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Test of tethered deorbiting of space debris

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Abstract

Current investigations on space tethers include their application to space debris deorbiting, specifically on the set of manoeuvres performed by a chaser tug to change the orbital parameters of a target body. Targets can be cooperative spacecraft at the end of their life or uncontrolled objects such as defunct satellites without clearly available capturing interfaces. In this latter case, a link joining tug and target may be misaligned with the target body inertia axes, influencing the attitude of both bodies; in case of rigid links, torques transmitted during tugging operations may overcome the tug attitude control system. This issue is clearly less significant in case of non-rigid connections, such as tethers; furthermore, with such connections the chaser can remain at a safe distance from the target during the whole deorbiting operation. On the other side, the initial phase of tethered space debris removal manoeuvres can be influenced by transient events, such as sudden tether tension spikes, that may cause longitudinal and lateral oscillations and, in case of resonance with the target attitude dynamics, could represent a serious issue for tug safety. In this paper it is proposed to provide the tug with a tether deployer mechanism capable to perform reel-in and reel-out, smoothing loads transmission to the target and damping oscillations. This concept is validated through a representative test campaign performed with the SPAcecRraft Testbed for Autonomous proximity operatioNs experimentS (SPARTANS) on a low friction table. A prototype of the deployer is manufactured and the deployment and rewind of a thin aluminium tape tether is proven. Test results include the verification of the tether visco-elastic characteristics with the direct measurement of spikes and oscillations and the estimation of the proposed system damping capabilities.

Keywords: Space Tethers, Deployment, Active Debris Removal, low friction test

Acronyms/Abbreviations

ADR	Active Debris Removal
CGA	Cold Gas Actuator
DoF	Degree of Freedom
EDT	Electrodynamic Tether
E.T.PACK	Electrodynamic Tether technology for Passive Consumable-less deorbit Kit
LWT	Low-Working-Function Tethers
MC	Motion Capture
PMD	Post Mission Disposal
S-DM	Scaled Deployment Module
SPARTANS	SPAcecRraft Testbed for Autonomous proximity operatioNs experimentS

1. Introduction

Since the introduction of the space tether concept [1], a wide number of applications from orbital momentum exchange devices to electrodynamic systems have been proposed; a complete review can be found in [2][3][4][5]. More recently, ground tests and numerical models focused on innovative uses of space tethers, among them formation flight [6][7], rendezvous and docking maneuvers [8], space tugging operations [9], and asteroids [10][11] and non-cooperative objects [12] capture.

To date, many investigations of space tethers are for applications in debris removal. The growing problem of space debris and their influence on the access to orbit became commonly recognized by the scientific community after the definition of the so-called "Kessler Syndrome" [13], introducing the risk of losing access to Earth orbit regions due to the constant growth of debris and the consequent catastrophic impacts cascade effect. Despite efforts to reduce new spacecraft influence on the debris environment (e.g., [14] [15]), the recent plans for large constellations [16][17] are constantly scrutinized and their short and long term influence on the space debris environment stability is under evaluation [18][19][20]. In this context the scientific community is evaluating further mitigation strategies, considering both the utilization of enhanced protections [21] and the implementation of Post Mission Disposal (PMD) [22] and Active Debris Removal (ADR) [23] operations. Among the different strategies for PMD and ADR [24], Electrodynamic Tethers (EDTs) have been investigated as a reliable and convenient solution in Low-Earth Orbit (LEO) [25][26]. For further information on EDTs and the most recent evolution, the Low-Working-Function Tethers (LWTs), see [27][28] and [29][30].

The advantages of tether systems are not limited to the disposal manoeuvre, as flexible connections between two modules reduce the loads transmitted between them with respect to solid joints. Furthermore, with such connections the vehicles involved can remain at a safe distance while maintaining a physical connection. For this reason, tethers have been also proposed for space tug configurations and both experimental investigation [31][32] and simulation activities [33][34][9] have been carried out.

