AUTONOMOUS CONSTELLATION MAINTENANCE SYSTEM*

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Abstract

At present, a large number of surveillance, scientific, and commercial communications constellations are being actively pursued by DoD, NASA, and the commercial space community. In many cases, these constellations will be made up of "LightSats" or small, low cost spacecraft. For such systems, operations costs, which are large in traditional systems, can become a dominant element of total system life cycle cost. This implies a need for low-cost autonomous constellation maintenance in order to allow such systems to be economically viable.

A low-cost, autonomous approach for precisely maintaining the structure of Earth-orbiting satellite constellations from LEO to GEO is currently under development at Microcosm under contract with the U.S. Air Force Phillips Laboratory[+]. This work has significant heritage in previous internal and government-funded work at Microcosm. Utilizing hardware already onboard most spacecraft along with navigation and control software developed by Microcosm over the last 5 years, we can maintain each satellite in a constellation to within ±5 km of a desired, predetermined orbital position without requiring complex inter-satellite communication or ground-based commanding. The entire process is carried out onboard by each individual spacecraft. Because the system does not require crosslinks, initial satellites can be deployed directly into the constellation structure and the overall system has very soft failure modes. The net savings in total annual operations costs for a LEO constellation is potentially on the order of 10% to 20% over current practice. The concept of a regularly scheduled (±0.7 sec) "Civil Orbit" will be introduced to illustrate how it greatly enhances some mission opportunities.

This low-cost constellation maintenance system is described here, illustrating its range of functionality and its application to different example constellations. The top-level system architecture is presented, showing the relation between the orbit control system and spacecraft attitude control system. Autonomous orbit control, the key system component which makes autonomous constellation maintenance possible, is also described. Simulation results are presented for the case of two satellites in the same orbit, separated by 10 sec in orbit phase.

Background

Microcosm, Inc. is currently investigating the feasibility of and doing the preliminary design for an autonomous satellite constellation maintenance system for Earth orbiting constellations from LEO to GEO. In recent years, a great variety of satellite constellation concepts have been proposed and some are actually under development today. In the military regime, systems such as Brilliant Eyes (now called Space Missile Tracking System, SMTS), MiLSTAR, and GPS are prime examples of existing and near-term constellations. In the NASA environment, the Earth Observing System (EOS) is a series of about 10 to 12 satellites that will provide systematic and continuous global coverage of the Earth's surface and atmosphere over about a 15 year period. Among commercial constellations, systems such as Iridium, GlobalStar, Teledesic, Orbcomm, and Odyssey are primary examples of large satellite systems in symmetric configurations which seek to optimize global coverage. Our proposed autonomous constellation maintenance system enables such coordinated satellite systems to maintain their structure to very high precision for much lower cost and risk than is currently available with ground-based orbit maintenance.

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Difficult coverage requirements involving continuous or partial (near-continuous) coverage are often the primary design constraint driving the selection of multi-satellite constellation architectures. A constellation configuration specifically designed to provide optimal coverage of a particular ground area is a coverage-based constellation. Additional requirements, such as high-resolution imagery for remote sensing, or high-signal power flux density for telecommunications, may further restrict the orbit selection to low or medium Earth orbit (LEO or MEO). The most widely discussed constellations typically consist of similar spacecraft in a symmetric distribution of orbital ascending nodes and phasing, providing continuous global coverage of the Earth. The U.S. military NavStar Global Positioning System (GPS) constellation is a prime example of a coverage-based constellation.

Constellation Maintenance

Constellation maintenance is the process of controlling the positions of all of the satellites within a coordinated satellite system at all times with respect to each other and, desirably, with respect to the ground.

At the most basic level, for a single satellite, we must maintain the orbit to overcome long-term secular perturbations. In GEO, all spacecraft require orbit maintenance in the East-West direction to avoid interference and possible collisions with other spacecraft. Most GEO satellites use North-South orbit maintenance to maintain a near-zero inclination. In low-Earth orbit, altitude maintenance is used to overcome atmospheric drag and achieve a longer working life. Other orbit types, such as Sun-synchronous or repeating ground track, may also require orbit maintenance.

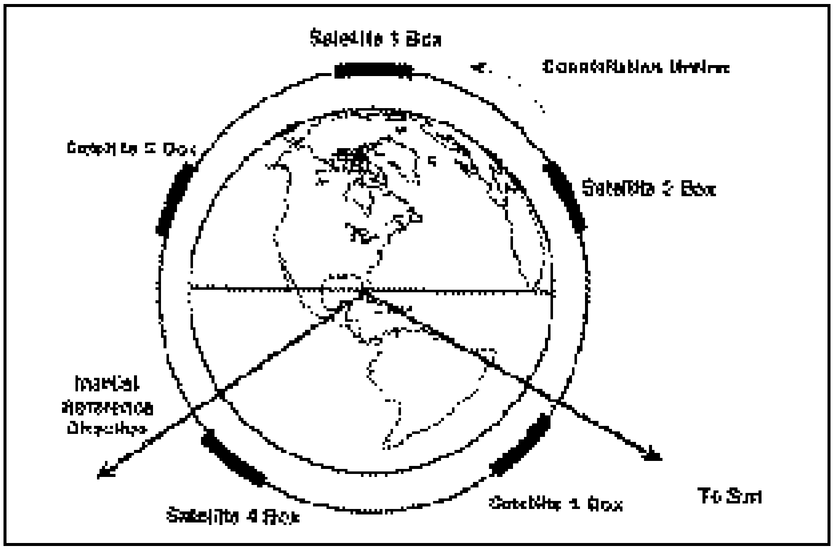

Figure 1. Constellation Maintenance Maintains Each Satellite in a "Box" Rotating With the Constellation

