Lecture Notes in Networks and Systems 978

Lino Marques · Cristina Santos ·
José Luís Lima · Danilo Tardioli ·
Manuel Ferre *Editors*

# Robot 2023: Sixth Iberian Robotics Conference

## Advances in Robotics, Volume 2

Springer

# Lecture Notes in Networks and Systems

# 978

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Editors

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## Advances in Robotics, Volume 2

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# Preface

This book contains a selection of papers accepted for presentation and discussion at ROBOT2023, the Sixth Iberian Robotics Conference, held in Coimbra, Portugal, during November 22–24, 2023. ROBOT2023 is part of a series of conferences that are jointly organized by Sociedade Portuguesa de Robótica (SPR)/Portuguese Society for Robotics and by Sociedad Española para la Investigación y Desarrollo en Robótica (SEIDROB)/Spanish Society for Research and Development in Robotics. The conference organization had also the collaboration of several universities and research institutes, including Institute for Systems and Robotics, University of Coimbra (ISR-UC); Polytechnic Institute of Bragança; University of Minho; University of Zaragoza; and Universidad Politécnica de Madrid.

ROBOT2023 builds on several previous events held in Zaragoza 2022, Porto 2019, Seville 2017, Lisbon 2015, and Madrid in 2013. The conference is focused on presenting research results, new developments, and applications in the field of Robotics in the Iberian Peninsula, although open to contributions from all over the world. ROBOT2023 featured four plenary talks on state-of-the-art subjects on robotics, the first one by **Paloma de la Puente** from the Universidad Politécnica de Madrid, Spain, on “Understanding the environment and the users: towards mobile robot navigation and interaction in the real world”, followed by **Denis Fernando Wolf** from the University of São Paulo, Brazil, on “Intelligent Vehicles: from autonomy to interaction”; **António Pedro Aguiar** from the University of Porto, Portugal, on “Model based control design combining Lyapunov and optimization tools to empower trusted autonomy of robotic vehicles”; and **Sven Behnke** from the University of Bonn, Germany, on “From Intuitive Immersive Telepresence Systems to Conscious Service Robots”.

ROBOT2023 included ninety scientific papers presented in fourteen thematic sessions organized in three parallel tracks. Some of these were Special Sessions organized by members of the Program Committee, to whom we are thankful for their hard work by promoting the conference and helping to make it a successful event. We also express our gratitude to the members of all the Program Committees and additional reviewers, as they were crucial for ensuring the high scientific quality of the event and to all the authors and delegates that, with their research work and participation, made this event a huge success.

Finally, we would like to express our gratitude to the local organization members, Sedat Dogru, Paulo Menezes, Cristiano Premebida, Hélder Araújo, Dylan Denizon, Vera

Baptista, and João Leite, for their hard and valuable work on the local arrangements, publicity, proceedings publication, financial issues, and website management.

November 2023

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# Aerial Robotics

# Control Framework for Take-Off of UAVs with Suspended Load in Pipeline Inspection

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**Abstract.** This paper presents a control framework for the retrieval operation of an inspection crawler from a pipeline, using an UAV (Unmanned Aerial Vehicle) with a cable. The inspection crawler inspects the pipeline until it is retrieved using the UAV with a cable. In order to create this control framework, the task has been divided in two different phases: the tethered UAV phase and the flight of the UAV with a suspended load. For each phase, we study the dynamic and we propose a specific controller. The control framework is composed of a controller obtained using the feedback linearization technique for the tethered phase, while the controller of the second phase is based on an IDA-PBC (Interconnection and Damping Assignment-Passivity Based Control) controller. The proposed control framework is validated through simulations in *Matlab-Simulink*, showing that the UAV can properly recover the inspection crawler from the pipeline and stabilizes with the crawler as a suspended load at a new position.

**Keywords:** Pipe inspection · Control Framework · Multirotors

## 1 Introduction

The development of UAVs (Unmanned Aerial Vehicles) in recent years has been driven by the wide variety of applications they offer [10,12], allowing to carry out tasks more efficiently than traditional methods. The rise of these aerial robots is due to their mechanical simplicity, their ability to reach places that were previously inaccessible or reduce considerably the risk. The fact that they are light and inexpensive makes them even more attractive. Some of these new applications are infrastructure inspections [5], inspections in industrial plants [2], search and rescue tasks [14], maintenance of bridges [13], turbines [4] or high-voltage cables [7] and pipeline inspections [8].

