MAMBO: MAnipulation with Multiples drones for soft Bodies

1. Introduction

Aerial robots meet many industrial needs, but their gripping capacity, reduced to a metal clip, is not adapted to complex objects. The MAMBO project offers a new solution: a soft gripper, composed of a soft body that can withstand a large deformation and thus adapt to any object shape. Lightweight, soft gripper can be larger and have no impact on the autonomy of drones.

In MAMBO, we propose to work on the first elementary bricks necessary for creating this soft gripper, which corresponds to the manipulation of a single soft body (a slender beam) by the combined action of two drones (Figure 1). The scientific developments associated with this goal are the first elementary developments necessary in order to attain this promising grasping strategy.

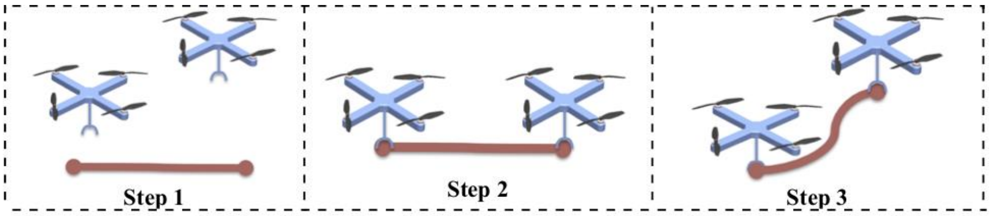

Figure 1. Manipulation of soft bodies (red body) with two drones in three steps : (1) Approaching phase, (2) Grasping phase and (3) Manipulating phase.

2. Consortium

The consortium was composed of the team ARMEN of LS2N in Nantes, and the team Rainbow of IRISA/Inria in Rennes.

3. Scientific program

The project goals have been reached thanks to a combination of advancements in soft body modeling, online state (deformation) reconstruction, and overall sensor-based control of the system UAVs+soft body. Several keypoints have been identified, in modeling (compromise accuracy/time of computation), state observation (compromise accuracy/ low-cost sensors), control of the system in flight (bi-level control) and soft body shape control (model-based trajectory planning combined with vision-based reactive trajectory tracking.). The objectives of the project have been reached by the development of two scientific axes:

- **Axis 1:** modelling of the full system (drones + soft body) and estimation of its state.
- **Axis 2:** high-level trajectory planning and low-level control of the system (drones + soft body)

The models defined in the first scientific axis has been used for several purposes, for instance in a preliminary motion planning step for generating trajectories able to perform a robotic task with complex motions, or for online control of the system in order to track a predefined trajectory, gain robustness to model uncertainties and reject disturbances, for which cases a good estimation of the state of the complete system (drones + soft body) is required. In addition, the control of the body shaping by the drones has been carried out in two different ways (complementary): model-based (prediction of the forces to be applied to the body in order to conform it in a given configuration) or vision-based (direct observation of the evolution of the shape by a camera and correction to fit as best as possible to the required planned trajectory).

3.1. Axis 1: Modelling

In this axis, we proposed approaches for modelling the soft bodies manipulated by multiple drones. We also studied the stability of the configurations of payloads attached to multiple cables, a sub category of flexible bodies, which has been used for the finale experiments in Rennes.

3.1.1. Dynamics modelling of soft bodies manipulated with drones

We proposed a new algorithm for solving the forward dynamics of soft and continuum robots consisting of rigid bodies connected in arbitrary topologies by localized joints and/or soft links, possibly actuated or not. The soft joints are modeled as Cosserat rods parameterized with strain modes. Unlike the literature approaches for simulating these models, our approach is designed to work with an implicit time-integration scheme. We choose the Newmark scheme, which is known to be among the best suited for stiff problems of nonlinear structural dynamics. Using such a scheme allows changing the differential algebraic equations (DAEs) of the robot into a system of nonlinear algebraic equations. At each time step, we solve this system with a Newton–Raphson scheme, requiring the residual and its Jacobian. To this aim we proposed a new recursive NE algorithm.

This algorithm has been applied to several case studies, in particular a soft body manipulated with two drones, in order to predict its dynamic motion (Figs. 2 and 3).

