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Physical Human-Robot Interaction With a Tethered Aerial Vehicle: Application to a Force-Based Human Guiding Problem

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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 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 with a controller, inspired by the literature on flexible manipulators, that computes the desired interaction forces that properly guide the human. The stability of the system is formally proved with a Lyapunov-based argument. The system is also shown to be passive, and thus robust to nonidealities like model and tracking errors, additional human forces, time-varying inputs, and other external disturbances. We also design a maneuver regulation policy to simplify the path following problem. The global method has been experimentally validated on a group of four subjects, showing a reliable and safe pHRI.

Index Terms—Aerial systems, force control, motion control, mechanics and control, physical human-robot interaction (pHRI).

I. INTRODUCTION

AERIAL robotics is one of the research fields receiving a constantly growing interest. This is motivated by the wide range of applications, which unmanned aerial vehicles are useful for, e.g., monitoring, agriculture, etc. Beyond these contact-free applications, many investments and efforts have been recently dedicated to Aerial physical interaction (APhI). Several research labs and companies are conceiving and studying new aerial

robots with manipulation capabilities that can interact with the environment [1].

The research community already proposed several solutions to enhance physical interaction capabilities of aerial vehicles. Examples are rigid tools or articulated arms attached to standard unidirectional-thrust aerial vehicles [2], [3], or to tilted/tiltable multirotor platforms that are fully actuated [4]. These works showed the feasibility of APhI for different tasks like pushing, sliding [5], and transportation, allowing new applications as contact-based inspection [6] and assembly.

It is natural that the presence of such robots in our daily life will grow as well. This requires the next generation of aerial robots to be able to safely and reliably interact with the environment, but also with humans. So far, human-robot interaction (HRI) has been rarely addressed in the aerial robotics community. Most of the works focus on remote control proposing bilateral teleoperation methods to help humans control single and multiple aerial vehicles [7]. Recently, the teleoperation problem has been extended to APhI as well [8].

In these cases, humans and robots are in separate environments and the interaction is only virtual. The study of scenarios where aerial robots share the same environment of humans is still poorly addressed and limited to contactless HRI [9], [10]. Peshkova *et al.* [11] and Cauchard *et al.* [12] proposed a survey on the use of natural communication means like gestures, speech, and gaze direction to let the human interface with the robot.

Another important topic recently explored is the social acceptance of aerial robots [13]. In [14] the problem is addressed from a design point of view, analyzing how the propellers of multirotor platforms affect the comfort of humans. In a different direction, a few papers [15], [16] recently started to investigate the social constraints (distance, speed, direction of approach, etc.) that should be applied to the motion of an aerial robot in the proximity of a human. While human-aware motion planning has been substantially studied for ground robots [17], it is still very preliminary for aerial robots.

Therefore, the works presented so far focus only on contactless HRI for aerial robots. On the other hand, physical human-robot interaction (pHRI) for aerial vehicles is still an unexplored domain. To the best of our knowledge, the only work addressing this topic is [18] where a compliant controller based on an admittance filter is proposed. Compliance with respect to external forces is shown, but the interaction with the human is

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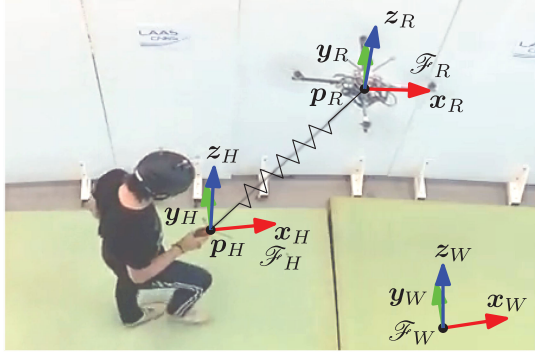


Fig. 1. Representation of the aerial human-tethered guiding system.

limited to simple contacts. The acceptance of touch-based HRI with aerial platforms is studied in [19].

Differently, research done on pHRI with ground manipulators is already quite extensive [20], [21]. Many control methods, most of them based on admittance [22] and passivity-based methods [23], have been proposed.

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 manuscript, we want to 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. Previous works [24]–[26] already showed that *tethered aerial vehicles* are very suitable for APhI. In [27], a complete study and literature review of the modeling and control for tethered aerial vehicles is provided. However, previous solutions cannot be directly applied because they consider the cable always taut. This would limit the validity of the proposed results. On the other hand, the modeling and control designs have been inspired by the study in [28] showing how the force along a cable can be used for cooperative-manipulation as indirect communication means among robotic agents.

The problem of guiding humans by aerial vehicles has indeed been already addressed in the literature but proposing contactless approaches only, e.g., based on sound [29] or vision [30]. In this work, we rather exploit the physical interaction using forces as more direct feedback. This solution particularly suits for persons with visual or hearing limitations. There have been a number of contributions of ground robots guiding humans [31], [32]. However, while they have considered a variety of capabilities to take into account human constraints and a variety of interaction modalities, only a small number of contributions considered pulling mobile robots or walking helpers for assisting elderly [33] or visually impaired people [34], [35]. However, the use of aerial vehicles in physical interaction with humans demands a careful treatment of the interaction forces and the stability of the system.

Inspired by the extensive literature of pHRI for ground manipulators, we first propose the use of an *admittance-based strategy* to make the robot comply with the human. We shall show that

exploiting this approach we can impose a desired cable force that has the function to pull the human toward the desired point. The design of such input requires particular attention due to the flexible nature of the physical link connecting the human to the robot. Taking inspiration from the theory on control of manipulators with elastic joints [36], we design a *robot-feedback solution* together with a feedforward term. The latter enforces the tautness of the cable. Approximating the human behavior as a mass-spring-damper system and considering the overall closed-loop system, we formally prove (though Lyapunov theory) that the proposed control method allows the robot to asymptotically steer the human to the desired position.

We also show that the system is *output-strictly passive*. This guarantees the stability of the system even in case of

- 1) model mismatches, disturbances and tracking errors,
- 2) time-varying reference for the human position, and
- 3) additional forces applied by the human to the cable (e.g., if he/she wants to stop).

This property grants robustness and safety of the method.

To address the problem of path following, we design a *maneuver regulation method* based on the works in [37] and [38]. This avoids the excessive growth of the tracking error which may lead to input saturation and, thus, instability, or too big deviations from the desired path.

The control performance and stability of the system are validated by real experiments first showing (from the best of our knowledge) safe and reliable physical interaction between a human and an aerial vehicle.

The manuscript is organized as follows. In Section II, we model the entire system. In Sections III and IV, we describe the proposed control strategy and we analyze the stability of the closed-loop system. The additional passivity property is shown in Section V. In Section VI, we describe the path following approach. The experimental results are reported in Section VII. Section VIII concludes this article.

II. MODELING

The system (see Fig. 1) is composed of an aerial vehicle tethered by a cable to a handle held by the hand of a human. To describe it, we define an *inertial frame*, $\mathcal{F}_W = \{O_W, x_W, y_W, z_W\}$, where O_W is the arbitrary origin and $\{x_W, y_W, z_W\}$ are its unit axes, with z_W opposite to gravity.

We consider the position of the human as the position of his/her hand holding the handle. A *body frame*, $\mathcal{F}_H = \{O_H, x_H, y_H, z_H\}$, is rigidly attached to the handle. Its origin O_H is centered in the point where the cable is attached to the handle. The state of the human is then given by the position of O_H and its linear velocity, defined by the vectors $\mathbf{p}_H = [p_{Hx} \ p_{Hy} \ p_{Hz}]^T \in \mathbb{R}^3$ and $\mathbf{v}_H = [v_{Hx} \ v_{Hy} \ v_{Hz}]^T \in \mathbb{R}^3$, respectively, both with respect to $\mathcal{F}_W$.

For the sake of designing a human-friendly robot controller, it is important to consider the human’s behavior when interacting with the environment. Ikeura *et al.* [39] analyzed the interaction forces during a task in which two humans cooperatively moves an object. It turned out that, for this kind of task, the human’s dynamics can be approximated with a mass-spring-damper system.

The validity of such a model has been confirmed in other works like [40]. In [41]–[43], this impedance model has been used as a basis to develop human-robot cooperative or teleoperated manipulation tasks. We consider the human's dynamics as

$$m_H \dot{\mathbf{v}}_H = -\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g \quad (1)$$

where $m_H \in \mathbb{R}_{>0}$ and the positive definite matrix $\mathbf{B}_H \in \mathbb{R}_{>0}^{3 \times 3}$ are the mass and apparent damping, respectively; $\mathbf{f}_c = [f_{cx} \ f_{cy} \ f_{cz}]^T \in \mathbb{R}^3$ is the cable force applied to the human at O_H ; $\mathbf{g}_H = m_H g \mathbf{z}_W$; $g \in \mathbb{R}_{>0}$ is the gravitational constant. Without loss of generality, we can assume the ground being flat and horizontal. $\mathbf{f}_g$ is the ground reaction force such that as follows:

- 1) $\mathbf{f}_g^T \mathbf{x}_W = \mathbf{f}_g^T \mathbf{y}_W = 0$;
- 2) $\mathbf{f}_g^T \mathbf{z}_W > 0$;
- 3) $\dot{\mathbf{v}}_H^T \mathbf{z}_W = \mathbf{v}_H^T \mathbf{z}_W = 0$, i.e., the human is constrained on the ground.

It follows that $\mathbf{f}_g = f_g \mathbf{z}_W$, where $f_g \in \mathbb{R}_{\geq 0}$ is the intensity of the reaction force. Notice that it has to be $\mathbf{f}_c^T \mathbf{z}_W < m_H g$. This prevents the human from being lifted by the robot. Practically, this is unfeasible for standard micro aerial vehicles.

The *human mass* m_H models the reactivity of the human to external forces. A low mass means a high willingness of following external forces. For a high mass, it is the opposite. The *damping effect* models the willingness of the human to stay still. Finally, in a mass-spring-damper system, the spring models the desire of reaching a specific point. However, in (1) there is no spring term since, in our scenario, the human is not aware of the desired path. The human simply follows the external force applied by the robot through the cable.

Remark 1: The precise modeling of the human body dynamics is out of the scope of this work. Through model (1), we want to capture only the macro navigation behavior of a human when pulled by an external force.

Remark 2: In this work, we focus on the control of the human hand position rather than his/her head position. This is motivated by the fact that a handle integrating positioning sensors like GPS, IMU, and cameras, is much more comfortable and wearable with respect to a fully equipped helmet. Nevertheless, the use of a kinematic model could be employed to estimate the human's head position if required.

The cable is attached from one side to the handle, and to the other side to the aerial vehicle at point O_R , which coincides with its center of mass. We define the *body frame* $\mathcal{F}_R = \{O_R, \mathbf{x}_R, \mathbf{y}_R, \mathbf{z}_R\}$, rigidly attached to the robot. Its configuration is described by the position of O_R with respect to (w.r.t.) $\mathcal{F}_W$ denoted by the vector $\mathbf{p}_R = [p_{Rx} \ p_{Ry} \ p_{Rz}]^T \in \mathbb{R}^3$. We complete the state of the robot with the linear velocity $\mathbf{v}_R = [v_{Rx} \ v_{Ry} \ v_{Rz}]^T \in \mathbb{R}^3$. We neglect the rotational coordinates and relative velocity since it is not relevant for the following derivations.

We assume that the robot is controlled by a position controller (e.g., MPC or SQP-based [44]), which minimizes the tracking error with respect to a desired C^2 trajectory, considering the full dynamics of the vehicle, its input and state limits, as well as

external disturbances. Thus, we can consider the robot closed-loop translational dynamics as the one of a double integrator plus a tracking error

$$\dot{\mathbf{v}}_R = \mathbf{u}_R + \boldsymbol{\delta} \quad (2)$$

where $\mathbf{u}_R \in \mathbb{R}^3$ is a virtual input to be designed, while $\boldsymbol{\delta} \in \mathbb{R}^3$ is a bounded variable that takes into account all the tracking errors due to model mismatches and uncertainties, input and state limits, external disturbances, and estimation errors. The model (2) means that the robot can track any desired acceleration $\mathbf{u}_R$ with a possibly nonzero error $\boldsymbol{\delta}$. This model is suitable for both multidirectional and unidirectional-thrust platforms. If we consider a multidirectional-thrust platform capable of controlling both position and orientation independently [45], (2) is a very good model of the closed-loop system with $\boldsymbol{\delta}$ very small. It is well known that a unidirectional-thrust vehicle is differentially flat w.r.t. to $\mathbf{p}_R$ and the rotation along the thrust direction (also called yaw angle). Therefore, the system is feedback linearizable and perfect tracking of any desired position trajectory of class C^4 (continuous up to the fourth time derivative) can be theoretically obtained. With $\boldsymbol{\delta}$ we take into account all possible errors. According to (2), the platform might seem “infinitely stiff” with respect to interaction forces. However, we shall suitably design the input $\mathbf{u}_R$ so as to reintroduce a compliant behavior.

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 O_H on the handle as

$$\mathbf{f}_c = t_c(\|\mathbf{l}_c\|) \mathbf{l}_c / \|\mathbf{l}_c\| \quad (3)$$

where $t_c(\|\mathbf{l}_c\|)$ represents the cable internal force intensity and $\mathbf{l}_c = \mathbf{p}_R - \mathbf{p}_H$. The force produced on the other end of the cable, namely on the robot at O_R , is equal to $-\mathbf{f}_c$.

In practice, the forces involved shall be very small (few newtons) and the distance between the human and the robot can be of few meters only. For these reasons, a thin and short cable can be used, which has negligible mass and inertia w.r.t. the ones of the robot and of the human.

Defining by $\bar{l}_c \in \mathbb{R}_{>0}$, the constant nominal length of the cable, we say that the cable is:

- 1) *Slack* when the distance between the two ends is shorter than $\bar{l}_c$. In this case, the cable force intensity is zero;
- 2) *Taut* when the distance between the two ends is equal or greater than $\bar{l}_c$. In this case, the cable force intensity follows Hooke's law.

In particular, $t_c(\|\mathbf{l}_c\|)$ is defined as

$$t_c(\|\mathbf{l}_c\|) = \begin{cases} k_c(\|\mathbf{l}_c\| - \bar{l}_c), & \text{if } \|\mathbf{l}_c\| - \bar{l}_c > 0 \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

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

Remark 3: Notice that $t_c(\|\mathbf{l}_c\|)$ can be any continuous and differentiable monotonically increasing function such that

$$t_c(\|\mathbf{l}_c\|) \geq \epsilon \|\mathbf{l}_c\| + \gamma, \text{ if } \|\mathbf{l}_c\| - \bar{l}_c > 0 \quad (5)$$

for some $\epsilon \in \mathbb{R}_{>0}$ and $\gamma \in \mathbb{R}$. This allows modeling more complex behaviors of the cable during the initial stretching/unstretching. We also consider the system to be always far from the maximum feasible tension.

III. CONTROL METHOD

Since the robot physically interacts with the human, it is important that the interaction is done in a compliant way, so as to always preserve stability and prevent the human to be armed or subjected to uncomfortable forces. For this problem, and more in general for physical interaction problems, a very common solution consists of using an *admittance control strategy* [46]. According to this method, the desired motion of the robot is computed as the one of an object with a specific admittance (mass, stiffness, and damping) subjected to the measured external force acting on the robot. In this way, one can reshape the apparent mechanical characteristics of the system. We define the robot control input u_R as

$$u_R = M_A^{-1} (-B_A v_R - f_c + u_A) \quad (6)$$

where the two positive definite diagonal matrices $M_A, B_A \in \mathbb{R}^{3 \times 3}$ are the virtual inertia and damping of the robot. $u_A \in \mathbb{R}^3$ is an additional input that will be defined in the following to achieve the desired control goal. Notice that to implement (6), only the state of the robot (p_R, v_R), and the force applied by the cable f_c are needed. The first can be retrieved with standard onboard sensors, while the second can be measured with a force sensor or estimated by a model-based observer [45].

It is useful to define the system state vector as $x = [p_H^T \ v_H^T \ p_R^T \ v_R^T]^T \in \mathcal{X} \subset \mathbb{R}^{12}$ and to write the dynamics in a more compact state form as $\dot{x} = f(x, u_A)$, where

$$f(x, u_A) = \begin{bmatrix} v_H \\ \frac{1}{m_H} (-g_H - B_H v_H + f_c + f_g) \\ v_R \\ M_A^{-1} (-B_A v_R - f_c + u_A) \end{bmatrix} \quad (7)$$

and f_c is computed as in (3). For the sake of deriving the control law and proving the asymptotic stability in nominal conditions, we consider a zero modeling error. Later we shall show the robustness of the method when $\delta \neq 0$.

Remark 4: The system has a *hybrid nature* characterized by two different behaviors according to the state of the cable.

