Investigation of the On-Orbit Conjunction Between the MCubed and HRBE CubeSats

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***Abstract*—On October 28, 2011 six CubeSats were launched as secondary payloads with the NASA NPP satellite aboard a Delta II rocket. Two of the 1U CubeSats, MCubed and HRBE, became unintentionally stuck together on orbit. The conjunction has been verified through the Doppler characteristics of the periodic telemetry transmissions of both satellites and by the fact that the U.S. Joint Space Operations Center is providing a single two line element set for both objects. The exact cause of the conjunction is unknown, and it is hypothesized that it was caused by the magnets in both satellites. Both CubeSats include a permanent magnet for passive attitude control. We have developed a simulation to determine if magnetic conjunction is possible, and if so, under what range of initial conditions. Using the actual mass and magnetic properties of both satellites, we have shown that magnetic conjunction is possible if the initial translational separation velocity between the CubeSats is sufficiently slow. This study provides useful lessons learned for CubeSat developers as well as a method for further investigation into CubeSat deployment dynamics.**

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1. INTRODUCTION

This paper presents simulation results to investigate the cause of the unexpected conjunction of two CubeSats after deployment from the launch vehicle. On October 28, 2011 six CubeSats[2] were launched as secondary payloads with the NASA NPOES Preparatory Project (NPP) satellite aboard a Delta II rocket. The CubeSats, launched as part of the NASA CubeSat Launch Initiative, were in three Poly Picosatellite Orbital Deployers (P-PODs), a standard deployment mechanism for CubeSats [2], [3]. One P-POD held a single 3U CubeSat, one P-POD held two 1.5U CubeSats, and the third held three 1Us. After a successful launch and CubeSat deployment, two of the 1U CubeSats became stuck together unintentionally. The conjoined CubeSats are MCubed, built by the University of Michigan, and the Hiscock Radiation Belt Explorer (HRBE, formerly known as Explorer-1 Prime, E1P), built by Montana State University. Both satellites utilize permanent magnets for passive attitude control, and it is hypothesized that the magnets caused the unintentional docking.

In this paper, we present simulations that were used to investigate if the hypothesized on-orbit magnetic conjunction is possible, and if so, under what range of initial conditions. The simulations show that magnetic docking is indeed possible. The remainder of this paper is organized as follows. In Section 2, we describe the CubeSat deployment and evidence of on-orbit conjunction. In Section 3, we present the simulator that was developed to investigate magnetic conjunction. Simulation results are given in Section 4 and lessons learned are discussed in Section 5. Conclusions are given in Section 6.

2. DESCRIPTION OF THE CONJUNCTION

CubeSats are commonly launched as secondary payloads into low-Earth orbit. They are attached to and deployed from the launch vehicle using a standardized launch vehicle interface, the P-POD. The three 1U CubeSats on the NPP launch and their P-POD are shown in Figure 1. After CubeSat integration into the P-POD, the P-POD is integrated onto the launch vehicle. The three P-PODs on the Delta II rocket are shown in Figure 2.

When the launch vehicle achieves the desired orbit for the CubeSats, they are deployed from the P-POD into space. Deployment consists of the P-POD door being released and the P-POD's spring plunger pushing the CubeSats out. The door is on the $+z$ side of the P-POD in Figure 1 and is open in Figure 1(a). The P-POD spring is designed to give the CubeSats 1.5 m/s of speed away from the P-POD. To aid in CubeSat separation from each other, the CubeSats are required to place spring plungers on their feet [1]. In the P-POD, the feet of each CubeSat are pressed against each other and the force of the P-POD door compresses the plungers. Upon deployment, the compression is released as the P-POD door opens, causing the CubeSats to separate.

The launch took place October 28, 2011 from Vandenberg Air Force Base. NPP was successfully placed into its orbit, and after an orbit change, the CubeSats were successfully deployed. As with all public satellites, the U.S. Air Force Joint Space Operations Center (JSpOC) tracks the objects and provides a two-line element set (TLE) for each CubeSat. However, for the six CubeSats, only five TLEs were provided.

