1Laboratoire des Sciences du Numérique de Nantes (LS2N) *Ma***nipulation with** *M***ultiples drones for soft** *Bo***dies** Implement simulator of fexible body under acton of ² Centre Inria de l'Université de Rennes λ **P** λ **a** λ *d* λ *x* λ *de i a* λ *de i de i d* $i²$ sufficient. The proposed shape control approach only approach only approach on $i²$ sufficient on $i²$ uses the length of the cable as *a priori* knowledge and the +Laborat

l,

MAnipulation with Multiples drones for soft BOdies François Chaumette² **Objective** $\mathbf S$ ciences du Numérique de Nantes (LS2N) 2Centre Inter I MECHANICAL DESIGN OF SOF Create fnite-dimensional model of infnite-dimensional physical sof body \mathbf{a} is a simulator of feature body under acton of \mathbf{b} two drones $D = \bigcup_{i=1}^n D_i$

Sébastien Briot¹, Abdelhamid Chriette¹, Isabelle Fantoni¹, Damien Six¹, Philipp T. Tempel¹, Frimpp 1. Temper,
François Chaumette², Alexandre Krupa², Paolo Robuffo Giordano², **Lev Smolentsev², Fabien Spindler²** Expect exponental error decay i.e., *e*˙*ⁱ* = *e* Mer^2

> 0 20 40 60 80 time (s)

Function (**s**) $\frac{320}{\pi}$ and $\frac{1}{\pi}$ and $\frac{1}{\pi}$

(a)

320

 $\overline{1}$

 α

 $\frac{320}{\sqrt{\frac{1}{\pi}} \cdot \alpha}$

v fy $time(s)$

0 20 minutes and the control of the time (s)

0 20 40 60 80 time (s)

0 20 40 60 80

0*.*2 0*.*0

 $\frac{1}{\sqrt{2}}$

 $^{-2}$ $\mathbf{0}$

0*.*25

a a"

v fz

SV S M aneuver

10 0 ˙

 $M \rightarrow v_i$ \rightarrow v_i \rightarrow v_i \rightarrow M 80 time (s)

SV S M aneuver

 $\hat{\mathbf{v}}_l$ $\widehat{v_{l_s}}$ *v*_{*l*} *v*_{*l*_{*z*} *v*_{*l*_{*z*} *v*_{*l*_{*z*}}}}

⁴ = (1*.*1*,* 1*.*3*,* ²⁷⁰*^o*). The

N

0 20 40 60 80 100 time (s)

(a)

time (s)

(b)

time (s)

e e

 \rightarrow 80

 \sim 80

(c)

time (s)

MAMBO main objective 11 EFSVEXSMVI HIW GMIRGIW HI 3ERXIW HI 3ERXIW HI 3ERXIW HI 3ERXIW HI 3ERXIW MX9RMZIVWMX the cable. Moreover, it is capable of operating with slack AAMBO main obiective and does not no cable extremities. In particular, the chain model considered

 $\mathcal{L}_{\mathcal{A}}$, and $\mathcal{L}_{\mathcal{A}}$ is a set of $\mathcal{L}_{\mathcal{A}}$

Long term: Design universal aerial gripper • In composed of flexible bodies. **Exercise our parabola model is not singular in the composed of flexible bodies.** order of flexible bodies.
 WPF 1: Methodology **1:** Methodology **and State Books and State Estimation Methodology**

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WEFIPPI +ERXSRM1

Short term: Manipulation of single soft body . L through combined action of two UAVs. • Highly coupled and non-linear system due to Propose a geometric controller on a1(3) for *m* markers rough combined action of two UAVs. The shape of p

• Parabola model for cable shape: $z = ax^2 + bx$ *•* An image processing method for real-time shape trackthe variation of variation of visual features $z = ax + b$ Shape interpolaton is more important than antcipated French government support granted to the Labex CominLabs excellence laboratories are to-one for $z = ax^2 + bx$ the shape of the cable. Its equation in the plane (*xt, zt*)

dynamics methods i.e., FDM and IDM can
In the used of the used of

- Proposed visual features extracted from RGB-D Extraction image: $\mathbf{s} = (a, b, \alpha)$
• Estimation ing and control using an RGB-D camera onboard the • Proposed visual features extracted from RGB-D • Ex Γ arabola mouel for each strategies $z = 0$
- the plane roll and yaw angles.
 • Extraction of pointcloud intersecting the plane $\frac{1}{2}$
The plane roll and vaw angles experies peak to *g*₁, a meale age commit-

