*Ma*nipulation with *M*ultiples drones for soft *Bo*dies

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WP 1: Mechanical Design of Soft Bodies and State Estimation

Objective

Mechanical Design of Soft Bodies and State Estimation

- Create finite-dimensional model of infinite-dimensional physical soft body
- Implement simulator of flexible body under action of two drones
- Design control approach to manipulate body into shape and validate experimentally

Methodology

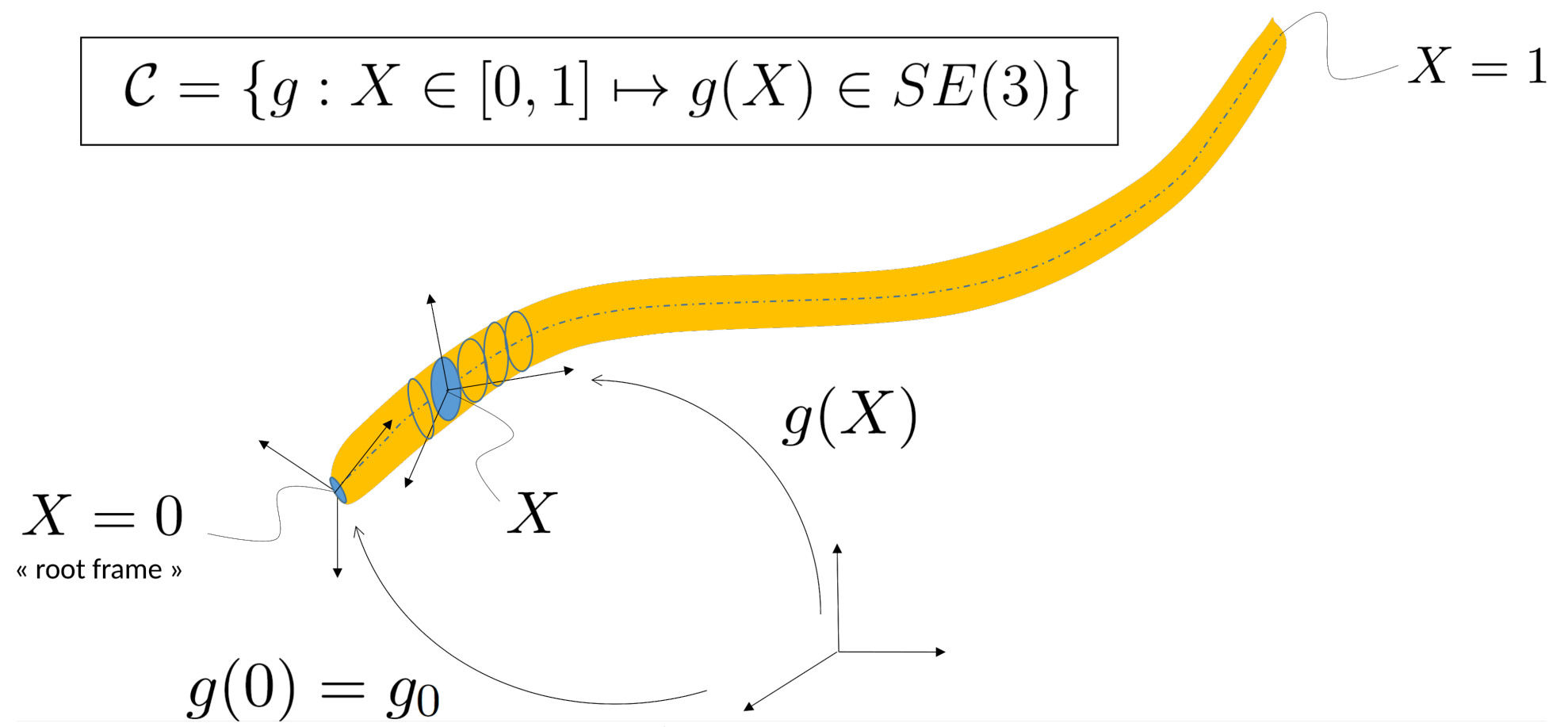


Figure 1. Cosserat brother's description of a flexible slender body.

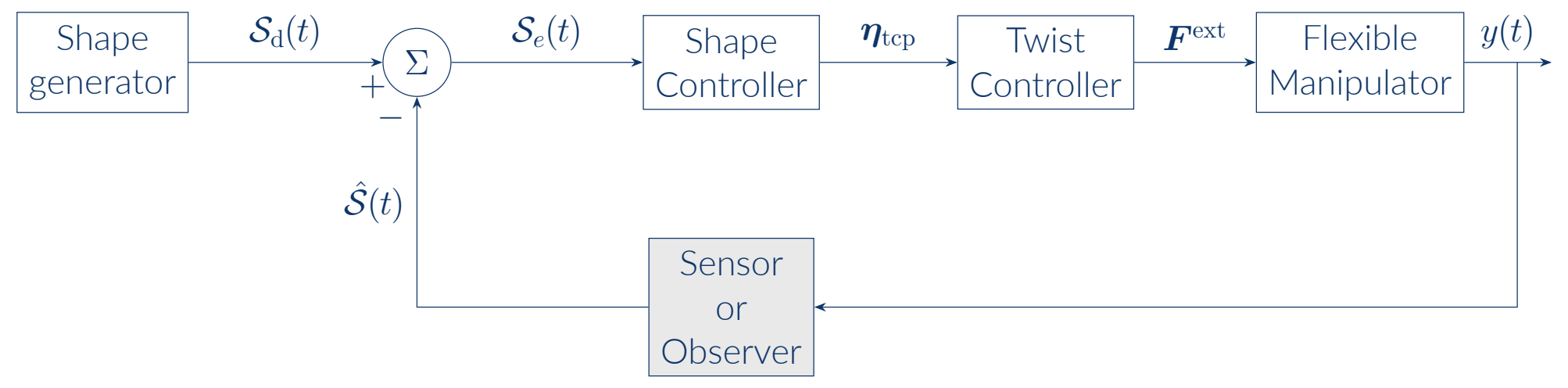
- Consider soft body a sequence of rigid cross-sections connected through active spherical joints
- Using Boyer et al. strain-based parametrization approach, we obtain a low-dimensional model