CubeSats are typically difficult to differentiate from each other during the first few days after launch due to their close

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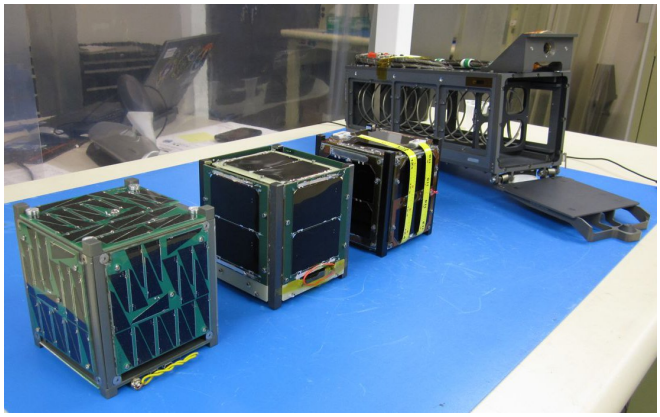
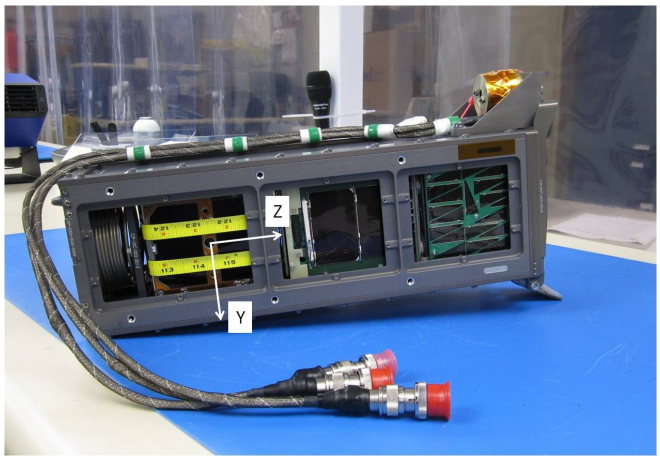
[2] A CubeSat is a standardized satellite form factor [1]. A one-unit (1U) CubeSat has approximate physical dimensions of $10 \times 10 \times 10$ cm^3 with an approximate mass of 1 kg. Two other common configutions are 2U ($10 \times 10 \times 20$ cm^3, 2 kg) and 3U ($10 \times 10 \times 30$ cm^3, 3 kg).



(a)The CubeSats before integration into the P-POD. Shown from left to right are AubieSat-1, HRBE, MCubed, and the P-POD.



(b)The CubeSats integrated into the P-POD. The body-fixed coordinate system of MCubed is shown; the HRBE body-fixed coordinate system is aligned with the MCubed body frame. From left to right, the order of the CubeSats in the P-POD is MCubed, HRBE, and AubieSat-1. AubieSat-1 is deployed first. In this photo, the access ports on the P-POD are open.

Figure 1: Three CubeSats and their P-POD that were launched with NASA NPP in October 2011. Photos provided by Cal Poly University.

proximity. As they move away from each other over time due to atmospheric drag and Earth's oblateness, they can be uniquely identified. MCubed and HRBE never moved away from each other. This was confirmed early in the mission by measuring the Doppler shift of HRBE and MCubed periodic telemetry transmissions. The Doppler shift indicated that the time of closest approach to the ground station was identical for HRBE and MCubed. This was still true weeks and months after launch, proving that the satellites are somehow conjoined.

From subsequent conversations with JSpOC, only five CubeSats were identified in the initial tracking approximately one hour after deployment. This suggests that the CubeSats became conjoined shortly after deployment. Therefore, we hypothesize that the CubeSats recontacted each other and became conjoined after P-POD deployment due to magnetic forces and torques.

Figure 2: The NPP satellite inside the Delta II nose cone. The three P-PODS are visible and indicated by the overlaid boxes. Photo credit: NASA/VAFB.

3. Simulator Development

We have developed a simulation to investigate the possibility of magnetic re-contact after P-POD deployment. In the following subsections, we present the assumptions used in developing the simulator, give the magnetic and mass properties of each satellite, and present the equations of motion.

Assumptions

Immediately after P-POD deployment, when the CubeSats are no longer in contact with each other, the only forces and torques that the satellites exert on each other are caused by their magnets. Each satellite utilizes a permanent magnetic for passive attitude control, and the dipoles of each satellite interact with the magnetic field created by the other. The simulation propagates the equations of motion for both satellites being deployed from the P-POD. The following assumptions were used in the development of the simulator:

1. The only forces and torques acting on the satellites are those caused by each satellite's permanent magnet. This is the only coupling between the satellites, but additional forces and torques act on each individual satellite that are not included in this simulation. The gravitational force is not included since the satellites are co-located and its effect on each is the same over short time periods. The dominant torque acting on the individual satellites is the magnetic control torque due to interaction between the satellite dipoles and the geomagnetic field. This torque is not included because it requires knowledge of the attitude of the P-POD at the time

of deployment, but the P-POD attitude is not currently known to the authors.

