Article

Sail Modules for use with "Space Tugs"

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Abstract: The paper introduces and describes the recent and still ongoing development activities performed in Luxembourg for *In-Orbit Attach Mechanisms for (Drag) Sails Modules to be operated from Space Tugs*. After some preparatory work aiming at understanding the possible operational aspects, three designs have been completed for their 3D (Metal and Plastic) Printing. The Plastic-printed prototype underwent a series of automated tests where a robotic arm, equipped with an advanced force sensor, replicated four docking scenarii in ideal and degraded modes. The observation of the forces and torques behaviors at and after impact allowed to characterize the typical patterns for the various contacts but also, to identify a type of impact potentially dramatic for the safety of the docking and its equipment: in case of off-axis approach, "point" contacts shall be avoided as they instantaneously transfer the total kinetic energy in a small area that could break.

Keywords: Spaceborne Sail; Drag Sail; Solar Sail; Space Tug; Docking; Berthing; Debris Mitigation; (Active) Debris Removal; Space Resources (Mining); Stopover Cycler.

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1. Introduction

In the future, some key Space applications like *(Active) Debris Removal* and *Space Resources (Mining)* could benefit from the combined use of Spaceborne Sails and/with "Space Tugs". The latter being in-orbit infrastructures offering stored resources and/or available services for other missions. Rendez-vous between satellites and On-Orbit Servicing (OOS) will thus become classical operations requiring multiple and repeated docking or berthing connections with or without transfers of materials.

The work presented in this paper relates to recent and ongoing activities in Luxembourg aiming at preparing the Team for these future challenges: Spaceborne Sail (Modules) are being developed, In-Orbit Attach Mechanisms are being investigated, prototyped and tested, this in the context of Spaceborne Sails stored onto and operated from Space Tugs as OOS Adds-on for de-orbiting, inter-planetary propulsion and/or transport of goods.

For comprehension, the *Spaceborne Sails* and *Space Tugs* systems are now introduced.

1.1. Spaceborne Sails

Since their inception back in 1921 by Constantin Tsiolkovski, spaceborne sails have been conceived as large deployable lightweight, flat and highly reflective membranes supporting photonic propulsion. The main historical projects of such "solar" sails were (a) the NASA developments for a rendezvous with the Halley's Comet in the 70', and (b) the international efforts for the Marco Polo race to the Moon supposed to start in 1992 [1]. Eventually, the first successful deployment and operation of a **Solar Sail (SRS)** in Space happened in 2010 with the Japanese IKAROS project [2].

It is interesting to recall here that photonic propulsion (thanks to solar sails) has been identified as one of the most powerful, elegant and versatile way of travelling in Space. Solar sails can indeed

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navigate towards or outwards the Sun and/or keep a stationary position in Space. In particular, for this research/paper on Spaceborne Sails combined with Space Tugs, the concept of solar-sail-based Stopover Cyclers for cargo transportation missions needs to be highlighted [3]:

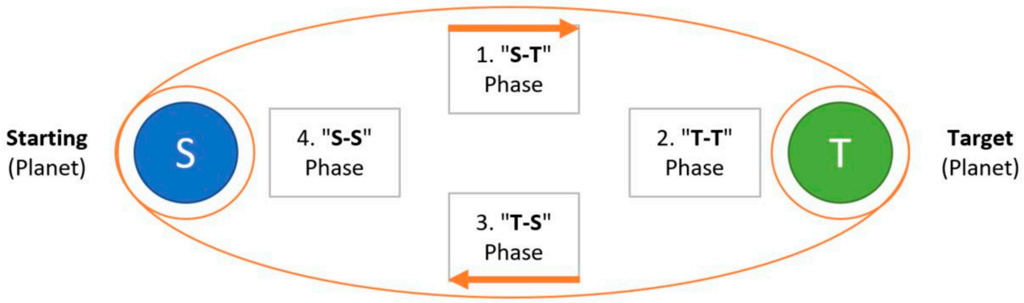
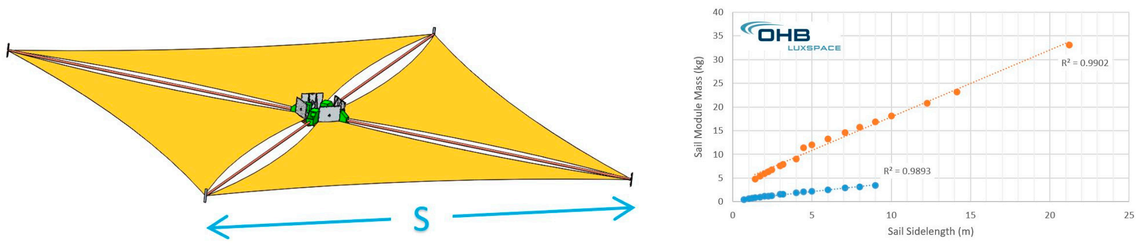


