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A Customer View of Goal-Based Operations for Human Space Exploration

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Goal-based operations, a form of operations that involves specifying *what* should be accomplished, as opposed to *how* operations are carried out, has the potential to significantly enhance human space exploration in a number of areas in both ground and space operations. Realizing this potential will require addressing several challenges, ranging from practical feasibility to operational reliability and user acceptance. We intend to provide a customer perspective and help address some of the challenges by: (1) highlighting general and specific challenges and opportunities that are consistent with human space exploration and that emphasize how goal-based operations might be of practical benefit to the human space exploration program; and (2) exploring ways to help increase confidence in goal-based operations. A strategy for building such confidence must consider: (a) incremental implementation of goal-based operations for increasingly ambitious operations leading eventually to high level goal-based operations, (b) the role of systems modeling in technology acceptance and infusion and (c) automation assessment tools for understanding how trust is developed, such as the Function-specific Level of Autonomy and Automation Tool (FLOAAT) developed by NASA/Johnson Space Center. We explore several challenges and opportunities for the near-term (International Space Station mission operations), the mid-term (human lunar missions), and the long-term (human Mars missions), that illustrate the potential benefits of goal-based operations.

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I. Introduction

NASA's new Vision for Space Exploration is far reaching and presents at least two categories of unique challenges. First, previous large scale human space programs such as Apollo, Space Shuttle, and the International Space Station (ISS) have not included the demands of long-duration surface missions and permanent surface outposts, some of which will involve long communications delays with Earth (in particular for Mars missions). Secondly, there is increasing focus on full lifecycle costs, and the lifecycle for the envisioned human space program is long-term and complex. The Vision for Space Exploration presents the prospect for unusually long, continuously evolving, and increasingly complex operations phases – for which technology and cost reduction measures will be expected to reduce operational complexity and lifecycle costs over the long-term, helping to sustain support for the program far into the future.

Goal-based operations has the potential to address both categories of challenges by making operations safer and more efficient, and by reducing operations complexities and costs over the long-term. Operations customers in human space exploration are seeking cost-effective operations, increased crew safety, and reduced workload which can reduce human error and help enable multi-mission operations. We hope to show how these needs might be met with goal-based operations and how confidence-building measures can be taken to help incorporate goal-based operations into the human space program so that the benefits of goal-based operations can be realized without incurring extra risk and unnecessary costs.

The space community has been improving operations through increasing automation over many years and there are near-term opportunities and projects in operations that demonstrate capabilities by providing incremental improvements. These projects bring together the communities of human space flight, earth orbiting spacecraft, planetary probes, and advanced computational methods. These communities are working in partnership to improve current operations and to design future operations, thus refining understanding of how to apply technology, such as goal-based operations, effectively resulting in reduced risk, cost, and increased return in both the near- and long-term. Indeed, the long-term nature of the new Vision for Space Exploration and the inevitable communications delays for human Mars missions argues for wise technology investments in the near-term that will provide longer-term return on investment – for example, goal-based operations can help with the inevitable requirement for crew autonomy during many phases of human Mars missions.

Goal-based operations for the purposes of this paper involves replacing pre-determined specifications for *how* operations are carried out, with goals (or constraints) of *what* should be accomplished. Goal-based operations is distinct from human-computer interaction, in that goal-based operations could either (a) be considered a subset of human-computer interaction whereby human specifications of goals to computer systems will trigger the goal execution and verification, and any status required along the way, or (b) goal-based operations could be considered to overlap with human-computer interaction in that goal-based operations might also involve systems that are not computers per se, or that might not necessarily involve humans in any significant way at all.

It is not the intent of this paper to precisely define what a goal is or isn't, but a very general working characterization of a goal might be: "a verifiable discrete objective that could either be very specific or general." We can envision a hierarchy of objectives or goals, and at any level in the hierarchy there is a goal that can be decomposed into lower-level sub-goals which define how the goal is to be achieved. Above any particular stated goal in the hierarchy are essentially "meta-goals" that indicate why we want to achieve a particular goal. Goal-based operations essentially involves moving up the levels in the hierarchy of goals. We want to specify goals at the highest level appropriate, with the implicit assumption that all sub-goals will be properly expanded and executed for a user. For example, the goal of detecting extraterrestrial life is a very general goal (that could be given to one or many agents) that could have many sub-goals such as "find liquid water", "obtain sample", "sequence molecular structure", etc. The lower level goals may have additional lower level goals that contribute to achieving the goals above them. The overall intent of goal-based operations would be to try to move up this hierarchy of goals, while striking the balance for what is reliably achievable via a goal-based operational approach. For example, it may not be reliably achievable to specify the highest level goal: "find extraterrestrial life", but it may be possible to achieve the goal: "find liquid water". Goal-based operations often also implicitly means that the automated system will respond on its own to locally sensed information in order to achieve the goal.

Section II presents a real world case study of goal-based operations being used today (Earth Observing-1), Section III explores challenges and opportunities in both general and specific terms related to goal-based operations, Section IV discusses several potential confidence-building avenues to pursue, and Section V highlights general conclusions.