2. The permanent magnets of each satellite act like ideal magnetic dipoles. This is an accurate approximation when the magnets are sufficiently far from each other. A near-field model should be considered in future work particularly for the MCubed magnet. Due to its length and close proximity to the edge of the CubeSat, it may be possible for the HRBE magnet to come sufficiently close to be in the near-field of the MCubed magnet [4].

3. Collisions are not included in the dynamics. The minimum allowable distance between magnets in the simulation is zero, but in reality the CubeSat structure provides a minimum distance between the magnets. This assumption is sufficient to study the potential for docking. If the satellites become close enough such that their structures are in contact, then the possibility of conjunction has already been verified without accounting for the dynamics after recontact.

4. AubieSat-1, the third CubeSat in the P-POD, does not affect the deployment dynamics. In this version of the simulation, AubieSat-1 is ignored. This is done since we are solely investigating the potential for recontact between MCubed and HRBE; AubieSat-1 also has a permanent magnet and may or may not play a role, and a logical next step is to include AubieSat-1 in the simulation.

5. The P-POD is not accelerating in inertial space. The equations of motion used in the simulation are only valid relative to an inertial (non-accelerating) coordinate frame, which we assume is attached to the P-POD. This is an approximation to simplify the calculations and does not significantly affect the behavior of the two satellites relative to one another.

The simulation is carried out by propagating the equations of motion for the dynamics of the two CubeSats in inertial space. The remainder of this section is divided into two subsections. The first provides the geometry and mass properties of the satellites and the equations of motion are given in the second.

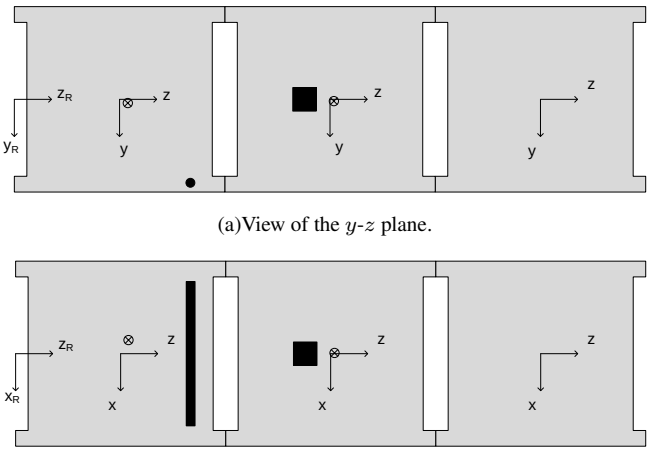
Geometry and Mass Properties

The mass and magnetic properties of each satellite, shown in Table 1, are critical parameters in the equations of motion. In the table, all values are resolved in the body-fixed coordinate system of each satellite. The magnet location defines the center of each magnet relative to the geometric center of the spacecraft. The center of mass location is also relative to the geometric center. The dipole vector points toward the north pole of the magnet, and both magnets are cylindrical.

The orientation of each CubeSat in the P-POD is shown in Figure 3. In this drawing, the CubeSats are shaded gray, the permanent magnets are colored black, the center of mass location is shown with the $\otimes$ symbol, and the body-fixed coordinate system of each satellite is shown originating at the geometric center. For comparison, this coordinate system is also shown in Figure 1(b). In the P-POD, the body-fixed coordinate systems are aligned with each other. The deployment direction is the $+z$ direction. The reference coordinate system used in the simulations, fixed to the P-POD, is shown to the left of the CubeSats and designed with the R subscript.

Equations of Motion

We use a state-space model to define the equations of motion. The states completely describe the three-dimensional dynamics and kinematics of both satellites, and the states are related by first order differential equations. There are 26 states total, which are composed of 13 for each satellite: six define position and velocity, four are quaternions used to parametrize attitude, and three are angular velocity. Throughout this section, we use subscripts i and j to denote the two different satellites, and it does not matter which satellite corresponds to each subscript. Dot notation is used for time derivatives, where $\dot{a}(t) = \frac{\partial a(t)}{\partial t}$, and the time argument (t) is omitted for compactness of the equations of motion.



