Mission Design and Trajectory Analysis for Inspection of a Host Spacecraft by a Microsatellite

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Abstract—The trajectory analysis and mission design for inspection of a host spacecraft by a microsatellite is motivated by the current developments in designing and building prototypes of a microsatellite inspector vehicle. A mission in which a host spacecraft is in orbit about Earth is covered in this paper. A toolset has been created, composed of both natural and forced motion trajectories. The toolset evaluates an inspection mission concept based on figures of merit over four primary operational modes: deployment mode, global inspection mode, point inspection mode, and disposal mode. Merit figures investigated include the quality of inspection through resolution, lighting conditions, viewing angles, total inspection coverage, tracking spacecraft constraints and consumables regarding telecommunications, spacecraft power, and fuel expenditure. This paper presents the design of the inspection mission design toolset and summarizes the performance of a baseline inspection mission concept of a host in Earth orbit.

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1. INTRODUCTION

Since the inception of the space age, there have been considerable advancements to the design, reliability, and fault management of a space vehicle. However, to this day, ground operators still lack an inexpensive method of visually observing on-orbit spacecraft operations in real-time. This is a problem that has been amplified with losses such as that of the Space Shuttle, Columbia, which might have been preventable, had it been possible to inspect the surface thoroughly before re-entry.

Macke et al. points out that “inspection” suggests a range of external observations, such as visual inspection for damage or creating field maps of the host vehicle’s RF, magnetic or nuclear emissions [1]. Other potential applications include aiding deployment or monitoring the environment of the host vehicle to provide space situational awareness [2]. Such a vehicle has applicability to an extensive range of host vehicle types – manned and unmanned spacecraft, including commercial communications satellites, scientific satellites, and the deployment of solar sails on sailcrafts. Future space vehicles may include many inspector-like vehicles, throughout the lifetime of their missions, providing on-orbit management when needed.

Due to the improvements in the miniaturization of spacecraft components in recent years, microsatellites on the order of 100 kg and under have become increasingly popular [3]. Lately, there has been interest in a cost-effective, small-mass (< 10 kg), and deployable microsatellite inspector (or microinspector), as a viable solution for visually inspecting a host spacecraft. Much of the published efforts exploring the microsatellite inspector concept have been on developing the spacecraft hardware. An analysis of the feasible trajectories would provide a valuable set of constraints and requirements on the hardware design of a microsatellite inspection vehicle. Therefore, the context of this paper is to analyze trajectories and design a baseline mission concept for the visual inspection of a host spacecraft by a microsatellite inspector. The
actual Guidance, Navigation, and Control (GN&C) of the microinspector are not considered.

The lack of a low-cost method of visually inspecting a spacecraft on-orbit has been an inconvenience to ground operators for decades. Only recently has there been a significant reduction in size and cost to spacecraft components to make the free-flying microsatellite inspector concept realizable. Due to the current developments in designing and building prototypes of a microsatellite inspector, interest has been expressed in designing a mission concept for inspection.

There are two types of missions that affect the dynamics of a microsatellite inspector operation: An orbiting mission (Earth, Mars, or other planet) where gravity plays a large part in orbital dynamics, and deep space in which the effects come primarily from the Sun. The limited mass, power, and fuel for a microsatellite inspector suggest that an analysis be performed on the possible host-relative trajectories to ensure safe proximity operations while using minimal system resources.

The objective of this paper is to analyze the range of natural and forced trajectories that may be utilized to form a mission for a visual inspection vehicle, in the face of various constraints and conditions. Natural motion trajectory analysis will be conducted using the Clohessy-Wiltshire, or CW equations, which proceed from a first-order linearization of the equations of motion [4]. The well-known inclined football trajectory is explored for collision avoidance mitigation. Forced motion will only be used for loitering at some particular relative position. In generating these trajectories, this paper uses simplified avoidance constraints. In Low Earth Orbit (LEO), the effect of atmospheric drag on spacecraft motion cannot be ignored. In the context of relative motion, only the differential drag needs to be considered. The effect of differential drag on the mission design for orbiting cases and the resolution to the problem will be further elaborated in this paper.

A baseline mission concept for an Earth orbiting mission will be presented and simulated based on the trajectory study. The mission design includes the disposal of the microinspector at the end of the inspection mission. Docking will not be considered as an option for the vehicle, and as such, will not be addressed in this paper. In order to rate the quality of the inspection mission, some of the possible figures of merit are discussed. The general spacecraft configuration and requirements for the simulation will be based on current microinspector developments at JPL. In the simulation and results section, this paper will include recommendations for a microinspector mission, mission performance criteria, and general hardware requirements.

In conjunction with JPL, a set of general specifications on the GN&C sensor performance and constraints (field of view, sun angle constraints, resolution, drift rates, etc.) have been determined for this study. The mission simulation for this paper will be loosely based on JPL’s hardware design for a microsatellite inspector, shown in Figure 1. As for the host spacecraft, the hardware specifications will proceed from the Crew Exploration Vehicle (CEV).

![Figure 1: Microspacecraft Hardware Design by JPL.](image)

Presented below are some of the mission and hardware requirements for a microsatellite inspector. The research, examples, and simulations in this paper have been conducted with regards to the following requirements:

- The host spacecraft has the following physical characteristics:
  - Dimension: length = 30 m, diameter = 5 m
  - Mass: 30 t
- The microsatellite inspector has the following hardware, sensor, and actuator requirements for the simulation:
  - Dimension: 8 x 8 x 2 in³
  - Mass: 3 kg
  - Sensors: Single camera (25° angle of view, 512 square pixel array), 2-axis sun sensor, 3-axis inertial measurement unit (IMU), star tracker, and laser range finder
  - Propulsion System: 8 cold-gas thrusters in pairs, each with a maximum thrust of 10 mN. The specific impulse is I_sp = 50 s. The maximum total Δv available for trajectory (translational) and ACS (Attitude Control System) maneuvers is 15 m/s.
  - Battery Power: The total capacity is 45 W·hr. The average power consumption of the microinspector is 14 W.
- Solar Array: Produces 25 W at 0° sun angle.
- Image Requirements and Camera Specifications:
  - Resolution: < 1 cm
  - 10 rows of pixel overlap between consecutive images
  - Pixel smear: < 1 pixel
- Keep-out constraints will be utilized in generating trajectories. A 10 m minimum distance constraint will be imposed in the simulations.

2. MISSION DESIGN STRATEGY

This section highlights the strategies used to create the trajectories of a mission concept for a microsatellite inspector.
Natural Motion

The trajectory development for the microinspector mission concept will be based on the solution to the Clohessy-Wiltshire or CW equations, which are also known as the Hill’s equations. These linearized differential equations describe the relative motion between two satellites that are in near-circular orbits about a planet and within a few kilometers of each other [6]. In Figure 2, the local-vertical rotating coordinate system (LVRCS) that is used for the CW solution is depicted. This coordinate system rotates at the orbital rate, \( \omega \). The position deviations (\( x \), \( y \), and \( z \)) in this coordinate system denote the location of the secondary vehicle in the LVRCS with the target vehicle placed at the origin [5]. The positive \( y \)-axis is lined up with the \( V \)-bar – the velocity vector of the host spacecraft. The positive \( x \)-axis lies along the \( R \)-bar – the radial axis. The orbital position vector is depicted by \( r \).

\[
\mathbf{r}(t) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix} = \begin{bmatrix} X_0 + b \sin(\omega t + \phi) \\ Y_0 - \frac{3}{2} \omega X_0 + 2b \cos(\omega t + \phi) \\ c \sin(\omega t + \psi) \end{bmatrix} + A_1(t) \mathbf{d}
\]

\[
\mathbf{v}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} \frac{b \omega \cos(\omega t + \phi)}{\omega^2} \\ -\frac{3}{2} \omega X_0 - 2b \sin(\omega t + \phi) \\ \omega \cos(\omega t + \psi) \end{bmatrix} + A_2(t) \mathbf{d}
\]

\[
\mathbf{a}(t) = \begin{bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \\ \ddot{z}(t) \end{bmatrix} = \begin{bmatrix} -b \omega^2 \sin(\omega t + \phi) \\ -2b \omega^2 \cos(\omega t + \phi) \\ -c \omega^2 \sin(\omega t + \psi) \end{bmatrix} + A_3(t) \mathbf{d}
\]

where,

\[
\begin{align*}
X_0 &= 4x_0 + 2b \omega \\
\frac{2b \omega}{\omega^2} &= b \cos(\phi) \\
\frac{b \omega}{\omega^2} &= c \sin(\psi)
\end{align*}
\]

\[
\begin{align*}
Y_0 &= y_0 - 2b \omega \\
\frac{2b \omega}{\omega^2} &= b \sin(\phi) \\
\frac{b \omega}{\omega^2} &= c \cos(\psi)
\end{align*}
\]

Equations (1) through (5) are linearized models of the Hill’s equations, \( \phi \) represents the semi-inclination of the ellipse, \( \psi \) is the angle between the major axis of the ellipse and the positive \( x \)-axis, \( \phi \) is the semi-major axis of the ellipse, and \( \psi \) is the semi-minor axis of the ellipse. The matrix \( A(t) \) in Eqn 5 describes the motion of the secondary vehicle with respect to differential accelerations, such as atmospheric drag and thrust, assuming that the forces are modeled as constants. The in-plane position equations in Eqn 1 imply that the state deviations trace out a 2x1 ellipse, with \( b \) as the semiminor axis if \( X_0 \) is zero. The semimajor axis of the ellipse is twice the length of \( b \), hence the name given to the ellipse. In Eqn 4, the quantities \( b \) and \( c \) are parameters that describe the size, and, \( X_0 \) and \( Y_0 \) represent the center of the relative motion. The parameters \( \phi \) and \( \psi \) are

Figure 2: Local-vertical Rotating Coordinate System (LVRCS)

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1 The image of Earth in Figure 2 was adapted from an online source, “3-D view of the Earth”, http://atlas.geo.cornell.edu/people/weldon/earth-3d.gif; accessed 3/27/2006.
phase angles describing where the actual state is located. The values for these parameters can be obtained from the initial conditions, as shown in Eqn 4.

