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Pseudo-bearing Measurements for Improved Localization of Radio Sources with Multirotor UAVs

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Abstract— **Localizing radio frequency (RF) sources is an important application for unmanned aerial vehicles (UAVs). Localization is often carried out by estimating bearing to an RF source, which can be achieved by rotating a directional antenna in place. Multirotor UAVs are well-suited for this sensing modality because they can efficiently rotate in place. However, a full rotation from a single location is needed to account for scale factors affecting the directional antenna's measurements. Although easy to perform, these rotations tend to be slow and delay localization. In this paper, we equip a multirotor UAV with a directional antenna *and* an omnidirectional antenna. The omnidirectional antenna serves to normalize measurements made by the directional antenna, yielding "pseudo-bearing" measurements. These bearing-like measurements are less informative than bearing measurements but do not require a full rotation, leading to more measurements and faster localization. We validate the normalization with antenna theory and ground tests. Claims of improved localization are validated with simulations and flight tests on a multirotor UAV. Our setup significantly reduces localization time compared to a multirotor UAV equipped with only a directional antenna.**

I. INTRODUCTION

Localizing radio frequency (RF) sources is an important application for unmanned aerial vehicles (UAVs). RF sources of interest include wireless nodes or beacons [1], radio-tagged wildlife [2], GPS jammers [3], and disaster beacons [4]. UAVs are well-suited for localization because they fly above obstacles that clutter and degrade RF signals, allowing for better measurements [5], [6]. UAVs can also be significantly cheaper than a manual, human solution. For example, current methods for localizing radio-tagged wildlife are tedious and labor-intensive [2], [6], [7]. Light aircraft have been suggested as a platform for locating GPS jammers [8], but retaining human pilots for the task is expensive.

A common localization scheme in mobile robotics is making successive bearing measurements by rotating a directional antenna in place [1], [9]–[12]. These antennas receive the strongest measurements when pointed at the RF source. After one (or several) rotations, the relative bearing to the RF source can be estimated. The antenna can be rotated with a special actuator or—in the case of multirotor UAVs—by rotating the entire vehicle. The received strength measurements depend on unknown factors like transmitter strength and distance to the transmitter. Full rotations are needed to normalize the measurements and estimate bearing. Unfortunately, rotations can be slow and delay localization.

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In this work, we focus on a multirotor UAV with a directional antenna. We augment this platform with an omnidirectional antenna. The measurements made by this extra antenna are affected by the same unknown scale factors; by comparing the directional and omnidirectional strength measurements, we can eliminate the unknown scale factors, yielding the gain contributed by the directional antenna. By comparing this contributed gain to the antenna's known gain pattern, a "pseudo-bearing" measurement can be made. This measurement is not a true bearing because multiple bearings in the gain pattern can have the same expected gain. Additionally, noise in the measurements made by both antennas mean the consolidated measurement provides a range of possible relative bearing estimates.

Although these pseudo-bearing measurements are less informative than true bearing estimates, they can be made at the sensor sampling rate instead of being limited to the time required for a UAV to rotate in place. The time to query an RF sensor is typically orders of magnitude faster than the time required to complete a rotation. More measurements are used and filtered, yielding a better estimate of the RF source location in less time. Further, these pseudo-bearing measurements are robust to scale factors that change in time. If the transmitting power of an RF source changes while a UAV is rotating, measurements made by a single directional antenna will be affected differently, making them impossible to compare. However, two antennas making measurements simultaneously will be affected equally at each time. Thus the scale factor is eliminated and the pseudo-bearing measurement is unaffected by time-varying effects.

The central contribution of this paper is presentation and demonstration of this two-antenna method and the resulting pseudo-bearing estimates. We validate the normalization theoretically and with ground tests, showing that normalization eliminates unknown factors such as transmitter distance. We validate improved localization speed in simulations; results suggest localization with pseudo-bearing measurements can be an order of magnitude faster than "rotate-for-bearing" modalities. Finally, we validate the two-antenna setup for aerial use by localizing a WiFi router with a small UAV.

II. RELATED WORK

Using UAVs for localization is an active area of research and many sensing modalities have been proposed. Early work relied on received signal strength measurements [6], [7], [13]. These methods typically assume a known transmitter strength and a well-modeled antenna. By comparing the received strength to the strength predicted by a location estimate, the location estimate can be updated. Though theoretically sound, these methods are not robust to modeling errors and were typically only simulated or tested on the ground [7], [13]. It is generally recognized that strength-based localization can fail in cluttered environments where obstructions interfere with signal strength [2]. Further, it requires knowledge of the transmitter strength, which is not always available.

Bearing-only localization is a popular alternative to strength measurements [1], [14]. However, instantaneously estimating bearing to an RF source requires beamsteering and antenna arrays, which can be heavy, expensive, and require careful calibration [2], [9]. The weight and delicacy are unsuitable for small UAVs that might operate in harsh environments.

To estimate bearing without beamsteering, a directional antenna can be rotated in place; the strongest measurements are made when pointing at the RF source. On ground robots, this rotation can be achieved with an actuator mounted on the robot [1]. However, special actuators for rotation incur additional weight and are not always appropriate for airborne systems. Therefore, UAV-based solutions typically rely on the vehicle's maneuverability to rotate the antenna. In one example, a directional antenna is attached to a monocopter that must rotate to fly [11]. Although rotations require less than a second, monocopter UAVs are rare.

More commonly used multirotor UAVs can rotate but do so more slowly. One approach is to have the multirotor UAV rotate constantly [15], but this complicates the control problem. The most common, current approach is to rotate in place to obtain a bearing estimate, fly to a new location, and rotate again [2], [3], [12], [16]. The time to complete a rotation and make a bearing estimate ranges from 24 to 45 seconds [2], [12]. The long time required to make a single rotation—and therefore a single measurement—significantly slows localization. Measurement times of half a minute are also particularly detrimental to multirotor UAVs, which typically have battery lives measured in minutes.