Constellations require orbit maintenance to prevent collisions between satellites and maintain the constellation pattern over time. In principal, we could use relative stationkeeping in which we maintain the relative positions between satellites but not their absolute position. In practice, this makes orbit maintenance more complex and will not save propellant or reduce the number of computations required. In a low-Earth orbit constellation with relative orbit maintenance, we would, in principle, maintain all satellites in the constellation to decay at the same rate as the slowest-decaying satellite at any time. But the entire constellation would still decay in this process. Therefore, it would slowly change its altitude and need to be reboosted at some later time.

The approach we are developing applies absolute stationkeeping, shown in Figure 1. Here each spacecraft is maintained within a mathematically defined box moving with the constellation pattern. As long as we maintain the constellation's altitude, absolute stationkeeping is just as efficient as relative stationkeeping. All in-track stationkeeping maneuvers are done firing in the direction of motion to put energy taken out by atmospheric drag back into the orbit. We put in more or less energy at any given time, depending upon the amount of drag and the atmospheric density.

The amount of drag makeup for any satellite in a constellation depends on the satellite's observed drift relative to its assigned box. At the forward edge of the box, the applied ΔV is increased, thus increasing the orbit altitude and period and sliding the satellite rearward in phase relative to the box. Similarly, at the trailing edge, the applied ΔV is decreased, thus decreasing the altitude and period and sliding the satellite forward in phase. Because of the high spacecraft velocities in LEO, timekeeping is critical to maintaining the satellites' relative positions. A one-second difference in time yields a 7 km difference in in-track position. Maintaining the same time throughout the constellation is important, but not difficult. Use of GPS receivers on LEO satellites will facilitate this requirement.

Although the perturbing forces are different, constellation maintenance in low-Earth orbit is analogous to stationkeeping in geosynchronous orbit. In-track and cross-track orbit maintenance in low-Earth orbit correspond to East-West and North-South stationkeeping, respectively, in GEO. Because the forces involved are different, the correspondence is not exact. Altitude maintenance is necessary in LEO to overcome drag. In GEO, this corresponds to maintaining the mean drift rate relative to the surface of the Earth at zero, so the stationkeeping box stays over a fixed location. In low-Earth orbit, this corresponds to maintaining the box at a mathematically fixed position in the constellation.

Autonomous constellation maintenance is smarter, cheaper, and lower risk than traditional methods of satellite orbit maintenance. It frees operations personnel to handle situations that need human intervention rather than mundane, routine tasks. It also allows operators to focus on long-term planning and system evolution. It is cheaper than traditional methods of ground-based orbit control, allowing major reductions in routine operations labor and scheduling and doing away with the need to "mother" the spacecraft. It is lower risk because it lowers the possibility of human-induced operations and communications errors characteristic of ground-based commanding.

Potential Users

As mentioned previously, there are a great number of proposed satellite constellations, military, civil, commercial, domestic, and international. Table 1 shows some of the major constellations which are currently operational or which are proposed to be emplaced within the next 10 years. All of these systems would benefit greatly from implementing autonomous constellation maintenance.

Table 1. Representative Earth Orbiting Satellite Constellations

Name	Operator	Purpose	Status	Type	Alt. (km)	Inc. (deg)	# sats	# planes
GPS	USAF/USN	navigation	operational	"Optimized 21"	20200	55	21 + 3 Spare	6
Glonass	Former USSR	navigation	operational	1/2-GEO	19100	64.80	21+ 3 Spare	3
Transit	US Navy	navigation	operational	LEO	1074	90˚	5 or 6	5 or 6
FLTSATCOM	USN	UHF comm.	operational	GEO	35800	4-5	4	1
Iridium	Motorola	commun-ication	planned 1996	polar	765	90	66	6
GlobalStar	Loral Cellular Systems	comm. (voice)	planned 1997	circular	1386	47,55	24/48	14 (8,6)
Odyssey	TRW Space & Tech. Group	comm. (voice)	planned	unknown	10,300	55	12	3
Ellipso	Ellipsat Corp.	comm. (voice)	planned 1994/95	elliptic	520/ 7800	116.5	15/6	Sev-eral
Aries	Constellation Comm. Inc.	comm. (voice, data, radio-location)	planned 1996	circular	1022	90	48	4
Starsys	Starsys Global Positioning	comm	planned late 1990's	circular	1300	60	24	6
OrbComm	Orbital Comm. Corp.	comm. - radio message	2 launched	circular	785	45	26	3

Table 1. Representative Earth Orbiting Satellite Constellations (Cont.)

