Innovative Rover Operations Concepts – Autonomous Planning Keeping a dog on the lead

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Abstract

The Innovative Rover Operations Concepts – Autonomous Planning (IRONCAP) is an ESA study project to explore and define the concepts and interactions needed to control and plan the activities of an interplanetary rover. Its aim is to develop a prototype system to support the science and engineering planning of an interplanetary rover using state-of-the-art methods and techniques in planning and scheduling combined with existing and/or developing ground segment systems and technologies. In this paper we outline the aims of the study giving a brief background to why this study is needed, present the current architecture for the prototype, detail the contrast between rover science operations planning and engineering operations planning illustrating any common or contrasting requirements, introduce the planning and scheduling techniques being investigated during the study and summarize the synergies with other ESA projects. We will conclude with a look at the current status of the project and present its current direction and outlook.

Introduction

IRONCAP is a study project being run by ESA, started in January 2011 and lasting for a period of 18 months. The work is being performed by a consortium of three members, the prime contractor VEGA Space GmbH with two partners FBK and TRASYS, each of them providing their own specific expertise to the study; VEGA bringing its expertise in operational ground segments and flying space missions, TRASYS with their extensive knowledge of rover operations & simulation and FBK providing the planning & scheduling experience of model synchronization and planning with uncertainty. This constellation provides for an effective and diverse knowledgebase on which the study will develop, providing a fruitful result. The initial objectives of the study are to:

- Assess and summarize the state-of-the-art concepts and technologies for operations of both orbiting spacecraft and rovers.
- Define advanced concepts for controlling and monitoring rover operations, considering the presence of autonomous planning and execution capabilities in the rover segment. Enabling cutting-edge technology shall be considered during the course of the study since the focus is on future rover missions.
- Identify possible engines and languages to handle the different types of planning data such as occurrences, event, activities and resources.
- Identify optimum ways to synchronize on-board and ground planning processes.

This will ultimately result in the development of a general-purpose proof-of-concept prototype of an Automated Ground Activity Planning/Scheduling and Validation System for rover operations, providing a coherent and complete working implementation.

Background

Currently planning of operations within ESA are usually distributed between two entities, one providing the science planning inputs and the other supplying the engineering planning inputs to the overall planning activities of any given spacecraft. Interactions between these two entities at a planning level are limited, usually with each having their own set of tools to perform analysis of previous activities and to facilitate the planning tasks, commonly having different knowledge built into them with no synchronization involved. One of the rationales for this study is to investigate and define ways to harmonize these interactions, developing concepts and techniques that are applicable to both entities. To do this an understanding of both entities is important to the study.

It is also important to understand the different levels of autonomy that are defined for space applications. There are four in total, as defined in the ECSS-E-70-11, which are:

- E1 - Execution under ground control
- E2 - Execution of pre-planned mission operations on-board
- E3 - Execution of adaptive mission operations on-board
- E4 - Execution of goal-oriented mission operations on-board

As can be expected, for space rover operations only the E2 to E4 levels are really applicable due to the time delays that are nominally involved and the synchronization of the daylight hours at the rovers location with that of the human controllers on Earth.

At level E2, the plans are time-tagged schedules of activities. The on-board controller will execute them and monitor the status of the execution. If some activity fails, the execution will be aborted, the controller will ensure that the payload and platform are in a safe state, and wait for further instructions from the ground.

At level E3, the execution of activities on-board can be triggered by events. The controller can monitor the status of the system and environment, and start or select activities to be performed on the basis of conditions on the on-board telemetry. In this case IRONCAP would therefore generate conditional plans that would integrate uncertainty on time, resource consumption, and environment or system state. The controller will monitor the execution of the plan together with the environment and system state and trigger the execution of the plan branches on the basis of their enabling conditions. If the plan execution fails, i.e. if at one stage none of the pre-compiled options in the conditional plan are valid, the controller will react in the same way as at the lower level of autonomy and wait for further instruction from the ground (although non-critical operations can continue to run in the background).

At level E4, the plan expected by the on-board controller is basically a high-level plan of goals with constraints, which will be mapped down to lower level activities by the on-board planning system. The goals and constraints that are passed to the on-board system will be expressed at a lower level of abstraction than the goals that are given as input to the IRONCAP. The on-ground planning process is therefore not limited to a process of merging and checking consistency of possible conflicting goals, but also to compile the on-ground timeline to the level of abstraction required by the on-board controller.