- 1) When $x \in \mathcal{X}_S = \{x \in \mathcal{X} \mid \|l_c\| - \bar{l}_c \leq 0\}$, the cable is slack and the cable force is zero, i.e., $f_c = 0$. In this condition, the robot and human evolve independently.
- 2) When $x \in \mathcal{X}_T = \{x \in \mathcal{X} \mid \|l_c\| - \bar{l}_c > 0\}$, the cable is taut and the cable force is nonzero, i.e., $f_c \neq 0$. In this condition, the robot and human interact with each other through the cable force.

When the cable is taut the system appears to be a couple of mass-damper elements connected by a spring. This system is similar to an elastic manipulator where the actuator (the robot) is connected to the end-effector (the human) by an elastic element (the cable). For this system, we want to control the position of the end-effector (human position) by the input force u_A generated

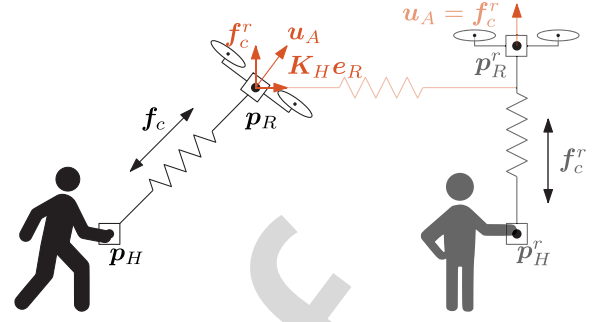


Fig. 2. Working principle of the control method. On the left the current state, on the right in opaque, the final desired state.

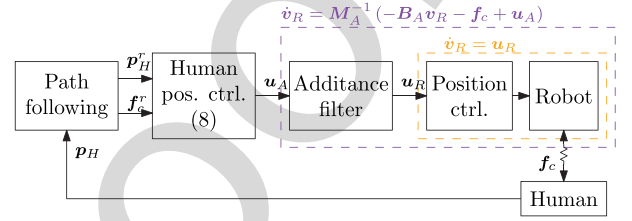


Fig. 3. Block diagram of the overall control method.

by the actuator (robot). Given this parallelism, we naturally took inspiration from the state of the art on control of manipulators with elastic joints [36].

Without the elastic element, the most natural choice for the design of a linear controller is to apply a simple proportional-derivative feedback from the end-effector position and velocity. However, considering a single link rotating on a horizontal plane and actuated with a motor through an elastic joint coupling, it has been proven that a feedback action entirely based on the end-effector position and velocity leads to instability, no matter the gain values [36].

The most preferred and grounded solution for manipulators with elastic joints is to apply a feedback completely based on the motor variables. If the proportional and derivative gains are strictly positive, then the closed-loop system will be asymptotically stable. Notice that, given a desired end-effector position, the desired motor value is computed inverting the dynamic model whose parameters need to be known.

To implement this control law, we only need a proportional feedback w.r.t. the robot position. The damping action w.r.t. the robot velocity is already present in (6). Thus, we set

$$u_A = K_H e_R + f_c^r \quad (8)$$

where $K_H = \text{diag}(k_H, k_H, 0)$ with $k_H \in \mathbb{R}_{>0}$, $e_R = p_R^r - p_R$ is the robot position error, p_R^r is the robot position of reference, and $f_c^r \in \mathbb{R}^3$ is a constant forcing input. In practice, f_c^r is the desired cable force. Fig. 2 explains the working principle of the controller, while Fig. 3 shows its block diagram.

IV. EQUILIBRIA AND STABILITY ANALYSIS

In the following, we shall show that, by properly choosing p_R^r and f_c^r , the control law (8) can steer the human position to the desired value.

Theorem 1: Let us define $\mathbf{p}_H^r \in \mathbb{R}^3$ as the human position reference such that $\mathbf{z}_W^\top \mathbf{p}_H^r = 0$. Considering the system (7) under the control law (8) where

$$\mathbf{f}_c^r = f_z \mathbf{z}_W \quad (9)$$

$$\mathbf{p}_R^r = \mathbf{p}_H^r + \mathbf{f}_c^r \left(\frac{1}{k_c} + \frac{\bar{l}_c}{\|\mathbf{f}_c^r\|} \right) \quad (10)$$

the zero velocity equilibrium $\bar{\mathbf{x}} = [\mathbf{p}_H^{r\top} \mathbf{0}^\top \mathbf{p}_R^{r\top} \mathbf{0}^\top]^\top \in \mathcal{X}_T$ is asymptotically stable if $0 < f_z < m_H g$.

Proof: Let us first compute the equilibrium state. Plugging (8) into (7) yields the final closed-loop dynamics

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{v}_H \\ \frac{1}{m_H} (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g) \\ \mathbf{v}_R \\ \mathbf{M}_A^{-1} (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{K}_H \mathbf{e}_R + \mathbf{f}_c^r) \end{bmatrix}. \quad (11)$$

Imposing the stability condition into (11), i.e., $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) = \mathbf{0}$, from the second row we get

$$\mathbf{f}_c = (f_g - m_H g) \mathbf{z}_W. \quad (12)$$

This means that at the equilibrium the cable force, and thus, the cable itself, have to be vertical. From the fourth row in (11) and replacing (12), we obtain

$$\mathbf{0} = (f_g - m_H g + f_z) \mathbf{z}_W + \mathbf{K}_H \mathbf{e}_R. \quad (13)$$

Expanding the components of $\mathbf{K}_H \mathbf{e}_R$ along the axes of $\mathcal{F}_W$, it is easy to verify that (13) is satisfied if

$$\mathbf{x}_W^\top \mathbf{e}_R = 0 \quad \mathbf{y}_W^\top \mathbf{e}_R = 0 \quad f_g = m_H g - f_z \quad (14)$$

which implies

$$p_{Rx} = p_{Rx}^r \quad p_{Ry} = p_{Ry}^r \quad \mathbf{f}_c = \mathbf{f}_c^r. \quad (15)$$

We recall that the intensity of the ground reaction force should be equal or greater than zero, i.e., $f_g \geq 0$. Thus, it has to be $f_z \leq m_H g$. Notice that there are no stable configurations for which $\mathbf{f}_c = \mathbf{0}$, i.e., such that $\|\mathbf{l}_c\| \leq \bar{l}_c$.

To conclude the computation of the equilibrium configuration, we need to calculate the position of the human $\mathbf{p}_H$, and the vertical position of the robot p_{Rz} . Replacing conditions (15) into (3), after a few simple calculations, we obtain

$$\begin{bmatrix} p_{Rx}^r \\ p_{Ry}^r \\ p_{Rz} \end{bmatrix} + \begin{bmatrix} p_{Hx} \\ p_{Hy} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \frac{f_z}{k_c} + \bar{l}_c \end{bmatrix}. \quad (16)$$

Replacing also (9) and (10), we finally obtain that, at the equilibrium, $\mathbf{p}_H = \mathbf{p}_H^r$ and $\mathbf{p}_R = \mathbf{p}_R^r$. Thus, the only equilibrium state for the system (7) is $\bar{\mathbf{x}} = [\mathbf{p}_H^{r\top} \mathbf{0}^\top \mathbf{p}_R^{r\top} \mathbf{0}^\top]^\top \in \mathcal{X}_T$.

Now we analyze the stability of the equilibrium state $\bar{\mathbf{x}}$ employing a Lyapunov-based analysis. Let us define the following Lyapunov function:

$$V(\mathbf{x}) = V_1(\mathbf{x}) + V_2(\mathbf{x}) + V_0 \quad (17)$$

where

$$V_1(\mathbf{x}) = \frac{1}{2} (m_H \mathbf{v}_H^\top \mathbf{v}_H + \mathbf{v}_R^\top \mathbf{M}_A \mathbf{v}_R + \mathbf{e}_R^\top \mathbf{K}_H \mathbf{e}_R) \quad (18)$$

$$V_2(\mathbf{x}) = \int_{l_{c0}}^{\|\mathbf{l}_c(t)\|} t_c(\tau) d\tau - \mathbf{l}_c^\top \bar{\mathbf{f}}_c \quad (19)$$

$$V_0 = f_z^2 / k_c + 2\bar{l}_c f_z. \quad (20)$$

We defined $l_{c0} = \|\mathbf{l}_c(0)\|$. In the following, we shall show that the defined Lyapunov function $V(\mathbf{x})$ is continuously differentiable and radially unbounded.

$V(\mathbf{x})$ is continuously differentiable because V_1 , V_2 , V_0 are clearly continuously differentiable.

We then show that (17) is *radially unbounded* (also called *coercive*), i.e., $\lim_{\|\mathbf{x}\| \rightarrow \infty} V(\mathbf{x}) = \infty$ with $\mathbf{x} \in \mathcal{X}$. We have that clearly $\lim_{\|\mathbf{x}\| \rightarrow \infty} V_1(\mathbf{x}) = \infty$ for $\mathbf{x} \in \mathcal{X}$. For V_2 , we first notice that, thanks to (5), there exist some $\epsilon \in \mathbb{R}_{>0}$ and $\gamma \in \mathbb{R}$ such that

$$\int_{l_{c0}}^{\|\mathbf{l}_c(t)\|} t_c(\tau) d\tau \geq \frac{\epsilon}{2} \|\mathbf{l}_c\|^2 + \gamma \|\mathbf{l}_c\|. \quad (21)$$

This implies that

$$\begin{aligned} \lim_{\|\mathbf{x}\| \rightarrow \infty} V_2(\mathbf{x}) &\geq \lim_{\|\mathbf{x}\| \rightarrow \infty} \epsilon \|\mathbf{l}_c\|^2 + \gamma \|\mathbf{l}_c\| - \|\mathbf{l}_c\| \|\mathbf{f}_c^r\| \\ &= \lim_{\|\mathbf{x}\| \rightarrow \infty} \|\mathbf{l}_c\|^2 \left(\frac{\epsilon}{2} + \frac{\gamma}{\|\mathbf{l}_c\|} - \frac{\|\mathbf{f}_c^r\|}{\|\mathbf{l}_c\|} \right) = +\infty. \end{aligned} \quad (22)$$

This is enough to show that (17) is radially unbounded.

In order to prove that $V(\mathbf{x})$ is positive definite, we show that it has a unique global minimum in $\bar{\mathbf{x}}$, i.e., $\bar{\mathbf{x}} = \arg \min_{\mathbf{x}} V(\mathbf{x})$ and $V(\bar{\mathbf{x}}) = 0$. Since $V(\mathbf{x})$ is continuous and radially unbounded, for [47, Th. 1.15], we can say that the Lyapunov function (17) has a global minimum. Now we can look for this minimum among the stationary points, i.e., the $\mathbf{x}$ where the gradient $\nabla V(\mathbf{x}) = \mathbf{0}$.

It is clear that $\nabla V_1(\mathbf{x}) = \mathbf{0}$ only if $\mathbf{v}_H = \mathbf{v}_R = \mathbf{0}$, $p_{Rx} = p_{Rx}^r$, and $p_{Ry} = p_{Ry}^r$. Regarding $V_2(\mathbf{x})$, let us consider its gradient w.r.t. the cable configuration $\mathbf{l}_c$. For every $\mathbf{x} \in \mathcal{X}_S$

$$\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) = \frac{\partial V_2(\mathbf{x})}{\partial \mathbf{l}_c} = \frac{\partial}{\partial \mathbf{l}_c} \left(\int_{l_{c0}}^{\|\mathbf{l}_c\|} t_c(\tau) d\tau \right) - \mathbf{f}_c^{r\top}. \quad (23)$$

Let us notice that for the Leibniz integral rule, we have that

$$\begin{aligned} \frac{\partial}{\partial \mathbf{l}_c} \left(\int_{l_{c0}}^{\|\mathbf{l}_c\|} t_c(\tau) d\tau \right) &= t_c(\|\mathbf{l}_c\|) \frac{\partial \|\mathbf{l}_c\|}{\partial \mathbf{l}_c} - t_c(l_{c0}) \frac{\partial l_{c0}}{\partial \mathbf{l}_c} \\ &= t_c(\|\mathbf{l}_c\|) \frac{\mathbf{l}_c^\top}{\|\mathbf{l}_c\|} = \mathbf{f}_c^\top \end{aligned} \quad (24)$$

where we used (3). Plugging (24) into (23) yields $\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) = \mathbf{f}_c^\top - \mathbf{f}_c^{r\top}$. It follows that $\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) = \mathbf{0}$ if and only if:

$$t_c(\|\mathbf{l}_c\|) \mathbf{l}_c^\top / \|\mathbf{l}_c\| = \mathbf{f}_c^\top = \mathbf{f}_c^{r\top}. \quad (25)$$

Condition (25) holds only if

- a) $t_c(\|\mathbf{l}_c\|) = \|\mathbf{f}_c^r\|$ and $\mathbf{l}_c / \|\mathbf{l}_c\| = \mathbf{f}_c^r / \|\mathbf{f}_c^r\|$; or
- b) $t_c(\|\mathbf{l}_c\|) = -\|\mathbf{f}_c^r\|$ and $\mathbf{l}_c / \|\mathbf{l}_c\| = -\mathbf{f}_c^r / \|\mathbf{f}_c^r\|$.

In these two cases, the cable produces the same force $\mathbf{f}_c^r$, but in case 1) the cable is stretched, while in case 2) the cable is compressed. However, cables cannot be compressed and, thus,

case 2) is not feasible for definition. The only solution is

$$\mathbf{l}_c = \left(\frac{1}{k_c} + \frac{\bar{l}_c}{\|\mathbf{f}_c^r\|} \right) \mathbf{f}_c^r \quad (26)$$

which, recalling (10), leads to the conclusion that $\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) = \mathbf{0}$ only if $\mathbf{p}_H = \mathbf{p}_H^r$ and $\mathbf{p}_R = \mathbf{p}_R^r$. This completes the proof that $\nabla V(\mathbf{x}) = \mathbf{0}$ only if $\mathbf{x} = \bar{\mathbf{x}}$, and, thus, $\bar{\mathbf{x}} = \arg \min_{\mathbf{x}} V(\mathbf{x})$. Finally, it is easy to verify that $V_1(\bar{\mathbf{x}}) = 0$ and V_0 has been defined such that $V_1(\bar{\mathbf{x}}) + V_2(\bar{\mathbf{x}}) = -V_0$, in order to make $V(\bar{\mathbf{x}}) = 0$. This proves that $V(\mathbf{x})$ is positive definite.

We can now compute the time derivative of (17). Similarly to (24), applying the Leibniz integral rule, we have that

$$\frac{d}{dt} \left(\int_{l_{c0}}^{\|\mathbf{l}_c(t)\|} t_c(\tau) d\tau \right) = t_c(\|\mathbf{l}_c\|) \frac{\partial \|\mathbf{l}_c\|}{\partial \mathbf{l}_c} \dot{\mathbf{l}}_c = \mathbf{f}_c^\top \dot{\mathbf{l}}_c. \quad (27)$$

Therefore, the time derivative of (17) is equal to

$$\begin{aligned} \dot{V}(\mathbf{x}) = & \mathbf{v}_H^\top (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g) \\ & + \mathbf{v}_R^\top (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{K}_H \mathbf{e}_R + \mathbf{f}_c^r) \\ & - \mathbf{v}_R \mathbf{K}_H \mathbf{e}_R + \dot{\mathbf{l}}_c \mathbf{f}_c - \dot{\mathbf{l}}_c \mathbf{f}_c^r. \end{aligned} \quad (28)$$

After few simple algebraic steps we get

$$\dot{V}(\mathbf{x}) = -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H - \mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R. \quad (29)$$

$\dot{V}(\mathbf{x})$ is clearly negative semidefinite, in $\mathcal{X}$.

