Research Article
Near-Earth Asteroid Surveillance Constellation in the Sun-Venus Three-Body System

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The threat of potential hazardous near-Earth asteroid (PHA) impact on Earth is increasingly attracting public attention. Monitoring and early warning of those PHAs are the premise of planetary defense. In this paper, we proposed a novel concept of surveillance constellation of heterogeneous wide-field near-Earth asteroid (NEA) surveyors (CROWN), in which six space-based surveyors are loosely deployed in Venus-like orbits to detect the NEAs along the direction of the sunlight. First, the concept and overall design of the NEA surveillance constellation are discussed. Second, the transfer and deployment trajectory of the surveyors are investigated based on the Sun-Venus three-body system. The Sun-Venus libration orbit is taken as the parking orbit, and its stable invariant manifolds are used to reduce the deployment fuel consumption. Next, the detection performance of the CROWN was evaluated considering constraints of apparent visual magnitude and field of view. The NEA orbit determination (OD) using the CROWN was studied and verified. Simulation results show that the CROWN can be deployed with a total velocity increment of approximately 300 m/s. During the 5 years of observation, 99.8% of PHAs can be detected and the OD precision is better than a single-surveyor system. This paper can provide a reference for the construction of future asteroid defense system.

1. Introduction

An enormous number of near-Earth asteroid (NEA) orbit around the Sun, and among them 2072 NEAs, which are recorded in the Minor Planet Center (MPC) database (Data available online at https://www.minorplanetcenter.net/data [retrieved July 2021]), belong to the class of potential hazardous near-Earth asteroids (PHAs) [1–7]. These PHAs frequently make close approaches to Earth’s orbit, and therefore, the hazard caused by PHAs is still a very real and ever-present threat [8, 9]. Two well-known events are the Tunguska event in 1908 [10] and the Chelyabinsk meteor event in 2013 [11, 12], in which a 17 m asteroid entered Earth’s atmosphere, damaged thousands of buildings and injured more than 1500 residents.

Faced with potential threats of PHA impacts, asteroid defense has been discussed with growing interest [13–15]. An asteroid defense system can be modeled as an OODA chain, that is, observation (O), orientation (O), decision (D), and action (A). A number of technologies for asteroid defense have been investigated, including the asteroid detection and classification [16–20], the asteroid orbit determination (OD) [21–23], and the trajectory design for in situ exploration [24–31]. Several asteroid deflection and redirection strategies are proposed [32, 33]. Among these issues, detection and early warning are the premises of the asteroid defense. The surveillance system is responsible for the early detection, tracking, and OD of NEAs [34]. The NEA surveillance systems can be divided into ground-based NEA surveillance and space-based NEA surveillance. As the name suggests, ground-based NEA surveillance systems refer to those installed on the ground. Many ground-based NEA surveillance systems have been developed such as Spacewatch [35], Catalina Sky Survey (CSS) [36], Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) [37–39], and ATLAS [40–45]. What is more, some ground-based NEA surveillance systems are being developed at the current time, for example, the Flyeye [46]. But those
ground-based surveillances are susceptible to factors related to the atmosphere and weather. They can only operate on nights [47–49] and cannot provide early warning of asteroids coming from the direction of the Sun [50].

The drawbacks of ground-based surveillance can be eliminated with a space-based platform. Space-based NEA surveillance systems have the advantages of flexibility, not limited by the atmosphere and weather, and large coverage [51]. Several space-based NEA surveillance missions have been carried out or planned, such as NEOWISE, NEOSSat, Arklyd, NEOCam, and Earthguard-I [34, 52, 53]. In these missions, the space-based telescopes are employed to observe NEAs from Earth’s orbit (the Sun Synchronous Orbit, SSO) [53, 54], the Earth-Sun L1/L2 Lagrange point [52, 55], and Mercury-like orbit [56]. Those space-based missions use only one surveyor (or telescope) for observation and detection. The field of view is still limited by the location of the surveyor. Usually, one space-based surveyor (with the limited apparent visible magnitude equaling to 24) can only cover 60%-80% of NEAs (or PHAs) after years of detection and many of them are lost due to the phase difference [57]. Recently, the concept of NEA surveillance constellation has been proposed in order to improve overall efficiency and provide even more flexibility [51, 58, 59]. In this paper, we proposed a new concept of NEA surveillance constellation on the Venus-like orbit, the CROWN (constellation of heterogeneous wide-field NEA surveyors). Compared with the SSO or Earth-Sun L1/L2 Lagrange point, the surveyors on Venus-like orbit can better cover the space inside the Earth’s orbit.

The CROWN is designed in the Sun-Venus three-body system. The constellation is composed of a mothership and six daughter surveyors. The mothership and one surveyor are deployed on a libration orbit in the Sun-Venus system and the other surveyors are distributed approximately evenly on the orbits which have similar orbital elements as the Venus orbit. Note that compared with deploying all the six surveyors on the Venus-like orbits, deploying one surveyor on the libration orbit can help save energy. This paper focuses on the overall mission plan and the performance evaluation from the top-level design. The transfer and deployment trajectories of the proposed constellation are investigated based on the three-body problem model. The invariant manifold is employed to reduce fuel consumption. The asteroid observation performance of the CROWN is analyzed considering the constraints of the apparent visible magnitudes and the extreme field of view. In addition, the OD precision for NEAs using the CROWN is discussed and analyzed based on Monte Carlo (MC) simulations.

The rest of this paper is organized as follows. Section 2 begins with a brief description of the overall mission. The methods and aspects for evaluating the performance of the proposed CROWN are presented in the following subsection. Section 3 details the design methods and results of the transfer and deployment. The observation performance of the surveillance constellation is tested in Section 4. Section 5 discusses the asteroid orbit determination problem, and the accuracy results are analyzed. Finally, the conclusions are given in Section 6.

