Formation Flying Mission for the UW Dawgstar Satellite[1]

Mark E. Campbell and Thomas Schetter
Department of Aeronautics and Astronautics
University of Washington
Box 352400
Seattle WA 98195-2400
206-543-6725
mcamp@aa.washington.edu, schetter@u.washington.edu

Abstract— An overview of a small satellite (< 15 kg) being designed and built by the University of Washington for multiple small satellite formation flying is presented. The Dawgstar nanosatellite is one of three satellites being built for a three satellite formation experiment termed ION-F, and is unique in its propulsive capability. The satellites will also utilize an integrated GPS/cross-link system to allow fast and accurate update of relative satellite positions. The three satellites are each a part of the AFRL/DARPA/NASA University Nanosatellite program, which addresses building unique small satellites and developing coordination experiments for space. The satellites are being designed for a Space Shuttle launch in January 2002.

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1. INTRODUCTION

The University of Washington (UW) Dawgstar satellite is a part of the AFRL/DARPA/NASA Nanosatellite program, and is designed with several mission objectives, including ionospheric measurements and formation flight and management. The UW Dawgstar, shown in Figure 1, is unique in its small size and full attitude and position control capability. This is a result of the design and integration of miniaturized pulsed plasma thrusters [1],[2]. The interest in formation design and management has peaked recently, but on-orbit demonstrations are still in the future. This paper describes the propulsion subsystem and formation flying mission for the UW Dawgstar, one third of the ION-F constellation.

The UW is teamed with Utah State (USU) and Virginia Tech (VT) in the Ionospheric Observation Nanosatellite Formation (ION-F) to design and build a constellation of three satellites. The teams are designing to a space shuttle in Jan ’02. Each university is building a satellite, while the team is collaborating on the science and formation flying missions, particularly subsystems such as inter-satellite communications. The UW Dawgstar is unique in this constellation because of its propulsive capability, supplied by eight pulsed plasma thrusters.

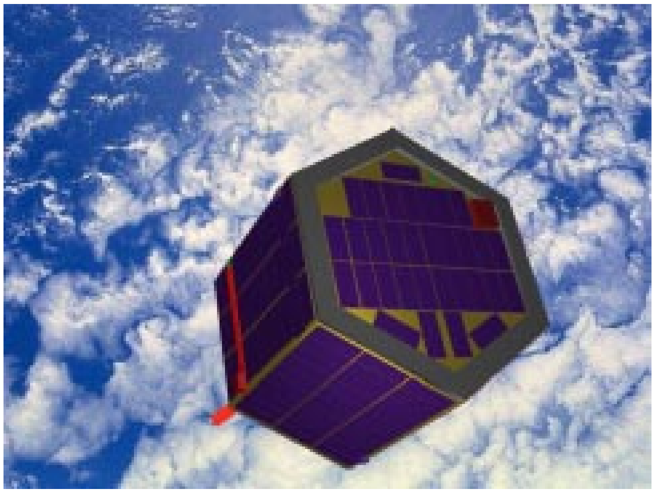

Figure 1: The UW Dawgstar Nanosatellite.

This paper describe the propulsive capability of the UW Dawgstar satellite, along with the nominal mission plan for formation flying. Then, algorithms for formation keeping and maneuvering are developed, including minimum fuel maneuvers, linear programming, and logic based LQR controllers. Several simulations of the UW Dawgstar formation flying mission are presented.

2. ION-F CONSTELLATION AND MISSION

The ION-F team of USU, UW, and VT will collaborate and focus on distributed ionospheric science and distributed multi-satellite control. ION-F focuses on mission objectives that would benefit TechSat21 and future Air Force and NASA missions. Although coordination between the universities is a challenge because of their geographic locations, it is currently successful because of several techniques, including on-location meetings, tele-conferencing, email and the Internet.

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[1] 0-7803-5846-5/00/$10.00 © 2000 IEEE

The ION-F constellation will address the following objectives and research issues:

- Basic research mission of investigating global ionospheric effects which affect the performance of space based radars, and other distributed satellite measurements
- Formation flying and local communication in a constellation of three satellites.
- Baseline potential new technologies including microthrusters, gimbaling magnetic attitude control, an advanced tether system, and an internet based operations center.
- Bring a unique, hands-on space experience to graduate and undergraduate students in many engineering disciplines.

From NASA Goddard [4], the following definitions occur: A constellation is two or more spacecraft in similar orbits with no active control by either to maintain a relative position. Formation flying is two or more spacecraft that use an active control scheme to maintain the relative positions of the spacecraft. The ION-F constellation will be a formation flying mission because the UW will utilize small pulsed plasma thrusters for active control, USU will utilize differential drag, and VT will use a HAN based warm gas propulsion system.

