GUIDANCE, NAVIGATION, AND CONTROL FOR THE DWARF MISSION

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The Demonstration with Nanosatellites of Autonomous Rendezvous and Formation-Flying (DWARF) mission consists of a pair of identical 3U CubeSats which will act as a spaceborne testbed to further advance, rigorously validate, and embed new relative navigation and control technologies in order to meet the needs of future distributed space systems. This paper focuses on the design and implementation of the DWARF on-board Guidance, Navigation, and Control (GNC) system. The DWARF mission will demonstrate unprecedented real-time centimeter-level navigation accuracy on board and new safe, robust, and autonomous relative orbit control algorithms.

INTRODUCTION

Distributed space systems (DSS) employ multiple co-orbiting units to enable advanced missions in space science, technology, and infrastructure. As mission concepts become more complex, future space architectures must address new challenges in relative navigation and control accuracy, robustness, and safety. The Demonstration with Nanosatellites of Autonomous Rendezvous and Formation-Flying (DWARF) mission, developed by the Stanford Space Rendezvous Laboratory (SLAB) in collaboration with Gauss S.R.L. and King Abdulaziz City for Science and Technology (KACST), seeks to demonstrate advancements in relative navigation and control to meet the needs of future ambitious distributed space systems. The on-board dedicated Guidance, Navigation, and Control (GNC) payload consists of software developed by SLAB and is integrated on board two identical 3U CubeSats using commercial-off-the-shelf (COTS) hardware. Both satellites can assume the role of chief and deputy in order to balance fuel consumption and double the mission lifetime. The GNC software is split into two integrated modules, navigation and control. The navigation module employs carrier-phase differential Global Navigation Satellite System (GNSS) techniques to demonstrate real-time centimeter-level precision through the use of Integer Ambiguity Resolution (IAR) on board in the presence of frequent control maneuvers. The control module will perform safe, robust, and autonomous formation acquisition, keeping, and reconfiguration at separations between 100 meters and 100 kilometers. These capabilities will be demonstrated in flight for the first time, enabling future missions such as virtual telescopes, optical interferometers, on-orbit servicers for lifetime prolongation and assembly of larger structures in space. Specifically, these technologies have been identified by NASA and NSF as enablers for missions such

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as Starling, a swarm of four satellites demonstrating the capability to navigation in deep space without Global Positioning System (GPS), Miniaturized Distributed Occulter/Telescope (mDOT), a precise formation intending to image a star, the Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX), a swarm that will study Earth’s upper atmosphere, and the Virtual Super-resolution Optics with Reconfigurable Swarms (VISORS), a swarm of three spacecraft that will perform solar observations. These missions are all under study and development at SLAB and will directly benefit from the algorithms described in this paper.

STATE OF THE ART

The concept of multiple spacecraft operating together was first demonstrated in the 1960s during the Gemini program, with advancements continuing through the Apollo program and the Space Shuttle. While these early demonstrations were rudimentary by current standards, they paved the way for recent spacecraft formation-flying and rendezvous missions that require more advanced autonomous navigation and control algorithms. Numerous science missions such as the Gravity Recovery and Climate Experiment (GRACE, 2002), the TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X, 2010), and the Magnetospheric Multiscale Mission (MMS, 2015) used multiple spacecraft to conduct unprecedented experiments for gravity field recovery, synthetic aperture radar interferometry, and magnetospheric observation, respectively. Another class of formation-flying and rendezvous missions are technology demonstrations, such as PRISMA (2010), CanX-4/5 (2014), and CPOD (2020). Advancements in DSS missions have demonstrated state-of-the-art navigation and control algorithms on board, while also moving from large, expensive spacecraft (GRACE, TanDEM-X) to smaller, cheaper nanosatellites (CanX-4/5, CPOD).

Precision navigation for DSS has largely been enabled through the use of GNSS, such as GPS. GNSS-based absolute positioning accuracies of 1m have been demonstrated for a single spacecraft in real time, while relative navigation using differential GNSS (dGNSS) techniques provide greatly higher accuracy. By exploiting synchronous measurements from two receivers, common errors can be cancelled out, resulting in low-noise relative measurements. This technique was validated on board in real time on missions such as PRISMA, where an Extended Kalman Filter (EKF) showed precise relative positioning results of less than 10cm (3D, RMS) between two small spacecraft throughout most mission scenarios. Similar results were obtained during the CanX-4/5 mission, demonstrating dGNSS for the first time on CubeSat avionics in flight.