Given the initial position and velocity of the microinspector, the CW solution characterizes the subsequent motion about the host vehicle in the LVRCF. A 2x1 elliptical “orbit” of the microinspector about the host has the same period as the orbital period of the host about the Earth. Fuel would only be expended at the beginning to insert the microinspector into the desired relative trajectory. Hence, it is desirable to exploit this quality of the natural dynamics, and use the CW solution during the mission design process. The operations of the microinspector that arise from an inspection mission will be in close proximity to the host vehicle, which validate the application of this analytic solution. Furthermore, utilizing the CW solution enormously simplifies the simulation of the mission concept, compared to numerically integrating the equations of motion.

The secondary vehicle does not actually “orbit” the host vehicle, but the instantaneous parameters result in an elliptical orbit-like motion. The $-\frac{1}{2}\omega X_0$ term in Eqn 1 explains why the motion is not truly elliptical when $X_0$ is zero. This term accounts for the drift that occurs in the elliptical “orbit”.

**Forced Motion**

It was stated that most visual inspection missions are not considered to be time-critical. However, for those missions that are constrained by time, designing the trajectories based solely on natural motion may not be adequate. It is conceivable that such a mission would be designed to include forced motion maneuvers, in addition to natural motion segments. In essence, for orbiting missions, the forced motion maneuvers are akin to targeting in the presence of disturbances. Given the initial position, $r_i$, final position, $r_f$, and the amount of time to reach the final position, $\Delta t$, the velocity vector to reach $r_f$ in $\Delta t$ can be determined by inverting the CW solution. These targeting equations are similar to the Lambert targeting solution. The CW solution for position can be reformulated to obtain this velocity vector.

$$v_i = \Phi_{r_i, r_0}^{-1}(\Delta t)[r_f - \Phi_{r_f, r_0}(\Delta t)r_i - A_1(\Delta t)d] \tag{6}$$

In practice, the value of $\Delta t$ needs to be chosen with care. Since the algorithm takes the inverse of $\Phi_i(\Delta t)$, this matrix must not be singular or close to singular. This implies that the orbital period, $P$, and integer multiples of $P$ cannot be used as $\Delta t$. In addition, the computed $\Delta v$ may cause the microinspector to collide with the host — another negative aspect of the forced motion method.

**Constraints**

This section introduces some of the up-front constraints that must be considered during the mission design phase. The constraints imposed by the microinspector hardware and mission directly impact the trajectory design for a microsatellite inspection mission.

**Avoidance Constraints**—The key issues associated with close proximity operations about the host are primarily collision avoidance and plume impingement by the microinspector. The microinspector may be required to have a model of the host vehicle residing on board for autonomous trajectory planning. It may also be necessary to have a keep-out constraint that describes a zone about the host spacecraft that cannot be impinged upon. By utilizing the natural 2x1 ellipse trajectory during orbiting missions, the risk of collision and plume impingement can be minimized. This type of motion is predictable and well behaved, and thus is suitable for a microinspector mission. Generalized avoidance constraints can be incorporated into the natural motion trajectory designs.

A symmetrical, rectangular box constraint is a simple, yet effective keep-out zone that can be applied. Such a constraint may be defined by the mission planner and would account for collision avoidance, as well as plume impingement.

For the cylindrical host model, some other keep-out zones that can be defined are a sphere, elliptical sphere, or a cylinder. The simulation in this paper will employ the box avoidance constraint, but can be extended to use these other keep-out zones.

**Fuel Constraints**—A micropropulsion system that a microsatellite would operate on has limited fuel. There is very little margin to recover from mistakes that may danger the host vehicle. During the mission simulation in this paper, the $\Delta v$ expended for each maneuver (translational and rotational) will be accumulated and used to rate the mission concept. The use of the CW solution to design trajectories will minimize the fuel expenditure for the mission, once again emphasizing the advantages of utilizing this analytic solution.

**Time Constraints**—Since a visual inspection by a microinspector is not considered to be time-critical, the CW solution is used in this paper to design the appropriate trajectories, without resorting to trajectory optimization methods. However, if ground operators foresee a need for time-minimal maneuvers, the forced motion method of generating trajectories can be employed with fuel penalty.

**Camera and Image Constraints**—The camera specifications and image requirements directly affect the trajectory planning process. For example, a maximum resolution for an image constrains the allowable distance of the microinspector from the host vehicle. The desired pixel smear determines the maximum velocity of the microinspector relative to the host. Also, there should be some pixel overlap between the images, to make sure the host surface is completely covered. It is apparent that these constraints and specifications must be accounted for in the mission planning.
Lighting—In order to obtain images of the host, present day methods require sufficient illumination. Utilizing the natural light from the Sun is preferred, since an artificial source of light would use up valuable energy resources. For an orbiting host mission, suitable lighting becomes a problem when the host vehicle is in the planet’s shadow. Also, when the microinspector is in line of sight with the Sun, the sun angle\(^2\) becomes an issue when there are solar cells aboard, because of the rate of power consumption versus the rate of recharging. The microinspector may be required to reorient itself every so often throughout its mission, such that the solar arrays face the Sun. The frequency of these maneuvers and the impact on the overall mission must be evaluated when examining the possible mission concepts.

Two simplified examples of Sun position vectors are presented here to illustrate the problems associated with lighting conditions. In both examples, the host vehicle is in a circular orbit about Earth, and rotating at the orbital rate, \(\omega\), in the inertial reference frame. The inertial Sun direction is assumed fixed, since the Sun motion is minimal during the time frame of an inspection mission. For the shadow analysis, the light rays from the Sun are assumed to be parallel, and the shadow forms a cylinder behind the Earth.

Example 1, shown in Figure 3, portrays a case in which the Sun lies in the host vehicle orbital plane. For a portion of the host’s orbit, the host will be in Earth’s shadow. During this time, no part of the host’s surface will be illuminated by sunlight and consequently, the microinspector cannot take images of the host vehicle without an artificial light source. For a circular orbit that is 500 km above the surface of the Earth, the orbital period is about 95 minutes. If the Sun vector is oriented as in Example 1, the host vehicle will be in Earth’s shadow for about 36 minutes, nearly a third of the time.

Example 2, shown in Figure 4, is a case in which the Sun is perpendicular to the orbit plane. In this case, the host vehicle always has line of sight to the Sun and is continuously illuminated. It should be pointed out that if not spinning, only one side of the host’s surface is lit throughout the orbit. Therefore, the microinspector will not be able to take images of the opposite side using natural light. The view in Figure 4 is from the orbit’s edge.

![Figure 4: Lighting Example 2: The Sun is perpendicular to the host vehicle orbit plane. The view is edge on.](image)

In order to take an image of a particular segment of the host vehicle’s surface, the segment must be sunlit and in the view of the camera on board the microinspector as shown in Figure 5.

![Figure 5: Lighting Condition and Camera View for Image Taking](image)

Using natural motion, the microinspector can be placed in a relative closed orbit about the host, giving ample opportunities for viewing many parts of the host’s surface. In a relative closed orbit or another type of natural motion, the attitude of the microinspector must be directed and controlled so that the camera’s boresight vector is pointed properly at the host. Continuous control of the vehicle’s attitude can take up a large percentage of the fuel budget. However, there are some aspects of the relative closed orbits that may be utilized to acquire excellent coverage of the host vehicle, while minimizing fuel usage due to attitude control.

The next case demonstrates how images of the host can be captured when utilizing natural relative motion to design trajectories for the microinspector mission concept. Figure 6a depicts the microinspector traveling in an out-of-plane 2×1 stationary ellipse about the host vehicle in the relative frame of reference. The geocentric Sun direction is in the host’s orbital plane. The host vehicle is rotating in a circular orbit about Earth, and rotating at the orbital rate, \(\omega\), in the inertial reference frame as in Figure 3, maintaining a local-vertical

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\(^2\)For the definition of sun angle used in this paper, refer to Figure 7
local-horizontal (LVLH) attitude. If the inclined 2×1 ellipse is nearly circular in the x-z plane as in this case, then a practical pointing solution is to have the camera’s boresight vector rotate in the x-z plane, such that the boresight vector stays normal to the V-bar (y-axis). This type of pointing motion is shown in Figures 6c–6d. One can immediately see the implications of achieving this type of boresight vector motion in the LVRCS. Assume a succession of these inclined 2×1 ellipses at different locations on the V-bar. With the current lighting condition and with the rotation of the boresight vector in the x-z plane, the microinspector can capture images of most of the host’s surface, if the length of the host lies on the V-bar. The position and attitude of the microinspector is shown in Figure 6b, and the motion of the boresight vector in inertial space is displayed in Figure 6a.

