Princeton SATELLITE SYSTEMS

ControlPlan

Newly developed under the support of a Navy Phase II.5 SBIR, Princeton Satellite Systems presents the ControlPlan software suite. It provides the advanced mathematical tools and frameworks needed for planning and collaborating on courses of action for complex systems.

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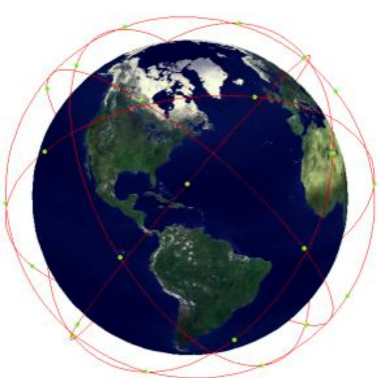
ControlPlan is cutting-edge decision support software that generates courses of action for operators of highly constrained, complex systems. By automating the computationally intensive aspects of planning, ControlPlan frees the operators to intuitively visualize and compare alternative courses of action. ControlPlan finds optimal solutions from physics-based models of the specific domain. It applies efficient numerical optimization methods to rapidly generate plans, allowing the human planner to respond quickly to failures, threats or environmental changes. Princeton Satellites Systems has used ControlPlan to implement avoidance maneuvers and communication frequency reconfiguration for the Navy's MUOS satellites.

Optimal Planning for Complex Systems

… ControlPlan automates the computationally intensive aspects of planning ….



Princeton Satellite Systems has been a pioneer in developing innovative technologies for satellite control and autonomy. Careful planning of satellite operations is crucial to ensure their continued safety and performance, but it's a daunting task. ControlPlan makes this job easier. Representing a new paradigm in decision support software, ControlPlan puts the user in full control.

By combining powerful optimization tools with a user-centric graphical interface, ControlPlan provides the ideal planning environment for any complex system. Users determine the priority of competing objectives and other model parameters. Alternative courses of action are computed automatically as solutions to numerical optimization problems, and then presented through rich graphical displays for analysis and comparison. Collaboration and chat across multiple clients enables plans to be shared and evaluated immediately, promoting more informed and effective decision-making.

With ControlPlan, we have already found new ways to increase satellite mission life, mitigate risks from collisions and interference, and optimally allocate sensor resources. The open architecture and general purpose algorithms powering this software make it a fit for nearly any system. Whether it is industrial operations, chemical processing, power grid control, financial planning, or trajectory optimization – ControlPlan can help.

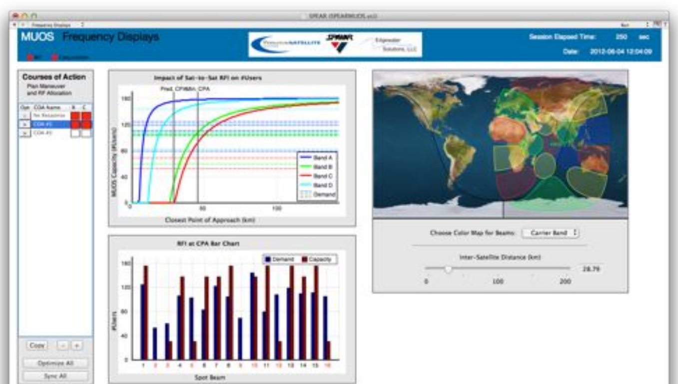
A New Paradigm in Course of Action Planning

ControlPlan is a multi-purpose decision-support tool developed for the Space and Naval Warfare Systems Command. Development began in 2009 under a Navy SPAWAR Phase I Small Business Innovation Research Contract (SBIR) with the goal of designing a planning tool for the highly configurable MUOS communications satellites. The original software was titled SPEAR (Satellite Planner for Execution and Reconfiguration) and was first developed as a client-server architecture with a Mac OS 10.7+ client. Work continued under a Phase II SBIR after a competitive down select from several Phase I companies, and continues today under a Navy SPAWAR Phase II.5 contract. The software has been ported to a web service application compatible with the Java Messaging System (JMS), and several new features are being incorporated.

...ControlPlan is designed to support a wide range of user groups and technology domains ....

