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Autonomous Navigation and Autonomous Orbit Control in Planetary Orbits as a Means of Reducing Operations Cost*

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ABSTRACT

Autonomous navigation and orbit control can provide both significant operations cost reduction and increased mission performance. By controlling the orbit to match a chosen reference, ground operations are significantly reduced and scheduling becomes highly predictable. In addition, the system uses less propellant than traditional orbit maintenance.

Microcosm flight demonstrated the first fully autonomous spacecraft navigation system, MANS, on the TAOS mission in 1994 and the first fully autonomous Orbit Control Kit, OCK, on UoSAT-12 in 1999. MANS used the Sun/Moon/Earth reference set for fully autonomous orbit determination and OCK used a GPS receiver for a navigation source. With modern sensor and processor technology, it is now possible to extend autonomous navigation to the use of stars and a central planet. This provides an exceptionally robust navigation solution for planetary missions with both singularity-free deterministic and high accuracy Kalman Filter solutions available. In turn, OCK can make use of the autonav solution to provide autonomous absolute orbit control independent of any external data or commands. Microcosm has a current contract with NASA JSC to develop accuracy estimates for various planetary autonav scenarios.

1. INTRODUCTION

For space applications, *navigation* means orbit determination, i.e., determining the 6 orbit elements or, equivalently, the 6 components of the position and velocity as a function of time. *Autonomous navigation* (AutoNav) is done on-board the spacecraft without outside intervention, although some inputs, such as clock updates, may be required from time to time. *Semi-autonomous navigation* uses some external man-made resources, such as GPS or ground beacons. In addition, we need to distinguish the external reference frame that the position and velocity are measured with respect to. *Absolute autonav* determines the orbit with respect to the planet or inertial space. *Relative autonav* determines the orbit with respect to another vehicle. Relative autonav is of use primarily for formation flying and rendezvous and docking missions.

Autonomous navigation is a key requirement for *autonomous, on-board orbit control*, also called *autonomous stationkeeping*,‡ which is the automatic maintenance by the spacecraft itself of all of its orbital elements.§ Because all the elements are controlled, the orbit is fully predictable and the position of the spacecraft at all future times is known in advance to within the accuracy of the control box.** In the most typical case of a spacecraft in a near circular low planetary orbit, the most important

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‡ "Stationkeeping" here means maintaining the satellite within a pre-defined control box (analogous to geosynchronous stationkeeping), not simply altitude maintenance which does not control the in-track phase and, therefore, does not allow the future positions of the satellite to be controlled or known.

§ As with autonov, *absolute stationkeeping* maintains the orbit with respect to inertial space and *relative stationkeeping* maintains it with respect to other satellites. For formation flying or rendezvous, relative stationkeeping is most appropriate. For constellations or single satellites, absolute stationkeeping has several disadvantages and no disadvantages that we are aware of. (See, for example, Wertz [2001], Sec. 13.4.1.) In this paper, we use autonomous stationkeeping or autonomous orbit control to mean absolute stationkeeping.

** The process of doing autonomous stationkeeping is covered by Microcosm patents No. 5,687,084 and 5,528,502.

elements to control are the period of the orbit and the in-track phase.

The benefits of using combined autonomous navigation and autonomous orbit control to reduce operations costs for planetary missions include:

- The ground station is relieved of a significant operational burden, because the absolute inertial position of the spacecraft is both known and can be controlled essentially indefinitely on board the spacecraft.
- The cost of planning experimental observations and reducing data is substantially reduced because the long-term position is controlled. There is no need for continuing planning and replanning cycles as the projected ephemeris is updated.
- Microcosm's approach to orbit control, OCK, uses less propellant than traditional orbit maintenance. (See discussion below.)
- Orbit control firings do not interfere with normal mission operations because autonomous orbit control uses a series of more frequent, but much smaller burns. (The average burn on the demonstration UoSAT-12 flight was 1.4 mm/sec.)
- Smaller and lighter weight thrusters and attitude control components can be used because the thruster burns are much smaller than for traditional orbit maintenance.
- Scheduling ground station operations and data collection is easier and can be done as far in advance as needed because the orbit is precisely controlled to a known reference.