Since $\dot{V}(\mathbf{x})$ is only negative semidefinite, to prove the asymptotic stability we rely on *LaSalle's invariance principle* [48]. The Lyapunov candidate $V(\mathbf{x})$ is a continuously differentiable function. Let us define a positively invariant set $\Omega_\alpha = \{\mathbf{x} \in \mathcal{X} \mid V(\mathbf{x}) \leq \alpha \text{ with } \alpha \in \mathbb{R}_{>0}\}$. By construction, Ω_α is compact since (17) is radially unbounded. Notice that Ω_0 contains only $\bar{\mathbf{x}}$. Then, we need to find the largest invariant set $\mathcal{M}$ in $\mathcal{E} = \{\mathbf{x} \in \Omega_\alpha \mid \dot{V}(\mathbf{x}) = 0\}$. A trajectory $\mathbf{x}(t)$ belongs identically to $\mathcal{E}$ if $\dot{V}(\mathbf{x}(t)) \equiv 0 \Leftrightarrow \mathbf{v}_H(t) = \mathbf{v}_R(t) \equiv \mathbf{0} \Leftrightarrow \dot{\mathbf{v}}_H = \dot{\mathbf{v}}_R = \mathbf{0}$. As we saw previously in the calculation of the equilibria, this is verified only if $\mathbf{x} = \bar{\mathbf{x}}$. Therefore, $\mathcal{M}$ contains only $\bar{\mathbf{x}}$. All conditions of LaSalle's principle are satisfied and $\bar{\mathbf{x}}$ is globally asymptotically stable. ■

To get more hints on the behavior of the system let us analyze it for $\mathbf{x} \in \mathcal{X}_S$ (slack cable). Human's and robot's dynamics are independent and the first results to be

$$m_H \dot{\mathbf{v}}_H = -\mathbf{B}_H \mathbf{v}_H. \quad (30)$$

Whatever is the initial condition $\lim_{t \rightarrow +\infty} \mathbf{v}_H(t) = \mathbf{0}$. Notice that the human will stop but his final position depends only on the initial conditions. For the robot dynamics, let us write first the dynamic equation along $\mathbf{x}_W$

$$m_A \dot{\mathbf{v}}_{Rx} = -b_A \mathbf{v}_{Rx} + k_H \mathbf{e}_{Rx} \quad (31)$$

where $m_A \in \mathbb{R}_{>0}$ and $b_A \in \mathbb{R}_{>0}$ are such that $\mathbf{M}_A = \text{diag}(m_A, m_A, m_A)$ and $\mathbf{B}_A = \text{diag}(b_A, b_A, b_A)$. It is easy to verify that the state $(\mathbf{v}_{Rx}, \mathbf{e}_{Rx}) = (0, 0)$ is asymptotically stable. The same for the robot dynamics along $\mathbf{y}_W$: the state $(\mathbf{v}_{Ry}, \mathbf{e}_{Ry}) = (0, 0)$ is asymptotically stable. On the other hand, the robot dynamics along $\mathbf{z}_W$ results to be

$$m_A \dot{\mathbf{v}}_{Rz} = -b_A \mathbf{v}_{Rz} + f_z. \quad (32)$$

Whatever is the initial condition, $\lim_{t \rightarrow +\infty} v_{Rz}(t) = f_z/b_A > 0$. This means that the robot horizontal position will tend to the desired one, while, along the vertical axes, it will tend to fly up until the cable will become taut. In fact, $\frac{d}{dt} \|\mathbf{l}_c(t)\| = \|\mathbf{v}_R(t) - \mathbf{v}_H(t)\| \rightarrow f_z/b_A > 0$. This means that $\|\mathbf{l}_c\|$ will grow until $\|\mathbf{l}_c\| > \bar{l}_c$, i.e., until the cable becomes taut. After this instant, the robot interacts with the human through the cable and eventually pulls him/her to the desired position. According to the specific initial condition, it might be that the state trajectory might pass from $\mathcal{X}_T$ to $\mathcal{X}_S$ several times. However, the previous Lyapunov-based reasoning proofs that eventually the system will converge to $\bar{\mathbf{x}}$, no matter the initial conditions.

Remark 5: Although the system seems passive for every virtual admittance of the robot, the dynamics of the robot actuators and sensors, as well as the real implementation of the control framework, impose minimum values for the virtual inertia and damping. This is in accordance with the practical intuition that minimum compliance of the interaction is required. Notice that the mechanical flexibility of some elements, e.g., the cable, helps in meeting such requirements.

V. ROBUSTNESS OF THE SYSTEM

Previously, we formally proved that an admittance strategy together with controller (8) asymptotically steer the human position to a desired constant position $\mathbf{p}_H^r$. This is valid if the human follows the force provided by the robot without exerting other forces except for the damping effect. In the following, we shall show the intrinsic robustness of the controller against time-varying position references, modeling errors, and possible additional human forces (e.g., if he/she wants to stop).

A. Time-Varying Position Reference

We remark that with the control law (8), the resulting final path followed by the human to arrive at the goal only depends on the initial conditions. In a real application, this is not a desired behavior, e.g., when a blind human must be guided to a specific point in an environment with possible obstacles. In this scenario, it is more likely that the human position reference is not constantly equal to the final goal position, but is rather a time-varying path $\mathbf{p}_H^r(t)$ that leads the human to the goal, avoiding obstacles, or possible sources of danger. To face this objective, taking into account a possibly time-varying path $\mathbf{p}_H^r(t)$, and time-varying desired cable force $\mathbf{f}_c^r(t)$, for $t \in [0, T]$, we modify the original control law (8) as

$$\mathbf{u}_A(t) = \mathbf{K}_H \mathbf{e}_{RT}(t) + \mathbf{f}_T^r + \mathbf{u}'_A(t) \quad (33)$$

where $\mathbf{e}_{RT}(t) = \mathbf{p}_R^r(T) - \mathbf{p}_R(t)$, $\mathbf{f}_T^r = \mathbf{f}_c^r(T) = f_z \mathbf{z}_W$, and $\mathbf{u}'_A(t)$ is such that $\mathbf{u}_A(t) = \mathbf{K}_H(\mathbf{p}_R^r(t) - \mathbf{p}_R(t)) + \mathbf{f}_c^r(t)$ for every $t \in [0, T]$. This is a simple way to gather in $\mathbf{u}'_A$ the time-varying desired quantities. It results that $\mathbf{u}'_A(t) = \mathbf{K}_H(\mathbf{p}_R^r(t) - \mathbf{p}_R^r(T)) + (\mathbf{f}_c^r(t) - \mathbf{f}_c^r(T))$.

To ensure that the system remains stable even when the human position reference is time-varying, i.e., for $\mathbf{u}'_A(t) \neq \mathbf{0}$, we shall prove that the system is output-strictly passive w.r.t. the input-output pair $(\mathbf{u}_1, \mathbf{y}_1) = (\mathbf{u}'_A, \mathbf{v}_R)$.

Theorem 2: If $\mathbf{u}_A$ is defined as in (33) for a certain $\mathbf{p}_H^r(t)$ and $\mathbf{f}_c^r(t)$, with $t \in [0, T]$, then system (7) is output-strictly passive w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}_1, \mathbf{y}_1) = (\mathbf{u}'_A, \mathbf{v}_R)$.

Proof: In the proof of Theorem 1, we already showed that (17) is a continuously differentiable positive definite function. Replacing (33) into (7), and differentiating (17), we obtain

$$\dot{V}(\mathbf{x}) = -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H - \mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R + \mathbf{u}_A'^\top \mathbf{v}_R \quad (34)$$

$$\leq -\mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R + \mathbf{u}_A'^\top \mathbf{v}_R = \mathbf{u}_1^\top \mathbf{y}_1 - \mathbf{y}_1^\top \phi_1(\mathbf{y}_1) \quad (35)$$

with $\phi_1(\mathbf{y}_1) = \mathbf{B}_A \mathbf{v}_R$. Since $\mathbf{y}_1^\top \phi_1(\mathbf{y}_1) \geq 0$ for every $\mathbf{y}_1 \neq \mathbf{0}$, we can conclude that the system (7) is *output-strictly passive* [48]. ■

Given the passivity of the system, we have that for a bounded input $\mathbf{u}'_A$, i.e., bounded reference trajectories, the overall energy of the system remains bounded too. Furthermore, the system stabilizes to a constant value as soon as $\mathbf{u}'_A$ becomes constant again. This means that, while the robot moves following $\mathbf{p}_R^r(t)$ and $\mathbf{f}_c^r(t)$, the overall state of the system will remain bounded. It will then converge to another specific equilibrium configuration when $\mathbf{u}'_A$ becomes constant.

B. Modeling Errors

As we mentioned in Section II, nonzero model errors might appear due to model uncertainties, nonlinear effects, external disturbances, etc. With $\delta \neq \mathbf{0}$, the system dynamics becomes

$$\mathbf{f}(\mathbf{x}, \mathbf{u}_A) = \begin{bmatrix} \mathbf{v}_H \\ \frac{1}{m_H} (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g) \\ \mathbf{v}_R \\ \mathbf{M}_A^{-1} (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{u}_A) + \delta \end{bmatrix}. \quad (36)$$

We shall show that the system remains stable also when $\delta \neq \mathbf{0}$.

Theorem 3: System (36) under the control law (8) is output-strictly passive w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}_2, \mathbf{y}_2) = (\delta, \mathbf{v}_R)$.

Proof: We can rewrite equations (36) and (8) as (7) and

$$\mathbf{u}_A = \mathbf{K}_H \mathbf{e}_R + \mathbf{f}_c^r + \mathbf{M}_A \delta \quad (37)$$

respectively. Noticing the similarity between (37) and (33), the proof follows as the one of Theorem 2. ■

Given the passivity of the system, we have that for a bounded model error δ , the overall energy of the system remains bounded too. Passivity is a well-known robust property, especially w.r.t. model uncertainties. This means that, to ensure the stability of the system, an accurate model of the system is not necessary, as far as the passivity is guaranteed.

C. Additional Human Force

In Section II, we modeled the human as a simple mass-damper system subjected to the force exerted by the cable only. Nevertheless, during the guidance, the human may want to stop or deviate from the desired path, e.g., to pick up an object. In these cases, the human will generate additional forces that will modify his/her trajectory. It is important that, even in this condition, the

system is guaranteed to be stable and that the state converges to the desired value as soon as the human forces go back to zero.

We define the vector $\mathbf{u}_H \in \mathbb{R}^3$ as the sum of all the forces applied by the human that generate a translational motion. The closed-loop system dynamics, expressed in (7), becomes

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{v}_H \\ \frac{1}{m_H} (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g + \mathbf{u}_H) \\ \mathbf{v}_R \\ \mathbf{M}_A^{-1} (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{u}_A) \end{bmatrix}. \quad (38)$$

To ensure that the system remains stable even when the human forces are not zero, i.e., for $\mathbf{u}_H \neq \mathbf{0}$, we shall prove that the system is output-strictly passive w.r.t. the input-output pair $(\mathbf{u}_3, \mathbf{y}_3) = (\mathbf{u}_H, \mathbf{v}_H)$.

Theorem 4: System (38) under the control law (8) is output-strictly passive w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}_3, \mathbf{y}_3) = (\mathbf{u}_H, \mathbf{v}_H)$.

Proof: In the proof of Theorem 1, we already showed that (17) is a continuously differentiable positive definite function. Considering (38) and differentiating (17), we obtain

$$\dot{V}(\mathbf{x}) = -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H - \mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R + \mathbf{u}_H^\top \mathbf{v}_H \quad (39)$$

$$\leq -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H + \mathbf{u}_H^\top \mathbf{v}_H = \mathbf{u}_3^\top \mathbf{y}_3 - \mathbf{y}_3^\top \phi_2(\mathbf{y}_3) \quad (40)$$

with $\phi_2(\mathbf{y}_3) = \mathbf{B}_H \mathbf{v}_H$. Since $\mathbf{y}_3^\top \phi_2(\mathbf{y}_3) \geq 0$ for every $\mathbf{y}_3 \neq \mathbf{0}$, we can conclude that the system (38) is *output-strictly passive* [48]. ■

Conclusions similar to the ones in Section V-A can be drawn. In particular, we have that for a bounded input $\mathbf{u}_H$, i.e., bounded human forces, the overall energy of the system remains bounded too. Furthermore, the system stabilizes to a constant value as soon as $\mathbf{u}_H$ goes back to zero or balance the cable force. This means that while the human moves subjected to a nonzero (but bounded) human force $\mathbf{u}_H \neq \mathbf{0}$, the overall state of the system will remain bounded. It will then converge to another specific equilibrium configuration as soon as $\mathbf{u}_H$ goes back to zero or balance the cable force.

In particular, considering the case in which the human wants to stop in a certain position $\mathbf{p}_H$, it has to be that $\mathbf{v}_H = \dot{\mathbf{v}}_H = \mathbf{0}$. This means that $\mathbf{u}_H = \mathbf{f}_c$. It is then easy to verify that the robot's position at the new equilibrium will be such that

$$\mathbf{l}_c = (\|\beta\| + \bar{l}_c k_c) \begin{bmatrix} k_c + k_H & 0 & 0 \\ 0 & k_c + k_H & 0 \\ 0 & 0 & k_c \end{bmatrix}^{-1} \frac{\beta}{\|\beta\|} \quad (41)$$

where $\beta = \mathbf{K}_H(\mathbf{p}_R^r - \mathbf{p}_H) + \mathbf{f}_c^r$. Using a Lyapunov-based argument similar to the one in the proof of Theorem 1, it is easy to show that such zero-velocity equilibrium state is asymptotically stable. This provides a high level of robustness to different human behaviors.

Following the same reasoning of Theorems 2–4, we can ensure that the system remains stable even when the human position reference is time-varying, there are nonzero model errors, and the human forces are not zero.

Theorem 5: System (38) under the control law $\mathbf{u}_A(t) = \mathbf{K}_H \mathbf{e}_{RT}(t) + \mathbf{f}_T^r + \mathbf{u}'_A(t) + \mathbf{M}_A \delta$ is output-strictly passive

w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}, \mathbf{y}) = ([\mathbf{u}_1^\top \mathbf{u}_2^\top \mathbf{u}_3^\top]^\top, [\mathbf{y}_1^\top \mathbf{y}_2^\top \mathbf{y}_3^\top]^\top)$.

Proof: The proof is trivial and follows the same steps of the proof of Theorems 2–4. ■

VI. PATH-FOLLOWING PROBLEM

In Section V-A, we shown that even if the human position and cable force of reference are time-varying, the system remains stable. This can be exploited for the problem of following a desired path. In the following, we shall define a strategy to lead the human along the desired path, allowing him/her to stop or slightly deviate from the path without causing instability.

Given a desired human path¹ defined by its *parametric representation* $\mathbf{p}_H^d(s) \in \mathbb{R}^3$, where $s \in [0, 1]$ is called *parameter*, we first define the desired cable force along the path $\mathbf{f}^d(s) \in \mathbb{R}^3$. This is the force that we would like the human feels all along the path. $\mathbf{f}^d(s)$ works as a feedforward term, i.e., it is the nominal pulling force that drags the human along the path. In standard path-following problems [49], this is similar to defining the desired velocity along the path. Inspired by most of the related works, we define

$$\mathbf{f}^d(s) = \mathbf{f}_{xy}^d(s) + \mathbf{f}_z^d \quad (42)$$

where

$$\mathbf{f}_{xy}^d(s) = \mathbf{f}_{xy}^d(s) \frac{\nabla_s \mathbf{p}_H^d(s)}{\|\nabla_s \mathbf{p}_H^d(s)\|}, \quad \mathbf{f}_z^d = f_z \mathbf{z}_W \quad (43)$$

and $\mathbf{f}_{xy}^d(s)$ is such that $\mathbf{f}_{xy}^d(1) = 0$. In particular, here, we chose a trapezoidal profile that starts with a nonzero value. Notice that the planar pulling force $\mathbf{f}_{xy}^d(s)$ is tangential to the path and correctly drive the human along the path. Furthermore, at the end of the path, i.e., for $s = 1$, $\mathbf{f}^d(1) = \mathbf{f}_z^d$, which guarantees $\mathbf{p}_H^d(1)$ being asymptotically stable if $\mathbf{p}_H^r = \mathbf{p}_H^d(1)$ and $\mathbf{f}_c^r = \mathbf{f}^d(1)$, as it is shown in Section IV.

Now that, we have the desired *maneuver* $\eta = \{(\mathbf{p}_H^d(s), \mathbf{f}^d(s)) \in \mathbb{R}^3 \times \mathbb{R}^3 \mid s \in [0, 1]\}$, considering the control strategy described so far [(6) and (8)], we seek a method to choose $\mathbf{p}_H^r(t)$ and $\mathbf{f}_c^r(t)$ such that $\mathbf{p}_H(t)$ asymptotically converges to the path $\mathbf{p}_H^d(s)$, i.e.,

$$\lim_{t \rightarrow \infty} \|\mathbf{p}_H(t) - \mathbf{p}_H^d(s^*(t))\| \quad (44)$$

for any smooth function $s^*(t) : \mathbb{R} \rightarrow [0, 1]$ [50]. We first set

$$\mathbf{p}_H^r(t) = \mathbf{p}_H^d(s^*(t)), \quad \mathbf{f}_c^r(t) = \mathbf{f}^d(s^*(t)). \quad (45)$$

We only have to define $s^*(t)$. A very simple way would be to define a time law such that $s^*(0) = 0$ and $s^*(T) = 1$ for a given time $T \in \mathbb{R}_{>0}$, e.g., using a spline or a linear function. However, this would fall into the *trajectory tracking* category, which suffers from some robustness issues. Imagine that the human decides to stop or to slightly deviate from the path. At the same time, the desired reference advances increasing the position error. If not tackled accurately, e.g., with saturations,

the increase of the position error might saturate the robot inputs making the system unstable. Even if inputs saturation are properly addressed, once the human decides to follow again the robot, the latter will try to quickly catch up with the moving desired state. The desired path will not be followed anymore, and possible collisions with obstacles may occur.