Name	Operator	Purpose	Status	Type	Alt. (km)	Inc. (deg)	# sats	# planes
Projet 21	Inmarsat	comm. (voice, data)		LEO, or elliptic w/high ecc			35/40	?
DMSP	military	meteoro-logical	operational	near-circular	822	99	2	?
Molniya	Former USSR	comm.	operational	highly elliptic	200-1000/ 26600	63.4	(many)	?
Draim 4	n/a (cont whole Earth coverage)	---	(theoretical)	elliptic	>38736	31.3	4	4
Walker 5	n/a (cont whole Earth coverage)	---	(theoretical)	Walker	>38655	43.7	5	5
DSP	military	military comm.	deploying	GEO	35800		16 (25 planned)	?
GOES	NASA/NOAA	meteoro-logical	operational	GEO	35800	0-7		1
TDRS	NASA	commun-ication	operational	GEO	35800	0-2	5	1
Westar	Western Union	commun-ication		GEO	35800	0-3		1
DSCS1	USAF	commun-ication	out of service	GEO	35800		26	
DSCS 2	USAF	commun-ication	operational	GEO	35800	1-9	16	1
DSCS 3	USAF	commun-ication	deploying	GEO	35800	0.1		1
Teledesic	Teledesic Corp	Telecom	proposed	LEO	700	98.2°	840+ 84 Spare	21

System Engineering (Stationkeep-ing Require-ments and Constraints)

System Function	*Primary*	*Back-Up*
Navigation	LEO : GPS GEO : Optical Navigation or GPS	LEO: Optical Navigation GEO: On-board Propagation
Attitude Determination	Standard Spacecraft	GPS
Orbit Control	Thrusters	
Attitude Control	Wheels / Thrusters for momentum dumping	
Software (Orbit, Attitude, Thruster Commanding, Collision Avoidance)	Microcosm Autonomous Navigation System (MANS) Precision Autonomous Navigation and Orbit Control Kit (PANOCK) Constellation System Database (Satellite Replacement, Satellite Rephasing Due to Loss of Member)	

Figure 2. Generic Autonomous Stationkeeping System Architecture

System Architecture

The top-level architecture for the autonomous constellation maintenance system can be looked at in various ways. One instructive view is to examine the various pieces necessary for a system to function. Figure 2 shows the essential elements of our proposed system.

System Engineering surrounds the standard elements of the system in this conceptual diagram, gluing them together into a coherent, integrated system. The system engineering element of the whole system is the part that takes into account items such as minimization of propellant usage, the proper choice of orbit control box size, and the lessening of disturbances to normal spacecraft functions caused by the operation of the stationkeeping system.

Originally it was conceived that system engineering would impact only upon the Orbit Control element of the system. However, through a little thought it became apparent that the system engineering portion of stationkeeping has ramifications on all elements within the system. For example, when a system engineering trade study determines that there must be a tightening of the nominal orbit control box size by a factor of ten, this has serious implications upon the navigational sensors and software. The improvement in position knowledge also allows, presumably, an increase in the accuracy of the Attitude Control system, assuming we use more accurate sensors. This increase in attitude knowledge *may* allow more judicious alignment of thrust vectors during orbit conrol maneuvering thus improving propellant usage.

Alternatively, a tightening of the orbit control box, as identified above, might require smaller, more frequent burns to control to the new limits. This requirement in turn, requires smaller thrusters so as to maintain an agreeably high efficiency of propellant usage. The change in thruster size, and possibly in management technique, has implications for the Attitude Control System and its momentum dumping function. Thus, it soon becomes apparent that the system engineering considerations of any specific system differentiates between different applications and requirements very quickly, and herein lies the rapid divergence from a generic system.

The generic system remains highly useful, however, as a starting point for any future applications, as a baseline system for all applications, and as a tool showing the innate commonality between all such systems.

