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An Optimization Method for Nano-satellite and Pico-satellite Separation through a Two Mass-One Spring System

Shu Ting Goh, Zi Rui Lau, and Kay Soon Low

Abstract

This paper studies the picosatellite ejection system from a nanosatellite, using one spring two mass ejection model. It is desired that both satellites maintain a long communication time after separation though they do not carry propulsion system. Moreover, the picosatellite is required to return to nanosatellite communication range in a given time period. The dynamic motion of the ejection system has been derived. The impact of ejection location, force and direction on the communication and separation time is studied. Results show that a continuous satellite communication could be maintained if the picosatellite is ejected in perpendicular to the flight path direction. However, the possible collision between the two satellites is to be taken into consideration.

I. INTRODUCTION

The CubeSat standard was proposed by California Polytechnic State University’s Multidisciplinary Space Technology Laboratory (MSTL) and Stanford’s Space Systems Development Laboratory (SSDL) during late 1990s. The program aims to provide college student an opportunity to experience the satellite development and operating process [1]. The program has several advantages, such as lower development time and cost [2].

The first CubeSat launch, which consists of six CubeSats developed by different institutions, were successfully launched into space in 2003 [2], [3]. Since then, the CubeSat program gains its popularity from both academic and industry. The total number of launch in each year has been increased. The CubeSat is capable of carrying various mission objectives. The earth observation is the common mission objective among the CubeSat mission [4], [5]. However, other studies, such as the GeneSat-1, which studies the genetic changes in bacteria in the space environment, and the Quakerfinder, which detects the Extremely Low Frequency magnetic wave at 600-900km altitude for earthquake detection purpose have been successfully conducted in space [1].

The satellite research centre (SaRC) of Nanyang Technological University (NTU) has an ongoing nanosatellite development program, VELOX-I. It is in its flight model stage and will be ready for launch in late 2013. VELOX-I

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carries an in-house developed remote sensing camera, a Small Photon-Entangling Quantum System (SPEQS) and a picosatellite. The remote sensing camera serves as the primary payload of the VELOX-I for earth observation purpose. The SPEQS, a quantum science payload is the secondary payload of the VELOX-I, which studies the quantum entanglement test in space environment. The picosatellite will be ejected from the nanosatellite to study non-constellation formation flying, and the wireless communication between two satellites. After the ejection, the nanosatellite periodically broadcasts a request signal. The picosatellite replies the signal back to the nanosatellite, together with its housekeeping information if it is within the communication range.

The small satellite ejection system from a larger satellite has been previously demonstrated by NASA, Japan and Canada Space Agency. The NanoSail-D2 was ejected from FASTSAT using the Poly Picosatellite Orbital Deployer (P-POD), a deployment system that is specifically designed to deploy the nanosatellite from satellite launch vehicle [6]. The Japan Canada Joint Collaboration Satellites (JC2Sat) are separated through a four intersatellite separation mechanisms[7], [8], [9]. While the NanoSail-D2 is left for free flight after the separation, the JC2Sat maintain their formation distance using the drag differential system[10]. The picosatellite ejection system in VELOX-I uses a one spring-two mass system. It is required to either maintain the longest possible communication period to the nanosatellite, or return to the nanosatellite communication range within a given period. However, both satellites do not carry propulsion or drag control system due to payload and size restriction. Thus, both satellite’s dynamic motions are uncontrollable after the ejection and optimizing the ejection system is necessary.

In this paper, the impact of ejection force, ejection location and ejection angle on the total communication time, and the separation period between the two satellites will be studied. The communication time is defined as the total time period which the picosatellite is within the nanosatellite communication range. The separation period is the total time required by both satellites to return to their communication range after they have drifted away from their communication range. The nanosatellite is assumed to be in the nadir pointing mode during the initial ejection phase. The picosatellite ejection direction is represented by a two-rotation sequence in Euler angle. The nanosatellite is rotated about the z-axis (or from earth center to nanosatellite), then followed by the rotation about the y-axis of the local reference frame. First, a simulation is conducted to study the total communication time and separation period between the two satellites using the Matlab software, with the assumption of no perturbation. Then, the simulation is also conducted using General Mission Analysis Tool (GMAT) to compare with the result obtain through the Matlab software.

