EO-1 Formation Flying Using AutoCon™[1]

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Abstract— In this era of faster, better, and cheaper, satellite on-orbit operations is a continued area of opportunity for reducing mission costs and enabling new science collection through automation. When a ground operation is supporting multiple spacecraft in a formation, the need for automation to perform mission design and maneuver planning operations is magnified; without it, some missions are cost-prohibitive. A partnership of AI Solutions, Inc. and the National Aeronautics and Space Administration's (NASA) Goddard Space Flight Center (GSFC) has developed a maneuver planning automation tool called AutoCon™. NASA is using AutoCon™ to validate and demonstrate the automation of maneuver planning for the formation flying of the Earth Observing –1 (EO-1) satellite with the Landsat-7 satellite.

Originally developed as a ground system tool, AutoCon™ has been scaled to fit on-board the EO-1 flight computer. The flight version of AutoCon™ plans maneuvers based on formation flying algorithms developed by GSFC, JPL, and other industry partners. In its fully autonomous mode, an AutoCon™ planned maneuver will be executed on-board the satellite without intervention from the ground.

This paper describes how AutoCon™ automates maneuver planning for the formation flying constraints of the EO-1 mission. AutoCon™ was modified in a number of ways to automate the maneuver planning on-board the satellite. This paper describes how the interface and functionality of AutoCon™ were implemented to support the on-board system, including the implementation of a GPS data smoother to produce accurate spacecraft states for maneuver planning.

The use of AutoCon™ as a completely autonomous on-board system will be implemented in phases. This paper presents the modes built into the system that will allow incrementally phasing in the autonomous functions. A number of safeguards have been designed in both AutoCon™ and the interfacing systems to alleviate the potential of mission-impacting anomalies from the on-board autonomous system.

TABLE OF CONTENTS

1. INTRODUCTION

The cost of on-orbit operations remains a significant and increasingly visible concern in the support of satellite missions. To reduce mission planning and on-orbit operations costs, and to enable better science return, NASA GSFC has teamed with AI Solutions, Inc. to develop AutoCon™, an automated maneuver planning tool.

NASA is using AutoCon™ as an on-board automation and formation control experiment on the New Millennium Program (NMP) Earth Observing (EO) -1 mission. AutoCon™ will automate the maneuver planning for the EO-1 mission. This paper is an extension of the paper in reference 1, and discusses the use of AutoCon™ as an autonomous flight system, and the phasing of this on-board system to autonomous operation.

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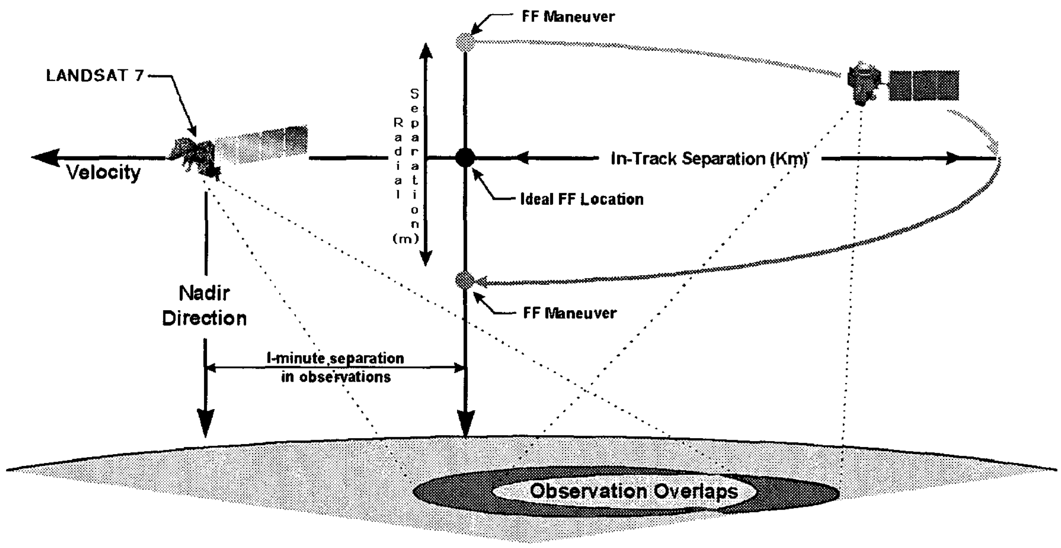
2. Automating Formation Flying

Formation flying entails the maintenance of two or more satellites orbiting the Earth with a required proximity to one another. An example of the orbit dynamics of formation flying is shown in Figure 1. The difference in ballistic coefficients of the two satellites produces the relative motion shown. As the chase satellite's orbit degrades and the satellite starts to approach the control satellite, a maneuver is required to raise the orbit of the chase satellite to restart the drift pattern.



