Low-Cost Autonomous Orbit Control About Mars: Initial Simulation Results

S. D. Dawson, L. W. Early, C. W. Potterveld, H. J. Königsmann
Microcosm Inc., Torrance, CA.

Abstract

Interest in studying the possibility of extraterrestrial life has led to the re-emergence of the Red Planet as a major target of planetary exploration. Currently proposed missions in the post-2000 period are routinely calling for rendezvous with ascent craft, long-term orbiting of, and sample-return from Mars. Such missions would benefit greatly from autonomous orbit control as a means to reduce operations costs and enable contact with ground stations out of view of the Earth. This paper present results from initial simulations of autonomously controlled orbits around Mars, and points out possible uses of the technology and areas of routine Mars operations where such cost-conscious and robust autonomy could prove most effective.

These simulations have validated the approach and control philosophies used in the development of this autonomous orbit controller. Future work will refine the controller, accounting for systematic and random errors in the navigation of the spacecraft from the sensor suite, and will produce prototype flight code for inclusion on future missions.

A modified version of Microcosm's commercially available High Precision Orbit Propagator (HPOP) was used in the preparation of these results due to its high accuracy and speed of operation. Control laws were developed to allow an autonomously controlled spacecraft to continuously control to a pre-defined orbit about Mars with near-optimal propellant usage. The control laws were implemented as an adjunct to HPOP.

The GSFC-produced 50 × 50 field model of the Martian gravitational potential was used in all simulations. The Martian atmospheric drag was modeled using an exponentially decaying atmosphere based on data from the Mars-GRAM NASA Ames model. It is hoped that the simple atmosphere model that was implemented can be significantly improved in the future so as to approach the fidelity of the Mars-GRAM model in its predictions of atmospheric density at orbital altitudes. Such additional work would take the form of solar flux (F10.7) and diurnal density dependencies. The autonomous controller is a derivative of the proprietary and patented Microcosm Earth-orbiting control methodology which will be implemented on the upcoming Surrey Satellite Technology (SSTL) UoSAT-12 and the NASA EO-1 spacecraft missions.

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1. Introduction

This work points the way to lowering the cost of routine operations at Mars. By implementing autonomous orbit control at Mars costs are lowered due to the possibility of automating data retrieval from the surface. A sample scenario where this technology could be of great benefit is sketched out below. Doubtless, there are other possible arenas where this technology could be of great benefit at Mars.

An orbiter around Mars is equipped with the Mars autonomous orbit control kit. It uses a modified Earth sensor to measure the apparent width of Mars and hence its altitude above the surface and the direction to Mars in spacecraft body coordinates. It uses a star sensor to provide information on its orientation with respect to the inertial frame. Coupling ephemeris data with the Earth/Mars data and the star tracker data one can solve for the position of the spacecraft with respect to Mars. A similar technique was successfully developed and demonstrated by Microcosm on the USAF mission TAOS in 1994. Positional accuracies of around the 1 km mark were achieved with this experiment [1, 10].

The orbiter has two missions; the mapping of Mars and the relay of data from surface stations back to Earth. These missions entail a Mars-centric navigational awareness for orbit control and an awareness of the relative geometry of the Mars-Earth link for relay back to Earth. Both missions could benefit greatly in terms of accuracy and ground track repeatability if a technology that could accurately autonomously maintain the orbiter's orbit essentially indefinitely were available to the mission.

Mapping of repeat targets could be done autonomously. Pre-programmed sequences of data gathering, perhaps including pre-planned orbit changes, could be used to maximize science return. Instead of 'fixing' an orbiter's orbit after the ground team has detected that it has gone a little astray from the target orbit, the autonomous system could modify the orbit on an orbit-to-orbit basis, thus maintaining much higher average orbital accuracy.

Surface stations could save power by relaying data to the orbiter and not back to Earth. This situation would only work if the ground pass of the orbiter could be predicted well in advance, that is potentially months if not years in advance. Therefore, in the extreme case, truly automated small stations could be produced with no downlink capability whatsoever, pre-programmed to send data at specific intervals. These stations would be analogous to the currently planned DS2 penetrator missions, or the Galileo and Huygens probes, except that they would have solar cells for long-term activity. Taken as such the stations could be spread around regions of interest, taking data autonomously, and relaying it up to the waiting relay station which would appear in the station's sky at the pre-programmed time. This scenario pre-supposes, of course, that the orbiter has successfully established an autonomously maintained orbit prior to the small surface stations launch date.