To avoid this issue, we implement a *maneuver regulation* approach similar to the one in [37] and [38], defining

$$s^*(t) = \arg \min_{s \in [0, 1]} \|\mathbf{p}_H^d(s) - \mathbf{p}_H(t)\|. \quad (46)$$

At every time t , the reference human position is the one belonging to $\mathbf{p}_H^d$ and closer to the actual human position. $\mathbf{f}_c$ is computed accordingly. It is clear that employing this solution, even if the human stops, the position error will not grow. In fact, $\mathbf{p}_H^r$ will remain the same. Notice that to have (46) well defined, $\mathbf{p}_H^d$ must be nonintersecting. Furthermore, it must be that $\mathbf{f}_{xy}^d(s) \neq 0$ for all $s \neq 1$. This is necessary to make the human always advance along the path.

Replacing the maneuver regulation policy (45) into the original controller (8), we obtain

$$\mathbf{u}_A(t) = \mathbf{K}_H(\mathbf{p}_H^d(s^*(t)) - \mathbf{p}_H(t)) + \mathbf{f}_{xy}^d(s^*(t)) + \mathbf{f}_z^d \quad (47)$$

where $\mathbf{p}_H^d$ is computed as in (10) with $\mathbf{p}_H^d$ and $\mathbf{f}^d$ instead of $\mathbf{p}_H^r$ and $\mathbf{f}_c^r$, respectively. The overall control action is divided into three parts as follows.

- 1) The first is a proportional term that tends to bring the robot (and, thus, the human) to the desired position.
- 2) The second is a feedforward force that tends to pull the human along the desired path.
- 3) The third is a forcing vertical force that prevents the cable to become slack.

Notice that as soon as $s^*(t) = 1$, (47) is equal to (8) where $\mathbf{p}_H^r = \mathbf{p}_H^d(1)$. Thus, the asymptotical stability of $\mathbf{p}_H^d(1)$ is ensured. The stability of the system for $s \neq 1$ is also guaranteed thanks to the passivity of the system.

Remark 6: Notice that to implement (46), the actual position of the human is required. This can be easily retrieved either with some embedded sensors in the handle (like GPS), or inverting (10) using the actual robot position and cable force.

VII. EXPERIMENTAL VALIDATION

A. Testbed Setup

The system employed in these indoor experiments is shown in Fig. 1. It consists of a quadrotor aerial vehicle connected by a cable to a handle hold by a human being. The latter is wearing all safety protections including glasses, gloves, and a helmet. The holder, simply built with a three-dimensional printer, is equipped with motion tracking markers to obtain a measure of $\mathbf{p}_H$. The experiments are performed indoor employing a motion capture system (MOCAP) to allow the tracking of the human hand. Here, the use of a reliable positioning system has also the advantage to enhance human safety. Notice that the proposed experiments still encapsulates the main challenges addressed in the work, i.e., the stability of pHRI. The integration of a redundant sensory

¹The path is considered given and is such that no obstacles are present in its proximity. The minimum distance to the obstacle will be given by the precision of the control method.

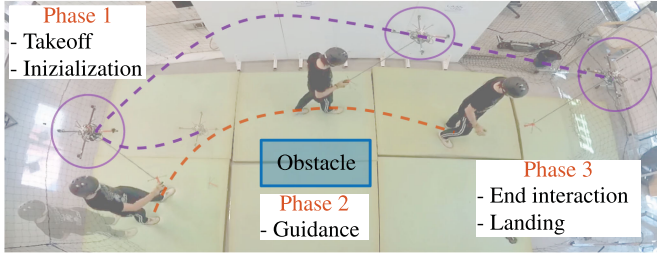


Fig. 4. Representation of the experimental phases. On each snapshot the robot is highlighted with a purple circle. Robot and human trajectories are marked with purple and red dashed lines, respectively.

suit for safe flights outdoors is not the focus of this manuscript and is left as future work.

The cable connecting the human-handle has a rest-length $\bar{l}_c = 1$ [m], and a negligible mass (less than 10 [g]). The aerial vehicle is a 1.3 [Kg] custom quadrotor platform equipped with a custom Paparazzi-based flight-controller, four brushless motor controllers running an in-house developed firmware that allows regulating the propeller speed in closed-loop [51], and an on-board PC that runs a UKF state estimator, a geometric position controller [52], and the admittance filter. The state estimator fuses the data coming from the onboard IMU (accelerometer and gyroscope) at 1 [kHz] and from the MOCAP (position and attitude) at 60 [Hz]. The measure of the cable force required in (6) is obtained with a model-based wrench observer [45]. These components run onboard at 1 [kHz] using the open-source software framework *TeleKyb3*.² The admittance filter parameters have been set to $M_A = 0.8I_3$ and $B_A = 2.4I_3$, where $I_3 = \text{diag}(1, 1, 1)$. Notice that to implement the controller, the virtual admittance parameters of the human are not needed.

The controller (8) and the path-following strategy described in Section VI are instead implemented in MATLAB/Simulink. The input u_A is computed based on the references p_H^r and f_c^r calculated as in (45), and sent to the onboard admittance controller at 100 [Hz] via a Wi-Fi connection. The gain k_H has been set equal to 4.5. This, together with the gains of the admittance filter, has been set after a tuning campaign aiming at optimizing the user experience. We wanted the user to feel a reasonable force, but still not too strong, and as smooth as possible. This has been also obtained properly choosing the desired force reference along the path. We set $f_z = 1$ [N] to keep the cable always taut, and $f_{xy}^d(s)$ as a trapezoidal profile such that $\max(f_{xy}^d(s)) = 1.5$ [N] and $f_{xy}^d(1) = 0$. Finally, $p_H^d(s)$ is a smooth path going from $p_H^d(0) = [-2 \ -0.5 \ 0]^T$ to $p_H^d(1) = [2 \ 0 \ 0]^T$, avoiding a virtual obstacle placed in the middle of the two points (see Fig. 4). The trajectory has been computed using a simple piecewise polynomial function.

The experiment is divided into three phases (see Fig. 4).

Ph.1: The human stays in a safe place. The robot takes off and goes into an initial point in position mode. After, the admittance filter is activated with $u_A = 0$. This allows the human safely grabbing the handle.

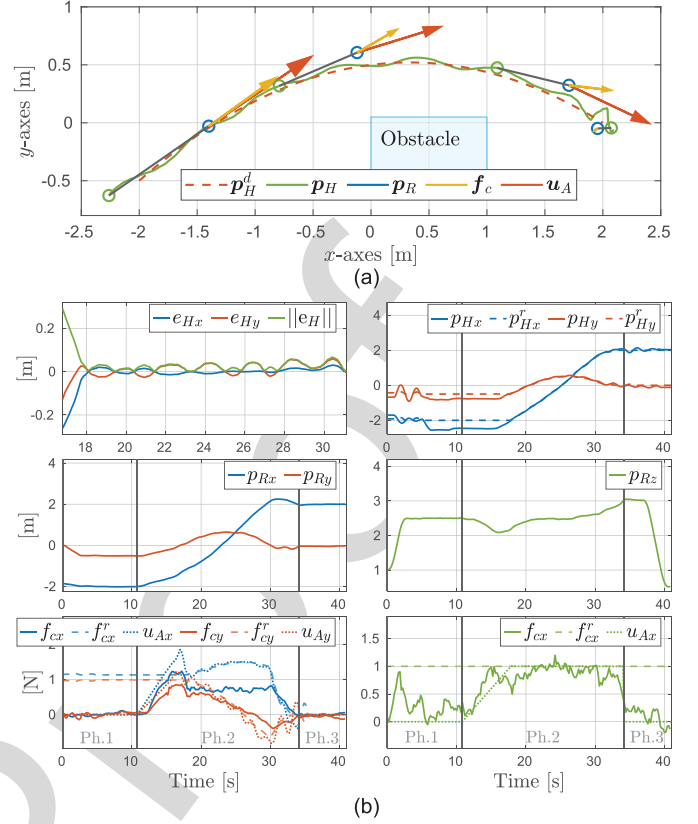


Fig. 5. Detailed experimental results of one subject. (a) Desired and actual human path showed in the xy plane. Four schematic representation of the system along the path are shown. The green and blue circles represent the human hand and the robot, respectively. The black line represents the cable. The red and yellow arrows represent the x-y components of u_A and f_c , respectively. (b) Plots of the human position error (zoomed during the guiding phase), desired and actual human hand position, robot position, and cable force.

Ph.2: Once the human holds the handle, the proposed guiding control, and path-following strategy are activated and the robot pulls the human along the desired path $p_H^d(s)$.

Ph.3: Once the human reaches the final position, the robot will be vertically placed on top of the handle. In this condition, the human feels no horizontal pulling force and can release the handle. The human guiding controller and the admittance filter are disabled. Finally, the robot lands in position mode.

During the experiment, the human is not blinded for safety reasons. Nevertheless, he/she is asked to look at the ground and not at the robot, focusing on the forces felt on the hand. This is done to encourage the human to be led feeling the forces that the robot is applying through the cable, instead of using it as a visual reference. Furthermore, the human is first “trained” on a different path to make him/her comfortable with the experiment, and confident with the reliability of the robot.

B. Experimental Results

In Fig. 5, we report the detailed results obtained with one participant of the experimental campaign. In Fig. 5(a), we show the desired and actual human path from the top, during Phase 2. We also schematically depict the system configuration at some instants to show how the robot pulls the human along the desired

²TeleKyb3 is freely [Online]. Available: <https://git.openrobots.org/projects/telekyb3>.

path. In Fig. 5(b), detailed quantities of the system along the full experiments are shown.

During *Phase 1*, the robot takes off and goes in the initial desired position. The nonzero estimated force along z_W corresponds to the weight of the handle that in this phase is suspended below the robot. The initial oscillations of p_{Hx} and p_{Hy} are also caused by the oscillations of the handle.

Passing to *Phase 2*, the robot starts moving to stretch the cable and pull the human. This can be seen from the estimated force along the cable. Looking at the human position error $e_H(t) = p_H^r(t) - p_H(t)$, we remark that its norm 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 nonzero forces. The experiment additionally validates the passivity of the system, which guarantees stability even in nonideal conditions. One can notice that, during Phase 2, there is an error between the desired horizontal force and the actual one. This is because the robot is moving and the damping plays against the generation of the desired force. Passivity-based methods are known to be very conservative. Practically, this is not a problem. If the human is moving toward the good direction, there is no need to increase the guiding force. On the other hand, if the human stops, the robot will apply the desired force, clearly showing the correct direction to the human.

Phase 3 starts when the human does not feel horizontal forces. He/she understands to be arrived at the desired position and so releases the handle. After, the robot lands.

To further validate the proposed system, we tested it with a group of four different subjects, performing the experiment twice. To evaluate the path-following performance, we define the path-following error with respect to the desired path as

$$e_H^P(s) = \min_{t \in [0, T]} \left((p_H(t) - p_H^d(s))^T p_H^{d\perp}(s) \right) \quad (48)$$

where $p_H^{d\perp}(s) \in \mathbb{R}^3$ is the normal vector to the path in the point $p_H^d(s)$, and $T \in \mathbb{R}_{>0}$ is the experiment final time. Given a certain point of the desired path $p_H^d(s)$, parameterized by s , $e_H^P(s)$ is the distance between $p_H^d(s)$ and the human position intersecting the normal to the path in $p_H^d(s)$. Notice that this definition is a *geometric error*; it does not depend on the velocity of the human, neither on his/her trajectory, but just on the geometric path.³ For each $s \in [0, 1]$, we then define the mean path-following error $\bar{e}_H^P(s)$, and the corresponding standard deviation (std) $\sigma_H(s)$

$$\begin{aligned} \bar{e}_H^P(s) &= \frac{1}{N} \sum_{j=1}^N e_{Hj}^P(s) \\ \sigma_H(s) &= \frac{1}{N-1} \sum_{j=1}^N \left(\bar{e}_H^P(s) - e_{Hj}^P(s) \right)^2 \end{aligned} \quad (49)$$

where N is the number of performed tests, and the subscript j indicates the j th test. Fig. 6 shows the global performance. One can notice that $\bar{e}_H^P(s)$ is always below 5 [cm], while the

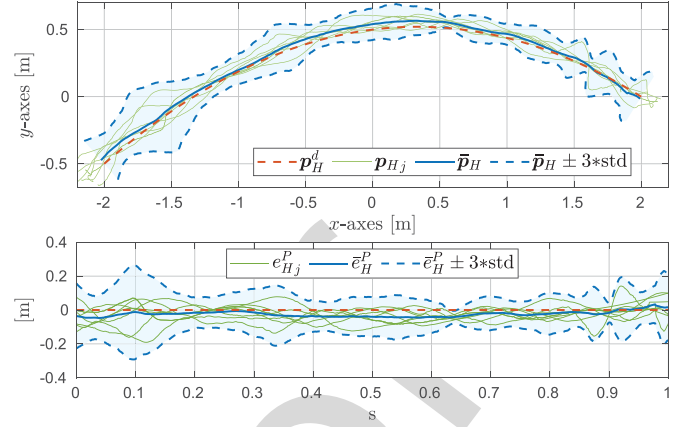


Fig. 6. Experimental results of eight tests with four subjects. *On the top*: the desired human path, the actual human path for the eight experiments, and the mean human path showed in the xy plane. *On the bottom*: the path-following error e_{Hj}^P for every experiment, and the mean path-following error.

maximum standard deviation is below 10 [cm]. This means that, according to the performed experiments, the human will always pass in a tube with diameter 60 [cm] around the desired path. This information could be used at the motion planning level to compute paths that stay sufficiently away from obstacles. We also remark that every subject behaves in a slightly different way (e.g., following the robot with a higher or lower speed, making stops, applying extra forces, etc.). Nevertheless, the system always maintains stability and provides good tracking performance. We remark that these results do not pretend to be statistically significant. The goal is to provide a global evaluation of the proposed method, which further validates its stability and robustness.

Notice that the human tends to stay always “outward” the desired curve. This is the effect of the human inertia that the robot controller does not take into account. Furthermore, we noticed that the human might have some difficulties understanding that he/she is arrived, resulting in useless small corrections. These marginal aspects are left to future works.

VIII. CONCLUSION

In this article, a system composed by a human *physically connected* to an aerial vehicle was studied for the first time. The human holds a handle that is connected by a cable to an aerial platform. The objective is to make the robot capable of safely guiding the human to a desired position, or along a desired path, by pulling him/her exploiting the tether.

We proposed a control strategy that makes the robot compliant to the human interaction and allows to exert forces to the human. These forces were properly designed to drive the human to a desired position. Using Lyapunov theory, we formally proved that the desired human position is asymptotically stable for the considered closed-loop system. Furthermore, we showed that the latter is output-strictly passive, which guarantees stability and robustness of the method even for time-varying inputs, nonzero model errors, and for nonzero extra human forces. An additional

³Other definitions of the distance between paths can be used. We believe that (48) allows to clearly show the envelope around the desired path in which the human will probably pass.

maneuver regulation strategy was designed to allow the robot guiding the human along a desired path.

The overall method was experimentally validated with a group of four subjects. The results showed that the system was able to keep the path-following error bounded. The robot correctly drives the human along the desired path, compensating for errors, and guaranteeing the stability.

From a practical point of view, we foresee the integration of onboard sensors for outdoor operations and for the onboard detection and avoidance of obstacles.

From a more scientific point of view, the human model could be enhanced to include the main body and arm elements, together with the heading. This should be considered in the controller to improve the control of the human configuration, i.e., position of the main body, heading, and relative position of the arm. A more precise hybrid position/force controller (like the one in [53]) could be applied, in order to finely control the intensity and direction of the force felt by the human, regardless to his/her velocity.

HRI aspects, like the acceptability of the system from the human, were not the focus of this work. However they will be analyzed in the future through a complete user study. A human-aware path planner could be designed to explicitly consider at the planning level a path acceptable by the human taking into account human-preferences in terms of distance to obstacles and dynamics of the motion [54], as well as adaptation to human pace [55]. The improvement of the indirect force-based communication between human and robot using additional stimulus should be investigated as well. Impulsive forces or wearable haptic devices could be used to enhance the human-robot interface. From one hand the robot should be able to estimate and then react to human intentions (e.g., start/stop the mission). From the other hand, the human awareness should be augmented providing additional information (e.g., distance to obstacles or the desired path).

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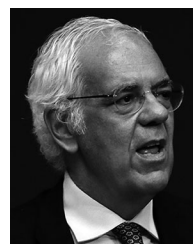


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and I-ARES projects, ESPRIT: MARTHA, PROMotion, ECLA, IST: COMETS, IST FP6 projects: COGNIRON, URUS, PHRIENDS, and FP7 projects: CHRIS, SAPHARI, ARCAS, SPENCER, H2020: MuMMER, France: ARA, VAP-RISP for planetary rovers, PROMIP, several ANR projects). His main research interests include robot decisional and control architectures, task and motion planning, multirobot cooperation, and human-robot interaction.