$$\begin{bmatrix} \mathbb{O} \\ \boldsymbol{Q}_{\mathrm{ad}} \end{bmatrix} = \begin{bmatrix} \mathcal{M}_{00} & \boldsymbol{M}_{0\epsilon} \\ \boldsymbol{M}_{\epsilon 0} & \boldsymbol{M}_{\epsilon\epsilon} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{\eta}}_0 \\ \ddot{\boldsymbol{q}}_\epsilon \end{bmatrix} + \begin{bmatrix} \boldsymbol{F}_v(\boldsymbol{q}_\epsilon, \dot{\boldsymbol{q}}_\epsilon, \boldsymbol{\eta}_0) \\ \boldsymbol{Q}_v(\boldsymbol{q}_\epsilon, \dot{\boldsymbol{q}}_\epsilon, \boldsymbol{\eta}_0) \end{bmatrix} + \dots$$
$$+ \begin{bmatrix} \boldsymbol{F}_c(\boldsymbol{q}_\epsilon, \boldsymbol{T}_0) \\ \boldsymbol{Q}_c(\boldsymbol{q}_\epsilon, \boldsymbol{T}_0) \end{bmatrix} + \begin{bmatrix} \mathbb{O} \\ \boldsymbol{K}_{\epsilon\epsilon}\boldsymbol{q}_\epsilon + \boldsymbol{D}_{\epsilon\epsilon}\dot{\boldsymbol{q}}_\epsilon \end{bmatrix}$$

  of the same form as a free-floating serial manipulator kinematic chain
- Dynamics methods i.e., FDM and IDM can be used one-to-one for our soft body system
- Control strategies conventionally used on rigid-link manipulators are transferable to our soft body

Shape Control of Soft Body

- Propose a geometric controller on SE(3) for m markers
$$e_i = \log(\boldsymbol{T}_i^{\mathrm{err}}) = \log(\boldsymbol{T}_i^{-1}\boldsymbol{T}_{m_i})$$
- Expect exponential error decay i.e., $\dot{e}_i = -\lambda e$
$$\dot{e}_i = \mathrm{D}_{\log}(\boldsymbol{T}_i^{\mathrm{err}})(\mathrm{Ad}_{\boldsymbol{T}_i^{\mathrm{err}}}\,\boldsymbol{\eta}_{m_i} - \boldsymbol{\eta}_i)$$
- With manipulation at the distal end, we express $\boldsymbol{\eta}_i$ as $\boldsymbol{\eta}_i \coloneqq \boldsymbol{\eta}_i(\boldsymbol{\eta}(s = 1))$
$$\mathrm{D}_{\log}(\boldsymbol{T}_i^{\mathrm{err}})\boldsymbol{\eta}_i = \mathrm{D}_{\log}(\boldsymbol{T}_i^{\mathrm{err}})\,\mathrm{Ad}_{\boldsymbol{T}_i^{\mathrm{err}}} + \lambda e_i\,,$$
  where
$$\boldsymbol{\eta}_i = -\int_1^s -\mathrm{ad}_{\boldsymbol{\xi}(s)}\,\boldsymbol{\eta}(s) + \dot{\boldsymbol{\xi}}(s)\,\mathrm{d}s\,,$$
$$\boldsymbol{\eta}(1) = \boldsymbol{\eta}_1$$
- Linear shape controller is only locally stable
- Create sequence of kinetostatically stable shapes for controller



Simulator

- Existing robotics simulation frameworks are limited to rigid joints
- Necessity to create simulator for MAMBO combining techniques of rigid multibody simulators with flexible bodies
- Proof-of-concept implemented as object-oriented framework in MATLAB: `gitlab.univ-nantes.fr/ls2n-armen/mambo/matlab-simulation-engine`
- Use of implicit Newmark-Beta time integration scheme, particular case of generalized α-scheme