Microcosm has been working on autonomous navigation and autonomous on-board orbit control since the late 1980's. For a summary of the process of autonav and autonomous orbit control, see Wertz [2001], Sec. 4.3 and 13.4. For background on the development of these technologies, see, for example Chao and Berstein [1992], Collins, et al. [1996], Glickman [1994], Koenigsmann, et al. [1996a, 1996b], Wertz [1991, 1996, 1999, 2001], Wertz, et al. [1998].) For a summary of the current status of autonav, orbit control, and other technologies appropriate to autonomous rendezvous and docking, see Wertz [2003]. Autonomous satellite technology development at Microcosm has been funded by internal R&D and over 20 contracts from various organizations. Development leading to the on-orbit demonstration of both autonomous navigation and autonomous orbit control was funded by multiple SBIR contracts from the Air Force Research Laboratories, Albuquerque, NM.

2. AUTONOMOUS NAVIGATION

For planetary orbits, autonav serves to reduce the load on DSN and reduce the cost of ongoing DSN support. In addition, it reduces the risk to the mission since the spacecraft will continuously know where it is in inertial space and, therefore, where the Earth is. Thus, a spacecraft which suffers an upset can recover, determine its orbit and attitude, point its solar arrays at the Sun and its communications antenna at the Earth without outside intervention. When coupled with autonomous orbit control, as described below, the ground station (and any other spacecraft or rovers that need the information) will also know where the spacecraft is continuously, even if it is not in direct communication. This open loop knowledge can be an important element in creating robust planetary exploration systems.

The traditional process for orbit determination is, of course, ground tracking. While not autonomous, it can be used to initialize or calibrate an on-board system if required and, in any case, is likely to serve as back up to any more autonomous activity. The general measurement sets available for navigation are illustrated in Fig. 1. All of these are potentially applicable to the navigation in planetary orbits:

Method 1. Position and velocity at one time. Used for injection from the launch vehicle or after a large thruster firing.

Method 2. Three or more observations of direction with respect to the background stars. (Traditional approach for determining the orbits of comets and asteroids.) Used for determining the relative orbit of a distant spacecraft. (See below.)

Method 3. Sequence of range and range rate measurements. This is the traditional ground tracking approach.

Method 4. Sequence of position observations. Basis for autonomous navigation using GPS.

Method 5. Sequence of observations of the inertial direction and distance to a nearby central body. Basis of most optical autonomous navigation. Provides a robust solution for autonav in planetary orbits.

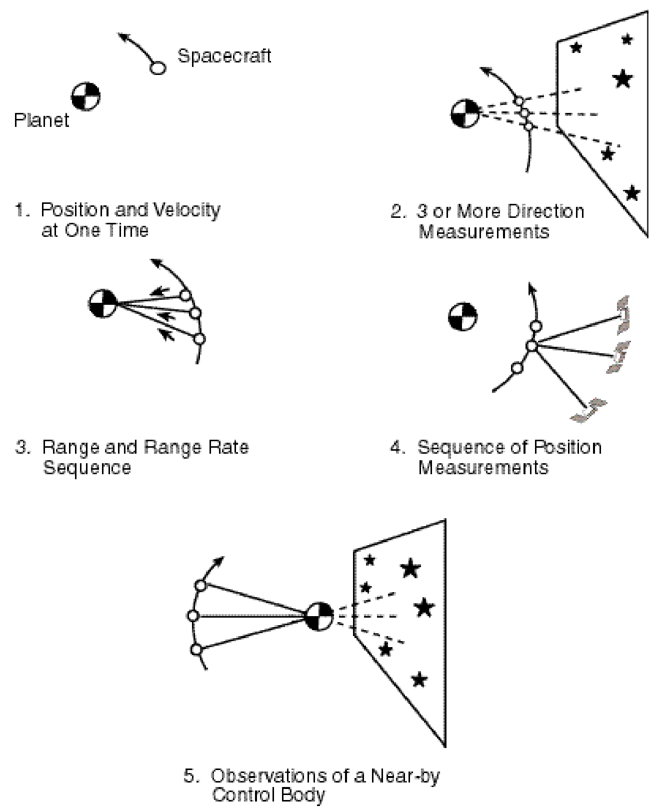

Figure 1. Basic Measurement Sets for Orbit Determination. See text for discussion. [Wertz, 2001, pg. 106]

