Human Physical Guidance by a Tethered Aerial Vehicle

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***Abstract*— Today, physical Human-Robot Interaction (pHRI) is a very popular topic in the field of ground manipulation. At the same time, Aerial Physical Interaction (APhI) is also developing very fast. Nevertheless, pHRI with aerial vehicles has not been addressed so far. In this work, we present the study of one of the first systems in which a human is physically connected to an aerial vehicle by a cable. We want the robot to be able to pull the human toward a desired position (or along a path) only using forces as an indirect communication-channel. We propose an admittance-based approach that makes pHRI safe. A controller, inspired by the literature on flexible manipulators, computes the desired interaction forces that properly guide the human. The stability of the system is formally proved with a Lyapunov-based argument. external disturbances. The global method has been experimentally validated showing a reliable and safe pHRI.**

I. Full-version

A full version of this work is available at `https://arxiv.org/abs/2005.06760`. If you wish to reference this work, please cite the full version [1].

II. Introduction

Aerial robotics is one of the research fields receiving a constantly growing interest. This is motivated by the very wide range of applications which *Unmanned Aerial Vehicles* (UAVs) could be useful for. Popular examples are monitoring, surveillance, agriculture and many others. Beyond these contact-free applications, many investments and efforts have been recently dedicated to *Aerial Physical Interaction* (APhI) [2]. Thanks to the several proposed platforms and control methods, the feasibility of physical interaction with aerial robots has been shown for different tasks like pushing and sliding [3], transportation [4], etc.

With the advance of aerial robotics, the presence of such robots in our daily life will grow as well. This means that the next generation of aerial robots must be able to safely and reliably interact with the environment, but also with humans. So far, *Human-Robot Interaction* (HRI), and in particular *physical Human-Robot Interaction* (pHRI) has been rarely addressed in the aerial robotics community.

To advance the study of pHRI methods for aerial robots, in this work we face one of the first systems in which a human and an aerial robot are tightly coupled by a physical means. In particular, we consider a human holding a handle which is in turn connected to an aerial vehicle by a cable (see Fig. 1). In this work, we design a control strategy that allows the robot to safely "physically guide" the human toward a desired position (or along a predefined path) exploiting the cable as a force-based communication means.

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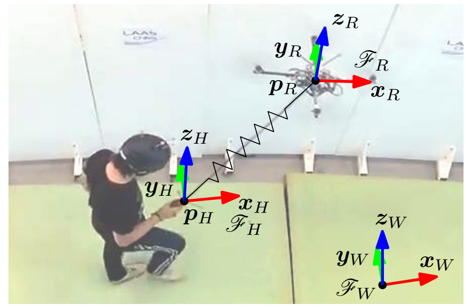

Fig. 1: Representation of the aerial human-tethered guiding system.

Inspired by the extensive literature of pHRI for ground manipulators, we firstly propose the use of an *admittance-based strategy* to make the robot comply with the human. We show that exploiting this approach we can impose a desired cable force that has the function to pull the human toward the desired point.

III. Modeling

The system here analyzed (see Fig. 1) is composed of an aerial vehicle tethered by a cable to a handle held by the hand of a human. We consider the position of the human as the position of his/her hand holding the handle. For the sake of designing a human-friendly robot controller, we approximate the human behavior as a mass-spring-damper system

$$m_H \dot{\boldsymbol{v}}_H = -\boldsymbol{g}_H - \boldsymbol{B}_H \boldsymbol{v}_H + \boldsymbol{f}_c + \boldsymbol{f}_g, \tag{1}$$

where $\boldsymbol{v}_H \in \mathbb{R}^3$ is the linear velocity (derivative of the position, $\boldsymbol{p}_H \in \mathbb{R}^3$); $m_H \in \mathbb{R}_{>0}$ and the positive definite matrix $\boldsymbol{B}_H \in \mathbb{R}^{3\times 3}_{>0}$ are the apparent mass and damping, respectively; $\boldsymbol{f}_c = [f_{cx}\ \ f_{cy}\ \ f_{cz}]^\top \in \mathbb{R}^3$ is the cable force applied to the human; $\boldsymbol{g}_H = m_H g \boldsymbol{z}_W$; $g \in \mathbb{R}_{>0}$ is the gravitational constant; $\boldsymbol{f}_g$ is the ground reaction force.

The cable is attached from one side to the handle, and to the other side to the aerial vehicle CoM. We assume that the robot is controlled by a position controller able to track any C^2 trajectory with negligible error in the domain of interest, independently from external disturbances. The closed-loop translational dynamics of the robot subject to the position controller is assumed as the one of a double integrator $\dot{\boldsymbol{v}}_R = \boldsymbol{u}_R$, where $\boldsymbol{v}_R \in \mathbb{R}^3$ is the linear velocity (time derivative of the robot position, $\boldsymbol{p}_R$), and $\boldsymbol{u}_R \in \mathbb{R}^3$ is a virtual input to be designed.

Afterward, we model the cable that connects the aerial vehicle and the handle, or equivalently the human hand, as a unilateral spring along its principal direction. We define the cable force produced at the handle as $\boldsymbol{f}_c = t_c(\|\boldsymbol{l}_c\|)\boldsymbol{l}_c/\|\boldsymbol{l}_c\|$,

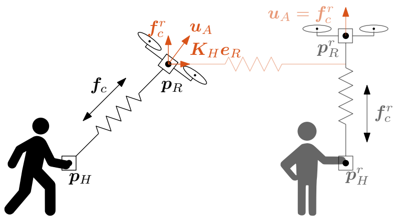

Fig. 2: Working principle of the control method. On the left the current state, on the right in opaque, the final desired state.

where $t_c(\|\boldsymbol{l}_c\|)$ represents the cable internal force intensity and $\boldsymbol{l}_c = \boldsymbol{p}_R - \boldsymbol{p}_H$. In particular, $t_c(\|\boldsymbol{l}_c\|)$ is defined as:

$$t_c(\|\boldsymbol{l}_c\|) = \begin{cases} k_c(\|\boldsymbol{l}_c\| - \bar{l}_c) & \text{if } \|\boldsymbol{l}_c\| - \bar{l}_c > 0 \\ \boldsymbol{0} & \text{otherwise} \end{cases}, \tag{2}$$

where $k_c \in \mathbb{R}_{>0}$ is the constant elastic coefficient.