II. A Case Study for Goal-Based Operations: EO-1

Earth Observing-1 (EO-1) was the first satellite in NASA's New Millennium Program Earth Observing series. EO-1 was designed for a 12-month mission to test 10 revolutionary land-imaging instruments and spacecraft technologies and to confirm that NASA could apply the new technologies to future missions, such as the next-generation Landsat satellites. It was launched November 21, 2000, and accomplished all of its technology-demonstration objectives within one year. Due to the success of the demonstrated instrument technologies, NASA Headquarters approved extending the mission life of EO-1. Presently, EO-1 is in its sixth year of extended operations (seventh overall).

During its second year of operations, EO-1 collaborated with another New Millennium Program mission called ST-6 by integrating its Autonomous Sciencecraft Experiment (ASE) software onto EO-1.[1,2] This served to transform EO-1's operations into a goal-based approach. ASE consists of various flight software components including an autonomous onboard planner called the Continuous Activity Scheduling Planning Execution and Replanning (CASPER). During the next 2 years, ASE was integrated and validated onboard EO-1. As a result of exceeding expectations, ASE/CASPER was made operational and was instrumental in reducing the annual cost of operating the mission from $5 million to approximately $2 million due to transitioning from command load based operations to goal-based operations.

During the first two years of operations, more than 60 steps were required to direct EO-1 to image each target. In addition, meetings were held as often as daily and later once a week by the mission systems engineer, the mission scientist, the flight operations scheduler, the United States Geological Survey (USGS) Earth Resources Operations System (EROS) science planner and others to construct the daily command loads which in essence was the daily image acquisition plan. In the new goal-based approach, imaging requests are submitted through a website to the automated ground-based scheduling software, Automated Scheduling and Planning Environment (ASPEN), which automatically sorts the requests by priority (including removing conflicting image requests) and then organizes the selected requests into a baseline goal file. Updates can continue to arrive from various sources including automated sensor web triggers such as our in-situ volcano tiltmeter in Kilauea, Hawaii. The updates are reconciled with the baseline goal file onboard EO-1 by CASPER, the autonomous onboard planner (flight version of ASPEN). These goal files and updated replacement records are automatically delivered, queued and uploaded at NASA Goddard Space Flight Center. As a result, all that users now have to do for an image request is to submit a record with the desired latitude/longitude. The combined ground/flight autonomy software take care of the rest. Planning and scheduling meetings, which used to be manpower intensive, are now held only to review system status and special requests. The savings is primarily gained from the decreased manpower required to execute the 60 steps (which have been dramatically reduced as per above) and elimination of meetings previously required to execute EO-1 imaging operations.

III. Challenges and Opportunities

A. General Challenges

The purpose of this section is to provide an overview of general operations challenges to act as a framework for assessing the opportunities and potential benefits of goal-based operations. Not all are meant to be directly relevant to goal-based operations, although most are related in some way as subsequent sections hope to show. General challenges in operations can be categorized as direct operational challenges that face operations personnel on a day-to-day basis and broader contextual challenges that act as external forces on operational organizations. Some direct operational challenges include:

(a) Uncertainty, e.g. specificity in controlling automation, such as targeting instruments to precise locations
(b) Maintaining situational awareness for operators and/or crew
(c) Unexpected and infrequent events, where positive events might be events such as opportunistic targets, extra time or energy resources to exploit, and following up on unanticipated good results (such as a test that was even more positive for substance of interest), and where negative events might be goal failure, environmental interaction (e.g., obstacle, radiation), system failure, etc.
(d) Operational workload and complexity, which can help enable and simplify multi-mission operations
(e) Ensuring that operational tasks on the ground and in space are executed properly

(f) Crew safety, which requires careful and conservative operational procedures
(g) EVA optimization, which makes the best use of EVA time and activities

Some broader institutional, financial, and political contextual challenges, all of which must be addressed to ensure overall long-term program sustainability, include:

(a) Lifecycle costs - e.g., staffing (where hiring, training, career trajectories, and retention are critical aspects), management attention (operations decisions and organizational development), and balancing risks and returns as well as costs and benefits
(b) Public support and benefits - e.g., involving the public and educational institutions in operations
(c) Mission perception - e.g., is the mission being executed in a way that makes sense and is satisfying to many stakeholders?
(d) Safety - e.g., avoiding catastrophic failures such as the loss of vehicles, critical assets, etc.

B. Opportunities

This section will discuss near-term opportunities such as International Space Station Mission Control Center operations, mid-term opportunities such as human lunar missions, and longer-term opportunities associated with human missions to Mars.

1. Near-term: Mission Control Center Operations for ISS

One approach to investigating opportunities, demonstrating value, and informing organizations about automation technologies is to develop applications for current International Space Station operations. With ISS, NASA has shifted from missions of up to two weeks with the Space Shuttle to ongoing support of a crew living in space. This support involves three shifts of flight controllers with 24/7 backroom support at Johnson Space Center. Two examples of near-term opportunities now being explored by ARC and JSC are for managing files onboard the ISS and for reducing staff during nights and weekends.