Another aspect of the microinspector that must be examined before designing the mission is the power system. This paper focuses specifically on a microinspector design that is equipped with solar cells for continuous operation in the Sun and batteries when solar energy is not available. The sun angle, Φ$_{sa}$, is defined here as the angle between the light ray from the Sun and the vector normal to the solar cells on the microsatellite. Figure 7 gives a graphical definition. This type of hardware setup for the microsatellite allows operation of all power consuming systems when the sun angle is less than some specified angle, Φ$_{sa,max}$, via the solar cells alone. During this time, if the battery reserves are less than the maximum capacity, these batteries can be recharged by the solar cells. Φ$_{sa,max}$ is less than or equal to 90°, and may be determined by the average power usage by the microsatellite. While Φ$_{sa}$ > Φ$_{sa,max}$, the microinspector can run off the batteries, until the sun angle is once again adequate for solar cell usage. In summary,

- Φ$_{sa}$ > Φ$_{sa,max}$: Batteries are discharging
- Φ$_{sa}$ < Φ$_{sa,max}$: Batteries are charging

In this paper, “solar cell mode” is when the batteries are charging, and “battery mode” is when the batteries are being discharged. In order to determine the proper specifications for the microinspector’s power system, the amount of time spent in solar cell mode and battery mode during a typical orbital maneuver needs to be evaluated. One obvious goal in designing a mission for a microinspector with solar cells is to stay in solar cell mode for the majority of the mission time. If the battery’s state of charge (SOC) is below the specified minimum SOC, it will become necessary to recharge by pointing the solar cells toward the Sun, during the mission. Since this takes time away from the inspection part of the mission, it is desired to avoid these recharging maneuvers, if possible. While still attaining the desired motion of the camera boresight vector, the orientation of the microinspector that minimizes Φ$_{sa}$ throughout the mission must be determined. For the following analysis, Φ$_{sa,max}$ is assumed to be 90°. Another assumption is that the solar cells are placed only on one side of the microsatellite, as shown in Figure 7. The camera viewpoint is located on one of the edges of this box-shaped

Figure 6: Lighting Case with Microinspector in Inclined 2×1 Stationary Ellipse: The Sun is in the host vehicle orbital plane. The camera’s boresight vector rotates in the geocentric inertial reference frame.
microinspector model.

The following case illustrates the problem. The microinspector is placed in an inclined 2×1 ellipse in the LVRCS. The camera’s boresight vector appears to rotate at the constant orbital rate in the LVRCS, and is always perpendicular to the V-bar, as in the previous example. The scales of the vehicles are exaggerated in all figures, in order to present the concept. The view down the V-bar looks circular for this particular case. To achieve this type of relative motion, a rotational $\Delta \alpha$ must be applied at positions $\mathbb{1}$–$\mathbb{4}$ to spin-up the attitude to the orbital rate in the directions shown in Figure 8b. The camera’s boresight vector follows the path illustrated in Figure 6e. With no further attitude control maneuvers, the solar cells are exposed to the Sun for less than a third of the orbital period. However, upon closer inspection, this example brings a new possibility to light. There is an extra degree of freedom about the camera’s boresight vector, which can be utilized to acquire more Sun exposure to the solar cells. In this example, the microinspector can be rotated $180^\circ$ about the boresight vector at positions $\mathbb{1}$ and $\mathbb{3}$, as shown in Figure 8. These rotations result in doubling the Sun exposure time, and consequently the time spent using the solar cells for operation. Under different lighting conditions and given enough fuel, the mission planner may choose to actively control the orientation of the microinspector about the boresight vector, in order to maximize the Sun exposure to the solar cells. This sun angle minimizing algorithm will be referred to as the Sun-nadir pointing scheme, for the remainder of this paper.

In reality, $\phi_{na,max}$ will be much less than $90^\circ$, due to the average power needed to continue running all systems on board the microinspector. Additionally, the battery reserves will not be completely depleted before conducting recharging maneuvers. The reader is referred to Ref [8] for more examples of how lighting affects the microinspector mission.

**Differential Drag**

Differential drag may be defined as the difference in atmospheric drag between two spacecraft vehicles. For the simulations in this paper, the differential drag is assumed to be constant between the host spacecraft and microsatellite inspector. This assumption describes the case in which the orientation of the host vehicle and microinspector do not change in the LVRCS. In a realistic situation the host vehicle or the microinspector may be rotating in the LVRCS, changing the value for differential drag — which depends on altitude — throughout the orbit. In this case, the differential drag will be somewhat sinusoidal, which could result in a complete or partial cancellation of the effect on the motion. Thus, the case of constant differential drag may be more detrimental to the relative motion than the sinusoidal case over an orbital period.

The atmospheric model used for the drag analysis in this section was taken from Vallado’s *Fundamentals of Astrodynamics and Applications* [6]. This model maintains that the density of the atmosphere decays exponentially with increasing
The atmospheric drag force for the microinspector and the host can be calculated by:

\[ F_d = -\frac{1}{2} \rho AC_d v_r v_r \]  

(7)

where \( \rho \) is the atmospheric density as before, \( C_d \) is the drag coefficient, \( v_r \) is the velocity relative to the atmosphere, and \( A \) is the reference area.

If \( F_{d,h} \) and \( F_{d,i} \) represent the drag force of the host vehicle and microinspector, respectively, then the atmospheric drag accelerations of each vehicle are given by:

\[ a_{d,h} = \frac{F_{d,h}}{m_h} \]  

(8)

\[ a_{d,i} = \frac{F_{d,i}}{m_i} \]  

(9)

where \( m_h \) is the mass of the host vehicle and \( m_i \) is the mass of the microinspector. The differential acceleration due to drag, \( a_d \), is the difference in the host and microinspector’s acceleration due to drag:

\[ a_d = \begin{bmatrix} a_{d,x} \\ a_{d,y} \\ a_{d,z} \end{bmatrix} = a_{d,h} - a_{d,i} \]  

(10)

The total velocity of the microinspector can be interpreted as the orbital velocity of the origin of the LVRCS added to the relative velocity of the microinspector in the LVRCS. The orbital velocity of the LVRCS dominates over the relative velocity of the microinspector. Hence, for the drag analysis in this paper, the relative velocity is not included in the drag force calculations. Since the greater part of the microinspector’s velocity is parallel to the V-bar of the host vehicle, \( a_{d,x} \) and \( a_{d,z} \) is assumed to be zero. Then, \( a_{d,y} \) represents the differential drag, which can be positive, negative, or zero. When the host vehicle has the greater drag, \( a_{d,y} \) is positive. When the microinspector has the greater drag, \( a_{d,y} \) is negative. With equal drag, the value of \( a_{d,y} \) is zero. This constant value, \( a_{d,y} \), will be part of the \( d_y \) component of \( d \) in Eqn 1–Eqn 3. For the remainder of this paper, the variable \( a_d \) will represent the differential drag, with the connotation that it lies along the y-axis of the LVRCS.

The rest of this section examines possible values for differential drag that are attained for the host and microinspector models outlined in the requirements. Table 1 displays those hardware specifications for the two vehicles.

Table 1: Host and Microinspector Models

| Specifications | Host Spacecraft | Microinspector |
|----------------|----------------|----------------|
| Dimensions     | length = 30 m  | 8 x 8 x 2 \text{in} \text{^3} or 8 x 8 x 2 \text{in} \text{^3} | 0.2 x 0.2 x 0.05 m \text{^3} |
| Edge Area      | 0.00065 m\text{^2/kg} | 0.00344 m\text{^2/kg} |
| Face Area      | 0.005 m\text{^2/kg} | 0.01376 m\text{^2/kg} |
| Mass           | 30,000 kg      | 3 kg           |
| Edge Area/mass | 19.63 m\text{^2} | 0.01 m\text{^2} |
| Face Area/mass | 150 m\text{^2} | 0.04 m\text{^2} |

Table 2 lists the differential drag values calculated for combinations of two different orientations for the host and microinspector vehicles — the edge (minimum reference area) and face (maximum reference area) — at 200 km, 500 km, and 700 km. In this table, the edge and face orientations are denoted by \( E \) and \( F \), respectively. The drag coefficient, \( C_d \), for both vehicles is set to 2 for the calculations in this section and for the simulations. \( H \) stands for the host vehicle and \( MI \) represents the microinspector.

Table 2: Differential Drag Values

| \( a_d \text{ m/s}^2 \) | Altitude [km] |
|------------------------|--------------|
| \( H \text{ MI} \) 200 | 500 | 700 |
| E F \(-2.0 \times 10^{-4}\) | \(-4.7 \times 10^{-7}\) | \(-2.3 \times 10^{-8}\) |
| E E \(-4.2 \times 10^{-5}\) | \(-9.9 \times 10^{-8}\) | \(-5.0 \times 10^{-9}\) |
| F F \(-1.3 \times 10^{-4}\) | \(-3.1 \times 10^{-7}\) | \(-1.6 \times 10^{-8}\) |
| F E \(2.3 \times 10^{-5}\) | \(5.5 \times 10^{-8}\) | \(2.8 \times 10^{-9}\) |

Depending on the orientation of the two spacecrafts, the sign of the differential drag may differ. If the microinspector stays edge on during its orbit, but the host vehicle rotates in the LVRCS, then the differential drag will be sinusoidal. In this case, the total effect on the microinspector’s motion relative to the host may be mitigated throughout each orbit. For the trajectory analysis and mission design for a microinspector in this paper, the host vehicle is assumed to be placed edge on in the LVRCS.

