Sensor Localization Using Hybrid RF/Optical Wireless Communications for an Aerial Data Mule

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Abstract—In this paper, we consider the problem of pairing a ground sensor with an aerial vehicle, both equipped with a hybrid communication system - radio frequency for low bandwidth data transmission and optical for high bit rate. These communication technologies are complementary and by coordinating them, it is possible to mitigate each other’s weaknesses. A challenging problem is positioning the flying robot within optical communication range, especially when the distance is large and the sensor location is unknown. In this work, we propose a solution to the problem of autonomously localizing the sensor node relative to the aerial vehicle. We take advantage of the hybrid communication scheme by developing a control strategy that uses the radio signal to guide the aerial platform to the sensor node. Once the optical-based signal strength is over a desired threshold the robot hovers within optical range. The control strategy is demonstrated through simulations that incorporate a realistic model for the hybrid communication link.

I. INTRODUCTION

Recently advances in technology have enabled commercially available robotic platforms capable of providing critical support to human teams in a variety of missions. For example, improvements in sensing methods, energy storage, processing power and communication range have enabled the use of wireless robotic networks in environmental monitoring [1] and target localization [2]. In addition, a wireless sensor network (WSN) can extend the situational awareness of first responders in hazardous terrain and confined spaces [3].

A common assumption is that the WSN is fully connected, i.e., there is a communication path between any two nodes in the network. However, this type of connectivity generally requires a very dense number of sensors or additional communication relay stations which can be impractical or expensive to implement [4]. Furthermore, the available communication rate may be insufficient to deliver the information collected by the sensors when the amount of data is large, such as the case of high-resolution images or video recordings.

Aerial robotic vehicles have the potential to alleviate these communication challenges by exploiting their mobility to gather information from in-situ wireless sensors. These information collectors are known as data mules [5]. Also, large-scale data transfers can be achieved by combining the broadcast capability of radio frequency (RF) with the high rate capacity of optical wireless (OW) links. Hybrid RF/OW links can offer temporary high throughput point-to-point communications within fixed and mobile wireless networks [6], [7]. In this hybrid scheme, the RF component is generally employed for link control, maintenance and backup functions, while the OW component is used for bulk data transfer. Thus, RF can be exploited to assist in the pointing and acquisition of the OW link because RF is largely insensitive to pointing and tracking errors. This approach is currently under development for internet connectivity in areas without sufficient infrastructure [8].

The concept of data mules has been of interest for several years, e.g., [5]. Here, communication nodes move randomly to collect data from sensors when they come into radio contact. In [9], the route of the data mule is optimized based on the sensor mobility model enhancing the collection of information. Data mules have been applied for underwater robots [10], [11]. For example, [11] presents an autonomous underwater vehicle (AUV) equipped with an acoustic/optical communication system. Using a gradient descent approach, the AUV can localize an underwater sensor node and upload the collected data. Recently, unmanned aerial vehicles (UAVs) have been employed as data mules to maintain network connectivity in sparse WSNs. UAVs are used in [12] to transport information packets among isolated groups of sensor nodes. In [13], a UAV collects information and updates its route based on the data from sensors already visited. A closely related application employs UAVs as mobile relays to maintain connectivity [14] or to reconnect disjoint segments in WSNs [15].

In this work, we assume that both the sensor and the aerial data mule are equipped with a hybrid RF/optical communication system - RF for low bandwidth transmission...
and optical for high rate transfer. Our concept is illustrated in Fig. 1(a), depicting a quadrotor employing radio signal strength to move towards a sensor node. Once the quadrotor is within a desired range, see Fig. 1(b), both the sensor node and the quadrotor can employ the optical link to carry out bulk data transfer. Therefore, the flying robot has to localize the sensor in order to upload/download data while staying within optical communication range. We develop a solution to autonomously localize the ground sensor node relative to the aerial vehicle assuming that the sensor position is unknown at all times. We exploit the hybrid communication scheme in order to solve this problem.

Typical approaches to localize a sensor node use radio-based systems as the only communication link [5], [9], [12], [13]. Methods for RF source localization include the use of received signal strength (RSS) measurements, so tracking RSS changes from a mobile agent helps to navigate to the source. The RSS spatial gradient can be estimated during movement and used in a control strategy, e.g., during exploration to simultaneously map an RF connectivity region around a base station [16]. The authors in [17] optimize the RSS spatial sampling to guide a UAV to a source on the ground. The rotation of a UAV combined with the RSS measurements of a directional antenna is exploited in [18], [19] to localize and track an RF source. In these works, an estimate of the angle of arrival (AoA) is performed at each rotation and the UAV follows the estimated direction. In this paper, we consider an aerial platform with four directional antennas, each one covering a quadrant. We use their RSS measurements to find a rough AoA and feed this to a controller which drives the quadrotor to the source. Furthermore, our link closure and control scheme can be enhanced by combining multiple AoA estimates over multiple known quadrotor positions, to localize the ground node [20].