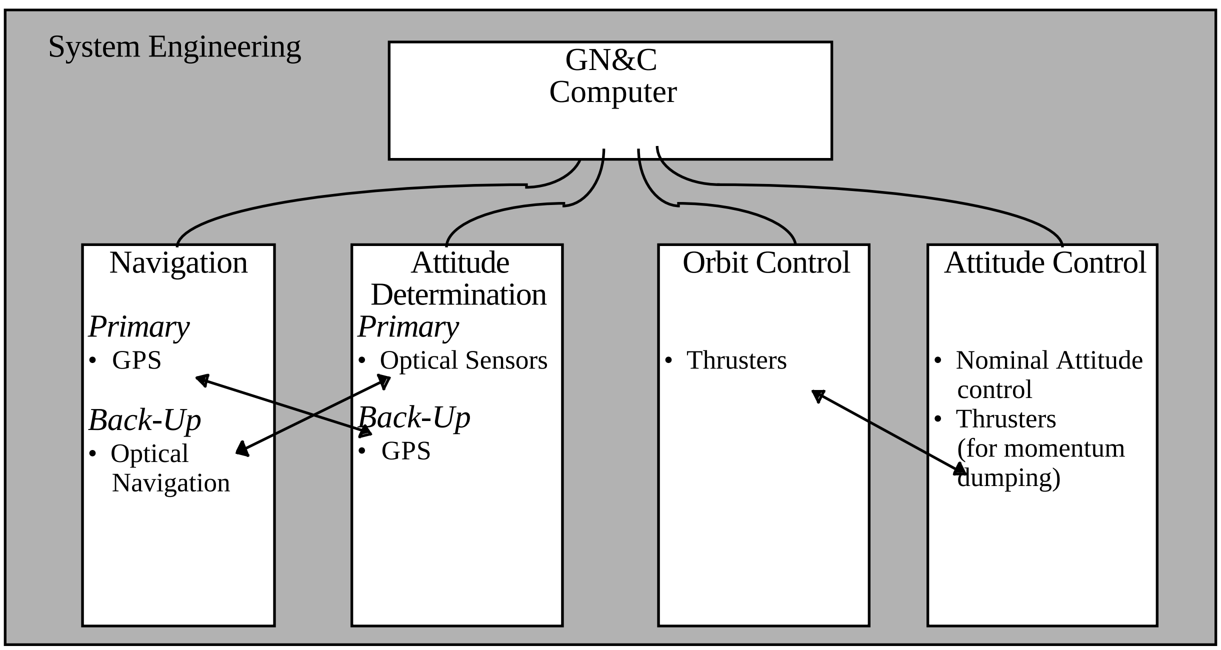

Figure 3. The Fundamentals of the Orbit Control Process, from a Hardware Perspective, showing Interaction with the Spacecraft ACS and Multiple Use of Components

The Guidance, Navigation and Control (GN&C) computer, as shown in Figure 3, is where the software and the brains of the system reside. A GPS-based navigation system, an orbit control module, and the more usual attitude determination and control software functions all reside side-by-side within the GN&C computer. This has the advantage of a common architecture and the easy availability of common routines to all modules.

The system will use a GPS receiver as the primary means of determining spacecraft position and velocity. Traditional optical sensors will be used to determine spacecraft attitude. Earth sensors, star sensors, and sun sensors can all be employed, along with gyroscopes. The GPS receiver can also provide attitude (to ±0.5°) as a back-up to the traditional attitude sensors. Likewise, the combination of an Earth sensor with any common inertial sensors (star sensor, gyro, sun/moon sensors) can provide satellite position and velocity as a back-up to the GPS receiver. Using on-board optical sensors to provide spacecraft position and velocity for autonomous orbit navigation[*] has been done with the Microcosm Autonomous Navigation System (MANS)[2,3], which launched on the Air Force Technology for Autonomous Operational Survivability (TAOS) spacecraft in 1994. The on-orbit testing has since been completed and position determination accuracy on the order of ±1.5 km (RSS) was achieved. MANS uses the sensed position of the sun and moon and the apparent angular diameter of the Earth to estimate position autonomously from any external source (ground-based or GPS).

A principal requirement for constellation maintenance is efficient operation at very low thrust levels. Autonomous constellation maintenance will generally imply a much larger number of very low thrust burns rather than a small number of burns done with a higher thrust system. This provides finer granularity and better control with no propellant penalty, except for a possible loss of efficiency in the thrusters themselves. Consequently, we are looking for a thruster system that provides a very small minimum impulse bit and high efficiency at low thrust levels. The low thrust levels substantially improve the efficiency of the navigation activity and, at the same time, significantly reduce the disturbance torques which the control system must overcome. In general, the orbit control thrusters represent the largest single disturbance torque on the attitude control system and, therefore, the potential impact of orbit maintenance on the cost of attitude control should be taken into account.

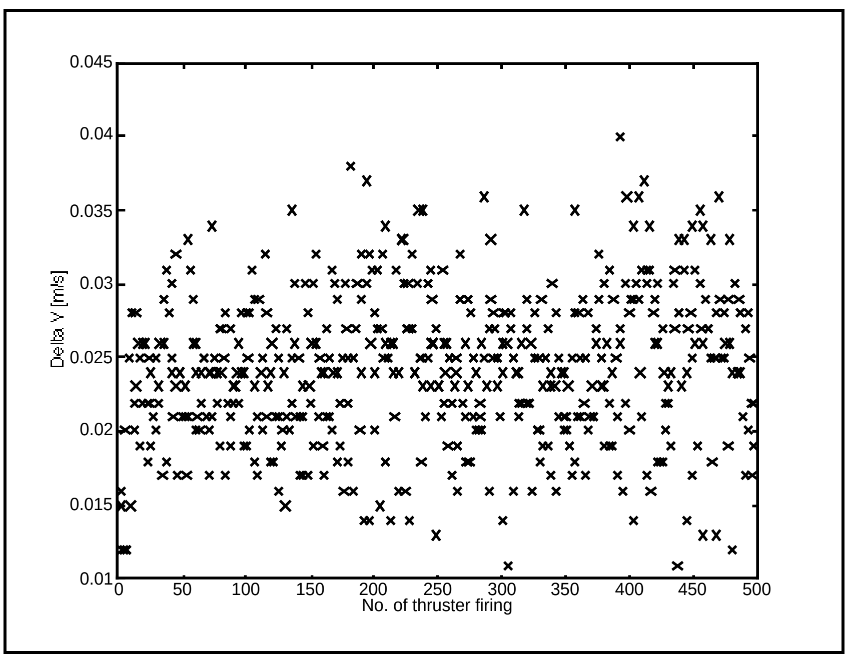

Figure 4. Delta-V Burns Required For Maintaining a Single Low-Earth Orbit Satellite (530 km circular orbit) During the Course of 6 Months.

[*] U.S. Patent No. 5,109,346, issued April 28, 1992.