Figure 1. The generic Stopover Cycler between a Starting and a Target Planet and its four phases: "*in the first one, referred to as S-T phase, the spacecraft is transferred from the starting to the target planet. The spacecraft then orbits around the target and waits for the next opportunity to return back. This waiting time at the target is denoted by T-T phase, whereas the return voyage towards the starting planet is called T-S phase. The stopover cycler ends with a waiting S-S phase at the starting planet, whose duration is equal to the time length necessary for the planets to return in the same relative configuration they occupied at time t0*" [3].

If spaceborne sails originated thus from missions requiring photonic propulsion, they have (recently) evolved towards other applications:

- as **Drag Sails (DRS)**, where the deployed area is exposed to atmospheric fluxes to bring in shorter time (satellite) debris down toward Earth and their relative destruction during re-entry.
- as **"Functional" Sails**, proposed for use either as large solar power generator, as antenna or other applications requiring the implementation of additional (flexible) functionalities on the deployed sail membrane.

Although several configurations exist, spaceborne sails have often been conceived as square flat systems made of four sail segments deployed by booms from a box-shaped "**Sail Module**". Two important parameters of (square) sails are the sidelength "*S*" and, the "*Sail Assembly Loading*" which is defined as the ratio of the complete sail module (i.e. sail film + all sail, booms structures and mechanisms) mass to the deployed sail area.



(**a**) (**b**)

Figure 2. Typical configuration of square sail deployed and tensed by four booms: (**a**) Drawing of typical sail module showing at the center the booms mechanisms and the sail containers from which the sail segments are deployed, forming ultimately a flat square of sidelength "S"; (**b**) Current and near-term sail module masses - for two booms technologies - behave almost linearly with respect to sail sidelength "S" [4].

Table 1. Current and future expectations for Sail Assembly Loadings [4-6]. Data is given in g.m^{-2}

Current (Max) [4]	**Current (Min)** [4]	**„Near"** [5,6]	**„Mid"** [5,6]	**"Far"** [5,6]
1150	41	30	10	1.5

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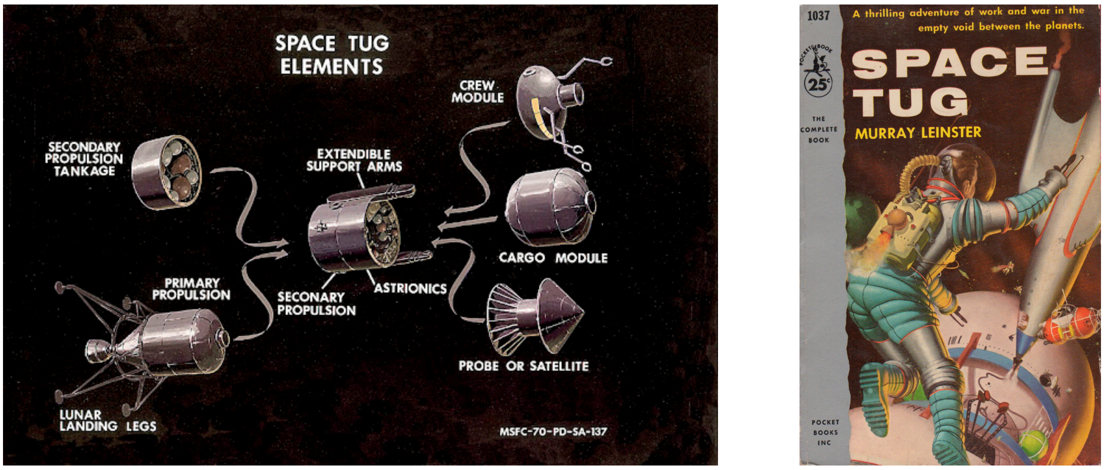
1.2. *"Space Tugs"*

The name "Space Tug" originates back from 1949/1953 [7]. Under this generic concept, reference is (still) made to modular infrastructures established/assembled in "parking" orbits and offering resources for On-Orbit Servicing (OOS) to other missions and/or satellites [8].