The paper is organized as follow. Next section gives an overview of the VELOX-I program. Then, the satellite dynamic motion during the ejection is presented, followed by the derivation of the two-mass one-spring system for the picosatellite and nanosatellite ejection. Finally, the simulations and results are presented, followed by the conclusion.

II. VELOX-I PROGRAM

The VELOX-I is an ongoing nanosatellite development program in NTU. It is currently in the flight model stage, and is expect to be launched in Q4 2013. Figure 1 shows the VELOX-I configuration in launch mode,
Fig. 1. The VELOX-I in (a)Launch configuration and (b) After deployment configuration.

and after the deployment. The VELOX-I has the size of $100\text{mm} \times 100\text{mm} \times 340\text{mm}$ with a mass of 4.5kg. The picosatellite dimension is expected to be $60\text{mm} \times 70\text{mm} \times 30\text{mm}$. The VELOX-I is expected to be launched into the sun-synchronous orbit at the altitude between 650-700km, with the mission life time of two years for the nanosatellite and one year for the picosatellite.

The VELOX-I program carries few mission objectives. The primary objective is providing an opportunity for the students in NTU to experience the development and operation of the nanosatellite. Several nanosatellite subsystems are in-house developed by the SaRC team, such as the attitude determination and control system, and the satellite power system. In addition, the VELOX-I carries three in-house developed payload for technology demonstration purpose. The remote sensing camera serves as the primary payload, both the SPEQS and the picosatellite serve as the secondary payload. It is noted that due to the P-POD design constraint, the camera lens will only be extended to the desired focus length after the nanosatellite has been stabilized (see Figure 1).

The remote sensing camera developed for VELOX-I is a Complementary metal-oxide-semiconductor (CMOS) image sensor. It is designed to capture a greyscale earth image at the resolution of $768 \times 512$, which is expected to be 21m on the ground for each pixel at the altitude of 650km. It is commonly known that the space-radiation reduces the CMOS sensor performance due to the leakage current, shift of threshold voltage and dark signal noise[11]. Therefore, the CMOS image sensor for VELOX-I is designed to improve its radiation hardness through reducing the leakage current and the voltage shift.

The SPEQS is developed to demonstrate the feasibility of conducting the quantum entanglement test in Low Earth
Orbit (LEO) through generating a high quality polarization entangled photon pair [12]. The collected polarization correlation data in space will be compared to the data on the ground to confirm quantum entanglement demonstration in the LEO. The SPEQS may also carry out its second mission objective, which is observing the long term behavior of single photon detectors and pump laser diode in LEO based on the Heralded Single Photon Source (HSPS)[13].

Figure 2 presents the 3D model and the qualification model (QM) of the picosatellite. After the ejection, the picosatellite and the nanosatellite perform the intersatellite communication through the XBEE communication module. The picosatellite transmits its house keeping data, such as satellite temperature, power and health status to the nanosatellite through the communication link. Due to the fact that the picosatellite ejection configuration impacts the total intersatellite communication time between two satellites, it is required to maximize the communication time between two satellites before the end of picosatellite mission lifetime. In addition, it is required to ensure the total communication time is long enough for both satellite to successfully perform the intersatellite communication.

III. SATELLITE DYNAMIC MOTION DURING EJECTION

This section presents the dynamic motion of two satellites during the picosatellite ejection process. Figure 3 illustrates the picosatellite ejection angles, $\phi$ and $\psi$, with respect to the nanosatellite flight path direction. Several requirements have been considered. First, the nanosatellite is maintained in the nadir pointing mode during the initial phase of ejection process, where its x-axis ($b_1$ direction) points along the flight path direction, and z-axis (negative $b_3$ direction as shown in Figure 3) points toward the earth center. In addition, two ejection angles, $\phi$ and $\psi$ are considered. The $\phi$ rotates about the $b_3$ axis in Figure 3, and $\psi$ rotates about the y-axis of reference frame resulted by the $\phi$ rotation angle. Thus, the ejection angle direction is expressed in term of 3-2 rotation sequence, with respect to the $b_1 - b_2 - b_3$ reference frame (or B-reference frame).

During the initial time, $t_0$, of the ejection process, both satellites are considered to have a same absolute position,
Fig. 3. The illustration of picosatellite ejection angle.