The largely manual management of ISS files exemplifies the lack of basic automation for routine tasks. For example, mail files for the crew are screened and merged by a backroom position that is staffed 24 hours a day. A "mirror" site of ISS files is maintained, enabling flight controllers to quickly see what is onboard and to test programs (e.g., verify schedule updates). The opportunity is to use goal-based operations for all file management between mission support and crew. This includes archiving and mirroring files, interpreting error messages (some files combine data and commands for updating databases and documents onboard), and notifying interested parties, while respecting constraints of communication windows and goals related to file types, timing/scheduling constraints (e.g., uploading on schedule input files for automated software on-board ISS), and privacy. For example, a crew member may request that a particular web page be transmitted that includes personal health data relevant to a procedure being rehearsed today. Thus, the file should be transferred by a certain time (inferred from the operations plan) and should not be mirrored (because it contains personal data).

The approach being used for ISS file management is to develop a distributed software agent system that manages file transfer tasks, while providing a means for operators to override or revise decisions (e.g., for scheduling and mirroring). The methodology involves a combination of 1) observation, 2) baseline simulation of current operations using the Brahms multi-agent work practice simulation system[3] (explicitly modeling people, geography, computer systems, communications), 3) collaborative redesign of the work system, 4) a future operations simulation that embeds the agent-based workflow automation tool, 5) validation of the tool and revised work processes by driving the simulation with several months of actual ISS file transfer data, and 6) finally integration of the agent-based workflow tool in the mission operations computing environment.

Agent-generated emails and computer agents speaking on the voice loop must fit within current organizational protocols, requiring broader modeling of the goals and priorities of flight operations. For example, could one send a reply email to a computer agent asking for additional information and could the agent then pass the question on to another person for assistance in interpreting an anomalous situation? If a person tells the computer agent on a voice loop that he is busy and will call back later, when should the agent stop waiting and try calling again? The challenges and opportunities for goal-based operations will increase as people attempt to relate automated services to the strategic and judgmental aspects of operations.

A related opportunity being explored is whether automation can be used to reduce personnel during daytime operations in a manner similar to how six ISS system disciplines (e.g., power, environmental control) are composed into two positions (called Gemini controllers) during nights and weekends. However, changes in work practices are dominated by broader organizational constraints of career paths, training, and 24/7 scheduling. The opportunities for goal-based operations are to include data reduction, trend recognition, and alerting about issues in satisfying goals. A possible approach is to use work practice simulation over long time-periods, simulating career trajectories, vacation scheduling, etc., using a what-if analysis to investigate alternative mixes of staffing capabilities (e.g., mix of specialists and generalists to cover range of scenarios in complex operations). The challenge to providing automation to replace specialists' technical knowledge is a potential loss of robustness for high-risk/emergency operations due to lack or unavailability of training or experience.

Relating goal-based operations to practical situations requires appreciating the nature of current systems, why they are the way they are, and impediments to change (e.g., security, hierarchical command and control organization, safety, technical limitations, perceived risk). Thus working on actual problems today in mission operations enables us to more clearly articulate goal-based operational methods and understand the issues of developing integrated systems.

2. *Mid-term: Human Lunar Missions*

Present NASA plans call for a range of activities at the moon, centered primarily around the establishment of a permanent lunar outpost. Constructing a lunar outpost, maintaining a habitat and associated support elements, and conducting long-duration surface science activities all present novel operational scenarios and challenges. Due to high radiation levels, crews may face severe limitations on the cumulative duration of their EVAs during anticipated 6-month long surface missions, forcing increased reliance on remotely-directed robotic systems for many surface activities. The need to keep the outpost functioning between instances of human presence may also encourage Earth-based control of surface robotic systems, despite several seconds of inherent time delay in the control loops. Assembly of a lunar habitat will likely require the operation of large robotic vehicles and the precise manipulation of relatively large structures requiring special care. Placing astronauts in the midst of such activities may be deemed too hazardous, driving the use of telerobotic systems, operated at a distance either under direct human control or via some level of human supervisory control. Large robotic vehicles could be used to perform a number of tasks ranging from cargo transport to habitat assembly, to digging and regolith placement for radiation shielding.

Habitat assembly could be accomplished by mating two or more modules or even mobile landers which, in some concepts, could incorporate human habitation modules. Mating could be accomplished by teleoperation which would require much time for human operation and rely on precise manual manipulation which is often difficult and tedious. If safety and task execution is not achieved, irreversible damage could be done, compromising the crew and the ability to build a lunar outpost. Goal-based operations could be used to specify tasks such as placing habitat components next to each other for assembly or possibly mating components directly. For example, two large habitat modules or large rovers might need to be mated to form the basic structure of a habitat or module that would be incorporated into the larger outpost structure. An astronaut should be able to simply say: "HAB MODULE 1, mate with HAB MODULE 2", triggering the automated mating process (based on positioning data, terrain assessments, etc.) that would require minimal monitoring and intervention, with the system figuring out how best to achieve the goal, perhaps with additional astronaut guidance as needed. This of course would require relatively sophisticated automation, but the main point is that an astronaut should be able to give a high level command for a critical, time consuming, and relatively sophisticated task so that human intervention can be limited and EVA time can be optimized. This will increase time for other tasks such as science and increased safety by minimizing direct interaction with, and precise manipulation of, large mobile assets.