NASA investigated the Space Tug concept thoroughly in the 70' [9]. At that time, it was intended to be a reusable multipurpose space vehicle designed to transport payloads to different orbital inclinations. Utilizing mission-specific combinations of its three primary modules (crew, propulsion, and cargo) and a variety of supplementary kits, the Space Tug would have been capable of numerous space applications:



(**a**) (**b**)

Figure 3. Two historical documents on "Space Tugs": (**a**) A NASA drawing showing the various modules considered; (**b**) Coverpage of one of the first document (1953) citing and defining the "Space Tug" concept [7].

As seen on Figure 3a here above, the typical (modular) resources stored and transferred to/from Space Tugs were, and are again, proposed to be [8,9]:

- Crew Modules;
- Cargo Modules;
- (Stored) Probe or Satellite;
- Primary and Secondary Propulsion Modules (e.g. for orbit control and/or repositioning);
- Propellant and/or Pressurant (for refuelling);
- Robotic Elements (e.g. for assembly, for berthing, for logistic);
- Landing Legs;
- Systems for (Active) Debris Removal.

In the present research project, it is proposed to consider the implementation of Spaceborne Sail Modules on Space Tugs to support missions like:

- De-orbiting and re-entry with "**Drag Sails**".
- Inter-planetary journeys (based on photonic propulsion) with "**Solar Sails**".
- Space resources (mining) and the relative transport of fluidic and/or solid material with "**Solar Trailers**" possibly with Stopover Cyclers to/from the Main Asteroid Belt.

These different Sail Module applications with Space Tugs will in any case require rendez-vous and docking/berthing operations hence specific interfaces, especially In-Orbit Attach Mechanism(s).

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2. Materials and Methods

2.1. "Actors" involved in (Drag) Sails Modules operations with/from Space Tugs

The focus of the research being In-Orbit Attach Mechanisms for (Drag) Sails Modules to be operated from Space Tugs, the project started by identifying the possible "Actors" involved, their operations and interfaces:

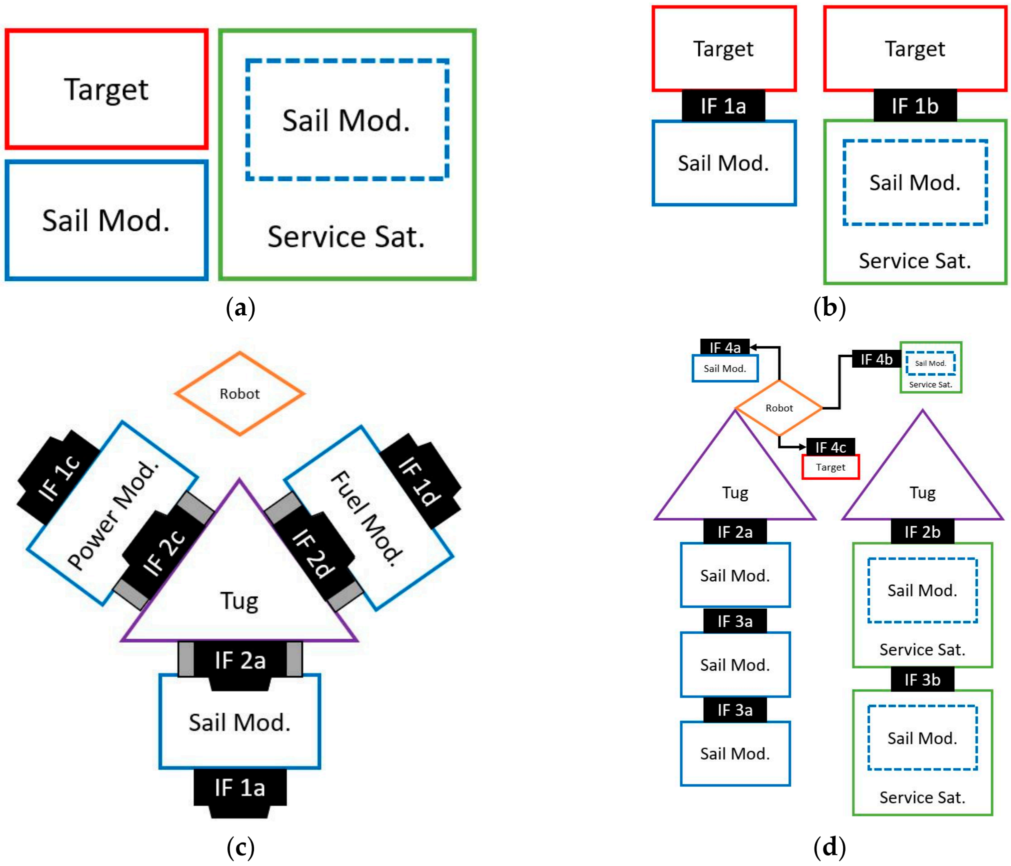

Figure 4. Main actors and interfaces involved in (Drag) Sail Modules operated from Space Tugs: (**a**) Target satellite, (Drag) Sail Module and Service satellite embedding or not a (Drag) Sail Module; (**b**) Possible interfaces/attachments providing a (Drag) Sail Module to the Target satellite; (**c**) The Space Tug and some of its offered modules awaiting OOS usage. The Space Tug can be conceived with or without a robot (e.g. arm); (**d**) A Space Tug with robotic arm offering Sail Modules (left); a Space Tug offering Sail Modules through Service Satellites each equipped with a Sail Module (right).