\( \mathbf{r} \), and velocity, \( \mathbf{v} \), which are:

\[
\begin{align*}
\mathbf{r}_n(t_0) &= \mathbf{r}_p(t_0) = \mathbf{r}^N (1a) \\
\mathbf{v}_n(t_0) &= \mathbf{v}_p(t_0) = \mathbf{v}^N (1b)
\end{align*}
\]

where the subscript \( n \) and \( p \) denote nanosatellite and picosatellite respectively, and superscript \( N \) denotes the position and velocity vector are expressed in inertial reference frame.

Let the position and velocity of both satellites at \( t_0 \) to be expressed in B-reference frame:

\[
\begin{align*}
\mathbf{r}_n^B(t_0) &= \mathbf{r}_p^B(t_0) = (A^N_B)^T \mathbf{r}^N (2a) \\
\mathbf{v}_n^B(t_0) &= \mathbf{v}_p^B(t_0) = (A^N_B)^T \mathbf{v}^N (2b)
\end{align*}
\]

where the superscript \( B \) denotes the B-reference frame, and \( A^N_B \) is the attitude matrix between the inertial reference frame and B-reference frame, which corresponds to:

\[
A^N_B = \begin{bmatrix}
\frac{\mathbf{v}^N}{\|\mathbf{v}^N\|} & \frac{\mathbf{v}^N \times \mathbf{r}^N}{\|\mathbf{v}^N \times \mathbf{r}^N\|} & \frac{\mathbf{r}^N}{\|\mathbf{r}^N\|}
\end{bmatrix}
\]

where \( \| \cdot \| \) denotes the vector magnitude and both \( \mathbf{r}^N \) and \( \mathbf{v}^N \) are the absolute position and velocity of nanosatellite at \( t_0 \).

At the time \( t_r \), which the spring is fully elongated (or both satellites are succesfully separated), the position of the picosatellite and the nanosatellite can be approximated as:

\[
\begin{align*}
\mathbf{r}_p^N(t_r) &\approx \mathbf{r}^N + A^N_B(\mathbf{v}^B_{t_r} + R_p(A^E_B)^T s) (4a) \\
\mathbf{r}_n^N(t_r) &\approx \mathbf{r}^N + A^N_B(\mathbf{v}^B_{t_r} - R_n(A^E_B)^T s) (4b)
\end{align*}
\]
Both $R_p$ and $R_n$ are the travelled distances by both satellites due to the spring elongation. The derivation of $R_p$ and $R_n$ are shown in Eqs. (18a) and (18b) in the next section. The vector $s$ in Eq. (4) is given as:

$$s = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T$$ (5)

In addition, $A_{EB}^E$ is the attitude matrix, which is resulted by both $\phi$ and $\psi$ rotation angles with respect to the B-reference frame. The matrix $A_{EB}^E$ is given as:

$$A_{EB}^E = \begin{bmatrix}
\cos \psi \cos \phi & \cos \psi \sin \phi & -\sin \psi \\
-\sin \phi & \cos \phi & 0 \\
\sin \psi \cos \phi & \sin \psi \sin \phi & \cos \psi
\end{bmatrix}$$ (6)

We assume that the elongation time is small $t_r < 1$, thus, the velocity changes due to the acceleration of satellite is negligible, $a_n t_r = a_p t_r \approx 0$. Then, the velocity of both satellites at $t_r$ are approximated as:

$$v_n^N(t_r) \approx A_{EB}^N (v^B + V_n(t_r) A_{EB}^E T s)$$ (7a)

$$v_p^N(t_r) \approx A_{EB}^N (v^B - V_p(t_r) A_{EB}^E T s)$$ (7b)

where $V_n$ and $V_p$ are the velocity changes due to the spring force, derived in Eqs. (15a) and (15b) in the next section.

IV. ONE SPRING-TWO MASS EJECTION MODEL

The satellite utilizes a single compression spring system to release the picosatellite from the nanosatellite. As indicated in previous section, two ejection angles, $\phi$ and $\psi$ are considered. Eqs. (4) to (7) show the approximated position and velocity of both satellites, after the ejection process, are in the function of $R_n$, $R_p$, $V_n$ and $V_p$. To compute these parameters, we first assume the maximum acceleration force occurs at the time instance the spring is allowed to be released. The acceleration force linearly decreases as the spring is elongated. Then, the acceleration both the satellites can be written as:

$$\ddot{x}^{(n)}(t) = c_1^{(n)} t + c_2^{(n)}$$ (8a)

$$\ddot{x}^{(p)}(t) = c_1^{(p)} t + c_2^{(p)}$$ (8b)

where $c_1$ and $c_2$ are the arbitrarily constant, superscript $(p)$ denotes picosatellite, and superscript $(n)$ denotes nanosatellite.