The objective of the ionospheric science mission is to understand the ionospheric density structures that can impose large amplitude and phase fluctuations on radio waves passing through the ionosphere. The constellation provides a unique opportunity to answer questions about ionospheric disturbances that can not be addressed any other way. A single satellite can only provided very limited information on the dimensions and evolutionary time scales of the ionospheric disturbances it flies through because a full orbit (92 minutes) must occur between observations. In general the situation is even worse than this because only truly zero inclination equatorial satellites have a good possibility of measuring the same region twice due to the co-rotation of the ionosphere with the Earth. This science investigation contributes to the TechSat21 basic research mission of investigating global ionospheric effects which affect the performance of space based radars. It also addresses broader Air Force interests in ionospheric effects on navigation an communication links.

The ION-F constellation will make the first global multi-satellite electron density measurements in the ionosphere, using a combination of a DC probe, plasma impedance probe, and GPS scintillation experiments.

3. DAWGSTAR SUBSYSTEMS AND COMPONENTS

This section summarizes the components used in the formation flying mission, namely the propulsion system and cross-link. The other subsystems are briefly described as well. For a more complete summary of the Dawgstar design, please refer to Ref. [3].

The UW Dawgstar structure is a hexagonal prism, 12.625 inches high, 9 inches on each side, and 18 inches across at its largest diameter. The structure consists of two hexagonal base plates and six side trusses. The primary load-bearing structure of each hexagonal base plate is an isogrid of Aluminum 6061-T651, with thin graphite/epoxy (Gr/E) face sheets fastened to the exterior surface.

Attitude determination will be done using a combination of a three axis magnetometer, three axis gyro, and four digital CMOS cameras for horizon and sun sensing. The magnetometer must be timed with the propulsion system because the PPT’s generate a large magnetic field, albeit for a very short duration. The cameras are experimental in nature, and are to be used as the back-up system.

The power is supplied by strings of 11 high efficiency solar cells to give a 22 V bus, and NiCd batteries. DC-DC converters are used for those components at 5 V and 12 V.

The L3 Communications T-400 transmitter is used for the downlink. This S-band frequency agile transmitter has been used for tactical video and telemetry applications, and meets IRIG standards. The L3 Communications CAR-915A receiver is used for the uplink receiver. This L-band receiver has crystal frequency control. The communication downlink uses one patch antenna, while the crosslink and uplink receiver antennas are monopole tape designs. Although only USU and VT will have ground station/satellite communications, an internet based operations center will enable each university to control its satellite (and constellation) from its own remote location.

The flight computer is an Onset TattleTale 8, with a Motorola 68332 processor. The VxWorks operating system will be used.

The Applied Physics Lab (APL) at Johns Hopkins University is currently developing an integrated GPS/cross-link system for ION-F through a grant by NASA Goddard Space Flight Center (GSFC). Preliminary specifications of this system include 450 MHz frequency, 200 mW transmit power, 2 kbps data rate, monopole tape antenna, and mass of 500 g. The system allows multiple receive frequencies, thus allowing the multiple satellites to communicate at the same time. The GPS receiver is integrated into the system, and adds an additional 200 g and 1.85 W. Orbit determination software will allow the accuracy of the relative satellite distances to be on the order of 10 m.

The thrusters are miniature versions of the traditional PPT thruster, to be flown on the EO-1 mission [1]. They are being designed in collaboration with Primex Aerospace Company, through a grant with the Washington Technology Center. The work attempts to reduce the mass and power of the propulsion system by 1) using ceramic capacitors, instead of oil filled capacitors, 2) using high voltage switches (~500V) to charge only the intended capacitor, and 3) to move, reduce, or remove the igniter, which selects and activates the correct thruster. A prototype of one thruster is shown in Figure 2, while a summary of the characteristics of the thruster system are given in Table 1. These specifications have since been verified experimentally; for more information on this and the entire Dawgstar propulsion system, please refer to Ref. [3].

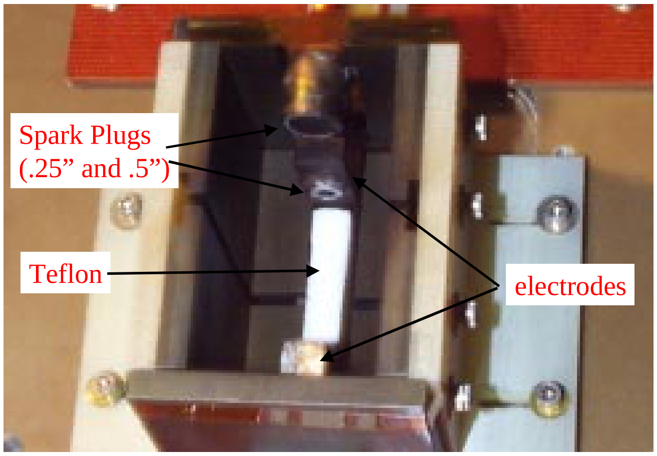

Figure 2: A prototype set-up of one thruster for the Dawgstar satellite.

Table 1: Summary for the PPT and μ-PPT.

	PPT	μPPT
Satellite Mass (kg)	100 – 5,000	5 – 100
Impulse Bit – IBIT (μNs)	700	65
Specific Impulse – ISP (sec)	1150	400
Energy – E (J)	50	5
Mass – m (kg)	4	1
Thrust – T (mN)	.7	0.07

The UW Dawgstar will utilize only eight thrusters for five-axis control in order to save mass. All six degrees of freedom are controllable, however, through coupling in the orbital dynamics. The system will contain four clusters of two thrusters each, with one capacitor per pair. One power processing unit with high voltage switches will power the system.