The DSN's resources could then best be utilized gathering data dumps from the orbiter and not simultaneously solving for the orbit. The DSN and other similar navigation organizations' resources would then be utilized at non-routine operations in situations where man-in-the-loop is useful – anomalous situations and deep space trajectory monitoring, planning and optimization.

Taken together, the benefits above are items which could be done now using today's labor-intensive interplanetary mission operations. This technology opens the way to remove the 'drudgery' from such operations while bringing more responsive orbit control than is currently available as orbits can be corrected as often as once per revolution.

1.1 Modifications to HPOP and constructing the Environment Models

Several modifications to Microcosm's commercial High Precision Orbit Propagator (HPOP) were necessary so as to enable the propagation of orbits about Mars. Some of these modifications are detailed below:

For Mars' attitude, the right ascension (α) and declination (δ) of the Martian north pole and the longitude of the Martian prime meridian (W) are computed using the expressions given in [3].

The positions of the standard solar system bodies are determined by evaluating the U. S. Naval Observatory’s compressed ephemeris, which is derived from the Jet Propulsion Laboratory’s DE200 ephemeris. [8, 5]

A third-body point-mass gravitational model and a solar radiation pressure model were incorporated. The acceleration caused by the Martian gravitational field is computed as shown in Long [7], but modified to use normalized instead of unnormalized gravity model coefficients. The acceleration caused by third-body point-mass gravity fields and by solar radiation pressure is also computed as shown in Long.

1.2 Atmospheric Drag Model

The acceleration caused by atmospheric drag is given by:

$$\bar{a} = -\frac{C_D A}{M}\frac{\rho}{2}\left|\bar{v}-\bar{v}_A\right|\left(\bar{v}-\bar{v}_A\right)$$

where:

$\bar{r}$ = position of spacecraft
$\bar{v}$ = velocity of spacecraft
$\bar{a}$ = acceleration of spacecraft
C_D = coefficient of drag of spacecraft
A = cross-sectional area of spacecraft perpendicular to velocity vector
M = mass of spacecraft
ρ = density of atmosphere
$\bar{v}_A$ = velocity of atmosphere

The density and velocity of the atmosphere will in general depend on certain other parameters, which will be denoted here by:

R = equatorial radius of central body
$\bar{\omega}$ = angular velocity of central body

1.3 Atmosphere Density Model

The atmospheric density is given by:

$$\rho = \rho_0\, e^{\frac{h_0-h}{s}}\left(\frac{R+h_0}{R+h}\right)^2$$

where

h = height of spacecraft above reference ellipsoid of central body
h_0 = reference height of atmosphere model
s = scale height of atmosphere model
ρ_0 = reference density of atmosphere model

The user is required to supply the last three parameters as input.

1.4 Mars Environmental Model

Specific characteristics of the Mars model used in the simulation effort are given below:

Mars gravity model used:	50 × 50 Mars Gravity Model (GMM-1) available from the GSFC Geodesy Branch
Atmospheric model:	Exponential scale height model used based on Mars-GRAM results for the following data:
Assumptions:	No dust storms; F10.7 @ 1 AU = 150 x 10^{-22} Wm^{-2} Hz^{-1}; Date and time: 1/1/2001 UT = 8:00

