Intelligent Control For Spacecraft Autonomy: An Industry Survey

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1. INTRODUCTION

The Space Operations and Support Technical Committee (SOSTC) of the American Institute of Aeronautics and Astronautics (AIAA) undertook a survey of the state of the industry in implementing autonomous spacecraft systems. The Advanced Concepts Subcommittee of the SOSTC developed the survey and compiled responses from twelve different organizations operating 88 different autonomous and/or intelligent systems supporting robotic spacecraft. The spacecraft represent commercial, science and military missions. Individual responses within this paper are referred to as projects, implementations or applications. The survey took place between March 2005 and March 2006.

Our objective in undertaking the survey and publishing the results is to inform the space community about the types of successful implementations of autonomous and/or intelligent systems. Note that a system can be either autonomous, or intelligent, or both. An autonomous system reacts to its external inputs and takes some action without operator control. An example is automatically monitoring spacecraft telemetry for fuel usage and tracking consumption as done on the Intelsat fleet of satellites. An intelligent system uses some internal algorithms to emulate a human expert in determining its course of action. The input may be generated by an operator, as in the case of a scheduling system that inputs requested activities and uses a heuristic search engine to produce an optimum, conflict-free schedule. If the input is generated automatically by the operational environment and fed into an intelligent system then you have both an autonomous and intelligent system. When this occurs onboard, you get what we refer to as an Autonomous Thinking Spacecraft that reacts to its environment and plans its own activities to achieve the mission goals. An example is the Autonomous Sciencecraft Experiment (ASE) developed by NASA Ames Research Center (ARC) and Jet Propulsion Laboratory (JPL) and flown on NASA's Earth Observing-1 (EO-1) mission since 2003. [1] The ASE software enables EO-1 to autonomously detect and respond to science events. ASE uses classification algorithms to analyze imagery onboard to detect change and science events. Detection of these events is then used to trigger follow-up imagery. Onboard mission planning software then develops a response plan that accounts for target visibility and operations constraints. This plan is then executed using a task execution system that can deal with run-time anomalies.

We chose to include both autonomous systems and intelligent systems in our survey and to treat them similarly. Both types of systems perform tasks that would otherwise be done by operators and therefore they increase the efficiency of the operations team. An underlying assumption is that autonomous and intelligent systems increase operational efficiency with acceptable levels of risk to the mission. Our survey does not attempt to prove this assumption as we feel it has been demonstrated in practice and covered sufficiently in the literature. See for example Bujewski, et. al. [2] and Sherwood et. al. [3]

Rather than simply list the implementations that we discovered in our survey, we categorize the systems in a number of ways and attempt to analyze them to give clues to where the high payoff areas lie and where more research is needed.

2. METHODOLOGY

The survey was designed to mine data from the direct experience of the SOSTC membership, given that the committee has representation across the breadth of the operations community. The first task was to design a framework so that the responses could be directly compared to each other, and cross-tabulated. This was accomplished by providing a fixed set of choices to some of the questions.

The subcommittee began with definitions of Mission Operations functions taken from Wertz & Larson [4] so we could compare the functional purpose of the project to the level of autonomy. Of the thirteen functions of a mission operations system described in Wertz & Larson we concluded that eight of them were possible candidates for autonomy. These eight functions are: Activity Planning and Development, Mission Control, Data Transport, Navigation and Orbit Control, Spacecraft Operations, Payload Operations, Data Processing, and Archiving and Maintaining the Mission Database. Although not all of these functions apply to every mission, it seems that the set is sufficient to describe all of the missions we surveyed.

Missions were categorized along other dimensions of interest:

- Level of Autonomy: Onboard Closed Loop, Stored Onboard Command Sequence, Event-Driven Rules, Intelligent System, and "Other "
- Mission Type: Geosynchronous Orbit (GEO), Low Earth Orbit (LEO), Interplanetary, Elliptical, L2
- Location of the Automation System: Ground, Space, Both
- System Timeframe: Retired System, Current Implementation, Planned Implementation, Research

Additionally, the survey requested descriptive information such as a name and description of the mission, and a name for the autonomy project that was attempted.

The survey was distributed to all members of the SOSTC, on a voluntary basis. A few members were unable to provide responses due to security or commercial sensitivity of their work, but most were able to respond. The members also distributed the survey to peers with which they had a professional relationship.

