Feasibility Analysis of Rendezvous and Docking Operations in LEO for CubeSats with Limited Delta-V Budget

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The NanoFF and NanoOOV missions of the Chair of Space Technology at Technische Universität Berlin aim to demonstrate formation flight capabilities using CubeSats in low Earth orbit. In addition to these missions, the presented research analyzes the feasibility of rendezvous and docking using two identical 3U CubeSats equipped with a single-axis electrothermal propulsion system and a tetrahedral reaction wheel system. The use of Gecko adhesives is proposed for docking, while a UHF-based intersatellite link is used to exchange information between the satellites. The satellites are planned to be launched into a passively safe helix orbit using one of the commercially available space tug companies. After commissioning, the satellites are brought safely to a predefined minimum relative distance where the onboard relative navigation sensors are calibrated until successful verification. The final docking approach is calculated based on the ground station visibility, eclipse conditions, and optimal docking velocity requirements. Subsequently, the Chaser satellite autonomously maneuvers towards the Target for docking up to a predefined minimum relative distance defined by the docking mechanism's geometrical constraints. Preliminary results suggest that the proposed formation control sequence is feasible within the limited amount of Δv and the available technologies.

1 Introduction

Recent developments in small satellite technology have made it possible for CubeSats to attempt complex missions in Low Earth Orbit. This research aims to explore the feasibility of using existing hardware and software components designed for previous CubeSat missions at TU Berlin, i.e. the Nanosatellites for Formation Flight (NanoFF) and the Nanosatellites for On-Orbit Verification (NanoOOV) missions, to enable successful rendezvous and docking. This will lead to more complex and ambitious university-led CubeSat missions, including orbital debris removal and satellite servicing, while minimizing cost and improving operational efficiency.

In this work, a docking mechanism based on bio-inspired micropatterned dry adhesives (MDA) is proposed. These so-called "Gecko Materials" enable adhesion to almost any surface based on intermolecular interactions and thus function both at atmospheric pressure and vacuum. For mushroom-shaped MDA, compressive loads are required to activate the adhesion forces. Recent findings [1, 2] suggest the existence of an operational window of relative velocities at which compressive loads at impact are able to activate the adhesion forces. This knowledge is used to design the final approach during docking.

The outcome of this research will be used to plan and design a technology demonstration mission called Nanosatellites for Rendezvous and Docking (NanoR&D), a successor of the NanoFF and the NanoOOV missions. This will demonstrate autonomous rendezvous operations, TU Berlin neXt generation 20 kg (TUBiX20) library for formation flight operations, ground-based operational capabilities, UHF-based inter-satellite link (ISL) capabilities, synchronized usage of relative navigation sensors, as well as docking/release capabilities. This will also contribute in the further development of in-orbit servicing, orbit-lowering, and orbit-raising services involving small satellites.

2 Requirements

The requirements for the NanoR&D mission related to mission operations, Attitude and Orbit Control System (AOCS), and ISL are primarily derived from the NanoFF mission.

2.1 Mission operations

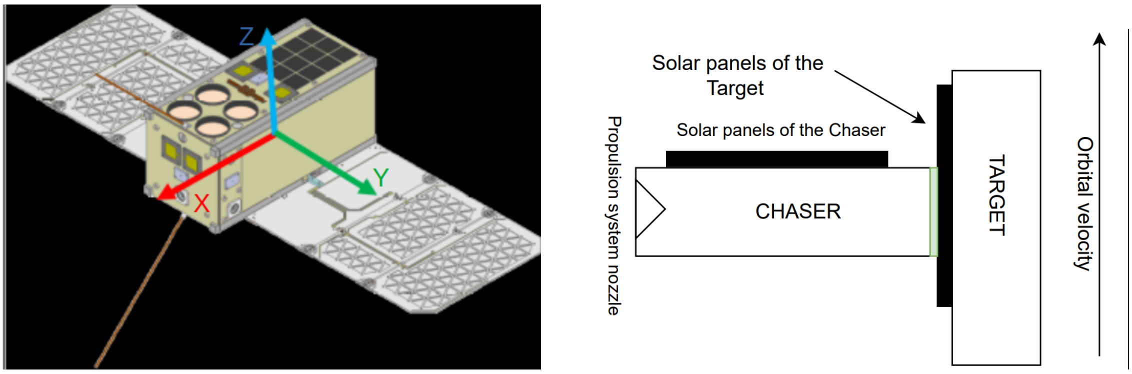
The exact type of the Gecko adhesives used for docking shall determine the optimal docking velocity [2]. Both the satellites shall have 3-axis attitude control, however only the Chaser shall use the propulsion system. The activation of the final rendezvous approach through a time tagged telecommand and the actual docking shall happen in the visibility of certain ground stations. The Chaser satellite shall be able to determine the relative distance as well as the attitude of the Target using the images taken from the Chaser's navigation cameras, along with the onboard data from the Target. Therefore, the sunlight conditions at the time and location of docking as well as the orientation of the satellites shall be optimal for docking.