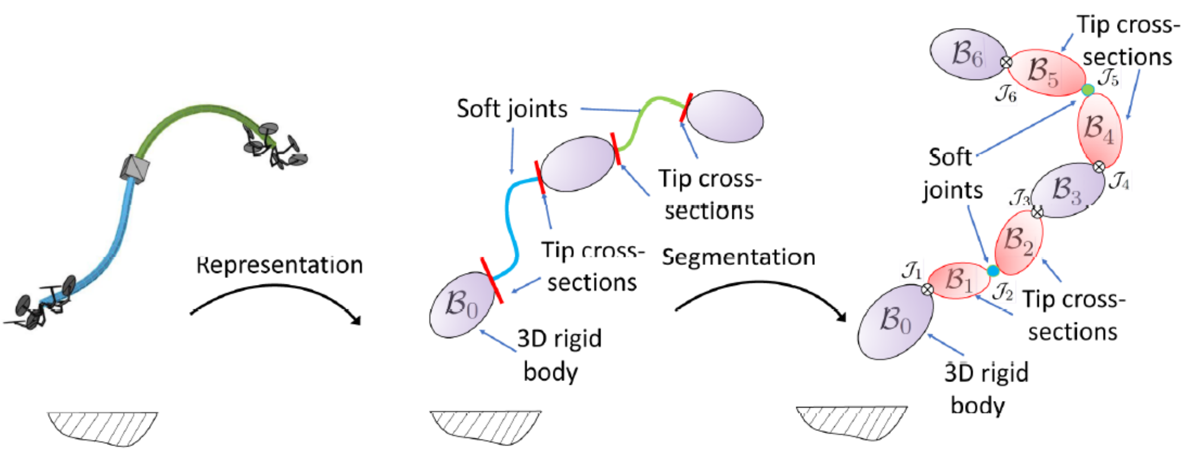

Figure 2. Segmentation of a cuboid mass attached to two rods moved by two flying drones. The two Cosserat rods are declared as joints J2 and J5, respectively. Their two tip-cross-sections are declared as rigid bodies (B1, B2) and (B4, B5), respectively.

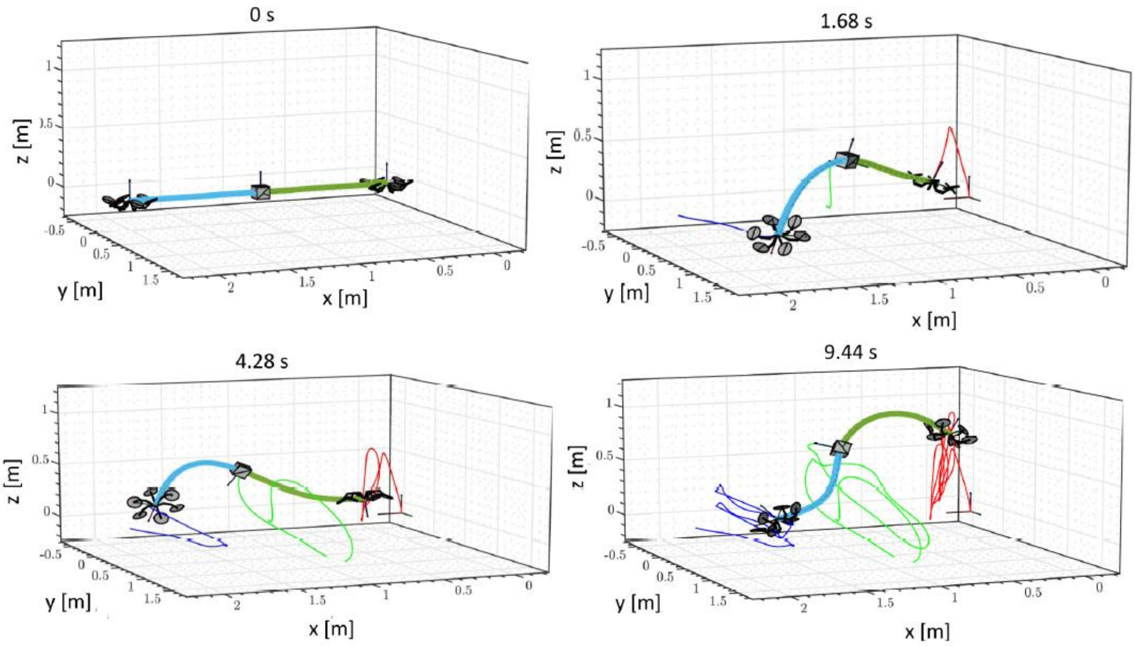

Figure 3. From left to right and top to bottom: Snapshots and trajectories of the two drones and the cuboid payload between t = 0s and t = 1.68, 4.22, and 9.44 s.