The orbital degradation due to various magnitudes of the differential drag can be described by the change in the semimajor axis, \( a \), of the microinspector’s orbit. This is essentially the change of the vehicle’s position along the x-axis in the LVRCS. Figure 9a illustrates the trajectory of a microinspector that is initially placed at the origin, over a time span of ten orbital periods (\( \approx 15.7 \text{hrs} \)). The host is in orbit about the Earth at an altitude of 500 km and located at the origin in the LVRCS. To simulate the motion of the microinspector, the \( C_W \) solution is used with \( a_d = -1 \times 10^{-8} \text{ m/s}^2 \). The negative value of \( a_d \) means that the microinspector has greater drag, which causes the semimajor axis of its orbit to decrease more than the host’s. The microinspector’s velocity becomes greater than the host’s velocity. Therefore, in the LVRCS, the microinspector appears to drift below and ahead of the host.

\( ^3 \) differential drag and differential acceleration due to drag are used interchangeably.
The microinspector is effectively spiraling inwards toward the Earth, relatively speaking.

Figure 9b shows a closer inspection of the orbital degradation over two orbital periods. The change along the x-axis, $\Delta x$, is constant per orbital period, but the change along the y-axis, $\Delta y$, is greater in the second period than in the first. A periodic motion in the degradation can be observed in the x-direction. $\Delta x$ and $\Delta y$ per orbital period can be calculated explicitly using the traveling ellipse formulation of the $CW$ solution, Eqn 1. Indeed, evaluation of these equations proves that the change in the motion along the x-axis is periodic due to the constant differential drag. Since the differential drag is assumed to exist primarily along the V-bar, only the in-plane motion due to the drag will be analyzed here.

![Graph](image)

**Figure 9:** Orbit Degradation Due to Differential Drag: $a_d = -1 \times 10^{-8} \text{ m/s}^2$

Table 3 lays out the orbital degradation in the first orbital period due to $a_d = 1 \text{ m/s}^2$.

| $a_d = 1 \text{ m/s}^2$ | Altitude [km] |
|--------------------------|---------------|
| 1st Period               | 200           | 500           | 700           |
| $\Delta x [m]$           | $9 \times 10^6$ | $10^7$        | $1.1 \times 10^7$ |
| $\Delta y [m]$           | $-4.2 \times 10^7$ | $-4.8 \times 10^7$ | $-5.3 \times 10^7$ |

from a sailcraft. This particular mission would probably require the microinspector to be placed afar and point at the host vehicle, in order to capture the entirety of the solar sail deployment. Another use for a microinspector would be to take images of the surface of a manned space vehicle for damage. Unlike the sailcraft mission, the microinspector would need to maneuver about the host vehicle to capture images of the complete surface. The resolution of the images would be considered an important measure of success for this mission. This section presents some figures of merit that would be useful in rating and designing an inspection mission. Most likely, no one figure of merit will be adequate in rating the quality of a mission. The mission designer must apply an appropriate weighting factor to each of several possible figures of merit.

**Fuel Expenditure**

Fuel expenditure is a figure of merit that is key in rating and designing any microsatellite mission. Because of the limited amount of fuel on board a typical microsatellite, trajectory design for a mission that minimizes fuel usage is highly desirable. Fuel expenditure can dramatically reduce the usable mission lifetime of the microinspector when a complex re-docking and re-fueling option is not available. This paper assumes that the microinspector has no momentum exchange devices on board for attitude control, and that the thrusters are used for both translational and rotational maneuvers.

**Host Surface Coverage**

For visual inspection missions that survey the total surface area of the host vehicle, a figure of merit is needed to ensure that the microinspector captures images of the entire surface. A simple method is to divide the surface of the host vehicle into segments. When the center point of a segment is in the field of view (FOV) of the camera and the segment is illuminated by sunlight, the complete segment is assumed to be viewed in this paper. The smaller the segments are made, the more accurate this assumption. Thus, throughout the course of the mission, the sections of the host that are viewed can be determined by this figure of merit. Figure 10 illustrates the points on the surface of the host vehicle model. A vector normal to the surface at each point is drawn in the figure. Figure 11 displays the surface area of the cylindrical host model. Each segment is represented by a number. If all the segments are viewed by the microinspector, then this figure of merit affirms that the microinspector successfully captures images of the total surface. The top row in Figure 11 represents the top of the host surface in the LVRC frame when the length is
along the V-bar. The fifth row represents the bottom of the host surface.

Figure 10: Points on Surface of Host Spacecraft

Figure 11: Surface Grid Labeling of Host Vehicle Segments

To determine whether or not a point on the surface of the host appears in an image taken by the camera, at least two conditions must be fulfilled:

1. Point is contained in FOV: \( \cos^{-1}\left( \frac{\mathbf{r}_{s,pt} \cdot \mathbf{r}_n}{|\mathbf{r}_{s,pt}| |\mathbf{r}_n|} \right) < \frac{\theta_{apo}}{2} \)
2. Point is viewable by the camera: \( \mathbf{r}_{s,pt} \cdot \mathbf{r}_n > 0 \)

\( \theta_{apo} \) is the angle of view of the camera, \( \mathbf{r}_{s,pt} \) is the boresight unit vector from the camera, \( \mathbf{r}_{c,pt} \) is the position vector from the camera to the point on the surface, and \( \mathbf{r}_n \) is the normal vector to the point on the surface.

Figure 12 provides an illustration of the vectors and angles used in the calculations to determine if the two conditions are met.

Figure 12: Host Surface and Camera Vectors and Angles

Frequency of Host Surface Coverage

Another figure of merit that is directly correlated with viewing points on the host’s surface is the frequency or total time that a point is viewed. In a typical mission, it is foreseen that some sections of the host’s surface may be captured more often than others. A figure of merit relating the frequency of the viewed points would provide knowledge on which sections the microinspector has more opportunities to view and image. In mission simulations, the frequency is determined by summing the number of times the point is in the FOV of the camera per time step.

Angles of Host Surface Coverage

The inspection mission may require the microinspector to take images of the host’s surface at different angles. The angle variety provided by the assorted images gives perspective on any possible damage to the surface. If all the images are taken normal to the surface, an object that is loose or raised may not be apparent. For a general overview of the host’s surface, it is desirable to acquire a multifaceted portrait of the vehicle through the images taken by the microinspector. A figure of merit that depicts the variety of angle views of the host surface would rate how close the mission is to achieving this goal.

Lighting

Some problems associated with lighting from the Sun were discussed earlier in the Lighting section. Even if the surface of the host vehicle is in the FOV of the camera, without proper lighting, the camera will not be able to take observable images. When available, utilizing sunlight to take photographs is preferable to using a flash illuminator, which would otherwise unnecessarily drain the battery. Additionally, the angle of incidence of the sunlight on the surface of the host must be sufficient.

A figure of merit which falls under the category of lighting is the availability of sunlight for image capturing. The three conditions that must be met to determine this are:

1. Sunlight illuminates the surface being viewed
2. The point is not in the shadow of the host itself
3. The point is not in the shadow of the Earth

Figure 13 provides an illustration of the vectors used in the calculation to determine if conditions 1 and 2 are met.

With \( \mathbf{r}_{s,LV RCS} \) as the Sun vector in the LVRCs, and all other variables as in the Host Surface Coverage section, the calculation to demonstrate that the point is illuminated by the Sun and not in the shadow of the host is as follows:

\[ \mathbf{r}_{s,LV RCS} \cdot \mathbf{r}_n > 0 \]

Figure 14 illustrates Earth’s shadow and the position of the
velocity of the microinspector for a camera exposure time of \( t_{ex} \) is given by:

\[
v_{max} = \frac{r_{c,pt} \tan \left( \frac{\theta_{ave}}{N} \right)}{t_{ex}}
\]  

(12)

where \( r_{c,pt} \), \( \theta_{ave} \), and \( N \) are as before.

**Battery Reserve**

The amount of battery power available at any given time is an important figure of merit. If the battery reserves are drained below a certain limit, the microinspector will need to stop its current task and point the solar cells toward the Sun to recharge. This also impacts fuel expenditure, as well as any time constraints. At any given time, the battery reserves can be roughly determined by:

\[
\text{Battery Reserves (W-hr)} = B_0 + 25 \int_{t_0}^{t} [\cos(\phi_{sa}) - \cos(\phi_{sa,max})] \, dt
\]

(13)

where \( B_0 \) is the battery reserve at \( t_0 \).