- The **Target satellite** is the satellite requiring the in-orbit attachment of a (Drag) Sail Module (for its de-orbiting/re-entry). The Target satellite could be cooperative or not.
- The **(Drag) Sail Module** is an Add-on, initially stored onto the Space Tug and planned to be attached to a Target satellite. This module is not equipped with any Attitude and Orbit Control Subsystem (AOCS) allowing autonomous docking with the Target satellite.
- The **Service satellite** offers OOS by bringing/attaching the (Drag) Sail Module to the Target satellite. The Service satellite like the (Drag) Sail Module is initially stored onto the Space Tug. It is capable to autonomously leave the Space Tug, approach the Target satellite, perform the rendez-vous connections, and deploy its (Drag) Sail if available. The Target satellite could also be equipped or not with robotic facilities.
- The **Space Tug** carries all service modules. It has AOCS capabilities, also to control/correct its orbit, and can be equipped or not with robotic facilities.

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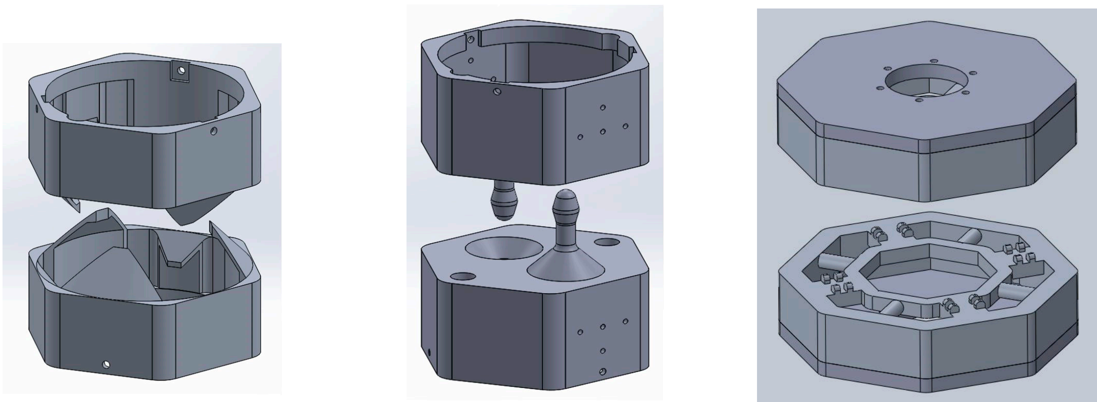
- The **Robot** is planned for berthing and/or in-orbit assembly. It can be "fixed" if installed onto and operated from the Space Tug, or "mobile" if installed onto and operated from the Service satellite.

2.2. In-Orbit Attach Mechanisms for (Drag) Sails Modules

Having understood the main operations and interfaces between involved actors, the project initiated the design of In-Orbit Attach Mechanisms for (Drag) Sail Modules. Three mechanisms consisting of two identical androgyne parts were derived:

- The 1st **Mechanism** shown hereafter in Figure 5a is based on the *International Docking System Standard* **(IDSS)** [10]. The prototype of the androgyne part features an envelope of 110 x 60.5 (height) mm. When 3D Metal (Aluminum) printed, each prototype will weigh about 254 grams.
- The 2nd **Mechanism** shown hereafter in Figure 5b is based on the *Universal Docking Port* **(UDP)** [11]. The prototype of the androgyne part features an envelope of 110 x 110 (height) mm. When 3D Metal (Aluminum) printed, each prototype will weigh about 371 grams.
- The 3rd **Mechanism** shown hereafter in Figure 5c is based on the concept proposed for the *ESA Mars Sample Return* **(MSR)** mission [12]. The prototype of the androgyne part features an envelope of 200 (dia.) x 50 (height) mm. When 3D (Plastic, here PLA) printed and assembled, each prototype weights about 329 grams.



(**a**) (**b**) (**c**)

Figure 5. The three In-Orbit Attach Mechanisms designed for the project: (**a**) based on the International Docking System Standard (IDSS) [10]; (**b**) based on the Universal Docking Port (UDP) [11] (**c**) based on the concept proposed for the ESA Mars Sample Return (MSR) mission [12].