2. Description of CROWN Mission Concept

2.1. Overall Mission Description. Generally, an asteroid defense system should obey the circle of OODA, which includes observation, orientation, decision, and action. The observation is the premise of the asteroid defense, which refers to the detection and early warning of the asteroids. The observation provides a follow-up measurement of those Earth-crossing objects. The more observations of a discovered object are made, its orbital information becomes more precise. After detection, the tracking and OD of the asteroids are performed. Combining the dynamics model and the measurements provided by the observation, a more accurate OD solution of the discovered NEA can be obtained. Orbit prediction and uncertainty propagation of these NEAs are performed to determine whether the target belongs to a PHA, which has a minimum orbit intersection distance with respect to the Earth within 0.05 au (astronomical unit). Then, the decisions are made on issuing the warning of the potential impacts and then preparing an approximate action for the evaluated level of threat. Finally, actions are performed for response to the impact threat.

The proposed CROWN is a key part of the asteroid defense system, which is mainly responsible for observation and orientation, i.e., the detection and early warning of the PHAs and tracking and OD of the target. The surveillance constellation contains a mothership and six daughter surveyors (space-based optical telescopes). The six daughter surveyors are loosely deployed on Venus-like orbits, monitoring the space inside the Earth orbits. To lower the deployment fuel consumption, a low-energy deployment using the Sun-Venus orbits is proposed. Mothership corresponds for providing the maneuverability required to transfer and deployment. The six daughter surveyors equip with the telescopes pointing the backward of the Sun and detect NEAs approaching from the Sun direction. An illustration of the proposed constellation is shown in Figure 1.

The main reasons of using a constellation on the Venus-like orbits can be summarized as the following two aspects. Firstly, the constellation on the Venus-like orbits has a better coverage over the space inside the Earth’s orbit. As shown in Figure 2, the single surveyor on the Earth trailing heliocentric orbit or the Sun-Earth L1 orbit cannot monitor the space from the direction of the Sun (the grey region in Figure 2(b)) as the telescope cannot observe directly at the Sun. However, these “forbidden spaces” can be available using an observer on the Venus-like orbit. Secondly, compared with the Mercury-like orbits, deploying a constellation on the Venus-like orbits is more energy-efficient. The Mercury-like orbits and the Venus-like orbits are two only locations inside the Earth’s orbit that are suitable for deploying a constellation. The Venus-like orbits are much close to the Earth; thus, these are beneficial for the deployment and communication.

2.2. Performance Evaluation Method and Aspects. In general, the performance of a surveillance constellation can be evaluated in aspects of the constellation, the surveyor, and the payload. As shown in Figure 3, for each aspect, both the ability and the cost are considered.
Figure 1: An illustration of the telescope constellation in the Sun-Venus three-body system.

Figure 2: Comparisons of different designs. (a) Venus-like orbit constellation. (b) Venus-like orbit surveyor. (c) Sun-Earth L1 orbit surveyor. (d) Earth trailing heliocentric orbit surveyor.
The circular restricted three-body problem (CRTBP) is employed to design the transfer orbit and perform OD. The dynamics in heliocentric inertial coordinate system and the accuracy are related to the geometric configurations of the surveyors and the measurement accuracy. The costs of the constellation contain the energy required for transfer, deployment, and maintenance. The performance of a single surveyor can be evaluated by the life-circle costs and the relatively favorable cost/benefit radios. The performance indexes of the payload include the sensitivity, accuracy, power consumption, and the price.

This paper focuses on evaluating the ability and cost at the level of the constellation. As the surveyors are loosely deployed, the cost for configuration maintenance is neglected. The cost of constellation includes the time and energy (velocity increment) of the transfer and the deployment. The cost, the convergence, and the OD performance of the CROWN are discussed in Sections 3, 4, and 5, respectively.

### 3. Transfer and Deployment Design

#### 3.1. Dynamic Model

The overall mission of the CROWN includes four stages, as shown in Figure 4. First, the combination of the mothership and the daughter surveyors approaches from the Earth to the Venus. Then, the combination enters the parking orbit (the Sun-Venus L1 halo orbit or the Sun-Venus L2 halo orbit) through the stable manifold. In the third stage, deployment is realized with the help of the Sun-Venus manifold. The mothership releases the daughter surveyors, and the daughter surveyors fly to the desired location through the unstable manifold. After releasing all the daughter surveyors, the mothership stays on the Sun-Venus Lagrange point orbit for relay communication. In the final (fourth) stage, a near-hexagon constellation is formed, and detection is carried out.

In this paper, two kinds of dynamic models, i.e., the dynamics in heliocentric inertial coordinate system and the dynamics in Sun-Venus rotating coordinate system, are presented. The dynamics in heliocentric inertial coordinate system is employed to design the transfer orbit and perform OD. The circular restricted three-body problem (CRTBP) dynamics is used to represent the motion of deployment in the Sun-Venus three-body system [60].

In the first stage, only the gravitational force caused by the Sun is considered:

$$ f(x(t), t) = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} v(t) \\ -\mu_s \frac{r(t)}{||r(t)||^3} \end{bmatrix}, \quad (1) $$

where $\mu_s = 1.327 \times 10^{11}$ is the heliocentric gravitational constant and $x(t) = [r(t)^T, v(t)^T]^T \in \mathbb{R}^6$ represents the state of the combination. $r(t) = [r_x, r_y, r_z]^T$ and $v(t) = [v_x, v_y, v_z]^T$ represent the position and velocity, respectively.