The E2 autonomy level is currently the norm for most ESA missions, even though typically applied to spacecraft and not rovers. The E3 autonomy level is foreseen for future ESA missions, although there are already experiences of this being built up within the Agency. Finally the E4 autonomy level is, for the time being, addressed at prototyping level only at ESA.

Where does IRONCAP fit in?

Innovative Rover Operations Concepts: Autonomous Planning (IRONCAP) is essentially a study on the definition of an autonomous Rover operations concept, and on the systems required on-ground to support these operations, from data acquisition, results analysis right through to the commanding of a rover. It complements, for the ground aspects, a parallel study started by ESA in September 2009, the Goal-Oriented Autonomous Controller (GOAC) study, which aims at defining and prototyping an on-board autonomous controller able to support the levels of autonomy up to level E4, which integrates on-board goal-oriented re-planning.

The study will enable ESA to bridge the gap between the science planning and engineering planning for rover operation, combining both concepts into a single prototype tool that can be used in both environments. It will provide concepts and techniques that can be used for current and future rover missions as well as providing the necessary integration with the GOAC study.

Foreseen Architecture

The current architecture of the system, shown in the Figure 1, takes into account the situational assessment needed by the science planners and the engineering planners and foresees and integrated 3D visualization component. The study has already highlighted the re-use of 3DROV for this purpose, a comprehensive system developed to visualize and simulate rover activities.

IRONCAP will allow the planner to generate plans of different kinds to fulfill the requirements imposed by the three different autonomy control levels, E2 to E4.

To this end we have so far identified the following four classes of plans to represent these four levels of autonomy:

- Class A1: This kind of plan is a simple sequence of activities with no conditional branches and with no flexibility on the duration of the activities, but allowing for parallel activities. This kind of plan will be suitable for the E2 level of autonomy.

- Class A2: This kind of plan extends A1 along two directions.
  - First, conditions with only one branch (e.g. "if (battery_level_good) then goto(x,y); experiment(1)") will be introduced. When the condition does not hold during the execution of the plan, then the execution stops.
  - Second, we introduce flexibility on the start time and duration of the activities, thus allowing for dependency on activities coded in relationship between activities.
- Class A3: This plan class further extends A2 by allowing for conditions with multiple branches by providing event-based autonomous operations to be executed on board.
- Class A4: This kind basically consists of a set of goals to be uploaded on board to achieve goal oriented mission re-planning. This kind of plans will be compliant with the kind of goals that the GOAC system will be able to support.

Plans belonging to class A1 to A3 allows for the execution of more than one activity in parallel. Plans of all four classes also associated with the set of assumptions used for plan generation to be monitored during the execution. Moreover, these plans are not only tagged with timing information, but also annotated with other situational checkers, e.g. checking the battery level.

These are early stages of the study project and it is entirely conceivable that further classes of plans could be required to be defined as more possibilities are investigated.

Planning and Scheduling

During the course of the study there will be many concepts and techniques to be considered with respect to the assessment capabilities of the prototype, the autonomous behaviors of rovers being supported and the planning/scheduling mechanisms required to successfully, efficiently and effectively perform rover operations. In this paper we present the concepts and techniques that have been assessed so far within the scope of the study, nominally the ones already known to the authors. As the study progresses further concepts and techniques will be assessed, documented within the project and, possibly, detailed in future works by the authors.

Science & Engineering assessment and planning

As with any rover mission, a situational assessment of the location of the rover has to be performed to establish the context in which the planning of operations can be performed. This situational analysis is performed on an engineering level and on a science level both with their own goals and objectives.

The science assessment is mainly concerned with the evaluation and assessment of what science has been achieved since the last assessment, what exciting new science could be done from what we see now, the science observations already planned to be performed and how to maximize the scientific return. This assessment usually involves the use of advanced graphical tools to analyze the captured data from the rover, establishing new points of interest to visit and determining the merits of the current science being performed. IRONCAP will not provide all the graphical tools for this type of analysis because they can be very specific to the scientific instrument used, although it is envisaged that some basic visualization graphics will be part of the prototype. The ultimate result of this assessment will be a new/modified set of goals to be evaluated and planned.