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Physical Human-Robot Interaction With a Tethered Aerial Vehicle: Application to a Force-Based Human Guiding Problem

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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 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 with a controller, inspired by the literature on flexible manipulators, that computes the desired interaction forces that properly guide the human. The stability of the system is formally proved with a Lyapunov-based argument. The system is also shown to be passive, and thus robust to nonidealities like model and tracking errors, additional human forces, time-varying inputs, and other external disturbances. We also design a maneuver regulation policy to simplify the path following problem. The global method has been experimentally validated on a group of four subjects, showing a reliable and safe pHRI.

Index Terms—Aerial systems, force control, motion control, mechanics and control, physical human-robot interaction (pHRI).

I. INTRODUCTION

AERIAL robotics is one of the research fields receiving a constantly growing interest. This is motivated by the wide range of applications, which unmanned aerial vehicles are useful for, e.g., monitoring, agriculture, etc. Beyond these contact-free applications, many investments and efforts have been recently dedicated to Aerial physical interaction (APhI). Several research labs and companies are conceiving and studying new aerial

robots with manipulation capabilities that can interact with the environment [1].

The research community already proposed several solutions to enhance physical interaction capabilities of aerial vehicles. Examples are rigid tools or articulated arms attached to standard unidirectional-thrust aerial vehicles [2], [3], or to tilted/tiltable multirotor platforms that are fully actuated [4]. These works showed the feasibility of APhI for different tasks like pushing, sliding [5], and transportation, allowing new applications as contact-based inspection [6] and assembly.

It is natural that the presence of such robots in our daily life will grow as well. This requires the next generation of aerial robots to be able to safely and reliably interact with the environment, but also with humans. So far, human-robot interaction (HRI) has been rarely addressed in the aerial robotics community. Most of the works focus on remote control proposing bilateral teleoperation methods to help humans control single and multiple aerial vehicles [7]. Recently, the teleoperation problem has been extended to APhI as well [8].

In these cases, humans and robots are in separate environments and the interaction is only virtual. The study of scenarios where aerial robots share the same environment of humans is still poorly addressed and limited to contactless HRI [9], [10]. Peshkova *et al.* [11] and Cauchard *et al.* [12] proposed a survey on the use of natural communication means like gestures, speech, and gaze direction to let the human interface with the robot.

Another important topic recently explored is the social acceptance of aerial robots [13]. In [14] the problem is addressed from a design point of view, analyzing how the propellers of multirotor platforms affect the comfort of humans. In a different direction, a few papers [15], [16] recently started to investigate the social constraints (distance, speed, direction of approach, etc.) that should be applied to the motion of an aerial robot in the proximity of a human. While human-aware motion planning has been substantially studied for ground robots [17], it is still very preliminary for aerial robots.

Therefore, the works presented so far focus only on contactless HRI for aerial robots. On the other hand, physical human-robot interaction (pHRI) for aerial vehicles is still an unexplored domain. To the best of our knowledge, the only work addressing this topic is [18] where a compliant controller based on an admittance filter is proposed. Compliance with respect to external forces is shown, but the interaction with the human is

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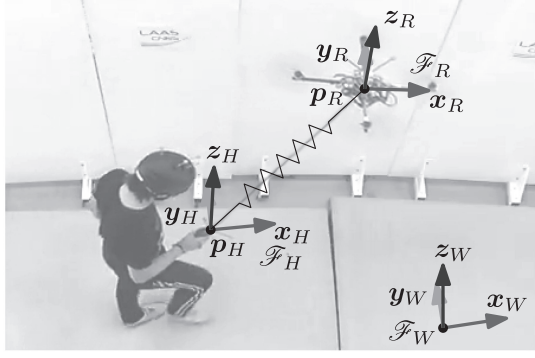


Fig. 1. Representation of the aerial human-tethered guiding system.

limited to simple contacts. The acceptance of touch-based HRI with aerial platforms is studied in [19].

Differently, research done on pHRI with ground manipulators is already quite extensive [20], [21]. Many control methods, most of them based on admittance [22] and passivity-based methods [23], have been proposed.

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 manuscript, we want to 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. Previous works [24]–[26] already showed that *tethered aerial vehicles* are very suitable for APhI. In [27], a complete study and literature review of the modeling and control for tethered aerial vehicles is provided. However, previous solutions cannot be directly applied because they consider the cable always taut. This would limit the validity of the proposed results. On the other hand, the modeling and control designs have been inspired by the study in [28] showing how the force along a cable can be used for cooperative-manipulation as indirect communication means among robotic agents.

The problem of guiding humans by aerial vehicles has indeed been already addressed in the literature but proposing contactless approaches only, e.g., based on sound [29] or vision [30]. In this work, we rather exploit the physical interaction using forces as more direct feedback. This solution particularly suits for persons with visual or hearing limitations. There have been a number of contributions of ground robots guiding humans [31], [32]. However, while they have considered a variety of capabilities to take into account human constraints and a variety of interaction modalities, only a small number of contributions considered pulling mobile robots or walking helpers for assisting elderly [33] or visually impaired people [34], [35]. However, the use of aerial vehicles in physical interaction with humans demands a careful treatment of the interaction forces and the stability of the system.

Inspired by the extensive literature of pHRI for ground manipulators, we first propose the use of an *admittance-based strategy* to make the robot comply with the human. We shall show that

exploiting this approach we can impose a desired cable force that has the function to pull the human toward the desired point. The design of such input requires particular attention due to the flexible nature of the physical link connecting the human to the robot. Taking inspiration from the theory on control of manipulators with elastic joints [36], we design a *robot-feedback solution* together with a feedforward term. The latter enforces the tautness of the cable. Approximating the human behavior as a mass-spring-damper system and considering the overall closed-loop system, we formally prove (though Lyapunov theory) that the proposed control method allows the robot to asymptotically steer the human to the desired position.

We also show that the system is *output-strictly passive*. This guarantees the stability of the system even in case of

- 1) model mismatches, disturbances and tracking errors,
- 2) time-varying reference for the human position, and
- 3) additional forces applied by the human to the cable (e.g., if he/she wants to stop).

This property grants robustness and safety of the method.

To address the problem of path following, we design a *maneuver regulation method* based on the works in [37] and [38]. This avoids the excessive growth of the tracking error which may lead to input saturation and, thus, instability, or too big deviations from the desired path.

The control performance and stability of the system are validated by real experiments first showing (from the best of our knowledge) safe and reliable physical interaction between a human and an aerial vehicle.

The manuscript is organized as follows. In Section II, we model the entire system. In Sections III and IV, we describe the proposed control strategy and we analyze the stability of the closed-loop system. The additional passivity property is shown in Section V. In Section VI, we describe the path following approach. The experimental results are reported in Section VII. Section VIII concludes this article.

II. MODELING

The system (see Fig. 1) is composed of an aerial vehicle tethered by a cable to a handle held by the hand of a human. To describe it, we define an *inertial frame*, $\mathcal{F}_W = \{O_W, x_W, y_W, z_W\}$, where O_W is the arbitrary origin and $\{x_W, y_W, z_W\}$ are its unit axes, with z_W opposite to gravity.

We consider the position of the human as the position of his/her hand holding the handle. A *body frame*, $\mathcal{F}_H = \{O_H, x_H, y_H, z_H\}$, is rigidly attached to the handle. Its origin O_H is centered in the point where the cable is attached to the handle. The state of the human is then given by the position of O_H and its linear velocity, defined by the vectors $\mathbf{p}_H = [p_{Hx} \ p_{Hy} \ p_{Hz}]^T \in \mathbb{R}^3$ and $\mathbf{v}_H = [v_{Hx} \ v_{Hy} \ v_{Hz}]^T \in \mathbb{R}^3$, respectively, both with respect to $\mathcal{F}_W$.

For the sake of designing a human-friendly robot controller, it is important to consider the human’s behavior when interacting with the environment. Ikeura *et al.* [39] analyzed the interaction forces during a task in which two humans cooperatively moves an object. It turned out that, for this kind of task, the human’s dynamics can be approximated with a mass-spring-damper system.

The validity of such a model has been confirmed in other works like [40]. In [41]–[43], this impedance model has been used as a basis to develop human-robot cooperative or teleoperated manipulation tasks. We consider the human's dynamics as

$$m_H \dot{\mathbf{v}}_H = -\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g \quad (1)$$

where $m_H \in \mathbb{R}_{>0}$ and the positive definite matrix $\mathbf{B}_H \in \mathbb{R}_{>0}^{3 \times 3}$ are the mass and apparent damping, respectively; $\mathbf{f}_c = [f_{cx} \ f_{cy} \ f_{cz}]^T \in \mathbb{R}^3$ is the cable force applied to the human at O_H ; $\mathbf{g}_H = m_H g \mathbf{z}_W$; $g \in \mathbb{R}_{>0}$ is the gravitational constant. Without loss of generality, we can assume the ground being flat and horizontal. $\mathbf{f}_g$ is the ground reaction force such that as follows:

- 1) $\mathbf{f}_g^T \mathbf{x}_W = \mathbf{f}_g^T \mathbf{y}_W = 0$;
- 2) $\mathbf{f}_g^T \mathbf{z}_W > 0$;
- 3) $\dot{\mathbf{v}}_H^T \mathbf{z}_W = \mathbf{v}_H^T \mathbf{z}_W = 0$, i.e., the human is constrained on the ground.

It follows that $\mathbf{f}_g = f_g \mathbf{z}_W$, where $f_g \in \mathbb{R}_{\geq 0}$ is the intensity of the reaction force. Notice that it has to be $\mathbf{f}_c^T \mathbf{z}_W < m_H g$. This prevents the human from being lifted by the robot. Practically, this is unfeasible for standard micro aerial vehicles.

The *human mass* m_H models the reactivity of the human to external forces. A low mass means a high willingness of following external forces. For a high mass, it is the opposite. The *damping effect* models the willingness of the human to stay still. Finally, in a mass-spring-damper system, the spring models the desire of reaching a specific point. However, in (1) there is no spring term since, in our scenario, the human is not aware of the desired path. The human simply follows the external force applied by the robot through the cable.

Remark 1: The precise modeling of the human body dynamics is out of the scope of this work. Through model (1), we want to capture only the macro navigation behavior of a human when pulled by an external force.

Remark 2: In this work, we focus on the control of the human hand position rather than his/her head position. This is motivated by the fact that a handle integrating positioning sensors like GPS, IMU, and cameras, is much more comfortable and wearable with respect to a fully equipped helmet. Nevertheless, the use of a kinematic model could be employed to estimate the human's head position if required.

The cable is attached from one side to the handle, and to the other side to the aerial vehicle at point O_R , which coincides with its center of mass. We define the *body frame* $\mathcal{F}_R = \{O_R, \mathbf{x}_R, \mathbf{y}_R, \mathbf{z}_R\}$, rigidly attached to the robot. Its configuration is described by the position of O_R with respect to (w.r.t.) $\mathcal{F}_W$ denoted by the vector $\mathbf{p}_R = [p_{Rx} \ p_{Ry} \ p_{Rz}]^T \in \mathbb{R}^3$. We complete the state of the robot with the linear velocity $\mathbf{v}_R = [v_{Rx} \ v_{Ry} \ v_{Rz}]^T \in \mathbb{R}^3$. We neglect the rotational coordinates and relative velocity since it is not relevant for the following derivations.

We assume that the robot is controlled by a position controller (e.g., MPC or SQP-based [44]), which minimizes the tracking error with respect to a desired C^2 trajectory, considering the full dynamics of the vehicle, its input and state limits, as well as

external disturbances. Thus, we can consider the robot closed-loop translational dynamics as the one of a double integrator plus a tracking error

$$\dot{\mathbf{v}}_R = \mathbf{u}_R + \boldsymbol{\delta} \quad (2)$$

where $\mathbf{u}_R \in \mathbb{R}^3$ is a virtual input to be designed, while $\boldsymbol{\delta} \in \mathbb{R}^3$ is a bounded variable that takes into account all the tracking errors due to model mismatches and uncertainties, input and state limits, external disturbances, and estimation errors. The model (2) means that the robot can track any desired acceleration $\mathbf{u}_R$ with a possibly nonzero error $\boldsymbol{\delta}$. This model is suitable for both multidirectional and unidirectional-thrust platforms. If we consider a multidirectional-thrust platform capable of controlling both position and orientation independently [45], (2) is a very good model of the closed-loop system with $\boldsymbol{\delta}$ very small. It is well known that a unidirectional-thrust vehicle is differentially flat w.r.t. to $\mathbf{p}_R$ and the rotation along the thrust direction (also called yaw angle). Therefore, the system is feedback linearizable and perfect tracking of any desired position trajectory of class C^4 (continuous up to the fourth time derivative) can be theoretically obtained. With $\boldsymbol{\delta}$ we take into account all possible errors. According to (2), the platform might seem “infinitely stiff” with respect to interaction forces. However, we shall suitably design the input $\mathbf{u}_R$ so as to reintroduce a compliant behavior.

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 O_H on the handle as

$$\mathbf{f}_c = t_c(\|\mathbf{l}_c\|) \mathbf{l}_c / \|\mathbf{l}_c\| \quad (3)$$

where $t_c(\|\mathbf{l}_c\|)$ represents the cable internal force intensity and $\mathbf{l}_c = \mathbf{p}_R - \mathbf{p}_H$. The force produced on the other end of the cable, namely on the robot at O_R , is equal to $-\mathbf{f}_c$.

In practice, the forces involved shall be very small (few newtons) and the distance between the human and the robot can be of few meters only. For these reasons, a thin and short cable can be used, which has negligible mass and inertia w.r.t. the ones of the robot and of the human.

Defining by $\bar{l}_c \in \mathbb{R}_{>0}$, the constant nominal length of the cable, we say that the cable is:

- 1) *Slack* when the distance between the two ends is shorter than $\bar{l}_c$. In this case, the cable force intensity is zero;
- 2) *Taut* when the distance between the two ends is equal or greater than $\bar{l}_c$. In this case, the cable force intensity follows Hooke's law.

In particular, $t_c(\|\mathbf{l}_c\|)$ is defined as

$$t_c(\|\mathbf{l}_c\|) = \begin{cases} k_c(\|\mathbf{l}_c\| - \bar{l}_c), & \text{if } \|\mathbf{l}_c\| - \bar{l}_c > 0 \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

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

Remark 3: Notice that $t_c(\|\mathbf{l}_c\|)$ can be any continuous and differentiable monotonically increasing function such that

$$t_c(\|\mathbf{l}_c\|) \geq \epsilon \|\mathbf{l}_c\| + \gamma, \text{ if } \|\mathbf{l}_c\| - \bar{l}_c > 0 \quad (5)$$

for some $\epsilon \in \mathbb{R}_{>0}$ and $\gamma \in \mathbb{R}$. This allows modeling more complex behaviors of the cable during the initial stretching/unstretching. We also consider the system to be always far from the maximum feasible tension.

III. CONTROL METHOD

Since the robot physically interacts with the human, it is important that the interaction is done in a compliant way, so as to always preserve stability and prevent the human to be armed or subjected to uncomfortable forces. For this problem, and more in general for physical interaction problems, a very common solution consists of using an *admittance control strategy* [46]. According to this method, the desired motion of the robot is computed as the one of an object with a specific admittance (mass, stiffness, and damping) subjected to the measured external force acting on the robot. In this way, one can reshape the apparent mechanical characteristics of the system. We define the robot control input u_R as

$$u_R = M_A^{-1} (-B_A v_R - f_c + u_A) \quad (6)$$

where the two positive definite diagonal matrices $M_A, B_A \in \mathbb{R}^{3 \times 3}$ are the virtual inertia and damping of the robot. $u_A \in \mathbb{R}^3$ is an additional input that will be defined in the following to achieve the desired control goal. Notice that to implement (6), only the state of the robot (p_R, v_R), and the force applied by the cable f_c are needed. The first can be retrieved with standard onboard sensors, while the second can be measured with a force sensor or estimated by a model-based observer [45].

It is useful to define the system state vector as $x = [p_H^T \ v_H^T \ p_R^T \ v_R^T]^T \in \mathcal{X} \subset \mathbb{R}^{12}$ and to write the dynamics in a more compact state form as $\dot{x} = f(x, u_A)$, where

$$f(x, u_A) = \begin{bmatrix} v_H \\ \frac{1}{m_H} (-g_H - B_H v_H + f_c + f_g) \\ v_R \\ M_A^{-1} (-B_A v_R - f_c + u_A) \end{bmatrix} \quad (7)$$

and f_c is computed as in (3). For the sake of deriving the control law and proving the asymptotic stability in nominal conditions, we consider a zero modeling error. Later we shall show the robustness of the method when $\delta \neq 0$.

Remark 4: The system has a *hybrid nature* characterized by two different behaviors according to the state of the cable.

- 1) When $x \in \mathcal{X}_S = \{x \in \mathcal{X} \mid \|l_c\| - \bar{l}_c \leq 0\}$, the cable is slack and the cable force is zero, i.e., $f_c = 0$. In this condition, the robot and human evolve independently.
- 2) When $x \in \mathcal{X}_T = \{x \in \mathcal{X} \mid \|l_c\| - \bar{l}_c > 0\}$, the cable is taut and the cable force is nonzero, i.e., $f_c \neq 0$. In this condition, the robot and human interact with each other through the cable force.