In the case of pipelines, refineries and industrial oil and gas plants have hundreds of meters of pipelines, which are exposed to corrosion and possible spills. These failures within an industrial plant, if consolidated, could cause fatal errors. In addition, these pipes can be located in risky places for humans. Hence,

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the use of UAVs proposes a new solution for pipeline inspections, offering a more efficient and faster way than traditional methods (crane, scaffolding, harness, ...), allowing companies to save time and money.

The solutions proposed involve an UAV that flies to the pipeline, where it is able to land thanks to a landing gear. It also has a system that allows to glide or roll along the pipeline and finally take off again once the mission is over. All this, with the needed sensors for the pipe inspection, allows to carry out the inspection properly, in search of faults or defects due to corrosion. This is the solution addressed in the HYFLIER project [9,18], being the MHYRO (Modular HYbrid RObot) [8], one of the examples of drones that flies to the pipeline, lands and moves along it. This robot has a built-in robotic arm with 3 DoFs (Degrees Of Freedom) thanks to its joints. The robotic arm is made of lightweight materials and acts once the multirotor has landed to facilitate the operation. Moreover, the MHYRO can also land on one or more pipes depending on the landing gear added to it. Thus, it has a crawler type landing gear that is used to land on a single pipeline, while a roller type landing gear is used to land on several pipelines that are not too far apart.

However, this solution presents certain problems, since it is a single aerial robot that performs the entire mission, both the take-off and the inspection, including the landing and movement on the pipeline. Due to this, limitations arise in terms of time of use, since the flight time limits the effective use of the UAV during the inspection. The batteries attached to the drone do not provide sufficient battery life to carry out inspections over the hundreds of meters that industrial plants possess. The first and simplest solution would be either to add more batteries or to make the batteries larger. However, the weight of the batteries already constitutes a high percentage of the total weight of the UAV, so it is not desirable to increase it further. Moreover, adding batteries would increase not only the weight but also the cost of the drone.

To deal with this problem, we propose a new solution based on a drone that transports a crawler thanks to a cable that joins them together. In this way, the UAV will take the crawler to the pipeline, depositing it on top of the pipeline. Then, the robotic crawler inspects the pipeline looking for faults or defects thanks to the sensors installed. After the inspection, the drone approaches the pipeline, deploys again the cable and take the crawler from the pipeline. In this work, we present the control framework for performing this new solution. This control framework is divided in two phase: the stabilization with certain angle of the UAV tethered with the crawler, and the flight with the crawler as a suspended load.

The rest of the paper is organized as follows. Firstly, the solution given to this problem is outlined in Sect. 2. Section 3 presents the dynamics of the system. Section 4 explains the control strategy used during the take-off. Section 5 validates the proposed control framework with simulations. Finally, Sect. 6 summarizes the conclusions of the work.

## 2 Problem Statement

The proposed solution of this work combines two applications of aerial robots: the transport of materials and the inspection of pipelines in industrial plants or refineries. Normally, these pipelines must be checked with high frequency to avoid possible catastrophes, which added to the large lengths of the pipelines makes human inspection of them totally inefficient. Not only because of the time it takes to carry out these checks, but also because the worker's life is put at risk.

The proposed solution is composed of a crawler and an UAV, that can be connected together with a cable. The robotic crawler can move along the pipeline, and it mounts all the sensors for performing the inspection, such as PEC (Pulsed Eddy Current) sensor or XR (X-Ray) sensor. For doing the pipeline inspection, the UAV takes off with the crawler attached to it through a cable. Then, the UAV release the robotic crawler on the pipeline. The robotic crawler moves along the pipelines and perform the inspection using its onboard sensors. When the inspection is finished, the UAV goes to pick up the crawler where it is located. For taking it, the UAV will use a cable that attaches the crawler, using for that a magnetic device or similar. Finally, the UAV takes off with the crawler attached as a suspended load. Figure 1 shows a schematic of the proposed solution, including all phases of the operation.