2.2 Attitude and orbit control system

Attitude determination shall be provided by two hot redundant AOCS nodes. Each node shall have four rate gyros, four magnetic field sensors and five Sun sensors. In addition, three star-trackers shall be located on three different faces of the satellite for providing accurate attitude information. For absolute and relative navigation, each node shall contain two multi-band Global Navigation Satellite System (GNSS) receivers, capable of working with GPS, Galileo, GLONASS and Beidou navigation systems. Each satellite shall have five laser retro-reflectors, each on five of it's six sides. These will be used to verify the accuracy of relative navigation algorithms based on GNSS raw measurements, which include pseudorange, carrier phase and Doppler measurements. Additionally, short-range, low-power, and high-accuracy radio detection and ranging (RADAR)/light detection and ranging (LIDAR) sensors along with short-range cameras (based on the star-tracker from the NanoFF mission) will be used for relative navigation. A tetrahedral reaction wheel system will be used for actuation, with each wheel providing a nominal torque of 1 mN m. A resistojet capable of providing Δv up to $9\,\mathrm{m\,s^{-1}}$, a maximum thrust of up to 4 mN and a minimum impulse bit of approximately 50 µN s will be used for orbit control. Further analysis will be done to assess the AOCS performance when the two satellites are docked to each other.

2.3 Satellite geometry

The proposed research considers two identical 3U CubeSats, each equipped with deployable solar panels and a mass of approximately 6 kg, including 80 g of fuel mass. The placement of various subsystems such as sensors and actuators will be strategically arranged to facilitate rendezvous and docking operations. A proposed approach is to dock the Chaser's shorter face into the Target's solar panels using gecko adhesives, as illustrated in Figure 1. Further investigations are underway.



(a) Satellite coordinate system (b) Preliminary docking concept

Figure 1: Proposed docking concept

2.4 Communication and inter-satellite-link

A stable communication link between multiple spacecrafts is critical for close proximity operations including docking. As the concept for rendezvous and docking is based on the NanoFF CubeSats, the options for a communication link are limited by the onboard transceiver hardware. S-Band as well as ultra-high frequency (UHF) transmitters are available but reception is only possible using UHF. Even though the higher bandwith provided by S-Band would be desirable, the dedicated patch antennas need to be oriented towards the other communication participants. This could interfere with the maneuvers required for rendezvous and docking. The omnidirectional UHF antennas do not require this procedure. Therefore we shall facilitate a UHF-based ISL. The limited bandwidth still needs to be considered. The data transfer rate has to be high enough to successfully determine the relative position and orientation of the Target. The ISL data consists of GNSS raw measurements, navigation solutions, attitude information, and certain safety flags. Assuming no other traffic, a datarate of up to 9.6 kbps can be achieved using the Mobitex protocol [3]. Including the estimated overhead introduced by transmission data structures, it is possible to transmit approximately 5 packets per second. A valid data packet every 5 s is also sufficient to meet the mission requirements, making the proposed UHF-based ISL approach a viable solution.

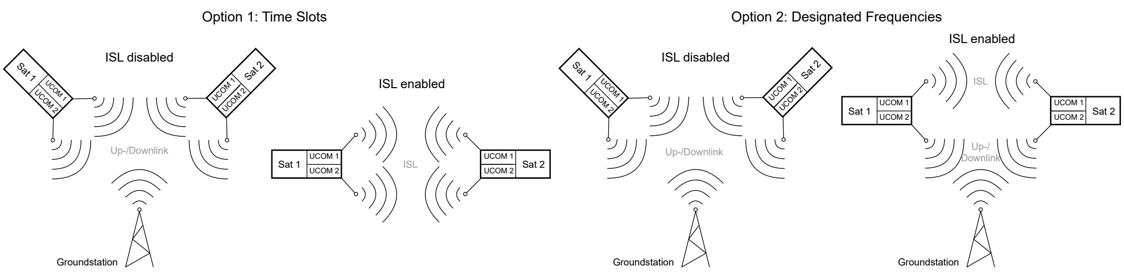


Figure 2: ISL operation modes

The hardware design has two redundant UHF communication (UCOM) nodes supporting half-duplex communication for UHF uplink/downlink. Each node has a separate transceiver and antenna setup, and can therefore be operated at a different frequency. While operating the desired ISL, the nominal function of the uplink shall still be available. These constraints allow for two different ISL operation options, as shown in Figure 2.