ControlPlan is designed to support a variety of user groups and technology domains, where the common focus is to provide a systematic method for rapidly developing and comparing alternative courses of action. The full decision support tool provides three main functions:

1) Customized user interfaces to facilitate user-configuration of plans, definition of requirements, objectives and priorities, and the selection of assets that may be used.



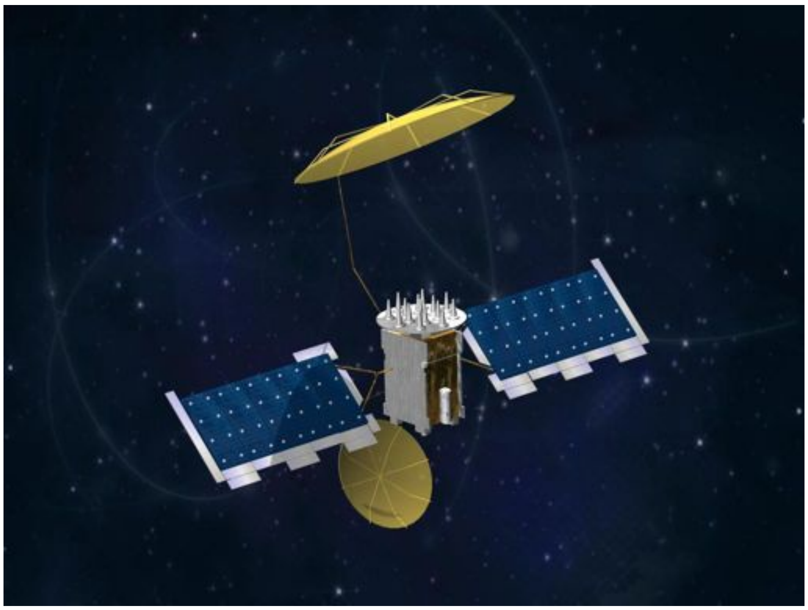
2) An optimization engine that enables reconfiguration scenarios to be formulated as optimization problems, then classified into problem types and solved using plug-ins to a library of standard optimization tools.

3) A menu of built-in displays and plug-ins for performing visualization, analysis and comparison for each course of action.

The underlying optimization framework includes an expandable library of automated problem formulation plug-ins. Each plug-in is responsible for generating a problem formulation data structure given user-supplied inputs from the user interface and additional data provided to the tool from external data sources. Several problem formulation plug-ins have been developed in Phase II and Phase II.5 to address specific reconfiguration scenarios that are of high interest to Navy SPAWAR and the JSpOC.

MUOS Satellite Program

The Mobile User Objective System (MUOS) is replacing the Ultra High Frequency (UHF) SATCOM system for the Department of Defense to provide our forces with modern worldwide communication services. MUOS will provide a major leap in capability with an approximate 10x increase in capacity over the current UHF Follow On (UFO) system.



The MUOS system provides global coverage using a constellation of four geosynchronous satellites plus one on-orbit spare, each operating 16 spot-beams with four wideband carriers. The communications technology of MUOS is adapted from a commercial third generation (3G) Wideband Code-Division Multiple Access (WCDMA) cellular phone architecture.

Some of the key services include:

- Priority-based access to communication services for voice, data, or a mixture of both
- On-demand access for point-to-point services and pre-defined networks
- Assured access to designated high priority communication services
- Support of pre-planned networks through a Network Management Center

The constellation is controlled through a satellite control facility (SCF) at Point Mugu, and all payload communications are routed through four radio access facilities (RAF) in Hawaii, Virginia, Sicily, and Australia.

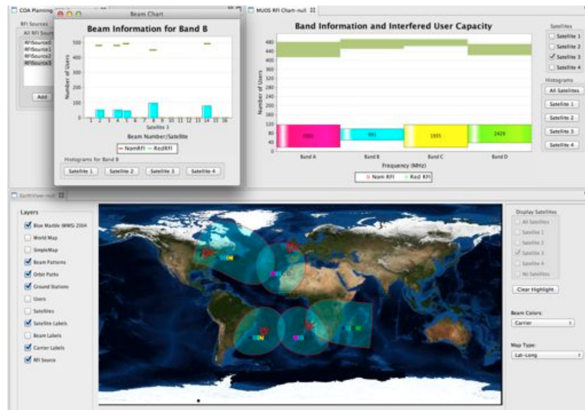
Two satellites have been launched thus far. MUOS-1 was launched on February 24, 2012, and MUOS-2 was launched on July 19, 2013. The full constellation is expected to be operational in 2015.