Intensive Simulative Study

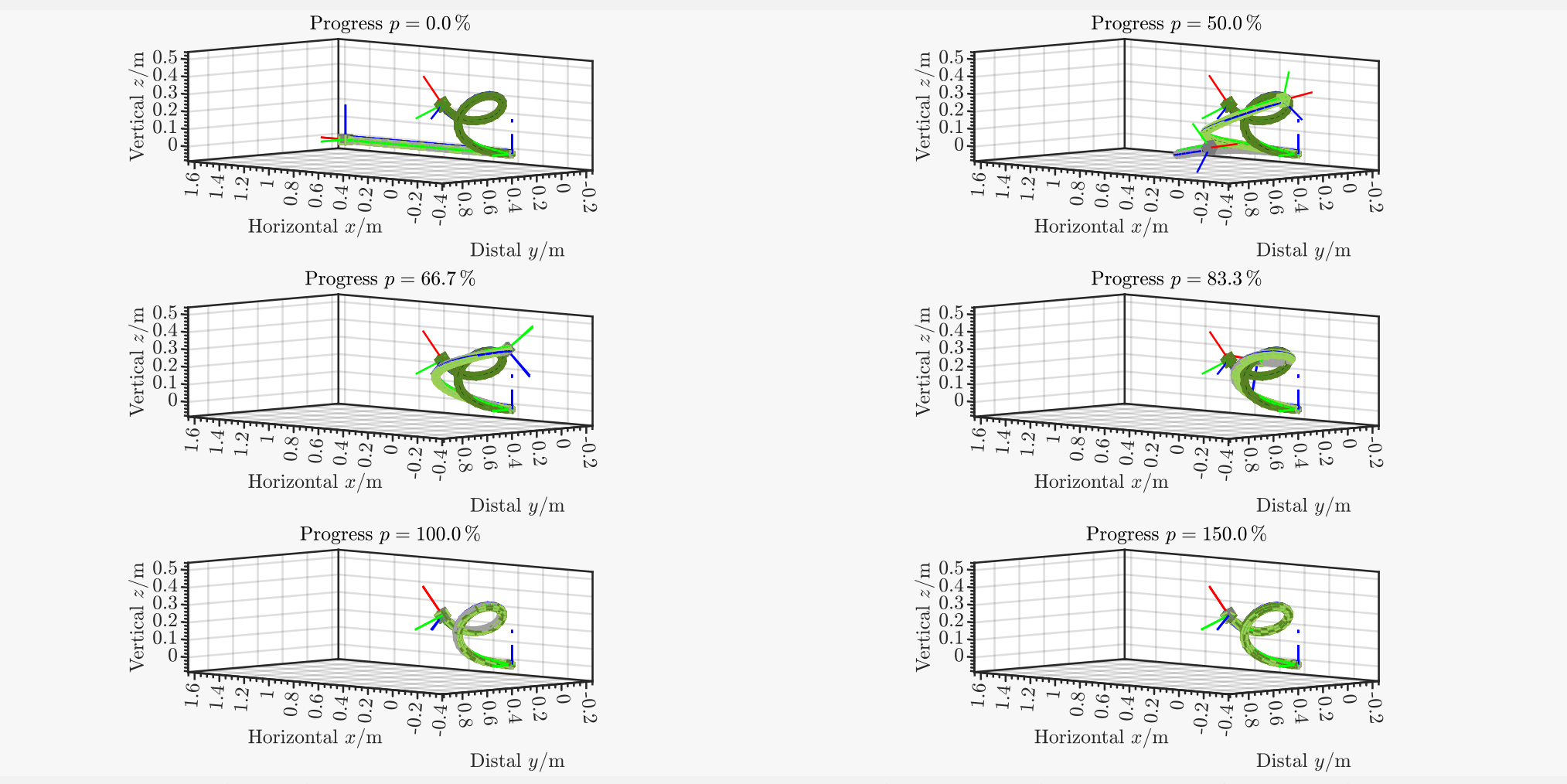


Figure 2. Stable deformation sequence of a test shape with one marker and 8 interpolation points.