(a)View of the y-z plane.

(b)View of the x-z plane.

Figure 3: Drawing of the CubeSat configuration inside the P-POD. From left to right are MCubed, HRBE, and AubieSat-1. The drawing is scaled 1:4 and shows the locations of the center of mass ($\otimes$) and permanent magnets (black) in each satellite (shaded gray). The CubeSats are deployed in the $+z$ direction; AubieSat-1 is first to exit the P-POD.

The first three states are satellite position in Cartesian coordinates. The 3×1 state vector $\vec{r}_i(t)$ is the position of the center of mass of the i-th satellite relative to the reference point, which is the origin of the reference frame shown in Figure 3 (the back of the P-POD). The time derivative of position is velocity, given by Eq. (1).

$$\dot{\vec{r}}_i = \vec{v}_i \tag{1}$$

The time derivative of velocity in an inertial frame is acceleration, which is given by Newton's Second Law of motion as in Eq. (2).

$$\dot{\vec{v}}_i = \frac{\vec{F}_i}{m_i} \tag{2}$$

In Eq. (2), m_i is the constant mass of the i-th satellite and $\vec{F}_i$ is the total force acting on the i-th satellite. The only forces included in the simulation are those exerted by the magnets of each satellite on the other. Given two magnetic dipoles $\vec{\mu}_i$, $\vec{\mu}_j$ and the position of the j-th dipole with respect to the i-th dipole, $\vec{r}_{\mu_j/\mu_i}$, the force acting on the i-th dipole caused by the j-th dipole is given by Eq. (3) [5], where μ_0 is the

Table 1: Mass and magnetic properties of the MCubed and HRBE satellites.

Property	**MCubed**	**HRBE**
Mass (kg)	1.08	0.96
Moment of inertia (kg-mm^2)	$\begin{bmatrix} 1672 & 210 & -393 \\ 210 & 4566 & -29 \\ -393 & -29 & 4434 \end{bmatrix}$	$\begin{bmatrix} 1730 & 2 & -56 \\ 2 & 1785 & -9 \\ -56 & -9 & 1863 \end{bmatrix}$
Center of mass location (mm)	$(-7.4,\ 1.9,\ 4.3)$	$(-0.4,\ 1.0,\ 2.1)$
Magnet location (mm)	$(0,\ 45.3,\ 37.8)$	$(0,\ 0,\ -13.8)$
Dipole vector (A-m^2)	$\begin{bmatrix} 1.4 & 0 & 0 \end{bmatrix}^T$	$\begin{bmatrix} 0 & 0 & 1.9 \end{bmatrix}^T$
Magnet length (cm)	7.5	1.3
Magnet diameter (cm)	0.5	1.3

permeability of free space and $\cdot$ is the dot product.

$$\vec{F}_i = \frac{3\mu_0}{4\pi}\left(-\frac{\vec{\mu}_i\cdot\vec{\mu}_j}{r^5_{\mu_j/\mu_i}}\vec{r}_{\mu_j/\mu_i} - \frac{\vec{\mu}_i\cdot\vec{r}_{\mu_j/\mu_i}}{r^5_{\mu_j/\mu_i}}\vec{\mu}_j - \frac{\vec{\mu}_j\cdot\vec{r}_{\mu_j/\mu_i}}{r^5_{\mu_j/\mu_i}}\vec{\mu}_i + 5\frac{\left(\vec{\mu}_i\cdot\vec{r}_{\mu_j/\mu_i}\right)\left(\vec{\mu}_j\cdot\vec{r}_{\mu_j/\mu_i}\right)}{r^7_{\mu_j/\mu_i}}\vec{r}_{\mu_j/\mu_i}\right) \quad (3)$$

In Eq. (3), $\vec{r}_{\mu_j/\mu_i}$ is a function of the location of the center of mass of both satellites ($\vec{r}_i$ and $\vec{r}_j$) as well as the location of the dipole of each satellite with respect to its center of mass. In all equations, all quantities must be resolved in the same coordinate frame. The attitude matrix is used to rotate between the satellite body-fixed frames and the inertial reference frame.