Princeton Satellite Systems has used ControlPlan to develop unique planning solutions for MUOS, supporting both payload operations and satellite control.

MUOS Example Scenarios

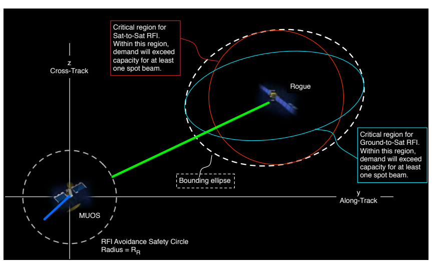
ControlPlan – MUOS Communication Planning with Extreme Interference

One of the most frequent and disruptive issues with satellite communications is the impact of radio frequency interference (RFI). It has the potential to degrade quality of service and completely drop connections. We have used ControlPlan to develop an optimal planning solution that maintains maximum connectivity in the presence of extreme RFI sources.

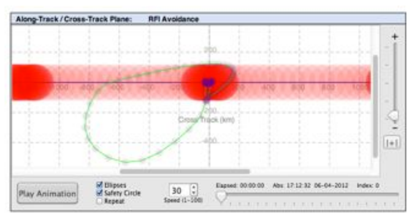


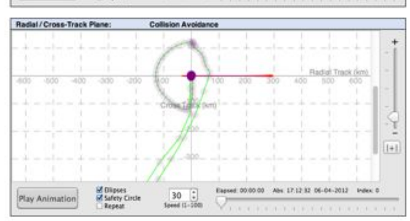
The user can develop courses of action that involve changes to the satellites' attitude, orbit, and beam loading. The optimization method finds solutions that maximize connectivity by physically moving the satellites to minimize RFI impact and by distributing power and demand across the full set of 256 channels.

ControlPlan – MUOS Protection from a Drifting Satellite



The GEO belt is a popular place! It is now filled with hundreds of satellites. Although each satellite nominally remains at its assigned station, satellites occasionally suffer failures and begin to drift along the belt. Also satellites that are new to the geosynchronous ring can interfere with operating satellites as they perform drift orbit maneuvers to get to their station. Any drifting satellite situation incurs risks of collision and communication interference to all satellites in its path.