The rest of the paper is organized as follows. Section II gives the problem statement, the localization of a sensor node by a quadrotor vehicle both equipped with a communication system which combines RF and OW technologies. The models for the RF and the OW channels of this hybrid system are detailed in Section III. The methodology to localize the sensor node without knowing its position is explained in Section IV. Our control strategy is evaluated through numerical simulations whose results are summarized in Section V. Finally, Section VI presents our concluding remarks.

II. PROBLEM STATEMENT

We assume that a sensor node deployed in an open environment is equipped with a hybrid RF/optical communication system. The RF component is used for relatively low data rate, while the optical component can manage high data transmission. We assume that a quadrotor has a similar hybrid wireless transceiver and it is able to communicate with the sensor when in range. The sensor uses an omnidirectional antenna, while the quadrotor has one directional antenna at the end of each one of its arms, see Fig. 2(a). Figure 2(b) shows the gain pattern of a directional antenna with a \(45^\circ\) main lobe. With this sectorization, the RSS can be measured at each antenna, a rough angle of arrival estimated, and the quadrotor can move towards the source.

Starting with the quadrotor at a significant distance from the sensor but within the RF range, our goal is that the aerial robot comes close to the sensor node such that the optical link can be employed to upload the data collected by the sensor. We assume that the exact location of the sensor is unknown to the quadrotor at all times. Our approach uses the RSS measurements of the four antennas to guide the flying vehicle towards the sensor. Once the quadrotor comes close enough to the sensor, it is able to detect the optical signal and hover within optical communication range. At this stage, the data transfer can be performed employing the optical link. In the next section, we detail the channel model for the hybrid RF/OW communication system.

III. HYBRID RF/OW CHANNEL MODEL

In general, separate channel models for the RF and OW links are mostly adequate to predict the hybrid system performance [7].

A. RF link

We assume an open environment, so that there is LOS between the air vehicle and the sensor node. We consider a multipath fading environment, e.g., with microwave radio. Therefore, we adopt a log-distance path-loss model [21] to describe the power loss between the sensor node (acting as transmitter Tx) and the quadrotor (acting as receiver Rx). For this model, the received signal strength of the \(i\)th quadrotor's antenna expressed in dB is given by

\[
P_{\text{RF},i} = P_{\text{TX}} - P_{o_i} - 10\kappa \log_{10} \left( \frac{d_i}{d_o} \right)^\chi, \tag{1}
\]

where \(i = 1, \ldots, 4\) indexes the four antennas. In (1), \(P_{\text{TX}}\) is the power transmitted by the sensor node, \(d_o\) is the reference distance, \(d_i\) is the distance between the sensor node and the \(i\)th quadrotor antenna, \(\kappa\) is the path-loss exponent, \(P_{o_i}\) is the reference path loss, and \(\chi\) is a zero-mean Gaussian random variable reflecting the attenuation (in dB) caused by flat fading.

Typical values for \(d_o\) are 1-10 m indoors and 10-100 m outdoors. The value of the path-loss exponent \(\kappa\) depends on the propagation environment. Its value ranges from 2 for free-space up to 6 for heavily cluttered environments. The reference path loss \(P_{o_i}\) can be calculated at the reference distance \(d_o\) by applying the Friis transmission equation

\[
P_{o_i} = 10 \log_{10} \left[ \frac{1}{G_{\text{TX}} G_{\text{Rx},i} \left( \frac{4\pi d_o}{\lambda} \right)^2} \right], \tag{2}
\]

where \(G_{\text{TX}}\) is the gain of the sensor's antenna, \(G_{\text{Rx},i}\) is the gain of the \(i\)th quadrotor's antenna, and \(\lambda = c/f\) is the wavelength of the transmitted signal (\(c\) is the speed of light and \(f\) is the communication frequency in Hertz). We set \(G_{\text{TX}} = 1\) since we assume an omnidirectional antenna for the sensor node. On the other hand, \(G_{\text{Rx},i}\) can take on a value
source can be described by the optical receiver axis. The radiant intensity of the optical
transmitter axis, and ψ be the pointing angle relative to the optical transmitter axis, and ψ be the incidence angle relative to the optical receiver axis. The radiant intensity of the optical source can be described by

\[ I_x = P \frac{m + 1}{2\pi \rho^2} \cos^m \phi, \]

where \( P \) is the average transmitted optical power, and \( m \) is the Lambert’s mode number expressing directivity of the source beam. This number is defined as

\[ m = \frac{-\ln 2}{\ln(\cos \Phi_{1/2})}. \]

Here, \( \Phi_{1/2} \) is the half-angle at half-power which describes the transmitter beam width.

