Self-Commanding Spacecraft (SCS)

Task Leaders

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Product Description

Technology and software to enable a spacecraft to accept goals, rather than commands, a so-called *self-commanding spacecraft*. This spacecraft would use software to automatically execute spacecraft commanding sequences from high level science and engineering goals. Engineering goals would include operations constraints such as "calibrate the camera once per 200 images or 2 weeks," or "do not allow reaction wheels to exceed level X of saturation." Science goals might be of the form of a prioritized target/experiment list. Technology to enable evaluation of spacecraft and mission designs by analyzing possible operations plans required by spacecraft and mission designs (PFMD). Quantitative metrics for evolution of planning technology are listed below. Longer term goals of operations costs reduction are listed in the section on Benefits.

	Current	End FY2000	End FY 2001
Constraints Represented	100-200	300-500	1000+
Plans Searched/second	150	200	300+

This is a **continuing, pull** task, and represents the merging of the previous self-commanding spacecraft and planning for mission design tasks.

Benefits

Past spacecraft missions have used large teams of highly knowledgeable personnel in an extremely labor-intensive effort to generate and validate spacecraft command sequences. This proposal targets *self-commanding spacecraft* technology, in which a spacecraft possesses, in on-board software, the knowledge and reasoning procedures to determine appropriate actions to achieve its mission objectives while preserving spacecraft health. Self-commanding spacecraft technology would have tremendous impact on mission operations.

- Because the spacecraft would command itself, the extremely costly sequencing elements of the mission operations team would be almost eliminated - dramatically reducing cost. JPL internal estimates [Ridenoure 1995] indicate that this technology could reduce mission operations costs by as much as 60% (excluding data analysis). *Use of automated planning and scheduling technology in the DCAPS system deployed by the Self Commanding Spacecraft Task in August 1997 for commanding the DATA-CHASER shuttle payload flying onboard STS-85 reduced commanding-related mission operations effort by 80% [Chien et al. 1998] as compared to manual generation of sequences.*
- Self-commanding spacecraft could also perform opportunistic science. When an unexpected opportunity occurs (such as a supernova or solar phenomena), the spacecraft could immediately respond with appropriate measurements rather than waiting until ground-based detection of the event, and subsequent uplink of commands to spacecraft.
- Self-commanding spacecraft, by using high performance automated planning and scheduling technology offer the potential to increase science return by producing operations plans that better optimize use of scarce science resources. *Use of automated planning and scheduling technology in the DCAPS system deployed by the Self*

Commanding Spacecraft Task in August 1997 for commanding the DATA-CHASER shuttle payload flying onboard STS-85 increased science return by 40% over manually generated sequences [Chien et al. 1998].

Technical Approach

This task will focus on three key technical issues in bringing automated planning and scheduling to mainstream spacecraft mission operations:

- **Dynamic Planning:** The planner must respond in a timely fashion to a (somewhat) dynamic, unpredictable environment. Spacecraft plans must often be modified in the event of fortuitous events such as observations completing early and setbacks such as failure to acquire a guidestar for a science observation.
- **Plan Quality and Optimization:** Spacecraft mission planning involves a heavy mix of hard and soft constraints. The planner representation must allow users to easily express both hard and soft constraints. The planner must be able to find plans that respect the hard constraints and are of high quality (e.g., appropriately optimize over soft constraints).
- **Design for Operability:** Mission planning can be used to analyze spacecraft and mission designs so that more informed decisions can be made about tradeoffs in spacecraft designs (e.g. battery size, solar panel size, buffer sizes) and mission design (e.g., trajectory analysis, downlink strategy). This type of analysis requires specialized planning strategies for analysis, such as methods for minimizing peak consumption of resources to determine required capacities.

In the following sections we describe our proposed work to address these issues.

Dynamic Planning: We propose further development of the Continuous Activity Scheduling Planning Execution and Replanning (CASPER) system. Rather than considering planning a batch process in which a planner it is presented with goals and an initial state, CASPER has a current goal set, a current state and projections into the future, and a current plan. At any time an incremental update to the goals or current state (an unexpected event or simply time progressing forward) may update the planner process. The planner is then responsible for maintaining a consistent, satisficing plan for the most current information. Incremental changes to the goals, initial state, or executed activities trigger iterative repair conflicts with the plan.

