SATELLITE FORMATION FLYING: ON-GROUND EXPERIMENT ON RELATIVE ORBIT ELEMENTS-BASED CONTROL

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Accurate preflight testing environments for formation flying are crucial in transitioning between numerical simulation and actual orbital flight. A 3 degree of freedom (DOF) experimental testbed was developed at the Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory to validate a relative orbit elements-based control strategy for satellite formation reconfiguration maneuvering. The experimental facility consists of two completely autonomous vehicles floating on an epoxy 4×4 m surface. The vehicles are equipped with compressed air thrusters to enable their movement on the frictionless floor while a PhaseSpace Impulse System determines their position and attitude. A numerical simulator describing the dynamics of the testbed was developed, using MATLAB and Simulink, to have a benchmark for cross checking experimental results. This paper presents the design and integration of the vehicles with their preliminary experimental results. An experiment based on an analytical control scheme of 3 tangential (T-T-T) finite-time maneuvers was conducted to generate a guidance. A feedback control law using a Linear Quadratic Regulator (LQR) was implemented to follow the guidance. The vehicle was able to accurately track a computed guidance trajectory within the accuracy of 0.06 m.

INTRODUCTION

The rapid growth of spacecraft proximity missions has brought forth a strong emphasis on the development of an accurate and precise on Earth guidance, navigation, and control (GNC) system.¹ These developments bring about major challenges in terms of the robustness and confidence of the GNC systems. In addition, spacecraft formation flying concepts are known as pivotal technology for advancements in commercial missions by NASA and the U.S. Air Force.¹ This is partly because the use of docking and proximity maneuvering is a key aspect in orbit refueling, debris mitigation, large orbiting structures building, and planetary specimen collection. The most used method of maneuvering, which incidentally is used by the International Space Station (ISS), uses a human operator in the control loop; as a result, full autonomy in docking maneuvering applications is a

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newly explored topic.² Therefore, rigorous on-ground and in orbit testing procedures, focused on both the software and hardware components, are typically planned to validate these systems. It is important to note that precision in the reconstruction of state and fine control are the two challenges when discussing the fundamentals of maneuvering; which are dependent on the chosen docking mechanism. Developing a GNC system for satellite formation reconfiguration maneuvering involves additional challenges such as accounting for both spacecraft by using absolute and relative based navigation, a high level of state detection, and computationally powerful yet light hardware.²

The first phase of mission development would be the on-ground testing phase; which is key in the design of a robust and reliable system for relative maneuvering. Many research centers and academies have put a motion on dedicating specific facilities to validate onboard software and hardware solutions for formation flying applications.² As an example, Romano et al.³ developed a 3 degree of freedom (DOF) planar testbed for said validation of autonomous proximity navigation and docking maneuvers. The testbeds in this facility consisted of four vehicles each having eight electro valve thrusters to manipulate motion on an epoxy coated surface. Each robot performs absolute navigation within the laboratory environment by employing an indoor pseudo-GPS for position and a magnetometer paired with a gyroscope for its attitude. Additionally, at Politecnico di Milano, Dipartimento di Ingegneria Aerospaziale, a test facility with two vehicles floating on air pads on a frictionless glass surface is used to test proximity and docking control algorithms.² Finally, Tsiotras et al. introduced a 5DOF experimental facility that allows realistic testing of spacecraft autonomous rendezvous and docking maneuvers.⁴ The testbed consists of a single vehicle made of two states, namely the upper and lower stages, connected by a hemi-spherical airbearing that allows the relative motion between the two elements. The spacecraft simulator incorporates a collection of different sensors, such as an inertial measurement unit (IMU), Sun/star sensors, three-axis rate gyros, attitude motion control, and variable speed control moment gyros (VSCMGs) for the rotational motion control of the upper stage.

The Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory at the University of Florida built upon past knowledge and designed a 3DOF experimental testbed for hardware-in-theloop validation of GNC algorithms for formation flying reconfiguration. The testbed utilized an air-bearing based spacecraft simulator to replicate a virtually frictionless environment. This technology was used to emulate a planar orbit between a deputy and chief spacecraft with the implementation of an autonomous distributed spacecraft control algorithm which used relative orbital elements. The testbed incorporates a space-qualified Tyvak Intrepid computer board so that it can mimic the hardware capabilities of a small spacecraft.

The ADAMUS lab recreated a deputy spacecraft as a robotic system to emulate the relative dynamics scenario, with 3DOF; this robotic system was mounted on air-bearings that allowed the vehicle to float on an epoxy coated floor. Figure 1 shows the relative dynamics scenario depicting three reference frames: Earth Centered Initial (ECI) frame and local reference frames for each spacecraft. The distances between the three objects can then be measured with respect to any chosen reference frame, where R_c and R_D are the distances between the Earth and the chief and deputy and ρ is the distance between the two spacecrafts. The chief spacecraft was represented as a point in the center of the epoxy floor as a virtual satellite. This system is known as a planar system.⁵ The position of the robotic system on the testbed was manipulated through thrust supplied from 8 air thrusters symmetrically placed on the robotic system. The position and attitude were measured using a motion capture software called "PhaseSpace". This software paired with a light emitting diode (LED) configuration on the robotic system allowed one to calculate the position and attitude of an object in respect to a defined reference frame. The experiment relied solely on the orbital path that the robotic system, or deputy, followed along the center of the testbed and was independent of

any motion that the chief would endure. The navigation of the experiment is based on the relative orbital elements model.



Figure 1. Relative dynamics scenario

This paper addresses the design of a 3DOF testbed for hardware-in-the-loop validation of GNC algorithms for formation flying reconfiguration. In more detail, it specifically focused on the following aspects:

- update of the hardware design of the existing floating vehicle;
- implementation on the hardware of the analytical control strategy for satellite formation flying maneuvering proposed by the authors in (Reference 5);
- development of a high accuracy numerical simulator describing the dynamics of the vehicles on the floor (i.e. including the testbed sensors and actuators models, and the disturbances accelerations) to have a benchmark for cross checking performance of the algorithms to be tested before applying them to the facility;
- discussion on the further hardware modifications to implement optimal formation reconfiguration maneuvering algorithm.

The ADAMUS lab's goal is to become an accredited testing facility for all control algorithms involving spacecraft proximity flight. The scenario created within the lab is similar to most scenarios discussed previously. The idea is to minimize all exterior perturbations, such as friction and air resistance, while also accounting for orbital perturbation, like J2 effects, to emulate a space environment.

Experimental Facility

The test bed that the experiment was conducted on was an enclosed 4 x 4 m epoxy covered floor (see Figure 2). Epoxy resin was used because of its low friction factor property.⁶ The robotic system utilized in the experiment is stationed on the test bed is accompanied by other moving vehicles developed by the ADAMUS lab. It is important to note that during the experiment, the other vehicles are positioned to not interfere with the testing phase. The cameras located above, which are mounted on the walls, are part of the PhaseSpace system to monitor the orientation and position of the robot during testing. During the testing phase, the room is sealed of any external air conditioning to avoid additional perturbations caused from external wind.



Figure 2. ADAMUS Laboratory Test Bed

The robotic system was equipped with three air bearings at its base which enabled it to float on top of the epoxy testbed and reproduced virtually frictionless motion. Eight compressed air thrusters are used for translational and attitude control. The thrusters consist of solenoid valves attached to custom made nozzles, which are commanded by a relay module. The pneumatic system installed on each of the vehicles consists of two 4500 psi air tanks and several pressure regulators to reduce the air pressure to the values of 100 psi and 165 psi required for the airpads and thrusters respectively (see Figure 3).