Both satellites’ speed and traveled distance are computed by integrating Eqs. (8a) and (8b) with respect to time, $t$, which correspond to:

$$\dot{x}^{(n)}(t) = \frac{1}{2} c_1^{(n)} t^2 + c_2^{(n)} t + c_3^{(n)}$$ (9a)

$$\dot{x}^{(p)}(t) = \frac{1}{2} c_1^{(p)} t^2 + c_2^{(p)} t + c_3^{(p)}$$ (9b)

$$x^{(n)}(t) = \frac{1}{6} c_1^{(n)} t^3 + \frac{1}{2} c_2^{(n)} t^2 + c_3^{(n)} t + c_4^{(n)}$$ (10a)
\[ x^{(p)}(t) = \frac{1}{6}c_1^{(p)}t^3 + \frac{1}{2}c_2^{(p)}t^2 + c_3^{(p)}t + c_4^{(p)} \quad (10b) \]

It is noted that \( x^{(n)}(t_r) = R_n \), \( x^{(p)}(t_r) = R_p \), \( x^{(n)}(t_r) = V_n \) and \( \dot{x}^{(p)}(t_r) = V_p \). Eqs. (10a) and (10b) show that there are 4 unknown parameters, \( c_1 \), \( c_2 \), \( c_3 \), and \( c_4 \) to be determined for each satellite. By considering that \( x^{(n)}(t_0) = x^{(p)}(t_0) = 0 \) and \( \dot{x}^{(n)}(t_0) = \dot{x}^{(p)}(t_0) = 0 \) at \( t = 0 \), then \( c_3^{(n)} \), \( c_4^{(n)} \), \( c_3^{(p)} \) and \( c_4^{(p)} \) are equal to zero. Then, two parameters, \( c_1 \) and \( c_2 \) are required to be determined for each satellite. However, \( R_n \), \( R_p \), \( V_n \) and \( V_p \) can be computed, without explicitly solving both \( c_1 \) and \( c_2 \).

Next, by considering the following conservation of energy and momentum between nanosatellite and picosatellite before and after the separation:

\[ E = \frac{1}{2}M_nV_n^2 + \frac{1}{2}M_pV_p^2 = \frac{1}{2}kL^2 \quad (11) \]

\[ M_nV_n = M_pV_p \quad (12) \]

where \( k \) is the spring constant, \( E \) is the spring energy, \( L \) is the total elongation length, and \( M_n \) and \( M_p \) are the nanosatellite and picosatellite mass respectively.

By substituting Eq. (12) into (11), the change of velocity, \( V_n \) and \( V_p \), expressed in terms of \( E \), \( M_n \) and \( M_p \) are given as:

\[ V_n = \sqrt{\frac{2EM_p}{M_n(M_n + M_p)}} \quad (13a) \]

\[ V_p = \frac{M_n}{M_p}V_n = \sqrt{\frac{2EM_p}{M_p(M_n + M_p)}} \quad (13b) \]

Assuming that the acceleration force exerted by the spring at \( t_r \) is equal to zero, \( \ddot{x}^{(n)}(t_r) = \ddot{x}^{(p)}(t_r) = 0 \), Eq. (8) becomes:

\[ c_2^{(p)} = -c_1^{(p)}t_r \quad (14a) \]

\[ c_2^{(n)} = -c_1^{(n)}t_r \quad (14b) \]

Considering the fact that \( \dot{x}^{(n)}(t_r) = V_n \) and \( \dot{x}^{(p)}(t_r) = V_p \) at \( t = t_r \), by substituting Eq. (14) into Eq. (9), we obtain:

\[ V_n = \frac{1}{2}c_1^{(n)}t_r^3 + c_2^{(n)}t_r = \frac{1}{2}c_1^{(n)}t_r^2 \quad (15a) \]

\[ V_p = \frac{1}{2}c_1^{(p)}t_r^3 + c_2^{(p)}t_r = \frac{1}{2}c_1^{(p)}t_r^2 \quad (15b) \]