An astronaut may also wish to deploy a team of small rovers to conduct detailed surface mapping, surveying, and analysis of a particular area. Several robots could be stowed inside a large rover for subsequent deployment at the appropriate time and place. An astronaut should be able to direct such an asset to a desired location with an intuitive goal-based command such as: "EXPLORER 1, proceed to Shackleton Crater Rim Observation Zone and survey minerals of entire zone with mini-rovers". This would initiate the transport of EXPLORER 1 to the observation zone where it would then deploy the mini-rovers it carries to conduct a coordinated mineralogical survey of the observation zone, the boundaries of which have already been pre-defined in a database. If the user provides direction for which there is uncertainty, the system could respond with the appropriate query such as, "Observation Zone boundaries not yet defined - please specify." This kind of scenario would make robots true partners in executing tasks that are of human interest.

3. *Long-term: Human Mars Missions*

Human missions to Mars will change how space operations are currently conceived.[4] The communication delay to Mars will almost certainly require capabilities to facilitate complete crew autonomy. Safety requirements and processes, especially for EVAs, will likely be more controlled given (a) new challenges presented by the Martian environment (e.g. terrain, mission objectives, contamination, etc.) and (b) the isolation of the crew in terms of real-time communications and (c) lack of relatively quick earth return options. These challenges point to the need for (a) increasing the fidelity of task execution, (b) dramatically reducing the time required for mundane and repetitive tasks, (c) efficient control of surface assets (especially controlling multiple assets simultaneously) such as rovers, ISRU devices, transport vehicles, habitat elements, construction equipment, etc. (d) increasing exploration time and science return, and (e) smart systems that require less operator training. All of the above will contribute to increased safety, optimized EVA time, increased science return, and overall mission success.

One challenging aspect of human Mars exploration will be the search for life. Large areas will need to be explored efficiently, in part to determine if areas are devoid of life so that contamination control constraints might be relaxed. This will require extensive robotic life-detection scout missions[5] that could be operated (a) telerobotically from a habitat, (b) in the field with an astronaut working with a team of rovers, or (c) completely autonomously. While telerobotic operation will undoubtedly be used extensively, and perhaps exclusively as areas are explored for the first time (again, due to contamination concerns or other safety concerns), having an explorer in the field eventually will be very useful for all the reasons for sending humans in the first place. Complete autonomous operations of robots is possible, but has its own set of challenges that may make it a lower priority option. Explorers will want to control assets in real-time from within a habitat and while outside in the field during EVAs. An optimal strategy for science and discovery, as well as many other tasks, will likely be humans working in the field with robots since a human can coordinate activity in real-time and in a creative and responsive manner.[6]

An explorer in the field with multiple rovers or multiple assets should be able to control those assets with high level goal-oriented commands so they do not have to deal with more complex commanding approaches such as cryptic command scripts. For example, if explorers wants to search for life using multiple robots with different life-detection capabilities, they should be able to say: “WATER-BOT 1, search for water”, or “ORGANICS-BOT 2, join WATER-BOT 1 and sample for organics”, or “DNA-SEQUENCER 1, proceed to ORGANICS-BOT 2 and sequence sample.” A higher level goal might even be “LIFE-DETECTION-BOT-TEAM 1, search for life within a 100 by 100 meter area”. If the explorer forgets to specify something, a response from the system would be to ask for clarification: “Please specify starting point relative to the search area”. The explorer would respond: “Your present location is the center of search area”. This would then kick off a series of autonomously-executed activities involving the coordination and cooperation of multiple robots to search for life.[7] A generalized version of such a scenario would allow a human explorer to essentially supervise, guide, or monitor any number of assets simultaneously so as to optimize EVA time and allow the explorer to attend to other things such as conducting other science or attending to safety measures while the assets are executing specified goals at the same time. Operations along these lines will be safer and much easier for an explorer to conduct and should require less training.

IV. Confidence Building

A. Incremental Implementation

The challenges and opportunities in the previous section are meant in part to point the way to incremental development strategies and incremental implementation steps that would ultimately build confidence in the use of goal-based operations in the longer-term – for example, for human Mars missions when such a capability may have its greatest return on investment since this when crew safety, crew time, task execution and crew autonomy will be critical and there will be less room for error and inefficiencies. By proving the usefulness and reliability of goal-based operations for smaller, well-bounded tasks in ground-based operations for well established human programs such as ISS (as outlined in sections III.B.1), managers and users in the human space program might be more willing to consider more robust applications of goal-based operations. Lunar missions that utilize goal-based operations, perhaps in manners similar to what is highlighted in Section III.B.2, will provide an opportunity to assess, and perhaps directly measure, the performance, benefits, and risks of more sophisticated EVA-oriented goal-based approaches as well as other complex non-EVA tasks. The Moon gives us an opportunity to learn first hand how to deal with the challenges associated with outpost construction and long-duration surface exploration activities. It will be far better to master these challenges and test automation such as goal-based operations during lunar missions – in preparation for going to Mars when safety and mission timelines will arguably be constraining and when mistakes could be far more costly.