2.3. Test Cases for the Automated Test at FANUC Luxembourg

As part of the In-Orbit Attach Mechanisms development, a verification plan has been prepared including an automated (i.e. robotized) test of the connection/matching between the two parts of the 3rd Mechanism. Considering a fixed "Passive" part and the other mobile "Active", four test cases have been identified (see Figure 6):

- **Nominal case**: ideal approach along the docking axis;
- **Non-nominal case 1**: misalignment of an angle α in the plane perpendicular to the docking axis;
- **Non-nominal case 2**: misalignment of an angle β out of the plane perpendicular to the docking axis;
- **Non-nominal case 3**: misalignment of a conic angle γ out of the plane of the docking axis.

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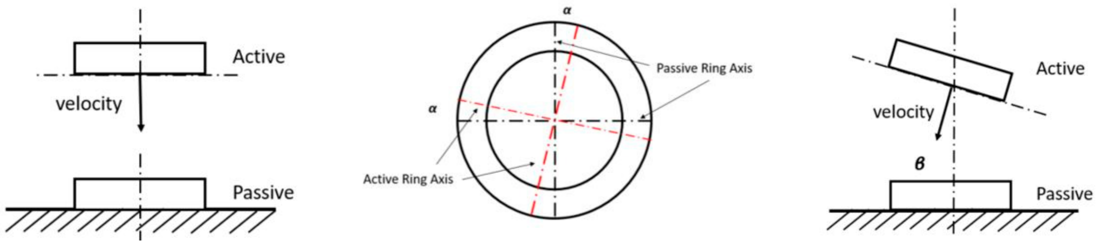


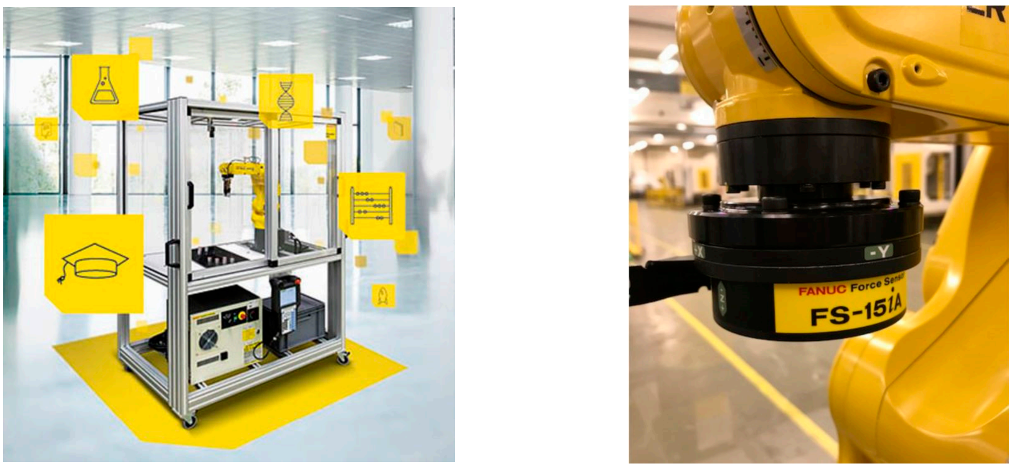
(**a**) (**b**) (**c**)

Figure 6. Three of the four test cases: (**a**) Nominal case: ideal approach along axis; (**b**) Non-nominal case 1: misalignment in the contact plane; (**c**) Non-nominal case 2: misalignment out of the contact plane.

2.4. Facility used for the Automated Test at FANUC Luxembourg

The facility kindly made available by FANUC Luxembourg for the automated test on the 3rd Mechanism was a slightly upgraded version of the *FANUC Educational Package* [13]. This compact "all-in-one" robotic facility, shown here after in Figure 7a, has been specifically designed for educational hands-on training in schools and universities. Upgraded with FANUC's auto-calibrating Force Sensor, the robotic facility used for the tests consisted in:

- FANUC's 6-Axis Mechanical Robot *LR-Mate 200iD/4S* (with max payload of 4 kg and reach of 550 mm) as part of the standard Educational Package.
- FANUC's auto-calibrating Force Sensor *FS-15iA*, as upgrade for these tests.
- FANUC's *ROBOGUIDE* Simulation Software.



(**a**) (**b**)

Figure 7. Robotic facility used for the automated test at FANUC Luxembourg, located in Echternach: (**a**) The FANUC Educational Package equipped with the 6-Axis Mechanical Robot LR-Mate 200iD/4S; (**b**) The auto-calibrating Force Sensor FS-15iA mounted on the robot of the facility.