IV. Control Method

For pHRI, and more in general for physical interaction problems, a common solution consists of using an *admittance control strategy*. We define the robot control input $\boldsymbol{u}_R$ as:

$$\boldsymbol{u}_R = \boldsymbol{M}_A^{-1}\left(-\boldsymbol{B}_A\boldsymbol{v}_R - \boldsymbol{f}_c + \boldsymbol{u}_A\right), \tag{3}$$

where the two positive definite diagonal matrices $\boldsymbol{M}_A, \boldsymbol{B}_A \in \mathbb{R}^{3\times3}$ are the virtual inertia and damping of the robot. $\boldsymbol{u}_A \in \mathbb{R}^3$ is an additional input that will be defined in the following in order to achieve the desired control goal.

Looking at the system dynamics when the cable is taut, it appears to be a couple of mass-damper elements connected by a spring. This system is similar to an elastic manipulator for which the most preferred and grounded solution is to apply a feedback completely based on the motor variables. Thus, we set:

$$\boldsymbol{u}_A = \boldsymbol{K}_H\boldsymbol{e}_R + \boldsymbol{f}_c^r, \tag{4}$$

where $\boldsymbol{K}_H = \mathrm{diag}(k_H, k_H, 0)$ with $k_H \in \mathbb{R}_{>0}$, $\boldsymbol{e}_R = \boldsymbol{p}_R^r - \boldsymbol{p}_R$ is the robot position error, $\boldsymbol{p}_R^r$ is the robot position of reference, and $\boldsymbol{f}_c^r \in \mathbb{R}^3$ is a constant forcing input. In practice, $\boldsymbol{f}_c^r$ is the desired cable force. Figure 2 explains the working principle of the controller.

Given a human position reference $\boldsymbol{p}_H^r \in \mathbb{R}^3$, we can show through Lyapunov theory that, under the controller (4) where

$$\boldsymbol{f}_c^r = f_z\boldsymbol{z}_W \tag{5}$$

$$\boldsymbol{p}_R^r = \boldsymbol{p}_H^r + \boldsymbol{f}_c^r\left(\frac{1}{k_c} + \frac{\bar{l}_c}{\|\boldsymbol{f}_c^r\|}\right), \tag{6}$$

the human position asymptotically converges to $\boldsymbol{p}_H^r$. Furthermore, we can also show that the system is passive, which guarantees the intrinsic robustness of the controller against time-varying position references and possible additional human forces (e.g., if he/she wants to stop).

V. Experimental Validation

The experiment is divided into three phases (see Fig. 3):

Ph.1 The human stays in a safe place. The robot takes off and goes into an initial point in position-mode to let the human safely grab the handle;

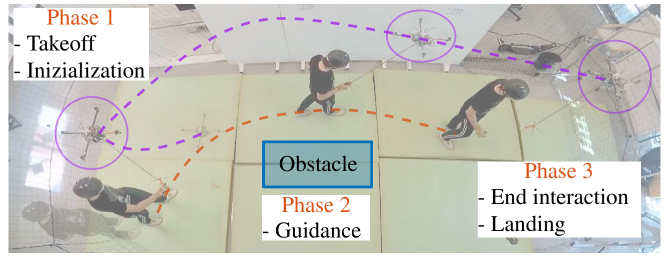

Fig. 3: Representation of the experimental phases. On each snapshot the robot is highlighted with a purple circle. Robot and human trajectories are marked with purple and blue dashed lines, respectively.

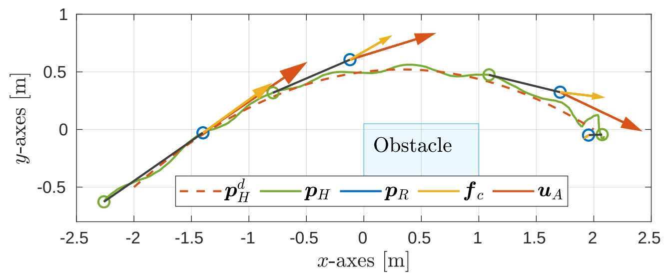

Fig. 4: The desired and actual human path showed in the x-y plane. Four schematic representation of the system are shown.

Ph.2 Once the human holds the handle, the proposed guiding control is activated;

Ph.3 Once the human reaches the final position, the robot will be vertically placed on top of the handle. The human does not feel any horizontal pulling force and can release the handle.

In Fig. 4, we report the results obtained with one participant to the experimental campaign. We remark that the human position error is always below 5 [cm]. Although the error is quite small, what is more important is that the stability of the interaction is always guaranteed, even though the human applies non-zero forces. A video of the experiment is available at `https://medihal.archives-ouvertes.fr/hal-02594623`.

VI. Conclusions

In this manuscript, a system composed by a human *physically connected* to an aerial vehicle as been studied for the fist time. We proposed a control strategy that makes the robot compliant to the human-interaction and allows to exert forces to the human that drive him/her to a desired position.

References

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