The total distance traveled by both satellites at \( t_r \) is equal to the spring elongation length, \( R_n + R_p = L \). Substitute Eq (10) into \( R_n + R_p = L \), we obtain:

\[ L = \frac{1}{6}c_1^{(p)}t_r^3 + \frac{1}{2}c_2^{(p)}t_r^2 + \frac{1}{6}c_1^{(n)}t_r^3 + \frac{1}{2}c_2^{(n)}t_r^2 \quad (16) \]

By substituting Eqs. (14) and (15) into Eq. (16), the \( t_r \) can be expressed in term of \( M_n, M_p, L \) and \( E \):

\[ t_r = \sqrt{\frac{9L^2M_nM_p}{8E(M_n + M_p)}} \quad (17) \]
Finally, substitutes Eqs. (15) and (17) into Eq. (10), the relative distance traveled by the nanosatellite and the picosatellite are:

\[ R_n = \frac{M_p L}{M_n + M_p} \]  
\[ R_p = \frac{M_n L}{M_n + M_p} \]  

Using Eqs. (14), (17) and (18), the ejection time, \( t_r \), the relative position, \( R_n \) and \( R_p \), and relative velocity, \( V_n \) and \( V_p \) between picosatellite and nanosatellite will be used to compute their respective absolute position and velocity in Eqs. (4) and (7) after the picosatellite is fully ejected from the nanosatellite.

V. SIMULATION AND RESULTS

Simulations are conducted to study the impact of ejection angles, location and spring constant on the total communication time, \( t_{comm} \), between the two satellites. The total separation period, \( t_{sep} \), between them is also investigated to study the subsequent intersatellite communication experiment. The \( t_{comm} \) is the total time period when both the satellites are within their communication range, and the \( t_{sep} \) is the total time period when both the satellites are out of their communication range. The nanosatellite is assumed to orbit at the altitude of 650km. In addition, its orbit is assumed to be a near circular orbit with the eccentricity of 0.001, and its orbit parameters are given as follow: the initial true anomaly, \( \theta(t_0) \), the right ascension of ascending node, \( \Omega \) and the argument of perigee, \( \omega \), are assumed to be 0 degree. The inclination of the nanosatellite is computed based on the sun-synchronous orbit equation, which can be found in Reference [14].

First, the simulation is conducted using the Matlab, by assuming both satellites do not experience any perturbation effect. Both satellites are propagated using the Kepler’s equation of motion [15]. The maximum simulation time, \( t_{max} \) is 350 days. Based on the hardware’s manufacturer data sheet, the maximum communication range between the two satellites is 3km, and the spring constant of 10N/m and 50N/m are considered. Here, the ejection location is assumed at the perigee position, \( \theta = 0 \) degrees. Both \( t_{comm} \) and \( t_{sep} \) are studied with respect to a given range of ejection angle and the spring constant.

Next, the simulation is conducted using the GMAT software to confirm the results obtain in the first simulation, and study the minimum distance between two satellites during the intersatellite communication phase to avoid any potential collision. The perturbation model is configured as follow: (1) The Earth Gravitational Model 1996 (EGM-96) with 10th degree and 10th order is considered; (2) The solar radiation pressure is assumed to be 1367W/m²; and (3) The MSIS-E-90 Atmospheric Model is considered. Here, the range of ejection angle is selected based on the result in the first simulation. However, three ejection locations are considered, the perigee position, \( \theta = 0 \) degrees, and apogee position, \( \theta = 180 \) degrees, and the semiminor axis location, \( \theta = 90 \) degrees. In addition, only the \( t_{comm} \) will be investigated in this simulation.

A. Results - MATLAB Perfect Model

Figure 4 presents the total \( t_{comm} \) between the two satellites with respect to different ejection angle. The ejection location is assumed to be 0 degree of true anomaly. Figure 4 shows that \( t_{comm} \) increases significantly when the
rotation angle is closed to 90 degrees. It is noted that the maximum $t_{comm}$ does not occur exactly at 90 degrees in both $\phi$ and $\psi$. For an ideal condition, e.g., there is no perturbation, a continuous intersatellite communication time which is more than 100 days can be achieved, if the picosatellite is ejected at the appropriate ejection angles. Furthermore, it is observed that varying the ejection spring constant from 10N/m to 50N/m results in similar behavior. In addition, it is observed that the $t_{comm}$ is identical for the case that both $\phi$ and $\psi$ are within other range of rotation angles.