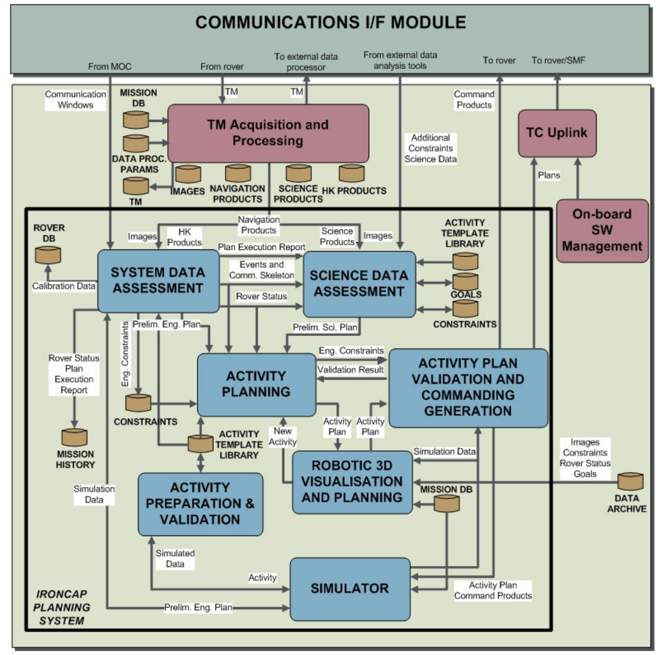

Figure 1 : IRONCAP Architectural Overview

In contrast to this the engineering assessment looks at the state of the space vehicle, taking a careful look at its health with respect to the last assessment. This would involve an evaluation of any energy sources on the space vehicle (i.e. batteries, solar panels, etc.) and their performance, evaluation of any moving parts on the vehicle (such as wheel motors, camera arms, internal relays, etc.) noting and reacting to any degradation in performance. As with the science assessment, graphical visualizations are needed to easily assess the current status of the rover.

Both assessments provide the goals and objectives for the next planning stage which may or may not conflict with each other. Therefore it is important to cater for both assessments when planning operations. During the study the collaboration and combination of these two situational assessment analyses will be investigated, ultimately resulting in a prototype which will support both necessary approaches.

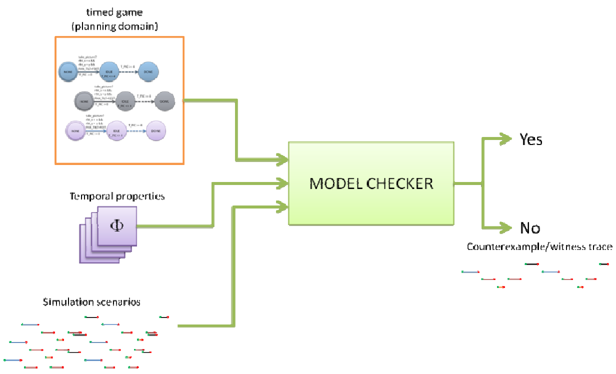

Figure 3: Model checker overview

Model Representation & Synchronization Concerns

Within IRONCAP model synchronization will be responsible for the update and synchronization of the model used for planning and for plan validation, and for the synchronization of the model used by an external simulator with the model used for reasoning. For the first kind of synchronization we envisage the use of formal methods techniques. In particular it can be further decomposed into update of the initial state used for successive plan generation and validation; update of the model used for all the formal reasoning; and finally update of the assumptions used for the plan generation. In the literature, we were, so far, not able to find many articles describing these approaches. However, within the project we are envisaging to tackle these problems as follows. For the synchronization of the initial state we will simulate the plan previously executed and downloaded to the rover. The simulation will start from the previously known state used for the previous plan generation. The simulation will be driven not only from the plan, but also from the information coming from the telemetry. Within this phase it is possible also that we discover problems in the model used for simulation, thus the synchronization of the initial state will be tightly integrated with the update of the reasoning model and of the assumptions. For the update of the model and of the assumptions under which to plan, we envisage to use techniques developed within the OMC-ARE project for fault-detection and identification. By exploiting the telemetry information we will identify possible faults, and or wrong assumptions, and we will use these information to revise the model (e.g. introduce new faulty-behavior, strengthen the assumptions, etc). What we propose within IRONCAP is to exploit and extend techniques defined and used within the OMC-ARE project (OMCARE), and those discussed in (Bozzano et al. 2008) and in (Cimatti, Guiotto, Roveri 2008).

