Acta Astronautica 122 (2016) 219–230

Contents lists available at ScienceDirect

Acta Astronautica

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

Design and test of a semiandrogynous docking mechanism for small satellites

Lorenzo Olivieri [a,*], Alessandro Francesconi [b]

[a] CISAS G. Colombo, Univeristy of Padova, via Venezia 15, 35131 Padova, Italy
[b] Department of Industrial Engineering, Univeristy of Padova, via Venezia 1, 35131 Padova, Italy

ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form
15 December 2015
Accepted 6 February 2016
Available online 15 February 2016

Keywords:
Docking
Small satellites
Androgyny

ABSTRACT

This paper presents a novel docking mechanism to provide small spacecraft with the ability to join and separate in space. At today small satellites mating technologies have never been verified in space nor scaled to CubeSat size; the few proposed ports implement simple probe-drogue interfaces, with the limitation to dock only with different-gender ports, or androgynous geometries, with complex and non-axis-symmetric latches. The mechanism presented in this work overcomes the aforementioned drawbacks, using a hybrid port that can act both as probe and drogue.

This paper presents the mechanism design and analysis, focusing on the port kinematics and on the load transmission during its actuation and docking procedures. Experimental verification allows us to validate numerical simulations and determine the operative range of the port in terms of alignment ranges allowing the solid joint creation. Transmitted loads always under 3 N are shown during the docking transient, while the port displays to manage misalignments up to 5° and 15 mm.

1. Introduction

Docking procedures are performed in space since the sixties [1], and mating technologies demonstrated to be key elements in missions such as the assembly of large space structures through several missions of small launch vehicles, their re-supply and crew exchange, as well as the servicing of in-orbit spacecraft and their retrieval at the end of mission. Docking mechanisms have been employed in space mission for more than 50 years: since the Apollo project, docking ports became unavoidable subsystems to connect different spacecraft. Unlike on the International Space Station, where the participation of different contractors from various countries led to the definition of common design requirements [2], as far as small scale vehicles are concerned, the issue of docking was not addressed at all since last decade. On the other hand, the development of a docking interface conjugating low development cost and a simpler design find its direct applications in the current small satellites market expansion: at today, CubeSat and small spacecraft restricted on board resources are still limiting complex and high performance applications, despite their advantages in terms of simplicity and cost. A performing docking system would provide small satellites assemblies the ability of reconfiguration, self-expansion and refurbishment through single modular units substitution, increasing their fault tolerance and creating scenarios of multipart modular space systems. Large structures such as segmented mirrors would be realized with important cost reductions, connecting many small independent components, allowing lower cost separate launches and making nanosatellite platforms competitive with respect to traditional space vehicles. The state of the art of formation flight, relative navigation and docking is represented by MIT SPHERES on board the ISS

* Corresponding author. Tel.: +39 049 827 6837.
E-mail addresses: olivieri.lrnz@gmail.com (L. Olivieri), alessandro.francesconi@unipd.it (A. Francesconi).

http://dx.doi.org/10.1016/j.actaastro.2016.02.004
0094-5765/

[3], three independent vehicles capable to perform precise relative navigation and proximity navigation. The SPHERES docking system, developed in the framework of SWARM [4] and then UDP (Universal Docking Port) projects, features an androgynous pin-hole architecture allowing a rigid mechanical connection and power and data transfer [5]. Its main drawbacks are represented by the exploitation of moving mechanical parts and the need for the modules to be oriented in a specific way about the roll axis in order to accomplish docking, as the interface is androgynous but not symmetric.

In addition to SPHERES, only few other connection systems for small-scale spacecraft have been developed to date, normally based on the probe-receptacle configuration. For instance, the Autonomous Microsatellite Docking System (AMDS) [6] of Michigan Aerospace exploits an extendible probe which is captured by the drogue and then retracts, causing the two vehicles to mate before a series of mechanical latches secures the connection. AMDS underwent testing in a microgravity environment during a parabolic flight. Another docking system was prototyped and tested in a microgravity environment by the Laboratory for Space System (LSS) of the Tokyo Institute of Technology: a 100 kg mothership was capable to capture or release nanosatellite-class daughter-ships [7].