Figure 4 shows the history of applied ΔV's for 6 months worth of orbits for a low-Earth orbiting satellite. The minimum value is 0.011 m/sec, and the thruster(s) used to make the orbit correction burn should be small enough to meet this value. We have determined that a 5 Newton thruster firing for about 1.8 sec is sufficient to provide this ΔV, assuming hydrazine propellant with I_{sp} = 200 sec and a spacecraft mass of 800 kg. This illustrates the typical thrust involved with autonomous orbit control.

The desire for very low thrust which minimizes the disturbance on the spacecraft suggests the potential of using electric propulsion for autonomous constellation maintenance. While electric propulsion poses the significant problem of extended delays for traditional orbit transfer which requires significant ΔV's, it has substantial advantages in constellation maintenance. It can provide a nearly continuous low level of thrusting to counteract environmental forces on an ongoing basis. In this sense, an electric propulsion orbit control system behaves much more like a traditional attitude control system. The disadvantages are the very high power level required and the fact that electric propulsion thrusters have not traditionally been a standard component on most smaller spacecraft. We are currently evaluating the advantages, disadvantages, and cost of using electric propulsion and will assess the potential for incorporating an option for electric propulsion in the overall constellation maintenance system architecture.

Autonomous Orbit Control

Autonomous orbit control[4] is the central element of Microcosm's Autonomous Constellation Maintenance System. Our Precision Autonomous Navigation and Orbit Control Kit (PANOCK), which we are currently developing under a Phase II Small Business Initiative Research (SBIR) contract to the USAF Phillips Laboratory (VT/Q), combines GPS-based navigation with autonomous orbit control. In the past, there has been no realistic alternative to orbit control from the ground. Now, however, substantial on-board computing and autonomous navigation systems have made autonomous orbit maintenance possible, economical, and safe*. Autonomous orbit maintenance can drive down overall mission cost and risk by conducting a major part of the day-to-day operations on-board the spacecraft. Autonomous orbit maintenance is a key component in a fully autonomous spacecraft bus, which can further reduce mission cost and risk.

To date, spacecraft in low Earth orbit (LEO) have been either uncontrolled or loosely controlled. By "loosely controlled," we mean that the average orbital elements are maintained, but the detailed motion of the spacecraft is affected strongly by varying atmospheric drag and other perturbations. The result is that the actual position of the satellite at future times can be predicted only by complex orbit propagation software and, in any case, is accurate for only short periods. This means that scheduling and planning, not only of orbit maintenance maneuvers, but of ground station passes and payload operations, is continually revised and updated. This prediction, planning, and re-planning represents a significant portion of the operations activity and, therefore, of the operations cost.

In a controlled orbit, the spacecraft, acting autonomously, makes a large number of small burns rather than a small number of larger ones. With the same or less total propellant expenditure, the spacecraft orbit elements are now maintained continuously and no complex orbit propagation is required to predict future spacecraft positions. This is similar to the situation which currently exists for spacecraft attitude control. It is done autonomously on-board most spacecraft with frequent small adjustments. There is no need for complex attitude propagation algorithms. Figure 5 shows the basic orbit control concept employing frequent application of very small propulsive burns at regular intervals based on a timing measurement at a reference location in the satellite orbit.

Another advantage of our proposed orbit control system is synergy with the attitude control system. The same thrusters and propellant can be used for both types of corrections and, in some cases, simultaneously. Orbit and attitude can be treated as a truly integrated control problem and a common system can control the spacecraft's total dynamic state. There is no longer a need for large orbit maneuver engines to perform routine orbit control maneuvers. Figure 6 shows the core components of PANOCK.

* U.S. Patent 5,528,502: "Satellite Orbit Maintenance System," June 18, 1996. Patent Allowed in Europe.