First, both UCOM nodes can be used for uplink/downlink without any ISL specific feature. The ISL will only be active in dedicated time slots. As both links are using the same frequencies, the time slots need to be managed carefully to avoid interferences. The potential to lock the operator out of the system is rather high, especially during the ISL time slot. The second option makes use of the two redundant setups. When the ISL is activated, one transceiver will take over ISL task specifically. It can change its operation frequency to avoid interferences with the uplink/downlink. This approach allows for simultaneous ISL and uplink/downlink operation but also weakens the redundancy concept of the nodes. However, if a fault in the communication node is detected, they can fall back to the regular redundant uplink/downlink operation.

3 Rendezvous approach

In this research, the relative motion of two satellites is represented by a set of dimensionless relative orbital elements (ROEs), which is defined as [4, 5]

$$\delta\alpha = \begin{bmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{bmatrix} = \begin{bmatrix} (a_2 - a_1)/a_1 \\ u_2 - u_1 + (\Omega_2 - \Omega_1)\cos i_1 \\ e_2\cos\omega_2 - e_1\cos\omega_1 \\ e_2\sin\omega_2 - e_1\sin\omega_1 \\ i_2 - i_1 \\ (\Omega_2 - \Omega_1)/\sin i_1 \end{bmatrix} \tag{1}$$

where subscript 1 denotes the terms of the Chaser satellite and subscript 2 denotes the Target satellite. The terms a, e, Ω, i, ω and M denote the standard (mean) Keplerian elements and $u = M + \omega$ denotes the mean argument of latitude. The terms $a\delta a$ and $a\delta\lambda$ represent the relative semi-major axis and relative longitude, respectively. $a\delta e_x$ and $a\delta e_y$ represent the components of the relative eccentricity vector, whose magnitude is represented by $a\delta e$. Similarly, $a\delta i_x$ and $a\delta i_y$ represent the components of the relative inclination vector, whose magnitude is represented by $a\delta i$.

The rendezvous approach can be broadly divided into two stages. The first stage comprises deployment, commissioning, and generation of a close range relative helix orbit. The second stage involves the final docking approach maneuver and completes with successful docking of the Chaser into the Target. The following sections describe them in details. Figure 3 represents the approach overview.

3.1 Deployment

The satellites shall be launched with a high precision into a partial helix relative orbit at 550 km altitude. This can be achieved by using the services of one of the commercially available space tug companies such as D-Orbit[1]. Similar to the approach planned for the NanoFF mission [6], D-Orbit's ION spacecraft shall launch the two satellites with an interval equal to an odd number multiple of half-orbital period of ION, ideally after 1.5 orbits. This creates a decent along-track gap between the satellites after launch, about 1 km to 2 km initially. This duration, approximately 143 min, gives ION sufficient time to reorient itself for the second deployment. The deployment directions are calculated in the radial tangential normal (RTN) frame of ION and have an angular separation of 20° to 30° between them, when seen from an inertial frame. The two deplyoments