Quaternions [6] are used to parametrize the 3×3 spacecraft attitude matrix, A_i, which is the rotation matrix that defines the orientation of the body-fixed coordinate frame of the i-th spacecraft relative to the reference frame as in Eq. (4). In Eq. (4), $\vec{a}$ is any 3×1 vector, $\cdot|_R$ denotes that it is resolved in the reference frame R, and $\cdot|_{B_i}$ denotes that it is resolved in the body-fixed coordinate frame of the i-th satellite, B_i.

$$\vec{a}|_{B_i} = A_i\ \vec{a}|_R \quad (4)$$

Quaternion kinematics are given by [6]

$$\dot{\vec{q}}_i = \frac{1}{2}\Xi\left(\vec{q}_i\right)\vec{\omega}_i\ , \quad (5)$$

where $\vec{\omega}_i$ is the angular velocity of the spacecraft relative to the reference frame and $\vec{q}_i$ is the 4×1 quaternion vector. Quaternions are a common parametrization of spacecraft attitude; the reader is directed to existing references such as [6] for the formal definition of quaternions, rotation matrices, and conversion between the two. Angular velocity evolves according to Euler's equation for rigid body dynamics,

$$\dot{\vec{\omega}}_i = J_i^{-1}\left(\vec{T}_i - \vec{\omega}_i\times\left(J_i\vec{\omega}_i\right)\right)\ , \quad (6)$$

where J_i is the 3×3 inertia matrix of the i-th satellite, $\vec{T}_i$ is the total torque acting on the i-th satellite, and $\times$ is the cross product.

The only torques included in the simulation are due to the dipole of one satellite interacting with the magnetic field caused by the other satellite. The torque acting on the i-th dipole due to the field of the j-th dipole is

$$\vec{T}_i = \vec{\mu}_i\times\vec{B}_{ji}\ , \quad (7)$$

where $\vec{B}_{ji}$ is the field from the j-th dipole at the location of the i-the dipole and is given by Eq. (8) [5].

$$\vec{B}_{ji} = \frac{\mu_0}{4\pi}\left(\frac{3\vec{\mu}_j\cdot\vec{r}_{\mu_j/\mu_i}}{r^5_{\mu_j/\mu_i}}\vec{r}_{\mu_j/\mu_i} - \frac{\vec{\mu}_j}{r^3_{\mu_j/\mu_i}}\right) \quad (8)$$

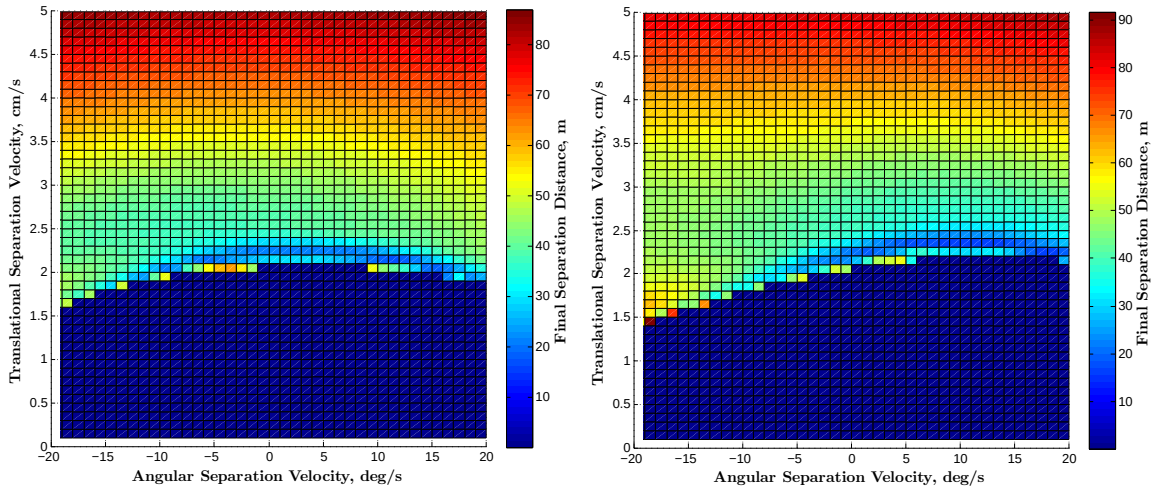
The equations of motion have been given in Eqs. (1), (2), (5), and (6). The states are coupled due to the magnetic force and torque dependence on satellite attitude and position, as shown in Eqs. (3), (7) and (8). To carry out the simulation, the initial state vector is propagated according to the equations of motion using MATLAB's *ode45*[3], a common implementation of a Runge-Kutta integrator. The P-POD spring and spring plungers on each CubeSat are not included in the equations of motion, but rather, they are manifested as initial conditions in the simulation.

