Vision-Based Teleoperation of Unmanned Aerial and Ground Vehicles

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Abstract—We present a novel vision-based teleoperation control framework for a team of an unmanned aerial vehicle (UAV) and an unmanned ground vehicle (UGV). Our control law allows a remote human user to teleoperate the team with some useful haptic feedback, while also ensuring the UAV-UGV coordination via the camera installed on the UAV (and seeing the UGV) and the velocity limitation of the UGV. For this, we first elucidate a geometric condition for the UAV and UGV velocities to ensure the UAV-UGV coordination by driving the image feature of the UGV to converge to a desired one on the image surface, while also guaranteeing that the UGV’s velocity, which is often much slower than that of the UAV, is under a certain specified bound. The UAV is then tele-controlled to track the teleoperation command as close as possible, yet, only to the extent permissible by this geometric condition. Simulation is performed to illustrate the theory.

I. INTRODUCTION

Vision-based control or visual servoing of robots has grown in its importance, since, in many applications, cameras provide affordable and efficient means for recognizing and sensing the surrounding environments and/or the manipulated/tracked objects. For mobile robots, the usage of the camera is even more promising (and thus demanded), particularly for outdoor applications, for which the frequently-used, yet, ground-fixed and expensive, motion capture systems (e.g., VICON®) are usually infeasible to deploy. Recently, visual-servoing of the unmanned aerial vehicles (UAVs) has also received much attention [1], [2] to truly make the UAV as a flexible robotic platform untethered from ground-bound measurement systems.

In this paper, we propose a novel teleoperation control framework for a team of an UAV and an UGV (unmanned ground vehicle), with a camera attached on the UAV to enforce the UAV-UGV coordination. More precisely, adopting the spherical camera description of [1], [3], we first elucidate a geometric condition for the UAV’s and UGV’s velocities to ensure that the image feature $p$ of the UGV converges to a desired one $p_d$ on the image surface (i.e., UAV-UGV coordination), even when the UGV’s velocity is limited by a certain bound. We then dictate the UAV to track the (velocity) teleoperation command from the remote user as close as possible, yet, only to the extent permissible by this geometric condition, thereby, maintaining the UAV-UGV coordination with a higher-priority while still allowing the user to teleoperate the UAV-UGV team. We also provide the remote human user with some useful haptic feedback on top of visual information (either from another front-facing onboard camera attached on the UAV or from fixed external cameras providing global vision information of the operation site). For this, we utilize our recently proposed passive set-position modulation (PSPM) [4], [5] to guarantee the passivity (i.e., stability) of the (bilateral) haptic feedback loop.

There are numerous results on the vision-based control of the UAVs for the pose stabilization and some tracking control relative to a fixed target (or ground). A backstopping stabilization controller using an onboard camera was proposed in [1], while two onboard cameras, one on the UAV and the other on the ground, were used in [2]. Optical flow are used to estimate horizontal velocity for stable hovering of eight rotor uav in [6]. Four kinematic IBVS (image-based visual-servoing) controllers were experimentally compared for the Cartesian positioning task in [7]. A (destabilizing) positive image feature feedback with (stabilizing) virtual spring approach was proposed in [8] to control the position and orientation of the UAV. All these results [1], [2], [6], [7], [8], yet, are about controlling the UAV relative to a fixed ground (or objects).

On the other hand, there are also many results for controlling the UAV relative to a moving target. Visual servoing for a UGV was proposed with an overhead camera that may be mounted on a UAV in [9]. However, the camera is assumed to be wide enough not to move to track the UGV so that camera motion is able to be neglected. In [10], position optimal estimation was suggested for cooperative strategy of multi-UAVs to tracking moving target, yet, vision sensor is only used for finding direction vector from UAVs to the target. Similarly, Particle filter and extended Kalman filter are used for estimation of moving target’s location on camera surface in [11] and [12], respectively. A vision-based control law for hovering and autonomous landing on a moving platform using optical flow was proposed in [13], while a vision-based algorithm using a density-based object representation was proposed in [14] to chase a moving target. In [15], a mobile robot is used as a moving target and an UAV tracks this mobile robot and lands on it autonomously. However, in these results [9], [10], [11], [12], [13], [14], [16], [15], the UAV unilaterally tracks the UGV, with no feedback from the UAV to the UGV. Differently to these, our teleoperation control relies on the interplay between the UAV’s and the UGV’s motions to maintain the UAV-UGV coordination while also taking into account the slower dynamics of the UGV (i.e., velocity bound).