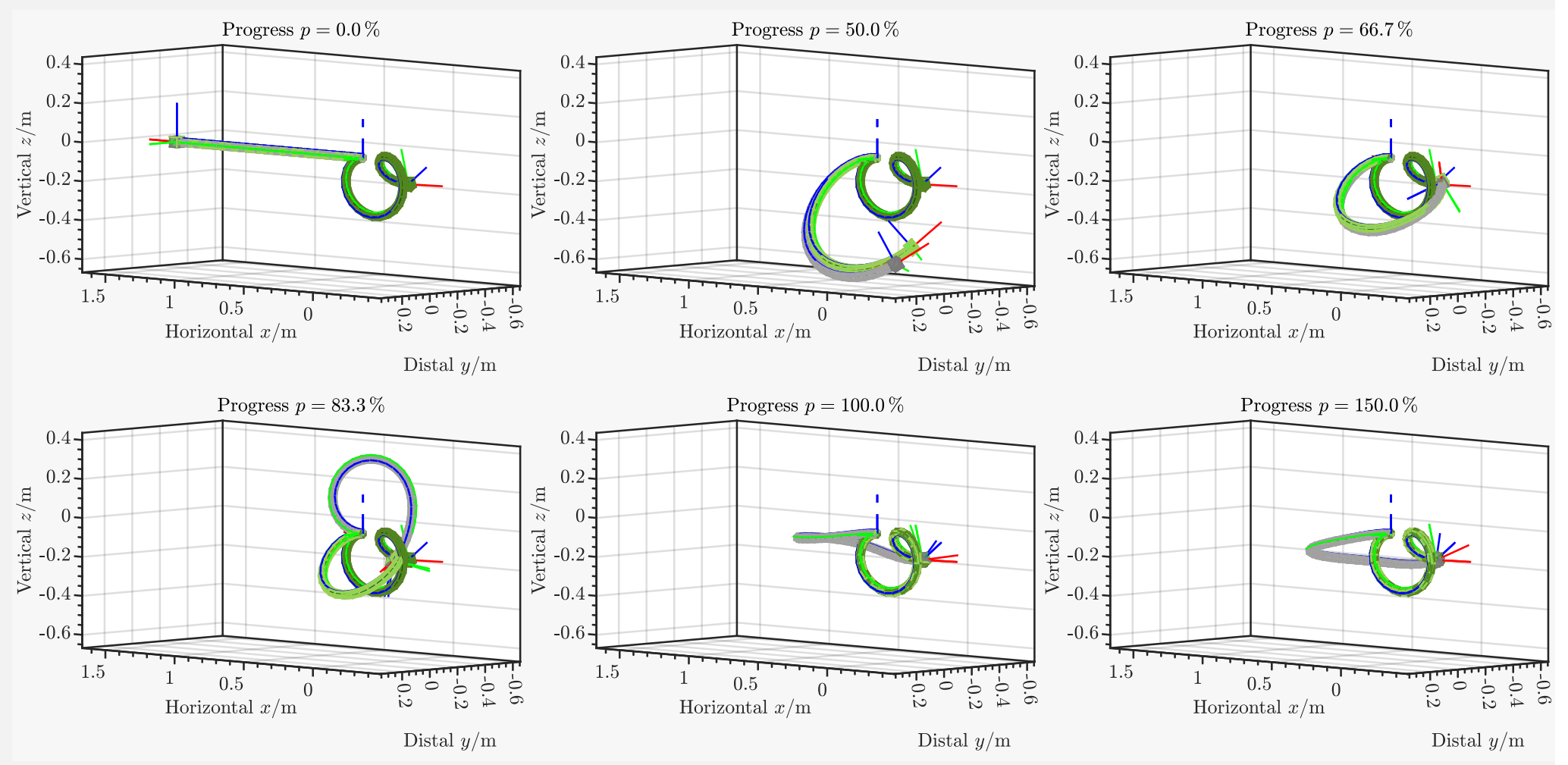
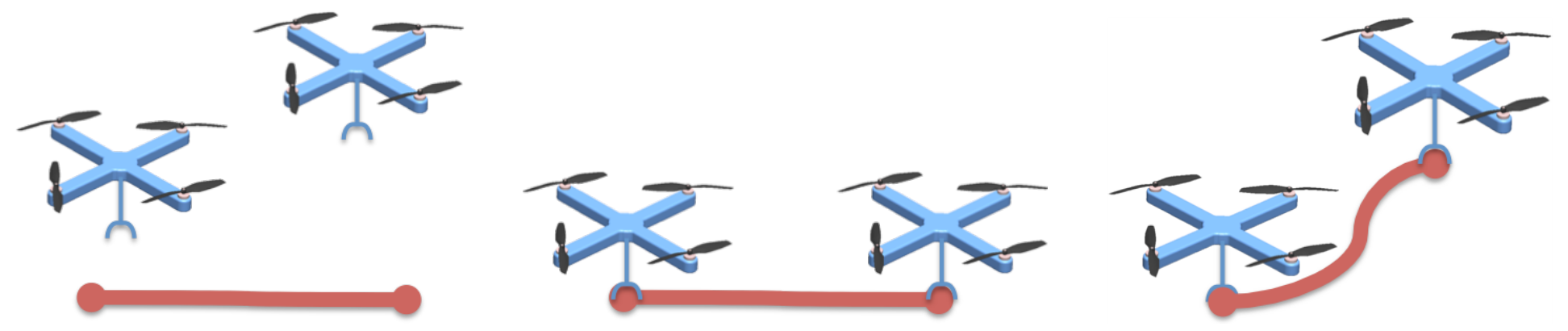


Figure 3. Unstable deformation sequence of a test shape with one marker and 32 interpolation points.

- Less markers provide for a more stable control of the shape
- First-order error dynamics for a second-order dynamical systems
  - Several cases cannot be stabilized past a certain high-deformation level
- Shape interpolation is more important than anticipated
  - Path to get near a desired shape impacts overall stability
  - Are paths directly connected?

Project: MAMBO

Long term: Design universal aerial gripper composed of flexible bodies
Short term: Manipulation of single soft body through combined action of two UAVs



(a) Approach phase. (b) Grasp/contact phase. (c) Manipulation phase.

Figure 4. Three main stages of manipulating a single soft body with drones.

Challenges

- Infinite number of DoFs in a soft body
- Only 4 DoFs for a quadrotor
- Underactuated system from the quadrotor perspective
- Highly coupled and non-linear system due to interaction of quadrotors

Work Packages

1. Mechanical design of soft bodies and state estimation
2. Control of underactuated systems with soft bodies and vision-based control
3. Experimental validation

Conclusions

- Developed mechanical model of a soft body including state estimation
- Implemented a simulation framework for rapid prototyping of control concepts
- Derived vision-based control law for underactuated system with soft bodies
- Validated experimentally how two drones lifting an object using a flexible body

Future Work

- Experimental validation of the tether cable control with two quadrotors on both experimental drone platforms of Rainbow and ARMEN team
- Describe stability of desired shape through qualitative values
- Develop optimal controller with second-order error dynamics
- Improve shape interpolation through an energy-optimal planner
- Disseminate results at conferences and thesis publications

Acknowledgements

This work carried out in the MAMBO project has received a French government support granted to the Labex CominLabs excellence laboratory and managed by the National Research Agency in the "'Investing for the Future"' program under reference ANR-10-LABX-07-01.