The FANUC's auto-calibrating force sensor FS-15iA has different features to achieve better performances. To test 3rd Mechanism, three of them have been used, according to the test case:

1. The **Constant Push** feature enables the robot to push with constant force in the z direction. This feature has been used for the Nominal case.
2. The **Phase Search** feature performs the phase search before the engagement, aligning the mechanism by rotating the active part. This feature has been used for the Non-nominal case 1 (roll misalignment).
3. The **Face Match** feature provides the robot with the ability of align and match the faces of the two parts. This feature has been used for the Non-nominal cases 2 and 3 (yaw/pitch misalignment).

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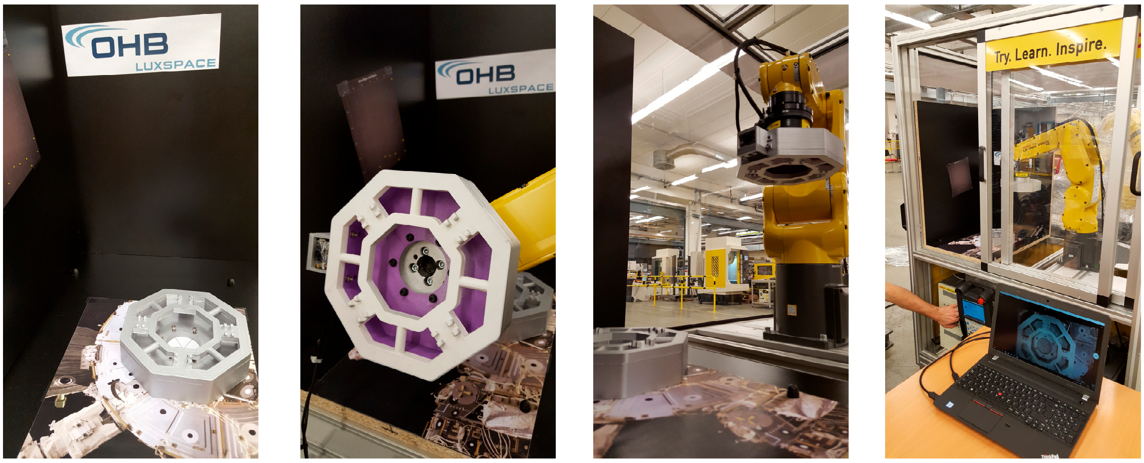
The few pictures shown on Figure 8 depict the final and complete test configuration used for all test cases:



(a) (b) (c) (d)

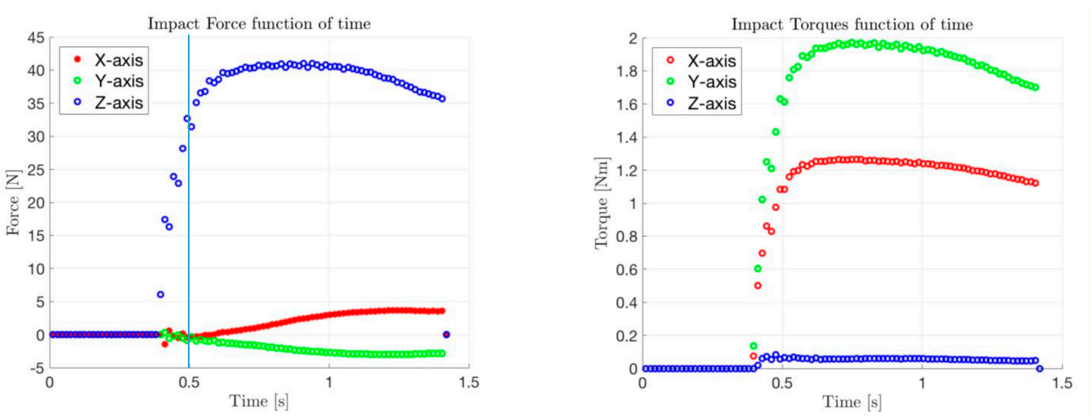
Figure 8. Final and complete test configuration used for the Automated Test on the 3rd Mechanism: (**a**) Passive part of the prototype fixed on the test bench; (**b**) Active part of the prototype (equipped with a "star tracker/docking" camera, visible on the left side) mounted on the robot via the force sensor; (**c**) A view with the principal elements of the test before sequence start (**d**) A view with the principal elements of the test during sequence – to note on the laptop: the image taken simultaneously by the mounted "star tracker/docking" camera.