A Matlab toolbox has been created and is available on:
https://gitlab.univ-nantes.fr/cosseroots/library/matlab
https://gitlab.univ-nantes.fr/cosseroots/example/tro-2023

These results have been published in **[3][5]**.

3.1.2. Stability analysis of payloads suspended by cables

We also dealt with the stability analysis of payloads suspended by cables, which can indeed be assimilated to sagging cable-driven parallel robots (CDPRs).

To the best of our knowledge, we have shown for the first time that the geometrico-static equations of such systems are local extrema of the functional describing the robot potential energy. For assessing the stability of the robot configuration, it was then necessary to check two types of conditions: The Legendre-Clebsch conditions coupled with the Jacobi conditions, which are well known in optimal control theory. We showed that, in normal conditions on Earth (except under water), the Legendre-Clebsch conditions are always verified. Moreover, we proved that some singularities of the system model are limits of stability.

Results have been validated via the study of a rigid object manipulated through the use of 6 cables.

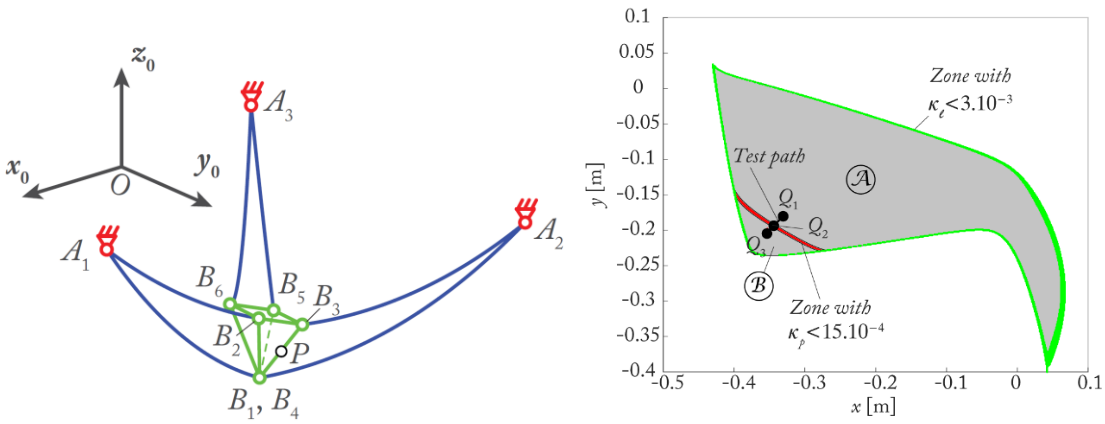

Figure 4. Rigid object manipulated through the use of 6 sagging cables (Left). Areas of the stable (Zone $\mathcal{A}$) and unstable (Zone $\mathcal{B}$) configurations for the object, when for fixed altitude and configurations.

These results have been published in **[4]**.

3.2. Axis 2: Control

3.2.1. Motion planning of a soft body manipulated with two drones

In order to manipulate a flexible body from a configuration A to a configuration B, a path of manipulation must be found. An infinity of configurations are potentially available all along the path for reaching the final configuration B, but only a few of them are physically feasible. In order to define a proper path of manipulation, we defined a kinematic (high-level) controller which interpolates first the body configuration into n steps, not necessarily reachable, and which then tries to reach the closest physically feasible configuration at the step k. Once this physically feasible configuration at step k is reached, a new interpolation is made with (n-k) configurations, for configuration k to the final configuration B (Fig. 5).