Figure 5 shows that the $t_{sep}$ is higher than 350 days except for the cases where both $\phi$ and $\psi$ are closed to 90 degrees (or 270 degrees). One reason is the mean motion difference between two satellites is in the order of $10^{-6} \text{deg/sec}$. Thus, both satellites require long period to return to their communication range. The relative distance between the two satellites, $r_{n/p}$, can be expressed as composite of polynomial and sinusoid function, which behaves
as an oscillator. Therefore, there is a possibility where both satellite would return to their communication for a short period after both satellites are drifted away from their communication range.

![Image](https://via.placeholder.com/150)

**Fig. 6.** The second $t_{comm}$ (in minutes) between two satellites with respect to different ejection angle and spring constant: (a) 10N/m, and (b) 50N/m.

Figure 6 shows the $t_{comm}$ after both satellites return to their communication range with respect to different ejection angle, which is denoted as second $t_{comm}$. The results show that both satellites will only return to their communication range if the picosatellite is ejected in a selected range of ejection direction. In addition, both figures show that higher spring constant (or ejection force) results a more narrow range of ejection direction for both satellite to achieve the similar condition. Figure 6 shows that the second $t_{comm}$ is in the range of 20 to 80 minutes, which is much lesser than the first $t_{comm}$ in Figure 4.

**B. Results - GMAT Perturb Model**

In the present of perturbation, Figure 7 shows that the perturbation significantly reduces the $t_{comm}$ between the satellites. Both satellites only able to perform the communication for maximum of five to six days before they are out of the communication range. Figure 7(b) shows that a higher $t_{comm}$ can be achieved if the picosatellite is ejected at the semiminor axis location ($\theta = 90$ or $\theta = 270$ degrees). However, all figures show that the maximum $t_{comm}$ does not occur at both $\phi$ and $\psi$ at 90 degrees, but at a specific combination. On the other hand, it has been observed that the $t_{comm}$ between the satellites always lower than an hour if the spring constant of 50N/m is chosen.

Although Figures 4 and 7 have shown the best possible range of the two ejection angles, $\phi$ and $\psi$, which could results in a high $t_{comm}$, the minimum relative distance between the two satellites should be studied to avoid any potential collision. Figure 8 presents the minimum distance between two satellites during the intersatellite communication experiment period. Both satellites drift away from each other at the time instance the picosatellite is ejected but will approach each other later. The minimum distance is measured during the phase when both satellites...
are approaching each other. It has been observed that the minimum distance range is proportional to the \( t_{\text{comm}} \), that is, higher \( t_{\text{comm}} \) results shorter minimum distance. For ejection direction where the \( t_{\text{comm}} \) is higher than two days, the minimum distance is observed to be within 12 to 14 meters. This result indicates that safe distance is maintained during the intersatellite communication experiment.

**VI. Conclusion**

This paper has presented the picosatellite ejection model from the nanosatellite. The ejection model is derived based on a two mass-single spring system, where the picosatellite is ejected in the direction based on a 3-2 rotation sequence, with respect to the nanosatellite nadir pointing mode reference frame. By considering the conservation of energy and momentum laws, the time required by the spring to be fully elongated, and the changes of position and velocity of the two satellites due to the spring force can be approximated.

Simulations have been conducted to study the impact of the ejection angle, spring force (or spring constant) and ejection location on the total communication time, \( t_{\text{comm}} \), and separation time, \( t_{\text{sep}} \) between two satellites. The results show that a \( t_{\text{comm}} \) of longer than 100 days can be achieved if the picosatellite is ejected in the direction with both \( \phi \) and \( \psi \) within 85 to 95 degrees. In addition, due to the oscillating characteristic of the two satellites relative distance, both satellites may return to their communication range for intersatellite communication experiment, after both satellite are drifted away from each other during the first time. In general, the \( t_{\text{sep}} \) between two satellites is much longer due to the fact that their mean motion difference are in the magnitude of micro degrees.

From the results, the maximum \( t_{\text{comm}} \) range is between 5 to 6 days, and the ejection location at semiminor axis has the highest possible \( t_{\text{comm}} \). It also shows that higher spring constant significantly reduces \( t_{\text{comm}} \). Furthermore, the study shows that the minimum distance between two satellites is at least 12 meter from each other.

**References**


Fig. 8. The minimum distance after ejection with respect to different ejection directions: (a) at perigee, (b) at semiminor axis, and (c) apogee.