When the cable is taut the system appears to be a couple of mass-damper elements connected by a spring. This system is similar to an elastic manipulator where the actuator (the robot) is connected to the end-effector (the human) by an elastic element (the cable). For this system, we want to control the position of the end-effector (human position) by the input force u_A generated

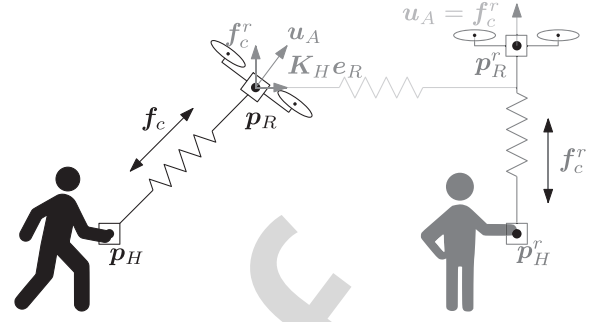


Fig. 2. Working principle of the control method. On the left the current state, on the right in opaque, the final desired state.

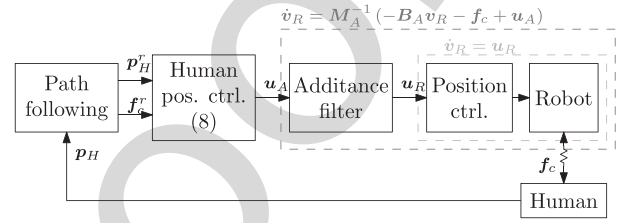


Fig. 3. Block diagram of the overall control method.

by the actuator (robot). Given this parallelism, we naturally took inspiration from the state of the art on control of manipulators with elastic joints [36].

Without the elastic element, the most natural choice for the design of a linear controller is to apply a simple proportional-derivative feedback from the end-effector position and velocity. However, considering a single link rotating on a horizontal plane and actuated with a motor through an elastic joint coupling, it has been proven that a feedback action entirely based on the end-effector position and velocity leads to instability, no matter the gain values [36].

The most preferred and grounded solution for manipulators with elastic joints is to apply a feedback completely based on the motor variables. If the proportional and derivative gains are strictly positive, then the closed-loop system will be asymptotically stable. Notice that, given a desired end-effector position, the desired motor value is computed inverting the dynamic model whose parameters need to be known.

To implement this control law, we only need a proportional feedback w.r.t. the robot position. The damping action w.r.t. the robot velocity is already present in (6). Thus, we set

$$u_A = K_H e_R + f_c^r \quad (8)$$

where $K_H = \text{diag}(k_H, k_H, 0)$ with $k_H \in \mathbb{R}_{>0}$, $e_R = p_R^r - p_R$ is the robot position error, p_R^r is the robot position of reference, and $f_c^r \in \mathbb{R}^3$ is a constant forcing input. In practice, f_c^r is the desired cable force. Fig. 2 explains the working principle of the controller, while Fig. 3 shows its block diagram.

IV. EQUILIBRIA AND STABILITY ANALYSIS

In the following, we shall show that, by properly choosing p_R^r and f_c^r , the control law (8) can steer the human position to the desired value.

350 *Theorem 1:* Let us define $\mathbf{p}_H^r \in \mathbb{R}^3$ as the human position
 351 reference such that $\mathbf{z}_W^\top \mathbf{p}_H^r = 0$. Considering the system (7)
 352 under the control law (8) where

$$\mathbf{f}_c^r = f_z \mathbf{z}_W \quad (9)$$

$$\mathbf{p}_R^r = \mathbf{p}_H^r + \mathbf{f}_c^r \left(\frac{1}{k_c} + \frac{\bar{l}_c}{\|\mathbf{f}_c^r\|} \right) \quad (10)$$

353 the zero velocity equilibrium $\bar{\mathbf{x}} = [\mathbf{p}_H^{r\top} \mathbf{0}^\top \mathbf{p}_R^{r\top} \mathbf{0}^\top]^\top \in \mathcal{X}_T$
 354 is asymptotically stable if $0 < f_z < m_H g$.

355 *Proof:* Let us first compute the equilibrium state. Plugging
 356 (8) into (7) yields the final closed-loop dynamics

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{v}_H \\ \frac{1}{m_H} (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g) \\ \mathbf{v}_R \\ \mathbf{M}_A^{-1} (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{K}_H \mathbf{e}_R + \mathbf{f}_c^r) \end{bmatrix}. \quad (11)$$

357 Imposing the stability condition into (11), i.e., $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) = \mathbf{0}$,
 358 from the second row we get

$$\mathbf{f}_c = (f_g - m_H g) \mathbf{z}_W. \quad (12)$$

359 This means that at the equilibrium the cable force, and thus, the
 360 cable itself, have to be vertical. From the fourth row in (11) and
 361 replacing (12), we obtain

$$\mathbf{0} = (f_g - m_H g + f_z) \mathbf{z}_W + \mathbf{K}_H \mathbf{e}_R. \quad (13)$$

362 Expanding the components of $\mathbf{K}_H \mathbf{e}_R$ along the axes of $\mathcal{F}_W$, it
 363 is easy to verify that (13) is satisfied if

$$\mathbf{x}_W^\top \mathbf{e}_R = 0 \quad \mathbf{y}_W^\top \mathbf{e}_R = 0 \quad f_g = m_H g - f_z \quad (14)$$

364 which implies

$$p_{Rx} = p_{Rx}^r \quad p_{Ry} = p_{Ry}^r \quad \mathbf{f}_c = \mathbf{f}_c^r. \quad (15)$$

365 We recall that the intensity of the ground reaction force should
 366 be equal or greater than zero, i.e., $f_g \geq 0$. Thus, it has to be
 367 $f_z \leq m_H g$. Notice that there are no stable configurations for
 368 which $\mathbf{f}_c = \mathbf{0}$, i.e., such that $\|\mathbf{l}_c\| \leq \bar{l}_c$.

369 To conclude the computation of the equilibrium configuration,
 370 we need to calculate the position of the human $\mathbf{p}_H$, and the
 371 vertical position of the robot p_{Rz} . Replacing conditions (15)
 372 into (3), after a few simple calculations, we obtain

$$\begin{bmatrix} p_{Rx}^r \\ p_{Ry}^r \\ p_{Rz} \end{bmatrix} + \begin{bmatrix} p_{Hx} \\ p_{Hy} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \frac{f_z}{k_c} + \bar{l}_c \end{bmatrix}. \quad (16)$$

373 Replacing also (9) and (10), we finally obtain that, at the equilib-
 374 rium, $\mathbf{p}_H = \mathbf{p}_H^r$ and $\mathbf{p}_R = \mathbf{p}_R^r$. Thus, the only equilibrium state
 375 for the system (7) is $\bar{\mathbf{x}} = [\mathbf{p}_H^{r\top} \mathbf{0}^\top \mathbf{p}_R^{r\top} \mathbf{0}^\top]^\top \in \mathcal{X}_T$.

376 Now we analyze the stability of the equilibrium state $\bar{\mathbf{x}}$ em-
 377 ploying a Lyapunov-based analysis. Let us define the following
 378 Lyapunov function:

$$V(\mathbf{x}) = V_1(\mathbf{x}) + V_2(\mathbf{x}) + V_0 \quad (17)$$

379 where

$$V_1(\mathbf{x}) = \frac{1}{2} (m_H \mathbf{v}_H^\top \mathbf{v}_H + \mathbf{v}_R^\top \mathbf{M}_A \mathbf{v}_R + \mathbf{e}_R^\top \mathbf{K}_H \mathbf{e}_R) \quad (18)$$

$$V_2(\mathbf{x}) = \int_{l_{c0}}^{\|\mathbf{l}_c(t)\|} t_c(\tau) d\tau - \mathbf{l}_c^\top \bar{\mathbf{f}}_c \quad (19)$$

$$V_0 = f_z^2 / k_c + 2\bar{l}_c f_z. \quad (20)$$

We defined $l_{c0} = \|\mathbf{l}_c(0)\|$. In the following, we shall show that
 the defined Lyapunov function $V(\mathbf{x})$ is continuously differen-
 tiable and radially unbounded.

$V(\mathbf{x})$ is continuously differentiable because V_1 , V_2 , V_0 are
 clearly continuously differentiable.

We then show that (17) is *radially unbounded* (also called
coercive), i.e., $\lim_{\|\mathbf{x}\| \rightarrow \infty} V(\mathbf{x}) = \infty$ with $\mathbf{x} \in \mathcal{X}$. We have that
 clearly $\lim_{\|\mathbf{x}\| \rightarrow \infty} V_1(\mathbf{x}) = \infty$ for $\mathbf{x} \in \mathcal{X}$. For V_2 , we first notice
 that, thanks to (5), there exist some $\epsilon \in \mathbb{R}_{>0}$ and $\gamma \in \mathbb{R}$ such that

$$\int_{l_{c0}}^{\|\mathbf{l}_c(t)\|} t_c(\tau) d\tau \geq \frac{\epsilon}{2} \|\mathbf{l}_c\|^2 + \gamma \|\mathbf{l}_c\|. \quad (21)$$

This implies that

$$\begin{aligned} \lim_{\|\mathbf{x}\| \rightarrow \infty} V_2(\mathbf{x}) &\geq \lim_{\|\mathbf{x}\| \rightarrow \infty} \epsilon \|\mathbf{l}_c\|^2 + \gamma \|\mathbf{l}_c\| - \|\mathbf{l}_c\| \|\mathbf{f}_c^r\| \\ &= \lim_{\|\mathbf{x}\| \rightarrow \infty} \|\mathbf{l}_c\|^2 \left(\frac{\epsilon}{2} + \frac{\gamma}{\|\mathbf{l}_c\|} - \frac{\|\mathbf{f}_c^r\|}{\|\mathbf{l}_c\|} \right) = +\infty. \end{aligned} \quad (22)$$

This is enough to show that (17) is radially unbounded.

In order to prove that $V(\mathbf{x})$ is positive definite, we show that it
 has a unique global minimum in $\bar{\mathbf{x}}$, i.e., $\bar{\mathbf{x}} = \arg \min_{\mathbf{x}} V(\mathbf{x})$ and
 $V(\bar{\mathbf{x}}) = 0$. Since $V(\mathbf{x})$ is continuous and radially unbounded,
 for [47, Th. 1.15], we can say that the Lyapunov function (17) has
 a global minimum. Now we can look for this minimum among
 the stationary points, i.e., the $\mathbf{x}$ where the gradient $\nabla V(\mathbf{x}) = \mathbf{0}$.

It is clear that $\nabla V_1(\mathbf{x}) = \mathbf{0}$ only if $\mathbf{v}_H = \mathbf{v}_R = \mathbf{0}$, $p_{Rx} =$
 p_{Rx}^r , and $p_{Ry} = p_{Ry}^r$. Regarding $V_2(\mathbf{x})$, let us consider its gra-
 dient w.r.t. the cable configuration $\mathbf{l}_c$. For every $\mathbf{x} \in \mathcal{X}_S$

$$\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) = \frac{\partial V_2(\mathbf{x})}{\partial \mathbf{l}_c} = \frac{\partial}{\partial \mathbf{l}_c} \left(\int_{l_{c0}}^{\|\mathbf{l}_c\|} t_c(\tau) d\tau \right) - \mathbf{f}_c^{r\top}. \quad (23)$$

Let us notice that for the Leibniz integral rule, we have that

$$\begin{aligned} \frac{\partial}{\partial \mathbf{l}_c} \left(\int_{l_{c0}}^{\|\mathbf{l}_c\|} t_c(\tau) d\tau \right) &= t_c(\|\mathbf{l}_c\|) \frac{\partial \|\mathbf{l}_c\|}{\partial \mathbf{l}_c} - t_c(l_{c0}) \frac{\partial l_{c0}}{\partial \mathbf{l}_c} \\ &= t_c(\|\mathbf{l}_c\|) \frac{\mathbf{l}_c^\top}{\|\mathbf{l}_c\|} = \mathbf{f}_c^\top \end{aligned} \quad (24)$$

where we used (3). Plugging (24) into (23) yields $\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) =$
 $\mathbf{f}_c^\top - \mathbf{f}_c^{r\top}$. It follows that $\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) = \mathbf{0}$ if and only if:

$$t_c(\|\mathbf{l}_c\|) \mathbf{l}_c^\top / \|\mathbf{l}_c\| = \mathbf{f}_c^\top = \mathbf{f}_c^{r\top}. \quad (25)$$

Condition (25) holds only if

- a) $t_c(\|\mathbf{l}_c\|) = \|\mathbf{f}_c^r\|$ and $\mathbf{l}_c / \|\mathbf{l}_c\| = \mathbf{f}_c^r / \|\mathbf{f}_c^r\|$; or
- b) $t_c(\|\mathbf{l}_c\|) = -\|\mathbf{f}_c^r\|$ and $\mathbf{l}_c / \|\mathbf{l}_c\| = -\mathbf{f}_c^r / \|\mathbf{f}_c^r\|$.

In these two cases, the cable produces the same force $\mathbf{f}_c^r$, but
 in case 1) the cable is stretched, while in case 2) the cable is
 compressed. However, cables cannot be compressed and, thus,

case 2) is not feasible for definition. The only solution is

$$\mathbf{l}_c = \left(\frac{1}{k_c} + \frac{\bar{l}_c}{\|\mathbf{f}_c^r\|} \right) \mathbf{f}_c^r \quad (26)$$

which, recalling (10), leads to the conclusion that $\nabla_{\mathbf{l}_c} V_2(\mathbf{x}) = \mathbf{0}$ only if $\mathbf{p}_H = \mathbf{p}_H^r$ and $\mathbf{p}_R = \mathbf{p}_R^r$. This completes the proof that $\nabla V(\mathbf{x}) = \mathbf{0}$ only if $\mathbf{x} = \bar{\mathbf{x}}$, and, thus, $\bar{\mathbf{x}} = \arg \min_{\mathbf{x}} V(\mathbf{x})$. Finally, it is easy to verify that $V_1(\bar{\mathbf{x}}) = 0$ and V_0 has been defined such that $V_1(\bar{\mathbf{x}}) + V_2(\bar{\mathbf{x}}) = -V_0$, in order to make $V(\bar{\mathbf{x}}) = 0$. This proves that $V(\mathbf{x})$ is positive definite.

We can now compute the time derivative of (17). Similarly to (24), applying the Leibniz integral rule, we have that

$$\frac{d}{dt} \left(\int_{l_{c0}}^{\|\mathbf{l}_c(t)\|} t_c(\tau) d\tau \right) = t_c(\|\mathbf{l}_c\|) \frac{\partial \|\mathbf{l}_c\|}{\partial \mathbf{l}_c} \dot{\mathbf{l}}_c = \mathbf{f}_c^\top \dot{\mathbf{l}}_c. \quad (27)$$

Therefore, the time derivative of (17) is equal to

$$\begin{aligned} \dot{V}(\mathbf{x}) = & \mathbf{v}_H^\top (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g) \\ & + \mathbf{v}_R^\top (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{K}_H \mathbf{e}_R + \mathbf{f}_c^r) \\ & - \mathbf{v}_R \mathbf{K}_H \mathbf{e}_R + \dot{\mathbf{l}}_c \mathbf{f}_c - \dot{\mathbf{l}}_c \mathbf{f}_c^r. \end{aligned} \quad (28)$$

After few simple algebraic steps we get

$$\dot{V}(\mathbf{x}) = -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H - \mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R. \quad (29)$$

$\dot{V}(\mathbf{x})$ is clearly negative semidefinite, in $\mathcal{X}$.