The Earth Observing - 1 (EO-1) and the Landsat-7 Missions are an example of formation flying. EO-1 has as a principal mission requirement to successfully complete 100 to 200 paired scene observations with Landsat-7 in order to validate the technologically advanced imagers on EO-1 (ref. 1). To enable the paired scene process, the EO-1 spacecraft must fly over the current groundtrack of Landsat-7 within +/-3 km. To maintain a safe operational distance between the satellites, the nominal along-track separation was chosen to be one minute. Due to the rotation rate of the Earth, the +/-3 km groundtrack offset tolerance translates into an alongtrack tolerance of +/- six seconds or approximately +/- 45 km.

The Landsat-7 mission will maintain its orbit based on its mission requirements, independent of EO-1. The EO-1 spacecraft is required to follow Landast-7 without breaking the alongtrack separation constraint even after a Landsat-7 maneuver. The drift pattern in Figure 1 is significantly altered when the control satellite, Landsat-7, performs a groundtrack control maneuver. After a Landsat-7 maneuver, the EO-1 satellite quickly drifts towards Landsat-7 causing the maneuver planning time to be shortened.

Historically, a full-time maneuver design analyst would be required to support the frequency of maneuvers for the EO-1 mission. This would significantly increase the cost of operations support.

AutoCon™, a ground-based mission planning tool, was developed to automate the maneuver planning for missions. Ground AutoCon™, or AutoCon™-G, includes a user friendly GUI, graphical plots (including 2D and 3D world maps) and report generation. AutoCon™ uses fuzzy logic to resolve multiple conflicting constraints, and plan maneuvers with little or no human interaction. Fuzzy logic can be used to control mission planning through a rule-based scheme. For example, a maneuver might be planned if the spacecraft is near a certain point in the orbit such as apogee or a descending node, and the time at the control center is around midday. Mission and instrument constraint rules can also be incorporated into a flexible maneuver-planning scenario. Hedges such as *almost*, *somewhat*, and *very* allow the rules to be adjusted easily.

The architecture of AutoCon™ was designed to support easy integration of maneuver control algorithms. For the EO-1 mission, GSFC and JPL have prepared control algorithms that have been implemented into AutoCon™. Additional algorithms will also be implemented from industry partners, during an extended mission phase, as the algorithms become available.

Designed to be flexible and extendable, AutoCon™ is built around a structure called an event. Events can be added as necessary to support new algorithms or capabilities, thus providing extensibility. To be flexible, AutoCon™ uses natural language scripting. The scripting provides the flow control for AutoCon™. Figure 2 shows the flow control for the EO-1 mission. For the EO-1 mission, AutoCon™ will be used to propagate the current EO-1 and Landsat-7 states