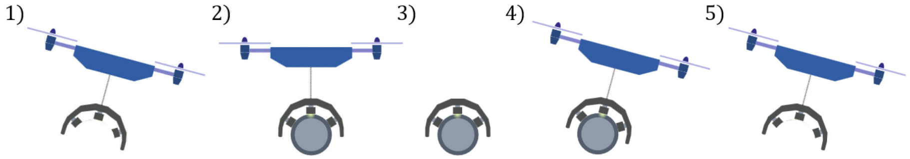


**Fig. 1.** Schematic of the operation: 1) Flight with UAV 2) Deployment of the crawler 3) Pipeline inspection with the crawler 4) Cable connection with the crawler 5) Take-off and flight with the crawler as a suspended load.

This work is focused on the control side of this operation, which poses several challenges. First, having the crawler suspended with a cable makes the UAV flight difficult as the center of gravity of the system is continuously displaced, which can destabilize the system. Because of this, traditional UAV controllers are not suitable for this type of flight. Then, as pipelines in refineries has others elements (pipelines, tanks, walls,..) in its proximity, the UAV may not be able to take-off from the pipe in the vertical direction with the crawler. Because of this, it is necessary to stabilize the UAV tethered to the crawler at a specific angle prior to takeoff. Figure 2 shows this limitation and the need for inclined take-off.

We focus on the stabilization of the tether UAV connected with the crawler and in the take-off with the crawler as a suspended load, as are the most challenging phases. We propose for each phase a controller that can deal with the challenges of the phase. In this work, we study the problem in the XZ plane.

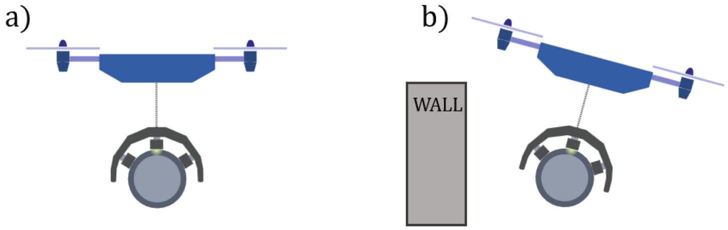


**Fig. 2.** UAV attached to the crawler before taking-off: a) the UAV can take off in the vertical direction (90°) and b) the UAV has to take off with a 60° angle due to the proximity of the wall.

# 3 Dynamics

## 3.1 Tethered UAV

In this stage, the drone is attached to the crawler with a cable, while the crawler keeps the contact with the pipe through a claw or magnetic devices. In order to take-off from the pipeline, the UAV can be stabilized with a certain angle to avoid possible collisions with the surroundings, as shown in Fig. 2. In this phase, the system has 2 DoFs (Degrees of Freedom), which are the pitch angle $\theta$ and the elevation angle of the cable $\varphi$. The dynamic equations for this phase are the following [15]:

$$ML\ddot{\varphi} = -Mg\cos\varphi + f_R\cos(\varphi + \theta) \tag{1a}$$

$$J\ddot{\theta} = \tau_R \tag{1b}$$

$$f_L = -Mg\sin\varphi + f_R\sin(\varphi + \theta) + ML\dot{\varphi}^2 \tag{1c}$$

where $M$ is the UAV mass, $J$ is the UAV inertia, $L$ is the length of the cable and $g$ is the gravity. In addition, the control force and torque of the UAV are represented with $f_R$ and $\tau_R$ respectively, while $f_L$ represents the tension force of the cable. All these variables are shown in Fig. 3.

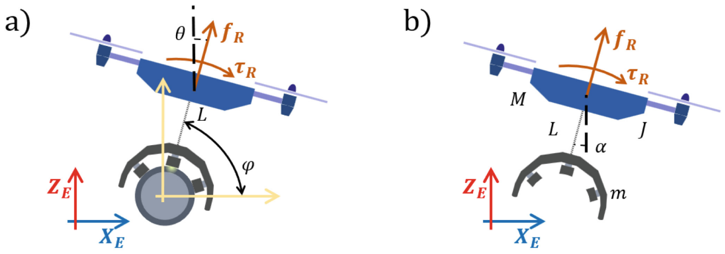


**Fig. 3.** Variables of the model: a) tethered UAV and b) UAV with suspended crawler.

### 3.2 UAV with Suspended Crawler

In the second stage of the task, the UAV transports the crawler suspended from a cable. To simplify the problem, we consider the cable inextensible and the crawler is assumed as a point mass. In this case, the system has 4 DoFs, which are the 2D position of the UAV $x$ and $z$, the pitch angle $\theta$ and the angle of the cable $\alpha$, as Fig. 3 shows. Using the Euler-Lagrange equations [3], the dynamic equations of the system remain:

$$
\begin{aligned}
-f_R \sin\theta &= (M+m)\ddot{x} + mL(\ddot{\alpha}\cos\alpha - \dot{\alpha}^2 \sin\alpha) && \text{(2a)}\\
f_R \cos\theta &= (M+m)\ddot{z} + mL(\ddot{\alpha}\sin\alpha + \dot{\alpha}^2 \cos\alpha) + (M+m)g && \text{(2b)}\\
\tau_R &= J\ddot{\theta} && \text{(2c)}\\
0 &= L\ddot{\alpha} + \ddot{x}\cos\alpha + \ddot{z}\sin\alpha + g\sin\alpha && \text{(2d)}
\end{aligned}
$$

where $M$ is the UAV mass, $J$ is the UAV inertia, $m$ is the crawler mass, $L$ is the cable length and $g$ is the gravity. In addition, $f_R$ is the control force and $\tau_R$ is the control torque applied by the UAV. These dynamics equations will allow to work on the controller of the system during the task.

## 4 Control

### 4.1 Tethered UAV

In order to control the elevation angle $\varphi$ and the force on the cable $f_L$ in the first phase, a feedback linearization [6] is applied to the system. This technique allows to convert a non-linear dynamics system into a linear and decoupled dynamics system, so that linear control techniques can be applied. This is carried out by canceling the non-linear terms, allowing the closed-loop system to be linear.

This control strategy allows $(\varphi,\ f_L)$ to follow the trajectories $(\varphi^d,\ f_L^d)$. To achieve this, the state vector is defined as $\mathbf{x}=[\varphi,\ \dot{\varphi},\ \theta,\ \dot{\theta}]^T=[x_1, x_2, x_3, x_4]^T$, the input vector as $\mathbf{u}=[f_R,\ \tau_R]^T=[u_1, u_2]^T$ and the output vector $\mathbf{y}=[\varphi, f_L]^T = [y_1, y_2]^T$ [15–17]. The dynamics of the system is now rewritten as:

$$
\begin{aligned}
\dot{x}_1 &= x_2 && \text{(3a)}\\
\dot{x}_2 &= a_1\cos(x_1) + a_2\cos(x_1+x_3)u_1 && \text{(3b)}\\
\dot{x}_3 &= x_4 && \text{(3c)}\\
\dot{x}_4 &= a_3 u_2 && \text{(3d)}
\end{aligned}
$$

where $a_1 = -g/L$, $a_2 = 1/(ML)$, $a_3 = 1/J$. The first approach of this technique gives the following matrix equation for the output vector:

$$
\begin{bmatrix} y_1^{(II)} \\ y_2 \end{bmatrix} = \begin{bmatrix} a_1\cos x_1 \\ MLx_2^2 - Mg\sin x_1 \end{bmatrix} + \underbrace{\begin{bmatrix} a_2\cos(x_1+x_3) & 0 \\ \sin(x_1+x_3) & 0 \end{bmatrix}}_{\mathbf{E}[\mathbf{x}]} \mathbf{u} \tag{4}
$$

However, the decoupling matrix $\mathbf{E}[\mathbf{x}]$ is not invertible, as $u_2$ does not appear in the equations. To deal with this problem, we differentiate the equations twice. In this case, the state vector is modified, considering the thrust and its derivative, resulting in $\overline{\mathbf{x}}=[\varphi,\ \dot{\varphi},\ \theta,\ \dot{\theta},\ u_1,\ \dot{u}_1]^T$, and the control vector $\overline{u} = [\ddot{u}_1, u_2]^T = [\overline{u}_1, \overline{u}_2]^T$, where $\ddot{u}_1 = \ddot{f}_R$. Doing this, we have:

$$\begin{bmatrix} y_1^{(IV)} \\ y_2^{(II)} \end{bmatrix} = \mathbf{b}(\overline{\mathbf{x}}) + \underbrace{\begin{bmatrix} a_2\cos(x_1+x_3) & -a_2a_3\sin(x_1+x_3)u_1 \\ \sin(x_1+x_3) & a_3\cos(x_1+x_3)u_1 \end{bmatrix}}_{\overline{\mathbf{E}}[\overline{\mathbf{x}}]} \overline{\mathbf{u}} \tag{5}$$