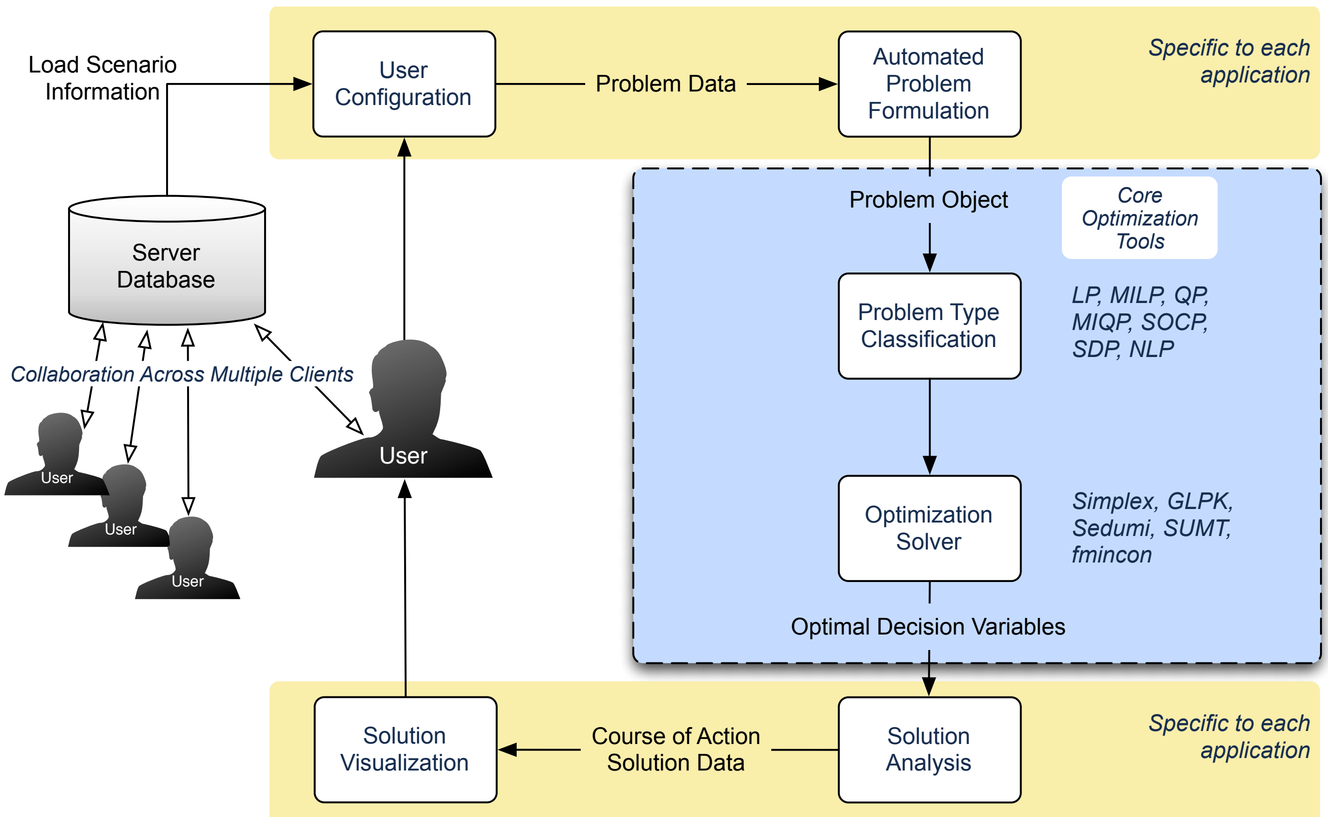




The image above illustrates the scenario. A satellite drifts towards MUOS along the horizontal axis. Using ControlPlan we find an optimal solution that first maneuvers MUOS to avoid collision and minimize RFI impact, and then optimally distributes power and demand over time as the satellite passes.

ControlPlan Software Suite

ControlPlan runs in a client-server architecture, allowing multiple users at any location to log in on separate clients and work simultaneously. The process of generating courses of action on one client is shown in the diagram below.



The user first selects a planning scenario and loads the information from the server.

User Configuration - set the priorities for the planning objectives, and optionally adjust the default values for model parameters, constraints, and algorithm settings.

Automated Problem Formulation – organize the data for the problem domain into the planning framework.

Problem Type Classification – determine the type of optimization problem.

Optimization Solver – select the solver from the library and compute the optimal solution.

Solution Analysis – process the optimal decision variables into the course of action and domain-specific performance metrics

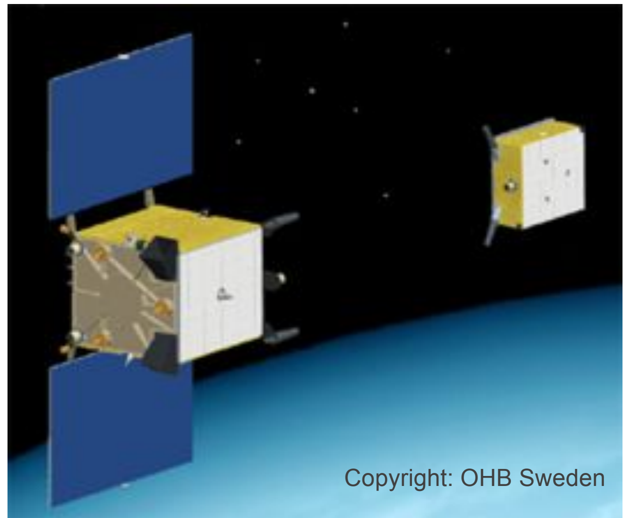
Solution Visualization - examine the merits of this course of action, compare it to other solutions, and share it with ControlPlan users.