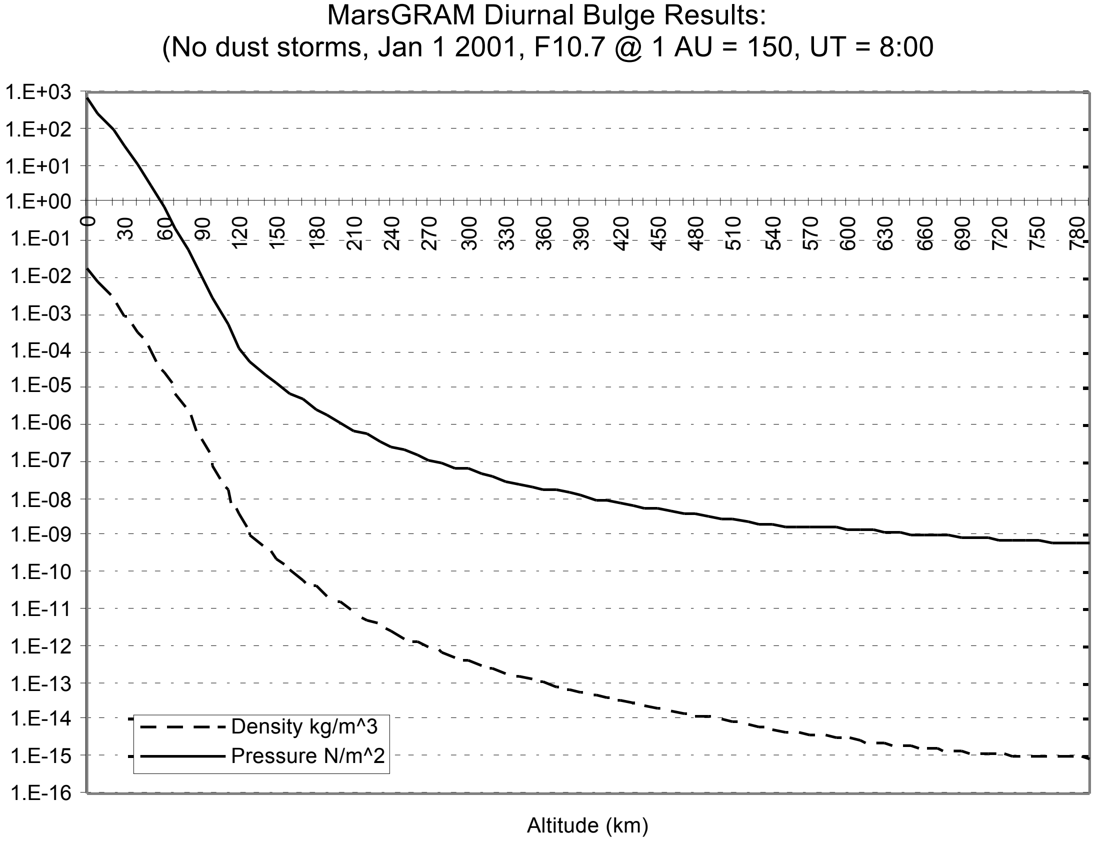

Figure 1 Mars Atmosphere Results from Mars-GRAM

The results from the Mars-GRAM model were used in the atmospheric modeling function in the environmental model in that the reference density at 250 km and the scale height at 250 km were calculated. This information is a good average approximation, of course, to the Martian atmosphere's real behavior over any altitude range; for example, the model used in the simulation lacks diurnal behavior. However, by utilizing a 'worst case' density, that is within the center of the diurnal bulge in the atmosphere, for a moderately high F10.7 value, then a simplified exponential decay model has a certain amount of credibility. Indeed, the whole point of a Martian orbit controller is to intimately maintain the spacecraft's altitude so that a decay in atmospheric density should never be experienced. This naturally assumes the controller works as designed.

1.5 Creation of a Mars Orbit Controller

The creation of a Mars Orbit Controller owes greatly to Microcosm's previous work in support of USAF's Phillips Laboratory-funded work on Earth-orbiting autonomous orbit control and constellation control [2, 6, 12]. From that initial work the adaptation to a Mars setting is more a case of adapting the environmental model than changing the basic structure or philosophy of the orbit controller. Obviously, the sensing of such an orbital situation will present its own very real challenges but these are not viewed as overly burdensome.

The Microcosm orbit control methodology is simple in its application, yet provides excellent results in terms of fuel consumption and accuracy of the maintained orbit. The measurement used is the precise timing of a reference plane crossing which usually is chosen as the Earth's equator. Deviations from an expected result are the error signal that the controller module works with. This signal is further filtered and massaged so as to produce the excellent results seen to date. A similar methodology is employed on Mars.