where the new decoupling matrix $\overline{\mathbf{E}}[\overline{\mathbf{x}}]$ is now invertible. Finally the following control action is obtained as:

$$\overline{\mathbf{u}} = \overline{\mathbf{E}}^{-1}(-\mathbf{b}(\overline{\mathbf{x}}) + \mathbf{v}) \tag{6}$$

where the virtual input vector is $\mathbf{v}=[v_1, v_2]^T$, and $e_1 = y_1^d - y_1$, $e_2 = y_2^d - y_2$ are the errors. Now, the control gains $k_{11}, k_{12}, k_{13}, k_{14}, k_{21}, k_{22}$ can be obtained using linear control techniques.

$$v_1 = y_1^{d(IV)} + k_{11}e_1 + k_{12}e_1^{(I)} + k_{13}e_1^{(II)} + k_{14}e_1^{(III)} \tag{7a}$$

$$v_2 = y_2^{d(II)} + k_{21}e_2 + k_{22}e_2^{(I)} \tag{7b}$$

### 4.2 UAV with Suspended Crawler

During the second phase, to stabilize the UAV while carrying the crawler, a controller following the *Interconnection and Damping Assignment-Passivity Based Control* (IDA-PBC) [11] has been designed. This type of control is useful for stabilizing linear systems through the Hamiltonian, with a closed-loop structure. To carry out the control, the system maintains a passive behavior with respect to a storage function while generating damping. It is an ideal method for systems where the equations of motion are calculated from the Euler-Lagrange method. In this case, the storage function will be the swing angle $\alpha$ and its value will be minimized, due to this, it will not appear on the control expressions.

The IDA-PBC strategy is then applied to the system, minimizing the cable twist angle. The *Hamiltonian* of the system is expressed as:

$$H(q,p) = \frac{1}{2}p^T M_d^{-1}(q)p + V_d(q) \tag{8}$$

where $M_d$ is a symmetric matrix defined positive, known as the inertia matrix in the closed loop, and the matrix $V_d$ represents the potential energy of the system, which must have a minimum known as $q_* = \text{argmin}\ V_d(q)$. As it is usual in PBC control systems, the inputs are decomposed as:

$$u = u_{es}(q,p) + u_{di}(q,p) \tag{9}$$

The first term $u_{es}(q,p)$ is in charge of reaching the desired energy, known as the energy shaping, while the second $u_{di}(q,p)$ will introduce damping into the system, and it is known as damping injector. Finally, after applying the steps developed on [3] the control expressions used are the following:

$$f_R = -K_b\dot{x} - K_d\dot{z} - K_e\dot{\theta} + (M+m)g - K_{pz}(z - z^d) \tag{10a}$$

$$\tau_R = -(K_a + K_c)\dot{x} - (K_b + K_e)\dot{z} - (K_c + K_f)\dot{\theta} - K_{px}(x - x^d) - K_{p\theta}(\theta - \theta^d) \tag{10b}$$

where the different constants $K_i$ are the control gains.

## 5 Simulations

The aerial robot chosen to perform the task is a quadrotor and its specifications are presented in the Table 1. The control gains have been adjusted to guarantee the control of an UAV with these characteristics. During the simulations, we suppose that the UAV is attached to the crawler with the cable, so it can start directly in the stabilization phase as tethered UAV. The simulations have been performed in *Matlab-Simulink*, and the videos of the simulations are available in [1].

**Table 1.** UAV and crawler variables.

| Variable | Symbol | Value |
|---|---|---|
| UAV mass | M | 4 kg |
| UAV inertia | J | 0.25 kg m$^2$ |
| Cable length | L | 1 m |
| Crawler mass | m | 0.6 kg |

In order to validate the proposed control framework, we perform two types of simulations: a vertical take-off and a inclined take-off. The vertical take-off corresponds with the retrieval of the robotic crawler from an isolated pipeline, where there is no obstacles close to the UAV, as presented in Fig. 2a. The inclined take-off corresponds with the retrieval of the crawler from a pipeline with obstacles in its surroundings, as Fig. 2b shows.

In the vertical take-off, the UAV starts with the following initial conditions: $\varphi_0 = 30°$, $\theta_0 = 0°$, where $\varphi$ is the angle between the cable and the horizontal plane and $\theta$ is the UAV pitch angle. During the first phase, the references are $\varphi^d = 90°$ and $f_L^d = 4\ N$, with all derivatives equal to zero. We impose that the UAV achieve these references in 5 s. After this, the UAV is oriented in the vertical direction, and applying the desired force, as Fig. 4 shows.