Multiple users can collaborate across different clients.

Core Optimization Tools

At its core, ControlPlan provides an optimization engine capable of solving a wide range of numerical optimization problems. A structured framework is used to fully define the variables, constraints and objectives of the problem with:

- Variable Bounds
- Variable Types
- Linear Objective Function
- Non-linear Objective Function
- Linear Constraints
- Non-linear Constraints



The Prisma mission was the first ever demonstration of sustained autonomous formation flying. PSS designed Prisma's safe orbit guidance algorithms.

$$
\begin{array}{ll}
\min\limits_{\boldsymbol{x}} & J(\boldsymbol{x}) = \boldsymbol{c}^T\boldsymbol{x} + \left(\boldsymbol{u}_0^T\boldsymbol{x} + \boldsymbol{v}_0\right) + \boldsymbol{x}^T P_0 \boldsymbol{x} + f(\boldsymbol{x}) \\
\text{Subject to} & A\boldsymbol{x} \le \boldsymbol{b} \\
& A_{eq}\boldsymbol{x} = \boldsymbol{b}_{eq} \\
& ||S_0\boldsymbol{x} + \boldsymbol{t}_0|| \le \boldsymbol{u}_0^T\boldsymbol{x} + v_0 \\
& ||S_l\boldsymbol{x} + \boldsymbol{t}_l|| \le \boldsymbol{u}_l^T\boldsymbol{x} + v_l \quad l \in [1, C] \\
& x^T P_k x + q_k^T x + r_k \le 0 \quad k \in [1, Q] \\
& g_i(\boldsymbol{x}) \le 0 \quad i \in [1, M_n] \\
& h_j(\boldsymbol{x}) = 0 \quad j \in [1, N_n]
\end{array}
$$

Depending upon the variable types and the presence or absence of nonlinear objectives and constraints, the problem may be classified as one of a set of well-defined problem types. ControlPlan has been designed to efficiently solve several different problem types using custom interfaces to open source solvers.

ControlPlan can solve linear programs (LP), mixed-integer linear programs (MILP), second order cone programs (SOCP), quadratic programs (QP), and non-linear programs (NLP) with non-linear constraints. Additional interfaces to new solvers are being added all the time, expanding ControlPlan's reach. The ControlPlan optimization core also provides some unique and useful features:

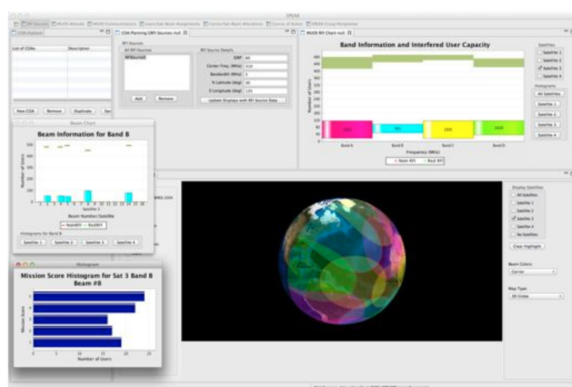
- Rapid feasibility assessment for problems with linear or non-linear constraints
- Automatic re-scaling of variables to improve numerical condition
- Automatic constraint relaxation using penalized slack variables
- Convenient methods to build constraints for linear time-varying dynamic systems

User Interaction

Complex systems such as power transmission networks, air traffic control, process control, power plants satellites and launch vehicles require the integration of automatic control systems and human decision-making. The complexity of these systems make it necessary for teams of engineers and operators to participate since no one person has the knowledge to operate such systems on their own. ControlPlan is designed as a collaborative tool. It allows each person to make certain that his or her subsystem is not ignored or their requirements unmet in the planning process.

For example, planning for satellite operations requires participation by all subsystems on a launch team. Any maneuver will have impacts on the power, thermal, payload, communications and attitude control subsystems. Subsystem engineers need easy-to-use and reliable means to add their inputs, which are often posed as constraints, into the planning process. For example, a sensor may have a sun stayout zone that must be enforced during attitude maneuvers or the temperature of a component must be held within certain bounds during payload operation.