B. Risk and Systems Dynamic Modeling

The mission operations environment is difficult for technology infusion opportunities. Implementing goal-based operations would require changes to culture, procedures, and platforms. While procedure development and verification are part of the daily operations task, and platform changes can be handled within the hardware and software change process, it is the culture change that presents the most substantial difficulty. New technologies often are shunned because of the perceived introduction of risk into the operations environment, even when the technology introduction is meant to reduce the present risk exposure.

Those new technologies that are nevertheless adopted usually serve to increase work capacity in such a way that additional output increases preparedness and therefore minimizes response time for unusual and unexpected events. When the new technology is infused in order to increase autonomy and adaptability so as to reduce the staffing support burden, it serves to reduce workload capacity in favor of efficiency. Before agreeing to reduce the support burden, the operations community – which is normally quite comfortable with its practices and risk posture – will have to be persuaded that such a technology infusion will maintain if not reduce the prevailing risk level.

Because successful technology infusion may depend upon a characterization of risk level, a model of operations risk may be necessary to facilitate the culture change. Although we do not develop the details here, it is useful to consider how such a model may help. For example, the operations community may perceive goal-based operations as a loss of fine-grained control and an associated increase in uncertainty about the details of what the remote agent is doing now or may do later. Is there a risk associated with this potential uncertainty? In current human missions, operators can generally evaluate the results of an individual low-level command before proceeding to send the next command. Typically, the operations team wants as much telemetry as possible from the remote agent to identify its state and anticipated course of action. If the operations team were to have fewer members, is there an associated increase in risk? Will all of the telemetry be scanned and analyzed? If there is an increase in risk, now much is tolerable? Are there ways to mitigate this risk? Along with cost and schedule impacts, these and other risk-related questions must be considered in the decision to adopt new technologies.

A risk model that represents the mission operations environment would include likelihood and consequence dimensions in relative terms and would capture all of the uncertainty, deliberation, and possible actions available to the operators. A decision-theoretic model, as one approach, would use telemetry and trajectory data as evidence, process that evidence into a probabilistic estimate of state, and then select and enact the ideal action to take given that state. A simulation would explore the evidence, state, and action space to feed a likelihood and consequence determination (for instance, the consequence of taking the wrong action under uncertainty) to characterize risk. This incidentally might reveal something about the ideal action set, just as it might reveal opportunities for sensor placement or ranking. Running this model without the introduction of a new technology such as goal-based operations provides a baseline for assessment of infusion opportunities. Running the model assuming the new technology is in place then enables a relative risk assessment comparing today's risk exposure with the risk exposure after infusion.

Real-time versions of such a model may prove useful during flight operations as a decision support tool, if sufficient fidelity and speed can be achieved. Calculations that take more than a second or two would either have to be cached or provide for best-so-far results. Ultimately, one would like to deploy this model on board the spacecraft as well, both for reasoning about its environment as well as reasoning about what the mission control center would be doing given the same situation.

Comprehensively modeling the operations environment and assessing risk via that model would be a substantial effort, but goal-based operations can serve as a relatively narrow focus that could serve as a manageable starting point and justification for this kind of model development. Such a model could be combined with (a) workflow models that are presently being pursued[8,9] (b) automation assessment tools such as FLOAAT (detailed in the next section), and perhaps ultimately with (c) cost models – all of which would contribute to a comprehensive operations modeling tool/environment that can serve many levels of organizations and programs. The long-term nature of the new human space exploration program opens the door for developing such a comprehensive model, which can be refined over time and help find efficiencies, assess technology infusion, and increase safety and mission success by reducing risk.

C. Automation and Autonomy Assessment Tools

Confidence building measures can be employed to raise the operational acceptance level of increased automation and autonomy functions like goal-based operations. However, a critical step in the process is determining the current level of confidence, or trust, that the human users would have in the system if it were automated. Understanding the current operations framework will aid in developing autonomous systems such as goal-based operations by enabling the assessment of what exactly should be automated and the degree of automation to implement. One tool, the Function-specific Level of Autonomy and Automation Tool (FLOAAT), can be used to specifically address these issues.

The FLOAAT Process, shown in Figure 1, is a practical application which analyzes separate levels of automation (human vs. computer execution/authority) and autonomy (ground vs. onboard execution/authority) for each of the 4 stages of decision-making (Observe, Orient, Decide, and Act).[10] Automation In the FLOAAT Process, domain-specific experts qualitatively evaluate a set of functionally decomposed requirements (decomposed from higher level requirements, concept of operation documents, and design reference missions) in a manner that yields a quantitative solution similar to the Cooper-Harper Scale[11] or the Bedford Workload Scale[12]. This quantitative solution maps directly to the FLOAAT Level of Autonomy and Automation (LOAA) Scales, which provide an easy-to-understand definition and implementation strategy for the different levels of autonomy and automation. The last step in the FLOAAT Process is to re-write the function-specific requirements based on the quantitative outputs and the definitions of those outputs from the LOAA scales. These updated requirements document an agreement between the function users and the function developers which is one critical step in the process to develop user trust.[13] As part of this process domain experts provide their assessment of the current operational levels as the challenges for implementing at higher levels of LOAA scales. This information can be used to identify areas that could limit trust in the automation of each individual function. In turn, these factors can be used to create a development and infusion plan that builds trust by specifically addressing these issues. The following section lists the factors that apply to trust of automation and autonomy.