Then, in $t = 15\ s$, the crawler detaches from the pipe, starting the second phase of the task. In this phase, the references are $X^d = 2\ m$ and $Z^d = 5\ m$. As Fig. 4 shows, the UAV can reach the desired position, having some oscillations of the suspended crawler. Finally, Fig. 5a shows the 2D trajectory followed by

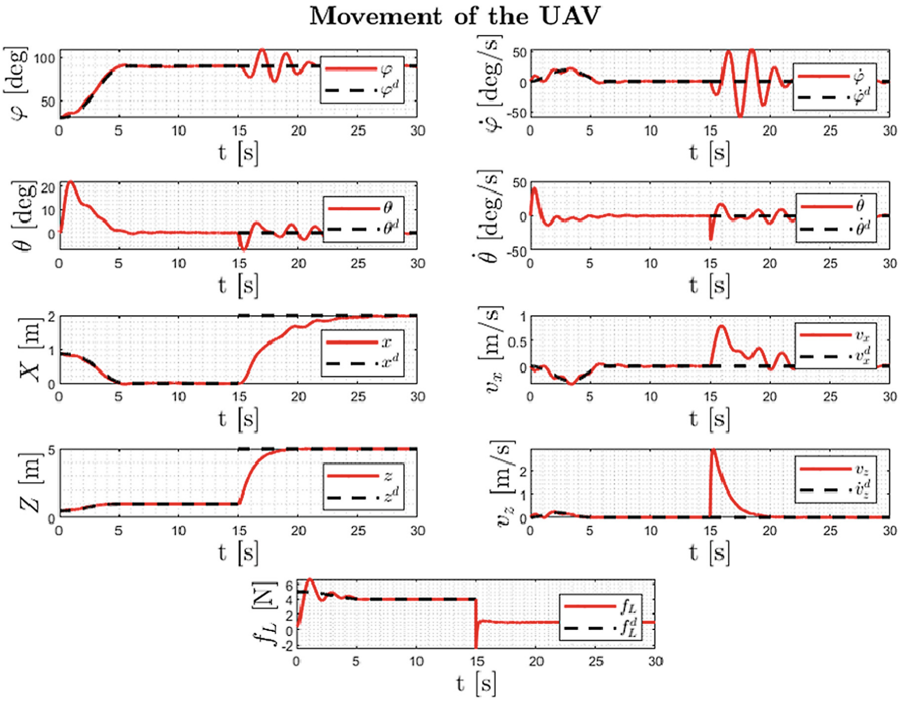
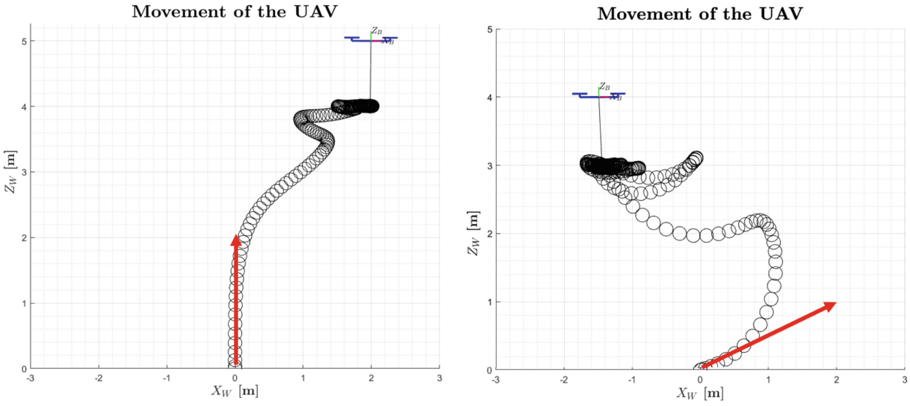


**Fig. 4.** Results of the vertical take-off. The initial conditions are $\varphi_0 = 30^\circ$, $\theta_0 = 0^\circ$, while the references for the first phase are $\varphi^d = 90^\circ$ and $f_L^d = 4\ N$ and for the second phase are $X^d = 2\ m$ and $Z^d = 5\ m$.



