Materials Research Proceedings 42 (2024) 108-112 https://doi.org/10.21741/9781644903193-24

Active debris removal employing a robotic arm equipped CubeSat

Federico Basana[1,a *], Francesco Branz[2,b] and Alessandro Francesconi[2,c]

[1]Centre of Studies and Activities for Space "Giuseppe Colombo" (CISAS), University of Padova, via Venezia, 15, 35131 Padova, Italy

[2]Dip. Ing. Industriale, Università degli Studi di Padova, via Venezia, 1, 35131 Padova, Italy

[a]federico.basana@phd.unipd.it, [b]francesco.branz@unipd.it, [c]alessandro.francesconi@unipd.it

Keywords: In Orbit Servicing, Active Debris Removal, CubeSat, Robotic Arm

Abstract. Space debris pose significant risks to functioning satellites. To mitigate the issue, the space sector is studying new technologies for Active Debris Removal (ADR) missions. Conventional methods rely on large and complex satellites equipped with robotic arms but the high economic cost of these may outweigh the benefit related with the debris removal. This paper proposes a novel, cost-effective approach. A 12U CubeSat equipped with a robotic arm is employed to attach an Elementary Servicing Unit (ESU) to target satellites. The CubeSat integrates essential subsystems such as power management, an Attitude and Orbit Control System (AOCS), a mono-ocular camera for navigation, and a four-degrees-of-freedom robotic arm. To study the feasibility of the mission, a simulator in the MATLAB/Simulink environment has been developed together with a guidance, navigation and control (GNC) system. In addition, a mock-up of the proposed CubeSat has been developed for testing a simple manoeuvre in relevant laboratory environment to attach the ESU to a target. The preliminary results obtained from the simulation and the design of the CubeSat mock-up are presented in the paper.

Introduction

Space debris are a risk for satellites in near-Earth orbits [1]. Their number is expected to grow in the next future due to the creation of large constellation and the proposed and launched small satellites in crowded orbits [2, 3]. Specifically, space debris are a danger since they may collide with operative satellites generating the Kessler's syndrome. To address this issue, satellites and space debris are constantly monitored in the context of the Space Surveillance and Tracking (SST) [4] and Space Situational Awareness [5]. If a risk of collision arises, the operative satellite has to perform a Collision Avoidance Manoeuvre [6] that results in a shortening of the mission lifetime. In addition, the definition of guidelines [7] has regulated the end-of-life procedures of a satellite with the aim of reducing the risk related with space debris. Specifically, in [7] the long-term effectiveness of some debris mitigation measures is studied: the removing of massive objects from the most densely populated orbits may result in a long-term stability of the space debris population. Hence, the interest in space missions with the goal of autonomously capture and remove a space debris has grown in the last decade. Several GNC strategies have been proposed [8] and some demonstration missions have been proposed, e.g., e.Deorbit [9], or performed as the Mission Extension Vehicle 1 (MEV-1) and Mission Extension Vehicle 2 (MEV-2) [10]. In general, these employ large and complex satellites equipped with robotic arms to perform the task required by the Active Debris Removal (ADR) mission. The cost related to the former approach are high and may offset the benefits seen by the operator related to the removal of the debris. Moreover, ADR missions require Close Proximity Operations (CPOs) between two satellites, hence there exists the risk of collision between the two.

This study introduces an innovative approach to satellite removal. A CubeSat sized satellite is used to perform the ADR tasks instead of a large and complex satellite. The main advantage of exploiting CubeSat system is that they are less expensive than large satellites and their development is faster [11]. In addition, the effects of an unforeseen collision between the servicer and the target are less severe under the space debris generation point of view according to EVOLVE 4.0 breakup model [12]. This work studies the feasibility of a CubeSat-sized servicer for ADR missions. Specifically, it presents the development of a mock-up for testing servicing manoeuvres in representative laboratory conditions. Together with the design of the mock-up, the paper shows the analyses performed in the MATLAB/Simulink environment to validate the guidance, navigation and control system of the mock-up.