The CRTBP model is utilized to investigate the dynamic motion of the second stage and the third stage. The dynamic model describing the motion in the Sun-Venus three-body system is formulated in a classical rotating coordinate system (see Figure 5). The origin $O$ of the reference frame is centered at the system barycenter, while the plane $(X, Y)$ coincides with the ecliptic plane, the $X$ axis points to the Venus, and the $Z$ axis is positive in the direction of the angular velocity vector $\omega$. For convenience, a normalized set of units is introduced, such that the total mass of the primaries, the Sun-Venus distance, and the universal gravitation constant are all equal to unity. Accordingly, the period of one Sun-Venus revolution is $2\pi$, and the (normalized) Venus mass is $\mu_v = 2.4513 \times 10^{-6}$.

Let $P(x, y, z)$ be the position vector of the object (the combination, the mothership, and the daughter surveyors), and the dynamic motion in CRTBP satisfies the following equations:

$$ \begin{align*}
\dot{x} - 2\dot{y} &= \frac{\partial \Omega}{\partial x}, \\
\dot{y} + 2\dot{x} &= \frac{\partial \Omega}{\partial y}, \\
\dot{z} &= \frac{\partial \Omega}{\partial z},
\end{align*} \quad (2) $$

### Figure 3: An illustration of performance evaluation aspects.
(a) Interstellar transfer

(b) Enter halo orbit

(c) Deployment

(d) Detection

Figure 4: Overall description of the transfer, deployment, and detection.

Figure 5: Rotating reference frame in the CRTBP.
where $\Omega$ is the effective potential:

$$\Omega = \frac{1}{2}(x^2 + y^2) + \frac{1}{2}\mu v_r r_{13} + \frac{1}{2}\mu v_r r_{23},$$

with

$$r_{13} = \sqrt{(x + \mu v)^2 + y^2 + z^2},$$

$$r_{23} = \sqrt{(x - 1 + \mu v)^2 + y^2 + z^2}.$$  

For the fourth stage, the surveyors fly on Venus-like orbits, which are mainly forced by the gravity of the Sun and perturbed by solar pressure and gravity of the Venus. The acceleration caused by the solar pressure is given as follows:

$$\mathbf{f}(\mathbf{x}(t), t) = \begin{bmatrix} \mathbf{r}(t) \\ \mathbf{v}(t) \end{bmatrix} = \begin{bmatrix} -\mu v & \mathbf{r}(t) - \mathbf{r}_v \\ \frac{C A m}{m_0 R_e^2} \mathbf{r}(t) \end{bmatrix},$$

where $\mathbf{r}_v$ denotes the position of Venus.

Thus, the dynamic motion is written as follows:

$$\mathbf{f}(\mathbf{x}(t), t) = \begin{bmatrix} \mathbf{r}(t) \\ \mathbf{v}(t) \end{bmatrix} = \begin{bmatrix} -\mu v & \mathbf{r}(t) - \mathbf{r}_v \\ \frac{C A m}{m_0 R_e^2} \mathbf{r}(t) \end{bmatrix},$$

where $\rho = \rho_0 (au)^2/\|\mathbf{r}(t)\|^2$ is the intensity of solar radiation at $\mathbf{r}(t)$; $\rho_0 = 4.5605 \times 10^{-6}(N/m^2)$ is the intensity of solar radiation at 1 au; $R_e = 1$ au; $au = 149597870$ km is the astronomical unit; $C$ is the effective illumination area, related to surveyors’ geometry and surveyors’ attitude, and $m$ is the mass of the detector.

3.2. Transfer Trajectory Design. In this subsection, the transfer trajectory from the Earth to the Sun-Venus L1/L2 (SVL1/SVL2) point halo orbits is given. The desired energy-saving transfer to the SVL1/SVL2 halo orbits can be obtained with three impulses. The first maneuver is imposed near the Earth to send the mothership into an Earth-Venus transfer orbit. Then, the second capture occurs at the perigee of the Venus to insert the mothership into a selected stable manifold. Finally, the third maneuver is implemented at the end of the stable manifold to target the final state, and then, the mothership enters the parking halo orbit.

To realize the above behaviors, first, the energy-optimal launch window is searched using the differential evolution algorithm and the orbit of the mothership is integrated forwards to the perigee. Then, a Poincaré map is used to find the matched manifold at the perigee of the Venus. Differential correction is applied to correct the position, and therefore, the velocity increment for capture is calculated. Under this framework, two detailed designs, i.e., SVL1 and SVL2, are given as follows.
First, the SVL1 case is considered. The amplitude of halo orbit is set as \(2 \times 10^5\) km. The stable manifold with a height of 245 km is chosen as the transfer trajectory from the perigee of Venus to the halo orbit. The optimal transfer trajectory of the transfer process is shown in Figure 6. The combination of the mothership and the daughter surveyors begins to transfer on August 11, 2021, flies over the Venus as November 6, 2022, and finally enters the Sun-Venus L1 halo orbit on February 26, 2023. The duration from the Earth to the Venus lasts for 452 days and the duration from the Venus to SVL1 halo orbit is 112 days. The total transfer process lasts for approximately 564 days, and the total velocity increment is approximately 2.81 km/s.

Then, the SVL2 case is discussed. The optimal transfer trajectory of the transfer process is shown in Figure 7. The transfer begins to transfer on October 17, 2022, and ends on June 22, 2024. The duration from the Earth to the Venus orbit lasts for 452 days and the duration from the Venus to SVL2 halo orbit is 112 days. The total transfer process lasts for approximately 564 days, and the total velocity increment is approximately 2.81 km/s.