In contrast to these autonomous vision-based control results for the UAV [1], [2], [7], [8], [13], [14], [16], [15], in this paper, we advocate vision-based teleoperation for the UAV-UGV team operation, since: 1) when the operation site is uncertain, unknown, or unexplored (e.g., search and rescue
in a disaster area), a fully-autonomous control is typically infeasible and teleoperation is often only a viable option; and 2) some tasks, which would be quite difficult when performed autonomously (e.g., SLAM [17], or motion/task planning), can be done relatively easily by the remote human operators using their sensory data (e.g., visual information and haptic feedback) and intelligent decision. There are several (recent) results on the teleoperation of a single or multiple UAVs (e.g., [5], [18]), yet, no UGVs are considered there. To our knowledge, our result in this paper is one of the very first results on the vision-based teleoperation of the UAV-UGV team, which would allow for many useful/interesting applications by exploiting their heterogeneous and complementary capabilities in an integrative way. The rest of this paper is structured as follows. Sec. II contains some preliminary materials on the UGV/UAV description and the spherical camera model [1], [3]. Sec. III presents our main result: a vision-based haptic teleoperation control law for the UAV-UGV team while ensuring the UAV-UGV coordination and the UGV’s velocity bound. Simulation results are then given in Sec. IV, and some concluding remarks in Sec. V.

II. PRELIMINARY

A. Unmanned Aerial and Ground Vehicles

Our vision-based teleoperation control law specifies the high-level desired velocity commands for the UAV and UGV. We then assume that the UAV and UGV possess some (arbitrary) well-functioning low-level controllers so that these velocity commands can be faithfully tracked by them. For instance, we may use the schemes [19], [20] for the quadrotor-type UAVs, while that in [21] for the unicycle-type wheeled UGV (with some modification/simplification). Similar separation of the high-level and low-level controls and the availability of the low-level controls for UAV and UGV were also used in [14].

With this low-level controls assumed both for the UAV and UGV, let us denote the position of the UGV relative to the inertial frame \( \{I\} \) by \( \bar{P} := [\bar{P}_1, \bar{P}_2, \bar{P}_3] \in \mathbb{R}^3 \), and that of the UAV by \( x := [x_1, x_2, x_3] \in \mathbb{R}^3 \). In this paper, we assume that UGV is moving on a flat ground so that \( \bar{P}_3 = 0 \). We also assume that the camera is installed on the bottom of the UGV, which is directed downward from the UAV’s body-frame \( \{B\} \) (i.e., along \( e_3^B \) direction), through which the UAV can see the UGV. See Fig. 1. The pose of this camera then is given by \( R \in \text{SO}(3) \), the rotation matrix of the body-frame \( \{B\} \) relative to the inertial-frame \( \{I\} \). Let us denote the angular rate of the camera represented in the body-frame \( \{B\} \) by \( w \in \text{so}(3) \). This \( w \) is related to \( R \) s.t.

\[
\dot{R} = RS(w)
\]  

where \( S(\ast) \) is the skew-symmetric operator s.t \( S(x)y = x \times y, \forall x, y \in \mathbb{R}^3 \).

B. Spherical Camera

Eyes are very effective and the main sensor for humans to avoid obstacles, recognize environments, and navigate in environments. To imitate the function of human eyes, cameras have been used. Some types of camera are: fish-eye, catadioptric, and spherical camera. Among them, in this paper, we choose the spherical camera [1], since it provides a natural geometry when associated with the \( \text{SO}(3) \) rotational motion of the UAV as shown in the following Sec. III.