Figure 3 shows the locations of the thruster pairs. Through the use of a 45 deg angle in the fuel bar/electrode plane, five degrees of freedom can be controlled directly. Referring to the numbering in Figure 3, direct control of five degrees of freedom is as follows:

- X: 2,3 and 6,7
- Y: 1,8 and 4,5
- θ_X : 1,4 and 5,8
- θ_Y : 2,7 and 3,6
- θ_Z : 1,3,5,7 and 2,4,6,8

Note that four thrust combinations require two thrusters to fire at once. Given two thrusters firing at 1 Hz, 13 W of power is required, which is the maximum power allotted to the propulsion subsystem.

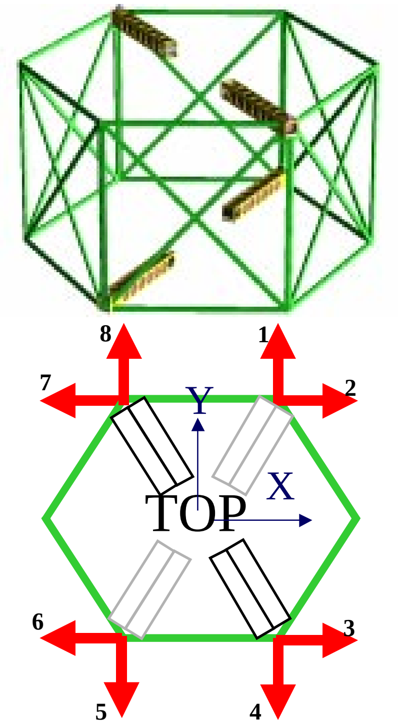

Figure 3: Locations of the eight thrusters for Dawgstar.

Much of the formation flying analysis to date is based on disturbance rejection from drag difference. Figure 4 shows the drag model for the Dawgstar satellite in Jan-Apr 2002, along with the maximum positional thrust in the X-direction, given by two thrusters. Note that the lifetime of the satellite is approximately three months. In addition, if the Dawgstar is to make it’s four month lifetime requirement, it must make-up drag at least by the end of the second month, which is when the absolute drag of the satellite counteracts the maximum thrust.

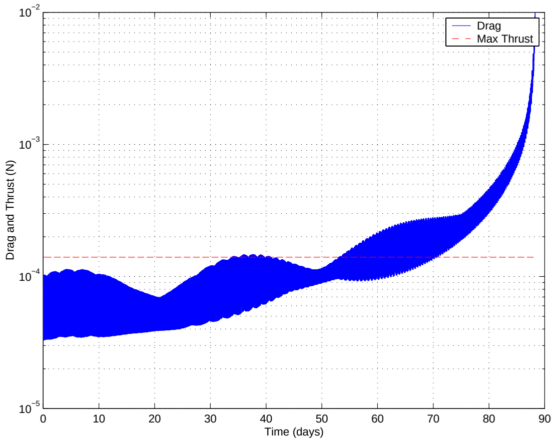

Figure 4: Drag versus time of the mission, with the largest producable thrust from two PPT thrusters.

Based on this analysis, the formation flying mission will only be two months long. Using this result, Dawgstar will have a two phased mission sequence: Phase I for formation flying and ionospheric science, and Phase II for drag make-up and ionospheric science. Table 2 shows a summary of the total Delta V required for the Dawgstar mission. The attitude control calculations are based on CP-CG = 2 cm, and the full drag model for 2002. Formation keeping is based on USU-UW differential drag, and formation maneuvering is based on full 1 Hz thrust (min time). Orbit maintenance is based on full drag make-up, which is equivalent to the thrust from two PPT's firing at 1 Hz.

Table 2: Total Delta V required for the Dawgstar mission.

	Phase I		Phase II	
	ΔV (m/s)	% Time	ΔV (m/s)	% Time
Attitude Control	3.4	100	6.5	100
Formation Keeping	13.8	90	n/a	n/a
Formation Maneuvering	4.8	10	n/a	n/a
Orbit Maintenance	n/a	n/a	38.5	0
Total	22.0		45.0	

4. FORMATION FLYING MISSION

Autonomous formation flying using satellite cross-links has not been accomplished in space. Even the EO-1/Landsat constellation to be flown in 2000 will use ground relay stations for formation flying [4]. Because of the complexity and challenge of formation flying, the goals of the ION-F mission are quite simple: 1) demonstrate inter-satellite communications; 2) demonstrate autonomous formation maneuvering with no ground communication except for higher level commands; 3) demonstrate autonomous formation keeping with no ground communication except for higher level commands. Notice that no level of precision has been specified, as only the demonstration of these technologies is the objective; all additional experiments are considered above the basic mission goals.