WP 2: Control of Underactuated Systems with Soft Bodies and Vision-Based Control

Objective

Shape Control of a Tether Cable Using Visual Servoing embedded on the drone

- Derivation of a geometric model for the control task
- Determination of relevant visual features and related interaction matrix
- Tracking of visual features from RGB-D vision
- Generation of the trajectories for the outputs of the drone from visual features

Methodology

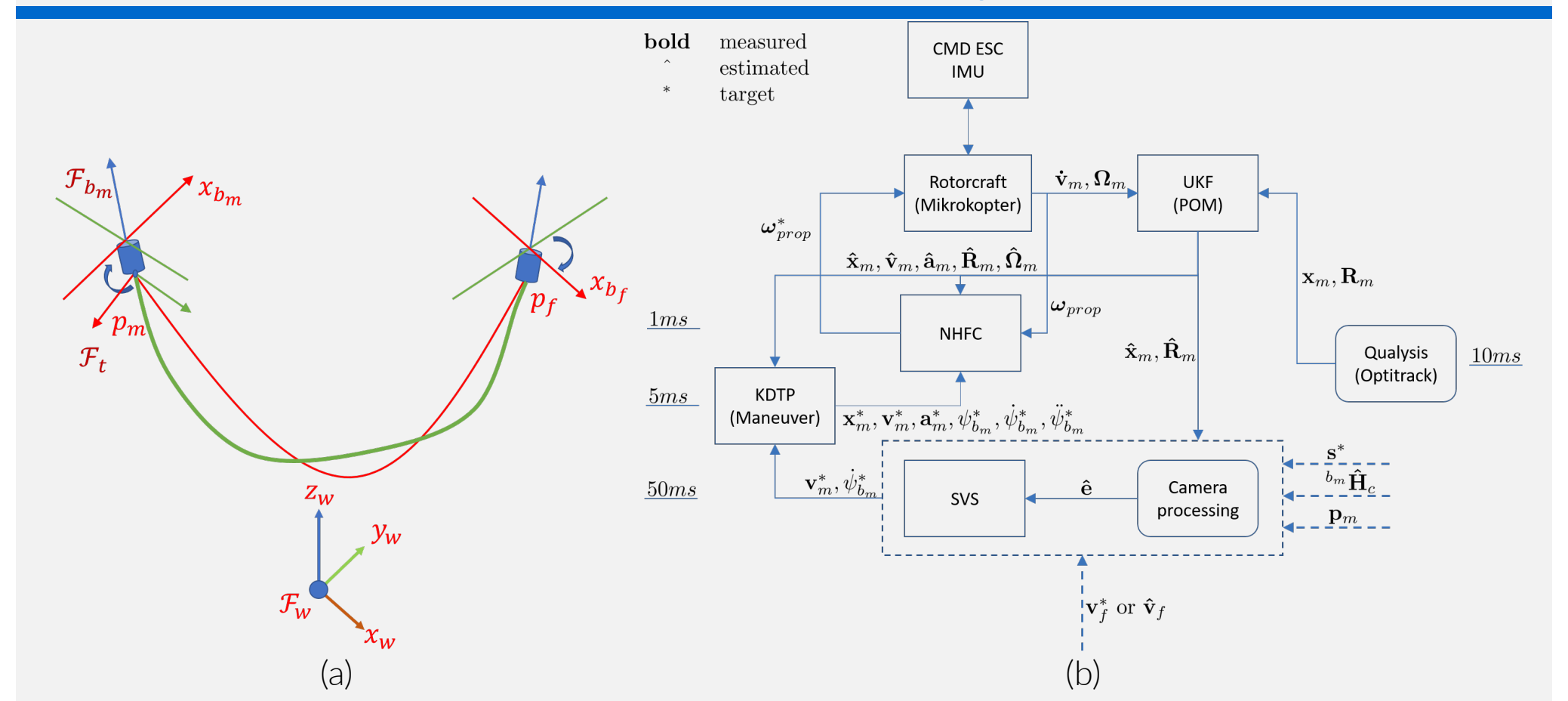


Figure 5. (a) Tether (green curve) and its parabola model (red curve) attached to the drones with corresponding frames; (b) Drone navigation stack diagram with all quantities used during control task

- Proposed visual features extracted from RGB-D image: $\boldsymbol{s} = (a, b, \alpha)$
- Visual error to minimize: $\boldsymbol{e} = \boldsymbol{s} - \boldsymbol{s}^*$
- Control law with a feed-forward term $\boldsymbol{v}_f$ and an integral term:
$$\boldsymbol{v}_m^* = \boldsymbol{v}_f + \lambda \boldsymbol{M}\hat{\boldsymbol{e}} + \mu \boldsymbol{M}\sum_i^N \hat{\boldsymbol{e}}_i$$
$$\dot{\psi}_{b_m}^* = -\lambda(\psi_{b_m} - \psi_{b_m}^*) - \mu\sum_i^N (\psi_{b_{mi}} - \psi_{b_m}^*)$$
  with control gain $\lambda > 0$, $\mu > 0$ and $\boldsymbol{M}$ relating the velocities of the cable attachment points with the velocities of the visual features
- Secondary control task of the quadrotor yaw ψ_{b_m} for observing the tether with an onboard RGB-D sensor while performing the cable shaping task