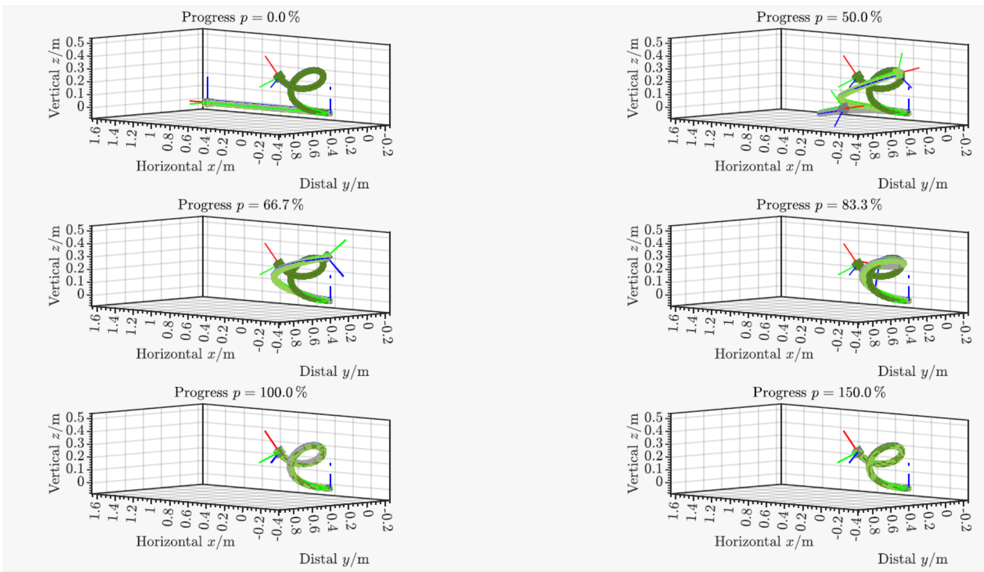

Figure 5. Stable deformation sequence of a test shape with one marker and 8 interpolation points.

A journal paper is currently under writing concerning these results.

3.2.2. Shape visual servoing of a suspended cable between two drones

We proposed a shape visual servoing control framework for performing the autonomous manipulation of a deformable cable subject to gravity and attached between 2 robotic manipulators. It relies on a visual servoing approach that uses an RGB-D camera to extract the shape of the cable and the yaw angle of the vertical plane that contains it. A closed-loop control was developed where we propose to use, as visual features, the coefficients (a, b) of a parabolic curve representing a coarse approximation of the shape of the cable and the yaw angle α of the vertical plane containing it. The objective of the shape visual servoing approach is to autonomously move the cable extremities to reach a shape described by desired visual features.
An important aspect of this study concerned the analytical derivation of the interaction model that relates the variations of these visual features to the velocities of the cable extremities. The proposed shape visual servoing approach was first tested and validated on an experimental setup consisting of a robotic arm manipulating one extremity of the cable and the other being attached to a static tripod (Fig. 6). In this experiment an eye-to-hand visual servoing configuration was considered with a static camera observing the cable. The results demonstrated the efficiency of the proposed visual servoing approach to deform the cable towards a desired shape configuration.

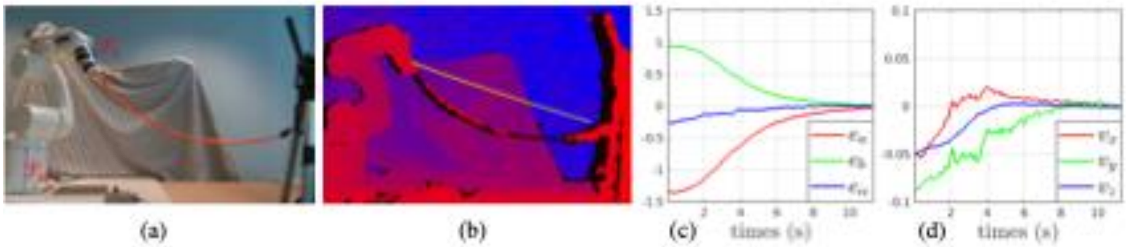

Figure 6. (a) RGB image. (b) Depth image with the cable target shape overlaid in yellow. (c) Evolution of the visual features error during the shaping task (parabola coefficients a,b and yaw angle α of the vertical plane containing the cable) . (d) Control velocity applied by the robot on the cable extremity.

These results have been published in **[2][6]**.

Subsequently, we extended this approach for manipulating a suspended flexible cable attached between two quadrotor drones. We designed a leader-follower control strategy, where a human operator controls the rigid motion of the cable by teleoperating one drone (the leader), while the second drone (the follower) equipped with an onboard RGB-D camera performs a shape visual servoing task to autonomously apply a desired deformation to the cable. An additional robotic task performing simultaneously with the shaping task was also developed to autonomously maintain the best visibility of the cable in the field of view of the onboard camera by controlling the yaw angular motion of the follower drone by visual servoing. Experimental results demonstrated the effectiveness of the proposed visual control approach to shape a flexible cable into a desired shape. In addition, we demonstrated experimentally that such system can be used to perform an aerial transport task by grasping

with the cable an object fitted with a hook, then moving and releasing it at another location. A short summary of the results obtained is presented in section 4.3.
To the best of our knowledge, we proposed the first onboard shape visual servo control approach for manipulating and deforming a cable to a desired shape configuration with quadrotor drones.
These results have been published in **[1]**.