The formation flying mission for the UW Dawgstar will consist of several phases, flying in formation with either USU or VT or both. After deployment and initial checkout of satellite subsystems such as the propulsion and cross-link, the following mission phases will occur:

1) drift to a separation of less than 1-2 km within a leader follower arrangement – while system checkouts occur
2) formation maneuvering to approximately 2-3 km
3) two-satellite formation maneuvering and keeping experiments for several weeks at satellite separation distance of 2-3 km
4) formation maneuvering to the same ground track with ~ 0.25 sec separation, and return to leader follower;
5) formation maneuver out to approximately 10-20 km and keep formation
6) More complex formation flying technologies will be examined including three satellite maneuvers with an exchange of command data, formation pointing.

The two formations to be attempted are shown in Figure 5. The leader-follower formation is exactly as the name implies: same orbital parameters, but at different times. The same ground track formation, termed "ideal" by NASA Goddard [4], is one in which two or more satellites have identical ground tracks.

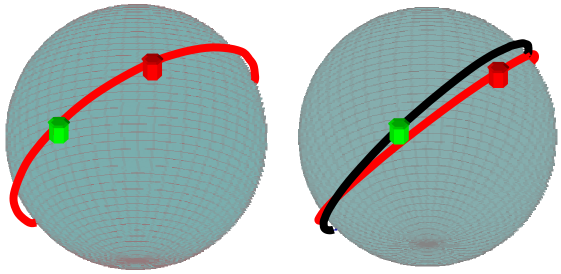
Leader-Follower
Same Ground Track

Figure 5: Two formations to be attempted by ION-F.

Examining the same ground track formation more closely, consider Figure 6. Shown are two satellites as they cross the equator at slightly different times (1,2,3). In the upper left, the first satellite crosses the equator (1) and then moves on (2,3). In the lower right, the second satellite is lagging behind (1), but within a small amount of time, it too crosses the equator (3). The Earth, meanwhile, is rotating (center, between the satellites). Note that over the small amount of time it takes the second satellite to cross the equator, the Earth exactly rotates such that the two satellites fly over the same point on the surface of the Earth.

The Same Ground Track formation can be simplified to a change in time (ΔT) between when the satellites pass over the same point on the Earth. Using the geometry of Figure 6, we see that the relative separations are given as

$$\Delta X = -V_x \Delta t + \omega_E R \Delta t \cos\theta_I$$
$$\Delta Y = \omega_E R \Delta t \sin\theta_I \cos(\omega_E t)$$

where all parameters are known, and the initial condition for $t = 0$ is defined at the equator.

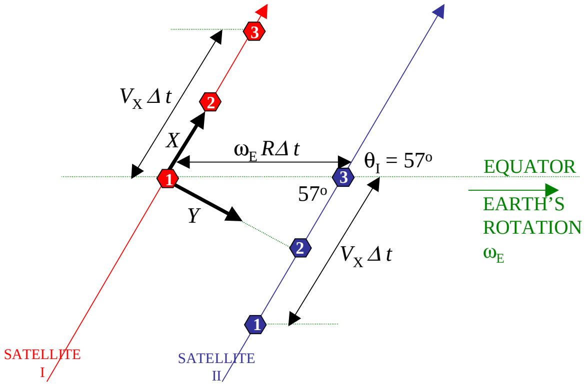

Figure 6: Pictorial description of the same ground track formation as the satellites pass over the equator.

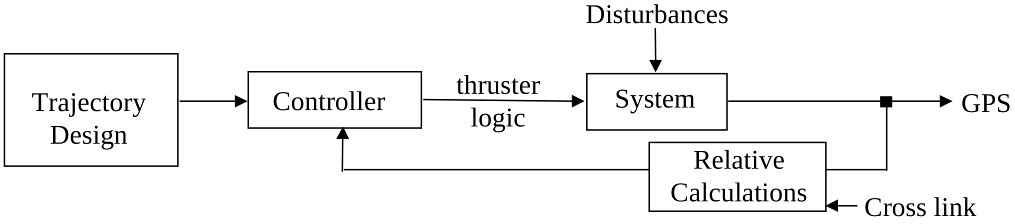

Figure 7: Flow diagram of the formation flying control logic. The attitude control system is not shown

For a ΔT of 0.13 sec,

$$\Delta X = -966\,\mathrm{m}$$
$$\Delta Y = 53\,\mathrm{m}\cos(\omega_E t)$$

the Delta V for this maneuver is approximately 0.06 m/sec. If the separation time is small enough, the Delta V required should be small as well. This is why the same ground track formation will be explored at relative separations on the order of several kilometers.

Formation Control Logic

The block diagram for the Dawgstar formation controller is shown in Figure 7. The flow diagram is set up such that trajectories are designed, and a logic controller reduces the tracking error in a servo manner. This allows the incorporation of both formation keeping and formation maneuvering approaches because the formation keeping is simply a constant trajectory. Note that the GPS and cross-link are integrated; by subtracting the signals, the relative positions can be found. In addition, the relative velocities will be available by using the integrated APL-JHU orbit determination software.