With this spherical camera, we then have the image geometry as shown in Fig. 1, where the image surface is given by the sphere with the radius of the focal length \( f \). In this paper, we set this \( f = 1 \) (i.e. unit radius sphere). On this image surface, we then have the image feature \( p := [p_1, p_2, p_3]^T \in \mathbb{R}^3 \) with \( ||p|| = 1 \) of the UGV as measured by the camera in the body-frame \( \{B\} \). This \( p \) is then given by

\[
p = \frac{P}{r(P)}
\]  

where \( P := [P_1, P_2, P_3] \in \mathbb{R}^3 \) is the position of the UGV as seen from the UAV in the body-frame \( \{B\} \), and \( r(P) \) is the relative depth of the spherical camera defined by \( r(P) := ||P||/f = ||P|| \), with \( f = 1 \).

The following facts will be used later: from \( p^T p = 1 \),

\[
p^T \dot{p} = 0, \quad \frac{\partial r}{\partial P} = p^T
\]  

where, for the second equality, we use \( p^T P = r(P) \) from (2). We can also show that

\[
P = R^T(\bar{P} - x), \quad V_P = R^T(\dot{\bar{P}} - \dot{x})
\]  

where \( \bar{P} \) and \( x \) are the UGV’s and UAV’s positions measured in the inertial frame \( \{I\} \); and also \( V_P \in \mathbb{R}^3 \) is the relative velocity between the UGV and the UAV as measured in the body-frame \( \{B\} \).

Using (1)-(3), we can write the evolution of the image feature \( p \) on the image surface s.t.

\[
\dot{p} = \frac{d}{dt}\left[ \frac{P}{r(P)} \right] = -\omega \times p + (I - pp^T) V_P
\]  

where we use (3) and also the fact that \( w \times p \) is orthogonal to \( p \). For details, please see [1]. Here, observe that the right hand side of (5) is contained in the null-space of \( p \) (i.e., satisfying \( p^T \dot{p} = 0 \)).
Fig. 2. Vision-based teleoperated coordination control architecture

III. VISION-BASED TELEOPERATION COORDINATION DESIGN

In this section, we design our vision-based teleoperation control law, which enforces the coordination between the UAV and UGV with the highest priority (e.g., to prevent the UGV from being lost in the UAV’s camera view) using the camera installed on the UAV, while allowing a human user to (haptically) teleoperate the UAV, whose teleoperation command will be modulated (or compromised) so as not to violate the UAV-UGV coordination given the possible bound of the UGV’s velocity (see (13)).

Fig. 2 shows our control architecture and the information flow within it, where: 1) a human user sends a teleoperation velocity command to the UAV; 2) our vision-based control law computes the desired velocity commands for the UAV and UGV, which allow these UAV and UGV to move according to the teleoperation command as much as possible, yet, only to the extent permissible by the UAV-UGV coordination requirement and the UGV’s velocity bound; 3) the low-level controllers then drive the UAV and the UGV to track their respective velocity commands; and 4) the human perceive the state of the UAV and its interaction with UGV via some form of haptic feedback on top of vision information provided by extra cameras. Let us start first with the UAV-UGV coordination control.

A. UAV-UGV Coordination Constraint

For the UAV-UGV coordination without loosen generality, we want the UAV to move right below the UGV along the $e_3^T$-direction in the inertial frame $\{I\}$. That is, if $R = I$, we want the image feature $p$ of the UGV on the image surface to converge to the desired image feature $p_d = [0; 0; 1]$. However, if the UAV’s attitude changes, which is typically required to incur the UAV’s Cartesian velocity $\dot{x}$ due to its under-actuation [20], [19], the camera view would also rotate, thus, although the UGV is still positioned directly under the UGV along $e_3^T$-direction as desired, enforcing $p_d = [0; 0; 1]$ w.r.t. the body-frame $\{B\}$ would require the UAV to deviate from its original position. Thus, following [1], we define $p_d$ to be time-varying in the body-frame $\{B\}$ s.t.

$$ p_d = R_T e_3^T = R_T [0 0 1]^T $$

with $\dot{p}_d = -w \times p_d \quad (6)$

where we use (1).