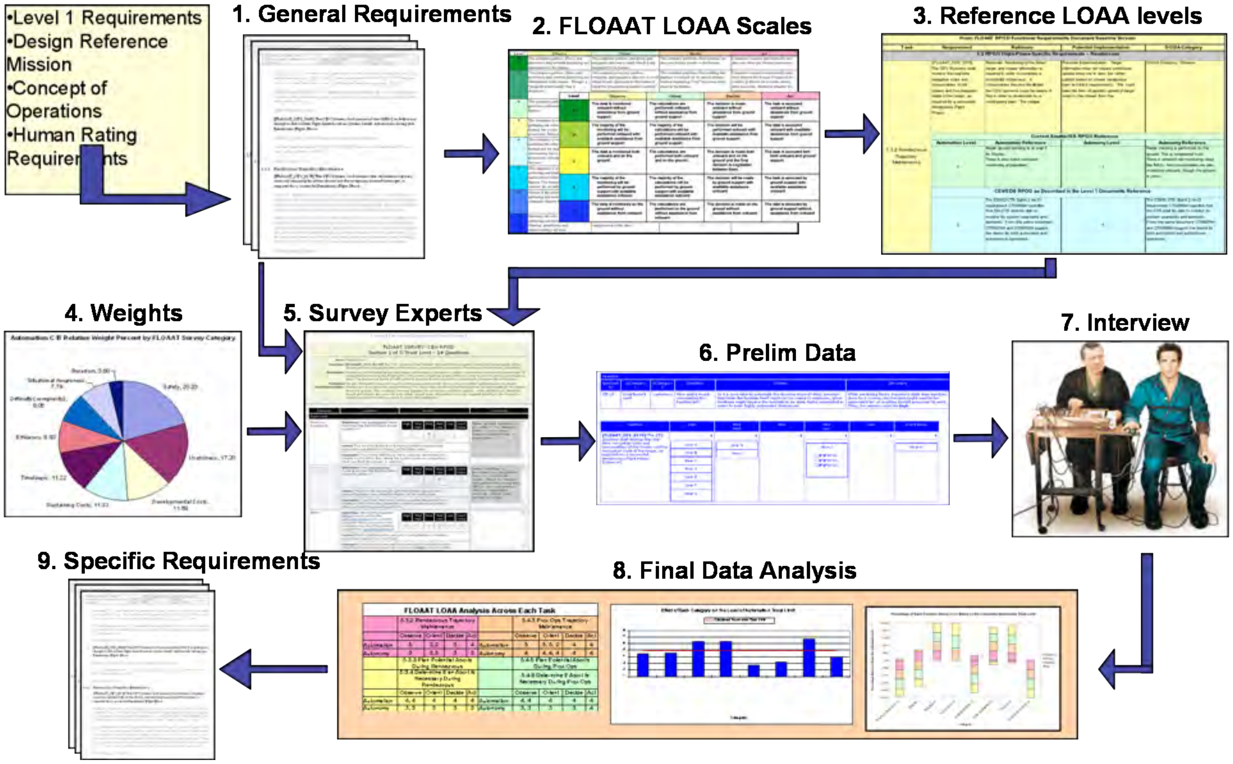

Figure 1. The FLOAAT Process, Version 4.0

1. The Trust Development Metrics

If the human user does not trust the newly developed automation software, then it does not matter how intelligent, beneficial, cost-efficient, or safe the software is designed to be. It will not be used. In one study of functionality for NASA's Orbital Space Plane trust was the limiting factor in automated software development 90% of the time.[14] The following metrics for levels of trust in automated and autonomous systems leverage off the experience of NASA in automating functionality on the Space Shuttle and International Space Station. In addition, the work of Sheridan[15] was incorporated to ensure an unbiased set of metrics. In order for human users to develop trust in automation, all of the following topics must be evaluated. In the FLOAAT process, weights measuring relative importance are assigned to each of these categories. Domain area experts are asked, "How much does this topic affect how automated you trust this function to be performed?

- Previous Experience: Experience with this function or similar functions in human spaceflight applications
- Difficulty (complexity): The level of complexity of the function regarding software and hardware
- Robustness: Ability to operate outside of the "certified environment"
- Correctness: A computer's ability to return a more optimal solution than a human
- Understandability (override): Ability of a human to understand the function enough to override the computer and perform the function manually, if necessary
- Training: Amount of training time saved by automating this function
- Operational Experience: Perceived amount of operational experience necessary before users will trust an automated version of this function

In order for ground-based mission control to develop trust in autonomous functionality, all of the following topics must be evaluated. As above, FLOAAT prescribes different weights to each of the categories based on previous experience. For autonomy the question is “How much does this topic affect how autonomous you trust this function to be performed?”