ControlPlan brings an unprecedented level of user interaction to the planning process. Planning activities are focused on distinct scenarios that are presented via interactive graphical displays, allowing the user to explore and understand the situation before planning. The user can then begin developing candidate courses of action (COA), using on-screen controls to set priorities, model parameters, and planning options. The optimization engine optimizes each COA, and multiple COAs can be compared side by side for in-depth evaluation.



The image to the right shows an example display for MUOS communication planning. The Earth view displays beam footprints, users and RFI sources, while the bar charts illustrate capacity and demand for selected users, beams and channels.

Planner Comparison

ControlPlan uniquely provides an integrated setting for situation awareness; plan development, reconfiguration, and analysis. There many domain specific planning tools such as Search and Rescue Optimal Planning System (SAROPS) but these are not adaptable to other problems. Other more general purpose tools perform planning and scheduling (e.g. ASPEN, EUROPA), but these work only for pre-determined operation plans and they do not natively include the situational awareness displays that a user needs.

Additionally, the ControlPlan framework is designed to support tradeoff analyses. Multiple plans are developed as potential courses of action and they can be thoroughly compared/contrasted with charts, tables and other detailed displays that are included in the user-interface. This gives users the freedom to develop and store a diverse set of plans to accommodate a wide range of scenarios.

Finally, ControlPlan runs on a client-server architecture, enabling collaboration among a distributed set of users. This is an important aspect of planning, as a typical satellite includes many different stakeholders. For example, this capability would enable planners at JFCC Space to develop and share course of action plans with other planners at the Regional SATCOM Support Center (RSSC) and operators at the Naval Satellite Operations Center (NAVSOC). This provides an unprecedented level of planning coordination and flexibility.

ControlPlan surpasses all planners in functionality and user interaction.

	ControlPlan	*ASPEN*	*EUROPA*
Interactive	Yes	No	No
Dynamical Optimization	Yes	No	No
Multiple Courses of Action	Yes	No	No
Scheduling	Yes	Yes	Yes
Planning	Yes	Yes	Yes
Collaborative	Yes	No	No
AI Based	No	Yes	Yes
Situation Awareness	Yes	No	No

Founded in 1992, Princeton Satellite Systems is an innovative engineering firm pushing the state-of-the-art in Aerospace, Energy and Control. We help our customers implement control systems that are easy to use and understand. We have been an integral part of the control system development for Cakrawarta-1 Communications Satellite, NASA ATDRS, the GPS IIR satellites and the Prisma space rendezvous robots. Our extensive satellite operations experience includes Asiasat, Telstar and Koreasat. We sell the MATLAB Spacecraft, Aircraft and Wind Turbine Control Toolboxes. Our patents range from imaging sensors to spacecraft maneuvering algorithms, wind turbines and nuclear fusion propulsion. Our staff provides user-focused engineering talent in developing and applying new and innovative solutions to any set of complex problems.

A variety of high tech organizations use Princeton Satellite Systems software products for their work. These include Energia (Russia), ESTEC, NASA, the Canadian Space Agency, the Swedish Space Corporation, Raytheon, General Dynamics, Lockheed Martin, Orbital Sciences Corporation, MIT Lincoln Laboratories, NEC, Boeing and many colleges and universities.

Princeton Satellite Systems regularly customizes and enhances our software to meet specific client requirements and finds this to be an effective way of growing our products and ensuring that they meets all of our clients' needs. Princeton Satellite Systems combines custom development with commercial software components to provide powerful control software in minimal time and with maximum flexibility to adapt to the latest customer requirements.

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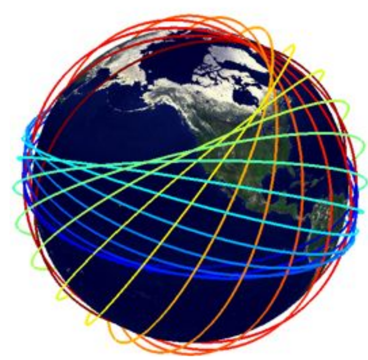

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