4. SIMULATION RESULTS

We have varied the initial translational and angular separation velocities to determine the range of initial conditions, if any, that result in magnetic conjunction. The initial separation velocities were varied from 0.1 to 5 cm/s in 0.1 cm/s increments, and the angular velocities were varied from -20 to 20 deg/s in 1 deg/s increments. The duration of each simulation was 30 minutes. The resulting separation distance between the two satellites at the end of the simulations are shown as a function of initial condition in Figure 4. In Figure 4(a), the initial angular velocity is about the CubeSat x-axis, and in Figure 4(b), the initial angular velocity is about the y-axis. The regions of zero separation distance are where magnetic conjunction occurs.

As seen in Figure 4, magnetic conjunction occurs for the entire range of initial angular velocities when the translational

[3] `http://www.mathworks.com/help/matlab/ref/ode45.html`, accessed October 2012



(a)The initial angular velocity is about the CubeSat x-axis.

(b)The initial angular velocity is about the CubeSat y-axis.

Figure 4: The separation distance between the two satellites is color-coded and shown as a function of initial linear and angular separation velocity. The angular velocity is of HRBE relative to MCubed. The separation distance is that after a 30 minute simulation. A separation distance of 0 indicates the satellites are conjoined. For the initial conditions that resulted in conjunction, the conjunction occurred within 25 seconds following P-POD deployment.

separation velocity is less than 1.5 cm/s. Conjunction is also possible from initial translational separation of up to 2.1 cm/s depending on the initial angular velocity. For initial conditions that resulted in magnetic conjunction, the conjunction occurred within 25 seconds of CubeSat deployment.

The trajectories of HRBE relative to MCubed resulting from two representative initial conditions are shown in Figures 5 and 6. The initial translational separation velocities are 2 cm/s (resulting in conjunction) and 3.5 cm/s (no conjunction) in Figures 5 and 6, respectively. In both figures, the angular velocity is 5 deg/s in the CubeSat y-axis. The satellites are represented by 10 cm cubes and the arrow in each satellite originating at the dipole location shows the dipole direction. The position and attitude of both satellites is resolved in the MCubed body-fixed coordinate system.

Two spring plungers are located on each CubeSat to aid in separation [1]. If the spring plungers behave linearly and all of their potential energy is converted to translational separation velocity, the resulting separation velocity of the CubeSats would be approximately 15 cm/s. But a pure conversion of the potential energy of the springs to translational separation velocity is an optimistic assumption. Energy is absorbed due to friction in the springs and between the CubeSats and P-POD, and the dynamics of the CubeSats is complicated by the fact that as soon as the P-POD door opens, the compression between the CubeSat spring plungers is released at the same time that all three CubeSats are pushed out of the P-POD by the main spring. The actual translational and rotational velocities of CubeSats coming out of the P-POD are not well characterized due to the lack CubeSat attitude data following deployment. The range of translational separation velocities used in the simulations was chosen since it shows the initial conditions resulting in magnetic conjunction, and the range of $+/-$ 20 deg/s was used for initial angular velocity because the maximum measured angular velocity of the RAX-2[4] CubeSat was approximately 20 deg/s [7]. Investigation into how much of this angular velocity was due to launch vehicle rotation compared to that resulting from P-POD deployment has not been completed.

[4]RAX-2 is a 3U CubeSat that was on the same launch vehicle as MCubed and HRBE.