### 4. Design Description

The strategies presented in Section 2 allow a straightforward mission design for a microsatellite inspector in a planet orbiting environment. The idea of utilizing natural dynamics in designing the trajectory was found to use extremely minimal fuel. In addition, the \( CW \) solution provides an easy method for calculating the positions, velocities, and accelerations for natural trajectories. Thus, in this section, a list of some of the natural relative trajectories that may be advantageously employed in a visual inspection mission is presented. These trajectories form a toolset that a mission planner can use in building an inspection mission. A baseline mission description for a microinspector utilizing the design strategies and the trajectory toolset is presented.

**Toolset**

This section recounts some of the natural relative motion presented thus far, as well as introducing a new set of trajectories that may be exploited in designing an inspection mission. An analysis of each trajectory is conducted on the basis of fuel usage, application to imaging, and time span, all in the LVRCS. The velocity magnitude of each of the following trajectories is much less than the maximum \( \Delta v \) that would be available on a microsatellite inspector.

**Stationary on V-bar**—One option for inspection is to place the microinspector behind or in front of the host, along the V-bar. In the LVRCS, the camera can be directed to point toward the
host. If the host is equipped with solar arrays or solar sails, the microinspector can capture the deployment phase while in this stationary position, relative to the host. Another application would involve the cooperation of the host vehicle. The host spacecraft can rotate about different axes in the LVRCS, allowing the microinspector to take images of the host until complete coverage is achieved. This stationary position may also be utilized as an intermediary point before embarking on the remainder of the inspection mission. In terms of the traveling ellipse parameters from the Natural Motion section, \( Y_0 \) defines where the microinspector is located on the V-bar relative to the host. All other parameters are set to a value of zero. Once the microinspector is put on the V-bar near the host vehicle with zero relative velocity, the microinspector stays at the position indefinitely, with fuel being used only for orbit maintenance. Refer to the Stationary On V-bar sub-figure in Figure 17.

Out-of-plane Oscillation across the V-bar—The microinspector can also be made to oscillate out-of-plane, while positioned on the V-bar. The out-of-plane magnitude is defined by the traveling ellipse parameter, \( c \). The position on the V-bar is designated by the value of \( Y_0 \). The Pure Out-of-plane sub-figure in Figure 17 portrays an out-of-plane motion, with \( c = 10 \text{ m} \), which requires a velocity burn of \( \Delta v = 0.00096 \text{ m/s} \), from a zero-velocity state on the V-bar. An out-of-plane motion with a magnitude of \( c = 20 \text{ m} \) requires \( \Delta v = 0.01992 \text{ m/s} \). The larger the magnitude, the greater the initial velocity needs to be to insert the microinspector into this oscillatory motion. If the length of the host spacecraft lies out-of-plane as in the figure, the advantage of the out-of-plane natural motion becomes apparent. Placed in this oscillatory motion, the microinspector can take images of the entire length of the host vehicle.

In-plane 2\( \times \)1 Ellipse— The 2\( \times \)1 elliptical motion, also known to the GN&C community as a football orbit, was introduced in the previous sections. The in-plane 2\( \times \)1 ellipse is a stationary relative closed orbit. The position of an in-plane 2\( \times \)1 ellipse along the V-bar may vary depending on the mission requirements. The cases presented next are considered to be basic to the trajectory toolset for an inspection mission.

An in-plane 2\( \times \)1 ellipse presents a stable and fuel-minimizing method of traveling about the host vehicle. The attitude of the microinspector can be regulated so that the camera’s boresight vector is fixed in the inertial reference frame. Once the microinspector is inserted into this stationary ellipse, no further fuel is needed to continue the motion about the host vehicle. Hence, the in-plane 2\( \times \)1 ellipse is not only an excellent choice for an inspection trajectory, it is also an ideal trajectory to be put into during intervals of non-imaging.

The In-plane 2\( \times \)1 Ellipse sub-figure in Figure 17 illustrates an in-plane 2\( \times \)1 ellipse, in which \( b = 20 \text{ m} \) and \( Y_0 = 0 \text{ m} \). All other traveling ellipse parameters are set to zero. The velocity burn for insertion is \( \Delta v = 0.022 \text{ m/s} \), from a zero-velocity state at 40 or -40 m on the V-bar. The velocity magnitude during a 2\( \times \)1 ellipse is minimum where the ellipse intersects the V-bar (y-axis) and maximum where it intersects the R-bar (x-axis). An ellipse that is twice the size of this one would require double the \( \Delta v \) for insertion.

The center of the in-plane 2\( \times \)1 ellipse can be offset along the V-bar as shown in Figure 15. This type of trajectory has advantages similar to the previous case. It may be utilized for inspection of the host spacecraft or for placing the microinspector in a stable relative motion during intervals of non-imaging. The velocity magnitude needed to insert the microinspector into the trajectory is \( \Delta v = 0.012 \text{ m/s} \).

![Figure 15: In-plane 2\( \times \)1 Ellipse: Center Not at Origin](image)

The center of the in-plane 2\( \times \)1 ellipse can also be offset along the V-bar as shown in the In-plane 2\( \times \)1 Ellipse (off-center) sub-figure in Figure 17, such that the trajectory intersects with the host vehicle. Although this type of trajectory is not suited for inspection purposes due to the danger of collision, using a portion of the trajectory is certainly a valid method for initially deploying the microinspector. One can envision the microinspector leaving the host, traveling along this trajectory, and stopping once it reaches the V-bar. The velocity magnitude needed to insert the microinspector into the trajectory is \( \Delta v = 0.012 \text{ m/s} \) and another \( \Delta v = 0.012 \text{ m/s} \) to stop at the V-bar.

Inclined 2\( \times \)1 Ellipse— Similar to the in-plane 2\( \times \)1 ellipse case, the inclined 2\( \times \)1 ellipse allows for a stable and fuel minimal method of orbiting about or near the host vehicle. The form of the trajectory is still a 2\( \times \)1 ellipse in-plane. The inclined portion of the trajectory comes directly from the addition of the out-of-plane oscillatory motion to the in-plane 2\( \times \)1 ellipse. A variety of inclined 2\( \times \)1 ellipses may be formed specific to the inspection mission, by varying the values for \( b, c, Y_0, \) and \( \psi - \phi \). \( X_0 \) must be zero for the relative orbit to stay stationary. In this study, two distinct forms of the inclined 2\( \times \)1 ellipse are presented for their natural benefits in visual inspection.

To obtain an inclined 2\( \times \)1 ellipse that is circular when viewed along the V-bar, the value for \( b \) and \( c \) must be equal. Additionally, \( \psi - \phi = 90^\circ \). For a host vehicle with its length along the V-bar, this type of trajectory permits the microinspector to get closer to the surface and take images with better resolu-
tion, with minimal risk of collision. The size of the inclined ellipse can be made much smaller than an in-plane ellipse, in part because of the out-of-plane factor and also due to the ellipse intersecting the R-bar instead of the V-bar. The camera’s boresight vector can be initiated to rotate in the plane of the ellipse. Another practical option is to direct the attitude of the microinspector, so that the camera’s boresight vector is normal to the V-bar, as in the Inclined 2×1 Ellipse sub-figure and the Inclined 2×1 Ellipse: Circular in the x-z Plane sub-figure in Figure 17. The velocity magnitude of this inclined 2×1 ellipse at \( \phi = 0^\circ \) and \( \phi = 180^\circ \) is the same as its in-plane counterpart: \( v = 0.011 \, \text{m/s} \). At \( \phi = 90^\circ \) and \( \phi = 270^\circ \), the velocity magnitude of the microinspector is \( v = 0.025 \, \text{m/s} \). Again, the period of the inclined 2×1 ellipse is equal to the orbital period of the host.

Because the trajectory does not intersect the V-bar, even if some drift occurs along the V-bar due to differential perturbing accelerations, there is no chance of collision. Thus, this motion is safe in terms of collision and easy to maintain.

The x-y plane view of an inclined 2×1 ellipse always has the 2×1 form. But in the orbital plane of the relative trajectory, the shape can be varied dramatically. The Inclined 2×1 Ellipse sub-figure and the Inclined 2×1 Ellipse: Circular in the Orbital Plane in Figure 17 illustrates one particular trajectory that can be achieved. The inclined (about the V-bar) ellipse is such that the motion is circular about the center of the relative orbit, and the trajectory intersects the V-bar. For a given value of \( b \), setting \( c = \pm b \sqrt{3} \) and \( \psi = \phi = 0^\circ \) gives the circular form in the relative orbital plane. The camera’s boresight vector can be controlled to rotate in this plane, while pointing toward the center of the circular relative motion. The microinspector is equidistant from this center throughout its motion, which may be beneficial to some inspection missions. These circular relative orbits, however, are always inclined 60° from the in-plane, possibly restricting their use. Since the orbit intersects with the V-bar, the danger of collision is also increased if the microinspector is close to the host.