After examining NASA's Levels of Autonomy for Aerospace Systems [5], the subcommittee defined six stages of intelligent reasoning, moving progressively from fully manual to an autonomous thinking spacecraft. The six stages into which we sorted the survey responses appear in **Table 2-1**.

The committee analyzed the responses and assigned each one to a stage. This was subjective, according to the consensus of the reviewers (the respondents were not asked to categorize their own projects). Finally, members of the subcommittee were assigned dimensions of the survey to cross-tabulate, which provided the results that follow.

3. ANALYSIS AND RESULTS

There were 88 total responses to the voluntary industry survey. Although we were pleased to receive the responses, this was not an exhaustive survey. and we do not claim that it is truly representative of the entire industry. We used many categories to define the projects and therefore some counts are very low for some of the individual characteristics. It is therefore dangerous to make sweeping generalizations about how this might apply across the industry. We do show the data in tables and graphs and use that to support our analysis. The sections below each detail the result of comparing a particular characteristic of the responses to their Intelligent Reasoning Stage distribution.

3.1 Application Timeframe

The total of 88 survey responses included 62 implementations that were classified as currently in operation. The responses that represented current implementations are highly skewed toward the lower levels of Intelligent Reasoning Stages. **Figure 3.1.1** shows a downward trend in the number of projects as the Intelligent Reasoning Stage increases. Of the 62 current implementations, 28 were at a Level 2, the lowest level of Intelligent Reasoning, decreasing steadily downward to only 2 at Level 5, before increasing back up to 5 implementations at a Level 6. This seems to reflect that while much is currently being implemented in the way of intelligent systems, the industry is generally taking things in small steps rather than giant leaps. It follows as an obvious consequence of integrating new technology and operations strategies.

3.2 Complexity

Another measure of the survey responses that we analyzed dealt with the complexity of the implementation. We categorized the applications as a component, a complete space or ground segment, or an integration across both the space and the ground segment. A component was defined as performing a single function, such as producing a schedule or searching for anomalies in telemetry. A segment integrated multiples functions either in flight or on the ground, such as searching telemetry, determining the probable cause of an anomaly and taking some action as a result. For implementations categorized as both Flight & Ground, they performed functions in both segments. An example is NASA's Remote Agent Experiment that flew on Deep Space 1. It replanned and executed activities onboard in response to the spacecraft environment, and also included tools on the ground to track the reasoning done onboard.

Table 3.2-1 shows the results of this complexity metric sorted into the Intelligent Reasoning Stage. Components represented by far the largest number of applications in our survey responses. Many of these components are commercial-off-the-shelf products that are generic by design and tailored to the specific application. **Figure 3.2-1** shows the distribution of the complexity metric into the Intelligent Reasoning Stages. A striking difference appears in the level of Intelligent Reasoning between the components and the applications that represented either a single segment or a combined flight and ground segment.

Although the components are less complex, they were at a much lower level of Intelligent Reasoning Stage than the single or integrated segments. This supports the earlier conclusion that the majority of implementations take an evolutionary, rather than a revolutionary approach. There are numerous instances of components that perform a single function at a low level of Intelligent Reasoning.

Another observation to be made about the segment entries is that they are all LEO missions. This makes sense, as it is less risky to test new technology near the earth where back-up, human intervention is readily achievable and the cost of launching an experimental spacecraft is relatively inexpensive compared to GEO and interplanetary missions. However the latter could probably benefit the most from autonomy or intelligent design due to time lags in communication.

3.3 Mission Operations Function

As mentioned in Section 2, we listed eight of the thirteen mission operations functions as having the potential for autonomy or intelligence and asked the respondents to choose which one of the eight applied to their project. However the responses only included results representing six of the functions. We did not receive any responses categorized in the areas of Mission Control or Archiving and Maintaining the Mission Database. Since there is sparse data for some of the mission operations functions, we use **Table 3.3-1** to show all of the responses.

The table shows that over 75% of the applications perform either the Activity Planning and Development or the Spacecraft Operations functions. These are the high payoff areas for implementations of autonomy or intelligence. They are functions that are performed often and are labor intensive, yet the decision-making process to a large degree can be described and coded in software. **Figure 3.3-1** graphs the level of Intelligent Reasoning for each of these functions.