The optical receiver can be modeled as an effective area \( A_{\text{eff}} \) collecting the incident radiation. This area is given by

\[ A_{\text{eff}}(\psi) = g(\psi) A \cos \psi, \]

where \( A \) is the receiver active area, and \( g(\psi) \) is the light-concentrator gain which for an ideal case is given by

\[ g(\psi) = \begin{cases} \frac{n^2}{\sin^2 \Psi_{\text{C}}} & \text{if } |\psi| \leq \Psi_{\text{C}}, \\ 0 & \text{otherwise.} \end{cases} \]

Here, \( n \) is the refractive index and \( \Psi_{\text{C}} \) is the half-angle field-of-view (FOV) of the optical detector.

Using (3) and (4), the optical signal strength in dB at the receiver is given by

\[ P_{\text{OW}} = 10 \log_{10} (I_x A_{\text{eff}}) + \zeta, \]

where \( \zeta \) represents the average optical power (in dB) produced by natural and artificial light sources. This background radiation is generally modeled as white, Gaussian, and independent of the received signal [25].

As shown in Fig. 2(c), we assume that the optical transceiver mounted on the quadrotor is always pointing down, while the one in the sensor node is always pointing up. Under this assumption, \( \phi = \psi \) at all times.

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<td><strong>RF link</strong></td>
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<td><strong>OW link</strong></td>
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A. Quadrotor Model

Let \( \{ \mathcal{W} \} \) be an inertial frame such that its unit vectors along the axes are given by \( \{ \mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3 \} \), with
\[
\mathbf{u}_1 = [1 \ 0 \ 0]^T, \quad \mathbf{u}_2 = [0 \ 1 \ 0]^T, \quad \mathbf{u}_3 = [0 \ 0 \ 1]^T.
\]

Let \( \{ \mathcal{B} \} \) represent a fixed-body frame attached to the center of mass of the aerial vehicle. Both frames \( \{ \mathcal{W} \} \) and \( \{ \mathcal{B} \} \) are illustrated in Fig. 1(a). The position vector of \( \{ \mathcal{B} \} \) with respect to \( \{ \mathcal{W} \} \) is denoted by \( \mathbf{r} = [x_q, y_q, z_q]^T \), while its orientation is expressed by \( \hat{\mathbf{v}} = [\alpha \ \beta \ \gamma]^T \).

The terms \( \alpha, \beta, \) and \( \gamma \) are the roll, pitch, and yaw Euler angles, respectively. We assume that the orientation of the rigid body with respect to the inertial frame is given by the \( z \times y \) rotation matrix
\[
\mathbf{R} = \begin{pmatrix}
c\gamma c\beta - s\alpha s\gamma s\beta & -c\alpha s\gamma & c\alpha s\beta + c\beta s\alpha s\gamma \\
c\beta s\gamma + c\gamma s\alpha s\beta & c\alpha c\gamma & s\alpha s\beta - c\beta c\alpha s\gamma \\
-c\alpha s\beta & sa & c\alpha c\beta
\end{pmatrix},
\]

where \( c \) and \( s \) are shorthand forms for cosine and sine, respectively. The full nonlinear dynamics of the quadrotor can be expressed as [14], [19], [26]
\[
m_q \ddot{\mathbf{r}} = -m_q g \mathbf{u}_3 + \mathbf{F} \mathbf{u}_3, \quad \dot{\mathbf{R}} = \hat{\mathbf{v}} \times \mathbf{R}, \quad \mathbf{J} \ddot{\hat{\mathbf{v}}} = -\mathbf{\Omega} \times \mathbf{J} \hat{\mathbf{v}} + \mathbf{M}, \tag{7}
\]

where \( m_q \) is the mass of the aerial vehicle, \( g \) is the gravitational constant, \( \Omega \) is the angular velocity of the vehicle expressed in the fixed-body frame, and \( \mathbf{J} \) is a constant inertia matrix. \( \mathbf{F} \) and \( \mathbf{M} \) are the total thrust and the torque control inputs applied to the quadrotor. The hat map \( \hat{\cdot} : \mathbb{R}^3 \to \text{SO}(3) \) is defined by the condition that \( \hat{\mathbf{a}} \mathbf{b} = \mathbf{a} \times \mathbf{b} \) for all \( \mathbf{a}, \mathbf{b} \in \mathbb{R}^3 \).