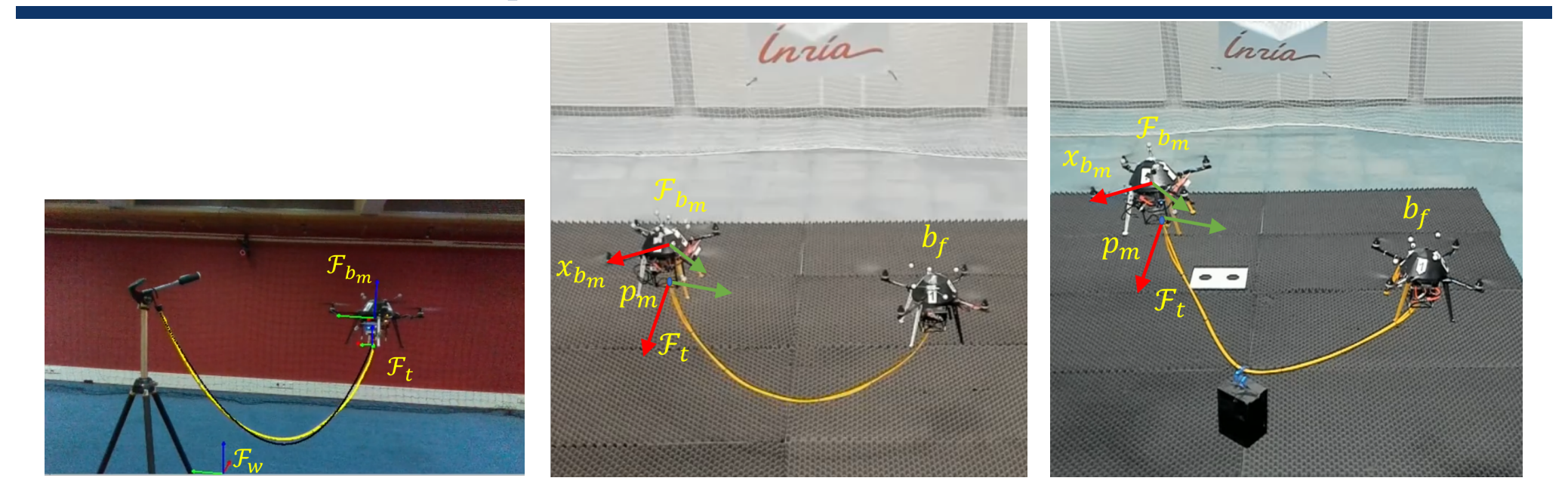
Matrix M

- $\boldsymbol{M} = \begin{bmatrix} -k_1\mathrm{s}_\alpha & -k_2\mathrm{s}_\alpha & -D\mathrm{c}_\alpha \\ k_1\mathrm{c}_\alpha & k_2\mathrm{c}_\alpha & -D\mathrm{s}_\alpha \\ D^2 + tk_1 & D + tk_2 & 0 \end{bmatrix}$ with $k_i = f(\boldsymbol{s}, D, L)$
  where L is the cable length
- Necessary condition to do the task is $\mathrm{rank}\,\boldsymbol{M} \equiv 3$
- The rank is less than 3 if and only if the cable is taut horizontally or vertically
- Above mentioned configurations represent local minima for the control task. Furthermore, given the Lyapunov candidate derivative $\boldsymbol{e}^T\dot{\boldsymbol{e}} = -\lambda\boldsymbol{e}^T\boldsymbol{M}^{-1}\widehat{\boldsymbol{M}}\boldsymbol{e}$ when $\widehat{D} = L$ the eigenvalues λ_i of the symmetric part of $\boldsymbol{M}^{-1}\widehat{\boldsymbol{M}}$ are always positive for a large number of target configurations $\boldsymbol{s}^*$, which guarantees convergence of $\boldsymbol{e}$ and regardless of what $\widehat{D} > 0$ used, $\lambda_3 > 0$ always guarantees convergence for e_α

Features tracking from RGB-D data

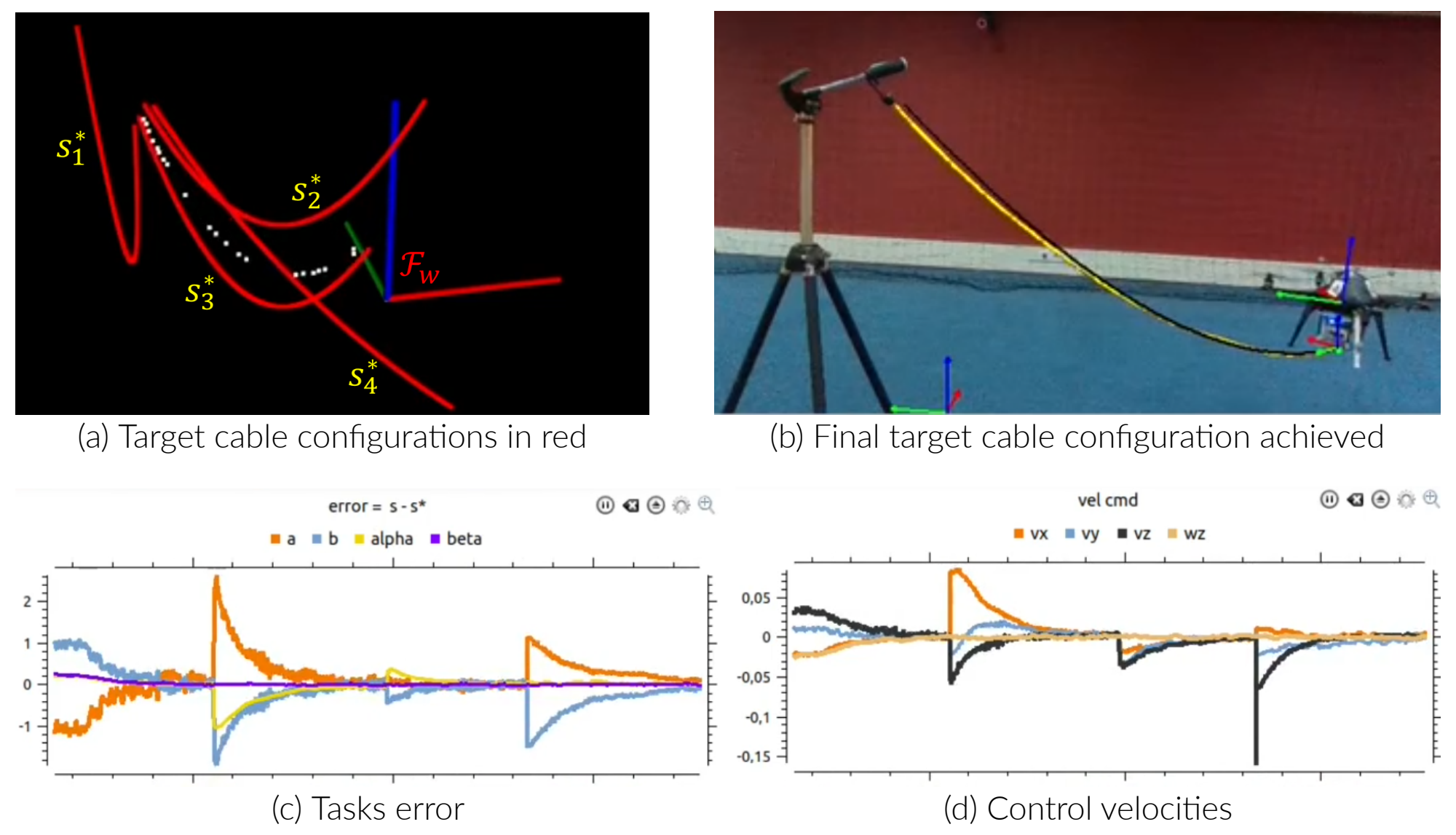
- Estimation of the normal to the plane containing the tether in the world frame from observed point-cloud with RANSAC algorithm
- Check normal sign such that $\boldsymbol{y}_t$ of $\mathcal{F}_t$ points toward the end of the cable
- Filtering of the normal using Kalman and estimation of the cable plane yaw α and of the pan of this plane from the gravity vector ϕ
- Projection of cable pointcloud into $\mathcal{F}_t$ using ${}^{b_m}\widehat{H}_c$ and $\boldsymbol{p}_m$ which are constant together with the drone odometry $\hat{\boldsymbol{x}}_{b_m}, \hat{\boldsymbol{R}}_{b_m}$
- Estimation of the parabolic coefficients a, b by least squares