For AutoNav in low Earth orbit, GPS is the obvious choice. A GPS receiver provided the navigation function for the orbit control demonstration on UoSAT-12 discussed below. However, with modern on-board computers and sensors a wide variety of truly autonomous approaches are feasible that can be used in planetary orbits where GPS is unavailable. Approaches that have been considered are summarized by Wertz [2001], Sec. 4.3. In 1994, Microcosm demonstrated fully autonomous navigation using the Earth, Sun, and Moon in low Earth orbit using the MANS technology [Anthony, 1992; Hosken and Wertz, 1995]. More recently, NASA's DS-1 spacecraft demonstrated autonomous navigation in interplanetary orbit [Rayman *et al.*, 1999, 2001]. MANS used the Moon and Sun as inertial references largely because they were easy to identify and unambiguous. However, modern star sensing has enabled a better approach. Consequently, we believe that the best current option for autonav in planetary orbits is to use star and planet sensing, using method 5 in Fig. 1. This approach is exceptionally robust in low planetary orbits because the angular size of the planet provides a sensitive measure of distance and, therefore, each measurement set provides a non-singular deterministic estimate of the 3-axis position of the spacecraft in inertial space. These can then be filtered to provide noise reduction and improved accuracy with very little potential for filter divergence. This robust character of the autonav solution is particular important for systems about distant planets that may need to operate for some time without ground supervision. This is a key reason for preferring this approach over others which require filtering measurements that contain inherent singularities. (For a discussion of singularities in spacecraft measurements and how to distinguish good and bad measurement sets, see Wertz [2001], Sec. 7.6.) Microcosm currently has a contract with JSC to access performance and feasibility of autonav using star and planet sensors.

The accuracy that can be achieved with autonomous navigation will depend on the orbit, the central body, and the sensing hardware being used. For low planetary orbits and planet and star sensing accuracies comparable to current attitude systems, an overall system accuracy on the order of 100 m to a few km is reasonable. Initial errors will be dominated by the systematic biases, including particularly the relative mounting between the planet sensor and the star sensor. However, these biases can be calibrated out, either by ground tracking, or by doing a set of calibration attitude maneuvers on the spacecraft.

One of the problems with any fully autonomous navigation approach is that there is no direct measurement of the velocity. This implies that the velocity will be determined by the equations of motion and a sequence of position observations. By the time a spacecraft has gone one or more orbits, the velocity can be determined with high accuracy, but it can not be autonomously measured immediately following a thruster burn. Because the magnitude of thrusters burns are rarely known to more than 95% accuracy, the burn serves to decouple the orbit solution prior to the burn from the post-burn orbit elements. Thus, in an autonomous system, the orbit is well-known prior to a thruster firing, but less well known immediately afterward. High accuracy orbit information is recovered within approximately one orbit after the burn. One of the advantages of autonomous orbit control as described below is that the system can filter through the very low thrust provided by the orbit control system, such that high accuracy orbit knowledge can be maintained continuously.

The above discussion applies to absolute autonav, i.e., knowing where the spacecraft is in inertial space. However, we may also want to know where we are relative to another spacecraft. This would be needed for rendezvous or intersatellite communications, for example. There are 4 general techniques for achieving this:

Assumed orbit. Since the accuracy requirements for intersatellite communications are typically modest, it may be possible to simply assume one or both of the orbits until such time as the satellites get close enough for some form of communication or relative navigation. Of course, the risk is that the assumed orbit is sufficiently in error that the communications or rendezvous fails.

Absolute Autonomous Navigation. Either vehicle may use autonomous navigation to determine its orbit. This could be GPS in low Earth orbit or true autonomous navigation in planetary orbits. If the target is using autonav, then the information needs to be communicated to the original spacecraft, either directly or via the ground.