(c) Kalman filtering of the normal and estimation of particular case of the normal direction of the armend-
- the plane foll and yaw angles.
• Extraction of pointcloud intersecting the plane.
• Estimation of norshalls coefficients a b by loost **M**
M₂
F
*M*₂
c
C
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C **December 100** and yaw angles.
● Extraction of pointcloud intersecting the plane. particular case of provided and the security of $\frac{1}{2}$ shape
	- Estimation of parabolic coefficients a, b by least $\frac{1}{2}$ *i* pointcioud intersecting the plane.
of parabolic coefficients a. b by least Interactive Studies of Studies Studies and Study and Study Cond-order error dynamics for a second-order order t
Figure Stimation of parabolic coefficients a. b by least

Objectives: experimentally coupled model of the tether cable and the visual features of the visual features of the visual features of the visual features of the tether cable and the visual features of the visual features Mechanical Design of Sof Bodies and State Estmaton

 \sim

• Create finite-dimensional model of infinite- base dimensional physical soft body. preate innite-u

> Secondary control task of the quadrotor yaw *bm* for observan the tether with an onboard RGB-D sensor

 $\mathbb{R}^{\mathbb{N}}$ $T_{\rm eff}$ is less than 3

Objective: Shape Control of a flexible cable using an onboard RGB-D camera and is controlled by visual *^f* ⁼ ^vb*^l* ⁺ R()Me ⁺ *^µ*R()M^X *i* model the cable is depicted in red. *F^t* stands for the cable al servoing embedded on the drone operator and the drone \hat{p} (the follower) is equipped with \hat{p} (the follower) is equipped with \hat{p} $\frac{1}{\sqrt{2}}$ \overline{a} and \overline{a} **F***b*_{*f*} $\frac{1}{2}$ *Ff f Ff***_{***f***}** *f*_{*f***}** *f*_{*f***}** *f <i><i>f***_{f**} *f <i><i>f***** *<i>f***** *<i>f <i>f***** *f f f f f f f f f f f f f f f*</sub></sub></sub> **motive:** Shane Control of a flexible cable us $\frac{1}{\frac{1}{\sigma_{\text{max}}}}$ and servoing embedded on the drone $\frac{1}{\sigma_{\text{max}}}}$ **Pictive:** Shape Control of a flexible cable us a paper position $\frac{1}{2}$ $\mathbb{E} \left[\mathbb{E} \left[\mathbb{$ *Qc*(*q*✏*, T*0) *K*✏✏*q*✏ + *D*✏✏*q*˙✏ **Z**_c tive: Shape Control of a flexible cable u *Fc*(*q*✏*, T*0)

Methodology: which is a state of the control of the contr part corresponds to an integral term with gain *µ* computed **• Methor** $\log y$ to the orientation angles $\log y$ \mathbf{F}_{ref} this non-vertical plane case, the relation between the relation between the relation between the relations of \mathbf{F}_{ref} \mathbb{F}_2 . Unstable deformation sequence of a test shape with one matter \mathbb{F}_2 Control strategies conventonally used on rigid-link $% \mathcal{N}$ kinematik chain chai Discription in the use of \mathcal{D}

I = ÿ.

> $\frac{1}{1}$ $\frac{1}{2}$

use a leader control of Underactual $\left\langle \cdot\right\rangle$ in was manipulated by a grounded robot arm. To the best of \mathbb{C} in the first orbit shape visual servo control approach for manipulating and . CONCIDENT CITUM IN \mathcal{L} is the system constant of \mathcal{L} \mathbb{R} IP $2 \cdot$ Control of Underactual \mathbb{R} $\frac{1}{\sqrt{100}}$ is assumption of the contract when the state $\frac{1}{\sqrt{100}}$ Describe stability of desired shape through qualitatve \mathcal{D} . **L.** Control of Original $\begin{smallmatrix} \texttt{S} & \texttt{$ **P** 2: Control of Underactua δ ontrol o ł $\frac{1}{2}$ *<i>F Qv*(*q*✏*, q*˙✏*,* ⌘0) $\overline{}$ *M* 2: Control of Underactual .
د \cdot *Fv*(*q*✏*, q*˙✏*,* ⌘0) *Qv*(*q*✏*, q*˙✏*,* ⌘0) $\overline{}$ 1 dCl

approach, we obtain a low-dimensional model model

The rest of the paper is organised as follows: Section II \ddagger $\frac{1}{\tau}$ details the low-level controller that generates the speeds to detail a speed controller that generates the speeds the speeds to detect the speeds to detect the speeds to det the speeds to det the speeds to det the speeds t \overline{a} $\frac{1}{\sqrt{2}}$ $\frac{1}{\tau}$ the shape of the cable from the data provided by the onboard