Mission description

The mission has the objective to deorbit a small satellite in LEO. In the scenario, the satellite, called target, is a 100 kg platform representative of the ones used by large constellations such as OneWeb or Starlink. The target is considered prepared for servicing: it has fiducial markers, e.g., ArUco markers, that aid the navigation algorithm of the servicer and it has an interface for being captured by another satellite. In addition, it is able to maintain its attitude during the capture manoeuvre. The satellite that perform the ADR operations, called servicer, is a 12U CubeSat equipped with a 4 Degree of Freedom (DoF) robotic arm. Besides the subsystems required for power and data generation and distribution, the servicer has an Attitude and Orbit Determination and Control system (AOCS) made of reaction wheels and thrusters that permit orbit and attitude manoeuvres. In addition, it features a navigation system based on a monocular camera for navigation. The robotic arm is used to manipulate and attach a Elementary Servicing Unit (ESU) to the target. The ESU is a 1U sized CubeSat that contains a drag augmentation device designed for deorbiting LEO satellites such as the Commercial Off The Shelf (COTS) drag sail "ARTICA CubeSat Deorbiting System". Once attached, the drag sail contained in the ESU will reduce the deorbiting time of the target exploiting the atmospheric drag. The mission is divided in several phases: (i) orbit transfer and phasing, (ii) far– and mid– range rendezvous, (iii) inspection, (iv) target approach, (v) target capture (vi) deorbiting. In the study only the fourth and fifth phases are considered. These two phases are the most critical under the GNC point of view since the servicer operates in the close proximity of the target.

The servicer mock-up

To study the feasibility of the proposed mission, a 12U CubeSat mock-up of the servicer satellite has been developed (Figure 1) [13]. The aim of the mock-up is to simulate simplified close proximity operations manoeuvres in a representative laboratory environment, i.e., a low-friction table. The mock-up employs a pressurized air system that features three air bearings that allow the

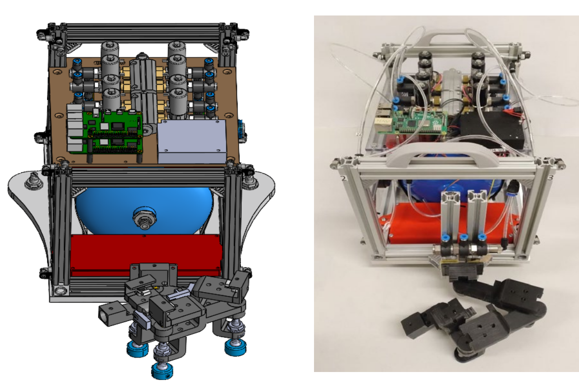

Figure 1: CAD representation of the mock-up (left) and developed mock-up (right)

floating of the module. In addition, 16 nozzles, connected to 8 electrovalves, permit the planar motion of the mock-up. A 2.5 L tank contains the pressurized air (10 bar) required for feed both

Materials Research Proceedings 42 (2024) 108-112 https://doi.org/10.21741/9781644903193-24

the air bearing and the thrusters. The main computer of the mock-up is a Raspberry Pi which has the function to control the module and the robotic arm. In addition, another Raspberry Pi is used for the navigation purposes i.e., image acquisition and processing. The latter board uses the CAN bus protocol to pass to the main computer the information concerning the relative pose of the mock-up with respect to the target. The robotic arm is mounted on a face of the mock-up and it is composed of four revolute joints, thus having four degrees of freedom. An air bearing is mounted under each joint to avoid the bending of the robotic arm caused by gravity. The joints are composed by DC motors connected to Hall-effect encoders that ensures the knowledge of the joints position. The end-effector is simplified as an electromagnet that permit to handle a mock-up of the ESU.