Figure 7: The optimal transfer trajectory of the SVL2 case. (a) Trajectory in the Sun Eclp2000 frame. (b) Trajectory in the Sun-Venus rotating frame.
Venus lasts for 500 days, and the duration from the Venus to SVL2 halo orbit is 115 days. The total transfer process lasts for approximately 615 days, and the total velocity increment is approximately 2.06 km/s.

3.3. Deployment Trajectory Design. The deployment is realized with the help of the Sun-Venus unstable manifold to save energy. Among the six daughter surveyors, one is deployed on the Sun-Venus halo orbit while the other five are deployed on the Venus-like orbit with different phase. As shown in Figure 8, by implementing a maneuver, the daughter surveyors depart from the parking halo orbits and enter the unstable manifold.

Note that the number of the daughter surveyors is not limited as six. One would expect that increasing number of the daughter surveyors enhance the observation performance. But it also brings heavier cost in launching and deployment. In this paper, six daughter surveyors are selected according to the comprehensive consideration of the launching cost, the ability of the mothership, and the observation performance.

Assume that the daughter surveyor \(\#i\) \((i \in \{1, 2, 3, 4, 5\})\) is released at epoch \(t_i\), by implementing a maneuver with an amplitude of \(\Delta v_i\) in the direction of the unstable manifold (the daughter surveyor \#6 is assumed to stay on the Sun-Venus halo orbit). Thus, the variables for designing the deployment trajectory are the releasing time \(t_i\) and the velocity increment \(\Delta v_i\). The objective for designing a constellation is to maximize the instantaneous viewing area. As the orbital planes of the six surveyors are very close to each other, the objective is equivalent to maximizing the minimal angle between any two surveyors and the Sun. In this case, the optimization problem under the inertial coordinate system

Table 1: The maneuver strategy of five daughter surveyors of the SVL1 case.

<table>
<thead>
<tr>
<th>Daughter surveyor</th>
<th>Velocity increment (km/s)</th>
<th>Releasing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.4175</td>
<td>January 8, 2026</td>
</tr>
<tr>
<td>#2</td>
<td>-0.8372</td>
<td>April 11, 2026</td>
</tr>
<tr>
<td>#3</td>
<td>-1.9548</td>
<td>April 18, 2026</td>
</tr>
<tr>
<td>#4</td>
<td>-0.8484</td>
<td>May 11, 2026</td>
</tr>
<tr>
<td>#5</td>
<td>0.0263</td>
<td>December 14, 2026</td>
</tr>
</tbody>
</table>
Figure 10: The optimal solution of the SVL2 case. (a) Orbits within five years. (b) Orbits within 100 days. (c) The deployment trajectory. (d) The enlarged view of the deployment trajectory.

is formulated as follows:

$$
\text{min} \quad J = - \max \left[ \theta_{ij}(t_f) \right] \\
= - \max \left[ \arccos \left( \frac{\mathbf{r}_i(t_f) \cdot \mathbf{r}_j(t_f)}{||\mathbf{r}_i(t_f)|| \cdot ||\mathbf{r}_j(t_f)||} \right) \right] \\
\text{s.t.} \quad \dot{x}_i(t) = f(x(t), t), \quad t \in [t_0, t_f] \\
\mathbf{v}_i(t_i) = \mathbf{v}_i(t_f) + \Delta \mathbf{v}_i \mathbf{d} \\
-\Delta \mathbf{v}_{\text{max}} \leq \Delta \mathbf{v}_i \leq \Delta \mathbf{v}_{\text{max}},
$$

(7)

where \( \mathbf{d} \) is the direction of the stable manifold, \( \Delta \mathbf{v}_{\text{max}} \) is the maximal velocity increment of the daughter surveyors who can provide when released from the halo orbits, and \( t_0 \) and \( t_f \) are the beginning and end of the deployment, respectively.

Equation (7) is solved using the genetic algorithm (GA). Two cases are discussed in detail. The first is the rapid deployment case. In this case, the SVL1 halo orbit is selected as the parking orbit and the daughter surveyors have strong maneuverability, with the maximal velocity increment given as 2 km/s. The second is a low-cost deployment case, in which the SVL2 halo orbit is taken as the parking orbit and the maximal velocity increment is 100 m/s. As the best of our knowledge, whether deployed using the SVL1 halo orbit or SVL2 halo orbit makes no difference to the performance of the final configuration. Therefore, for the sake of space, the results of the SVL2 rapid deployment and SVL1 low-cost deployment are not shown in the paper.

In the SVL1 rapid deployment case, \( \Delta \mathbf{v}_{\text{max}} = 2 \text{ km/s} \). The beginning time \( t_0 \) is set to January 1, 2026, and the end \( t_f \) is set to January 1, 2029. The amplitude along z-axis is set to be \( 2 \times 10^8 \text{ km} \). Figure 9 presents the orbits and the deployment trajectory. The velocity increments of the five daughter surveyors of the SVL2 case are shown in Table 2.

<table>
<thead>
<tr>
<th>Daughter surveyor</th>
<th>Velocity increment (km/s)</th>
<th>Releasing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.0480</td>
<td>July 5, 2026</td>
</tr>
<tr>
<td>#2</td>
<td>-0.0838</td>
<td>August 10, 2026</td>
</tr>
<tr>
<td>#3</td>
<td>0.0618</td>
<td>August 28, 2026</td>
</tr>
<tr>
<td>#4</td>
<td>-0.0890</td>
<td>May 22, 2028</td>
</tr>
<tr>
<td>#5</td>
<td>-0.0218</td>
<td>June 10, 2028</td>
</tr>
</tbody>
</table>
surveyors are 0.0263 km/s, -0.8372 km/s, -1.9548 km/s, 0.4175 km/s, and -0.8484 km/s, as shown in Table 1. The total velocity increment required is 4.0845 km/s. The daughter surveyor #3 has the largest velocity increment because it transfers farthest from the mothership. During the three years of deployment, the first year is used for releasing and the rest is for the daughter surveyors to approach the corresponding states.