Similarly, in the framework of DLR iBOSS project [8] an androgynous interface for berthing has been designed by Aachen, Berlin and Karlsruhe Universities in the framework of DLR iBOSS project for replaceable modular components [8]; it employs a simple cam mechanism, able to lock four latches through the rotation of a drive section.

At CISAS G. Colombo (University of Padova) the experiments ARCADE [9] and ARCADE-R2 [10] were developed to test a gender-mate interface inspired by Russian Soyuz's. ARCADE experiment was part of a wider research program on docking mechanisms by CISAS: the positive results collected by ARCADE flights together with the experience acquired in the design phase inspired further works on both gender mate [11] and androgynous [12] interfaces concepts as well as this work.

All the cited docking ports present (1) simple probe-drogue interfaces, unable to dock with same-gender ports, or (2) androgynous geometries, that can overcome that problem, but usually employ complex and non-axis-symmetric latches to perform the docking manoeuvre. The solution proposed in this paper overcomes the aforementioned drawbacks, using a semi-androgynous shape-shifting mechanism that actuating one interface changes the port into a “drogue” configuration, letting the other port penetrate it and closing around to create a solid joint.

This paper describes the design of the proposed docking mechanism, and introduces the simulation process assessing the port kinematics and the loads transmitted during actuation and docking transient. An instrumented prototype for simple laboratory test is then presented, to experimentally validate the design process and the numerical simulations and determine the port operative range in terms of maximal allowed misalignments to perform a docking procedure. The remainder of this paper is then organized as follows: the concept of semi-androgyny is introduced in Section 2 and the developed interface is presented. Sections 3 and 4 respectively describe the mechanism dynamical simulations and its evaluation on the dedicated test-bed.

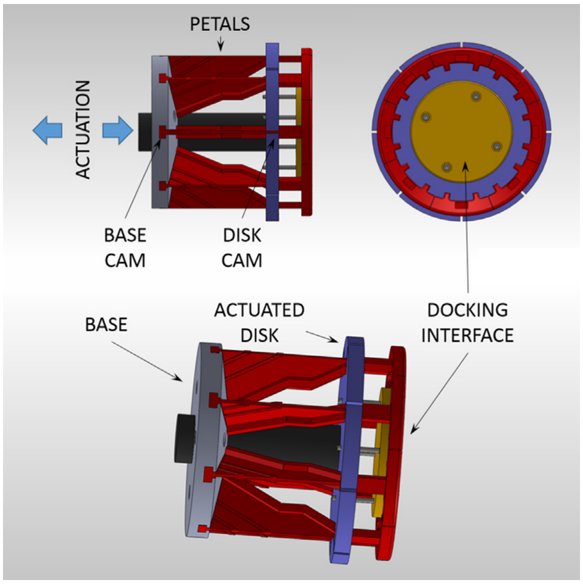

Fig. 1. 3D model of the interface.

2. Mechanism description and working principle

The proposed port (see Fig. 1) is composed of eight petals, able to open and close to shape-shift the interface between two different configurations. They are mounted on a base, where they are able to move radially thanks to a system of linear sliding cams (base cam mechanism); the movement of the actuated disk, which is able to slide backwards and forwards opening and closing the structure, controls their positions (disk cam mechanism).

Both the opening mechanism and the petals shape are developed from a trade-off between different solutions. First of all, translational cams were preferred to rotational joint due to the complexity of the latter that would arise in the design and realization of curve profiles. The zigzag shape of the petals cam allows the petals to reach three different opening position, as visible in Fig. 2: (1) a fully closed configuration, when the port is inactive, (2) a fully open shape as the mechanism acts as drogue, and (3) the mated one, as the interface is closed around its twin.

In Fig. 3 (simplified sketch) it is possible to see the port working principle: after the approach phase (A) one of the interfaces shifts its shape to the drogue configuration, in order to receive the other port, through the movement of the actuated disk (B). After the opening of the petals the two mechanisms can move to contact (C) and the movement of the actuated disk closes the left port petals around the right port ones, while the docking interfaces push each other, stiffening the joint with a pre-load (D), that depends only by the linear actuator stroke.

This solution allows us to conjugate the shape shifting and the locking actuations, using only one actuator for