Since $\dot{V}(\mathbf{x})$ is only negative semidefinite, to prove the asymptotic stability we rely on *LaSalle's invariance principle* [48]. The Lyapunov candidate $V(\mathbf{x})$ is a continuously differentiable function. Let us define a positively invariant set $\Omega_\alpha = \{\mathbf{x} \in \mathcal{X} \mid V(\mathbf{x}) \leq \alpha \text{ with } \alpha \in \mathbb{R}_{>0}\}$. By construction, Ω_α is compact since (17) is radially unbounded. Notice that Ω_0 contains only $\bar{\mathbf{x}}$. Then, we need to find the largest invariant set $\mathcal{M}$ in $\mathcal{E} = \{\mathbf{x} \in \Omega_\alpha \mid \dot{V}(\mathbf{x}) = 0\}$. A trajectory $\mathbf{x}(t)$ belongs identically to $\mathcal{E}$ if $\dot{V}(\mathbf{x}(t)) \equiv 0 \Leftrightarrow \mathbf{v}_H(t) = \mathbf{v}_R(t) \equiv \mathbf{0} \Leftrightarrow \dot{\mathbf{v}}_H = \dot{\mathbf{v}}_R = \mathbf{0}$. As we saw previously in the calculation of the equilibria, this is verified only if $\mathbf{x} = \bar{\mathbf{x}}$. Therefore, $\mathcal{M}$ contains only $\bar{\mathbf{x}}$. All conditions of LaSalle's principle are satisfied and $\bar{\mathbf{x}}$ is globally asymptotically stable. ■

To get more hints on the behavior of the system let us analyze it for $\mathbf{x} \in \mathcal{X}_S$ (slack cable). Human's and robot's dynamics are independent and the first results to be

$$m_H \dot{\mathbf{v}}_H = -\mathbf{B}_H \mathbf{v}_H. \quad (30)$$

Whatever is the initial condition $\lim_{t \rightarrow +\infty} \mathbf{v}_H(t) = \mathbf{0}$. Notice that the human will stop but his final position depends only on the initial conditions. For the robot dynamics, let us write first the dynamic equation along $\mathbf{x}_W$

$$m_A \dot{\mathbf{v}}_{Rx} = -b_A \mathbf{v}_{Rx} + k_H \mathbf{e}_{Rx} \quad (31)$$

where $m_A \in \mathbb{R}_{>0}$ and $b_A \in \mathbb{R}_{>0}$ are such that $\mathbf{M}_A = \text{diag}(m_A, m_A, m_A)$ and $\mathbf{B}_A = \text{diag}(b_A, b_A, b_A)$. It is easy to verify that the state $(\mathbf{v}_{Rx}, \mathbf{e}_{Rx}) = (0, 0)$ is asymptotically stable. The same for the robot dynamics along $\mathbf{y}_W$: the state $(\mathbf{v}_{Ry}, \mathbf{e}_{Ry}) = (0, 0)$ is asymptotically stable. On the other hand, the robot dynamics along $\mathbf{z}_W$ results to be

$$m_A \dot{\mathbf{v}}_{Rz} = -b_A \mathbf{v}_{Rz} + f_z. \quad (32)$$

Whatever is the initial condition, $\lim_{t \rightarrow +\infty} \mathbf{v}_{Rz}(t) = f_z/b_A > 0$. This means that the robot horizontal position will tend to the desired one, while, along the vertical axes, it will tend to fly up until the cable will become taut. In fact, $\frac{d}{dt} \|\mathbf{l}_c(t)\| = \|\mathbf{v}_R(t) - \mathbf{v}_H(t)\| \rightarrow f_z/b_A > 0$. This means that $\|\mathbf{l}_c\|$ will grow until $\|\mathbf{l}_c\| > \bar{l}_c$, i.e., until the cable becomes taut. After this instant, the robot interacts with the human through the cable and eventually pulls him/her to the desired position. According to the specific initial condition, it might be that the state trajectory might pass from $\mathcal{X}_T$ to $\mathcal{X}_S$ several times. However, the previous Lyapunov-based reasoning proofs that eventually the system will converge to $\bar{\mathbf{x}}$, no matter the initial conditions.

Remark 5: Although the system seems passive for every virtual admittance of the robot, the dynamics of the robot actuators and sensors, as well as the real implementation of the control framework, impose minimum values for the virtual inertia and damping. This is in accordance with the practical intuition that minimum compliance of the interaction is required. Notice that the mechanical flexibility of some elements, e.g., the cable, helps in meeting such requirements.

V. ROBUSTNESS OF THE SYSTEM

Previously, we formally proved that an admittance strategy together with controller (8) asymptotically steer the human position to a desired constant position $\mathbf{p}_H^r$. This is valid if the human follows the force provided by the robot without exerting other forces except for the damping effect. In the following, we shall show the intrinsic robustness of the controller against time-varying position references, modeling errors, and possible additional human forces (e.g., if he/she wants to stop).

A. Time-Varying Position Reference

We remark that with the control law (8), the resulting final path followed by the human to arrive at the goal only depends on the initial conditions. In a real application, this is not a desired behavior, e.g., when a blind human must be guided to a specific point in an environment with possible obstacles. In this scenario, it is more likely that the human position reference is not constantly equal to the final goal position, but is rather a time-varying path $\mathbf{p}_H^r(t)$ that leads the human to the goal, avoiding obstacles, or possible sources of danger. To face this objective, taking into account a possibly time-varying path $\mathbf{p}_H^r(t)$, and time-varying desired cable force $\mathbf{f}_c^r(t)$, for $t \in [0, T]$, we modify the original control law (8) as

$$\mathbf{u}_A(t) = \mathbf{K}_H \mathbf{e}_{RT}(t) + \mathbf{f}_T^r + \mathbf{u}'_A(t) \quad (33)$$

where $\mathbf{e}_{RT}(t) = \mathbf{p}_R^r(T) - \mathbf{p}_R(t)$, $\mathbf{f}_T^r = \mathbf{f}_c^r(T) = f_z \mathbf{z}_W$, and $\mathbf{u}'_A(t)$ is such that $\mathbf{u}_A(t) = \mathbf{K}_H(\mathbf{p}_R^r(t) - \mathbf{p}_R(t)) + \mathbf{f}_c^r(t)$ for every $t \in [0, T]$. This is a simple way to gather in $\mathbf{u}'_A$ the time-varying desired quantities. It results that $\mathbf{u}'_A(t) = \mathbf{K}_H(\mathbf{p}_R^r(t) - \mathbf{p}_R^r(T)) + (\mathbf{f}_c^r(t) - \mathbf{f}_c^r(T))$.

To ensure that the system remains stable even when the human position reference is time-varying, i.e., for $\mathbf{u}'_A(t) \neq \mathbf{0}$, we shall prove that the system is output-strictly passive w.r.t. the input-output pair $(\mathbf{u}_1, \mathbf{y}_1) = (\mathbf{u}'_A, \mathbf{v}_R)$.

Theorem 2: If $\mathbf{u}_A$ is defined as in (33) for a certain $\mathbf{p}_H^r(t)$ and $\mathbf{f}_c^r(t)$, with $t \in [0, T]$, then system (7) is output-strictly passive w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}_1, \mathbf{y}_1) = (\mathbf{u}'_A, \mathbf{v}_R)$.

Proof: In the proof of Theorem 1, we already showed that (17) is a continuously differentiable positive definite function. Replacing (33) into (7), and differentiating (17), we obtain

$$\dot{V}(\mathbf{x}) = -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H - \mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R + \mathbf{u}_A'^\top \mathbf{v}_R \quad (34)$$

$$\leq -\mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R + \mathbf{u}_A'^\top \mathbf{v}_R = \mathbf{u}_1^\top \mathbf{y}_1 - \mathbf{y}_1^\top \phi_1(\mathbf{y}_1) \quad (35)$$

with $\phi_1(\mathbf{y}_1) = \mathbf{B}_A \mathbf{v}_R$. Since $\mathbf{y}_1^\top \phi_1(\mathbf{y}_1) \geq 0$ for every $\mathbf{y}_1 \neq \mathbf{0}$, we can conclude that the system (7) is *output-strictly passive* [48]. ■

Given the passivity of the system, we have that for a bounded input $\mathbf{u}'_A$, i.e., bounded reference trajectories, the overall energy of the system remains bounded too. Furthermore, the system stabilizes to a constant value as soon as $\mathbf{u}'_A$ becomes constant again. This means that, while the robot moves following $\mathbf{p}_R^r(t)$ and $\mathbf{f}_c^r(t)$, the overall state of the system will remain bounded. It will then converge to another specific equilibrium configuration when $\mathbf{u}'_A$ becomes constant.

B. Modeling Errors

As we mentioned in Section II, nonzero model errors might appear due to model uncertainties, nonlinear effects, external disturbances, etc. With $\delta \neq \mathbf{0}$, the system dynamics becomes

$$\mathbf{f}(\mathbf{x}, \mathbf{u}_A) = \begin{bmatrix} \mathbf{v}_H \\ \frac{1}{m_H} (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g) \\ \mathbf{v}_R \\ \mathbf{M}_A^{-1} (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{u}_A) + \delta \end{bmatrix}. \quad (36)$$

We shall show that the system remains stable also when $\delta \neq \mathbf{0}$.

Theorem 3: System (36) under the control law (8) is output-strictly passive w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}_2, \mathbf{y}_2) = (\delta, \mathbf{v}_R)$.

Proof: We can rewrite equations (36) and (8) as (7) and

$$\mathbf{u}_A = \mathbf{K}_H \mathbf{e}_R + \mathbf{f}_c^r + \mathbf{M}_A \delta \quad (37)$$

respectively. Noticing the similarity between (37) and (33), the proof follows as the one of Theorem 2. ■

Given the passivity of the system, we have that for a bounded model error δ , the overall energy of the system remains bounded too. Passivity is a well-known robust property, especially w.r.t. model uncertainties. This means that, to ensure the stability of the system, an accurate model of the system is not necessary, as far as the passivity is guaranteed.

C. Additional Human Force

In Section II, we modeled the human as a simple mass-damper system subjected to the force exerted by the cable only. Nevertheless, during the guidance, the human may want to stop or deviate from the desired path, e.g., to pick up an object. In these cases, the human will generate additional forces that will modify his/her trajectory. It is important that, even in this condition, the

system is guaranteed to be stable and that the state converges to the desired value as soon as the human forces go back to zero.

We define the vector $\mathbf{u}_H \in \mathbb{R}^3$ as the sum of all the forces applied by the human that generate a translational motion. The closed-loop system dynamics, expressed in (7), becomes

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{v}_H \\ \frac{1}{m_H} (-\mathbf{g}_H - \mathbf{B}_H \mathbf{v}_H + \mathbf{f}_c + \mathbf{f}_g + \mathbf{u}_H) \\ \mathbf{v}_R \\ \mathbf{M}_A^{-1} (-\mathbf{B}_A \mathbf{v}_R - \mathbf{f}_c + \mathbf{u}_A) \end{bmatrix}. \quad (38)$$

To ensure that the system remains stable even when the human forces are not zero, i.e., for $\mathbf{u}_H \neq \mathbf{0}$, we shall prove that the system is output-strictly passive w.r.t. the input-output pair $(\mathbf{u}_3, \mathbf{y}_3) = (\mathbf{u}_H, \mathbf{v}_H)$.

Theorem 4: System (38) under the control law (8) is output-strictly passive w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}_3, \mathbf{y}_3) = (\mathbf{u}_H, \mathbf{v}_H)$.

Proof: In the proof of Theorem 1, we already showed that (17) is a continuously differentiable positive definite function. Considering (38) and differentiating (17), we obtain

$$\dot{V}(\mathbf{x}) = -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H - \mathbf{v}_R^\top \mathbf{B}_A \mathbf{v}_R + \mathbf{u}_H^\top \mathbf{v}_H \quad (39)$$

$$\leq -\mathbf{v}_H^\top \mathbf{B}_H \mathbf{v}_H + \mathbf{u}_H^\top \mathbf{v}_H = \mathbf{u}_3^\top \mathbf{y}_3 - \mathbf{y}_3^\top \phi_2(\mathbf{y}_3) \quad (40)$$

with $\phi_2(\mathbf{y}_3) = \mathbf{B}_H \mathbf{v}_H$. Since $\mathbf{y}_3^\top \phi_2(\mathbf{y}_3) \geq 0$ for every $\mathbf{y}_3 \neq \mathbf{0}$, we can conclude that the system (38) is *output-strictly passive* [48]. ■

Conclusions similar to the ones in Section V-A can be drawn. In particular, we have that for a bounded input $\mathbf{u}_H$, i.e., bounded human forces, the overall energy of the system remains bounded too. Furthermore, the system stabilizes to a constant value as soon as $\mathbf{u}_H$ goes back to zero or balance the cable force. This means that while the human moves subjected to a nonzero (but bounded) human force $\mathbf{u}_H \neq \mathbf{0}$, the overall state of the system will remain bounded. It will then converge to another specific equilibrium configuration as soon as $\mathbf{u}_H$ goes back to zero or balance the cable force.

In particular, considering the case in which the human wants to stop in a certain position $\mathbf{p}_H$, it has to be that $\mathbf{v}_H = \dot{\mathbf{v}}_H = \mathbf{0}$. This means that $\mathbf{u}_H = \mathbf{f}_c$. It is then easy to verify that the robot's position at the new equilibrium will be such that

$$\mathbf{l}_c = (\|\beta\| + \bar{l}_c k_c) \begin{bmatrix} k_c + k_H & 0 & 0 \\ 0 & k_c + k_H & 0 \\ 0 & 0 & k_c \end{bmatrix}^{-1} \frac{\beta}{\|\beta\|} \quad (41)$$

where $\beta = \mathbf{K}_H(\mathbf{p}_R^r - \mathbf{p}_H) + \mathbf{f}_c^r$. Using a Lyapunov-based argument similar to the one in the proof of Theorem 1, it is easy to show that such zero-velocity equilibrium state is asymptotically stable. This provides a high level of robustness to different human behaviors.

Following the same reasoning of Theorems 2–4, we can ensure that the system remains stable even when the human position reference is time-varying, there are nonzero model errors, and the human forces are not zero.

Theorem 5: System (38) under the control law $\mathbf{u}_A(t) = \mathbf{K}_H \mathbf{e}_{RT}(t) + \mathbf{f}_T^r + \mathbf{u}'_A(t) + \mathbf{M}_A \delta$ is output-strictly passive

w.r.t. the storage function (17) and the input-output pair $(\mathbf{u}, \mathbf{y}) = ([\mathbf{u}_1^\top \mathbf{u}_2^\top \mathbf{u}_3^\top]^\top, [\mathbf{y}_1^\top \mathbf{y}_2^\top \mathbf{y}_3^\top]^\top)$.

Proof: The proof is trivial and follows the same steps of the proof of Theorems 2–4. ■

VI. PATH-FOLLOWING PROBLEM

In Section V-A, we shown that even if the human position and cable force of reference are time-varying, the system remains stable. This can be exploited for the problem of following a desired path. In the following, we shall define a strategy to lead the human along the desired path, allowing him/her to stop or slightly deviate from the path without causing instability.

Given a desired human path¹ defined by its *parametric representation* $\mathbf{p}_H^d(s) \in \mathbb{R}^3$, where $s \in [0, 1]$ is called *parameter*, we first define the desired cable force along the path $\mathbf{f}^d(s) \in \mathbb{R}^3$. This is the force that we would like the human feels all along the path. $\mathbf{f}^d(s)$ works as a feedforward term, i.e., it is the nominal pulling force that drags the human along the path. In standard path-following problems [49], this is similar to defining the desired velocity along the path. Inspired by most of the related works, we define

$$\mathbf{f}^d(s) = \mathbf{f}_{xy}^d(s) + \mathbf{f}_z^d \quad (42)$$

where

$$\mathbf{f}_{xy}^d(s) = \mathbf{f}_{xy}^d(s) \frac{\nabla_s \mathbf{p}_H^d(s)}{\|\nabla_s \mathbf{p}_H^d(s)\|}, \quad \mathbf{f}_z^d = f_z \mathbf{z}_W \quad (43)$$

and $\mathbf{f}_{xy}^d(s)$ is such that $\mathbf{f}_{xy}^d(1) = 0$. In particular, here, we chose a trapezoidal profile that starts with a nonzero value. Notice that the planar pulling force $\mathbf{f}_{xy}^d(s)$ is tangential to the path and correctly drive the human along the path. Furthermore, at the end of the path, i.e., for $s = 1$, $\mathbf{f}^d(1) = \mathbf{f}_z^d$, which guarantees $\mathbf{p}_H^d(1)$ being asymptotically stable if $\mathbf{p}_H^r = \mathbf{p}_H^d(1)$ and $\mathbf{f}_c^r = \mathbf{f}^d(1)$, as it is shown in Section IV.

Now that, we have the desired *maneuver* $\eta = \{(\mathbf{p}_H^d(s), \mathbf{f}^d(s)) \in \mathbb{R}^3 \times \mathbb{R}^3 \mid s \in [0, 1]\}$, considering the control strategy described so far [(6) and (8)], we seek a method to choose $\mathbf{p}_H^r(t)$ and $\mathbf{f}_c^r(t)$ such that $\mathbf{p}_H(t)$ asymptotically converges to the path $\mathbf{p}_H^d(s)$, i.e.,

$$\lim_{t \rightarrow \infty} \|\mathbf{p}_H(t) - \mathbf{p}_H^d(s^*(t))\| \quad (44)$$

for any smooth function $s^*(t) : \mathbb{R} \rightarrow [0, 1]$ [50]. We first set

$$\mathbf{p}_H^r(t) = \mathbf{p}_H^d(s^*(t)), \quad \mathbf{f}_c^r(t) = \mathbf{f}^d(s^*(t)). \quad (45)$$

We only have to define $s^*(t)$. A very simple way would be to define a time law such that $s^*(0) = 0$ and $s^*(T) = 1$ for a given time $T \in \mathbb{R}_{>0}$, e.g., using a spline or a linear function. However, this would fall into the *trajectory tracking* category, which suffers from some robustness issues. Imagine that the human decides to stop or to slightly deviate from the path. At the same time, the desired reference advances increasing the position error. If not tackled accurately, e.g., with saturations,

the increase of the position error might saturate the robot inputs making the system unstable. Even if inputs saturation are properly addressed, once the human decides to follow again the robot, the latter will try to quickly catch up with the moving desired state. The desired path will not be followed anymore, and possible collisions with obstacles may occur.