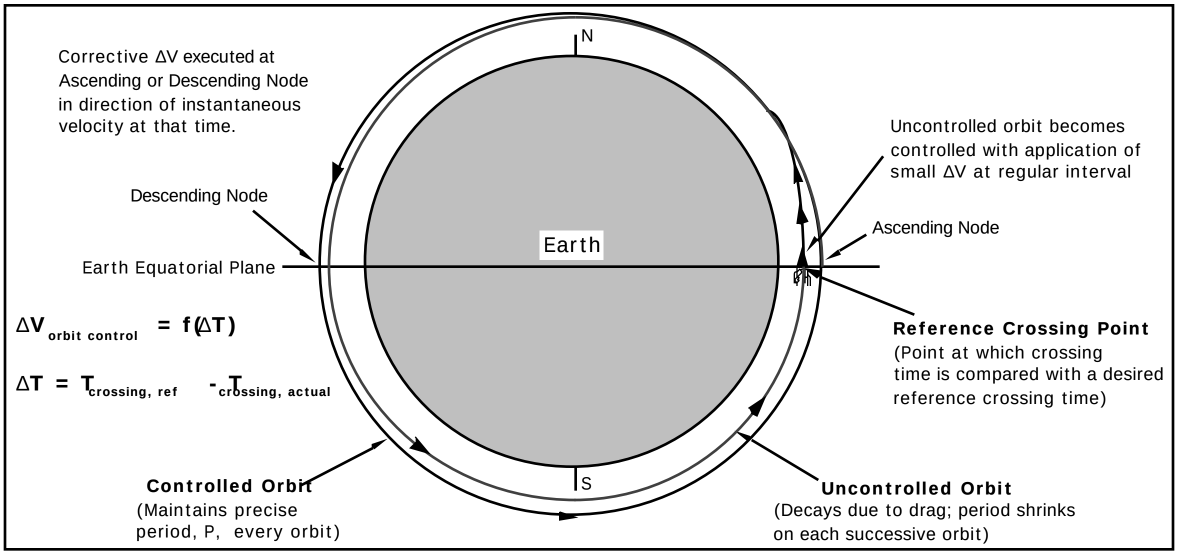

Figure 5. Orbit Control Concept

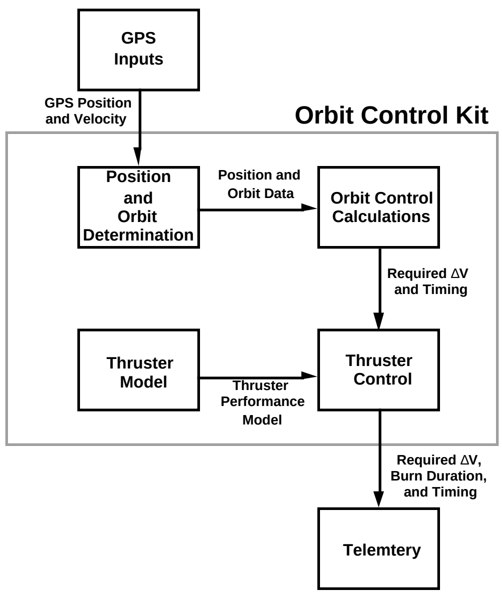

Figure 6. PANOCK Core Components

The precision autonomous navigation function of PANOCK is especially attractive to commercial systems requiring higher accuracy than the position error that standard commercial GPS receivers yield, typically ±100 m RSS. High accuracy mapping satellites may require very high accuracy orbit determination. Filtering GPS data with a Kalman Filter derived from the on-orbit Microcosm Autonomous Navigation System, MANS, can provide the user with RMS position accuracy of approximately 5 times better than that from GPS alone.

System Benefits

Controlled orbits can lead to substantially reduced operations costs for constellations for several reasons. First, of course, is the elimination of the need for ground-based stationkeeping and maneuver planning, command uploading, execution, and verification for each separate member of the constellation. Second, the cost associated with the normal operations processes of orbit determination, prediction, and propagation are eliminated. However, perhaps the largest cost saving is due to the elimination of the need to continuously update the schedule of future activities. In normal operations activities, future events are approximately planned but detailed scheduling will depend upon the specific timing of the satellite which cannot normally be predicted. Therefore, schedules are more-or-less continuously revised and updated as events get closer. In the controlled orbit, or "Civil Orbit," the future position of the satellite is fully known (to within approximately 0.7 sec) *before launch.* Consequently, the schedule of future events can be developed entirely in advance of launch, if desired. This of course does not imply that the schedule cannot be changed while the satellite is flying, to meet operational purposes, but simply that the schedule can be set by operations personnel rather than by the natural, often unpredictable variations in satellite motion.

Autonomous orbit control also substantially reduces the computational burden both on the ground and on the spacecraft. Without orbit control we need high precision orbit propagation in order to even approximately predict the future position of the satellite. In a controlled orbit the orbit propagator is no longer necessary either on the ground or in space. This is analogous to the common process of on-board attitude control. A detailed attitude dynamics simulation of the spacecraft is frequently used to model the behavior of the spacecraft and determine the control laws. However, once the control laws have been set, they are implemented on board the spacecraft and the detailed dynamic model is no longer needed. We do not run on the ground or in space a continuing model of attitude dynamics. We simply allow the attitude control system to maintain the orientation of the spacecraft. Precisely the same process occurs with autonomous orbit control. We use the control process to maintain the satellite where we have planned for it to be. There is no need for the orbit propagator because the satellite is not in a freely varying orbit but in one which is being fully maintained with frequent small thruster firings.

It is important to note that this higher level of control comes about without requiring any additional propellant and may actually represent a slight propellant saving. Specifically, in order to control or maintain a low Earth orbit, we need to restore the ΔV which atmospheric drag takes out. The ΔV which must be applied over the course of time is simply the total ΔV that drag has applied over the same time. If we are to keep the satellite from lowering its altitude, we must occasionally reboost it back to the altitude at which it began. In the traditional process of orbit maintenance we do this with occasional thruster firings, whereas in a controlled orbit we do this with a larger number of much smaller burns which ultimately provide the same total ΔV. The only differences in ΔV come about because of changes in the efficiency of the thrusters or because of the slightly lower drag in the controlled orbit since the satellite continuously remains at a higher altitude.

Although no additional propellant is used, we do have much tighter control over the satellite position. This is particularly important in constellations in which we are interested in both maintaining the structure of the constellation and potentially communicating with other satellites using open-loop, cross-link communications. The same process could be applied for stationkeeping in geosynchronous orbit using comparable logic.* A significant advantage of autonomous geosynchronous orbit control is that the ΔV can be done more frequently and, consequently, a much smaller control box can be maintained. For example, it may well prove feasible to put as many as four satellites in a single geosynchronous slot currently occupied by one satellite. This could significantly enhance the utilization of GEO.