The GNC algorithm and results

Different GNC algorithms can be used to control the robotic arm and the module. The free-floating strategy controls the motion of the end-effector keeping the base uncontrolled. In this fashion the reaction torques created by the manipulator, which are disturbances for the mock-up attitude, are not controlled and are free to affect the attitude of the mock-up. This method is used if the mass of the satellite is much greater than the mass of the manipulator so that the disturbances are negligible. Another strategy is called free-flying, in which two control plants work in parallel to maintain the pose of the satellite and move the end effector respectively. In this fashion the disturbances generated by the manipulator are balanced by the AOCS of the satellite. In both the free-floating and free-flying approaches, the redundancy of the manipulator can be leveraged to reduce the disturbance torques as shown in [14]. An alternative is the combined control strategy, where the satellite actuators and the robotic arm joints are seen as multiple degrees of freedom of the same control plant. Hence, the controller can employ the thrusters at the same time as the robotic arm is extending to grab the target [15].

A simulator has been developed in the MATLAB/Simulink environment to simulate the manoeuvre. In this study the free-floating method is applied. During the target approach (which starts 0.6 m distant from the target) the robotic arm is kept in the folded configuration and a PID controller commands the thruster to reach a hold point 0.2 m distant from the grasping point. The pose information is provided to the GNC system as the ideal value (measured by Simulink) plus a white noise to simulate the real behaviour of a sensor. Then, the control start moving the end-effector to reach the grasping point while leaving the satellite body free to evolve under the disturbance torques generated by the manipulator motion. During the manoeuvre, the guidance defines the pose of the end effector in the cartesian space. Using the inverse kinematics of

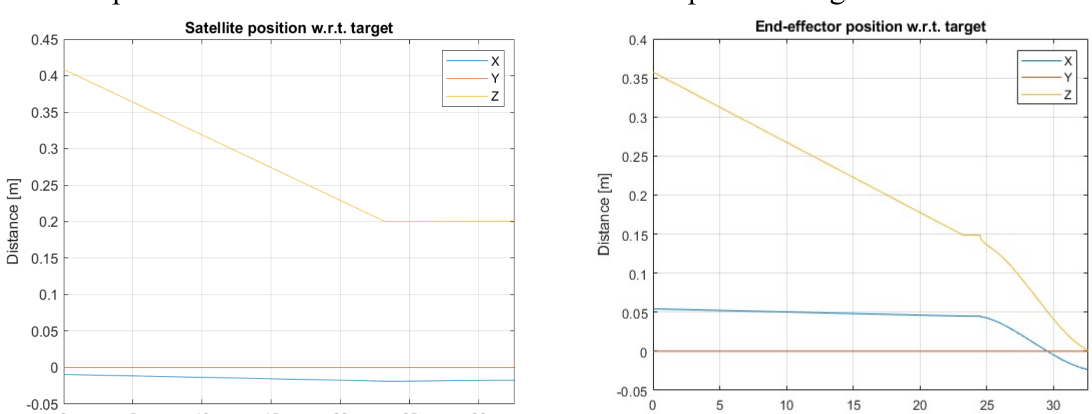

Figure 2: Satellite position w.r.t. the target (left), end-effector position w.r.t. the target (right).

redundant manipulators, the commanded joint positions are retrieved. Then, the commanded signal is compared with the value measured by the encoders and it is provided to a PI controller to obtain the voltage required for the motor actuation.

Figure 2 shows the simulation results. In the first 22 s the mock up approaches the target. Then, it waits 1 s and starts moving the robotic arm to bring the end effector to the grasping point. The end effector reaches the target with an error in module lower than 0.02 m. In addition, from these preliminary results it can be seen how an error in the satellite base is reflected to the end effector position during the motion.

Conclusions

In this study a novel approach to the Active Debris Removal is proposed. Specifically, it has been studied the feasibility of using a CubeSat sized servicer to attach a drag sail to a satellite in LEO. A mock-up of the CubeSat has been developed for testing purposes in relevant laboratory environment. A free-floating GNC algorithm has been developed and tested in the MATLAB/ Simulink environment. The preliminary results shown the good performances of the algorithm and the importance of a robust and precise control during CPOs with a robotic arm. Future works will investigate other control strategies both in simulation and in laboratory environment.