Validation and Verification

For model and plan validation and verification we envisage to use symbolic model checking technique exploiting Satisfiability Modulo Theory (Audemard, Cimatti, Kornilowicz, Sebastiani 2002), (Bozzano et al. 2005a), (Bozzano et al. 2005b), (Bruttomesso 2008), (Cimatti, Griggio, Sebastiani 2008) and abstraction refinement (Clarke, Kurshan, Veith 2010), (Clarke 2003). This will be further analyzed and investigated during the course of the study.

Reasoning

For planning and scheduling we envisage to exploit hybrid-game approaches based on a mechanism of generate and test (similar to the one of (Brafman, Hoffmann 2004), (Hoffmann, Brafman 2006)) but extended to the hybrid domain case), where we will use satisfiability modulo theory model checking techniques to generate a candidate solution, and then we will check, also with model checking techniques that the candidate solution is a real solution for the considered planning and scheduling problem.

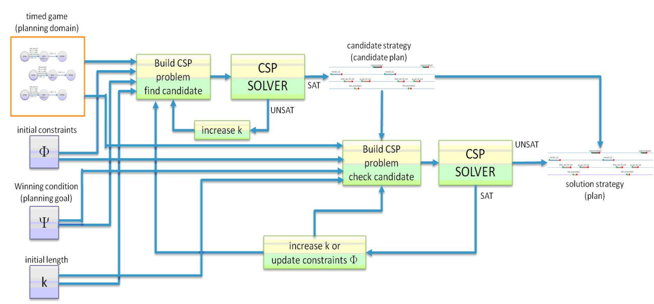

Figure 2: Provisional reasoning algorithm based on timed game approach

Re-use of Existing Software/Concepts

As part of the exploration of software that could potentially be re-used for this development, the APSI framework (Steel et al. 2009) is also being considered in the context of this study. APSI offers a structured and flexible library for effective modeling and solving of the planning and scheduling problems in different domains. The framework is based on the concept of timelines representing the temporal evolution of the system and of the environment. An initial analysis shows that the framework should be extended to allow expressing non-deterministic effects at the discrete level, specifying uncertainty on the duration of activities, and uncertainty on the resource consumption/production within an activity. Moreover, we see an extension to the framework to model explicitly the sensors (i.e. the observations). As far as a goal language is concerned, the possibility to associate goals with some sort of preference (e.g. mandatory, or nice to achieve if resource allow for) will also be assessed during the course of the study for its applicability.

Concepts verification and validation

Many concepts and technologies will be used during the course of the study, some being new to the space developments others being re-used from existing space systems. To this end it is vital that these concepts are demonstrated in contexts familiar to the space domain. With this in mind, and as a key part of the project, two demonstration test cases will be defined, one being based on the interaction with the GOAC project and the other one making use of a suitable rover simulator (i.e. 3DROV). The scenarios themselves need to be further investigated and, as a preference, aligned with the scenarios defined within the GOAC study and the MMI for Exploration study (MMI4EXPL). Within the context of these test case studies the autonomy levels E2 to E4, as described previously, will need to be exercised to fully demonstrate the concepts and techniques developed through the project, the results of which we hope to present at future conferences and workshops.

Conclusion

This paper has presented an outline of the current and initial status of the IRONCAP project being developed by ESA. IRONCAP will set the ground for the planning and scheduling of operations and activities of future ESA interplanetary Rover missions and possibly other type of missions. It will develop and evolve the concepts required to successfully and efficiently perform rover operation at the three main levels of autonomy, providing a prototype tool which will bring the science and engineering situational assessments together into a common tool. Even though the project is in its earlier stages the vision of a fruitful outcome is very important and thus the exploration of new and developing concepts and techniques is an exciting prospect for the project team.

The project is currently under development with an end of project planned for August 2012. So watch this space for future workshops and conferences.

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