 $\overline{}$ can be seen in Fig. 1. The attachment points p*^f* and p*^l* e
al the cable to gravity by a simple parabole to gravity be calculated to gravity be calculated to gravity by a simple parabola \mathcal{T} $\overline{}$ $\frac{1}{2}$ al
og $\mathring{\mathbb{1}}$ $\overline{1}$

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Challenges Publications (a) Side view (b) Isometric view (, Alexandre Krupa² Dlog(*^T* err *ⁱ*)⌘*ⁱ* ⁼ Dlog(*^T* err , Paolo Robufo Giordano² 1Laboratoire des Sciences du Numérique de Nantes (LS2N) 2Centre Inria de l'Université de Rennes a blications of a few individual error decay i.e., b *^e*˙*ⁱ* ⁼ Dlog(*^T* err

• Infinite number of DoFs in a soft body.
• Cable from parabolic feature • L. Smolentsev, A. Krupa, F. Chaumette. Shape visual servoing of a tether cable from parabolic features. IEEE Int. Conf. on Robotics and
 Or a quadrotor.
 Proven the Conference of a soften with *May* 2023. casic Trom parasone reatures: TEEE Int. Com. on Rose
Automation, ICRA'23, pp. 734-740, London, UK, May 2023. entsev, A. Krupa, F. Chaumette. Shape visual servoing of
from parabolic features. IEEE Int. Conf. on Robot v, A. Krupa, F. Chaumet:
Parabolic features

dynamics

approach, we obtain a low-dimensional model mod

 ϕ_{r} where $\omega = 60.7\%$

 $\label{eq:dist} \text{Distal } y/\text{m}$ regress $p=150.0\,\%$

 \mathbb{Z}^2

" " 이히 이렇게 있을 것은 다 나 ...
- Hotizontal s/m
- Hotizontal s/m " Distance of March 2011 USIL OF CHANGE AND Distance Descriptional s/m Distance Of CHANGE AND
- Hotizontal Systems Profile Of Change and Distance of Change and D $\frac{1}{2}$ observed point-cloud by RANSAC algorithm. • Kalman filtering of the normal and estimation of also corresponds to the x axis of *Ft*, is expressed in *F*^w $\begin{array}{lllllllll} \textbf{RMSDAMM} & \textbf{RMSDAMM} & \textbf{DMSM} & \textbf{DMSM$ e Kolmon filtoring of the normal on the method we propose to method we propose to method we propose to measure the measure that \Box

Results:

material mechanical properties. In contrast, our method relies

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\mathbf{r} \qquad \begin{bmatrix} \mathbf{O} \\ \mathbf{Q}_{\text{ad}} \end{bmatrix} = \begin{bmatrix} \mathcal{M}_{00} \ \mathcal{M}_{0\epsilon} \\ \mathcal{M}_{\epsilon 0} \ \mathcal{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} \mathbf{O} \\ \boldsymbol{K}_{\epsilon \epsilon} \boldsymbol{q}_{\epsilon} + \boldsymbol{D}_{\epsilon \epsilon} \dot{\boldsymbol{q}}_{\epsilon} \end{bmatrix}
$$

⇒ Model linear in acceleration of the same form as a free-foatne form as a free-foatne serial manipulator \mathbf{r} \rightarrow ividuel little Control strategies conventonally used on rigid-link $\overline{}$ acceleration

interaction of quadrotors.

interaction of quadrotors.

*x i*⁴ *Challongos*

Propose a shape controller for modifying the body Propose a shape controller for modifying the body 1 ad⇠(*s*) ⌘(*s*) + ˙⇠(*s*) ^d*s ,* Linear shape controller is only locally stable Propose a shape controller for modifying the body Dynamics methods i.e., FDM and IDM can be used Propose a shape controller for mode

t p =

0

A (1)

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Distal w

Objective

- e action of two grones.
In the cable capital and cable the manipulate hody into • Implement simulator of flexible body under $\begin{bmatrix} 0 \\ Q \end{bmatrix}$ action of two drones. $[Q_{\varepsilon}$
- Design control approach to manipulate body into shape and validate experimentally. $\overline{\text{shape}}$ and validate experimentally. one presents simulate experimentality.