[1] `https://www.dorbit.space/`

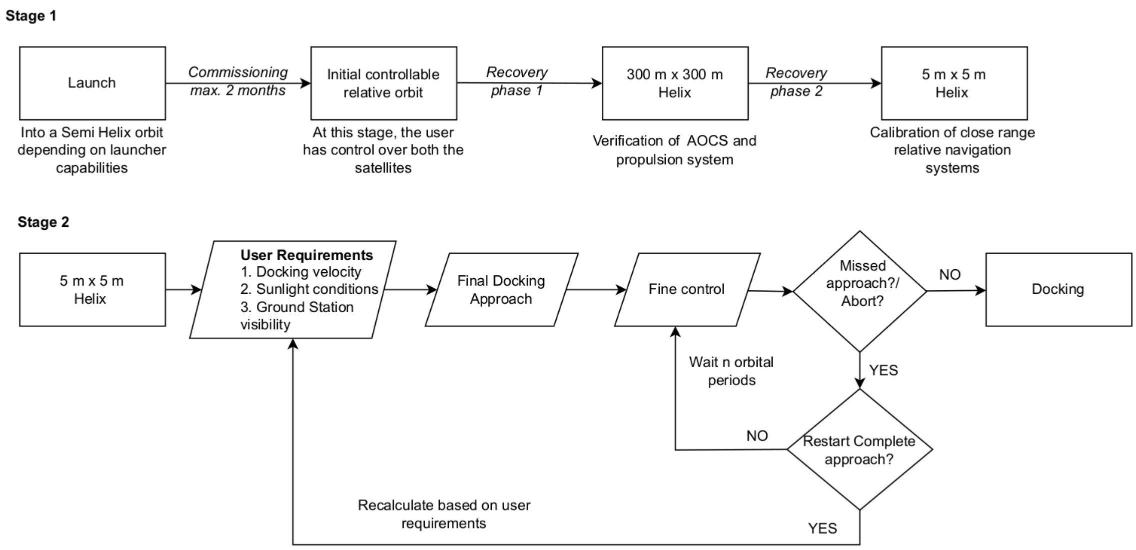


Figure 3: Rendezvous Approach overview

happen at the highest and lowest points of ION's orbit (at $u = 90^\circ$ and $u = 270^\circ$), close to the poles. This ensures that the satellites have the same mean inclination while having a slightly different mean right ascension of ascending node.

3.2 Generation of a close range helix orbit

Assuming a maximum commissioning duration of two months, the two satellites will be initially brought to a relative helix orbit with parallel/anti-parallel relative $\boldsymbol{\delta e}/\boldsymbol{\delta i}$ vectors of magnitude 300 m (denoted as $300\,\text{m} \times 300\,\text{m}$) [6]. This will verify the functioning of the AOCS and the propulsion system. After this, satellites will be commanded to a smaller helix orbit of $5\,\text{m} \times 5\,\text{m}$, where the close range relative navigation sensors such as navigation cameras and RADAR/LIDAR sensors will be checked and if necessary calibrated against the relative position values obtained using the raw measurements from on-board GNSS receivers. To conserve Δv during relative orbit control, standard four impulse maneuver sets, each consisting of three tangential burns and one normal burn, have been considered [7]. The maximum amount of Δv required to generate the close range helix orbit has been set at $3.5\,\text{m}\,\text{s}^{-1}$. Simulation results show that this is achiveable, with reasonable considerations.

3.3 Final docking approach using coarse control

In the second stage, an optimal rendezvous approach is calculated depending on the necessary docking velocity, sunlight conditions, and ground station visibility. For optimal use of the relative navigation cameras, docking shall happen when the satellites are in Sun phase. To get the optimal docking velocity as well as repeated docking opportunities, the so called Gauss's variational equations have been used [8]. This leads to the instantaneous change in ROEs produced by an impulsive maneuver at a specific location in orbit, as presented in eq. (2).

$$\begin{aligned} a\Delta\delta a &= +2\delta v_T/n, & a\Delta\delta\lambda &= -2\delta v_R/n \\ a\Delta\delta e_x &= +(\delta v_R/n)\sin u_M + 2(\delta v_T/n)\cos u_M, & a\Delta\delta i_x &= +(\delta v_N/n)\cos u_M \\ a\Delta\delta e_y &= -(\delta v_R/n)\cos u_M + 2(\delta v_T/n)\sin u_M, & a\Delta\delta i_y &= +(\delta v_N/n)\sin u_M \end{aligned} \tag{2}$$

where δv_R, δv_R and δv_R represent the Δv values in RTN frame and n represents the mean motion of the Chaser. u_M represents the argument of latitude of the Chaser at the epoch of the maneuver.

A final docking approach with the user-defined docking velocity in a purely radial direction (with respect to the Chaser) has been found to be the optimal approach. This ensures that the final docking approach does not lead to a change in the mean semi-major axis of the Chaser with respect to the Target. This gives an opportunity for docking once every orbit, without significant addtional Δv usage. The final docking approach uses the standard four impulse maneuver set as well, as mentioned in section 3.2. A simple eclipse model has been used for calculating the sunlight conditions [9].