B. Control Strategy

A controller that guarantees stability for small deviations from the hover position is presented in [26]. We adapt this controller to guide the quadrotor to follow a desired direction vector \( \mathbf{v} \) expressed with respect to \( \{ \mathcal{W} \} \). Let \( \mathbf{u}_v \) be the unitary vector of \( \mathbf{v} \), then we define the following vector
\[
\mathbf{a} = k_a \mathbf{u}_v - \hat{\mathbf{r}}, \tag{8}
\]
where \( k_a \) is a scalar gain. Using \( \mathbf{a} = [a_x \ a_y \ a_z]^T \) defined by (8), we can find the appropriate roll \( \alpha^* \) and pitch \( \beta^* \) angles according to
\[
\alpha^* = \frac{1}{g} \left( a_x \sin \gamma^* - a_y \cos \gamma^* \right), \quad \beta^* = \frac{1}{g} \left( a_x \cos \gamma^* + a_y \sin \gamma^* \right). \tag{9}
\]

We assume that the quadrotor has to keep its initial yaw angle, so \( \gamma^* = \gamma_0 \). Then, the control law for the torque input is
\[
\mathbf{M} = -K_R \mathbf{e}_R - K_\Omega \mathbf{e}_\Omega, \tag{10}
\]
where \( \mathbf{e}_R = [\alpha - \alpha^* \ \beta - \beta^* \ \gamma - \gamma^*]^T \), and \( K_R, K_\Omega \) are diagonal gain matrices. In addition, the control law for the total thrust is
\[
\mathbf{F} = -m_q \left( g + k_v a_z \right), \tag{11}
\]
where $k_n$ is a control gain.

C. Direction Estimate

For each antenna, we make $N$ RSS measurements per $T$ seconds as the quadrotor moves. Let $P_{RF}(t)$ be the RSS measurement at time $t$ for the $i$th antenna given according to (1). Then, we maintain an average RSS value for each antenna which we denote as $Q_i$. Using an exponentially weighted average, we update $Q_i$ according to

$$Q_i \leftarrow \eta Q_i + (1 - \eta) P_{RF}(t),$$

where $i = 1, \ldots, 4$ indexes the four antennas and $\eta \in (0, 1]$ is a forgetting factor.

Every $T$ seconds, we proceed to find the direction estimate vector $\mu$ in the following manner:

1) Using the average RSS for the four antennas, we form the vector of average RSS measurements as

$$\bar{Q}_{RF} = [Q_1 \ Q_2 \ Q_3 \ Q_4]^T.$$  

2) From $\bar{Q}_{RF}$, we form its min-max normalization which is given by

$$\bar{Q}_{RF} = \frac{1}{\Upsilon - \upsilon} (\bar{Q}_{RF} - \upsilon 1),$$

where $\Upsilon = \max(\bar{Q}_{RF})$, $\upsilon = \min(\bar{Q}_{RF})$, and $1$ is a $4 \times 1$ vector of ones.

3) We compare the average RSS of antennas 1 and 3 to find the largest between them. Notice that antennas 1 and 3 (and similarly 2 and 4) have maximum spacing with respect to the center of mass of the quadrotor, see Fig. 2(a).

4) Let $\ell_{13}$ be the location of the antenna selected in Step 3 with respect to the fixed-body frame $\{B\}$. Also, let $\bar{Q}_{13}$ be the normalized average RSS associated with it.

5) We simultaneously repeat Steps 3 and 4 for antennas 2 and 4. As result, we obtain $\ell_{24}$ and $\bar{Q}_{24}$.

6) We determine the direction estimate vector as

$$\mu = \mathbf{R} \left( \bar{Q}_{13} \ell_{13} + \bar{Q}_{24} \ell_{24} \right).$$

Notice that this vector is defined with respect to $\{W\}$.

We also maintain an exponentially weighted average for the optical signal strength. Let $P_{OW}(t)$ be the optical signal strength at time $t$ found by (6), then we obtain its average $O$ by

$$O \leftarrow \eta O + (1 - \eta) P_{OW}(t).$$

If the average optical signal strength is lower than a predefined threshold $\tau_{OW}$, the desired direction $v$ for the control strategy (Section IV-B) is the vector $\mu$ given by (15). Otherwise, $v$ is the zero vector to command the quadrotor to hover.

Next, we present numerical simulations of the proposed approach.