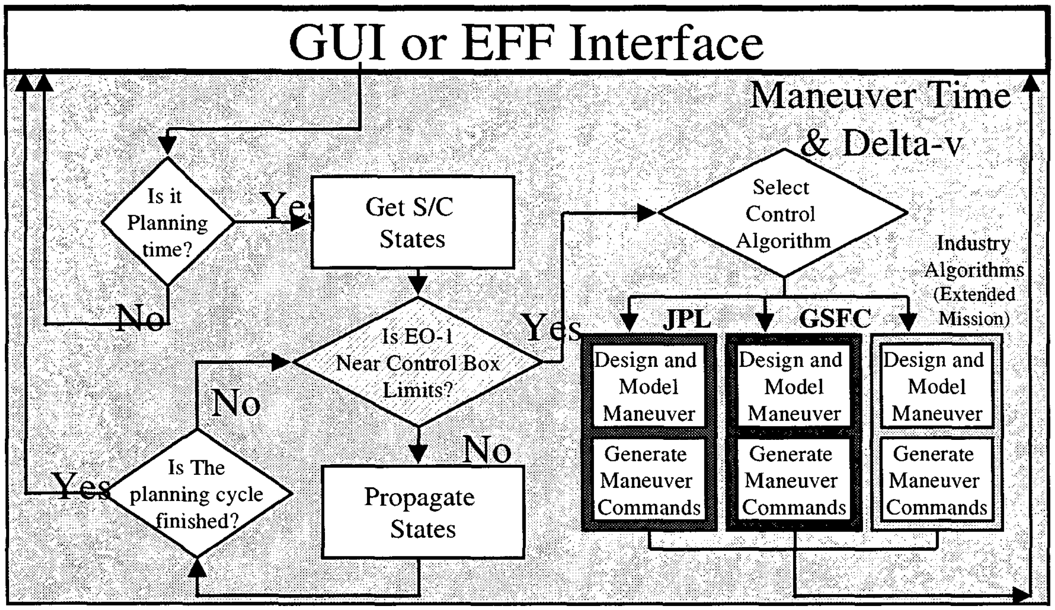


Figure 2 - AutoCon Control Flow

while simultaneously evaluating alongtrack separation and other operational constraints. Once the constraints are close to being exceeded, the appropriate control algorithm is called to calculate the necessary maneuver to maintain the formation.

AutoCon™ is also scalable in such a way as to be put on-board the spacecraft, and provide completely autonomous control including formation control.

3. AutoCon™ Flight

The on-board flight version of AutoCon™, or AutoCon™-F, developed for EO-1 consists of a subset of the ground based AutoCon™ application with a flight software interface. To conserve on-board resources, only the objects and methods required to support EO-1 formation flying are incorporated

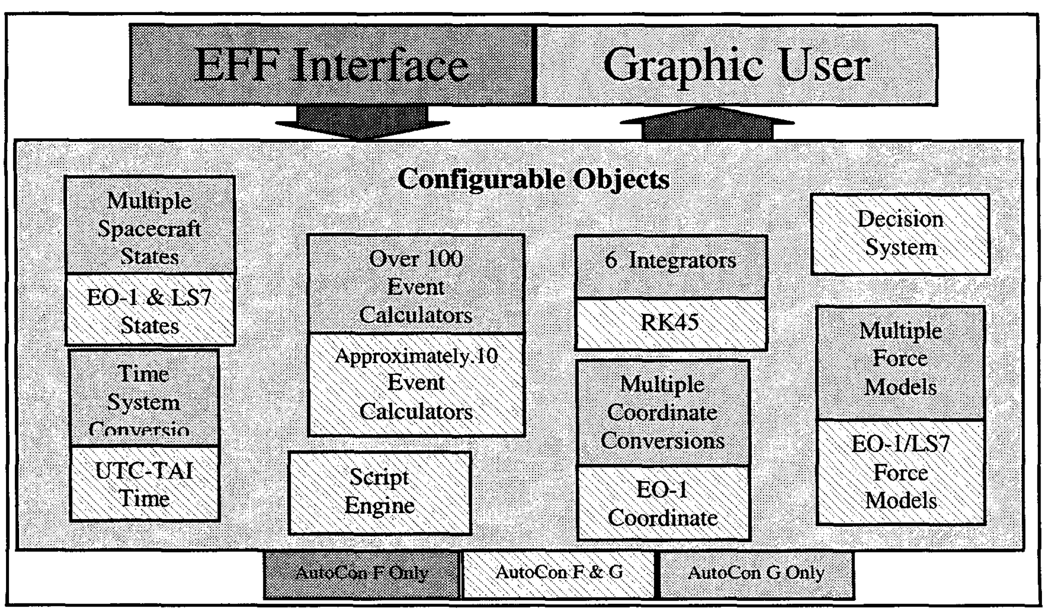


Figure 3 – AutoCon™ Events and Objects

in the AutoCon™ -F system. Figure 3 shows the functionality included in the flight and ground versions of AutoCon™. The flight interface, or Enhanced Formation Flying (EFF) software, interfaces directly with the spacecraft Command and Data Handling (C&DH) system to retrieve all AutoCon™ required data, including GPS position information, and to create command loads for computed burn times and durations.

AutoCon™-F inherits from its object-oriented C++ design its ground-based counterpart. The ground system was developed with the user interface separate from the basic computational engine to provide portability and flexibility to use as flight software with minimal modifications. Scaling the existing ground software for on-board use not only saves money in porting, but also saves in testing, since the development path automatically provides a ground reference system.

Since AutoCon™ was originally designed as a ground system automation tool, a number of interface changes needed to be performed to convert the system for use on-board the EO-1 spacecraft.