References

[1] T. Maclay, D. Mcknight, Space environment management: Framing the objective and setting priorities for controlling orbital debris risk, Journal of Space Safety Engineering 8 (1) (2021) 93–97. https://doi.org/10.1016/j.jsse.2020.11.002

[2] H. G. Lewis, G. G. Swinerd, R. J. Newland, The space debris environment: future evolution, The Aeronautical Journal 115 (1166) (2011) 241–247. https://doi.org/10.1017/S0001924000005698

[3] L. Olivieri, A. Francesconi, Large constellations assessment and optimization in leo space debris environment, Advances in Space Research 65 (1) (2020) 351–363. https://doi.org/10.1016/j.asr.2019.09.048

[4] P. Faucher, R. Peldszus, A. Gravier, Operational space surveillance and tracking in europe, Journal of Space Safety Engineering 7 (3) (2020) 420–425. https://doi.org/10.1016/j.jsse.2020.07.005

[5] M. Polkowska, Space situational awareness (ssa) for providing safety and security in outer space: implementation challenges for europe, Space policy 51 (2020). https://doi.org/10.1016/j.spacepol.2019.101347

[6] Z. Pavanello, et al., A Convex Optimization Method for Multiple Encounters Collision Avoidance Maneuvers, AIAA SciTech Forum, Orlando, Florida, (2024). https://doi.org/10.2514/6.2024-0845

[7] H. Klinkrad, P. Beltrami, S. Hauptmann, C. Martin, H. Sdunnus, H. Stokes, R. Walker, J. Wilkinson, The esa space debris mitigation handbook 2002, Advances in Space Research 34 (5) (2004) 1251 – 1259. https://doi.org/10.1016/j.asr.2003.01.018

[8] Stolfi, A., Gasbarri, P. & Sabatini, M. Performance Analysis and Gains Tuning Procedure for a Controlled Space Manipulator Used for Non-cooperative Target Capture Operations. Aerotecnica Missili & Spazio. 97, 3–12 (2018). https://doi.org/10.1007/BF03404759

[9] S. Estable, et al.: Capturing and deorbiting envisat with an airbus spacetug. results from the esa e.deorbit consolidation phase study. Journal of Space Safety Engineering 7(1), 52–66 (2020). https://doi.org/10.1016/j.jsse.2020.01.003

[10] C. Gohd, A northrop grumman robot successfully docked to a satellite to extend its life. URL https://www.space.com/northrop-grumman-mev-2-\docks-intelsat-satellite

[11] M. Mozzato, M. Bemporad, S. Enzo, F. Filippini, R. Lazzaro, M. Minato, D. Visentin, A. Dalla Via, A. Farina, E. Pilone, F. Basana, L. Olivieri, G. Colombatti and A. Francesconi, "Concept and Feasibility Analysis of the Alba Cubesat Mission," Aerotecnica Missili & Spazio.

[12] N.L. Johnson, P.H. Krisko, J.-C. Liou, P.D. Anz-Meador, NASA's new breakup model of evolve 4.0, Advances in Space Research, Volume 28, Issue 9, 2001,1377-1384, https://doi.org/10.1016/S0273-1177(01)00423-9

[13] S. Galleani, T. Berthod, A. Caon, L. Lion, F. Basana, L. Olivieri, F. Branz, A. Francesconi, Mechanical and pneumatic design and testing of a floating module for zero-gravity motion simulation, XXVII AIDAA Congress, 4-7 september 2023, Padova, Italy. https://doi.org/10.21741/9781644902813-118

[14] F. Basana, F. Branz: Simulation of robotic space operations with minimum base reaction manipulator. Journal of Space Safety Engineering 9 (2022). https://doi.org/10.1016/j.jsse.2022.06.005

[15] Z. Pavanello, et al.: Combined control and navigation approach to the robotic capture of space vehicles. In: 72nd International Astronautical Congress (IAC) (2021)