Now, define the image feature tracking error $e := p - p_d$. Then, by enforcing $p \to p_d$, we will be able to achieve the UAV-UGV coordination. This can be achieved if we can drive $\dot{p}$ in (5) to behave according to following desired error dynamics

$$ \dot{p} = \dot{p}_d - \gamma (p - p_d) =: u_p. $$

This desired dynamics, however, is not always achievable. This is because, although $\dot{p}$ should be contained within the null-space of $p$ (i.e., $\dot{p} \in \text{null}(p)$ - see (5) or $p^T \dot{p} = 0$ (3)), in general, $u_p \notin \text{null}(p)$. To address this constraint, we modify the above control law $u_p$ to be

$$ \dot{p} = \frac{1}{p^T p_d} (I - pp^T)(\dot{p}_d - \gamma (p - p_d)) \quad (7) $$

which is now contained within the null-space of $p$, with $I - pp^T$ spanning the 2-dimensional $\text{null}(p)$ (i.e., $\text{rank}(I - pp^T) = 2$ with $p^T (I - pp^T) = 0$). This also implies that the modified control law (7) is the projection of $u_p$ on $\text{null}(p)$ with the scaling $1/(p^T p_d)$, which will become 1 when $p \approx p_d$.

**Proposition 1** Consider the dynamics of $p$ in (7). Then, if $p^T(0)p_d(0) > 0$, $e(t) = p(t) - p_d(t) \to 0$.

**Proof:** First, let us define the error $e$ projected on the null-space $\text{null}(p)$ s.t.

$$ e_p := (I - pp^T)(p - p_d) = (I - pp^T)e $$

and define the Lyapunov function $W_p$ s.t. $W_p := \frac{1}{2} e_p^T e_p$. We can then achieve that:

$$ W_p = e_p^T e_p = [(I - pp^T)(p - p_d)]^T \frac{d}{dt} [(I - pp^T)(p - p_d)] $$

$$ = -\gamma e_p^T e_p \quad (8) $$

where, for this result, we use the facts that $(I - pp^T)pp^T = 0$ and $(I - pp^T)(I - pp^T) = (I - pp^T)$ from (3) with $p^T p = 1$.

This (8) then shows that the projected error $e_p \to 0$. Let us then see if the real error $e = p - p_d$ also converges to the origin. For this, note that, from the definition of $e_p$ above, $e_p \to 0$ means that $p - p_d \to \lambda p$ with some $\lambda \in \mathbb{R}$, since $\text{rank}(I - pp^T) = 2$. However, since $p$ and $p_d$ are both on the unit image sphere, this condition $(1 - \lambda)p - p_d \to 0$ can be attained only with $p \to p_d$ or $p \to -p_d$ (i.e., antipodal equilibrium).

The antipodal equilibrium (i.e., $p \to -p_d$), yet, we can rule out. This is because, with $p^T(0)p_d(0) > 0$, to achieve $p \to -p_d$, $p$ is required to rotate away from $p_d$ such that, at some point, it must become orthogonal to $p_d$ with $p^T p_d = 0$. At this point of $p^T p_d = 0$, the projected error $e_p$ on the null-space of $p$ will attain the maximum value with $\|e_p\| = 1$. Yet, with $p^T(0)p_d(0) > 0$, we have $\|e_p(0)\| < 1$, and, moreover, the above Lyapunov analysis (8) shows that $\|e_p(t)\|$ is non-increasing. This then implies that $p \to -p_d$ is impossible and we only have $p \to p_d$, i.e., $e(t) \to 0$. This completes the proof.