To avoid this issue, we implement a *maneuver regulation* approach similar to the one in [37] and [38], defining

$$s^*(t) = \arg \min_{s \in [0, 1]} \|\mathbf{p}_H^d(s) - \mathbf{p}_H(t)\|. \quad (46)$$

At every time t , the reference human position is the one belonging to $\mathbf{p}_H^d$ and closer to the actual human position. $\mathbf{f}_c$ is computed accordingly. It is clear that employing this solution, even if the human stops, the position error will not grow. In fact, $\mathbf{p}_H^r$ will remain the same. Notice that to have (46) well defined, $\mathbf{p}_H^d$ must be nonintersecting. Furthermore, it must be that $\mathbf{f}_{xy}^d(s) \neq 0$ for all $s \neq 1$. This is necessary to make the human always advance along the path.

Replacing the maneuver regulation policy (45) into the original controller (8), we obtain

$$\mathbf{u}_A(t) = \mathbf{K}_H(\mathbf{p}_H^d(s^*(t)) - \mathbf{p}_H(t)) + \mathbf{f}_{xy}^d(s^*(t)) + \mathbf{f}_z^d \quad (47)$$

where $\mathbf{p}_H^d$ is computed as in (10) with $\mathbf{p}_H^d$ and $\mathbf{f}^d$ instead of $\mathbf{p}_H^r$ and $\mathbf{f}_c^r$, respectively. The overall control action is divided into three parts as follows.

- 1) The first is a proportional term that tends to bring the robot (and, thus, the human) to the desired position.
- 2) The second is a feedforward force that tends to pull the human along the desired path.
- 3) The third is a forcing vertical force that prevents the cable to become slack.

Notice that as soon as $s^*(t) = 1$, (47) is equal to (8) where $\mathbf{p}_H^r = \mathbf{p}_H^d(1)$. Thus, the asymptotical stability of $\mathbf{p}_H^d(1)$ is ensured. The stability of the system for $s \neq 1$ is also guaranteed thanks to the passivity of the system.

Remark 6: Notice that to implement (46), the actual position of the human is required. This can be easily retrieved either with some embedded sensors in the handle (like GPS), or inverting (10) using the actual robot position and cable force.

VII. EXPERIMENTAL VALIDATION

A. Testbed Setup

The system employed in these indoor experiments is shown in Fig. 1. It consists of a quadrotor aerial vehicle connected by a cable to a handle hold by a human being. The latter is wearing all safety protections including glasses, gloves, and a helmet. The holder, simply built with a three-dimensional printer, is equipped with motion tracking markers to obtain a measure of $\mathbf{p}_H$. The experiments are performed indoor employing a motion capture system (MOCAP) to allow the tracking of the human hand. Here, the use of a reliable positioning system has also the advantage to enhance human safety. Notice that the proposed experiments still encapsulates the main challenges addressed in the work, i.e., the stability of pHRI. The integration of a redundant sensory

¹The path is considered given and is such that no obstacles are present in its proximity. The minimum distance to the obstacle will be given by the precision of the control method.

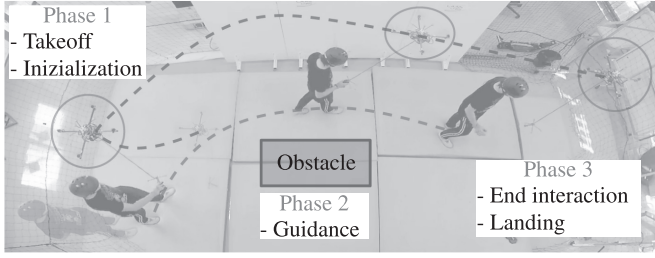


Fig. 4. Representation of the experimental phases. On each snapshot the robot is highlighted with a purple circle. Robot and human trajectories are marked with purple and red dashed lines, respectively.

suit for safe flights outdoors is not the focus of this manuscript and is left as future work.

The cable connecting the human-handle has a rest-length $\bar{l}_c = 1$ [m], and a negligible mass (less than 10 [g]). The aerial vehicle is a 1.3 [Kg] custom quadrotor platform equipped with a custom Paparazzi-based flight-controller, four brushless motor controllers running an in-house developed firmware that allows regulating the propeller speed in closed-loop [51], and an on-board PC that runs a UKF state estimator, a geometric position controller [52], and the admittance filter. The state estimator fuses the data coming from the onboard IMU (accelerometer and gyroscope) at 1 [kHz] and from the MOCAP (position and attitude) at 60 [Hz]. The measure of the cable force required in (6) is obtained with a model-based wrench observer [45]. These components run onboard at 1 [kHz] using the open-source software framework *TeleKyb3*.² The admittance filter parameters have been set to $M_A = 0.8I_3$ and $B_A = 2.4I_3$, where $I_3 = \text{diag}(1, 1, 1)$. Notice that to implement the controller, the virtual admittance parameters of the human are not needed.

The controller (8) and the path-following strategy described in Section VI are instead implemented in MATLAB/Simulink. The input u_A is computed based on the references p_H^r and f_c^r calculated as in (45), and sent to the onboard admittance controller at 100 [Hz] via a Wi-Fi connection. The gain k_H has been set equal to 4.5. This, together with the gains of the admittance filter, has been set after a tuning campaign aiming at optimizing the user experience. We wanted the user to feel a reasonable force, but still not too strong, and as smooth as possible. This has been also obtained properly choosing the desired force reference along the path. We set $f_z = 1$ [N] to keep the cable always taut, and $f_{xy}^d(s)$ as a trapezoidal profile such that $\max(f_{xy}^d(s)) = 1.5$ [N] and $f_{xy}^d(1) = 0$. Finally, $p_H^d(s)$ is a smooth path going from $p_H^d(0) = [-2 \ -0.5 \ 0]^T$ to $p_H^d(1) = [2 \ 0 \ 0]^T$, avoiding a virtual obstacle placed in the middle of the two points (see Fig. 4). The trajectory has been computed using a simple piecewise polynomial function.

The experiment is divided into three phases (see Fig. 4).

Ph.1: The human stays in a safe place. The robot takes off and goes into an initial point in position mode. After, the admittance filter is activated with $u_A = 0$. This allows the human safely grabbing the handle.

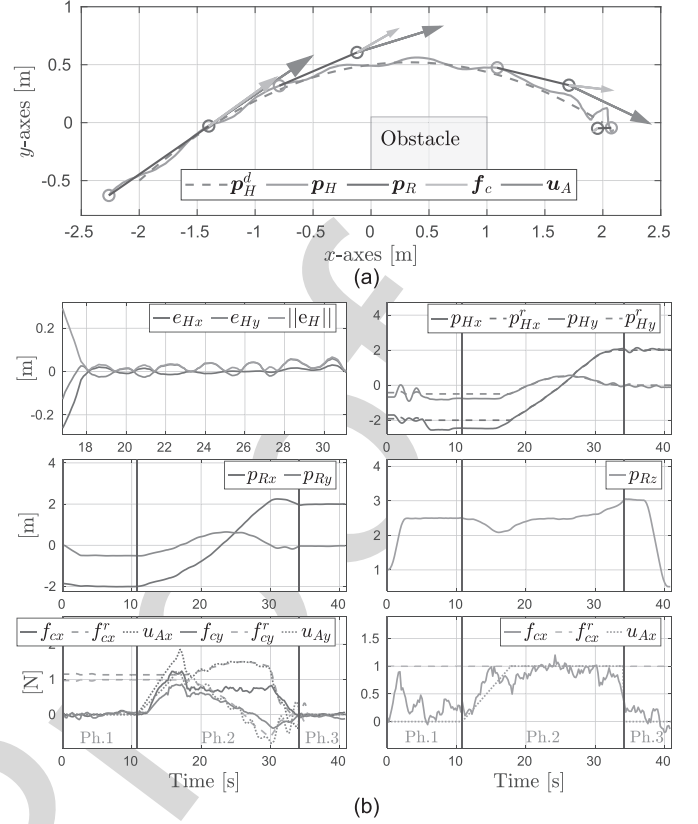


Fig. 5. Detailed experimental results of one subject. (a) Desired and actual human path showed in the xy plane. Four schematic representation of the system along the path are shown. The green and blue circles represent the human hand and the robot, respectively. The black line represents the cable. The red and yellow arrows represent the x-y components of u_A and f_c , respectively. (b) Plots of the human position error (zoomed during the guiding phase), desired and actual human hand position, robot position, and cable force.

Ph.2: Once the human holds the handle, the proposed guiding control, and path-following strategy are activated and the robot pulls the human along the desired path $p_H^d(s)$.

Ph.3: Once the human reaches the final position, the robot will be vertically placed on top of the handle. In this condition, the human feels no horizontal pulling force and can release the handle. The human guiding controller and the admittance filter are disabled. Finally, the robot lands in position mode.

During the experiment, the human is not blinded for safety reasons. Nevertheless, he/she is asked to look at the ground and not at the robot, focusing on the forces felt on the hand. This is done to encourage the human to be led feeling the forces that the robot is applying through the cable, instead of using it as a visual reference. Furthermore, the human is first “trained” on a different path to make him/her comfortable with the experiment, and confident with the reliability of the robot.

B. Experimental Results

In Fig. 5, we report the detailed results obtained with one participant of the experimental campaign. In Fig. 5(a), we show the desired and actual human path from the top, during Phase 2. We also schematically depict the system configuration at some instants to show how the robot pulls the human along the desired

²TeleKyb3 is freely [Online]. Available: <https://git.openrobots.org/projects/telekyb3>.

path. In Fig. 5(b), detailed quantities of the system along the full experiments are shown.

During *Phase 1*, the robot takes off and goes in the initial desired position. The nonzero estimated force along z_W corresponds to the weight of the handle that in this phase is suspended below the robot. The initial oscillations of p_{Hx} and p_{Hy} are also caused by the oscillations of the handle.

Passing to *Phase 2*, the robot starts moving to stretch the cable and pull the human. This can be seen from the estimated force along the cable. Looking at the human position error $e_H(t) = p_H^r(t) - p_H(t)$, we remark that its norm 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 nonzero forces. The experiment additionally validates the passivity of the system, which guarantees stability even in nonideal conditions. One can notice that, during Phase 2, there is an error between the desired horizontal force and the actual one. This is because the robot is moving and the damping plays against the generation of the desired force. Passivity-based methods are known to be very conservative. Practically, this is not a problem. If the human is moving toward the good direction, there is no need to increase the guiding force. On the other hand, if the human stops, the robot will apply the desired force, clearly showing the correct direction to the human.

Phase 3 starts when the human does not feel horizontal forces. He/she understands to be arrived at the desired position and so releases the handle. After, the robot lands.

To further validate the proposed system, we tested it with a group of four different subjects, performing the experiment twice. To evaluate the path-following performance, we define the path-following error with respect to the desired path as

$$e_H^P(s) = \min_{t \in [0, T]} \left((p_H(t) - p_H^d(s))^T p_H^{d\perp}(s) \right) \quad (48)$$

where $p_H^{d\perp}(s) \in \mathbb{R}^3$ is the normal vector to the path in the point $p_H^d(s)$, and $T \in \mathbb{R}_{>0}$ is the experiment final time. Given a certain point of the desired path $p_H^d(s)$, parameterized by s , $e_H^P(s)$ is the distance between $p_H^d(s)$ and the human position intersecting the normal to the path in $p_H^d(s)$. Notice that this definition is a *geometric error*; it does not depend on the velocity of the human, neither on his/her trajectory, but just on the geometric path.³ For each $s \in [0, 1]$, we then define the mean path-following error $\bar{e}_H^P(s)$, and the corresponding standard deviation (std) $\sigma_H(s)$

$$\begin{aligned} \bar{e}_H^P(s) &= \frac{1}{N} \sum_{j=1}^N e_{Hj}^P(s) \\ \sigma_H(s) &= \frac{1}{N-1} \sum_{j=1}^N \left(\bar{e}_H^P(s) - e_{Hj}^P(s) \right)^2 \end{aligned} \quad (49)$$

where N is the number of performed tests, and the subscript j indicates the j th test. Fig. 6 shows the global performance. One can notice that $\bar{e}_H^P(s)$ is always below 5 [cm], while the

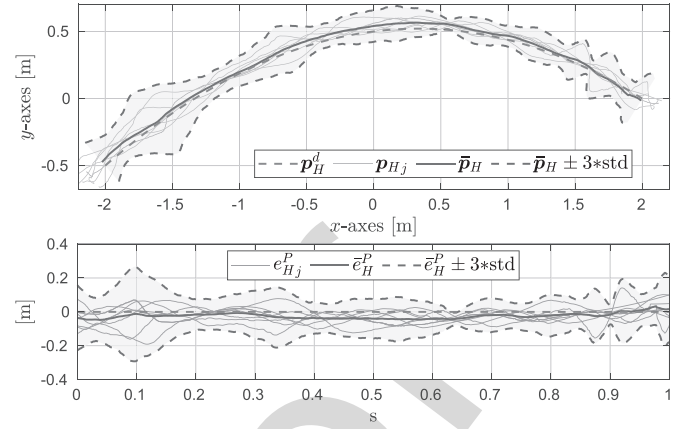


Fig. 6. Experimental results of eight tests with four subjects. *On the top*: the desired human path, the actual human path for the eight experiments, and the mean human path showed in the xy plane. *On the bottom*: the path-following error e_H^P for every experiment, and the mean path-following error.

maximum standard deviation is below 10 [cm]. This means that, according to the performed experiments, the human will always pass in a tube with diameter 60 [cm] around the desired path. This information could be used at the motion planning level to compute paths that stay sufficiently away from obstacles. We also remark that every subject behaves in a slightly different way (e.g., following the robot with a higher or lower speed, making stops, applying extra forces, etc.). Nevertheless, the system always maintains stability and provides good tracking performance. We remark that these results do not pretend to be statistically significant. The goal is to provide a global evaluation of the proposed method, which further validates its stability and robustness.

Notice that the human tends to stay always “outward” the desired curve. This is the effect of the human inertia that the robot controller does not take into account. Furthermore, we noticed that the human might have some difficulties understanding that he/she is arrived, resulting in useless small corrections. These marginal aspects are left to future works.

VIII. CONCLUSION

In this article, a system composed by a human *physically connected* to an aerial vehicle was studied for the first time. The human holds a handle that is connected by a cable to an aerial platform. The objective is to make the robot capable of safely guiding the human to a desired position, or along a desired path, by pulling him/her exploiting the tether.

We proposed a control strategy that makes the robot compliant to the human interaction and allows to exert forces to the human. These forces were properly designed to drive the human to a desired position. Using Lyapunov theory, we formally proved that the desired human position is asymptotically stable for the considered closed-loop system. Furthermore, we showed that the latter is output-strictly passive, which guarantees stability and robustness of the method even for time-varying inputs, nonzero model errors, and for nonzero extra human forces. An additional

³Other definitions of the distance between paths can be used. We believe that (48) allows to clearly show the envelope around the desired path in which the human will probably pass.

maneuver regulation strategy was designed to allow the robot guiding the human along a desired path.

The overall method was experimentally validated with a group of four subjects. The results showed that the system was able to keep the path-following error bounded. The robot correctly drives the human along the desired path, compensating for errors, and guaranteeing the stability.

From a practical point of view, we foresee the integration of onboard sensors for outdoor operations and for the onboard detection and avoidance of obstacles.

From a more scientific point of view, the human model could be enhanced to include the main body and arm elements, together with the heading. This should be considered in the controller to improve the control of the human configuration, i.e., position of the main body, heading, and relative position of the arm. A more precise hybrid position/force controller (like the one in [53]) could be applied, in order to finely control the intensity and direction of the force felt by the human, regardless to his/her velocity.

HRI aspects, like the acceptability of the system from the human, were not the focus of this work. However they will be analyzed in the future through a complete user study. A human-aware path planner could be designed to explicitly consider at the planning level a path acceptable by the human taking into account human-preferences in terms of distance to obstacles and dynamics of the motion [54], as well as adaptation to human pace [55]. The improvement of the indirect force-based communication between human and robot using additional stimulus should be investigated as well. Impulsive forces or wearable haptic devices could be used to enhance the human-robot interface. From one hand the robot should be able to estimate and then react to human intentions (e.g., start/stop the mission). From the other hand, the human awareness should be augmented providing additional information (e.g., distance to obstacles or the desired path).

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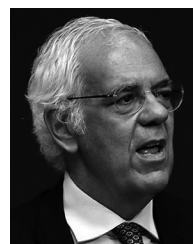
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