3.4 Fine control

The final docking approach puts the Chaser and Target into a relative orbit where the relative velocity is approximately $5\,\mathrm{cm\,s^{-1}}$. This is low enough to perform fine control for minor relative orbital corrections for docking using a single axis thruster. In this research, fine control comprises two burns having both radial and tangential components, sufficiently spaced apart according to user defined inputs. This allows the Chaser to have the correct orientation according to the radial and tangential components of the necessary Δv. Figure 4 represents an overview of fine control, where t_1, t_2, and t_3 represent the user defined timespans.

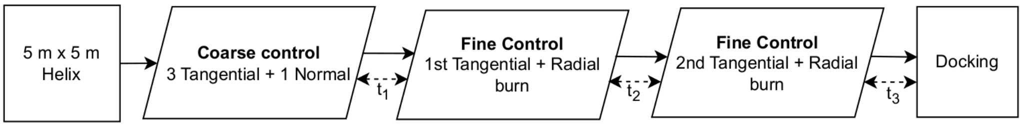


Figure 4: Fine control overview

Equation (2) can be represented in matrix form for fine control, as shown in eq. (3).

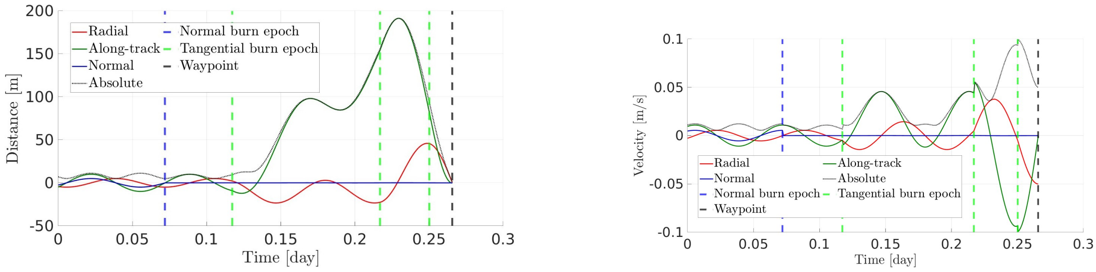
$$\begin{bmatrix} 0 & 2 & 0 & 2 \\ -2 & -3(u_{t_f}-u_{b_1}) & -2 & -3(u_{t_f}-u_{b_2}) \\ \sin u_{b_1} & 2\cos u_{b_1} & \sin u_{b_2} & 2\cos u_{b_2} \\ -\cos u_{b_1} & 2\sin u_{b_1} & -\cos u_{b_2} & 2\sin u_{b_2} \end{bmatrix} \begin{bmatrix} \delta v_{R_1} \\ \delta v_{T_1} \\ \delta v_{R_2} \\ \delta v_{T_2} \end{bmatrix} = -n \begin{bmatrix} b_{a\delta a} \\ b_{a\delta\lambda} \\ b_{a\delta e_x} \\ b_{a\delta e_y} \end{bmatrix} \tag{3}$$

where δv_{R_1}, δv_{T_1} represent the radial and tangential components of the first fine control burn. δv_{R_2}, δv_{T_2} represent the radial and tangential components of the second fine control burn. u_{b_1}, u_{b_2} represent the arguments of latitude of the Chaser at the epochs of the first and second fine control burns, respectively. u_{t_f} represents the argument of latitude of the Chaser at the rendezvous epoch. $b_{a\delta a}$, $b_{a\delta\lambda}$, $b_{a\delta e_x}$, and $b_{a\delta e_y}$ represent the desired changes in $a\delta a$, $a\delta\lambda$, $a\delta e_x$, and $a\delta e_y$, respectively.