This Prop. 1 then shows that the control law (7) will guarantee the image feature tracking $p \to p_d$, thereby, enforce the UAV-UGV coordination. We now convert this control law.
Inertial frame \( \{I\} \)

One point determined by \(- R(\alpha \xi_1 + \beta \xi_2)\)

One line determined by \(- \delta R p\), where \(\delta \in \mathbb{R}\)

\(\dot{\bar{P}}\) on the \(xy\) plane \& \(\| \dot{\bar{P}} \| \leq \bar{U}\)

Coordination cylinder \(C_{cyl}\)

\[
(7) \text{ into a condition on the UAV velocity } \dot{x} \text{ and the UGV velocity } \dot{P}. \text{ For this, equating (7) with (5), we can obtain }
\]

\[
(I - p p^T) V_P = \begin{bmatrix} \omega \times p + \frac{1}{p^T p} (I - p p^T) (\dot{p}_d - \gamma (p - p_d)) \end{bmatrix}
\]

\[
= f(p, p_d, \omega, r(P))
\]

where \(V_P = R^T (\dot{P} - \dot{x})\) as defined in (4) and \(\dot{p}_d = - w \times p_d\) as stated in (6).

Here, since \((I - p p^T)\) spans the 2-dimensional null-space of the right hand side of (9) is contained within this \(\text{null}(p)\), we can write the solution \(V_P\) for (9) by

\[
V_P = \alpha \xi_1 + \beta \xi_2 + \delta p
\]

where \(\xi_1, \xi_2 \in \mathbb{R}^3\) are the orthogonal unitary basis of \(\text{null}(p)\) with \(\| \xi_1 \| = 1\) and \(\xi_1^T \xi_2 = 0\), and \(\delta \in \mathbb{R}\) can be any arbitrary number. By injecting this expression of \(V_P\) into (9), we then have:

\[
\dot{x} = - R(\alpha \xi_1 + \beta \xi_2 + \delta p + \dot{P}) + \dot{\bar{P}}
\]

(12)

where \(\xi_i\) is again the basis for \(\text{null}(p)\), \(\delta \in \mathbb{R}\) can be any arbitrary number, and \(R\) is the rotation matrix of the UAV. For (12), let us also assume that the possible velocity of the UAV \(\dot{P}\) is bounded s.t.,

\[
\| \dot{P} \| \leq \bar{U}.
\]

Recall also that the UGV’s motion is planar, that is, \(\dot{\bar{P}} = [\bar{P}_1; \bar{P}_2; \bar{P}_3] \in \mathbb{R}^3\) with \(\bar{P}_3 = 0\).

Taking these into account, we can then construct coordination cylinder \(C_{cyl}\) as shown in Fig. 3 in the inertial frame \(\{I\}\), where the oblique cylinder’s center is located at \(- R(\alpha \xi_1 + \beta \xi_2)\), its center-axis along the vector \(R p\), and its radius on the inertial-frame’s \((e_1, e_2)\)-plane given by \(U\).

Note that, as long as \(\dot{x}\) of the UAV is contained within this coordination cylinder \(C_{cyl}\) (i.e., satisfying (12)), we can find the UGV’s velocity \(\dot{P}\) in the inertial-frame \(\{I\}\) (i.e., given by the \((e_1, e_2)\)-planar vector from the center-line to this \(\dot{x}\)), with which the UGV can follow the UAV (flying with \(\dot{x}\) to maintain the UAV-UGV coordination, under the UGV’s velocity bound (13). Here, note that both \(\dot{x}\) and \(\dot{P}\) are in the inertial frame \(\{I\}\), with \(\dot{P}\) being the \((e_1, e_2)\)-planar vector in \(\{I\}\).

This then says that, if the human’s teleoperation command dictates the UAV to fly with \(\dot{x} \in C_{cyl}\), we can achieve the desired teleoperation behavior and also the UAV-UGV coordination at the same time under the UGV’s velocity bound constraint (13). Yet, if the human’s command requires the UAV to fly with the velocity outside of this coordination cylinder \(C_{cyl}\), the intended teleoperation behavior and the UAV-UGV coordination cannot be achieved at the same time. In the next Sec. III-B, we consider this problem, i.e., how to incorporate the teleoperation while ensuring the UAV-UGV coordination (i.e., \(p \to p_d\)) under the UGV’s velocity limitation (13).