Relative Autonomous Navigation. If one spacecraft can see the other move as a point of light against the background stars, then relative autonomous navigation is possible. If its approximate position is known, picking out the target can be done by watching for "stars" that move relative to the rest of the star field. (Computations for the approximate brightness of the target are given by Wertz [2001], Sec. 11.6.) The process for doing relative autonav is the same as that used for many years in classical astronomy to determine the orbits of comets and asteroids by watching their motion with respect to the background stars. (This is Method 2 in Fig. 1.) Substantially improved accuracy is possible compared to absolute autonomous navigation because only a single star sensor is needed and there are no intersensor mounting angle biases, which is often the largest error source in absolute autonav.

Autonomous Orbit Control. As discussed below, Microcosm has flight demonstrated fully autonomous orbit control. The key element for relative navigation is that the orbit is fully controlled to a pre-specified set of parameters. Thus, even if the spacecraft are not communicating, each will know where the other is and where it will be at all future times. By eliminating the need for cross-links or other communication between the satellites, autonomous orbit control can substantially simplify the process of relative navigation in planetary orbits. Basically, the position of the other satellite is known because it is controlled to be there.

3. AUTONOMOUS, ON-BOARD ORBIT CONTROL

A major milestone in the development of on-orbit systems occurred in October 1999, with the first flight demonstration of fully autonomous, on-board orbit control. The Microcosm *Orbit Control Kit* (OCK) software was flown on the Surrey Satellite Technology Limited (SSTL) UoSAT-12 spacecraft, where it co-resided on a customized 386 on board computer, developed by SSTL, with their attitude determination and control software. For a discussion of the implementation see Wertz, et al. [2000]. UoSAT-12 was launched in April 1999. The OCK on-orbit demonstration was conducted Sept. 23 to October 22, 1999. Gurevich, et al., [2000] provides a detailed discussion of the software configuration, data flow, and flight results which are summarized below.

In the current implementation, orbit control consists of two principal software components. *Precision Autonomous Navigation*, PAN, provides on-board orbit determination (i.e., autonomous navigation) using a version of Microcosm's High Precision Orbit Propagator, HPOP. As implemented on UoSAT-12, PAN uses GPS measurements over an extended period. However, for planetary orbits, it could equally use autonav measurements. Note that autonomous navigation is not needed for orbit control (just as attitude prediction is not needed for attitude control), but serves to fill in inevitable coverage holes and provides precise, continuous orbit information. The Orbit Control Kit, OCK, generates thruster firing commands that are implemented by the on-board Attitude Control System. PAN and OCK can be used independently or together, as PANOCK.

	On-orbit	Simulation
Atmosphere	Real	MSIS
F10.7	Real	Measured
Duration (days)	29	29
Performance (sec, 1σ)	± 0.12	± 0.14
Performance (km, 1σ)	± 0.9	± 1.02
No. of Burns	53	48
Maximum Burn (mm/s)	2.7	4.9
Minimum Burn (mm/s)	0.053	0.19
Mean Burn (mm/s)	1.4	1.6
Sum of Burns (mm/s)	73.3	76.3
ΔV to Restore Altitude	85 – 100 mm/s	

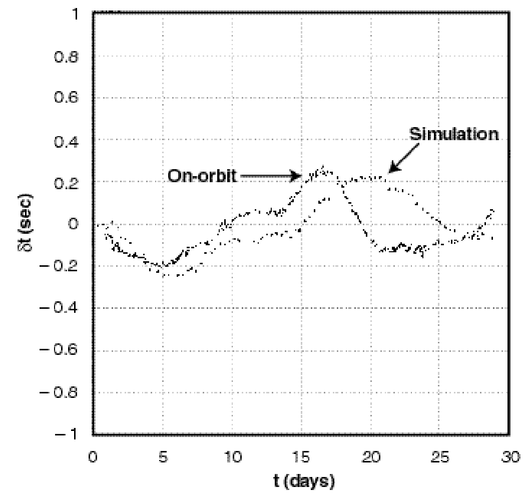

Figure 2. Simulation Results vs. On-Orbit Performance. The total delta V required was consistent between on-orbit data and the simulation to within 4%. Based on the simulation, the delta V required to restore the altitude (but not recover the in-track phase) was 85 to 100 mm/sec, implying a delta V savings with OCK of 10% to 25% for this period.

