Acta Astronautica 118 (2016) 168–186

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Development of an integrated spacecraft Guidance, Navigation, & Control subsystem for automated proximity operations ☆

Peter Z. Schulte *, David A. Spencer

Space Systems Design Laboratory, Georgia Institute of Technology, 270 Ferst Dr., Atlanta, GA 30332-0150, USA

ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form
11 August 2015
Accepted 12 October 2015
Available online 23 October 2015

Keywords:
Spacecraft Guidance Navigation & Control
Small satellites
Proximity operations
MATLAB/Simulink
Six degree of freedom simulation
Flight software

ABSTRACT

This paper describes the development and validation process of a highly automated Guidance, Navigation, & Control subsystem for a small satellite on-orbit inspection application, enabling proximity operations without human-in-the-loop interaction. The paper focuses on the integration and testing of Guidance, Navigation, & Control software and the development of decision logic to address the question of how such a system can be effectively implemented for full automation. This process is unique because a multitude of operational scenarios must be considered and a set of complex interactions between subsystem algorithms must be defined to achieve the automation goal. The Prox-1 mission is currently under development within the Space Systems Design Laboratory at the Georgia Institute of Technology. The mission involves the characterization of new small satellite component technologies, deployment of the LightSail 3U CubeSat, entering into a trailing orbit relative to LightSail using ground-in-the-loop commands, and demonstration of automated proximity operations through formation flight and natural motion circumnavigation maneuvers. Operations such as these may be utilized for many scenarios including on-orbit inspection, refueling, repair, construction, reconnaissance, docking, and debris mitigation activities. Prox-1 uses onboard sensors and imaging instruments to perform Guidance, Navigation, & Control operations during on-orbit inspection of LightSail. Navigation filters perform relative orbit determination based on images of the target spacecraft, and guidance algorithms conduct automated maneuver planning. A slew and tracking controller sends attitude actuation commands to a set of control moment gyroscopes, and other controllers manage desaturation, detumble, thruster firing, and target acquisition/recovery. All Guidance, Navigation, & Control algorithms are developed in a MATLAB/Simulink six degree-of-freedom simulation environment and are integrated using decision logic to autonomously determine when actions should be performed. The complexity of this decision logic is the primary challenge of the automated process, and the Stateflow tool in Simulink is used to establish logical relationships and manage data flow between each of the individual hardware and software components. Once the integrated simulation is fully developed in MATLAB/Simulink, the algorithms are autocoded to C/C++ and integrated into flight software. Hardware-in-the-loop testing provides validation of the Guidance, Navigation, & Control subsystem performance.

☆ This paper was presented during the 65th International Astronautical Congress in Toronto, Canada.

* Corresponding author.
E-mail addresses: pzschulte@gatech.edu (P.Z. Schulte), david.spencer@aerospace.gatech.edu (D.A. Spencer).

http://dx.doi.org/10.1016/j.actaastro.2015.10.010

1. Introduction

There is an increased need for autonomous Proximity Operations (ProxOps) in such applications as rendezvous and docking for human space exploration and sample return missions, satellite servicing and on-orbit inspection, construction, and debris mitigation. Many autonomous ProxOps systems have been developed and proven in flight for large and complex systems [1–3] and are increasingly being used with small satellites [4,5]. Development of spacecraft Guidance, Navigation, and Control (GN&C) software architectures often involves bringing together individually developed algorithms and evaluating them using both simulation and hardware-in-the-loop testing [6]. The process of spacecraft GN&C algorithm development and integration using Model-Based Design in Simulink and later autocoding into flight software (FSW) has been exercised by the Orion spacecraft team at NASA's Johnson Space Center [7]. Even though Orion uses autocode from Simulink as a cornerstone of its GN&C FSW validation, many of its GN&C algorithms were originally prototyped in C code and later converted to Simulink block diagrams. Previous uses of selective autocoding of GN&C algorithms into flight software include the design of the Space Maneuver Vehicle by Boeing [8], the German Phoenix project by EADS [9], and the Cluster Flight Application by Emergent Space Technologies [10]. In each of these cases, some of the GN&C algorithms and software functions were autocoded from Simulink while others were hand-coded into the final FSW.