### B. Teleoperation Control Design

Let us denote the teleoperation velocity command for the UAV by \(\dot{x}_c \in \mathbb{R}^3\). This teleoperation command \(\dot{x}_c\) may or may not be within the coordination cylinder \(C_{cyl}\). To address the possible conflict between this teleoperation command and the UAV-UGV coordination, here, with a higher-priority given on the UAV-UGV coordination (i.e., to keep \(p \to p_d\) in the camera view), we define the (high-level) desired velocity commands for the UAV (i.e., \(\dot{x}_d\)) and the UGV (i.e., \(\dot{P}_d\)) in such a way that \(\dot{x}_d\) is designed as close to \(\dot{x}_c\) as possible, yet, only to the extent allowable by the UAV-UGV coordination (12) and the UGV’s velocity bound (13). More precisely, given the teleoperation command \(\dot{x}_c\), we choose \(\dot{x}_d\) and \(\dot{P}_d\) s.t.

\[
\min_{\dot{x}_d} \| \dot{x}_c - \dot{x}_d \|
\]

\[
\text{subj. } \dot{x}_d = - R(\alpha \xi_1 + \beta \xi_2 + \delta p) + \dot{P}_d
\]

(14)

\[
\| \dot{P}_d \| \leq \bar{U}, \quad [\dot{P}_d]_3 = 0, \quad \delta \in \mathbb{R}
\]

where \([*]_3\) is the \(e_3\)-component of \(* \in \mathbb{R}^3\) (i.e., \([*]_3 := [*]_3\) for \(* = [x_1, x_2, x_3]\), the second line enures that \(\dot{x}_d \in C_{cyl}\) (i.e., UAV-UGV coordination), and the third line the UGV’s velocity bound constraint (13). Here, since the cost function and the constraints are all convex, the solution \((\dot{x}_d, \dot{P}_d)\) exists and is unique. In the following, we provide explicit solution of (14) when 1) \(\dot{x}_c \in C_{cyl}\) and \(\dot{x}_c \notin C_{cyl}\).

1) When \(\dot{x}_c \in C_{cyl}\): Since \(\dot{x}_c \in C_{cyl}\), we simply set \(\dot{x}_d = \dot{x}_c\) (i.e., full accommodation of teleoperation command \(\dot{x}_c\)). We can also obtain \(\dot{P}_d\) from (14), for which \(\delta\) can be computed by

\[
\delta = - \frac{[\dot{x}_c + R(\alpha \xi_1 + \beta \xi_2)]_3}{[R p]_3}
\]

(15)

from (14) by using the fact that \([\dot{P}_d]_3 = 0\) with \(\dot{x}_d = \dot{x}_c\), where \([*]_3\) is the \(e_3\)-component of \(*\). Here, note that \([R p]_3 \neq 0\) (i.e., \(e_3\)-component of the vector \(p\) relative to the inertial frame
\( \{I\} \text{, unless the UGV is located on the same height as the}
\text{UAV, which we assume not to happen in this paper. With this}
\delta, \hat{P}_d \text{ is then given from (14) by}
\[
\hat{P} = \dot{x}_c + R(\alpha \xi_1 + \beta \xi_2 + \delta p).
\]
Note that, in this case, choosing \( \dot{x}_d \text{ and } \hat{P}_d \text{ as above, we can}
\text{fully realize the desired teleoperation behavior (i.e., } \dot{x}_c, \text{ while also}
\text{satisfying the UAV-UGV coordination (12) and the UGV's}
\text{velocity limitation (13).}
\]
2) When \( \dot{x}_c \notin C_{\text{cyl}} \): In this case, if the UAV flies with the
\text{command } \dot{x}_c, \text{ the UAV-UGV coordination would be compro-
\text{mised, which may also incur the image feature } p \text{ of the UGV}
\text{to be lost from the UAV's camera view. To avoid this, the}
\text{algorithm (14) modulates the teleoperation command } \dot{x}_c
\text{ by choosing the UAV's desired velocity command } \dot{x}_d \text{ to be the closest}
\text{point on the coordination cylinder } C_{\text{cyl}} \text{ from } \dot{x}_c. \text{ See}
\text{Fig. 4. Once this } \dot{x}_d \text{ is given, we can then solve } \hat{P}_d \text{ similar as}
\text{before, by using (15) with } \dot{x}_c \text{ replaced by this } \dot{x}_d. \text{ Note that,}
\text{in this case, } \dot{x}_d \text{ is on the surface of the coordination cylinder}
\text{ } C_{\text{cyl}} \text{, implying that, to preserve the UAV-UGV coordination, the}
\text{UGV should "catch up" the UAV with its maximum speed } U
\text{ (13).}