The testbed utilizes the PhaseSpace Impulse System to determine the position and the orientation of the vehicles. It consists of three main components: i) an array of 12 cameras situated around the testbed, ii) 6 LEDs placed in key locations on the vehicles for determining the attitude and position of the vehicle, and iii) a dedicated computer for the position and attitude (quaternion) computation. The cameras capture the images of the flashing LEDs.The PhaseSpace computer determines the position of each LED according to its flashing frequency (specific to each LED). All on-board subsystems of the floating vehicle are powered by a Lithium-Ion battery. The battery is connected to a Power Management System from Ocean Server Technology, namely the Intelligent Battery and Power System (IBPS). It recharges the batteries using a safety charging circuit when connected to the 120V grid and provides the required power at 5-12-24V voltages (see Figure 4). Specifically, the IBPS provides 5V power to the onboard computer and 12V power to a secondary DC-DC converter, which brings the voltage to 24V to supply the thrusters' electro-valves. Ultimately, the vehicles are equipped with the Intrepid computer board equipped with a AT91SAM92G0 Processor (@400 MHz. Table 1 lists the testbed components along with the manufacturers.



Figure 3. 3 DOF robotic system

#	Component	Part #	Manufacturer
1	4000 psi, 50cu, Paintball Air tanks (Thruster)	P07B-001	Luxfer
2	4000 psi, 50cu, Paintball Air tanks (Feet)	P07B-001	Luxfer
3	Solenoid Valves (x8)/Thrusters	EH2012	Gems Sensors
4	Battery Pack	BA95HC-FL	OceanServer
5	Battery Housing	Custom	Custom
6	PhaseSpace LEDs		PhaseSpace
7	Battery Management Module	BB-04SR	OceanServer
8	DC-ATX Converter	DC123SR	OceanServer
9	DC-DC Step-Up Converter	DC1U-1VR	OceanServer
10	8-Channel 5V Solid State Relay Module	101-70-111	SainSmart
11	Intrepid Board		Tyvak

Figure 4 illustrates the testbeds architecture. The PhaseSpace is used to determine the position and the attitude of the vehicle moving on the frictionless floor with respect to an inertial fixed reference frame, referred to as $\{F\}$ from now on, which is placed to be at the center of the floor. This pose information is transferred to the vehicle through the wi-fi network. The control solution is calculated by the Intrepid on-board computer and sent to the relay module board for commanding the eight electro-valve thrusters.



Figure 4. Subsystem interaction of Experimental Facility

PROCEDURE

In the experiment, the projection of the orbit of the deputy around the chief is represented on the epoxy floor by the robotic system. This representation is the Local Vertical Local Horizontal (LVLH) reference frame of the chief with the chief at the center of the frame as a virtual satellite. The LVLH reference frame refers to the coordinate system local to the chief. Figure 1 shows the chief's LVLH frame with the subscript, *C*. The goal of the experiment was to start at an initial orbit and use a control strategy to arrive at a desired orbit. A control strategy that was based on three tangential burns (T-T-T) was used to generate the Cartesian reference trajectory for the robotic system.⁵ A feedback control law using a Linear Quadratic Regulator (LQR) was then implemented on the robotic system.

Orbital Scenario

In this study, the in-plane formation reconfiguration problem is addressed. Recall that the trajectory reconfiguration problem denotes the achievement of a certain relative configuration between two spacecrafts, referred to as chief and deputy, in a given interval of time. The relative

formation geometry can be described through different state representations. Here, the relative orbit element (ROE) parameterization is used to describe the relative motion, i.e.⁷

$$\delta \boldsymbol{\alpha} = \begin{bmatrix} \frac{a_d}{a_c} - 1 \\ (u_d - u_c) + (\Omega_d - \Omega_c) c_{i_c} \\ e_{xd} - e_{xc} \\ e_{yd} - e_{yc} \\ i_d - i_c \\ (\Omega_d - \Omega_c) s_{i_c} \end{bmatrix} = \begin{bmatrix} \delta a \\ \delta \lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{bmatrix}$$
(1)