In the SVL2 low-cost deployment case, the maximal velocity increment is set to be $\Delta v_{\text{max}} = 100$ m/s. Rapid deployment is impossible for this case, and long-term deployment is requested. The beginning time $t_0$ is set to January 1, 2026, and the deployment period is set to 5 years. The corresponding optimal solution is shown in Figure 10 and Table 2.

4. Detection Performance of the Constellation

4.1. Object Population. NEA is defined as asteroids whose perihelion distance, $q$, is less than 1.3 au. NEA consists of four groups, i.e., Atira, Aten, Apollo, and Amor, according to their perihelion distance, aphelion distance, and semimajor axes. PHAs are asteroids whose minimum orbit intersection distance with respect to the Earth is within 0.05 au. Moreover, the absolute magnitude of PHA is usually defined within 22, which is larger than 140 m in size. However, it is noted that some NEAs with smaller sizes (smaller than 140 m) are also of significant interest because their potential impact is nonnegligible but are more difficult to detect and will likely provide much shorter warning times compared with larger objects.

In this paper, a total of 2072 PHAs among 13916 NEAs are considered, as shown in Figure 11. The asteroid data come from the International Astronomical Union’s Minor Planet Center (MPC). The locations of the PHAs on January 1, 2031 are shown in Figure 12.

4.2. Asteroid Observation Model. To capture the asteroid in the telescope’s field of view, two constraints must be satisfied: the apparent visible magnitudes and the extreme field of view.

The absolute magnitude is to describe how bright an asteroid is. The absolute magnitude is the averaged apparent magnitude defined in the Johnson V band, which is viewed using a full rotation cycle in the location at 1 au from both the Earth and the Sun, and with the solar phase angle equaling to 0. The absolute magnitude can be approximately estimated by the asteroid’s size and geometric albedo as follows:

$$\log_{10} D = 3.1236 - 0.2H - 0.5 \log_{10} p_V,$$

where $H$ is the absolute magnitude, $D$ is the diameter in km and $p_V$ is the geometric albedo, respectively.

However, the absolute magnitude $H$ is introduced at the zero phase angle, where few asteroids are located. In regard to dealing with real photometric data, visible magnitude is used. The visible magnitude is extrapolated from the absolute magnitude by considering the influence of the phase angle of observation:

$$V(\kappa) = H + 5 \log_{10}(\Delta \times r) - 2.5 \log_{10}[(1 - G)\Phi_1(\kappa) + G\Phi_2(\kappa)],$$

where $V(\kappa)$ is the apparent visible magnitude, $\kappa$ represents the phase angle, and $G$ represents the slope parameter.
As shown in Figure 13, \( \Delta \) denotes the distance from the asteroid to the telescope and \( r \) denotes the distance from the asteroid to the Sun. \( \Phi_1(\kappa) \) and \( \Phi_2(\kappa) \) are two basis functions normalized at unity for \( \kappa = 0 \), which are approximated by the following:

\[
\Phi_1(\kappa) = \exp\left(-3.33 \tan^{0.63} \frac{1}{2} \kappa\right),
\]

\[
\Phi_2(\kappa) = \exp\left(-1.87 \tan^{1.22} \frac{1}{2} \kappa\right).
\]

Note that the values of slope parameter are available for only a few asteroids, and most of which are unmeasured. Thus, for those unavailable, the \( G \) is taken as \( G = 0.15 \) in the simulation. Assume that the limited apparent visible magnitude of the telescope is \( V_{\text{max}} \), and the constraint of the apparent visible magnitudes is expressed as follows:

\[
V \leq V_{\text{max}}.
\]

The second constraint is the extreme field of view. The direction of the targeted asteroid is defined using the azimuth angle \( \alpha \) and elevation angle \( \beta \). The azimuth angle \( \alpha \) is the angle between the projection of the line-of-sight in the telescope’s orbital plane and the direction of the center of vision, and elevation \( \beta \) is the angle between the projection of the line-of-sight in the plane perpendicular to the telescope’s orbit and the direction of the center of vision. Moreover, as shown in Figure 14, the telescope’s field of view is described by a rectangle, defined by two angles \( \alpha_{\text{max}} \) and \( \beta_{\text{max}} \). Therefore, the constraint of the field of view is given as follows:

\[
|\alpha| \leq \alpha_{\text{max}},
\]

\[
|\beta| \leq \beta_{\text{max}}.
\]

4.3. Simulated Observations. Assume that the mission begins on January 1, 2031 and lasts for five years. The total numbers of currently known potentially hazardous near-Earth asteroids, of which there are 2072, were taken from the MPC database. The telescopes’ extreme field of view is set to 45°: \( \alpha_{\text{max}} = 45° \) and \( \beta_{\text{max}} = 45° \). The limited apparent visible magnitude of the telescope is given as \( V_{\text{max}} = 24 \). Note that the configurations of the two cases in Section 3.3 are almost the same. Thus, only one case, \( i.e. \), the SVL1 rapid deployment case, is simulated.

First, the visibility of the asteroids in the database is simulated. As shown in Figure 15, the blue dots represent the visible asteroids and the red stars represent the invisible asteroids. Among the 2072 potential hazardous near-Earth asteroids, 2068 are visible and the visible ratio is 99.81%. Only four of them are invisible, \( i.e. \), 1999 XS35, 2011

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Notes:
- Figure 12: The location of the PHAs on January 1, 2031. The orbits and locations of Mercury, Venus, Earth, and Mars are shown.
- Figure 13: Phase relationship between the Sun, telescope, and asteroid.
- Figure 14: An illustration of the telescope’s extreme field of view.
GS60, 2015 KL157, and 2016 CC30, which are detailed in Table 3. Two main reasons can account for why these four asteroids are invisible. The first is that the targeted asteroid is too far away from the constellation, and then, it exceeds the extreme field of view. Another reason is that the minimal visible magnitude is larger than 24. This means that although the asteroid enters the extreme field of view, the brightness is poor and therefore cannot be detected.