Clear and obvious changes to the Earth orbiter case include the measurement apparatus which produces the timing data for the control module to work with. Other changes would include a greater appreciation of the relatively large J2 term on Mars over that of the Earth; the density of the upper Martian atmosphere as compared to the Earth's – the atmospheric density at 250 km altitude on Mars is roughly equivalent to the density to be found at 250 km on Earth; the relatively larger gravity anomaly size which shows up as a tesseral superposition of daily sinusoidal terms in the evolution of the spacecraft's period; and the lower orbital velocities.

Despite these changes from the Earth-orbiting case, the Martian environment is generally very similar to that of an Earth orbit in an orbit control sense and so allowed a rapid transitioning of the Microcosm Earth orbiting orbit controller to the Martian case.

1.6 Results

A 250 km near circular, 93 degree inclination orbit was chosen as the test case for the Mars controller. This orbit could be a typical sun-synchronous orbit about Mars. Initial runs were made to determine the exact period of a hypothetical drag free satellite. The period was determined by measuring the time of the ascending node over several months, hence averaging out tesseral terms in the Martian gravity field. This orbit period is then used as the reference input period to the controller.

When the orbit controller is activated, and appropriate gains chosen for feedback to the controller, then the orbit is stabilized against the atmospheric drag, and the periapsis rotation. Figure 2 shows the time late at the ascending node for a six month simulation. The time late is defined as the difference between the actual time of the ascending node, and the predicted time based on the reference input. In essence, the remaining error is an orbital phase error; multiplying the time late by the orbital velocity gives an idea of the phase error at the equator.

Due the relatively large equatorial bulge in the Martian gravity field – that is, the J2 term – orbits with even small eccentricities have a sizable rotation of the argument of periapsis. This rotation will cause an oscillation in the time of the ascending node unless it is actively controlled. For the test case this oscillation had a period of about 60 days, and a peak-to-peak cumulative magnitude of over 50 s. Not only does the orbit controller have to contend with the atmospheric drag, but also with this periapsis rotation. This periapsis rotation causes the large anomalous transients seen in the time late at the ascending node in Figure 2 since the descending node's time late is essentially uncontrolled.

Examining the time late at the descending node, Figure 3, one finds the tell-tale signature of an eccentric orbit in a non-frozen condition [11]. The next stage of orbit control is to actively move the orbit to frozen conditions, i. e., a combination of setting the argument of perigee to 90° or 270° and maintaining the orbit's altitude, inclination and most importantly, its eccentricity to pre-defined values. This control was done using Microcosm's proprietary algorithms.

These algorithms were active in the simulation results shown and are responsible for the slow reduction in the amplitude of time late at the descending node oscillation, but are overwhelmed by the 'distance' that these orbital elements are in eccentricity versus argument of perigee (e vs. ω) phase space from frozen conditions. Clearly, results would be much more compelling for an orbit that was initially close to the frozen orbit regime, as has been found with Earth analogues. In this case, unfortunately, time and lack of resources precluded a search for better initial conditions.

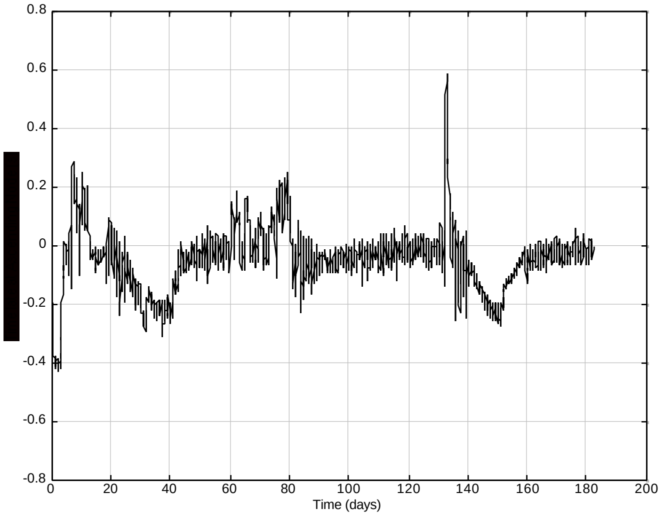

Figure 2 Mars Orbit Controller Results – Time Late at Ascending Node for 6 months