CASPERs design goal is to accept activity and state updates on 1 second to 10 second timescale. This enables more up to date information regarding the execution status of activities as well as monitored state and resource values. This introduction of the planner into the short term planning horizon can also be motivated by current operations scenarios taken from the Space Infra-red Telescope Facility (SIRTF) operations scenarios [Mittman, 1997]. In this operations scenario, the observatory is in a near-earth orbit and has a set of observation targets and their prioritizations. However, it is difficult to project exactly how future execution of the plan will proceed. For example, if spacecraft is able to acquire the target quickly (as compared to conservative settling times and time for search for the target), and observation may complete significantly ahead of schedule. Alternatively, if the spacecraft repeatedly fails to acquire a guidestar required by an observation, an observation may be terminated. This also has the effect of completing the activity ahead of schedule but with a failed outcome. Within this operations context, a short-term planner would decide which observations to sequence next. Such a planner would need to consider all targets currently on the observation list, their visibility windows, and their relative positions in the sky (for reasons of slew minimization and for observation quality issues). The short term planner would also need to track other resource management issues such as data management relating to engineering and science observations and coordination with downlink windows.

Our iterative repair approach continues our work on high-speed local search techniques [Chien et al. 1998] that has proven robust in actual applications. In terms of related work, iterative algorithms have been applied to a wide range of computer science problems such as traveling salesman [Lin and Kernighan 1973] as well as Artificial Intelligence Planning [Chien & DeJong 1994, Simmons 1988, Sussman 1973]. Iterative repair algorithms have also been used for a number of scheduling systems. The GERRY/GPSS system [Zweben et al 1994, Deale et al. 1994] uses iterative repair with a global evaluation function and simulated annealing to schedule space shuttle ground processing activities. The Operations Mission Planner (OMP) [Biefeld and Cooper, 1991] system used iterative repair in combination with a historical model of the scheduler actions (called chronologies) to avoid cycling and getting caught in local minima. Work by Johnston and Minton [Johnston and Minton 1994] shows how the min-conflicts heuristic can be used not only for scheduling but for a wide range of constraint satisfaction problems. The OPIS system [Smith 1994] can also be viewed as performing iterative repair. However, OPIS is more informed in the application of its repair methods in that it applies a set of analysis measures to classify the bottleneck before selecting a repair method. In exploring iterative repair and local search techniques we are exploring approaches complementary to backtracking refinement search approach used in the New Millennium Deep Space One Remote Agent Experiment Planner [Muscettola et al. 1997].

Plan Quality and Optimization Previous work in the Self Commanding Spacecraft task and other NASA planning in scheduling efforts has enabled representation of many of the hard constraints frequently occurring in spacecraft mission operations. However considerably less effort has been devoted towards representation of soft constraints and preferences for typical spacecraft operations applications (one notable exception is [Johnston and Miller 1994] which uses suitability functions to represent temporal preferences of science observations).

In previous work in the SCS task, we have developed an initial language for specifying planning preferences. Our language specifies a set of plan parameters, and then allows expression of preferences over the values of these parameters. The individual scores for these parameters are then combined into an overall plan score. Plan optimization can then be viewed as optimization over the surface defined by the space of plans and their scores.

The planner then uses this preference scoring information to direct search to improve the score. For each type of structure of the scoring function, search operations have been characterized. Some of these search operations increase a particular element of the score while guaranteeing to not reduce other elements of the score. Other operations improve one element of the score but may reduce other elements.

Numerous types of preferences are expressible in our language. One type is the existence of and placement of activities in the plan. Other preferences relate to the temporal placement of activities. These may be simple preferences such as for the start time of observations. More difficult and currently not representable are complex preferences such as the relative timing of a sequence of observations (e.g., I want 12 observations roughly 14 hours apart and under the following lighting conditions). Temporal preferences also include preferences on the durations of activities. Activity preferences may also include preferences to maximize the number of activities, such as observations. Alternatively, they might also specify preferences for activity parameters, such as take the images as close to the target as possible, or when vibration onboard the spacecraft is at a minimum. Another class of preferences involve state variables. Examples of this type of preference include constraints such as: keep the imaging device closed when not in use, prefer to minimize the power cycling of the instrument, or have the inertial reference units warmed up for up to one day ahead of any trajectory correction maneuver. A third class of preferences concerns spacecraft resources. This class of preferences would include preferring to minimize propellant usage or preferring to minimize the thermal range of the spacecraft.