3. Results

The following sections present the impact forces and torques resulting from the automated tests (all conducted with constant approach velocity of 3 cm/sec, starting from the same height above the interface plane) for the four test cases. Where noticeable some interpretation as well as the experimental conclusions that can be drawn are given.

3.1. Nominal Case

The Nominal case deals with an ideal approach along the docking axis Z:



(a) (b)

Figure 9. Nominal Case (v=0.030 m/s): (**a**) Forces at impact (**b**) Torques at impact.

The impact (step) force along Z is noticeable around 0.5 second, the level is kept almost constant after contact by the "constant push" feature of the Force Sensor. The smaller forces and torques along the X and Y axis after contact have been attributed to possible misalignments, loss of fixations and

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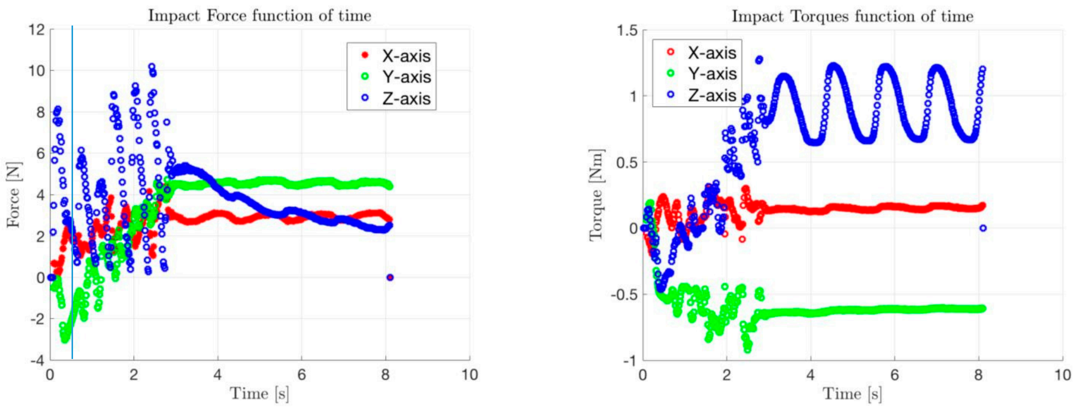
geometrical features of the 3D printed parts. However, such "real" effects will need to be considered for future design activities at mechanism and at system level (especially for what relates to relative attitude control during docking).

3.2. Non-nominal Case 1

The Non-nominal case 1 deals with a misalignment of an angle α in the plane perpendicular to the docking axis Z:



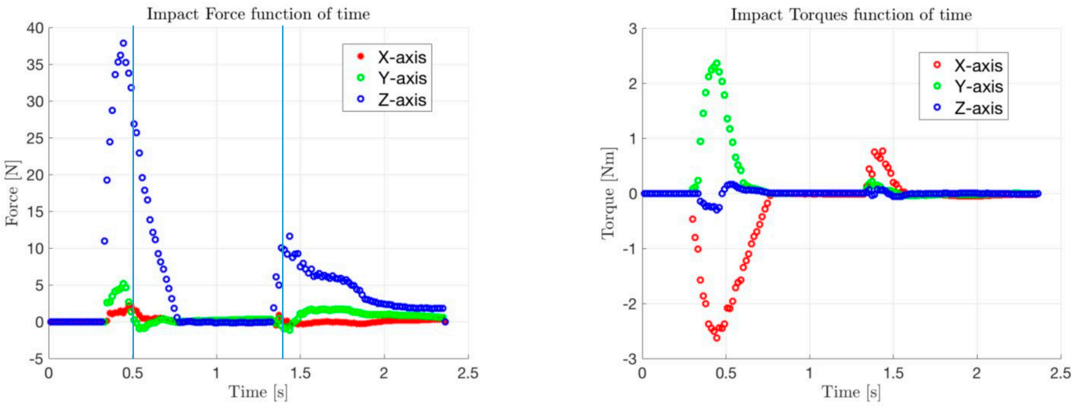
(**a**) (**b**)

Figure 10. Nominal Case (v=0.030 m/s ; α=2 deg): (**a**) Forces at impact (**b**) Torques at impact.

A clear and unique impact (force) along Z is not noticeable around 0.5 seconds. Instead, oscillatory behaviors can be observed and attributed to the control laws implemented by the "phase search" feature of the Force Sensor.

3.3. Non-nominal Case 2

The Non-nominal case 2 deals with a misalignment of an angle β out of the plane perpendicular to the docking axis Z (the Active part impacts the Passive part along edges/borders):



(**a**) (**b**)

Figure 11. Nominal Case (v=0.030 m/s ; β=3 deg): (**a**) Forces at impact (**b**) Torques at impact.