Navigation accuracies have been further improved by fixing the carrier-phase ambiguities to their integer values, a technique referred to as Integer Ambiguity Resolution. However, due to computational overhead and a lack a guarantee of correctly fixing the integers, IAR has never been performed in flight. GRACE used IAR in post-processing to demonstrate 1mm (1D range-only, 1σ) relative positioning accuracy at a separation of 200km when compared with the high-precision on-board K/Ka-band ranging system. More recently, advances in spacecraft avionics have allowed for more complex algorithms such as IAR to be run on board in real time. The Distributed Multi-GNSS Timing and Localization system (DiGiTaL) is a navigation payload for nanosatellites that achieves centimeter-level positioning accuracy and nanosecond-level time synchronization throughout arbitrarily sized swarms. A reduced-dynamics estimation architecture on board each individual satellite processes low-noise measurements from multiple GNSS constellations and frequencies to reconstruct the full formation state with high accuracy. DiGiTaL demonstrated successful IAR to provide less than 1cm (1D, RMS) of relative positioning accuracy in real time for a swarm of four spacecraft over short baselines using full CubeSat avionics in the loop. The system was developed
Advancements have also been made to push towards robust and autonomous control of spacecraft relative motion. An on-board relative control software aims to minimize the delta-v cost of a set of impulsive control actions while achieving a desired relative state in fixed time. Recent flight demonstrations of impulsive control such as the Spaceborne Autonomous Formation Flying Experiment (SAFE) on PRISMA and the TanDEM-X Autonomous Formation Flying (TAFF) system cast the relative orbit reconfiguration problem into quasi-nonsingular relative orbit element (ROE) space. Use of the ROE state representation overcomes the limitations of the Cartesian-based linear models of relative dynamics like the Hill-Clohessy-Wiltshire equations (HCW) and Yamanaka-Ankerson (YA) equations, which are accurate only for small spacecraft separations. The ROE state allows for linearization of the equations that govern relative motion without loss of generality.

In addition, use of the ROE state provides a geometric intuition that can be exploited to derive simple geometric conditions for collision avoidance and safety, called relative eccentricity/inclination (E/I) vector separation. Typically, mission designers maintain safe separation using a relative spacecraft configuration called the safety ellipse, which is defined such that the relative motion in the radial-tangential/radial-normal (RT/RN) planes is bounded and periodic. The Restore-L mission, set to launch in 2020, plans to use safety ellipses in their approach trajectory. However, in his thesis, D’Amico showed that the minimum separation between the spacecraft over several orbits can be expressed analytically as a function of the ROE, and derived simple expressions for the relationship between the relative eccentricity vector and relative inclination vector that ensure that the satellites will maintain a prescribed relative distance in the radial/cross-track plane. The method was implemented successfully in several missions such as GRACE, TanDEM-X/TerraSAR-X, and PRISMA.

Though recent missions have employed the use of the ROE state representation, formation control implementation has been restricted to near-circular orbits. In particular, TAFF used pairs of along-track maneuvers separated by half an orbital period, which is optimal for in-plane control in near-circular orbits, but is infeasible in eccentric chief orbits. SAFE used additional radial and cross-track maneuvers, but radial control was only used in certain modes, and not optimally.

To improve upon the state-of-the-art in autonomous, on-board spacecraft relative orbit control, Chernick et al. developed globally energy-optimal closed-form impulsive control algorithms developed for orbits of arbitrary eccentricity. The solutions are derived using the domain-specific benefits of the ROE state representation and leveraging the geometric advantages of reachable set theory, a tool commonly used to assess cost-reachability and safety and only recently used in control itself. The maneuver planning algorithms do not assume the form of the maneuvers; unlike the aforementioned missions that are limited to near-circular orbits, Chernick’s relative control algorithms are robust to orbit regime and therefore employ radial, tangential, and normal (RTN) maneuvers to achieve an optimal reconfiguration solution, in-plane and out-of-plane alike. The DW ARF mission is the first in-flight demonstration of these globally optimal control algorithms. In addition, DW ARF will employ a newly developed collision avoidance method inspired by D’Amico’s method which guarantees passive safety throughout a reconfiguration, even if a maneuver fails.
SYSTEM OVERVIEW

This work presents a full system architecture for a dedicated GNC payload that implements novel algorithms in flight for the first time. Figure 1 details the DwarF payload, including communication with external systems. In addition to the system software, the payload also consists of a GNSS receiver, two GNSS antennas, an Inter-Satellite Link (ISL), and a cold-gas propulsion system.