Figure 2 shows the results of the on-orbit demonstration. The vertical axis is time late crossing the ascending node, relative to the target time. The system maintained a 1-sigma error of ±0.12 sec (= 0.9 km) for the 29 day period. The system made 53 thruster burns with an average burn of only 1.4 mm/sec. This represents substantially less than 1 millionth of the orbital velocity of 7.5 km/sec.

The OCK software demonstrated substantial robustness during the flight. At the beginning of the demonstration only 1 of 2 commanded thrusters was firing. This anomaly was undetected at the time. Consequently, the system initially had half of the intended thrust level. Midway through the demonstration the error in the spacecraft software (unrelated to OCK) was found and fixed such that both thrusters began firing. However, no adjustments were made to the flight software, either initially or when the error was corrected. This "half thrust/full thrust" was responsible for the dip and rise in the plot in Fig. 1. However, the system remained stable and fully controlled at all times.

A similar problem occurred with the GPS receiver which was also being tested at the time. We had anticipated and designed for outages of up to 5 minutes due to the GPS satellite geometry at the UoSAT-12 altitude. Because of the ongoing receiver testing, data outages of up to 8 hours occurred. Again the system processed the available data and continued to provide good control for the entire period.

In order to validate the system simulation we attempted to reproduce the on-orbit results by using real solar flux data for the period of the demonstration and a raw GPS state vector from the navigation software for initialization. These results are also shown in Fig. 2. The simulation projected a total burn of 76.3 mm/sec vs. and actual total burn of 73.3 mm/sec. Thus, the two are in good agreement. (The thruster error described above was modeled in the simulation.) Once the simulation had been validated, it was used to test the propellant savings. Specifically, another run was made with the stationkeeping burns turned off. At the end of the 29 days, the thrusters were fired in the simulation to restore the original altitude, but not the in-track phase. (Restoring the phase would have taken even more propellant.) Simply restoring the altitude required 85 to 100 mm/sec, depending on the conditions to be matched. This implies a delta V savings using OCK of 10% to 25% for the demonstration flight.

Finally, the simulation was also used to predict the results over a full 11-year solar cycle. The simulation was run using Microcosm's High Precision Orbit Propagator (HPOP) using the JGM-3 gravity field (truncated to 21 x 21), MSIS-86 atmospheric model using historical F10.7 values plus random noise on the solar flux, solar radiation perturbations, and third body solar and lunar perturbations from the standard JPL ephemerides. Although the atmospheric density changed by about two orders of magnitude, the OCK control gains were not changed for the entire run. The results show a 3-sigma time late over the entire period of ~0.08 sec (= 600 m). [Gurevich and Wertz, 2001].

Autonomous, on-board control offers several technical capabilities not previously available to space missions:

- All of the orbital elements of the spacecraft are controlled automatically
- This means that the spacecraft follows a fully predictable orbit pattern, such that the position of the spacecraft at all future times is known as far in advance as desirable and the ground track (or inertial track) of the spacecraft can be made to follow a predefined pattern which can be changed at the convenience of the user
- The process for computing future positions is sufficiently simple that it can be included in virtually any ground-based equipment that uses a general purpose microprocessor
- There is a longer planning horizon for all future activities such as payload and maneuver planning and dealing with potential problems of ground coverage or physical or RF interference.
- Disturbance torques are much lower than with more traditional orbit control processes such that the size and responsiveness of control actuators can be reduced and restrictions on the timing of stationkeeping maneuvers can be reduced or, most likely, eliminated.

All of this is achieved using less propellant than more traditional orbit control techniques. There are two distinct mechanisms for propellant savings. First for any planetary orbit in which atmospheric drag is relevant, autonomous stationkeeping maintains the satellite at the top of its altitude range, rather than allowing it to drift down and then be reboosted. Because atmospheric density increases exponentially with decreasing altitude, this means that the satellite will be continuously maintained in the lowest possible drag environment, as was demonstrated by the UoSAT-12 performance.

The second propellant savings comes about if maneuvers are required at any time, such as for ground station coverage or to provide better coverage of a planetary target. The critical issue for propellant utilization is to do the maneuver as far in advance as possible. With autonomous stationkeeping we know the position of our satellite as far in advance as needed. Consequently, maneuvers can be done as soon as the need becomes known and, therefore, significantly reduce the propellant required. Since propellant usage is proportional to the velocity change for small maneuvers, the propellant required will be inversely proportional to the time allotted between the maneuver and the event.

