on Earth.*
  - **Targets:** *task {jettison, start engine, stop engine, moving}.*
- *Self-scheduling_2*: Autonomously determine what task to perform next in the course of pursuing the Orbit-placement Objective:
  - **Actors:** *MMO, CPM, Mercury, the Sun, Base on Earth.*
  - **Targets:** *task {start engine, stop engine, spin-up, moving}.*
- *Self-scheduling_3*: Autonomously determine what task to perform next in the course of pursuing the Orbit-placement Objective:
  - **Actors:** *MPO, CPM, Mercury, the Sun, Base on Earth.*
  - **Targets:** *task {control engine, spin-up, moving}.*

Figure 4 depicts another partial goals model showing the relationships between the Orbit-placement Objective and the assisting self-* objectives, providing mission behavior alternatives with respect to the Orbit-placement Objective. Some of the assisting self-* objectives inherit the Orbit-placement Objective and consecutively, the main objective's target (*bringing into orbit both MMO and MPO*) is kept in all of those self-* objectives. The mission will switch to one of the assisting objectives when either a specific task must be performed (e.g., jettison) or alternative autonomic behavior is required due to extreme conditions (e.g., high irradiation emitted by the Sun).

5. CONCLUSION

To properly develop autonomous unmanned systems, it is very important to properly handle their autonomy requirements. In this paper, we presented an Autonomy Requirements Engineering (ARE) approach intended to solve this problem. The proposed ARE model uses the Goal-Oriented Requirements Engineering (GORE) approach to elicit and define the system goals, and then applies a special Generic Autonomy Requirements (GAR) model to derive and define assistive and often alternative goals (objectives) the system may pursue in the presence of factors threatening the achievement of the initial system goals. Once identified, the autonomy requirements might be further specified with a proper formal notation. This approach has been used in a joint project with ESA on identifying the autonomy requirements for the ESA's BepiColombo Mission. In this paper, we presented a case study where ARE was applied by putting GAR in the context of space missions to derive autonomy requirements and goals models incorporating autonomicity via self-* objectives.

Future work is mainly concerned with further development of the ARE model including adaptation of existing formal methods to specify (and eventually verify and validate) autonomy requirements.

6. ACKNOWLEDGMENTS

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