Then, the ability of the surveillance system to observe asteroids is analyzed. The total duration of the asteroids’ visible arcs in the database is shown in Figure 16(a) and Table 4. It can be seen that more than 94.5464% of targets are visible for more than 100 days. Figure 16(b) and Table 5 give the maximum duration of asteroid visible arcs. The maximum duration of only 0.4826% of the targets is less than 20 days, which is inadequate for an acceptable orbit estimation. Moreover, more than 64.6718% of targets’ maximal durations are longer than 40 days, indicating they could be well determined. Figure 16(c) illustrates the number of asteroids’ visible arcs. For most asteroids, multiple arcs are visible, which also improves the orbit determination. The number of maximal observers in visible arcs is shown in Figure 16(d). Most targets could be detected by only one telescope, and only approximately 29.1505% could be observed by two different telescopes at the same time.

Figure 17 illustrates the apparent visual magnitude of the asteroids when it is first observed and the average apparent visual magnitude when visible. The abscissa is the interval of the apparent visual magnitude of the asteroid, and the ordinate is the number of asteroids in the corresponding interval when visible. For the most potential hazardous near-Earth asteroids, the apparent visual magnitudes when first observed are in the interval (23, 24], and the average apparent visual magnitudes when visible are in the interval [22, 24]. Considering the telescope’s observation efficiency, the technical difficulty of realizing the limited apparent visible magnitude, and the efficiency of utilizing the limited apparent visible magnitude, it is reasonable to set the limited apparent visible magnitude of the telescope to 24.

Moreover, the influence of the limited apparent visual magnitude on the performance of the telescopes is investigated. The quantity of observable asteroids in the database is chosen to measure the performance. The results are shown in the first row in Table 6. It is shown that the ratio of observable asteroids in the database when $V_{\text{max}} = 24$ is 99.8069%. When the limited apparent visual magnitude is declined to $V_{\text{max}} = 23$, the corresponding ratio drops by 99.4208%. When it is improved to $V_{\text{max}} = 25$, the ratio increases to 99.9517%.

In addition, the virtual PHAs are employed to test the performance of the proposed surveillance constellation. This is because the distribution of PHAs in the simulations suffers from a selection bias, which may lead to incorrect results of the performance test. To overcome this shortcoming, 100000 virtual samples of NEAs are firstly

<table>
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<tr>
<th>$V_{\text{XS35}}$</th>
<th>17.7758</th>
<th>0.9471</th>
<th>19.4361</th>
<th>20.6</th>
<th>0.15</th>
<th>33.9586</th>
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</thead>
<tbody>
<tr>
<td>$V_{\text{GS60}}$</td>
<td>3.3569</td>
<td>0.9228</td>
<td>19.2689</td>
<td>19.0</td>
<td>0.15</td>
<td>24.5552</td>
</tr>
<tr>
<td>$V_{\text{KL157}}$</td>
<td>2.6405</td>
<td>0.6182</td>
<td>35.5608</td>
<td>19.1</td>
<td>0.15</td>
<td>24.4431</td>
</tr>
<tr>
<td>$V_{\text{CC30}}$</td>
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<td>0.5857</td>
<td>35.5632</td>
<td>20.0</td>
<td>0.15</td>
<td>24.6971</td>
</tr>
</tbody>
</table>

Table 3: Invisible asteroid in the database.
generated. These virtual NEAs are generated according to the four-dimensional debiased orbit and absolute-magnitude distribution proposed by Granvik et al. [62–64]. The orbit and absolute-magnitude distributions of these virtual NEAs are shown in Figure 18. As a comparison, the orbit and absolute-magnitude distributions of the 13916 real NEAs are also illustrated in Figure 18. It can be seen that the distributions of the virtual NEAs are in line with the real ones. Among the 100000 virtual BEAs, 10198 are tested and selected as the PHAs. The quantities of observable asteroids among these virtual samples with different limited apparent visual magnitude are listed in the second row in Table 6. These virtual asteroids can be regarded as those PHAs have not been detected so far and can be used to evaluate the performance of searching for unknown PHAs. It can be seen that the performance of detecting existed PHAs is better than detecting virtual asteroids, with quantity higher than 11%-33%. For example, when $V_{\text{max}} = 24$, the ratio of observable asteroids among the existed PHAs in database is 99.8069%, while...

Figure 16: Telescope’s ability to observe asteroids in the database. (a) Total duration of asteroids’ visible arcs. (b) Maximum duration of asteroids’ visible arcs. (c) Number of asteroids’ visible arcs. (d) Number of maximal observers in visible arcs.