4 Simulation

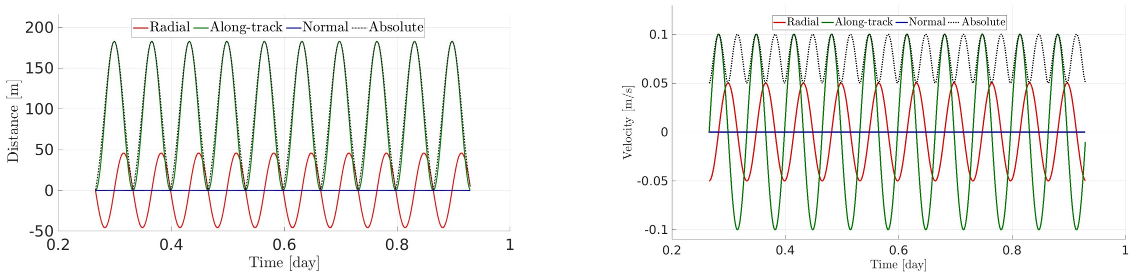
Simulations were performed considering the approach introduced in section 3. The satellites were considered to be in a $5\,\mathrm{m} \times 5\,\mathrm{m}$ helix orbit initially, as listed in Table 1. The desired ROEs were calculated according to the approach in section 3.3. The final docking approach initiated over San Martin ground station in Antarctica. Docking was set to happen over Berlin during Sun phase, with the approach duration set to four orbital periods of the Chaser. The optimal docking velocity was set to be $5\,\mathrm{cm\,s^{-1}}$. The maximum amount of Δv required for successful docking was set at $3\,\mathrm{m\,s^{-1}}$. The minimum duration between the approach initiation and the epoch of the first burn was set to 24 min. The timespans t_1, t_2, and t_3, as introduced in section 3.4 were set to 10 min, 5 min, and 2 min, respectively. Perturbations include 20 x 20 Earth gravity field and MSISE90 atmospheric model [10].

Figure 5 shows the relative position and relative velocity over time during the final docking approach, which lasts over a period of approximately six hours. The relative position and relative velocity are approximately 0 m and 5 cm s^{-1}, respectively, at the end of the docking approach. Figure 6 shows the relative position and relative velocity over time after the final docking approach up to ten orbital periods of the Chaser. Here the relative position and relative velocity become approximately 0 m and 5 cm s^{-1} once every orbit, providing multiple docking opportunities. As can be seen in fig. 7, using fine control reduces the minimum relative distance between the satellites. Table 1 shows that the error in the final ROEs, when using fine control is lower as compared to the case when only coarse control is used. The increase in Δv usage resulting from the use of fine control is approximately 8.9 mm s^{-1}, which is within the defined limit.



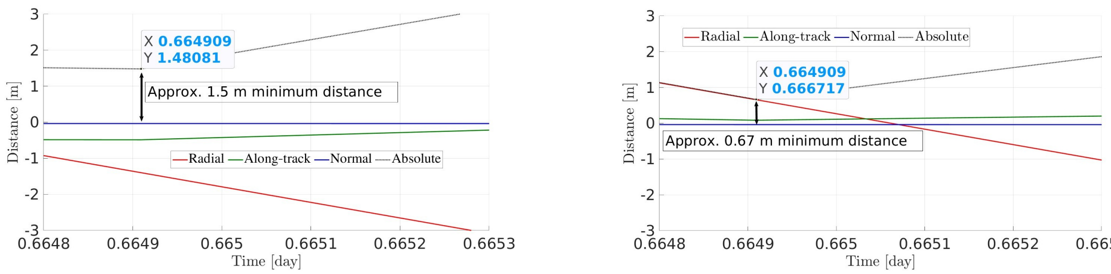
(a) Relative Distances (b) Relative Velocities

Figure 5: Relative distances and velocities during the rendezvous approach



(a) Relative Distances (b) Relative Velocities

Figure 6: Relative distances and velocities after the first rendezvous approach



(a) Without Fine Control (b) With Fine Control

Figure 7: Comparison of minimum rendezvous distances without and with fine control

Table 1: Effect of fine control on the final relative orbital elements and docking approach Δv usage

	$a\delta a$	$a\delta\lambda$	$a\delta e_x$	$a\delta e_y$	$a\delta i_x$	$a\delta i_y$	$\Delta \boldsymbol{v}$ [mm s^{-1}]
Initial [m]	0.00	0.00	0.00	5.00	0.00	5.00	—
Desired [m]	0.00	91.33	−39.55	22.83	0.00	0.00	—
Coarse control error [cm]	0.5	21.62	90.17	186.11	−4.34	2.65	29.322
Fine control error [cm]	0.7	0.98	0.02	1.09	−4.42	2.56	38.261

5 Conclusion and outlook

The development of CubeSat formation flight with rendezvous and docking capabilities requires careful consideration of mission operational requirements and constraints. In line with the NanoR&D mission proposal, this study analyzes the safe formation flight from deployment to successful docking, while taking into account the relative orbit elements and leveraging the natural perturbations for lower Δv usage. The study also considers fine control for minor relative orbital corrections within the predefined Δv limit and exchanging orbit and attitude data between the satellites through inter-satellite links at regular intervals. Future research will focus on developing near miss protocols, relative navigation algorithms, and ensuring sufficient battery levels during rendezvous approach, among other considerations.

Acknowledgement

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