Prox-1 is a small satellite mission designed, built, and operated by students at the Georgia Institute of Technology (Georgia Tech) under the University Nanosatellite Program at the Air Force Research Laboratory (AFRL). The primary mission of Prox-1 is to demonstrate automated relative trajectory control in Low-Earth Orbit with a non-cooperative target for an on-orbit inspection application [11]. The Prox-1 team is advancing the state-of-the-art by developing all of its GN&C algorithms completely within an integrated MATLAB/Simulink environment rather than integrating externally developed algorithms. The team is also autocoding the entire GN&C flight software rather than hand-picking which algorithms to autocode. The single autocoded GN&C software block is then validated using hardware-in-the-loop testing. By utilizing this integrated approach for GN&C software development and testing, the reliability and robustness of the software is demonstrated, yielding a fully validated GN&C subsystem for flight. This paper will introduce the Prox-1 mission, describe the GN&C algorithms and hardware components, and present the streamlined development and implementation approach that is being utilized by the Prox-1 GN&C subsystem team.

2. Prox-1 mission description

The Prox-1 mission begins with deployment of Prox-1 as a secondary payload from the Space Test Program-2 launch on the SpaceX Falcon Heavy launch vehicle. Once deployed, body-mounted solar panels will begin battery charging, and the flight processor will boot up. Next, magnetic torque rods will detumble the spacecraft. Once angular rates have been nulled, a spacecraft checkout phase ensues where on-orbit functionality is characterized, including the flight qualification of new subsystem technologies including the Honeybee Robotics TORC control moment gyros (CMGs) [12], the Jet Propulsion Laboratory Advanced Micro-Sun Sensor [13], the FLIR/Arizona State University microbolometer thermal imager [14], and the University of Texas at Austin 3D-printed cold gas propulsion unit [15].

The target spacecraft for the Prox-1 mission is The Planetary Society's LightSail, a 3U CubeSat that is designed to demonstrate solar sail technology [16]. LightSail is stowed inside of Prox-1 during launch and is deployed on-orbit using a Poly Picosat Orbital Deployer (P-POD) device following Prox-1 checkout. A period of time is allowed for the two spacecraft to drift apart, and orbit determination is performed on the ground to determine the trajectories of both vehicles. After orbit determination has been completed, a series of ground-in-the-loop maneuvers will be performed to complete Prox-1 rendezvous with LightSail to within visual sensor range of 100–200 m. At this point, automated ProxOps begin. The Prox-1 GN&C subsystem acquires the target spacecraft in its thermal imager field of view (FOV) for relative navigation and maneuvers the spacecraft into a formation flight orbit with respect to LightSail.

During ProxOps Phase I, Prox-1 performs a Rest-to-Rest maneuver to move from the initial formation flight location to a point closer to LightSail, and station-keeping capability is demonstrated for multiple orbits. During ProxOps Phase II, Prox-1 enters into a Natural Motion Circumnavigation (NMC) of LightSail using a relative elliptical orbit. During the ProxOps mission phases, Prox-1 performs all maneuvers without communication from the ground or cooperation from LightSail. After the primary mission is complete, Prox-1 performs on-orbit inspection to image the deployment of LightSail's 32 m^2 solar sail. Finally, once all primary and secondary mission requirements are completed, Prox-1 is deorbited using a deployable drag device.

3. Guidance, Navigation, & Control (GN&C) subsystem overview

The Guidance, Navigation, & Control (GN&C) subsystem for Prox-1 is made up of navigation algorithms and sensor components used to determine the satellite attitude and trajectory state, guidance algorithms to determine desired trajectories, and control algorithms and actuator components to control the attitude and perform propulsive maneuvers.

3.1. Navigation algorithms and sensor components

Each of the navigation algorithms is used to determine the state of the spacecraft based on inputs from various sensors. The fine attitude determination requirement for the mission is to obtain attitude knowledge within 1.5° per