- Previous Experience: Experience with this function or similar functions in human spaceflight applications
- Effort: Amount of computational or mental processing required to complete the function
- Correctness: The onboard systems ability to return a more optimal solution than the ground systems
- Training: Amount of crew training required to perform this function without ground support
- Understandability (override): Ability of the crew to understand the function enough to perform it without ground support
- Safety (Necessity): Necessity of the function onboard to maintain safe vehicle operation when communication with ground systems is lost

The factors listed above can be used to understand how trust can be developed in automation and autonomy. These factors are important to consider in each phase of the spacecraft and operations design process. If properly addressed, these issues can help developers address concerns and build trust during early development.

2. Examples of near-, mid-, and long-term trust development strategies for goal-based operations

For near-term low earth orbit mission operations of the Orion spacecraft, the Automation and Autonomy (A&A) strategy is being defined currently in the Crew Exploration Vehicle (CEV) System Requirements Document. For time-critical ascent abort decision making, CEV requirements dictate that onboard A&A software will be included that can decide when an abort is necessary and can automatically initiate an abort. This is a leap in trust of automation over the Space Shuttle paradigm where the abort software was located on the ground and the crew pushbuttons were the only mechanism for abort initiation. For longer time horizon events like aborts on orbit, the ground-based mission controls and onboard crew are expected to perform the abort decision-making using information provided by automated software. For all flight phases, Orion will have to meet requirements that allow the crew and ground to override, inhibit, enable the automated onboard software. Currently, none of the planned software uses goal-based operations. In every case, specific procedures are outlined instead of allowing the vehicle to determine its own method for achieving the goal. However, the capability to determine achievable ascent aborts autonomously represents an increase in the use of automated software for human spaceflight.

It will be the mid-term lunar missions that will have the first real opportunity for testing the human-automation relationship using goal-based operations. The lunar outpost missions are being planned for long duration stays (e.g. 6 months) on the lunar surface. There will be robotic aides for the crew to help perform both sophisticated science tasks and simple everyday tasks. In order for the crew and ground-based mission controllers to develop trust in the automation, a trust leap in at least one of the above metrics is necessary. This may come in the form of a Space Station Development Test Objective which raises the previous experience metric by showing the ability of automation to perform tasks. Software developers can decrease the perceived complexity of the application by showing the users the algorithms involved. This may also have the benefit of increasing the users’ understanding of the code and will enable knowledge of the boundaries of what the code was designed to do and what it wasn’t designed to do. Having a clear boundary for the automation will also help the training aspects as the users will know when the developers want the automation to be trusted. The lunar outpost missions will be good test mission for eventual Mars missions. This should enable the goal-based operations development community the ability to prove concepts without having to wait for a mission to Mars. However it is still expected there will be ground-based mission controllers watching all automated operations in real-time. In many cases, fault recovery will be performed by these mission controllers.

In the long-term, crew sizes will not be large enough to perform all of the necessary activities on Mars missions. Thus, the use of robotic aides is expected. The necessity of automation can be a major driver for developing trust. When there is no alternative, and the human knows that the objective can only be achieved with computer skills, humans have shown the ability to develop trust in automation. The time delays between Earth and Mars will make it hard for the ground-based mission controllers to perform the fault recovery tasks for the robotic aides. Thus, by necessity, the level of autonomy will need to be raised driven by workload and safety concerns. A method to gain trust by the users is to show them that the effort for the crew member on the surface is too high to maintain knowledge of all of the robotic aides. Also, by thoroughly testing of the algorithms on previous lunar missions the correctness of the automation to self-recover from faults can be proven. This is critical to establishing trust in the automation to perform goal-based operations without constant supervision.

D. Communication Standards for Goal-Based Operations

The success of a goal-based system, whether it tightens a single bolt, maintains a habitat environment, or directs a rover traverse, depends on clear specification of the goal to be achieved. The operator's intent must be unambiguously captured and communicated to the system that will fulfill that intent. Otherwise, the system may perform in unexpected ways, with the system doing a fine job of achieving the wrong goal. Humans often do not manage to communicate intent clearly to each other, and may require several interchanges to resolve ambiguity. In some cases, misunderstandings may be maintained or propagated for extended time periods before the problem is even identified.

As long as goal-based systems are rudimentary (that is, operating at the low end of the goal hierarchy), such misunderstanding of operator intent may be unlikely or impossible. Some automated systems may be designed to satisfy a single goal (or small enumerated set), specified during development and holding for the entire operational lifetime of the system. A rover traverse may be specified as a set of coordinates with an appropriate radius of acceptability. But as goal-based systems move up the goal hierarchy, and become capable of handling a wider range of more complex goals, capture of intent may become a greater challenge.

When goal-based systems reach a level for which natural-language commanding is desired (e.g., in cases where the operator is an EVA astronaut), there may be a need to establish a spoken goal specification language, analogous to a high-level computer language, in which operators will need to be well-versed. Acceptance and trust of such systems will be partly determined by the usability of this interface.