Experimental Results



(a) First experiment with one drone and $\mu = 0$ (b) Second experiment with two drones (c) Third experiment with box grasping $m_{box} = 0.3kg$

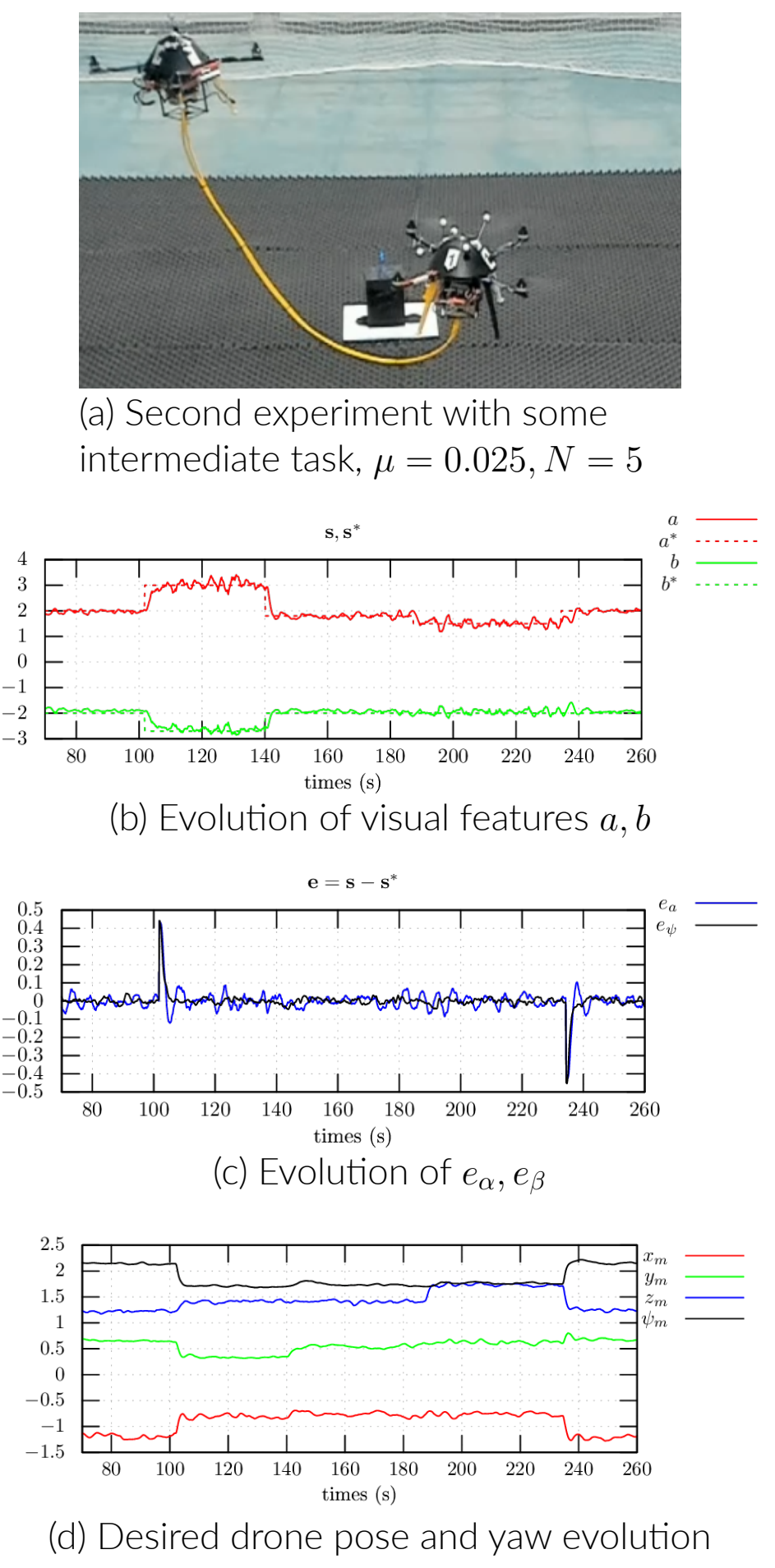
Figure 6. Three experiments with cable shape control and manipulation using drones.