In this context, the H2020 Future Emerging Technologies FET OPEN Project E.T.PACK – Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit [35] is currently investigating a number of technologies for PMD with EDTs [36][37], including safe tether deployment [38]. In this paper, some preliminary tests on tether technologies for deorbiting are presented. In particular, a tether deployment and retrieval mechanism developed in the framework of ETPACK project is introduced. A breadboard prototype of the deployer was manufactured and the deployment and rewind of a thin aluminium tape tether were tested. Test results include the determination of the tether visco-elastic characteristics, the direct measurement of spikes and oscillations and the estimation of the proposed system damping capabilities. The prototype, while designed principally for the ETPACK kit tether deployment, can be employed also for tethered systems formation flight and space tugging, thanks to the capability to control both the tether deployment and retrieval.

1.1 Tether deployment background

One of the most challenging operations with tethers is the deployment phase, as several issues have to be taken into consideration, such as the libration stability during the process [39][40][41]. The most investigated approach, employed also on the TSS-1 demonstration [42], starts with releasing a tethered tip mass from the host spacecraft (i.e. the ETPACK deployer kit from the main spacecraft, or the tagging unit from a tugged satellite). Due to the negligible authority of gravity gradient forces acting on the system after separation, the tip mass is provided with an initial momentum to reel the tether out; once few hundreds of meters are deployed, the gravity gradient can become the leading driver in the deployment process. A continuous control of the tip mass is requested during the deployment, as uncontrolled oscillations can lead to system instability (see [43] for a more detailed description of stability conditions and range). To provide the requested stability, reference deployment trajectories can be defined and optimal values for the tip mass initial attitude and velocity can be computed; the values adopted for ETPACK are reported in [38].

The deployer shall therefore be able to follow the predefined deployment profiles by providing the requested initial momentum and by controlling the tape reel-out by passive or active control systems. Mechanical (springs [44][45][46]), electro-mechanical (deployed masts [47]) or propulsive (cold gas actuators [38][48]) systems have been proposed to provide the initial momentum, with the latter one selected for ETPACK. With regards to deployment mechanisms, they can be classified in three main categories: stationary spools, rotating reels, and folded “origami”, depending on the tether stowing strategy; again, for this work a rotating reel configuration was selected.

Among the several in-space (e.g.: TSS-1 [42][49], ProSEDS [50] – cancelled after Shuttle Columbia accident, YES II [51][52], SEDS [53], SEDS II [54]) and ground verifications on deployment mechanisms ([44][45][55]), only the TSS-1 [49] and the STAR prototype [45] demonstrated the ability to reel in. More recently, the TEPCE CubeSat technology demonstrator was conceived and flown to deploy a 1-km-long tether; to date, confirmation of 500-m deployment is available [56]. The low success rate of tethered systems can be related to the complexity of deployment operations, in which minimal disturbances such as internal components friction can greatly influence the reel-out process up to stop completely the tether deployment. For this reason the proposed deployer employs a system of motorized pulleys to control the tether motion and to decouple the internal mechanism dynamics from the external motion subjected to orbital dynamics.

An important constraint for E.T.PACK deployer mechanism is the utilization of a tape tether instead of a round wire. This was first introduced by BETs project [28] due to tapes higher survivability to space debris impacts [57], their increased performance in collecting electrons and the faster deorbiting they provide. The utilization of a tape greatly affects the design of the deployer mechanism, as the bulk and shape of a tape coil is different from a wire one, as well as the extraction technology to deploy it.

1.2 Paper contents

The remainder of this paper is organized as follows. Section 2 presents the deployer concept, while Section 3 introduces the experimental setup employed for tests reported and discussed in Section 4.