**Table 4: Total duration of asteroids’ visible arcs.**

<table>
<thead>
<tr>
<th>Interval (unit: day)</th>
<th>0-100</th>
<th>100-500</th>
<th>500-1000</th>
<th>1000-1500</th>
<th>1500-2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counts</td>
<td>113</td>
<td>906</td>
<td>564</td>
<td>364</td>
<td>125</td>
</tr>
<tr>
<td>Quantity</td>
<td>5.4536%</td>
<td>43.7258%</td>
<td>27.2201%</td>
<td>17.5675%</td>
<td>6.0328%</td>
</tr>
</tbody>
</table>

**Table 5: Maximum duration of asteroids’ visible arcs.**

<table>
<thead>
<tr>
<th>Interval (unit: day)</th>
<th>0-20</th>
<th>20-40</th>
<th>40-100</th>
<th>100-500</th>
<th>500-1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counts</td>
<td>10</td>
<td>722</td>
<td>1153</td>
<td>162</td>
<td>25</td>
</tr>
<tr>
<td>Quantity</td>
<td>0.4826%</td>
<td>34.8455%</td>
<td>55.6467%</td>
<td>7.8185%</td>
<td>1.2065%</td>
</tr>
</tbody>
</table>
the corresponding ratio is declined to 81.0355\% for virtual samples. This declination can be explained by the "survivorship bias": the PHAs in database themselves are easy to be detected because they have suitable relative locations and relatively large value of the absolute magnitude. However, the randomly generated virtual samples usually include those difficult-to-detect asteroids, which leads to a drop of the observing performance.

5. Orbit Determination Pipeline Design

In this section, the potential application for the PHA OD using the surveillance constellation is discussed. The asteroid orbit determination model is established using optical measurements. The unscented kalman filter (UKF) is employed to solve the asteroid OD problem and the OD accuracy is analyzed based on the Monte Carlo (MC) simulation. Note that the issue of the initial OD of a newly discovered object is also important. However, this paper is aimed at providing an overall design of the surveillance constellation on the Venus-like orbits. The problems of the initial OD using the proposed surveillance constellation will be investigated in our future studies.

5.1. Asteroid State Estimation Model. Apart from detection or early warning, the proposed surveillance constellation can also be applied for tracking and determining the orbits of the PHAs because the telescopes can provide line-of-sight information. The problems, such as the order of the determination errors and how long it should take to track one asteroid under a given accuracy requirement, come as follows. Thus, it is of great significance to have knowledge on accuracy of the orbit determination system.

When the target asteroid is visible in the camera image. The coordinates of the target in the telescope image plane can be obtained. Usually, the orbits and the attitudes of the detectors are known and the coordinates in the telescope image plane can be replaced by the direction vector from the detector to the targeted asteroid [65, 66]:

\[
    z = h(x) + \epsilon = \frac{r - r_i}{\|r - r_i\|^3} + \epsilon, \tag{13}
\]
where $\mathbf{x}$ is the state of the targeted asteroid to be estimated, $\mathbf{r}_i$ is the position of the surveyor $i$, and $\boldsymbol{\varepsilon} = [\varepsilon_x, \varepsilon_y, \varepsilon_z]^T$ denotes the Gaussian-distributed observation noise.

Considering the special circumstances that the targeted asteroid could be observed by two surveyors, e.g., the surveyors $i$ and $j$, then the observation model is rewritten as

**Figure 18:** Orbit and absolute-magnitude distribution of the real NEAs and the virtual samples.

**Figure 19:** Comparisons of $\sigma$ bounds between one observer-case and two observer-case.
The dynamic model of the navigation system is in Equation (1). Therefore, the OD system is given as follows:

\[
\dot{x} = f(x) + w,
\]

\[
\begin{bmatrix}
\dot{r}_x \\
\dot{r}_y \\
\dot{r}_z \\
\dot{v}_x \\
\dot{v}_y \\
\dot{v}_z
\end{bmatrix} = \begin{bmatrix}
\frac{r - r_j}{\|r - r_j\|^3} \\
\frac{r - r_i}{\|r - r_i\|^3} \\
\end{bmatrix} + \varepsilon.
\] (14)

The dynamic model of the navigation system is in Equation (1). Therefore, the OD system is given as follows:

\[
\begin{aligned}
\dot{x} &= f(x) + w, \\
\dot{z}(x) &= h(x) + \varepsilon,
\end{aligned}
\] (15)

where \( w \in \mathbb{R}^6 \) is the model noise.

5.2. State Estimation Simulation. First, the PHA Icarus is chosen as the targeted asteroid, and the mothership and the daughter surveyor #2 in the SVL1 rapid deployment case are used. The OD begins on January 1, 2031, and ends after 60 days of observation. UKF is used to estimate the system state from optical measurements. The initial estimated ephemeris errors of the asteroid are given as follows: 1000 km per axis for the position and 100 m/s per axis for the velocity. The standard deviation (STD) of the measurement noise is set as \( 10^{-5} \) per axis (around 2 arcsec).

The case of using only the mothership and using both the mothership and the daughter surveyor #2 are simulated. MC simulations are performed to show the orbit determination accuracy expressed by position and velocity in the orbit system. To compare the efficiency and accuracy of different cases, the \( \sigma \) bounds of determination errors are shown in Figure 19. The initial \( \sigma \) bounds of each direction of the

### Table 7: Orbit determination accuracy of Icarus with one observer and two observers (unit: km for position, m/s for velocity, and % for convergence ratio).

<table>
<thead>
<tr>
<th></th>
<th>( r_x )</th>
<th>( r_y )</th>
<th>( r_z )</th>
<th>( v_x )</th>
<th>( v_y )</th>
<th>( v_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One observer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial STDs</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Final STDs</td>
<td>10.5376</td>
<td>23.3332</td>
<td>8.0189</td>
<td>0.0164</td>
<td>0.0068</td>
<td>0.0071</td>
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<tr>
<td><strong>Two observers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial STDs</td>
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<td>1000</td>
<td>1000</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Final STDs</td>
<td>5.0522</td>
<td>5.0691</td>
<td>3.6254</td>
<td>0.0073</td>
<td>0.0021</td>
<td>0.0051</td>
</tr>
</tbody>
</table>