![Figure 1: Architecture of DwarF GNC payload](image)

To perform these navigation and control tasks, DwarF requires inputs from various sources from the spacecraft. The system receives messages from the GNSS receiver that includes measurements and GNSS broadcast ephemeris data. It is also necessary to have attitude and maneuver information, the latter of which is either generated internally within the control subsystem of the DwarF payload or provided via telecommand. In addition, the GNC payload requires all of the above information from the other spacecraft which is received via the ISL. Finally, telecommands are sent to the payload from ground to set parameters and to trigger different modes of operation. As an output, DwarF provides absolute and relative orbit information, including both the orbit state and associated covariance, and control maneuver commands for formation keeping and reconfiguration. As described above, information necessary for ISL communication is sent to the other spacecraft, and telemetry data is generated to monitor the system and output to ground.

Navigation for DwarF is accomplished using DiGiTaL, which integrates a multi-GNSS receiver and antenna system with an Inter-Satellite Link (ISL) to provide centimeter-level relative positioning accuracy in real time. The DiGiTaL payload has a 0.5U CubeSat form factor, with a maximum power requirement of 3W and a mass of 225g. DiGiTaL shares synchronous low-noise measurements from receivers on each spacecraft through the ISL and forms powerful error-cancelling combinations in an EKF to precisely estimate absolute and relative orbits of the satellites.

These combinations are formed from the raw code and phase measurements from each receiver into the coarse Group And Phase Ionospheric Correction (GRAPHIC) and precise single-difference carrier-phase (SDCP) data types. The SDCP measurements are formed as differences of carrier-phase measurements from two receivers tracking the same GNSS service vehicle, creating a relative measurement between the receiving antennae’s phase centers with millimeter-level noise. Once the measurements are processed, the filter performs the additional step of IAR using the Modified Least-Squares Ambiguity Decorrelation Adjustment (mLAMBDA) method. To increase the robustness of the IAR process, a series of checks are performed including the Success Rate Test and the Discrimination Test, as well as the novel Residual Test. This final test checks the measurement residuals before and after the ambiguities are fixed to ensure that IAR did not incorrectly
set the ambiguities, which would be seen as a bias in the post-fit residual of the corresponding measurement.

The DW ARF control system is implemented as a regularly called finite state machine within the framework of the GNC payload and is defined as a set of states, transition conditions, and actions. There are three modes, \texttt{NONE}, \texttt{RECONFIG}, and \texttt{KEEP}, associated with no control, reconfiguration control, and formation keeping, respectively. \texttt{KEEP} is the default mode for the controller, and is only changed if a reconfiguration command is received from ground. The state machine is the same for formation keeping and reconfiguration/acquisition, but the source of guidance commands changes: external for reconfiguration/acquisition, internal for keeping. Otherwise, the controller plans and executes formation keeping maneuvers according to a set formation keeping window and nominal relative (orbit element) state. In addition, there are seven states associated with actions that are performed whenever the state machine is called and until associated transition conditions are satisfied. This paper will detail the actions and transition conditions that allow data to flow through the state machine.

Much of the maneuver planning within the control software occurs in the \texttt{PLAN\_CONTROL} state. As discussed previously, the software utilizes the in-plane and out-of-plane globally-optimal closed-form control solutions developed by Chernick et al.\textsuperscript{32} leveraging reachable set theory and the ROE state representation. The planner is robust to orbit regime, and produces maneuver schemes that are provably optimal.\textsuperscript{32} In reconfiguration cases that cannot be reached optimally, the same algorithms can be used to generate quantifiably sub-optimal solutions.

The \texttt{PLAN\_CONTROL} state also handles performance bounds, constraints, collision avoidance, and failure mitigation. Using relative state covariance data from the navigation module, the controller uses a new method to assess maneuver scheme performance. Given a desired confidence level and a covariance matrix, an \textit{n}-dimensional bounding box is fitted to an \textit{n}-dimensional error ellipsoid to determine if performing a reconfiguration is viable (if a given maneuver scheme will achieve the desired end state within reasonable bounds). In addition, the controller uses a set of conditions based on relative E/I vector separation to check that the deputy (controlled) spacecraft does not enter a configured “keep-out-area” (KOA) around the chief (reference) spacecraft, which assures that they do not collide, even in the case of a maneuver failure. If the maneuver planner fails to meet those conditions, the planner attempts to re-plan the reconfiguration for a configured number of ‘pings’ to the state machine. If it cannot successfully re-plan that reconfiguration in time, the controller returns automatically to autonomous formation keeping.