Work in future years focuses on effective search of the optimization space (including characterization of local and global optima). While there has been previous work in planning in the presence of global optimization criteria [Williamson & Hanks 1994, Williamson & Hanks 1996], this work presumes that it is possible to find search operators for which strong monotonicity properties over plan quality can be proven. Unfortunately, for the spacecraft operations domain, it seems likely that the optimization spaces will be extremely rough and difficult to characterize. Consequently, we propose to develop characterizations of local optima for heuristic search strategies that will hopefully be able to enable quick discovery of good solutions with local optima guarantees [Aarts and Korst 1990]. In cases where it is necessary to find higher quality solutions (with corresponding higher search cost), random restart methods could be used to improve solution quality.

Planning for Spacecraft and Mission Design The job of mission design engineers is to identify a spacecraft design and mission profile that will maximize the mission objectives while minimizing cost and staying within feasibility constraints (cost, mass, operations constraints, etc).

Often spacecraft and mission design occurs in the context of activity plans for key mission scenarios. Just as a simulation allows designers to better understand how the design artifact would behave, a plan helps mission designers to understand how a specified spacecraft design will execute a given mission design. For example: How many observations will it take? What are the resource margins? How much slack time is there for contingencies?

We have developed an automated planning system that takes as input spacecraft parameters (e.g., spacecraft slew rates, battery capacity), mission parameters (e.g., frequency of communication passes, trajectory), and an objective function (e.g., science per dollar). The planner generates a mission activity plan that is locally optimal with respect to the objective function. This enables mission engineers to quickly evaluate several designs.

This system has been used and is in continuing use to support design trade studies for a number of missions including the Citizen Explorer Mission and the Space Interferometry Mission. It is currently baselined for use by the LightSAR mission as well. Because of funding restrictions we will be limited in our further development of this technology but we will extend the planner to perform capacity analyses and minimize maximum capacity usage in order to highlight mission and spacecraft design trades.

Status and Milestones

FY99 SCS accomplishments include:

- Development of the CASPER prototype [Chien et al 1999] for integrated planning and execution.
- Demonstration of the CASPER prototype on MDS scenarios
- Demonstration of a hybrid CASPER/MDS Goal Achieving Modules system on MDS Scenarios
- Supported the demonstration of ASPEN[Rabideau et. al. 1999, Estlin et al. 1999a] and CASPER [Estlin et al, 1999b] to plan for distributed rovers.
- Development of initial plan optimization language and capability

FY99 PFMD accomplishments include:

- Support of evaluation of orbital options, observation tiling strategies, and power options for SIM mission.
- Support of LightSAR initial mission studies.

FY 2000 Milestones:

- Prototype for migratable flight/ground automated planning capability for X.2000-2 delivery

- Deployment for Citizen Explorer automated mission operations
- Prototype capability for representing and reasoning about plan quality and plan optimization

FY 2001 Milestones:

- Technology transfer of migratable flight/ground automated planning capability for X.2000-2 delivery
- Transfer of plan quality and optimization work to X.2000-2

Qualifications of Presenters

Dr. Chien has been performing planning and scheduling research for over 10 years and has authored over 100 refereed publications at conferences such as AAAI, IJCAI, NIPS, and AIPS as well as journals such as Artificial Intelligence Journal, JAIR, IEEE Intelligent Systems, and IEEE Transactions on Pattern Analysis and Machine Intelligence. He has served as a chair and organizer for multiple symposia and conferences including AIPS98 and AIPS2000. He has presented tutorials on planning and scheduling at numerous AAAIs and IJCAIs. Dr. Chien has held numerous element and task lead positions at JPL, and is currently the lead for Planning and Language for the Mission Data Systems Project.

Dr. Ben Smith has been leading the Planning for Mission Design Task for the past 2 years. Dr. Smith was the DS1 Remote Agent Experiment (RAX) Planner Deputy Lead, and the RAX Deputy Program Element Manager as well as the RAX Operations Lead. Ben has authored numerous publications in planning, knowledge acquisition for planning, testing of autonomous systems, and planning for mission design.

Customer Relevance

The intended users for this task are NASA flight projects represented in Space Science Enterprises, Mission to Planet Earth (MTPE), and HEDS (both via application to Ground Station Automation and for combined human robotic exploration). Our focus has been Space Science, we have been working closely with MDS which represents several future JPL missions and TMOD which represents the tools and mission operations service provider to future JPL flight projects.