Input Interface

AutoCon™ was designed with a complete graphical user interface allowing the user to change inputs through dialog windows and to view results in plots, and 2D and 3D graphs. This portion of the user interface would not be required for the flight version. For user friendliness and readability, the underlying inputs to the core AutoCon™ system are ASCII files, with only a few exceptions. The flight system interface requires binary table inputs, control of the system through commands and operating modes, and the collection of results through telemetry.

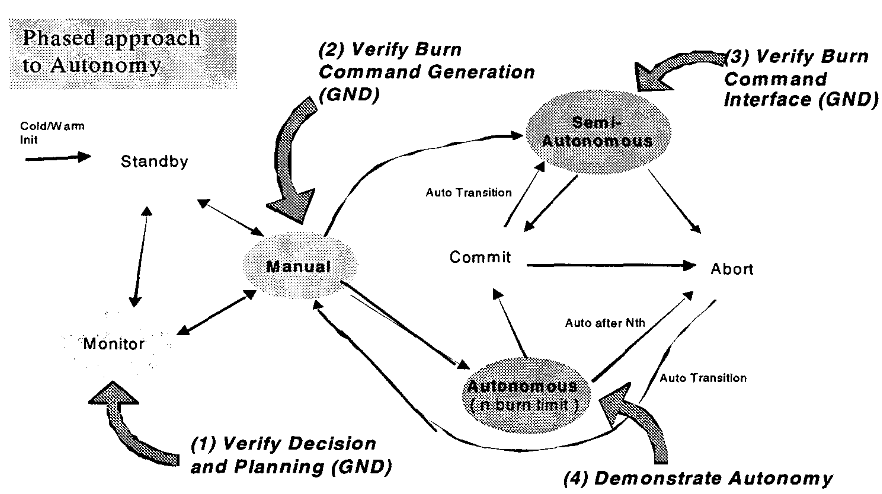
The ground version of AutoCon™ was modified to accept binary table files as an alternative input method to the ASCII file input. Binary tables are used because they are more compact and provide an accepted format for upload to the satellite. To accommodate all the inputs and maintain the flexibility of AutoCon™, 12 different inputs had to be converted to tables. Because EO-1 has a table size limit of 3000 bytes, the planetary input data had to be broken out in to three separate tables.

Data Integrity

To ensure table data integrity, AutoCon™ was implemented with the capability to validate the tables before use. Validation design required that all tables include three fields. The first two fields in the table are the table identifier number and the table size in bytes. These two fields are checked to ensure that the correct table was uploaded and accessed by AutoCon™. The last field in all tables is a checksum that is computed using a standard 32-bit Cyclic-Redundancy Check (CRC) method.

Data Accuracy

Ensuring an accurate input state to AutoCon™-F is crucial for autonomous operation on-board EO-1. On EO-1, the GPS TENSOR™ software using a Kalman filter processes raw GPS data that consists of pseudorange and Doppler measurements. Orbital states obtained from the GPS TENSOR™ have RMS position and velocity errors of 35.7 m and 5.2 cm/s, respectively (ref. 4). The requirement for an AutoCon™-F input state for the GSFC algorithm is that the errors in radial position and velocity be no larger than 5 m and 2 cm/s, respectively. Thus, the GPS TENSOR™ solution alone is not adequate, and an additional stage of optimization was required. This stage has been



implemented as a discrete fixed interval data smoother, which uses the Rauch, Tung and Striebel algorithm (ref. 5). The Kalman filter underlying the smoother was adapted from the GPS Enhanced Orbit Determination Experiment (GEODE)-lite software (ref. 6). On EO-1, the smoother will collect approximately one orbit of GPS data to produce an accurate EO-1 state for AutoCon™ maneuver planning. The expected accuracy is 5 meters in position and 2 cm/s in velocity.

4. SAFETY MODES

One of the major concerns of the EO-1 mission is to make sure that the autonomous maneuver system is as safe as possible. There was considerable concern, for example, that an autonomous system would cause the thrusters to fire for too long and jeopardize the mission. Several safeguards were created to alleviate such concerns. These include a standard 48 hours notice before any planned maneuver (the time length is adjustable) and a phased approach to autonomy. The 48-hour notice gives the ground time to review the planned maneuver before its execution. Figure 4 displays the "levels' of autonomy or phases and transition flow. These include a monitor mode, which allows burn plans to be generated and reviewed, a manual mode, which allows maneuvers to be predicted but not implemented and a semi-autonomous mode, which allows burns to be verified by the ground before execution. Even the autonomous mode can be interrupted by ground command. Also, the autonomous mode is limited to a specified number of burns before it automatically transitions back to manual mode. A complete description of the safety modes is provided in Table 1.