V. Conclusion

A general productive approach to changing the practice of human space operations is incremental. Starting with existing ground operations, implementing standard (COTS) automation for routine operations, and introducing improved architectures will eventually build confidence in goal-based operations. At each step, the developers and purveyors of the specific application of goal-based operations will need to prove that the investment is justified through increased performance and reduced risk to mission and crew. An incremental approach will (a) bring near-term value and increase awareness and understanding of technology opportunities, (b) develop a technical and organizational foundation for designing future operations for human lunar and Mars missions, and (c) reveal strengths, limits, and future opportunities for technology, allowing better targeted research and development.

Using goal-based operations has the potential for more efficient, safe, and productive human space exploration operations and will require demonstrations of that value, as well as continuing investment in research to advance the field. This can be accomplished partly by creating strong partnerships between researchers and operations organizations – some of which is being done today. Successful advanced operations will also require respecting limitations of automation and its application by human users, for example by designing systems from the start for "mixed initiative interaction" that includes both automation and human control, using methods such as goal-based operations.

Lupisella, M., D. Mandl, A. Mishkin, M. Berry, W. Clancey, R. Proud, J. Hart. A Customer View of Goal-Based Operations for Human Space Exploration. Paper AIAA 2007-2712, presented at InfoTech 2007, Rohnert Park, CA.

References

[1] Sherwood, R., Chien, S., Davies, A., Mandl, D., and Frye, S. "Real-time Decision Making on EO-1 Using Onboard Science Analysis," SPIE, Hawaii, 2004.

[2] Davies, A. G., Baker, V., Castano, R., Chien, S., Cichy, B., Doggett, T., Dohm, J., Greeley, R., Rabideau, G., Sherwood, R., Williams, K. K., and the ASE Team (2003), "Autonomous Volcanic Activity Detection with ASE on EO-1 Hyperion: Applications for Planetary Missions," Abstract, DPS 35, Monterey, CA., BAAS Vol. 35, No. 4, 41.14, p 1002.

[3] Clancey, W. J., Sachs, P., Sierhuis, M., and van Hoof, R. (1998). "Brahms: Simulating practice for work systems design. Int. J. Human-Computer Studies," Vol. 49, pp. 831-865.

[4] Mishkin, A., Lee, Y. Korth, D., and LeBlanc, T., "Human-Robotic Missions to the Moon and Mars: Operations Design Implications", In Proceedings of IEEE Aerospace Conference, paper #1400, Big Sky, MT, 2007.

[5] Race, M., Criswell, M., and Rummel, J. "Planetary Protection Issues in the Human Exploration of Mars," Paper Number 2003-01-2523, International Conference on Environmental Systems (ICES), Vancouver, B.C., July 2003.

[6] Clancey, W.J. "Roles for agent assistants in field science: Understanding personal projects and collaboration," IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews, Special Issue on Human-Robot Interaction, Vol. 34, No. 2, May 2004, pp. 125-137.

[7] Lupisella, M., "Cooperative Agents and the Search for Extraterrestrial Life," Innovative Concepts for Agent-Based Systems, edited by W. Truszkowski, C. Rouff, and M. Hinchey, Lecture Notes in Artificial Intelligence, Springer Berlin, 2002, pp. 408-416.

[8] Sierhuis, M., Clancey. W. J., Seah, C., Trimble, J., and Sims, J. "Multiagent modeling and simulation in human-robot mission operations work system design," Journal of Management Information Systems, Vol. 19, No. 4, 2003, pp. 85-128.

[9] Clancey, W. J., Sierhuis, M., Alena, R., Berrios, D., Dowding, J., Graham, J. S., Tyree, K. S., Hirsh, R. L., Garry, W. B., Semple, A., Buckingham Shum, S. J., Shadbolt, N. and Rupert, S. 2005. "Automating CapCom Using Mobile Agents and Robotic Assistants," American Institute of Aeronautics and Astronautics 1st Space Exploration Conference, Jan. 2005. Available as AIAA Meeting Papers on Disc [CD-ROM]: Reston, VA, and as an Advanced Knowledge Technologies Project ePrint [http://eprints.aktors.org/375]

[10] Boyd, J. R. "The Essence of Winning and Losing," Excerpts in presentation format found on the web at http://www.defense-and-society.org/fcs/ppt/boyds_ooda_loop.ppt, 1996. Downloaded February 2005.

[11] Cooper, G. E. and Harper. R. P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

[12] Roscoe, A. Assessing pilot workload in flight. Advisory Group for Aerospace Research & Development Conference Proceedings, No. 373: Flight Test Techniques. Neuilly-sur-Seine, France. NATO. 1984.

[13] Proud, R. W., Hart, J. J., "FLOAAT, A Tool for Determining Levels of Autonomy and Automation, Applied to Human-Rated Space Systems", In Proceedings of AIAA 1st Infotech@Aerospace Conference, Doc. # AIAA-39351-706, Crystal City, VA, 2005.

[14] Proud, R. W., Hart, J. J., 2005.

[15] Sheridan, T. B. *Telerobotics, Automation, and Human Supervisory Control*. The MIT Press. 1992.