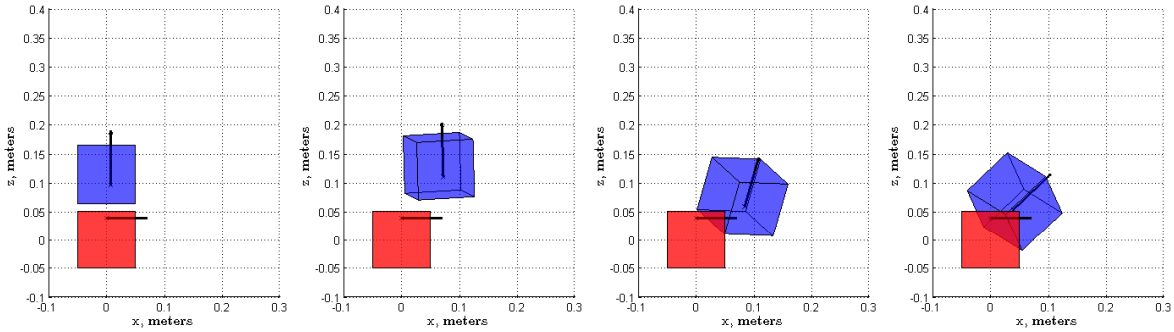
Table 2: A sample of dipole strengths of the passive magnetic control system of other CubeSats. The dipole strengths of MCubed and HRBE are shown in Table 1.

CubeSat (size)	Dipole Strength (A-m^2)	Reference
KySat-1 (1U)	0.59	[8]
XI-IV (1U)	0.05	[9]
CCSWE (3U)	0.3	[10]
QuakeSat (3U)	2.9	[11]

The dipole strengths of MCubed and HRBE are relatively high compared to other CubeSats, a sample of which are shown in Table 2. Since the weaker dipoles will result in weaker forces and torques, weaker dipoles should be less likely to result in magnetic conjunction. To quantify this expectation, we have repeated the simulations with a magnetic dipole strength of 0.5 A-m^2 in each satellite while keeping all other simulation parameters the same. The results are shown in Figure 7. The simulations indicate that magnetic conjunction is possible if the translational separation velocity is less than 0.6 cm/s, significantly less than the initial conditions resulting in conjunction when simulating the actual dipole strengths shown in Table 1.

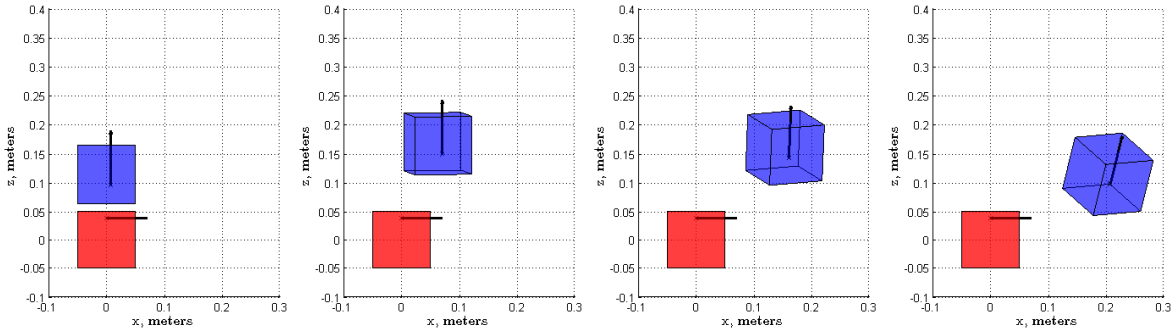
5. Lessons Learned

The simulations have shown that magnetic conjunction between MCubed and HRBE is possible. The separation velocity at which conjunction occurs is less than the expected separation velocity of CubeSats, but actual CubeSat separation velocity after P-POD deployment is unknown. If the conjunction was indeed due to the magnets, the simulations of this paper indicate that the translational separation velocity