V. SIMULATION RESULTS

To simulate our approach, we begin with the aerial vehicle at the position $[-5 \ 5 \ 5]^T$ m, and the sensor node at $[3 \ -2 \ 0]^T$ m. The quadrotor gathers 100 samples of the signal strength for the RF and OW link every second as the quadrotor moves, so $N = 100$ and $T = 1$ s. We update the average signal strength for each antenna $Q_i$ by (12) and the optical signal strength $O$ according to (16). Every second, we find the direction vector $\mu$ following the steps detailed in Section IV-C. As indicated at the end of this section, if $O \leq \tau_{OW}$ (for our case $\tau_{OW} = -20$ dBm) then the desired direction for the control strategy is $v = \mu$. Otherwise, $v$ is the zero vector commanding the quadrotor to hover. Once the desired direction vector $v$ is chosen, we find the quadrotor control inputs by applying (8) to (11). Then, we update the state of the aerial robot according to the model in (7).

The vector $\mu$ estimated according to the procedure detailed in Section IV-C is shown at different time instants in Figs. 4(a) and 4(c). In these figures, we also illustrate the contour isolines for the RF link in the azimuth plane. The RF contour lines are the average signal strength without random fading, and are included as a background reference. In this simulation, the source direction vector $v$ generally points towards the RF source enabling the quadrotor to approach the sensor node. We depict in Figs. 4(b) and 4(d) the path described by the quadrotor as well as its final position. For these figures, we also plot the contour isolines for the OW link in the azimuth plane. As in the RF contours, the optical contour lines are plotted without considering noise and are included only for visual reference. The quadrotor converges to a position above the sensor node such that the optical link is above the predefined power threshold enabling optical communications, see Fig. 5(c).

To check convergence of quadrotor position, we compute the $x$-$y$ and $z$ relative distances to the sensor node, defined as

$$\Delta_{xy} = \sqrt{(x_{q} - x_{s})^2 + (y_{q} - y_{s})^2},$$

$$\Delta_{z} = |z_{q} - z_{s}|,$$

respectively. Here, $x_{s}, y_{s},$ and $z_{s}$ are the $x, y,$ and $z$ position coordinates of the sensor node, respectively. The evolution of these relative distances are shown in Fig. 4(e). Around 18 s after starting the simulation, $\Delta_{xy} \approx 0.21$ m and $\Delta_{z} \approx 4.1$ m, so that the quadrotor is above the sensor node. After this time, the quadrotor decreases its height to increase the optical link power (see Fig. 5(c)) maintaining a close relative distance with the sensor such that $\Delta_{xy} \leq 1$ m. The height decreases until the quadrotor hovers at an altitude of $\approx 3.5$ m and the $x$-$y$ relative distance with respect to the sensor is $\approx 0.2$ m.

We plot the signal strength received by the four antennas, antennas 1 and 3 in Fig. 5(a) and antennas 2 and 4 in Fig. 5(b). Roughly speaking, the direction estimate vector $\mu$ is generally determined based on antennas 1 and 4 for the first 15 s. This occurs because of the initial orientation of the quadrotor with respect to the source bearing. After initial
approach, the control maintains a good relative position within optical range, see Fig. 4(d). As seen in Figs. 5(a) and 5(b), the RF signal strength has some significant drops. This occurs when the quadrotor is generally above the RF source, such that the source bearing no longer aligns with the main lobe of the antenna. We also plot the signal strength for the optical link, see Fig. 5(c). The optical signal is detected approximately 13 s after starting the simulation. Then, the optical signal strength grows surpassing the prescribed threshold \( \tau_{OW} \). After convergence, the average optical signal strength is approximately -20.1 dBm.

VI. CONCLUSIONS

An autonomous aerial platform with hybrid radio-optical communications can be employed to gather sensor node data. This bi-modal communication scheme can eliminate the necessity of precise relative localization between the sensors and the flying robot. We proposed and demonstrated through numerical simulations a control strategy for the flying robot such that it moves towards the sensor node using RF measurements. The key idea is to find an estimate of the direction to follow using the RSS measured by four directional antennas installed on the aerial vehicle. Once the optical signal strength is above a predefined threshold, the quadrotor hovers close to the sensor node such that the optical link can be maintained at a desired signal strength.

Important topics for future work include coupling the RSS-assisted direction estimation with other sensors, e.g., a camera, to improve the sensor localization for accurate pointing of the optical beam, extension to the case of one or multiple mobile sensor nodes, refinement of our analytical framework for the case of cluttered environments, and experimental validation of our approach for micro-sized robotic platforms working in indoor environments.

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Fig. 5. Received signal strength: (a) for antennas 1 and 3, and (b) for antennas 2 and 4. (c) Signal strength for the optical link.