A logic based controller based is used based on the discrete thrust of the PPT's. For instance, the following occurs:

if $u_{\mathrm{ASK}} > 1.4 \cdot 10^{-4}$N, then thrust $1.4 \cdot 10^{-4}$N

Formation maneuvering is based on trajectories and algorithms from the UW, NASA Goddard, USU and VT. The UW has been exploring both simple forms of trajectory designs (step and ramp), and more complex versions (minimum time and minimum fuel based on linear programming). Much of this is based on linear relative dynamics between the two satellites.

Orbital Dynamics for the Leader Follower Formation

To analyze the motions of formation flying satellites (i.e. the motion of one satellite with respect to another), it is useful to treat their local movements as first order perturbations about a reference orbit. The obtained linearized equations, often named as *Clohessy-Wiltshire* equations, are in general quite accurate since the size of the array is very small compared to the size of the reference orbit. If the reference orbit is a circular Kepler orbit, the linearized set of equations are known as the *Hill's equations* [5]. These equations, given in terms of the reference orbital frequency w_n and the relative spacecraft accelerations in the respective directions in the LVLH-coordinate frame[2], are

$$\begin{aligned} \ddot{x} &= 2w_n \dot{z} + f_x \\ \ddot{y} &= -w_n^2 y + f_y \\ \ddot{z} &= -2w_n \dot{x} + 3w_n^2 z + f_z \end{aligned} \qquad (1)$$

The relative acceleration terms *f* account for all non-central force effects, such as drag, thrust, solar pressure etc.

Applied to the Leader Follower formation for the UW and USU nanosats, the Clohessy-Wiltshire equations can be expressed in state space form by

$$\dot{\underline{x}} = A\underline{x} + B\underline{u} + B_d u_d$$

$$\dot{\underline{x}} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2w^2 \\ 0 & -w^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3w^2 & -2w & 0 & 0 \end{bmatrix} \underline{x} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{m} & 0 \\ 0 & \frac{1}{m} \\ 0 & 0 \end{bmatrix} \underline{u} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{m} \\ 0 \\ 0 \end{bmatrix} u_d \qquad (2)$$

where

$$\underline{x} = \begin{bmatrix} x_x & x_y & x_z & \dot{x}_x & \dot{x}_y & \dot{x}_z \end{bmatrix}^T \text{ and } y = \begin{bmatrix} y_x & y_y & y_z \end{bmatrix}^T \qquad (3)$$

is the relative state vector, and $\underline{u}$ is the control vector (assuming that no thrust is needed in the *z*-direction), and u_d represents the resulting drag force in the x-direction.

The Leader Follower formation consists of a relative in-track separation between two spacecraft, which can be expressed as a movement from an initial position

$$\underline{x}_0 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \qquad (4)$$

to a final position

$$\underline{x}_{final} = \begin{bmatrix} x_{reference} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T . \qquad (5)$$

Notice that the in-track separation results only in a change in

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[2] In the LVLH-coordinate frame, the *x*-axis is the velocity direction, the *z*-axis nadir, and *y*-axis is the cross-axis.

the x-direction in the LVLH-frame. Maneuvering into the same ground track formation is similar, but now the Y direction has a cosine component to it.

Linear Programming Techniques

With the benefit of having linearized relative dynamics, the UW has explored the use of a linearized optimization technique. One well understood technique is Linear Programming (LP), which has been applied to formation planning in a similar manner [6],[7]. In an LP, an objective function is optimized, subject to linear equality/inequality constraints, and sign restrictions on variables. The standard form of an LP is given by (Minimization Form)

$$z(x) = \sum_{j=1}^{n} c_j x_j \quad (6)$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i\,,\; i = 1,..,m \quad (7)$$

and

$$x_j \ge 0\,,\; j = 1,..,n\,. \quad (8)$$

where equation (6) is the objective function, (7) are the constraints, and (8) are sign restrictions on the decision variables x_j. In the standard form, all the decision variables must be nonnegative.

The problem formulation for the LP in the case of the Leader Follower Maneuver is to move the spacecraft from an initial position $\underline{x}_0$ given by (4) at time t_0 to a desired final state $\underline{x}_{reference}$ given by (5) at time t_{final} in n time steps. Considering the fuel optimal problem, the decision variables are the control sequence for the time interval $t = t_0,..,t_{final}$, and the objective is to minimize the control input $\underline{u}$ (i.e. thrust) into the system. The constraints are to achieve the final state within a pre-defined error bounds ε at the final time t_{final}, and not to exceed the maximum thrust limit $\underline{u}_{max}$.