where $e_{x(\cdot)} = e_{(\cdot)}c_{\omega_{(\cdot)}}$ and $e_{y(\cdot)} = e_{(\cdot)}s_{\omega_{(\cdot)}}$ denote the components of the eccentricity vector. In Eq. **Error! Reference source not found.** the subscripts "*c*" and "*d*" label the chief and deputy satellites respectively, whereas $s_{(.)} = sin()$ and $c_{(.)} = cos()$. Considering this model, the in-plane reconfiguration problem indicates the achievement of the desired in-plane components of the ROE vector reported in Eq. (1) within the maneuvering interval, *T*, i.e. $[\delta a(T), \delta \lambda(T), \delta e_x(T), \delta e_y(T)]^T = [\delta a_{des}, \delta \lambda_{des}, \delta e_{x,des}, \delta e_{y,des}]^T$.

In this scenario, both the chief and the deputy are orbiting around the Earth and the deputy is orbiting around the chief. The initial mean chief orbit is shown in Table 2 in Keplerian orbital elements. The initial and desired relative orbital elements are shown in Table 3.

Table 2. Initial mean chief orbit.

a_c (km)	e_{xc} (dim)	e_{yc} (dim)	i_c (deg)	Ω_{c} (deg)	u_c (deg)
6578	0	0	8	0	0

	$a_c \delta a$	$a_c \delta \lambda$	$a_c \delta e_x$	$a_c \delta e_y$	$a_c \delta i_x$	$a_c \delta i_y$
	(m)	(m)	(m)	(m)	(m)	(m)
Initial relative orbit, $\delta \alpha_0$	0	2e3	0.5	0.5	0	0
Desired relative orbit $\delta \boldsymbol{\alpha}_{i}$	0	0	0.4	0.4	0	0

Table 3. Relative orbit at the initial and final maneuver time.

Guidance Calculation

An analytical control strategy for the satellite in-plane formation reconfiguration can be derived using the closed-form solution of the relative dynamics as proved by the authors in (Reference 6) under the following assumptions: i) the chief is moving on a near circular orbit (i.e., $e_c \rightarrow 0$); ii) the perturbing effects of the J2 are the most significant; iii) the control acceleration profile is a piecewise constant function $f(t) = [f_x(t), f_y(t)]^T \in \mathbb{R}^2$ defined in the maneuvering interval $[t_0, T]$ as (see Figure 5)

$$f_{(.)}(t) = \begin{cases} \bar{f}_{(.)}^{(j)} = const \neq 0, \ t_{(.),0}^{(j)} \le t \le t_{(.),f}^{(j)}, & \bar{f}_{(.),j} \in \mathbb{R}, \ j = 1, \dots, 3\\ 0, \ otherwise \end{cases}$$
(2)

where the term $n_{(.)} \in \mathbb{N}$ denotes the number of finite-time maneuvers along the axis (.) within the interval $[t_0, T]$, whereas $t_{(.),0}^{(j)}$ and $t_{(.),f}^{(j)}$ indicate the initial and final instant of time of the *j*-th maneuver. If the above assumptions are met, a control solution can be analytically determined for the following maneuvering scheme:⁶

• 3 tangential (T-T-T) finite-time maneuvers



Figure 5. Piecewise constant acceleration profile for a generic axis

This analytical T-T-T control scheme was used as the control algorithm to reconfigure the satellite formation, assuming the initial and desired orbits reported in Table 2 and Table 3.