Note that the Intelligent Reasoning level for Activity Planning and Development is much lower overall than for the Spacecraft Operations function. This indicates that the planning and scheduling area has seen a lot of applications that automatically process inputs to build a schedule in a straightforward, procedural manner without a lot of intelligence in actually trying to optimize the schedule. On the other hand, monitoring of telemetry and reacting to new situations, whether anomalous or expected, has been an area where successful applications have a high degree of intelligent reasoning.

3.4 Location of the Application

Each application is implemented either in the ground system, onboard, or both on the ground and onboard. The overwhelming majority or the responses were implemented in the ground system. **Figure 3.4-1** shows the distribution of the location and the Intelligent Reasoning Stage assigned to each project. Although most applications are located in the ground system, the ones implemented onboard or in both show a higher level of Intelligent Reasoning. This result seems counterintuitive given the model of proving new technologies on the ground before migrating them to space. It could possibly be explained by two factors. One is the greater need for intelligence onboard robotic spacecraft where no human operator exists to react quickly to events and when going into a safe mode for every minor disturbance results in reduced mission success. The corollary is that human operators are available on the ground. Budgetary constraints are the main impediments to adding more humans to solve complex problems and although organizations are seeing budgetary pressures along this line, they may not yet be to the point that there is a critical need to introduce intelligent ground systems.

3.5 Mission Type

Not surprisingly, most of the Mission Types for the projects were for geostationary or low-earth orbit mission designs as shown in **Figure 3.5-1**. For the Elliptical, Interplanetary and L2 entries, totaling 12 altogether, all but one is Intelligent Reasoning Stage 2. The GEO category reveals a little more risk-taking spirit with six Intelligent Reasoning Stage 4 entries out of 23 total. GEO satellites also enjoy the advantage of fairly constant ground communication opportunities, so some risk-taking is apparently tolerable. The largest numbers of entries, 53, are in LEO, and in LEO we find the highest Intelligent Reasoning levels by a wide margin. This makes sense, as it is less risky to test new technology near the earth where back-up, human intervention is readily achievable and the cost of launching an experimental spacecraft is relatively inexpensive compared to GEO and interplanetary missions.

4. CONCLUSIONS

From the analyses we see that there are several high payoff areas where autonomous and intelligent systems have provided significant benefits to mission operations. Many successful implementations apply to the functional areas of Activity Planning & Development and Spacecraft Operations. These functions are performed often and are labor intensive. The internal decision-making capability and the external interfaces are well understood. Most of the successes applications are implemented by components that perform a single function. Many of these components are commercial-off-the-shelf products that are generic by design and tailored to the specific application.

Since much of the applications represent small evolutionary steps towards autonomous systems, further research needs to focus on integrating multiple independent autonomous systems into a plug-and-play architecture that supports fully autonomous space and ground segments. Progressing through the six Stages of Intelligent Reasoning involves varying levels of autonomy to fit a particular mission scenario. Techniques that enable this advancement include adjustable autonomy, mixed autonomy and progressive autonomy, as described in Rouff [6]. Adjustable autonomy allows the operations staff to determine the level of control to give to the system. Often more control is relinquished by mission operations as the autonomous system proves itself to be trustworthy. Mixed autonomy employs autonomous systems and humans working together to achieve the same goal. Often the details are automated and the higher-level decisions left to the human experts. Rouff defines progressive autonomy in terms of autonomous agents, where progress is achieved through increasing the capability of an agent or adding additional agents to perform new tasks. Rather than limiting the definition to agents, we prefer to view progressive autonomy as including all systems whose capabilities are advanced through increasing the functions performed by any form of autonomous system.

We have shown that LEO orbit missions are more numerous and employ the highest levels of intelligent reasoning in our survey responses. More study is needed to investigate the unique challenges of interplanetary missions. The long communication delays and large timeframes without contact with mission control drive the need for spacecraft to react to its environment to maximize the mission objectives. Increased onboard resources, such as more powerful space qualified processors and low-power memory, will be needed to perform advanced functions onboard.

One of the objectives of the survey was to inform the space community about the types of successful autonomous systems. For more information please see the American Institute of Aeronautic and Astronautics (AIAA) Space Operations & Support Technical Committee (SOSTC) main website located at http://www.aiaa.org/tc/sos/.

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