### Table 8: Convergence ratios with one observer (unit: %).

<table>
<thead>
<tr>
<th></th>
<th>( r_x )</th>
<th>( r_y )</th>
<th>( r_z )</th>
<th>( v_x )</th>
<th>( v_y )</th>
<th>( v_z )</th>
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<tbody>
<tr>
<td>Hathor</td>
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<td>98.4197</td>
<td>99.9732</td>
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<td>99.9933</td>
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<td>80.6972</td>
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<td>Orpheus</td>
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<td>99.9833</td>
<td>99.9662</td>
</tr>
<tr>
<td>OH</td>
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<td>80.0894</td>
<td>98.1711</td>
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<tr>
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<td>83.3296</td>
<td>90.9870</td>
<td>91.1770</td>
<td>99.9743</td>
<td>99.9838</td>
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<tr>
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<td>99.9882</td>
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</tr>
<tr>
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<td>81.5979</td>
<td>99.9839</td>
<td>99.9918</td>
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<tr>
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<td>96.4213</td>
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<td>97.3835</td>
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<td>99.9939</td>
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</tr>
<tr>
<td>Average</td>
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<td>93.1091</td>
<td>96.8255</td>
<td>99.9798</td>
<td>99.9740</td>
<td>99.9911</td>
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</table>
### Table 9: Convergence ratios with two observers (unit: %).

<table>
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<th></th>
<th>$r_x$</th>
<th>$r_y$</th>
<th>$r_z$</th>
<th>$v_x$</th>
<th>$v_y$</th>
<th>$v_z$</th>
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<td>Geographos</td>
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<td>Average</td>
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<td>98.7884</td>
<td>99.3330</td>
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<td>99.9978</td>
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</tbody>
</table>

### Table 10: Convergence ratios of virtual asteroids with one observer (unit: %).

<table>
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<tr>
<th></th>
<th>$a$</th>
<th>$r_x$</th>
<th>$r_y$</th>
<th>$r_z$</th>
<th>$v_x$</th>
<th>$v_y$</th>
<th>$v_z$</th>
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<td>99.9606</td>
<td>99.9829</td>
<td>99.9923</td>
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<td></td>
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<td>96.3677</td>
<td>99.9770</td>
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<td>99.9545</td>
<td>99.9982</td>
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</table>
position and velocity are 1000 km and 100 m/s, respectively. The blue lines represent the case with one observer, and the red lines represent the case with two observers. As the MC simulations are conducted with the same system parameters, it can be concluded that the orbit determination accuracy with two observers is better than case with one observer. Moreover, the estimation errors of the two observer-case converge faster than those of the one observer-case. For the case with two observers, the determination errors converge to near zero after only approximately 10 days, while the requested duration for one observer-case is 40 days. The reasons why the one observer-case is poorer than the two observer-case are as follows. Previous studies have revealed that the observation configuration can impact the OD performance of an angle-only OD system [23, 65]. For researched PHA OD problem, the observation configuration using one observer is usually poor as the visible arc is short. However, using two observers can help improve the observation configuration and thus improve the OD accuracy [65].

To further compare the accuracy of the two cases, the detailed final convergence results are given in Table 7. As the square root of covariance, the STD has the same convergence tendency as the covariance and reflects the estimation accuracy more intuitively. With the same initial STDs, the convergence ratios (defined in Equation (16)) of the two observer-cases are higher than those of the one observer-case, indicating that two observers outperform one observer in terms of global convergence.

\[
\text{Convergence ratio} = \frac{\text{STD}_{\text{initial}} - \text{STD}_{\text{final}}}{\text{STD}_{\text{initial}}} \times 100\%.
\]

Moreover, the OD accuracy of another 20 PHAs using both one observer and two observers is presented in Tables 8 and 9. The mean convergence ratios of the position and the velocity using one observer are around 89%-96.8255% and 99.9%, respectively, and the convergence ratios using two observers are larger than 98.5%. Finally, to further test the OD performance of the proposed CROWN, MC simulations are performed on the generated virtual samples (the same virtual samples as those in Section 4). The results are shown in Tables 10 and 11. Compared with the results in Tables 8 and 9, the OD accuracy of these virtual samples is a little poorer than that of the existing PHAs. It is obviously shown that the OD using two observers shows better capability than OD using one observer with respect to the accuracy. The OD accuracy test results indicate another advantage of using the surveillance constellation; that is, the surveillance constellation can provide observations in different directions, and therefore, a more accurate OD can be obtained compared with the single surveyor.

6. Conclusion

This paper presented and analyzed a mission concept of a surveillance constellation of near-Earth object surveyors. The constellation is designed in the Sun-Venus three-body system and deployed on the Venus-like orbits. The
constellation contains a mothership and six daughter surveyors. The mothership provides maneuver ability for transfer and deployment. The six daughter surveyors are deployed on the Venus-like orbits and monitor the space inside the Earth’s orbit. The deployment can be completed within five years using values of less than 300 m/s velocity increment. The surveillance constellation can provide effective early warning for almost all PHAs. Only 4 of 2072 PHAs are invisible during the 5-year mission. Moreover, the surveillance constellation can also be applied for asteroid orbit determination (OD) and the OD accuracy is approximately 5 km after 40 days of measurement using one surveyor or 10 days of measurement using two different surveyors. Based on this work, the system scheme design, payload instruments, in-orbit observations, and data analysis pipelines could be further conducted in the future.

Data Availability

The data used to support the findings of this study are available from the author upon reasonable request.

Conflicts of Interest

The authors declared that they have no conflicts of interest to this work.

Authors’ Contributions

Xingyu Zhou and Xiangyu Li contributed to the literature review, the simulation, the writing, and the revision of the paper. Zhuoxi Huo performed the literature review and the mission architecture. Linzhi Meng and Jiangchuan Huang contributed to validation of method and revised this paper.

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