C. Human Haptic Interface

Although other interacting modalities are also possible, to
\text{allow a remote human user to intuitively teleoperate the UAV-}
\text{UGV team, following [5], [20], we design the human haptic}
\text{teleoperation interface as follows. First, the teleoperation ve-
\text{locity command } \dot{x}_c \text{ for the UAV is command by the remote}
\text{human user through their haptic device s.t. } \dot{x}_c(t) := \eta(t)
\text{ where } q(t) \in \mathbb{R}^3 \text{ is the position of the haptic device and}
\eta \in \mathbb{R} \text{ is some scaling to match the workspace size of the}
\text{haptic device and the UAV's velocity. This velocity command}
\text{ } \dot{x}_c(t) \text{ then allows us to circumvent the issue of the master-
\text{slave kinematic dissimilarity (i.e., master device workspace}
\text{is bounded, while that of the the UAV-UGV team unbounded}
\text{[22]).}
\text{On the other hand, on top of the vision information on the}
\text{motion of the UAV (either via cameras attached on the UAV}
\text{(i.e., body-fixed perspective) or installed in its environment}
\text{(i.e., global perspective)), we also provide haptic perception}
\text{of the UAV's velocity to the human user. For this, we first}
\text{define the haptic feedback signal } y(t) \text{ s.t. } y(t) := \frac{1}{\eta} \dot{x}(t) \text{ where}
\dot{x}(t) \text{ is the UAV's velocity and } 1/\eta \text{ is the scaling compatible}
\text{with } \dot{x}_c(t). \text{ This haptic signal } y(t) \text{ is then sent to the human}
\text{user through some discrete-time communication network (e.g.,}
\text{Internet). Let us denote its reception by } y(k) \text{ at the reception}
\text{time } t_k. \text{ Then, we haptically present this information } y(k)
\text{ to the human via the following haptic device control torque: for}
\text{ } t \in [t_k, t_{k+1}]
\text{ }
\tau(t) = -Bq - K_1 q - K_0 (q - \bar{y}(k))
\text{where } B, K_1, K_0 \in \mathbb{R}^{3 \times 3} \text{ are the symmetric and positive-
\text{definite gain matrices, and } \bar{y}(k) \text{ is the modulation of } y(k)
\text{through the passive set-position modulation (PSM [4]). This}
\text{PSM can then enforce passivity (thus, robust interaction sta-
\text{bility) of the master-side, even if the communication channel}
\text{is imperfect (e.g., Internet), the device is engaged by a wide-
\text{range of human users, or other forms of the haptic signal } y(t)
\text{is used. See [5], [4], [20] for more details.}