It should be noted that the navigation module uses a Cartesian-based state for ease of use with GNSS, in particular GPS, which operates in the World Geodetic System (WGS) 84 Earth-fixed frame. However, the control module operates using an orbital element state to take advantage of geometric properties and slowly varying dynamics. Therefore, it is necessary for a transformation to take place between the navigation and control modules for both the absolute and relative states. This is done using well-known Cartesian to osculating Keplerian orbital element transformations, followed by a transformation to mean orbital elements, including J2 effects, which uses an iterative approach with a Newton-Raphson solver using the Jacobian of the nonlinear transformation.\textsuperscript{39} Then, the quasi-nonsingular ROE are constructed by their definition in Eq. (3) in Chernick et al.’s paper\textsuperscript{32} for use in maneuver planning.
VALIDATION

To validate the system design of the DW ARF payload, extensive hardware-in-the-loop (HIL) testing is conducted at Stanford University’s GNSS and Radiofrequency Testbed for Autonomous Navigation of DSS (GRAND) shown in Figure 2. A high-fidelity orbit propagator simulates the truth orbit, while navigation and control algorithms are embedded on an 800 MHz Endeavour flight computer with a Novatel OEM628 GNSS receiver that is stimulated from an IFEN GNSS Signal Simulator. Based on the navigation solution and telecommanded reconfiguration messages, control maneuvers are planned and incorporated in both the truth propagator and the navigation filter.

The capabilities of the DW ARF GNC payload will be demonstrated in a mission example in a LEO, sun-synchronous orbit. The system will perform formation keeping around a set nominal relative state until a ground-commanded reconfiguration is received. Performance bounds, minimum separation requirements, and delta-v maxima and minima restrictions are imposed on the system.

The initial phase of the experiment demonstrates formation keeping capabilities, specifically about a relative orbit given by

$$\delta \alpha_{nom,0} = \begin{bmatrix} 0 & 0 & 30 \cos(\pi/4) & 30 \sin(\pi/4) & 60 \cos(\pi/4) & 60 \sin(\pi/4) \end{bmatrix}^T \text{ m.} \quad (1)$$

The deputy spacecraft must first acquire this state from its initial state of

$$\delta \alpha_0 = \begin{bmatrix} 0 & 100 & 20 \cos(\pi/3) & 20 \sin(\pi/4) & 40 \cos(\pi/6) & 40 \sin(\pi/4) \end{bmatrix}^T \text{ m.} \quad (2)$$

Maneuvers are planned and executed to maintain these relative orbit elements on a scheduled 2.5 orbit cycle. During this phase, the navigation system will initialize its state from the GNSS receiver and begin to filter measurements, followed by the activation of IAR.

After sufficient time is allowed for initialization and demonstration of formation keeping, a reconfiguration command is received from ground. The new set of relative orbit elements is given by

$$\delta \alpha_{f,des} = \begin{bmatrix} 1000 & 300 \cos(\pi/4) & 300 \sin(\pi/4) & 80 \cos(\pi/4) & 80 \sin(\pi/4) \end{bmatrix}^T \text{ m.} \quad (3)$$

This reconfiguration is to be completed within 2.5 orbits. When the new desired state is reached, $$\delta \alpha_{f,des}$$ in Eq. (3) becomes the new nominal formation, and the controller returns to KEEP mode about this state. This formation is kept for the remainder of the experiment. Table 1 outlines the timing of the experiment.

Figure 2: GRAND testbed configuration. Red line indicates data flow for DW ARF testing.
### Table 1: Experiment timing for demonstration of formation keeping and reconfiguration

<table>
<thead>
<tr>
<th>Initial time (orbits)</th>
<th>Current relative state (m)</th>
<th>Desired relative state (m)</th>
<th>Duration (orbits)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Initial (Eq. (2))</td>
<td>Nominal (Eq. (1))</td>
<td>2.5</td>
<td>RECONFIG</td>
</tr>
<tr>
<td>2.5</td>
<td>Nominal (Eq. (1))</td>
<td>Nominal (Eq. (1))</td>
<td>2.5</td>
<td>KEEP</td>
</tr>
<tr>
<td>3*</td>
<td>Nominal (Eq. (1))</td>
<td>Eq. (3)</td>
<td>2.5</td>
<td>RECONFIG</td>
</tr>
<tr>
<td>5.5+</td>
<td>New nominal (Eq. (3))</td>
<td>New nominal (Eq. (3))</td>
<td>2.5</td>
<td>KEEP</td>
</tr>
</tbody>
</table>

* The reconfiguration command is received during a formation keeping cycle. As long as the state is safe to reconfigure, the state machine mode will change immediately to RECONFIG.

The paper demonstrates navigation and control performance results from this experiment. Specifically, it is shown that the system achieves the predicted centimeter-level relative positioning accuracy throughout the simulation in the presence of formation keeping and reconfiguration maneuvers. The experiment also demonstrated that the system attains the desired relative state within 5% of the commanded state in both formation keeping and reconfiguration.

### REFERENCES