A clear and first impact (force) along Z is noticeable around 0.5 seconds, a second and reduced impact (force) along Z is also noticeable about 1 second later. This second impact results from the "face match" feature of the Force Sensor that rotates the Active part to ensure the final perfect contact between the parts.

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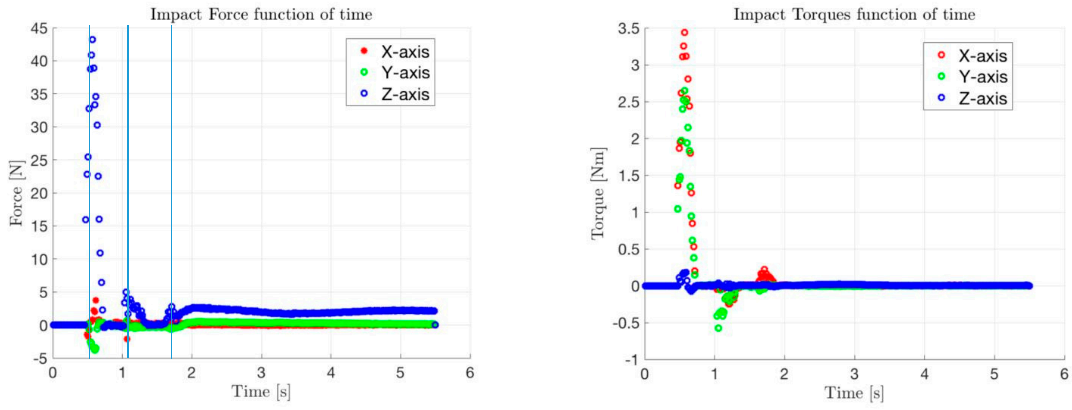
3.4. Non-nominal Case 3

The Non-nominal case 3 deals with a misalignment of a conic angle γ out of the plane of the docking axis Z (the Active part impacts the Passive part on corners):



(**a**) (**b**)

Figure 12. Nominal Case (v=0.030 m/s ; γ=3.6 deg): (**a**) Forces at impact (**b**) Torques at impact.

A clear and first impact (force) along Z is noticeable around 0.5 seconds, two other reduced impacts (forces) along Z are also noticeable subsequently. These smaller impacts result again from the “face match” feature of the Force Sensor that rotates the Active part to ensure the final perfect contact between the parts. The level of the first impact is similar to the one observed in the Nominal case and Non-nominal 2 case, however it applies here instantly to the corners (i.e. points) and not to distributed areas (like faces or edges/borders).

4. Discussion

A TRL 4 has been reached thanks to the automated test on the 3D (Plastic) printed prototype of the 3rd In-Orbit Attach Mechanism designed for (Drag) Sail Modules to be operated from Space Tugs. The lessons learned and the technical results obtained will be re-injected in subsequent design activities.

An important observation was made with the Non-nominal case 3 were contact impact occurred at/by corners: from there, awareness was raised with respect to non-nominal first point contacts injecting all the kinetic energy in a single, reduced area. In case of important misalignment such a failure mode could indeed destroy mission critical equipment necessary for a safe docking.

Although not planned, the Team will now consider any future opportunities to repeat the performed automated test on the prototypes of the 1st and 2nd In-Orbit Attach Mechanisms that should be 3D (Metal) printed during the year 2018.

Acknowledgments: The presented project for the pre-development of In-Orbit Attach Mechanisms for (Drag) Sails Modules to be operated from Space Tugs largely benefitted from the grant received by the still running EU/H2020 “*Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies*” (ReDSHIFT) project, covering also the costs to publish in open access for dissemination objectives. The graph shown in Figure 2b has been derived for the ESA/ESOC “*Environmental Aspects of Passive De-orbiting Devices*” project. The project also largely benefitted from the kind support offered by FANUC Luxembourg. Villmools Merci!

Author Contributions: In this project, hence for this research article, the various authors made the following individual contributions: F. Dalla Vedova defined and coordinated the complete research programme and wrote the paper, P. Morin initiated the investigations of the In-Orbit Attach Mechanisms and designed the first two concepts, Th. Roux investigated on combined use of star tracker and docking camera for use with Space Tugs, R. Brombin pursued the investigations of the In-Orbit Attach Mechanisms and designed/produced/tested the third concept, A. Piccinini conducted the automated tests on docking and N. Ramsden facilitated and coordinated the complete automated tests campaign.

Conflicts of Interest: *"The authors declare no* [known] *conflict of interest."* Also *"The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results*".

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