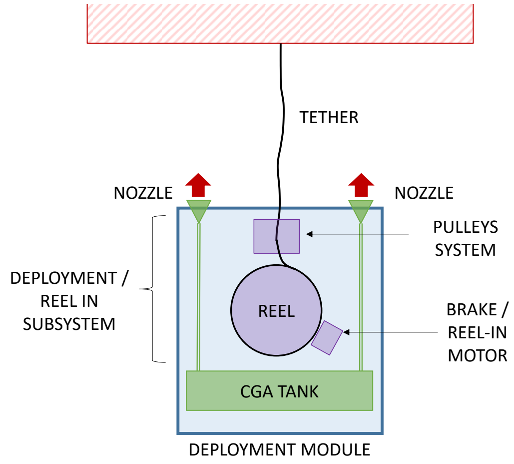

Fig. 1: Sketch of the proposed deployment module

2. Tether deployment module

The deployer mechanism described in this work in the framework of the E.T.PACK project is sketched in Fig. 1. It consists of a Cold Gas Actuator (CGA) propulsive unit, employing two nozzles, a tank, and the relative fluidic system, and a deployment / reel-in subsystem, composed by a rotating reel, a system of pulleys to control the tape deployment, and a motor coupled to the reel to brake it during deployment and actuate it during reel-in operations. Thanks to the pulleys system, the proposed layout is able to decouple the tether dynamics outside of the deployment module from the one of the internal mechanisms, leading to a safer deployment. With this configuration, the whole module can act as tip mass during the deployment, as well as perform the reel-in operations by switching the motor function.

The capability of the proposed module to deploy and retrieve a tether was assessed with a campaign of tests on a low-friction table, as described in the following sections.

3. Experimental setup

The experimental setup consists in a scaled deployment module (S-DM) mounted on board an air carriage system including three air bearings on its bottom part for a low-friction motion on a low-friction test table. The S-DM is shown in Fig. 2, with its main subsystems highlighted: the CGA, the deploy and reel-in subsystem, and the control and communication electronics. The whole module is painted in black to reduce the interference by multiple reflexions with the laboratory motion capture system.

The air carriage system and the test table are part of the SPARTANS facility [58][59][60][61], that can be seen in Fig. 3. The facility consists in a 3x2 m test table and a spacecraft test mock-up (composed by a translational module and an attitude module); a Motion Capture (MC) system with 6 infrared cameras tracks the motion of the mock-up.

In the investigated configuration the S-DM is directly mounted on SPARTANS mock-up translational module replacing the original attitude module. With this configuration the S-DM acquires three degrees of freedom (DoF), the two translations on the test table and the rotation around the local vertical axis. The free end of the tether is constrained to a dedicated structure on one edge of the test table.

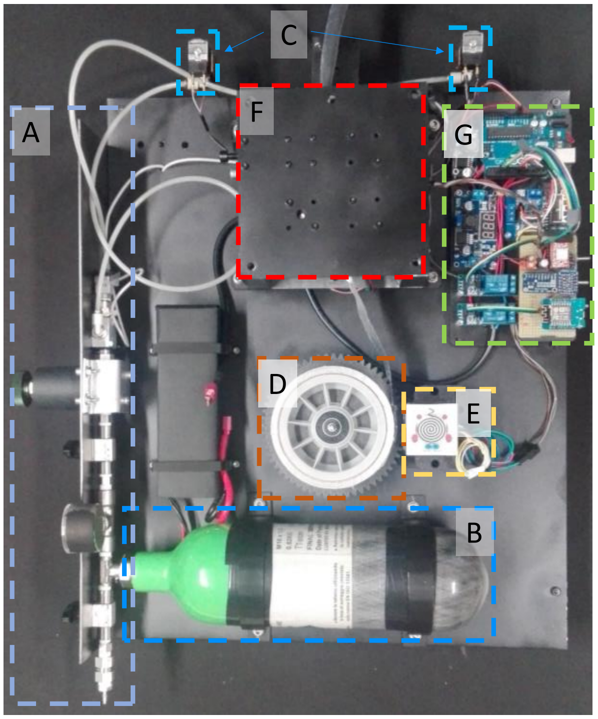

Fig. 2: scaled deployment module with CGA (A - fluidic system, B - tank, C - nozzles), deployment and reel-in subsystem (D -rotating reel, E - brake/reel-in motor, F – pulleys system), and G – electronics.