Control System

The robotic system used a feedback control loop law based on LQR to follow the guidance that was generated from the analytical T-T-T control scheme. The following equations describe the dynamic system and the properties of the LQR control system (see Eq. (3) - (10)). The dynamic system, written in Eq. ((5) where, x is the state of the deputy in terms of position and velocity in the LVLH reference frame, u is the thrust vector of the air thrusters on the robotic system, where f is the force and τ is the torque, the subscripts denote which direction the vectors are in, and A and B are weighted matrices that are shown below with 0_{3x3} being a 3x3 zero matrix, I_{3x3} being a 3x3 identity matrix, and m_r being the mass of the robot. This LQR technique minimizes the quadratic cost function, shown in Eq. (8). The weighting factors for the state matrix and the input control function are shown in Eq. (10). These weighting factor values were found iteratively

by seeing what values would provide the best results with the numerical simulator. In both factor matrices, the planar state, the x and y-direction were given higher values because the force and the torque in these directions are controlled, while only the torque is controlled in the z-direction. The z-direction component of the state was still needed to control attitude.

$$\boldsymbol{x} = [\boldsymbol{x} \ \boldsymbol{y} \ \boldsymbol{z} \ \dot{\boldsymbol{x}} \ \dot{\boldsymbol{y}} \ \dot{\boldsymbol{z}}]^T \tag{3}$$

$$\boldsymbol{u} = [f_x f_y f_z \tau_x \tau_y \tau_z]^T \tag{4}$$

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u} \tag{5}$$

$$A = \begin{bmatrix} 0_{3x3} & I_{3x3} \\ 0_{3x3} & 0_{3x3} \end{bmatrix}$$
(6)

$$B = \begin{bmatrix} 0_{3x3} \\ I_{3x3} * \frac{1}{m_r} \end{bmatrix}$$
(7)

$$J = \int_0^\infty (x^T Q x + u^T R u) dt \tag{8}$$

$$Q = \begin{bmatrix} 1000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1000 \end{bmatrix}$$
(9)
$$R = \begin{bmatrix} 5.5 & 0 & 0 \\ 0 & 5.5 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
(10)

RECONFIGURATION MANEUVER ON THE ADAMUS FACILITY

Reference Frames

Figure 6 shows the inertial and local reference frames that were used throughout the experiment. Note that $\{F\}$, is the inertial reference frame located at the center of the epoxy floor. This reference frame is provided by the Phasespace detection and represents the LVLH reference frame of the chief satellite. The local reference frame, $\{R\}$, is located at the geometrical center of the robotic system and represents the LVLH reference frame of the deputy satellite. The quantity, r_D^{meas} , is the measured position vector of the robotic system.



Figure 6. Inertial and local reference frames

Orbital Motion Simulation on the Testbed

To emulate the relative orbital motion between the deputy and the chief spacecraft using the aforementioned testbed, it is necessary that the vehicles' actuator systems reproduce the inertia acceleration/torque due to the orbital motion of the satellites as well as the gravitational force/torque (aside from the control signal in the case of deputy vehicle). In addition, all orbital quantities (i.e. accelerations/torques/velocity/distance) and parameters must be scaled to satisfy the testbed constraints (i.e. facility autonomy and floor dimension). To do this, three different scale factors are defined, namely *length*, *time*, and *mass* scale factors, such that:

- the maximum scaled orbital relative distance between the spacecraft does not exceed the floor dimension;
- the vehicle representing the deputy spacecraft completes the maneuver within the maximum autonomy time (i.e. the lowest value between the time needed to empty the air pressured tanks and that required to discharge the onboard battery);
- the scaled satellites' masses are equal to the floating vehicles masses.

Control Law Implementation on the Hardware

Figure 7 illustrates the control system architecture implemented on the onboard computer of the deputy vehicle. Only the deputy vehicle (i.e. the deputy spacecraft) is assumed to be maneuverable in this study. First, the measured position vector, r_D^{meas} , and the attitude state, q_D^{meas} , relative to the inertial reference frame $\{F\}$ provided by the PhaseSpace system are fed into an Extended Kalman Filter (EKF) to reconstruct the translational and angular velocity and filter out the measurements noise. Note that the $\{F\}$ represents an LVLH reference frame attached to a virtual chief satellite moving on a circular J2 perturbed orbit. Then, the EFK output is scaled according to the length, time, and mass scale factors. Finally, the mean orbital elements of the deputy are computed using the linear mapping developed by Brouwer and Lyddane and the nonlinear relations between Cartesian state and osculating elements.^{8,9,10} Once the control profile is computed, the guidance trajectory in terms of the mean relative orbital elements can be found. Using the linear mapping developed by Brouwer and Lyddane, the guidance trajectory can be converted into a