**Horizontal Above/Below**—The CW solution shows that the microinspector can be made to move in a relative straight line above or below the host in-plane. This type of motion can be used to view the top or bottom of the host vehicle at a constant distance from the V-bar, if the host is not rotating in the LVRCs. Also, a nonzero value for \( c \) will result in an out-of-plane sinusoidal motion. The Horizontal sub-figure in Figure 17 shows what this type of motion looks like, relative to the host vehicle, which maintains a LVLH attitude. The velocity magnitude needed to set the microinspector to traverse in a straight line depends on the position deviation along the R-bar (x-axis), and is given by Eqn 14. The velocity is applied parallel to the V-bar, which makes the microinspector appear to move above or below the host vehicle depending on the sign of the radial deviation from the host.

\[
v = -\frac{3}{2} x \omega \tag{14}
\]

**In-plane Traveling Ellipse**—The traveling ellipse occurs when the center of the stationary ellipse along the radial vector is not located on the V-bar of the host spacecraft. In traveling ellipse parameters, the value of \( X_0 \) is nonzero. By shifting the center of the original 2×1 ellipse up or down along the radial axis, the ellipse appears to move backwards or forwards, respectively. In general, a drifting ellipse in-plane is usually an undesirable phenomenon due to possible collision with the host.

Inserting the microinspector into an in-plane traveling ellipse trajectory is an effective method of disposing the vehicle once the inspection mission is completed. The In-plane Traveling Ellipse sub-figure in Figure 17 illustrates two instances of the microinspector leaving its initial stationary position on the V-bar via a traveling ellipse. The fuel needed to enter such a trajectory is extremely small compared to the total fuel on board a microinspector.

**Spiral Orbit**—The spiral orbit is essentially an inclined traveling ellipse. Given the right set of conditions, the microinspector can be made to drift along the V-bar in a spiraling loop with no further use of fuel, as shown in the Spiral: Inclined Traveling Ellipse sub-figure in Figure 17. In this particular figure, the host is in a circular orbit about the Earth at an altitude of 500 km. The initial velocity magnitude of the spiral orbit is \( v = 0.011 \, \text{m/s} \) from a zero velocity state. The spiral orbit can be initiated from a corresponding inclined 2×1 ellipse. By applying a \( \Delta v \) parallel to the V-bar, the microsatellite can be made to spiral forwards or backwards. The effect of applying \( \Delta v \) parallel to the V-bar is elaborated further in the appendix of Ref [8]. The camera’s boresight vector can be pointed toward the host’s surface. This is an excellent method of capturing images of the host’s surface, while using very little fuel. For host vehicles, whose length is along the V-bar, this method can be used to inspect most of the host’s surface by utilizing a tunnel-like motion around the host vehicle. Similar to the first in-plane ellipse case (circular in x-z plane), there is no chance of collision as the microinspector travels along the spiral trajectory. Thus, the motion is safe in the presence of disturbing differential accelerations. While traveling forwards or backwards, there is no possibility of collision. Each loop of the spiral orbit is approximately one orbital period. The values for \( b, c, X_0 \) and \( \phi - \psi \), which determine the size and shape of the spiral, will depend on the camera specifications and image requirements.

**Tear-drop Orbit**—This trajectory is so named because of its tear-drop shape. The trajectory is actually just a segment of one revolution of the traveling ellipse; however, the ease in which the tear-drop form can be kept with periodic maintenance makes it a useful trajectory to include in the toolset. The time to traverse a tear-drop orbit is less than one orbital period, since it is a section of the traveling ellipse. Thus for
missions that are constrained in time, utilizing tear-drop orbits may be a practical choice, with the trade-off being periodic fuel expenditure.

The shape and the position of the tear-drop orbit may be chosen to encircle the host vehicle, as illustrated in the In-plane Tear-drop sub-figure in Figure 17. The motion of the microinspector is purely in-plane. Without the \( \Delta v \) burn at the point of intersection of this tear-drop orbit, the microinspector will follow the path of a traveling ellipse. The “period” or \( \Delta t_{td} \) of this tear-drop orbit is about 99% of the orbital period of the host, \( \Delta v \cong 0.005 \text{ m/s} \), which is applied in the negative \( x \)-direction every \( \Delta t_{td} \). The camera’s boresight vector can be rotated in the LVRCS to capture images of the host vehicle. Since \( \Delta t_{td} \) is less than the orbital period, the boresight vector needs to be rotated at a constant angular rate of \( \frac{2\pi}{\Delta t_{td}} \text{ rad/s} \). The deviation of the ellipse’s center is positive along the radial axis. If the deviation is negative, then the microinspector would move along a traveling ellipse path in the opposite direction. The \( \Delta v \) burn would then have to be applied in the positive \( x \)-direction to achieve a tear-drop orbit about the host vehicle.

The tear-drop orbit may also be designed to have an out-of-plane component. Because the out-of-plane motion is sinusoidal with a period equaling the orbital period of the host vehicle and \( \Delta t_{td} \) is less than the orbital period, the out-of-plane location of \( \Delta v \) will vary from burn to burn. Over time, the tear-drop orbits form a set that stays within a band defined by the out-of-plane traveling ellipse component, \( c \). The motion is akin to a lissajous figure in three dimensions. The Out-of-plane Tear-drop sub-figure in Figure 17 displays the same in-plane tear-drop shape from before, but with an out-of-plane component of \( c = 3 \text{ m} \). The \( \Delta v \) burns are equivalent in magnitude and direction.

The tear-drop orbit can also be formed near the host vehicle as in the Tear-drop Near Host sub-figure in Figure 17. This type of trajectory can be utilized to take an image of a particular point on the host vehicle, without resorting to station-keeping. Station-keeping at a position above or below the host would require much more fuel consumption than this tear-drop orbit. Since only one snapshot of the point on the surface is needed to determine if the vehicle has been damaged, this tear-drop trajectory will be used. It is not necessary to continue traveling about the tear-drop shape, and thus extra burns are not needed. Nevertheless, if it is desired to have the microinspector travel about the tear-drop orbit, then similarly a \( \Delta v \) burn is required each time the microinspector reaches the point of intersection. The smaller the tear-drop orbit becomes, the closer the total \( \Delta v \) is to the fuel for station-keeping at the limiting point. This is one method for mechanizing the station-keeping method.

Notice that the tear-drop shape can be eliminated altogether, to form a dip in place. Figure 16 illustrates this trajectory.

![Figure 16: Dip Near Host](image)

Before the natural motions presented in the toolset can be utilized to piece together a mission, it is necessary to list the possible transfers from one type of motion to another. Figure 17 portrays a flowchart of the natural motions from the toolset and the transfers between them. Many of the trajectories listed in the toolset are subsets of the inclined 2x1 ellipse and the inclined traveling ellipse. Thus, in the flowchart, the trajectories that proceed from these categories are shown in the dashed boxes. All of the trajectories in the flowchart are natural motion, except for the tear-drop orbits, which lead to station-keeping.

There are a variety of methods of computing the transfer trajectories to maneuver from one natural relative motion to another. The forced motion method can be employed in this case to insert the microinspector into the desired natural motion. However, this method is expensive in terms of fuel usage compared to the use of natural dynamics. Hence, the transfer trajectories for the simulations in this paper will be computed using the natural relative dynamics described by the \( \text{CW} \) solution. A description of several of the transfer trajectory computations can be found in Ref [8]. Based on these computations, a set of positions, impulse velocities, and times, which describe the natural motions and the transfers, are compiled into an input array that is used by the mission simulation.

**Estimation of \( \Delta v \) Burns**

The position, magnitude, and direction of the \( \Delta v \) burns are not explicitly computed for orbit maintenance and attitude control in the simulation created for this study. Nevertheless, to attain more realistic fuel costs for a microinspector mission, the simulation does include estimations of the fuel used during orbit maintenance due to differential drag, and to spin-up the microsatellite about a body-fixed axis. This section discusses how the \( \Delta v \) estimation is done for both cases.

**Orbit Maintenance due to Differential Drag**—The Differential Drag section introduced the problem of differential drag and the resulting impact on the motion of a microsatellite inspector via the \( \text{CW} \) equations. This constant differential acceleration due to drag may be used to estimate the amount of fuel required per orbital period, by the microinspector. If \( a_d \) is the magnitude of the differential drag and \( P \) is the orbital period, then the total \( \Delta v \) needed per orbit to overcome the
degradation caused by differential drag is given by:

\[ \Delta v = a_d P \]  (15)

The \( \Delta v \) for each burn can be determined by dividing the total \( \Delta v \) by the number of burns per orbit. The direction of each individual burn must be opposite to the direction of the differential drag vector, \( a_d \).

The mission simulation in Section 5 includes the estimates of fuel use for maintenance due to differential drag, based on Eqn 15. Using the results from the Differential Drag section, a few of the \( \Delta v \) estimates at different altitudes are given here, when both the microinspector and the host are edge on. At 500 km, the magnitude of the differential acceleration due to drag is computed to be \( a_d = 9.9 \times 10^{-8} \). By Eqn 15, the \( \Delta v \) required for orbit maintenance is \( 5.63 \times 10^{-4} \) m/s per orbit. At lower altitudes, the \( \Delta v \) required will be much larger, but may still be feasible depending on the fuel capacity. For the host and microinspector specifications in this paper, at an altitude of 200 km, \( a_d = 4.16 \times 10^{-5} \). Hence, the \( \Delta v \) required per orbit is 0.22 m/s, which is much less than the budgeted total \( \Delta v \) of 15 m/s.