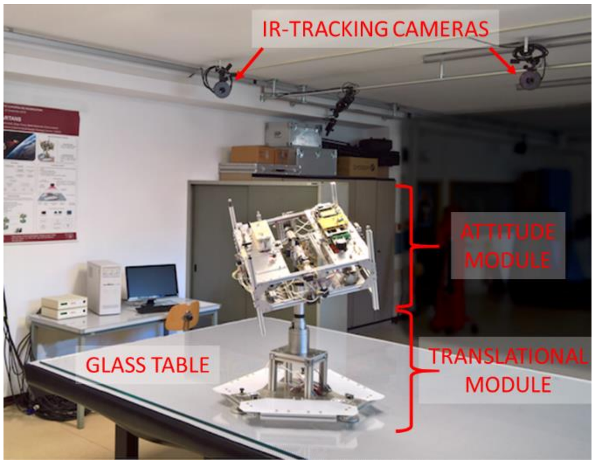

Fig. 3: SPARTANS test table and free-floating module.

The S-DM is equipped with a Wi-Fi communication link; an external control station is employed to start experiments, log data and monitor the whole system.

4. Experimental campaign

The experimental campaign reported in this section consisted in four different activities: the verification of (1) the CGA thrusters force authority and (2) the tape mechanical characteristics and the tests of (3) deployment and (4) retrieval manoeuvers.

4.1 Thrusters authority

The CGA thrusters are designed as simple convergent nozzles and a linear relation between inlet pressure and thrust force is expected. The inlet pressure is directly measured with an on-board sensor placed in the low-pressure section of the fluidic subsystem; the data live stream is transmitted through the Wi-Fi link to the control station. To evaluate the thrust, the S-DM is connected with a thin line of about 1.5 m to a load cell constrained to one vertex of the test table; independently from the mechanical characteristics of the line, once the system is in steady state configuration (i.e. the S-DM does not present rotational and translational motions) the load cell measures the force actuated by the two thrusters on board the S-DM. Experimental results (red dots) are reported in Fig. 4 with a first-order fit (blue dashed line), indicating a linear relation between the inlet static pressure and trust authority, with a coefficient of determination R^2=0.9997.

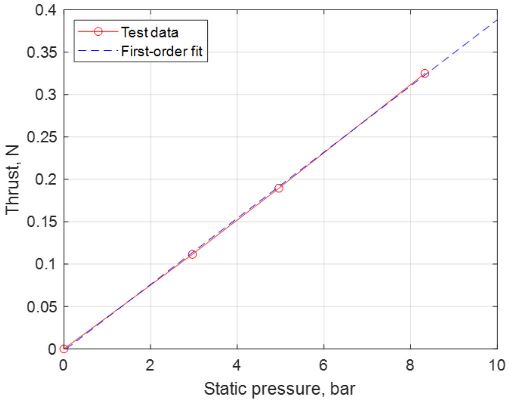

Fig. 4: Measured authority of one thruster (red) and linear fit (blue dashed lines).

4.2 Tape mechanical characteristics verification

The stiffness and damping of a flexible line can be verified by applying a constant tensile load in slack conditions and then measuring the line dynamic response in terms of tension spikes, oscillations, and damping. With the proposed experimental setup, the verification can be performed by constraining a section of the line with known length to a fixed structure and to the S-DM, and then actuating the S-DM thrusters with the line in the initial slack condition.

Due to the high stiffness of the employed aluminium tape (about 30 kN/m for a sample 1.5 m long), the verification is performed in two steps. First, the setup employed for thrusters authority verification is used to test the proposed method with a 1.5 m long polyamide line with diameter of 0.3 mm (theoretical stiffness of 129 N/m); the S-DM motion detected with the MC system is reconstructed and compared to simulations, as well as loads measured with the load cell mounted on the constrained end. In a second phase, the line is substituted with the aluminium tape and the test is repeated with the same parameters but without the load cell, whose stiffness is comparable to that of the tape and might therefore invalidate the experiment. This approach allows a first validation of the proposed method with the elastic polyamide line and then the verification of the tape characteristics.