(a) Vertical take-off

(b) Inclined take-off

**Fig. 5.** 2D trajectory followed by the robotic crawler in both simulations.

the crawler, marked as black circles, while the initial orientation is marked as a red arrow.

For the second case, the tilted take-off, the UAV starts with the following initial conditions $\varphi_0 = 90°$ and $\theta_0 = 0°$. During the stabilization phase of the tethered UAV, the references are $\varphi^d = 45°$ and $f_L^d = 1\ N$. We can see as the elevation is now $\varphi^d = 45°$, as the UAV will take-off in a tilted direction in order to avoid possible collisions with the surroundings, as Fig. 2b shows. The UAV achieves these values in $t = 5\ s$, while in $t = 15\ s$ the second phase starts.

In the second phase of the task, the UAV flies with the crawler as a suspended load with references $X^d = -1.5\ m$ and $Z^d = 4\ m$. As Fig. 6 shows, the UAV converges to the reference position, despite the oscillations of the crawler. In addition, Fig. 5b shows the 2D trajectory followed by the crawler, marked as black circles, while the initial orientation is marked as a red arrow.

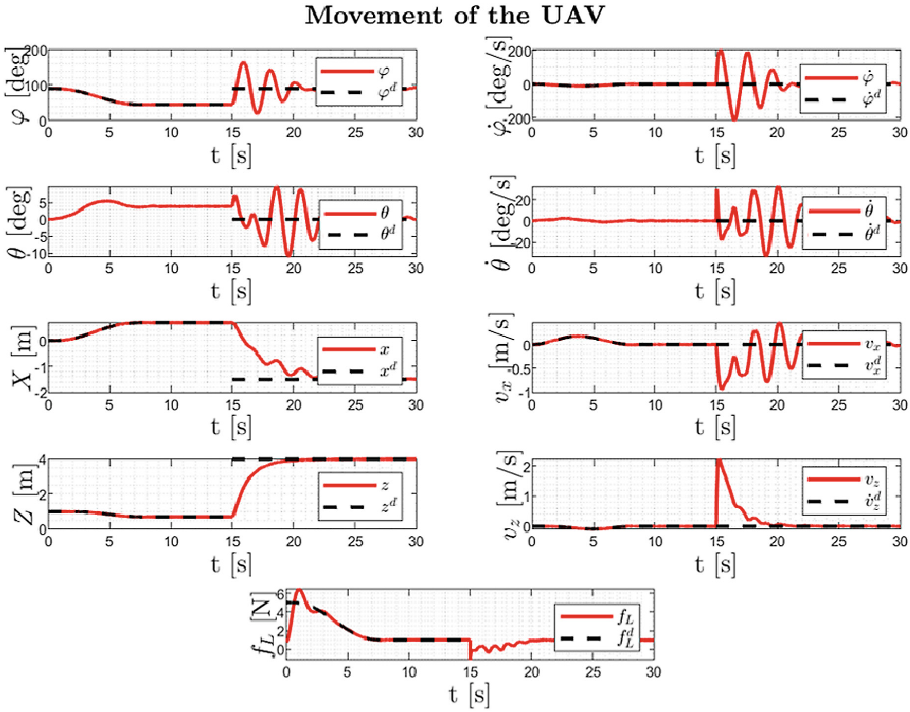


**Fig. 6.** Results of the tilted take-off. The initial conditions are $\varphi_0 = 90°$ and $\theta_0 = 0°$, while the references for the first phase are $\varphi^d = 45°$ and $f_L^d = 1\ N$ and for the second phase are $X^d = -1.5\ m$ and $Z^d = 4\ m$.

## 6 Conclusion

This paper has presented a control framework to an alternative solution for pipe inspections with UAVs. After a first approach to solve the problem with UAVs such as the MHYRO [8], our solution divides the task between two robots, an UAV and a robotic crawler. The UAV is assumed to be able to fly and deploy the crawler over the pipeline, which can slide along the pipelines. This work has proposed a control framework for the retrieval of the crawler from the pipeline with the UAV, which is a challenging task. The control framework is composed of two different controllers. The first controller, obtained through feedback linearization, stabilizes the UAV attached to the crawler. The second controller, obtained through IDA-PBC, minimizes the oscillations during the flight with the crawler as a suspended load. The control framework has been validated with simulations, showing that the UAV can perform properly the retrieval of the crawler from the pipe in the 2D case.

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