The discrete state space Hill's equations (2) can be rewritten as

$$\underline{x}(n+1) = A\underline{x}(n) + B\underline{u}(n) + B_d u_d\,, \quad (9)$$

where it is assumed that the drag forces is not time dependent, i.e. $u_d \equiv u_d(i),\; i = 1,...,n$. In order to express the state $\underline{x}(n)$ explicitly as a function of the former states and the system matrices, a discrete convolution is used and equation (9) can be rewritten as

$$\begin{aligned}\underline{x}(n) = A^n\,\underline{x}(0) + \sum_{i=1}^{n-1} A^{n-(i+1)} B\underline{u}(i)\\ + \sum_{i=1}^{n-1} A^{n-(i+1)} B_d \begin{bmatrix} u_d & 0 & 0 \end{bmatrix}^T\end{aligned} \quad (10)$$

or

$$\begin{aligned}\underline{x}(n) = A^n\,\underline{x}(0) + \begin{bmatrix} A^{n-1}\mathbf{B} & A^{n-2}B & \dots & AB & B \end{bmatrix}\cdot\underline{\tilde{u}}\\ + \sum_{i=1}^{n-1} A^{n-(i+1)} B_d \begin{bmatrix} u_d & 0 & 0 \end{bmatrix}^T\end{aligned} \quad (11)$$

where

$$\underline{\tilde{u}} = \begin{bmatrix} \underline{u}(0)^T & \underline{u}(1)^T & \dots & \underline{u}(n-2)^T & \underline{u}(n-1)^T \end{bmatrix}^T. \quad (12)$$

The standard form of an LP requires all decision variables to be *nonnegative*. In the expressions above, the decision variables $\underline{\tilde{u}}$ are *unrestricted* in sign because the control can be both positive and negative. Therefore one must substitute

$$\begin{aligned}&\underline{\tilde{u}} = \underline{\tilde{u}}^+ - \underline{\tilde{u}}^-,\\ &\underline{\tilde{u}}^+ \ge 0 \qquad ,\\ &\underline{\tilde{u}}^- \ge 0\end{aligned} \quad (13)$$

in order to ensure that all decision variables are nonnegative. Setting $A' = \begin{bmatrix} A^{n-1}B & A^{n-2}B & \dots & AB & B \end{bmatrix}$ and $F_d = \sum_{i=1}^{n-1} A^{n-(i+1)} B_d \begin{bmatrix} u_d & 0 & 0 \end{bmatrix}^T$, the LP can be formulated as

$$\min\; z(x) = \left\| \begin{bmatrix} \underline{\tilde{u}}^+ & \underline{\tilde{u}}^- \end{bmatrix} \right\|_1$$

$$\text{subject to} \begin{cases} \underline{\tilde{u}}^+ \le \underline{u}_{\max} \\ \underline{\tilde{u}}^- \le \underline{u}_{\max} \\ \underline{\tilde{u}}+ \ge 0 \\ \underline{\tilde{u}}^- \ge 0 \\ -A'\underline{\tilde{u}} \le \underline{\varepsilon} + A^n\,\underline{x}_0 - \underline{x}_{reference} + F_d \\ A'\underline{\tilde{u}} \le \underline{\varepsilon} - A^n\,\underline{x}_0 + \underline{x}_{reference} - F_d \end{cases} \quad (14)$$

Note that setting $z(x) = \left\| \underline{\tilde{u}}^+ - \underline{\tilde{u}}^- \right\|_1$ as the objective instead of $z(x) = \left\| \begin{bmatrix} \underline{\tilde{u}}^+ & \underline{\tilde{u}}^- \end{bmatrix} \right\|_1$ would also result in a feasible solution. But the LP in this case will try to force the objective to be in the negative range, such that the decision variables $\underline{\tilde{u}}^-$ are maximized and the decision variables $\underline{\tilde{u}}^+$ are minimized, which is not desirable.

The LP (14) can be simplified, using

$$\hat{A} = \begin{bmatrix} -A' & A' \end{bmatrix}^T$$
$$\underline{\hat{b}} = \begin{bmatrix} \underline{\varepsilon} + A^n \underline{x}_0 - \underline{x}_{reference} + F_d & \underline{\varepsilon} - A^n \underline{x}_0 + \underline{x}_{reference} - F_d \end{bmatrix}^T$$
$$\underline{\hat{u}} = \begin{bmatrix} \underline{\tilde{u}}+ & \underline{\tilde{u}}- \end{bmatrix}^T$$

and then finally be written compactly as

$$\min \; z(x) = \left\| \underline{\hat{u}} \right\|_1$$

$$\begin{cases} \underline{\hat{u}} \le \begin{bmatrix} \underline{u}_{\max} & \underline{u}_{\max} \end{bmatrix}^T \\ \underline{\hat{u}} \ge \underline{0} \\ \hat{A}\underline{\hat{u}} \le \underline{\hat{b}} \end{cases} . \qquad (15)$$

5. SIMULATION RESULTS

Figure 8-10 show several results for simulating the Dawgstar satellite within the ION-F formation flying mission. The results focus on the differential drag between the UW and USU satellites, and no other disturbances.