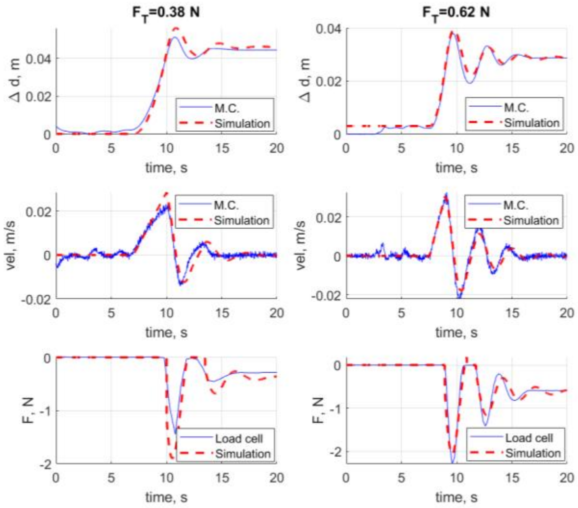

Fig. 5: Polyamide line mechanical characteristics verification with low (left) and high (right) thrust level: comparison of experimental data (solid blue lines) with simulations (dashed red lines). From top to bottom: S-DM translation, S-DM velocity, and force on constraint.

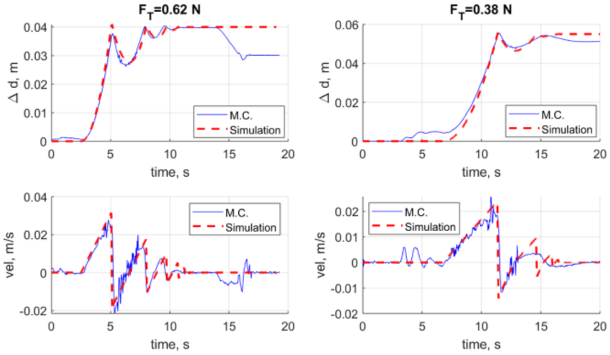

Fig. 6: Aluminium tape mechanical characteristics verification with low (right) and high (left) thrust level: comparison of experimental data (solid blue lines) with simulations (dashed red lines). From top to bottom: S-DM translation and S-DM velocity.

Results for the polyamide line are reported in Fig. 5, for two different thrust conditions (0.38 N and 0.62 N). It can be seen that experimental data match simulations results; small discrepancies can be related to residual friction effects between the module and the test table.

Aluminium tape verification results can be seen in Fig. 6. As previously mentioned, due to the higher stiffness of the tape with respect to the polyamide line the load cell is removed from the setup to avoid undesired effects. To match simulations with experimental data a high damping coefficient (480 Ns/m) is employed; the consequent damping ratio of 0.22 is higher than expected for aluminium alloys and can be related to memory effects of the tape sample undergoing testing.

4.3 Deployment manoeuvre

The objective of this test is the verification of the deployer capability to follow a predefined reference deployment trajectory, in terms of tether length and length rate. While in operative configurations the deployment would last tens of minutes (up to one hour in [38]), the test table available area limits it to less than one minute. Despite such constraint, the test allows to determine the behaviour of the deployment system and to verify the capability to follow a reference reel-out profile. Furthermore, the test aims to verify the capability of the deployment motor to follow a profile with a high initial acceleration as well as to monitor the effect of such acceleration on the S-DM dynamics. The reference profile therefore presents an initial acceleration of 7 mm/s^2 (about one third of the in-orbit case value, as reported in [38]), and then a constant-velocity phase at 0.1 m/s.

Fig. 7 reports the results of a deployment test, with the reconstructed trajectory from the MC system, the comparison of the deployment profiles with the reference ones, and some frames from the deployment video. It can be noted that the S-DM is capable to follow the pre-imposed deployment profile, with minimal discrepancies related to the dynamical response of the tape (small oscillations and spikes).

It can be noted that the S-DM is subjected to a small rotation on its centre of mass around the vertical axis, which is aligned to the tape coil axis: due to angular momentum conservation, the initial coil angular acceleration causes a small counter-rotation on the module. This issue will be addressed in future upgrades of the deployment hardware with a dedicated attitude control strategy modulating the module thrusters firing. It shall be underlined that the tape tension creates a restoring torque on the S-DM opposing the coil-induced torque, limiting the rotation to less than 45 deg.