Implementing autonomous orbit control can reduce not only the cost but also the risk associated with orbit maintenance. In normal orbit maintenance, the potential error sources are dominated by command generation and communications, and the consequences of a single error can be substantial. In the case of autonomous orbit control all of these are effectively eliminated. The commanding process is done on board in an automated and thoroughly verified sequence which significantly reduces the communications problem, and entirely eliminates, for example, the problem of the wrong command being sent to the wrong satellite in a constellation. Perhaps most important,

*In geosynchronous orbit, the logic is comparable to a controlled Earth orbit but the forces involved are different. In geosynchronous orbit, north-south stationkeeping is required due primarily to solar and lunar perturbations and east-west stationkeeping due to high order harmonics in the Earth's geopotential. The net effect, however, is the same as drag in low Earth orbit—a secular drift that must be more-or-less continuously opposed.

however, the consequences of a failed maneuver are inherently benign. In the spacecraft attitude control system, a failure for even a brief period can be disastrous for the satellite. The satellite can tumble and point the solar arrays away from the sun, the antennas away from the Earth, and a sensitive payload directly at the sun. At a minimum this represents a major interruption of service and can potentially destroy the mission. In contrast, in a series of low thrust orbit burns, if one of them is not made, or is even made entirely in the wrong direction, the consequences are minimal. The satellite will drift slowly from its assigned position. There is ample time for the ground to analyze the problem, determine what has occurred, and provide corrective action. The only consequence is that the satellite will have drifted slightly further from its assigned position than would have otherwise have been the case. In many orbit control scenarios, the impact of a single burn not executing would probably remain entirely unnoticed so long as subsequent burns executed successfully. Thus, the process is inherently fail safe, which is significantly different than the process of either traditional orbit maintenance or large orbit maneuver burns.

In addition, with autonomous orbit control, the impact of the orbit control burns on the rest of the spacecraft is much more modest than with traditional orbit raising maneuvers. In most cases, thruster firings are by far the largest single disturbance torque which the spacecraft ever sees. Consequently the entire spacecraft control process must be sized to accommodate these large disturbances. When the torques are made smaller by using lower thrust, the required control authority is also reduced such that it may be possible to simplify or reduce the cost of the attitude control system. In addition, there will be less interference with payload operations, such that it may be possible to continue normal payload activities during very brief thruster firings which may last for only a fraction of a second.

Stationkeeping at Higher Altitudes

Above LEO orbit altitudes (> 1000 km), atmospheric drag becomes less of a concern. This has two immediate ramifications for constellation maintenance. Drag acts in a single, well-defined direction (i.e., opposite the the spacecraft velocity vector), which acts to stabilize the system and dominates other perturbations like solar radiation pressure and luni-solar third body gravitational effects, until we reach very high altitudes. Also, the terrestrial gravity field at greater altitudes is “smoothed”, meaning that the Earth more closely acts as a point mass in an astrodynamical sense. There are still variations in the gravitational field but these are now the longer period terms such as J_2 and J_4. The spacecraft is more prone to drift according to predictable processes causing a slow increase in eccentricity. This can have very damaging effects on long term stability for large-scale constellations, such as GPS or GlobalStar. We propose moving towards “frozen orbit” conditions where the control system drives towards a fixed (small) non-zero eccentricity, keeping the inclination, altitude, and argument of perigee fixed. This stops eccentricity variations and effectively fixes the orbit by “playing off” J_2 and J_3.

Geosynchronous Earth Orbit (GEO) satellites have their own unique set of orbit perturbations. Luni-solar perturbations are the largest effect by a factor of 10 and cause an increase in orbit inclination (depending on the inclination of the Moon’s orbit to the ecliptic and the time of year for solar perturbations). The average inclination growth is 0.9° per year. The Earth’s triaxiality (out of roundness of the equator) tends to pull the spacecraft to the East or West depending on its initial position. The spacecraft then oscillates back and forth about a “null” point at 75° E or 255° E longitude. Solar radiation pressure causes an eccentricity to be built up perpendicular to the solar direction, i.e., rotates with the sun. These effects are well known and predictable.

Both East-West and North-South stationkeeping in GEO are comparable to in-track stationkeeping in LEO. The perturbing force operates in only one direction and the purpose of orbit control is to negate the ΔV induced by the perturbation. The stationkeeping process will be similar to the LEO situation, executing short burns applied more frequently (one every one or two days). The higher accuracy is a result of burn frequency and does not require more propellant. Autonomous GEO stationkeeping can make use of any of the navigation methods available, including GPS, optical navigation, or ground tracking. The final result will be a much tighter level of control, with no additional propellant utilization, and more satellites populating current GEO slots.

Constellation Examples

There are several varieties of Earth orbiting spacecraft constellations, some of which have flown and many of which are still nothing more than concepts. The main types we have focused on in the development of the autonomous constellation maintenance system are big LEO constellations, such as Teledesic, small close formations of satellites, and GEO slot-packing systems. Table 3 shows 3 very different constellation types, with their associated in-track drift, frequency of required maintenance ΔV maneuvers, and applicability to real scenarios. A big LEO constellation, consisting of tens or hundreds of satellites will have very stringent stationkeeping requirements to maintain uniform global coverage and to avoid the prospect of inter-satellite collision. Small, close satellite formations may also have strict stationkeeping requirements to maintain the structure of the formation, especially for stereo imaging or interferometry applications.