Attitude Control System—The equations of motion used in the trajectory and mission simulation for this study are in 3DOF, since the CW solution is being utilized. Therefore, the position, velocity, and accelerations are explicitly computed for the microsatellite inspector's orbital (translational) motion. Although the attitude maneuvers are not simulated with any equations of motion, the orientation of the microinspector is included in the simulation as a specified variable. Because the angular rates of the vehicle are not directly computed, the fuel costs associated with attitude control must be estimated. For the simulation in Section 5, the attitude control of the microinspector is largely based on the constant angular rate method introduced in the Lighting section. Therefore, an estimate of the \( \Delta \theta \) required to spin-up the microsatellite about a body-fixed axis is needed. Refer to Ref [8] for details on the method of attitude control fuel estimation used in the simulations.
Station-keeping

Station-keeping of the microinspector may be necessary when images of a specific part of the host’s surface are required. For LEO missions, the fuel usage for station-keeping is primarily associated with resisting the effects of differential gravitational acceleration between the host vehicle and the microinspector. The $\Delta v$ burns for station-keeping are not explicitly calculated from the equations of motion, nor are they directly applied to the simulations in this paper. Instead, an estimate of the $\Delta v$ required for the duration of station-keeping is included in the fuel costs for the total mission. The differential gravity can be calculated from the acceleration vector in Eqn 3, given the desired position for station-keeping in the LVRCS and setting $d$ to zero. The initial velocity components are set to zero. Let $a_g$ be the differential gravity. Then, the $\Delta v$ required can be estimated by multiplying the continuous acceleration needed to overcome the effects of $a_g$ and the total time at the desired position. The continuous acceleration is simply the opposite of $a_g$. Thus, if $\Delta t$ is the time at the desired position, the magnitude of $\Delta v$ is given by:

$$\Delta v = \|\Delta v\| = \Delta t |a_g|$$

(16)

To simulate station-keeping using the $CW$ equations, a differential acceleration that is equal in magnitude and opposite in direction to the differential gravity is applied as a part of $\delta$ of Eqn 1.

Baseline Mission

This section presents a baseline microinspector mission concept for a host vehicle in orbit about Earth.

1. Mode 1: Deployment of Inspector from Host Spacecraft
   In mode 1, the microsatellite inspector is deployed from the host vehicle to a stationary position on the V-bar, a specified distance away. During this mode, the microinspector prepares for the inspection process. This may include calibration and testing of the on board sensors.

2. Mode 2: Global Inspection
   In mode 2, the microinspector carries out a global inspection of the host vehicle’s surface. Starting from its initial position on the V-bar, the microinspector is dispatched to maneuver autonomously about the host vehicle for the inspection process. The trajectories that make up the global inspection mode are pre-computed to observe all necessary constraints and requirements. The global inspection process entails maneuvering the microinspector and controlling its attitude, such that complete coverage of the host vehicle’s surface is achieved through the images taken by the on board camera. Once the global inspection is complete, the microinspector returns to a specified position on the V-bar for further commands.

3. Mode 3: Point Inspection
   In mode 3, the microsatellite inspector maneuvers to a specified position near the host vehicle and is properly oriented for point inspection. The specified position is chosen by ground operators after reviewing the images taken during the global inspection mode. Close-up images of a particular point or points on the host’s surface may be desired after the images from the global inspection are assessed. If so, the positions and attitudes of the microinspector to acquire these images are uploaded to the microinspector that is awaiting instructions while on the V-bar. Once the specified position is reached, station-keeping maneuvers are executed until all images are taken. Following the point inspection process, the microinspector returns to the V-bar for further commands.

4. Mode 4: Disposal of Inspector
   In mode 4, the inspection function of the microinspector has been fulfilled, and safe disposal of the vehicle is initiated. The microinspector must not collide with the host vehicle, and in the case of an Earth orbiting mission, should eventually burn up in the Earth’s atmosphere. The “disposal” methods include a safe re-docking with the host.

5. Mission Design Simulation Results

In this section, an overview of the mission simulation for the Earth orbiting scenario is given and simulations of the baseline mission at two different altitudes are presented. Based on the figures of merit, the results of the simulation will be discussed and analyzed to check if the defined requirements are met. In this paper, the figures of merit will be weighted equally. Also, general requirements for the microinspector hardware are recommended based on the results.

Simulation Overview

The 3DOF baseline mission simulation for a microsatellite inspector is based on the solution to the $CW$ equations. The $CW$ solution was detailed in the Natural Motion sub-section under Section 2. The four microinspector mission modes, which make up the baseline mission, were described in the Baseline Mission section. The microinspector and host hardware specifications are simulated based on the requirements presented in the Requirements section.

The altitude and inclination of the host’s orbit about Earth are specified. In the simulation, a set of trajectory and trajectory transfer combinations are employed to accomplish the task laid out by each mode. The trajectories are chosen from the toolset presented in Section 4, subject to the mission design strategies discussed in Section 2. The transfers between the trajectories are carried out by the methods described in Section 4. For the inspection modes — Mode 2 and Mode 3 — the camera’s boresight vector is oriented to point at the host, as in Figure 6, Section 2. The baseline mission simulation presented here does not include any additional maneuvers to recharge the battery upon energy depletion, nor does it employ a sun angle minimizing scheme. The $\Delta v$ used for orbit maintenance due to differential drag and attitude control
is estimated. Finally, point inspection is simulated utilizing the station-keeping method from the Estimation of $\Delta v$ Burns sub-section in Section 4. In all simulations presented in this paper, the host spacecraft is placed in the LVRCS so that the length lies along the V-bar. Thus, it is rotating in the inertial reference frame at the orbital rate to maintain a constant LVLH attitude. The simulations of the baseline inspection mission in this section are conducted at LEO.

**Baseline Mission Simulation: 500 km**

The hardware specifications for this simulation are based on the microinspector and host spacecraft descriptions from the requirements defined earlier. The following list outlines the design specifications for the baseline mission results presented in this section.

- The host spacecraft is in a circular orbit around Earth at an altitude of 500 km at a 0° inclination.
- Since the minimum allowable distance from the surface during imaging is 10 m, in this simulation, the microinspector stays greater than 10 m from the host’s surface, with an additional buffer of 0.1 m, for extra margin. Thus, the minimum distance to the host’s surface is 10.1 m here.
- The geocentric inertial Sun position vector is along the positive X-axis of the geocentric inertial reference frame.
- The spirals are 4 m apart, so that the images have greater than 10 pixels of overlap, laterally.
- The total time for the inspection mission is about 35P, where 1P = 1.577 hr. The time-step for the simulation is $\approx 57$ s. This does not include the disposal mode.

**Mode 1: Deployment of Inspector**—The In-place 2×1 Ellipse sub-section described how a segment of the intersecting 2×1 ellipse could be employed to deploy the microinspector to a safe position on the V-bar. This method is utilized in this simulation. The microinspector maneuvers to a position behind the host on the V-bar. When it attains the desired position on the V-bar, an appropriate $\Delta v$ is imparted by the thrusters to stop the motion in the LVRCS. Figure 18 illustrates the deployment of the microsatellite inspector from the host spacecraft. Sitting on the V-bar allows for some system check-out time.

**Mode 2: Global Inspection**—A simple and effective method of maneuvering down the length of the V-bar was presented in the Spiral Orbit sub-section. With the spiral trajectory, the attitude of the microinspector can be controlled such that the boresight vector of the camera on board points normal to the surface of the host. Therefore, the global inspection mode in this baseline simulation consists of the transfer trajectory from the microinspector’s initial position on the V-bar to the spiraling motion and the transfer trajectory at the end of the spiral to a stationary position on the V-bar. The beginning and end position of the spiral motion is chosen so that the entire length of the host spacecraft is covered. The trajectories for Mode 2 are displayed in Figure 19.

**Figure 18: Baseline Mission (500 km Earth Orbit): Mode 1**

The minimum distance from the microinspector to the host’s surface is 10.1 m throughout the spiral trajectory. Although the trajectory in Figure 19 allows the total surface of the host to appear in the compilation of the images, there are still periods in which images may not be taken due to a lack of sunlight. In these cases, a flash illuminator must be used unless the host vehicle cooperates and changes its orientation.

**Mode 3: Point Inspection**—After the images taken during global inspection are reviewed by ground operators, specific areas may then be designated for closer inspection. Based on the host surface location uploaded to the microinspector, the vehicle can compute a trajectory from its initial waiting position on the V-bar to a position and attitude that will give the best possible image resolution, while keeping outside the constraint zone. Figure 20 depicts these trajectories.

**Mode 4: Disposal of Inspector**—In the previous modes, the microinspector corrected for the undesirable motion caused by atmospheric drag. At the end of the inspection mission, this motion can be utilized to dispose of the microinspector. From a stationary positive position on the V-bar, a small $\Delta v$ can be imparted by the microinspector, causing it to move away from the host spacecraft. The appendix in Ref [8] shows the effects of imparting a $\Delta v$ parallel to the V-bar. Based on those results, in this simulation, a $\Delta v$ is applied in the negative y-direction to achieve the motion shown in Figure 21. The microinspector can be oriented with respect to the host vehicle, such that the differential drag is negative, which causes the altitude of the microinspector to decrease.
Figure 21, notice the steady decrease of the deviation along the radial axis (x-axis). In time, the microinspector will naturally burn up in the Earth’s atmosphere.

**Figures of Merit**

The figures of merit from the *Mission Assessment* section are used in this section to discuss the quality of the inspection trajectories chosen for the baseline mission simulation at 500 km from the Earth’s surface.