4.3 Reel-in operations example

The capability to reel-in the tape is an important feature of the proposed system. Fig. 8 reports an example of a reel-in manoeuvre at a constant retrieval velocity of 0.02 m/s, with the reconstructed trajectory from the MC system, the reel-in and reel-in rate profiles, and some frames from the corresponding video. In this test after the initial acceleration the coil rotation is constant; the thrusters are firing during the whole manoeuvre to maintain the tape in tension. Again, it can be noted an initial rotation of the S-DM due to the initial angular acceleration of the tape coil; as expected, the tape creates a small restoring torque opposing the module rotation.

This test demonstrates the proposed system general capability to reel-in at constant velocity; further investigation will be performed to verify the capability to follow a reference retrieval profile and the possibility to perform it without the assistance of the propulsion system.

5. Conclusions

This paper presented the low-friction tests of a tether deployer and reel-in system developed in the framework of the H2020 ETPACK project. The system is based on a rotating coil concept, with a system of pulleys to control the deployment and a motor coupled to the coil to brake it during the reel-out and actuate it for the reel-in. The proposed system is integrated on a small module equipped with a cold gas system for propulsion purposes, and it is tested on the low-friction test table of the SPARTANS facility.

The first tests verified the cold gas system trust authority and the employed aluminium tape mechanical characteristics; it was found that a linear relation exists between the inlet static pressure and the thrust and that the aluminium tape presents a larger damping ratio than expected, due most likely to memory effects present in the tested tape sample.

A controlled deployment test demonstrated the system capability to reel-out the tape following a reference trajectory; it has been found that the angular acceleration of the tape coil affects the attitude of the deployment module but does not influence the deployment profile. Similarly, a reel-in test demonstrated the capability of the proposed system to retrieve the tape.

It can be concluded that the proposed system demonstrated its desired features. Future works will focus on two main topics: the attitude control of the module during the manoeuvres will be implemented by modulating the thrusters firing and more complex deployment and retrieval operations will be tested.

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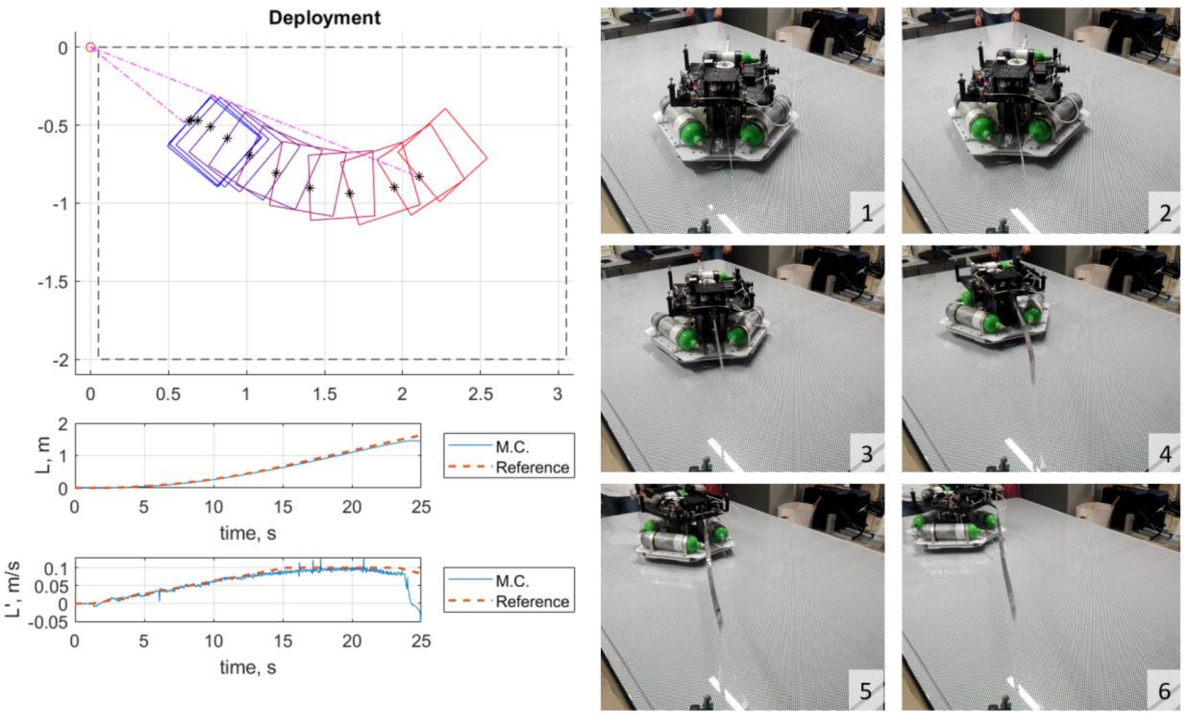