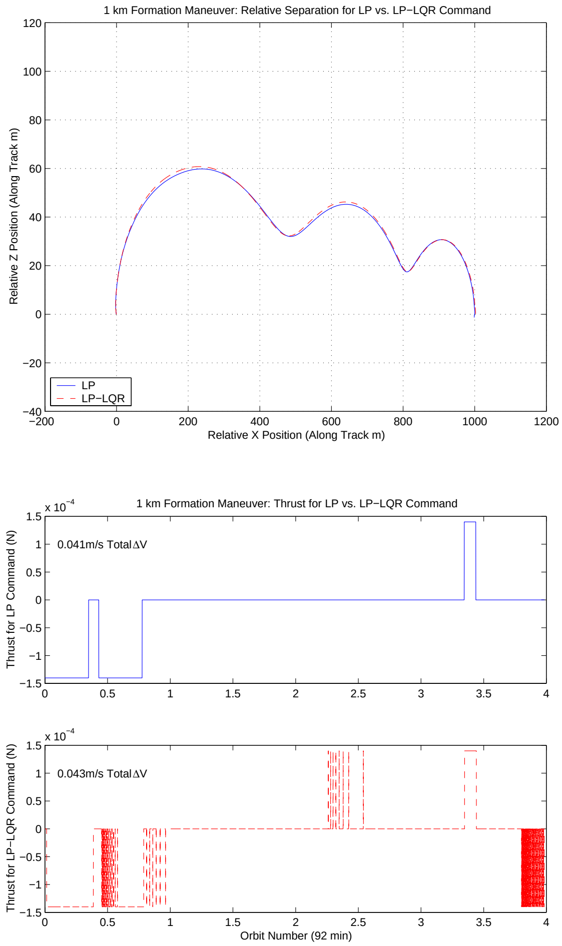

Figure 8: Leader-follower formation maneuver using minimum fuel based LP commands, and combination of LP maneuver and LQR logic for disturbance rejection.

Figure 8 shows the relative X and Z separations, and the thrust for a 1 km leader-follower formation maneuver using minimum fuel based LP commands (generated from the LP and run in open loop), and combination of LP maneuver and LQR logic for disturbance rejection. Notice that the actual trajectories are very similar, and the Delta V difference is quite small. As these other disturbances are added into the simulation, the LP results would be in error because they are essentially open loop, while the LP-LQR results would converge quite nicely as long as the disturbances are relatively small.

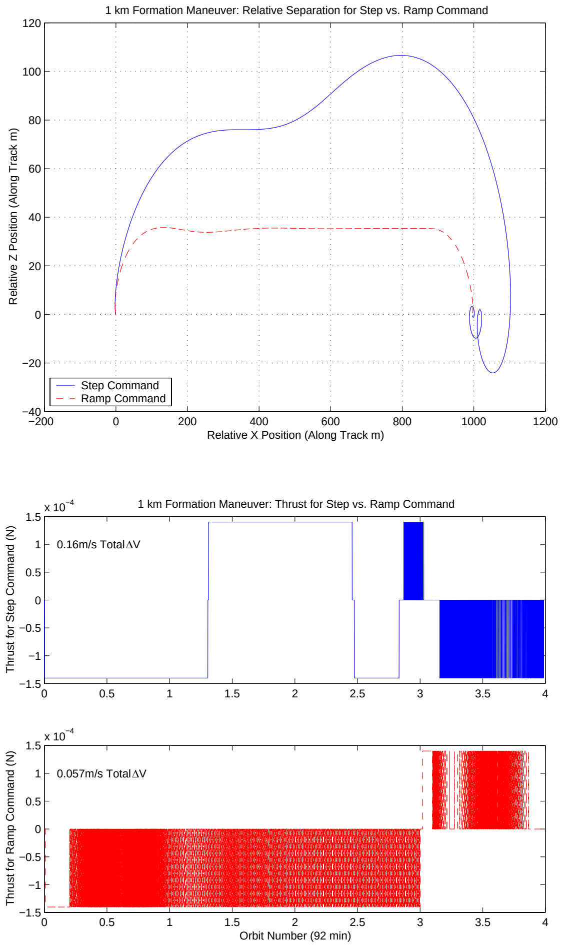

Figure 9: Formation maneuver using a step and ramp commands, and LQR based controller logic for disturbance rejection.

Figure 9 shows the relative X and Z separations, and the thrust for a 1 km leader-follower formation maneuver using step and ramp trajectories, and logic based LQR for disturbance rejection. Notice that Delta V is quite high for the step trajectory – this is because the trajectory is essentially a minimum time problem, as seen by the constant thrust profile in Figure 9. The results for the ramp trajectory are comparable to the LP based results in time, with only a small cost in fuel usage.

Figure 10 shows the relative X, Y, and Z separations, and the thrust for a same ground track formation maneuver. The along track and elevation looks very similar to the previous cases. But, as shown in the bottom of Figure 10, there is now a Y axis thrust component that causes the trajectory to match the given time varying trajectory.