IV. SIMULATION

We consider a quadrotor-type UAV with a camera facing
down to see the UGV for achieving the UAV-UGV coordina-
\text{tion. The human operator can see and teleoperate the team of}
\text{UAV and UGV from outside (i.e., global information). Also, for}
\text{the UGV, we assume its evolution can be represented by a}
\text{kinematic unicycle-type wheeled mobile robot [21], with}
\text{the image feature } p \text{ corresponding to the marker attached on its}
\text{rotation center (i.e., axle center). For the UAV’s low-level}
\text{control (i.e., for } \dot{x} \rightarrow \dot{x}_d), \text{ we utilize the backstepping control}
\text{scheme of [20], while for the UGV, we use the following}
\text{control to make } \dot{P} \rightarrow \bar{P}_d:
\[
\begin{bmatrix}
\dot{u} + pu^2 \\
\phi^2 \\
\theta \\
\end{bmatrix}
\begin{bmatrix}
\cos(\phi) & \sin(\phi) & 0 \\
-\sin(\phi) & \cos(\phi) & 0 \\
0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
\frac{\dot{u}}{u} \\
\dot{\phi} \\
\dot{\theta} \\
\end{bmatrix}
\text{ where } u, \phi \in \mathbb{R} \text{ are the linear velocity input and the angle}
\text{of the UGV, } \rho > 0 \text{ is the control gain, and } \bar{P}_d \text{ is computed}
\text{numerically. During our simulation, } u \neq 0. \text{ This control is}
\text{derived similar to [20], the details of which will be reported}
\text{in a future publication. Of course, other low-level controllers}
\text{may also be used instead of (16) (e.g., [21]).}
\text{We assume that the UAV is equipped with IMU (inertial}
\text{measurement unit) and we can obtain } R, w \text{ from this IMU}
\text{(and also } \dot{p}_d = -w \times p_d \text{ for (9)). The relative depth } r(P)
\text{can also be computed by } r(P) = h/\cos \theta, \text{ where } \theta \text{ is the}
\text{angle between } Rp \text{ and } e^T_z := [0 \ 0 \ 1]^T \text{ in the inertial frame}
\text{and } h \in \mathbb{R} \text{ is the UGV's height. These } \theta \text{ and } h \text{ can also be}
\text{measured by using the camera and barometer. Using } R \text{ and}
\text{a number of markers on the UGV with the known geometry}
\text{among them, we can also convert } \bar{P}_d \text{ into the UGV's body-
\text{frame, which can then be tracked by the UGV using its local}
\text{controller and local velocity sensing (e.g., encoder, LIDAR)}
\text{both typically formulated in the UGV's body-frame.}

\text{The simulation results are shown in Figs. 5-7, where we can}
\text{see that the human can teleoperate the UAV-UGV team while}
\text{the UAV-UGV coordination is achieved by using the camera}
\text{(Fig. 5). In this simulation, the human command is circular}
\text{trajectory; 2) the image feature } p \text{ converges to the desired one}
\text{after some initial transient and also with } R(t) \rightarrow I \text{ (Fig.}
\text{6); and 3) both the projected and un-projected image tracking}
Fig. 5. Position trajectories of the UAV and UGV.

Fig. 6. Evolution of the image features on the image sphere.

Fig. 7. Image feature tracking error, $|e|$, $|e_p|$, $e_{p0}$ Out of the cylinder.

Some possible directions for future research include: extension of the proposed framework to the case of multiple UGVs and UAVs on non-flat ground; and inclusion of the low-level UAV and UGV dynamics directly into the control design.

REFERENCES


errors (i.e., $\varepsilon_p, \varepsilon$) converge to zero exponentially while the UAV’s motion stabilized (Fig. 7).

V. CONCLUSION

We present a novel vision-based teleoperation control framework for a UAV/UGV team, which allows a remote human user to teleoperate the UAV, while guaranteeing the UAV-UGV coordination using a camera attached on the UAV and seeing the UGV. A certain geometric condition is derived to ensure the UAV-UGV coordination and the UGV’s velocity limitation, while the teleoperation command is modulated if it demands the violation of this condition, while also minimizing the deviation of the UGV’s velocity from this teleoperation command. Simulation is performed to illustrate the theory. Some possible directions for future research include: extension of the proposed framework to the case of multiple UGVs and UAVs on non-flat ground; and inclusion of the low-level UAV and UGV dynamics directly into the control design.

OUTCOME

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