Fig. 7: Deployment test, with reconstructed module position from Motion Capture (top left), tether deployed length and velocity compared with reference profile (bottom left), and captured video frames (right).

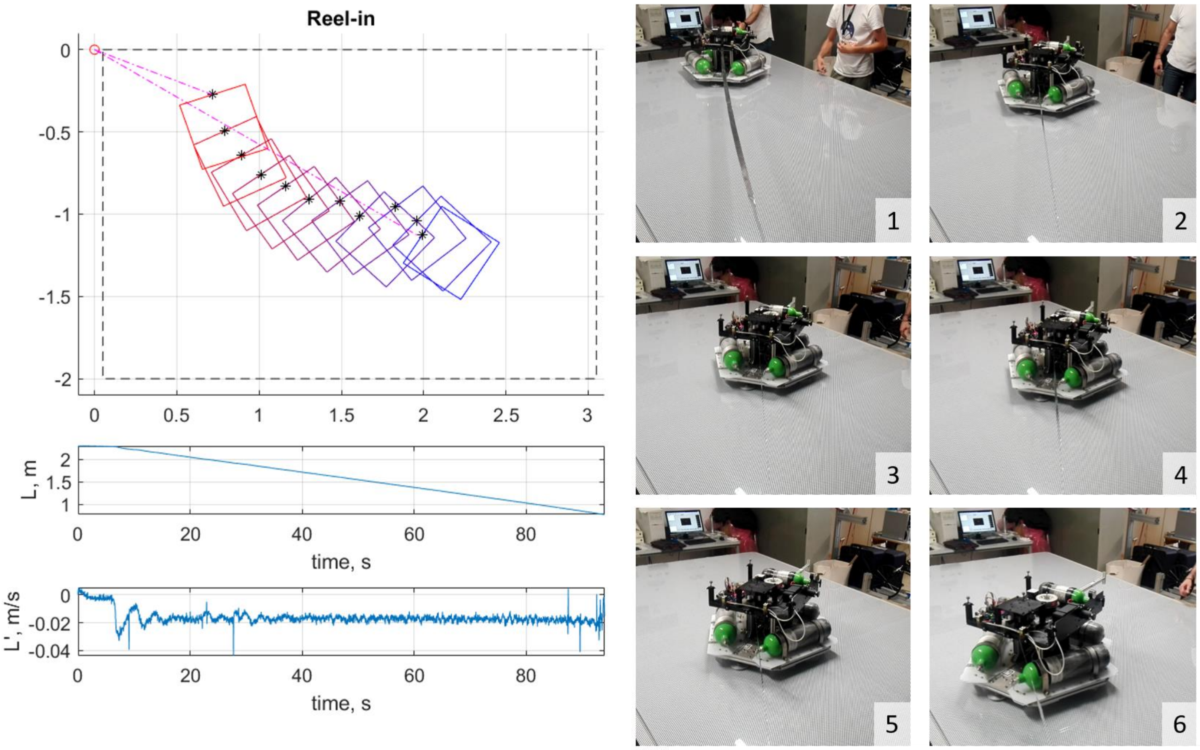

Fig. 8: Reel-in test, with reconstructed module position from Motion Capture (top left), tether deployed length and velocity (bottom left), and captured video frames (right).

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