Mission Data System(MDS): MDS is a JPL effort to develop a multi-mission ground and flight software system to support future JPL missions. ASPEN, developed under SCS funding has already contributed timeline and resource management approaches to the MDS architecture. CASPER also has been identified as future MDS Planner, from TMO Advanced Planning & Sequencing Technology Development Plan (1/99, Starbird): *"The architecture will be able to operate without a full-fledged planner, but will also be able to incorporate one. Ultimately, the continuous planning approach described below will be used."*

Contact: Dr. Thomas Starbird, Lead, Planning and Execution, MDS Project, JPL, thomas.starbird@jpl.nasa.gov, (818) 354-1033. (see letter of support, scanned and hardcopy)

TMOD: *TMOD performs mission operations for virtually all JPL missions. The TMOD Technology program has co-funded the development of CASPER and has identified CASPER as being central to its mission needs in Mission Planning and Execution. In the Mission Planning and Execution TMOD Requirements Analysis (February 1999, Amador, Grenander, & Wilson) they identify CASPER as addressing all of the planning and control mission requirements and 14 out of the total 31 mission requirements in Mission Planning and Execution.*

Contact: Mr. Robert K. Wilson, Program Element Manager, Mission Planning and Execution, Telecommunications and Mission Operations Directorate, JPL, robert.k.wilson@jpl.nasa.gov, +1 (818) 254-1128. (see letter of support – scanned and hardcopy)

Colorado Space Grant College (CSGC), University of Colorado (CU): CSGC has used the ASPEN planner in analysis and design of the Citizen Explorer (CX-1) satellite. ASPEN is also to be used for mission operations of CX1 which launches in December 1999. The Citizen Explorer project and ASPEN usage will demonstrate advanced end to end mission operations architectures for low-cost mission operations as well as showcase automated planning and scheduling technology. CSGC is contributing significant personnel resources towards this collaboration, the mission operations team is currently estimated at 4 FTE's for 2 years for a total of 8WY co-support.

Contact: Professor Elaine Hansen, Director, Colorado Space Grant College, University of Colorado, elaine@rodin.colorado.edu, +1 (303) 492-3141. (see hardcopy letter of support)

Space Interferometric Mission (SIM), LightSAR: SIM has used the Planning for Mission Design (PFMD) s/w in their mission design. LightSAR is planning to use it for mission design and analysis. See enclosed hardcopy letters of support.

Contact: SIM: John Reimer, Mission Design Lead, SIM, john.reimer@jpl.nasa.gov, (see letter of support)

LightSAR: Jeff Hilland, Mission Design Engineer, LightSAR, jeff.hilland@jpl.nasa.gov. (see letter)

Microsoft Games Division: Based on our technology development of CASPER involving real-time computation limited planning Microsoft is providing funding via the JPL Technology Affiliates Program focused on development of the AI players for MechCommander 3.

Contacts: Glenn Doren, Lead AI software Engineer, MechCommander 3, glenndor@microsoft.com,
Jennifer Schlickbernd, JPL Technology Affiliates Program, jennifer.schlickbernd@jpl.nasa.gov.

Carnegie-Mellon University, Engineering Animation, Inc., Ford Motor Company: Via the NASA Robotics Engineering Consortium, and in collaboration with Steve Smith of Carnegie-Mellon University, we have proposed adapting and extending the PFMD concept for use in evaluating and improving factory layouts for automotive manufacturing. Engineering Animation has agreed to provide co-funding for this effort, they are a leading provider of software and services in this area to a number of automotive manufacturers, most notable Ford Motor Company.

Contacts: Steve Smith, Carnegie-Mellon University, sfs@cs.cmu.edu, Dave Sly, Engineering Animation Inc., Tim Wagner, Ford Motor Company.

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June 7, 1999

To: Evaluation Committee,
Thinking Systems Thrust Area,
Cross Enterprise Technology Development Program

From: T. Starbird *TWS*
Lead, Execution & Planning Domain
Mission Data Systems Project
Jet Propulsion Laboratory

Subject: Support for Self-Commanding Spacecraft Task

The purpose of this letter is to indicate my support for the work in development and deployment of Automated Planning and Scheduling Technology for spacecraft commanding funded by the Self-Commanding Spacecraft (SCS) Task led by Dr. Steve Chien at JPL and funded by the Thinking Systems Thrust Area of the CETDP.