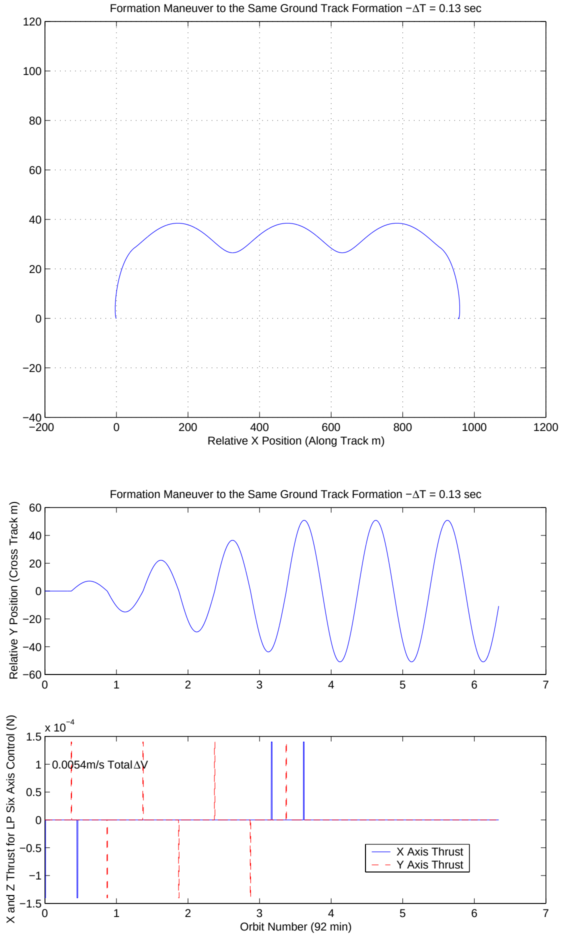

Figure 10: Results of a formation maneuver to the same ground track formation. Notice the Y axis separation is now a function of time.

The final simulation is an LP minimum fuel based leader follower maneuver, similar to that shown in Figure 8. It is compared to a similar maneuver, but now using six-axis control capability. The trajectories are identical to those shown in Figure 8, and are thus not presented. The thrust profiles are shown in Figure 11. Notice that the total Delta V is identical; a result of the fact that the minimum fuel maneuver does not use Z axis thrust. This helps to justify the use of only five of the six axes of thrust within the Dawgstar satellite.

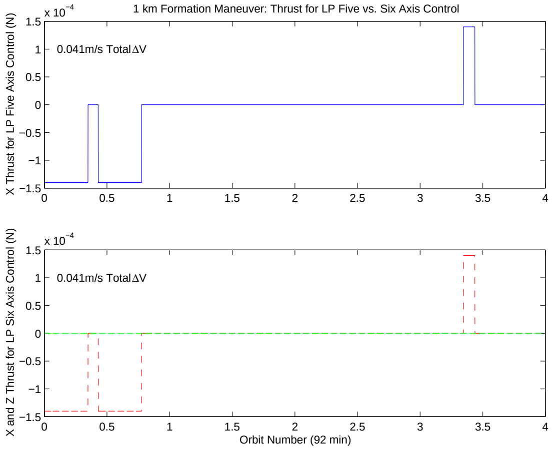

Figure 11: Comparison of five and six axis control for the Dawgstar satellite: Notice that there is no Z thrust required for changes in the X direction.

6. CONCLUSIONS

The propulsion system and formation control mission for the Dawgstar nanosatellite have been presented. The eight PPT's allow direct control of five degrees of freedom, while the sixth is coupled with the orbital dynamics. A logic based LQR controller is used to reject disturbances from a tracking control loop. The trajectories can be generated in several ways, but linear programming techniques work quite well. Simulations show that the formation flying mission is conceptually valid, and the removal of the Z axis thrust is not a large concern.

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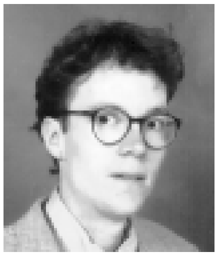
8. BIOGRAPHY

Mark Campbell *is an Assistant Professor in the Department of Aeronautics and Astronautics at the University of Washington. He received his Ph.D. from MIT in 1996, and continued at MIT as a Research Associate/Lecturer. While at MIT, Dr. Campbell developed space based model uncertainties, and designed 250 robust controllers implemented on-orbit for MACE, a dynamics and control laboratory flown on Space Shuttle Endeavour in 1995. Dr. Campbell's current research interests are in multiple satellites and autonomous systems such as aircraft and spacecraft, and actively controlled structures. Dr. Campbell has over 30 publications publications in the areas of dynamics, smart materials, control, and is co-authoring an interdisciplinary book to be published in 2000 by Cambridge University Press titled "High Performance Structures: Dynamics and Control"*



Thomas Schetter *is a Graduate Student in the department of Aeronautics and Astronautics at the University of Washington. He received his Dimploma (B.Sc.) in Mechanical Engineering in 1995 from the University of Stuttgart, Germany and was working from then to August 1998 for the German car manufacturer AUDI AG , Ingolstadt. His responsibilities included the off-line programming and simulation of spot welding and material handling robots. Mr. Schetter was also heavily involved in introducing of a new manufacturing technology for metal bending applications using off-line programmed robots. Mr. Schetter is now pursuing his M. Sc. in Aeronautics and Astronautics at the UW and he is working with Prof. Campbell on formation flying of small satellites, concepts of intelligent satellite teams (ISTs) and autonomous control applied to multiple satellite clusters.*