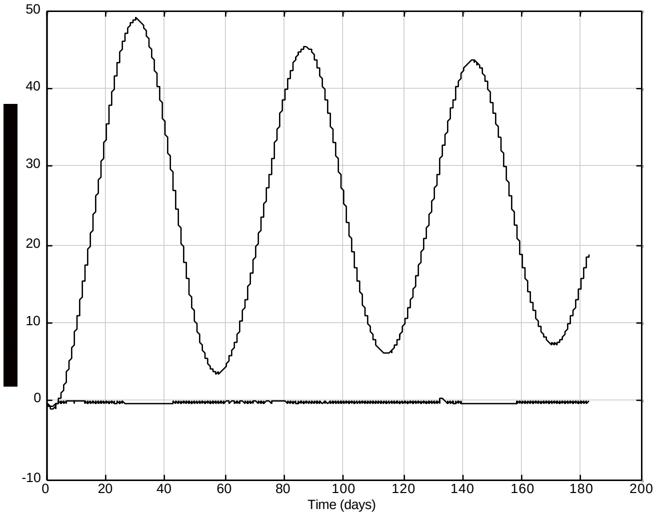

Figure 3 Time Late in seconds at the Ascending and Descending Nodes (lower and upper traces respectively). See text for explanation.

Due to drag and the periapsis rotation, the time late of the ascending node oscillates about in an apparently chaotic manner despite being controlled. This is caused by the fact that the controller is being largely denied the opportunity to *only* control period reduction due to atmospheric drag and instead contends with the large oscillations in the figure of the orbit caused by the rapid perigee motion as vividly depicted by the motion of the time late at the descending node.

Figure 4 shows the Δv commanded by the thruster over the course of the 1 year (1 Earth year) simulation. The total ΔV used during the six month simulation was 15.3 m/s for a total of 2351 orbits, or an average ΔV per orbit of 6.51 mm/s. Note that there were 888 burns commanded; the largest being 2.6 cm/s, the average burn magnitude being 1.7 cm/s, and the smallest being 0.7 cm/s.

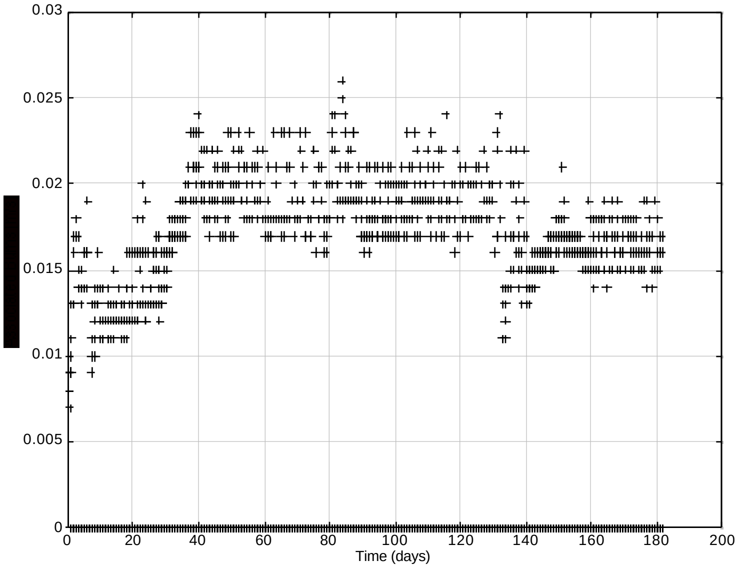

Figure 4 Δv Applied During Six Months of Operations for an Autonomously Controlled Low Mars Orbiter (@250km altitude)

2. Conclusion

The initial investigation of applying Earth-orbiting autonomous orbit control methodology as developed by Microcosm to conditions at Mars has shown that the approach is valid [4]. Significant additional work remains to be done to bring the Mars-based work to a par with the orbit controllers currently under development at Microcosm. Especially significant additional work would involve introducing a more realistic Martian atmospheric model into the environment model, the study of frozen orbit conditions at Mars, and the extension of some of the more advanced control features of the Microcosm Earth-orbiting orbit controller to the Mars case. Despite these deficiencies the prospect of long-term sub-quarter second control in the in-track direction would seem to be within reach. Once achieved, the benefits to the long-term remote exploration of Mars seem to be worth further investigation.

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