In my role as lead of the Execution & Planning Domain of the Mission Data Systems (MDS) Project, I am responsible for developing the Goal-based Control Architecture (called the GAM architecture). Dr. Steve Chien is a member of the control architecture design team and has been enabling us to take advantage of planning and scheduling technology in general and SCS-developed technology in specific.

Basic elements from the ASPEN planning system developed as part of the SCS Task have contributed significantly to the MDS GAM architecture. These elements include resource management and timeline data structures. Hence, SCS has already contributed to MDS.

Additionally, the SCS task has as one of its key components the development of the CASPER continuous planner technology (co-funded by TMOT). This is a technology that allows a planner to re-plan in response to changing circumstances (changing resource usage, activity completion, changing goals) in a timely fashion.

This feature is critical for seamless integration with the GAM architecture since a GAM must respond in a timely fashion to changes in goals, sub-goal status, etc. This requirement makes traditional batch-oriented planners unsuitable for interleaving with GAMs. Indeed, the CASPER technology was developed in response to a requirement from Bob Rasmussen (MDS Software Architect) and Kim Gostelow (MDS Software Engineer).

Current plans are for the basic GAM architecture to rely solely on hard-coded GAMs for automation. But the design of the GAM architecture will be one that allows CASPER to be plugged in as an onboard planner, thereby enabling its future use as the technology is accepted by flight projects. This technology insertion path is documented in the Advanced Planning & Sequencing Technology Development plan that I wrote (January 1999).

Thus, the SCS task has already contributed significantly to the basic MDS GAM architecture. Additionally, future plans are for MDS to use CASPER technology developed by SCS and TMOT. Because of this past contribution and expected future contribution I strongly support the continued funding for the SCS task.

JET PROPULSION LABORATORY

INTEROFFICE MEMORANDUM
TMOD/MS&A-99.020
June 25, 1999

TO: Cross Enterprise Technology Development Program
Thinking Systems Area

SUBJECT: Self Commanding Spacecraft Task/
Automated Planning and Scheduling Technology

REFERENCE: Letter of Support

The purpose of this letter is to indicate my support for the work being funded by the Thinking Systems Area of the Cross Enterprise Technology Development Program. More specifically, I will address the Self-Commanding Spacecraft Task at JPL being led by Dr. Steve Chien.

In my role as Work Area Manager at JPL for the Mission Planning and Execution Technology Area in the Office of the Telecommunications and Mission Operations Directorate (TMOD), I am responsible for identifying, managing, and deploying mission support technologies relevant to spacecraft commanding functions.

Automated planning and scheduling technology is proving to be critical to any automated mission operations being necessitated by low cost reliable future missions. Consequently, automated planning and scheduling technology is of great importance to both the ground and on-board mission planning and spacecraft analysis areas of mission operations.

Under Dr. Chien's leadership, the Self-commanding spacecraft task is making a significant contribution to the TMOD mission operations concepts. Under the joint funding of CETDP (via the Self Commanding Spacecraft Task), TMOT (TMOD Technology Office), and MDS (TMOD's Mission Data System), Dr. Chien has been developing the Continuous Activity Scheduling Planning Execution and Replanning (CASPER) system for autonomous spacecraft. Current TMOT and MDS plans are to incorporate CASPER technology into their future mission support as identified in the Advanced Planning and Sequencing Technology Development Plan developed by Tom Starbird and concurred by myself (ref. Advanced Planning and Sequencing Technology Development Plan, Starbird, January 1999). The importance of this technology is further indicated by the fact that it was identified as supporting 15 out of 31 identified mission requirements in the Mission Planning and Execution area. (ref. Mission Planning and Execution TMO Technology Requirements, Amador, Grenander, & Wilson, 17 Feb 1999)

It is my understanding the many of the current plans for the Self-Commanding Spacecraft task continue to be closely aligned with TMOD's mission operations technology, consequently, I expect that this work will continue to significantly contribute to the TMOD program objectives. Therefore, I strongly recommend the continued support & funding of the Self-Commanding Spacecraft task.

Robert K. Wilson
Work Area Manager, Mission Planning and Execution
Telecommunications and Mission Operations Directorate