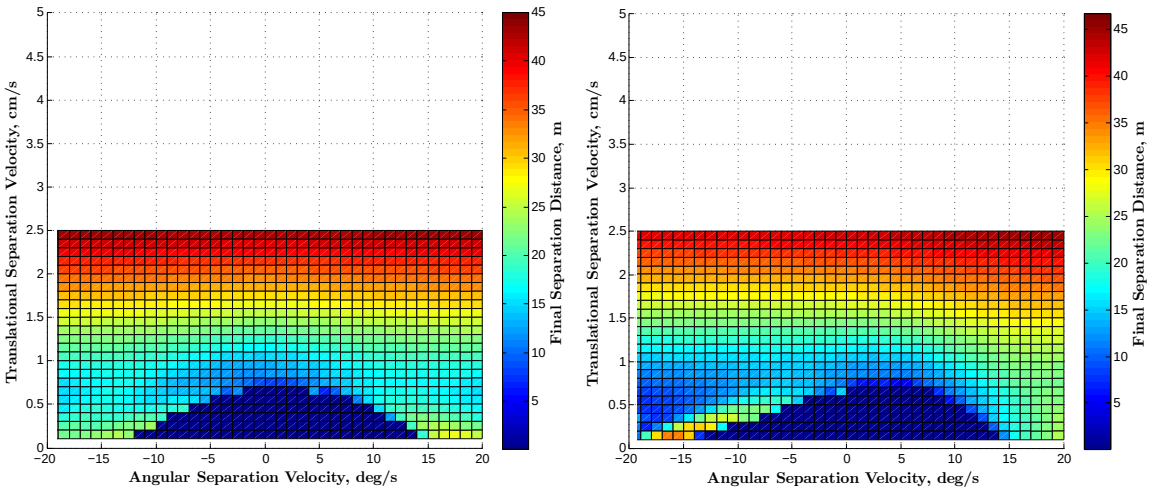
(a) $t = 0$ (b) $t = 2$ (c) $t = 4$ (d) $t = 6$

Figure 5: The MCubed and HRBE trajectories resulting from an initial translational separation velocity of 2 cm/s and an angular separation velocity of 5 deg/s in the y-axis of HRBE relative to MCubed. Relative locations and orientations are shown at elapsed times of $t = 0, 2, 4$ and 6 seconds. The satellites are shown in the MCubed body-fixed frame. MCubed is shaded red and HRBE is shaded blue. The arrows in each satellite are the dipole vectors originating at the dipole location in each satellite. These initial conditions result in conjunction.



(a) $t = 0$ (b) $t = 2$ (c) $t = 4$ (d) $t = 6$

Figure 6: The MCubed and HRBE trajectories resulting from an initial translational separation velocity of 3.5 cm/s and angular separation velocity of 5 deg/s in the y-axis of HRBE relative to MCubed. All other conditions are the same as Figure 5. These initial conditions do not result in conjunction.



(a)The initial angular velocity is about the CubeSat x-axis. (b)The initial angular velocity is about the CubeSat y-axis.

Figure 7: The results of simulations in which both satellites have a dipole strength of 0.5 A-m^2. All other simulation parameters are the same as what produced the results of Figure 4.

of the CubeSats was less than 2.1 cm/s. This suggests that a thorough study of the deployment dynamics resulting from the CubeSat spring plungers and the P-POD main spring would be useful.

Another factor to consider is the size of the permanent magnets used on CubeSats. There is currently no requirement limiting the magnet strength of CubeSats [1]. The analysis of other CubeSat developers has shown that dipole strengths near 0.5 A-m^2 are sufficient for passive attitude control [8], [10], which is approximately one third the size of both the MCubed and HRBE magnets. The simulations of this paper indicated that if the dipoles of both satellites were 0.5 A-m^2, magnet conjunction would only occur of translational separation velocities were less than 0.6 cm/s.

6. Conclusions

We have performed simulations to investigate the possibility of on-orbit magnetic conjunction between two CubeSats following deployment from the P-POD. Conjunction of MCubed and HRBE on-orbit has been confirmed by JSpOC tracking (one TLE for two objects) and the Doppler characteristics of the periodic transmissions of both satellites. The exact cause of the conjunction is unknown, and we hypothesize that it was caused by the magnets within each satellite that were intended for passive attitude control. Using the actual mass and magnetic parameters of the two satellites, we have shown that magnetic conjunction is possible if the translational separation velocity of the two CubeSats following P-POD deployment is less than 2.1 cm/s. Natural continuations of this work to increase the fidelity of the simulations would be to include the geomagnetic field, a near-field model of the satellite magnets, and the third CubeSat in the P-POD, AubieSat-1, in the simulations. These additions are left for future work. The simulation method and the lessons learned from this paper are useful for CubeSat developers and for further investigation into CubeSat deployment dynamics.

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Biography

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James Cutler is an Assistant Professor of Aerospace Engineering at the University of Michigan. He received his B.S. in Computer and Electrical Engineering from Purdue University and his M.S. and Ph.D. in Electrical Engineering from Stanford University. His research interests center on space systems – a multidisciplinary approach to enabling future space capability with a particular emphasis on novel, nanosatellite missions. He is co-PI on the first NSF sponsored satellite mission, the Radio Aurora Explorer (RAX). Prof. Cutler's teaching interests are in all things space related.