Cartesian state. This desired Cartesian state is then subtracted from the measured Cartesian state to generate an error, e_D^F , that will be inputted into the Linear Quadratic Regulator (LQR) control scheme. The inertial accelerations are scaled back to be compliant with the testbed constraints and added to the control accelerations from the LQR. Ultimately, the thruster function converts the total control acceleration into an input for the eight electro-valves.



Figure 7. Onboard software functional scheme

Numerical Simulator of ADAMUS Facility

A MATLAB/Simulink simulator of the facility was developed to prototype the control implementation algorithms with the robot. This high accuracy numerical simulator describes the dynamics of the vehicles on the floor, including the testbed sensors and actuators models, and the disturbances accelerations. Figure 8 shows the simulated guidance computed by the control law implementation and how the response of the robotic system computed by the simulator. Figure 9 shows the error in position between the guidance and the simulated robotic system position. Figure 10 shows the error in velocity. Figure 11 shows the angular velocity of the simulated robotic system. Figure 12 shows the thruster history of the simulated robotic system.





Figure 12. Simulated robotic system thruster history

RESULTS

At the time of writing this paper, the facility did not have the controller implementation onto the Intrepid computer board. The impulsive control algorithm was implemented through a Windows computer with MATLAB/Simulink. The Windows computer followed the same software architecture as the Intrepid board as (see Figure 7). Figure 13 shows the vehicle tracking the guidance computed from the T-T-T control scheme. Figure 14 shows the position error of the vehicle tracking. Figure 15 shows the velocity error of the vehicle tracking. Figure 16 shows the angular velocity of the robotic system. Figure 17 shows the thruster history of the robotic system.





DISCUSSION

The results show that the vehicle is capable of following a given guidance path. These results are compared with the expected results from the numerical simulation. The larger position error can be attributed to several factors. The physical capabilities of the equipment can be a source of error in the detection of the position of the robotic system. These include an error in the Phasespace detection, as well as the amount of thrust used throughout the control profile. Towards the end of the experiment, the position error increases. This can be attributed to the air tanks running low on fuel to propel against overshooting thrusts. The errors associated with the thrusts can be overcome through more development on the LQR gains, so overshoot of thrust can be minimized.

Towards the end of the maneuver, the robotic system seems to diverge away from the guidance (see Figure 13). This seems to imply that the LQR fails for these certain values of weighting factors.

In the future, this same experiment will be conducted, but through the Intrepid computer board. This will demonstrate the testing capabilities of the robotic system and its ability as a validation tool. Future experiments are also planned to simulate other maneuvering schemes such as two radial/tangential (RT-RT) finite-time maneuvers.⁵

CONCLUSION

This paper has introduced the development of a 3DOF testbed for hardware-in-the-loop validation of GNC algorithms for formation flying reconfiguration. The hardware design and facility capabilities were discussed along with their combined interface. The in-plane formation reconfiguration problem was addressed using a relative formation geometry. A control strategy was then analytically found with a 3 tangential (T-T-T) finite-time maneuvers. With the computed control profile, the guidance trajectory was found and converted into the Cartesian state. The guidance state was subtracted from the measured robotic system state and was input into an LQR control scheme. This was done using a numerical simulator and an experimental run with the robotic system on the test bed. The experiment showed an expected result, but with a lower order of accuracy than the simulation.

Further work consists of reducing the error in the state of the robotic system. This experiment will be replicated with computations through the Intrepid computer board. Future experiments may include other impulsive schemes such as the 2 radial/tangential (RT-RT) finite-time maneuvers.

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