(a) Target cable configurations in red (b) Final target cable configuration achieved

(c) Tasks error (d) Control velocities

Figure 7. One drone visual servoing experiment.



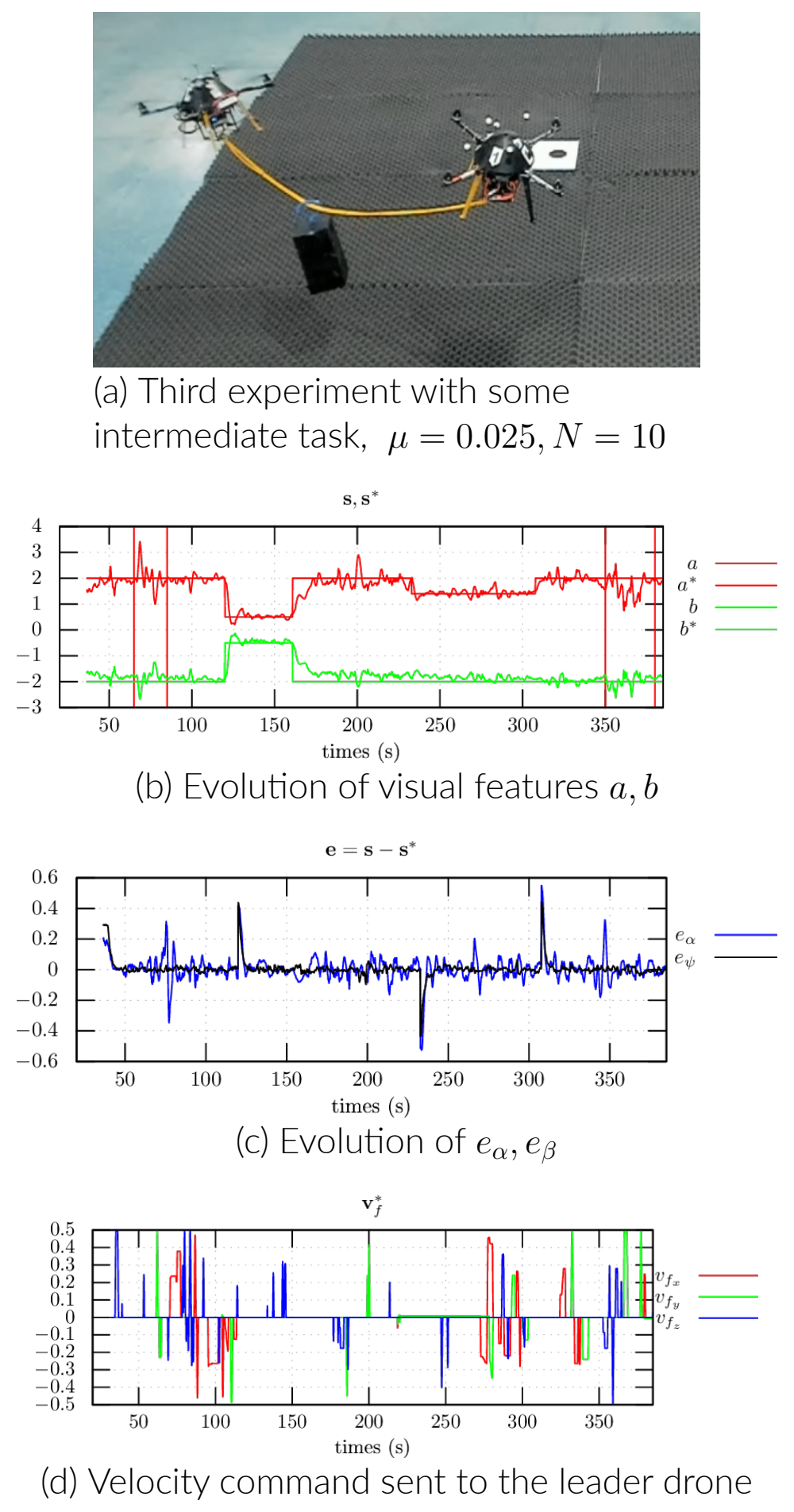
(a) Second experiment with some intermediate task, $\mu = 0.025, N = 5$

(b) Evolution of visual features a, b

(c) Evolution of e_α, e_β

(d) Desired drone pose and yaw evolution

Figure 8. Slack cable manipulation



(a) Third experiment with some intermediate task, $\mu = 0.025, N = 10$

(b) Evolution of visual features a, b

(c) Evolution of e_α, e_β

(d) Velocity command sent to the leader drone

Figure 9. Box manipulation with a cable

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CominLabs Days, Inria Centre at Rennes University, Rennes, France
September 25 to 27, 2023

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