Shape Control of Soft Body

• Underactuated system from the quadrotor

fexible bodies

Determinaton of relevant visual features and related

interacton matrix

while performing the cable shaping task

where *L* is the cable length

horizontale sono control di un or vertecali all'antico di un or vertecali all'antico di un or vertecali all'an
District di un originale di un

*D*b = *L* the eigenvalues *ⁱ* of the symmetric part of

confguratons *s*⇤, which guarantees convergence of *e* and regardless of what *D >* b 0 used, ³ *>* 0 always

 \mathcal{A} $f_{\rm eff}$ task. Furthermore, given the Lyapunov μ

ⁱ) = log(*^T* ¹

ⁱ Tmi

Dynamics model of the Cosserat body (*strain-* $\frac{1}{2}$
based parameterization): **Dynamics model of the Cosserat body** (strain-Dynamics model of the Cosserat body (s $U(s)$ based parametrization-based parametrization-based parameterization-based parameterization-based parameterization-based parameterization-based parameterization-based parameterization-based parameterization-based para **i** of the Cosserat body (*strain ^M*⁰⁰ *^M*0✏*M*✏⁰ *^M*✏✏ ⌘˙⁰

ⁱ)(Ad*^T* err

ⁱ ⌘*mi* ⌘*i*)

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

Consider sof body a sequence of rigid cross-sectons

Z*s*

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كان التي تحت التي ت Automation, ICRA 23, pp. 734-740, London, UK, May 2023.

adrotor L. Smolentsev, A. Krupa, F. Chaumette. Shape visual servoing of a cable

suspended between two drones. IEEE Robotics and Automation Letters L. Smolentsev, A. Krupa, F. Chaumette. Shape visual servoing of a cable
suspended between two drones. IEEE Robotics and Automation Letters
(also precented at IEEE/PSLInt. Conf. IPOS 2025). To appear 2024 suspended between two drones. IEEE Robotics and Automation Let
(also presented at IEEE/RSJ Int. Conf. IROS 2025), To appear 2024. , Damien Six¹ \ddot{a} $5₁$
	- $\frac{1}{2}$ and $\frac{1}{2}$ are presenced at REE, Assume communications (supplem ESE).
The University of Rennes, March 2024. University of Rennes, March 2024.
E. Boyer, A. Gotolli, B. Tompel, V. Lobastard, E. Boy *x*-p-carron *x*
ighly coupled and non-linear system due to the luminority e visual s $\mathcal{O}(\mathcal{O}(\log n))$
		- F. Boyer, A. Gotelli, P. Tempel, V. Lebastard, F. Renda, S. Briot. Implicit
time interesting simulation of relate with rigid bodies and Cosessat rede time integration simulation of robots with rigid bodies and Cosserat rods based on a Newton-Euler recursive algorithm. IEEE Transactions on Robotics, vol. 40, no. 1, pp. 677-696, 2024. the gravity vector **In frame in the proper** given by the base of the base **Project: MAMBO WP 2: Control of Underactuated Systems with Soft Bodies and Vision-Based Control** versity of Rennes, March 2024.
oyer, A. Gotelli, P. Tempel, V. Lebastard, F. Renda, S. Briot. Implicit based on a Newton-Euler recursive algorithm. IEEE Transactions
Robotics, vol. 40, no. 1, pp. 677-696, 2024. *botics, vol. 40, no. 1, pp. 677-696, 2024.*

Methodology two drones

physical sof body

Implement simulator of fexible body under acton of

Design control approach to manipulate body into shape

, Sédan Briot_{ien} Briot_{ien} Briot_{ien} Briot_{ien}
Briot_{ien} Briot_{ien}

Consider sof body a sequence of rigid cross-sectons

Controller

Controller

Manipulator

or

 \overline{a}

 $\overline{ }$

WP 1: Mechanical Design of Soft Bodies and State Estimation Infnite number of DoFs in a sof body drone from visual features Projecton of cable pointcloud into *^F^t* using *bmH*b*^c* and WP 1: Mechanical Design of Soft Bodies and State Estimation with the drone that is extracted that is extracted t odometry *^x*ˆ*bm, ^R*ˆ*bm* and tracked from RGB-D data. the parabola that represents the tether has as coordinates: **WP 1: Mechanical Design of Soft Bodies and State Estimation WP 1: Mechanical Design of Soft Bodies and State Estimation** physical sof body *^e*˙*ⁱ* ⁼ Dlog(*^T* err ediac and Ctato Ectimation

 \Box Eqministration

2. Control of underactuated systems with sof bodies and

vision-based control 3. Experimental validaton

state estmaton

Implemented a simulaton framework for rapid

using a fexible body