In addition to AutoCon™-F's built-in safety features, the attitude control system (ACS) limits all burns to 60 seconds or less. The stored command sequence also limits burn duration. Even in the fully autonomous mode, only three successive burns will be executed before a manual command is required from the ground. Additionally, EO-1 has a watch-dog timer to make sure no task, such as AutoCon™-F, exceeds CPU utilization, depriving other critical tasks processing time. Finally, the spacecraft has a safehold mode that can disable AutoCon™, if necessary.

Standby
- Pend on incoming data and send it to the bit bucket
- Otherwise do nothing

Monitor - (AutoCon-F executes with maximum safety for S/C)
- Invoke AutoCon-F only
- Report maneuver planning data to ground
- No maneuver commands are generated

Manual - (AutoCon-F executes with ground as safety)
- Generate maneuver commands (table loads) and send to ground only
- All burns must be command from the ground in their entirety
- Ground can loopback command from EFF telemetry if desired to execute burn

Semi-Autonomous - (Ground still in loop for go/no-go)
- Send maneuver commands (table loads) to the Stored Command Processor (SCP)
- Do not enable Absolute Time Sequence (ATS), Relative Time Sequence (RTS) in SCP
- Must switch to Commit Mode to allow loaded burn to execute
- Inaction will cause loaded burn to expire

Commit - (allow an EFF loaded burn to execute)
- Enable ATS and RTSs in SCP to permit loaded burn to be executed
- Required at least 2 hours before time of burn
- Autonomously switch to Semi Autonomous Mode upon completion

Abort - (abort an EFF loaded burn and clean up)
- Disable the ATS and RTSs in SCP to prevent execution of burn
- Clean up from any preparation for burn
- Autonomously switch to Manual Mode upon completion

Autonomous - (allow EFF to control the orbit)
- Closed loop orbit maintenance
- Use Commit Mode to switch back to Semi-Autonomous Mode and not abort a planned burn
- Ground can still monitor with 48 hour notice to burn
- Switch to Semi-Autonomous Mode after N burns. Safety for unattended operation

5. EARLY ORBIT RESULTS

Nominal Implementation Timeline

As of the writing of this draft, the EO-1 mission is scheduled to launch NET April 2000. The post-launch phase of the EO-1 mission is divided into three major periods. For 30 to 90 days just after launch, the spacecraft will enter a check out phase. During this time, AutoCon™-F will be turned on and set to monitor mode. This period will begin the validation process for the GSFC algorithm. The AutoCon™-F generated burn plans will be compared with expected burn plans and actual ground operations.

Following the checkout phase, the mission phase will begin. At this point AutoCon™ will enter manual, semi-autonomous and, finally, autonomous mode for the GSFC algorithm, and during each step, the algorithm's performance will be validated. After about 3 months of operation under the GSFC algorithm, the JPL algorithm will be uploaded to the spacecraft and the validation process repeated at each step to validate the JPL algorithm.

Finally, during the extended mission, the industry provided algorithms will be uploaded to the spacecraft, and tested in the same manner. Currently two industry algorithms are planned.

Maneuver Planning Results

The initial operational mode of the on-board maneuver planning system is the monitor mode. In this mode, AutoCon™-F will produce maneuver plans, but the plans will only be sent to the ground and not forwarded to the on-board command system. Once the maneuver plan is received at the satellite operations control center, the plan will be compared against the maneuver plans generated on the ground by the Flight Operation Team (FOT).

Estimated Cost Savings

Automated formation flying for the EO-1 mission will be carefully and gradually implemented as an experiment. As the phasing in to autonomy progresses successfully, the EO-1 mission will benefit from the reduction in operations required for maneuver support. More savings will be realized for future missions that implement this flight proven technology. For a mission such as EO-1, the estimated operational cost savings for the mission would be approximately 1-staff person over the life of the mission.

6. SUMMARY

To achieve low cost missions with complex or stringent orbit constraints such as in formation flying, autonomous maneuver control needs to be realized. Only through autonomous control will some missions, especially formation control missions be possible. Without automation technologies, complicated formation and maneuver intensive missions are cost-prohibitive. The AutoCon™ maneuver planning automation system has been implemented as a ground and on-board flight system for the EO-1 mission. As the EO-1 mission progresses, the first steps towards the reality of autonomous on-board orbit control will be recognized.

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