Orbit control simulation results for constellation A are shown in Figure 7 below. The constellation consists of two satellites in a 530 km circular, sun-synchronous orbit, separated by 10 sec in orbital phase. This run shows the evolution of the in-track, cross-track, and radial errors (all in km) over the course of two days of orbits (about 30 orbits). The in-track dispersion error quickly reaches about 2 km and then stabilizes there. Both satellites are being actively controlled, with small thruster burns being executed about once per orbit. The leading satellite has an area to mass ratio which is twice that of the trailing satellite. The cross-track and radial dispersions are relatively insignificant over this period of time. This type of constellation is of interest to Earth observing missions, which want to take advantage of the long baseline between the instruments on the two spacecraft. This example is illustrative of what level of control is achievable for constellations in low-Earth orbit.

The largest LEO constellation yet proposed, Teledesic[5], is baselining 840 satellites plus 84 spares in 21 orbit planes (44 satellites per plane) inclined at 98.2° to the equator, with adjacent ascending nodes spaced at 9.5°. Each satellite has a design life of 10 years. When an active satellite fails, all satellites in its orbit plane reposition themselves to fill the gap. This type of constellation requires precise control to avoid collisions and to maximize ground coverage. Having satellites drift in phase off of the nominal requirement by only a few degrees can cause significant coverage gaps. The need for uniform coverage in addition to the need to avoid collisions leads to a rough stationkeeping requirement of 48 km in in-track dispersion (corresponding to a desired intra-plane satellite phase separation of 360°/44/21 = 0.390°). This is readily achievable with our proposed autonomous constellation maintenance system.

Table 3. Sample Constellations Considered for Autonomous Stationkeeping

	Constellation A	*Constellation B*	*Constellation C*
Defining Parameters	530 km; 2 S/C 10 seconds apart	Big LEO	GEO Cluster
Range of satellite in-track drift (km)	≤ ~ 2 km negating natural perturbations, e.g., J2 & J4 ("moving box" following contours of gravity field); ~ 10 km accepting natural perturbations ("stiff box")		±10 km within cluster (desired); desired to be « 0.1° longitude; estimate of center point to 0.002° with GPS, 0.01° with optical[1]
Frequency of Δv maneuvers (hours)	≥ ~ 2 hours	≥ ~ 2 hours	≥ 24 hours
System applicability	EO-1 & LandSat; LEO Clusters	Teledesic; Iridium; Odyssey, etc.	GEO Comm Sats "Slot-Packing"

[1] 10 km is size of cluster; 0.1° is size of current GEO slot allocations; controlling center to 0.002° with GPS assumes position control with an accuracy 10 times worse than conservative position determination of 100 m RSS; 0.01° assumes 1 km position knowledge using optical navigation. This level of accuracy is similar to that achievable through the 'quantized' nature of GEO North-South stationkeeping. The N-S drift through inclination growth can only be negated through corrective burns at the nodes of the orbit, i.e., twice per day. This leads to a quantized effect very similar in size to controlling the position with an accuracy 10 times worse than position determination accuracy.

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Figure 7. Stationkeeping Simulation Results for A Two-Satellite LEO Constellation

Lastly, autonomous constellation maintenance at GEO would enable higher satellite density per traditional GEO slot. Autonomous navigation at GEO is an issue which has not been solved, although approaches similar to LEO autonav do seem to offer reasonable potential. Optical navigation at GEO which uses the Earth's angular diameter to determine distance will yield poor accuracy. Combinations of sensors which can place the Earth against the star background, such as Honeywell's ERADS system, offer promise at solving part of the problem. We estimate that GEO optical autonav with an accuracy on the order of 1 km RSS is reasonable to expect with current technology. Using GPS at GEO has not been proven, but one proposed method employing filtering of signals from at most three visible satellites and signal propagation through periods of signal loss yields RSS position determination accuracy of 120 meters[6]. This can be improved to 30 meters with an on-board atomic clock.

GEO cluster constellations would maximize use of current GEO slots. By carefully varying the inclination and eccentricity of the cluster's members, we can produce a circular motion about the standard Geosynchronous orbital location. Varying individual members' argument of perigee produces a "chain of pearls" effect. Through this method, we can pack up to 10 satellites into one valuable GEO slot 0.1° wide in longitude. This would be achievable with autonomous navigation solutions of ±100 meters in position, RSS, which may ultimately be demonstrated with GPS-based or optical autonav.

Conclusions

Our simulations to date indicate that absolute constellation maintenance is achievable with a stationkeeping box size on the order of ±5 km for low-Earth orbits, with less fuel expenditure than would be required in the traditional stationkeeping mode. Through GEO cluster stationkeeping, we are confident that 10 satellites could be packed into one GEO slot 0.1° wide in longitude, assuming that the satellites can take advantage of GPS for navigation information. Microcosm is currently pursuing a flight test for our single-satellite orbit control kit, which will flight validate the key technology which will make autonomous constellation maintenance possible and affordable.

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