4. COST REDUCTION ENABLED BY AUTONOMOUS STATIONKEEPING

In spite of the significant technical advantages, the most substantive benefits of autonomous stationkeeping are reduction of both cost and cost risk. Costs can potentially be reduced in the following principal areas:

- The operations cost of orbit maintenance is essentially eliminated. The costs here include: ground collection of navigation data, ground based orbit determination, preferred orbit position determination, thruster command generation, command uploads, verification of command uploads, and verification of command execution. Basically, the ground operations required for orbit maintenance is reduced to occasional monitoring. In addition, the ground-based system to perform this work is used only for backup and can likely be developed for significantly less money.
- The cost of planning and scheduling (often representing 50% of operations cost) is reduced for several reasons:
  - Replanning and rescheduling as an event approaches due to drift in orbital elements is eliminated. Since orbital position is known for the life of the mission, the need to update planning based upon better ephemeris prediction is no longer needed. Atmospheric drag no longer plays a role in mission planning.
  - Planning and scheduling can be done on a business basis as convenient for the users (i.e., at monthly, quarterly, or annual meetings), rather than as dictated by astrodynamics.

With autonomous stationkeeping, planning and scheduling are done on a business basis, not as astrodynamics dictates.

  - Because the impact of the burns is minimal (the burns are very small), there is no interaction between timing of stationkeeping maneuvers and the payload event planning. Most payloads will be able to continue operation through the stationkeeping maneuver without interruption.

- The cost and complexity of transmitting spacecraft ephemerides to various users is eliminated. The spacecraft ephemerides can be provided to users electronically at the beginning of the mission.

- Lower propellant usage (and, therefore, increased mass margin or longer spacecraft life and lower cost per year) for both normal stationkeeping and rephrasing as discussed above.

- Spacecraft cost and weight are reduced due to
  - The use of smaller thrusters.
  - The maximum disturbance torques are reduced, which typically dictate both the size and responsiveness of attitude control components.
  - There is potential to eliminate cost and complexity of a separate ACS stationkeeping mode and even separate stationkeeping ACS hardware (i.e., gyros).

A key issue is the reduction in the disturbance torque environment. Normally, thruster firings represent the largest disturbance torque on the spacecraft and may interfere with payload operations. Consequently, there is often a planned "stationkeeping mode" in the spacecraft control system in which normal operations are stopped, the thrusters are fired, and then operations are resumed. Clearly, such an activity needs to be coordinated with the users so as to minimize the adverse impact.

In contrast, autonomous stationkeeping can use thruster burns that are very small, typically only several times the minimum impulse bit of a small thruster. In most cases, this can be made small enough that the disturbance torque is absorbed entirely by the control system and is effectively unnoticed by the spacecraft. (This is essentially comparable to the spacecraft control system; i.e., the payload doesn't care when the control system chooses to command the reaction wheel to speed up to maintain the stability of the platform.) This not only eliminates the need for a separate stationkeeping mode, it also eliminates interference with the payload and the need to coordinate payload operations and stationkeeping activities. This robustness was unintentionally demonstrated on UoSAT-12. The system had been designed to fire two thrusters on opposite sides of the center of mass to eliminate disturbance torques. One of the thrusters wasn't working for the first half of the test period. However, this went unnoticed because the stationkeeping burns were sufficiently small that the full disturbance torque was easily absorbed by the control system.

5. CONCLUSIONS

The specific impacts of autonomous stationkeeping performance enhancements and cost and risk reduction will, of course, depend on the details of the specific mission. Nonetheless, it is clear that some level of cost, mass, and risk reduction will occur for essentially all planetary orbiter missions. In addition, this technology enables some missions and mission elements, such as automated one-way data transmission or automated coverage of selected ground targets, which would not otherwise be possible. Because these features are very fundamental to the mission design, the greatest impact occurs when autonomous navigation and stationkeeping is incorporated early in the mission design process.

In summary, autonomous, on-board orbit control can fundamentally change the way planetary missions operate. It is a key component in extending the philosophy of "faster, better, cheaper" to 21st century satellite operations.

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