4. Publications and outreach

4.1. PhD students and Postdocs partially funded by CominLabs

- Phd Student: Lev Smolentsev, IRISA/Inria Rennes. Shape visual servoing of a suspended cable. PhD of Univ. Rennes defended on March 18, 2024 (Nov. 2020-March 2024).
- Postdoc: Philipp Tempel, LS2N. Dynamics modelling of soft bodies manipulated with drones (Nov. 2021-Nov. 2023).

4.2. Matlab Toolbox

For dynamics modelling of soft bodies:
https://gitlab.univ-nantes.fr/cosseroots/library/matlab
https://gitlab.univ-nantes.fr/cosseroots/example/tro-2023

4.3. Benchmark and experimentations

Two experimental scenarios were set up on the Rainbow drone platform to test and validate the manipulation of a deformable linear object by a pair of UAVs (Fig. 7).
In the first scenario, we tested the autonomous shaping task of the flexible cable by the follower drone while the leader drone is maintained in a hovering mode. A succession of desired cable shapes was performed successfully by the follower drone thanks to its onboard control based on the proposed shape visual servoing.

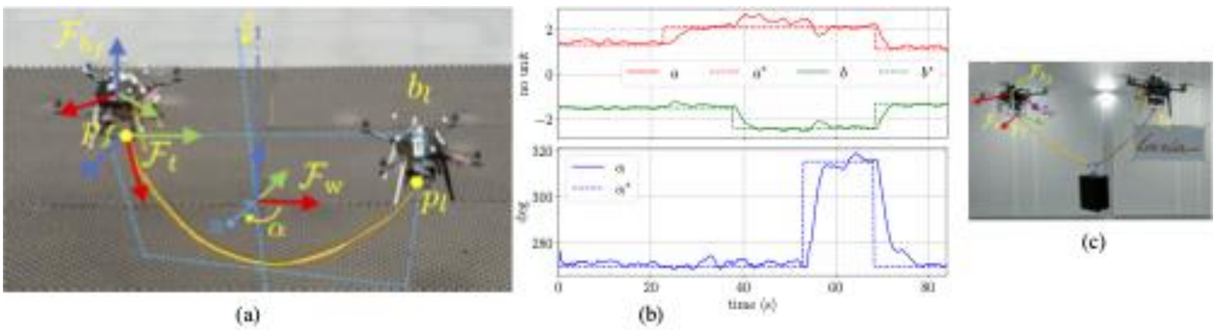

Figure 7. (a) Scenario 1: cable manipulation. (b) Desired (dotted line) and current visual features (coefficients a,b and yaw angle α). (c) Scenario 2: leader following, box grasping and transportation.

In the second scenario, we first proceed as previously, but while the leader drone is teleoperated, and, in a second phase, we manipulate the cable in order to pick up a box lying on the floor and transport it to another location.

The results of the experiments of these two scenarios are presented in the video available on the web link:
https://www.youtube.com/watch?v=wpdDFQFdxc4

4.4. Publications

[1] L. Smolentsev, A. Krupa, F. Chaumette. Shape visual servoing of a cable suspended between two drones. IEEE Robotics and Automation Letters (also presented at IEEE/RSJ Int. Conf. IROS 2025), 2024, Vol. 9, No. 12, pp. 11473-11480.

[2] L. Smolentsev, A. Krupa and F. Chaumette. Shape visual servoing of a tether cable from parabolic features. ICRA'23, London, May 2023.

[3] P. Tempel, F. Boyer, S. Briot, P. Robuffo Giordano and A. Chriette. Simulating the Manipulation of Flexible Bodies Through Drones. ICRA 2022 Workshop "New frontiers of parallel robotics" (second edition), Philadelphia, USA, May 27, 2022.

[4] S. Briot and J.P. Merlet. Direct Kinematic Singularities and Stability Analysis of Sagging Cable-driven Parallel Robots. IEEE Transactions on Robotics, 2023, Vol. 39, No. 3, pp. 2240-2254.

[5] F. Boyer, A. Gotelli, P. Tempel, V. Lebastard, F. Renda and S. Briot. Implicit Time Integration of Continuum Robots Dynamics Based on the Newton-Euler Recursive Computation of their Lagrangian Model. IEEE Transactions on Robotics, 2024, Vol. 40, No. 1, pp. 677-696.

[6] L. Smolentsev. Shape visual servoing of a suspended cable. PhD thesis of University of Rennes, defended on March 18, 2024 (URL).