The fuel expended during the entire mission for translational motion is much less than the total available $\Delta v$ of 15 m/s, as shown in Figure 22a. The translational maneuvers take only about 0.2 m/s in fuel. Table 2 shows that the differential drag is a small factor at 500 km. Thus, the $\Delta v$ used for orbit maintenance throughout the mission is also small, which can be seen in Figure 22a from the 2nd period to the 24th period. The estimated rotational $\Delta v$ is also below the total available fuel, but is much larger than the $\Delta v$ used for the translation motion. Figure 22c illustrates the total $\Delta v$ used, which is a little over half the available 15 m/s of fuel.

Based on the fuel expenditure simulation results, the majority of the propellant is used for the attitude control of the microinspector. In order to lower the fuel costs, the focus must be directed to developing a fuel-optimal attitude control algorithm. Further analysis must be conducted to accurately estimate the fuel usage for specific attitude control schemes and to understand the coupling dynamics between the orbital and attitude motion.

Although the rotational $\Delta v$ is estimated here, the primary scope for fuel expenditure in this baseline simulation is the translational $\Delta v$. At a 500 km altitude, the inspection trajectories in this baseline simulation are found to be excellent on the basis of fuel use.

The numbered labels of the points or segments on the host surface used in the simulation were graphically shown in Figure 11. Figure 23 illustrates the frequency at which the points on the host surface are viewed. The greater frequency is di-
rectly related to the darker shade in this figure. For the point inspection portion of the mission, the microinspector captures images of the host surface segment numbered by $3\pi$, which is viewed 81 times over the total number of time-steps. This figure of merit shows that with the Sun position vector along the positive X-axis in the geocentric inertial frame of reference and the microinspector traveling in a spiral trajectory, the camera on board has more opportunities to image the top portion of the host spacecraft. Therefore, the few opportunities to image the bottom of the host vehicle with natural lighting conditions must not be wasted.

Figure 23: Viewing Frequency of Points on Host Surface

Figure 24 displays a plot of time vs. the percentage of the host surface covered by the images taken by the microinspector. As the microinspector spirals along the length of the host, the percentage of surface coverage increases gradually until 100% is reached. This figure of merit shows that the spiral motion proves to be a good choice for an inspection trajectory. The microinspector is given the opportunity to capture images of the entire surface via the spiral trajectory, which utilizes very little fuel. A flash illuminator is not needed in this particular case.

Figure 24: Time vs. Percentage of Host Surface Coverage

Figure 25 illustrates that except for the end points, the images of the host surface are at a variety of different angles. Thus, the viewing angle figure of merit shows that the trajectories chosen for the baseline simulation give the ground operators a
more complete view of any damage done to the host’s surface. If images of the end points at different angles are desired, the microinspector can maneuver into an inclined 2×1 ellipse and orient the attitude accordingly.

![Figure 25: Viewing Angles for Points on Host Surface](image)

Figure 25: Viewing Angles for Points on Host Surface

Figure 26a displays the average resolution of the images that are taken throughout the mission. The average resolution of the images taken during the global inspection mode is under 1.1 cm, which is slightly above the desired minimum resolution of 1 cm. This is shown in Figure 26b. However, since this value is an average, the actual resolution of a surface point at the center of the field of view will be less than or equal to 1 cm. The average resolution of the images taken during the point inspection mode is 0.9 cm. Thus, this figure of merit illustrates that the images taken using the trajectories in this simulation adequately meet the image resolution requirement.

Figure 27 illustrates the magnitude of the microinspector’s velocity relative to the host spacecraft. The maximum speed during the global inspection mode is about 0.0327 m/s. According to Eqn 12, the maximum camera exposure time needs to be less than 0.263 s at a distance of 10.1 m, if the desired pixel smear is less than one pixel.

Figure 28 shows a plot of time vs. the sun angle. During the global inspection mode, the sun angle stays below 90°, which gives continuous Sun exposure to the solar cells. A Sun-nadir pointing algorithm may be utilized with this baseline mission to further minimize the sun angle. However, the trade-off of such an algorithm is the high cost of fuel.

Figure 29 shows that the battery is drained after about five orbital periods. Thus, this result shows that the microinspector must occasionally stop its inspection process and conduct maneuvers to point at the Sun to recharge the battery. Compared to employing a Sun-nadir pointing algorithm throughout the mission, this method of battery charging increases the time needed to complete the inspection mission. However, it is much more fuel efficient, since the number of attitude maneuvers to point the solar cells toward the Sun is limited, and the fuel used to maintain the appropriate attitude is small. The Sun-nadir pointing algorithm uses much more fuel, because it must maintain the correct boresight vector orientation, while...
minimizing the sun angle. Without any kind of recharging scheme, the battery reserve is quickly consumed.

**Figure 28: Time vs. Sun Angle**

In summary, the figures of merit demonstrate that the trajectories chosen for the baseline inspection mission allow for successful inspection of the host spacecraft. The total fuel expenditure is only a little over half the available 15 m/s, even with the conservative rotational $\Delta v$ estimate. The inspector can take images capturing the entire surface of the host by using natural sunlight alone. The image resolution requirement of $< 1 \text{ cm}$ can be attained with the 10 m keep-out constraint. The exposure time of the camera must be restricted to $< 0.263 \text{s}$. The battery reserve figure of merit shows that the microinspector must periodically halt the inspection mission and point toward the Sun to recharge the battery.

**Baseline Mission Simulation: 200 km**

The baseline mission for a microsatellite inspector simulated at 200 km is presented in this section.

- The host spacecraft is in a circular orbit around Earth at an altitude of 200 km at a 0° inclination.
- The minimum distance from the surface during imaging is 10.1 m, similar to the 500 km case.
- The geocentric inertial Sun position vector is along the positive X-axis of the geocentric inertial reference frame.
- The spirals are 4 m apart, so that the images have greater than 10 pixels of overlap, laterally.
- The total time for the inspection mission is about 35 $P$, where $P = 1.577 \text{ hr}$. The time-step for the simulation is $\approx 53 \text{ s}$. This does not include the disposal mode.

The main difference between the results from this simulation at 200 km and the previous simulation at 500 km is the fuel consumption for translational motion. All other results are similar. The fuel expended during the entire mission for translational motion is still less than the total available $\Delta v$ of 15 m/s, as shown in Figure 30a. However, the total translational $\Delta v$ is much larger when compared to Figure 22a. This increase in fuel consumption is primarily due to the larger value of differential drag at the lower altitude. The $\Delta v$ used for orbit maintenance throughout the mission is much greater at the lower altitude. The total rotational $\Delta v$ estimate is nearly equivalent to the 500 km case, as shown in Figure 30b. Figure 30c illustrates the total $\Delta v$ used.

The maximum velocity magnitude during the global inspection mode at the lower altitude is 0.0454 m/s, which is slightly greater than the inspection mission at 500 km. This translates to a camera exposure time of less than 0.246 s to attain less than one pixel smear.

6. CONCLUSION

A trajectory analysis for the mission design of a microsatellite inspector vehicle was conducted and presented in this paper. The study covered an Earth orbiting mission scenario. For the orbiting case, a natural motion trajectory for inspection of the host spacecraft was primarily designed utilizing the solution to the $CW$ equations. The key factors affecting an inspection mission were discussed and detailed in this paper. The relative motion space was first explored via the $CW$ solution. From this analysis, a toolset of trajectories that would potentially be useful for vehicle inspection was developed. The methods, used in this paper, for calculating the transfer motion between these trajectories were also based on the $CW$ solution.

A baseline mission design concept for a microinspector was presented, which consisted of a deployment mode, a global inspection mode, a point inspection mode, and a disposal mode. The 3DOF simulation of the baseline mission was based on the trajectory toolset and transfer methods. The altitude and inclination of the host spacecraft’s orbit about Earth were specified for the simulation. The attitude of the microinspector was not simulated; however, the fuel usage by the attitude control system was estimated. Factors that could be used to score the successfulness of an inspection mission were also outlined. These figures of merit were used to show the effectiveness of the chosen baseline inspection mission. The hardware requirements and constraints employed in the simulation were based on JPL’s microinspector design.
Simulations of the baseline inspection mission were conducted for LEO at altitudes of 500 km and 200 km. The main conclusion for these scenarios was that the attitude motion consumed considerably more fuel than the translational motion at altitudes higher than 200 km. The total available $\Delta v$ of 15 m/s was found to be more than adequate for the entire mission at both altitudes. In order to accurately estimate the fuel expenditure for attitude control, it is recommended that a six-degree-of-freedom simulation of the microinspector’s orbital motion and attitude be developed, with fuel optimizing attitude control techniques. It was determined that to complete the inspection mission, the microinspector needs to periodically take time out of its inspection tasks and recharge the batteries by pointing at the Sun. The simulated baseline mission was able to attain image resolutions that were less than or equal to the desired maximum resolution of 1 cm, during the global inspection and point inspection mode. The minimum distance avoidance constraint of 10 m was not violated in achieving this imaging goal. The maximum relative velocity magnitude for both the 500 km and 200 km altitude cases in the baseline mission simulation showed that the camera exposure time should be less than 0.5 s to achieve less than one pixel smear.

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