Previous research uses full rotations because unknown scale factors affect received strength measurements. For example, transmitter location is unknown in localization. Any difference between strength measurements made at different locations can be attributed to orientation *or* changed distance to the transmitter. Therefore, many "rotate-for-bearing" strategies normalize a pattern of measurements made at one location, eliminating transmitter distance as a factor. In cross-correlation, the measured strength pattern is directly normalized and shifted angularly [1]. The relative bearing estimate is the shift at which the normalized pattern most closely matches the known gain pattern. Another estimate is the heading where the maximum strength measurement occurs [11]. This method is effectively a normalization—if the measurements are made at the same location, they can be directly compared because the distance to a stationary target remains unchanged.

III. NORMALIZATION

Our focus is improving multirotor UAVs that estimate bearing with a directional antenna. We propose augmenting these systems with an inexpensive omnidirectional antenna. Because an omnidirectional antenna's gain is independent of its orientation, changes in measured strength reveal information about environmental scale factors. This information can be used to eliminate scale factors from the directional antenna's measurements, leaving the gain provided by the directional antenna. By comparing this gain with the directional antenna's gain pattern, we obtain an instantaneous "pseudo-bearing" without performing a full rotation.

A. Theory

Theoretical justification for the normalization process follows from antenna theory. It extends similar derivations in the localization literature [10]. The power P_{dir} received by a directional antenna is

$$P_{\text{dir}}(d) = \frac{P_t G_t G_{\text{dir}} \lambda^2}{(4\pi)^2 d^2 L}, \tag{1}$$

where P_t is the transmitter power, G_t is the transmitter antenna gain, G_{dir} is the directional antenna gain, L is a system loss factor, λ is the wavelength of the RF signal, and d is the distance between the transmitter and receiver. Received power is often expressed in dB:

$$10 \log P_{\text{dir}}(d) = 10 \log \frac{P_t G_t \lambda^2}{(4\pi)^2 d^2 L} + 10 \log G_{\text{dir}}. \tag{2}$$

The first term on the right-hand side of Eq. (2) captures the effects of various factors on the measurement. Without loss of generality, we consider only the effects of distance and transmitter power and denote this term as $P(d, P_t)$. The second term on the right-hand side of Eq. (2) is the directional antenna gain in dB and is denoted $g_{\text{dir}}(\theta)$, where θ is the relative bearing from the receiving antenna to the transmitter.

The left-hand side of Eq. (2) represents the power received by the directional antenna in dB. We denote this s_{dir} and present a simplified equation for measured power:

$$s_{\text{dir}} = P(d, P_t) + g_{\text{dir}}(\theta). \tag{3}$$

Eq. (3) shows that strength measurements will differ from the directional antenna gain by the factor $P(d, P_t)$. This term is the unknown scale factor that requires normalization.

Normalization can be carried out by adding an omnidirectional antenna. The power received by an omnidirectional antenna is

$$s_{\text{omni}} = P(d, P_t) + g_{\text{omni}}, \tag{4}$$

where g_{omni} is the antenna's gain. This gain is independent of bearing to the RF source and is typically known a priori.

If both antennas are colocated and measure simultaneously, the distance d, the transmitter power P_t, and the scale factor $P(d, P_t)$ will be the same for both antennas. By inserting Eq. (4) into Eq. (3), this scale factor can be eliminated:

$$g_{\text{dir}}(\theta) = s_{\text{dir}} - s_{\text{omni}} + g_{\text{omni}}. \tag{5}$$

Eq. (5) shows that the gain contributed by the directional antenna can be estimated from the omnidirectional gain and the power measured by both antennas.

B. Hardware Setup

To take advantage of the result from Eq. (5), a directional antenna and an omnidirectional antenna need to make measurements simultaneously. Although the normalization method could work for any RF signal, we use 2.4 GHz 802.11 wireless (WiFi) in our experiments.

The directional antenna used in this work is a 9 dBi Yagi-Uda antenna (L-com model HG2409Y-RSP). This antenna has a 60° beamwidth, where beamwidth is the angular width over which the gain is at least half (i.e., within 3 dB) of its highest value. This antenna costs $30 USD.

The omnidirectional antenna used is a 5 dBi rubber duck antenna (L-com model HG2405RD-RSP). This antenna is omnidirectional in the horizontal plane, which is the plane of interest because a multirotor UAV rotates in this plane. In the vertical plane, the antenna has a large beam-width of 120°. A large vertical beamwidth is desirable because the RF source and UAV will not be at the same altitude. This antenna costs $10 USD.

Each antenna is connected to an RN-XV WiFly Module through an RP-SMA connector. Each of these modules is connected to a Sparkfun XBee Explorer, which connect to a computer through USB. Serial communication between the computer and the WiFly allows the relative signal strength indicator (RSSI) to be queried. Returned RSSI values are expressed in dBm. The combined cost of a WiFly Module and XBee Explorer is $60 USD.

C. Validation

Ground experiments validated the normalization procedure. A router was placed in an open field. The directional and omnidirectional antennas were mounted together and placed at varying distances from the router.

The mounted antennas were rotated in place and RSSI measurements were taken. Ten RSSI values for each antenna were queried at 10° intervals. This allowed the construction of mean gain patterns for each antenna. Fig. 1 shows patterns obtained 30 feet from the router. The power measured by the omnidirectional antenna is roughly constant, as expected.

The normalization was performed by applying Eq. (5) to the mean gain patterns for each antenna. Fig. 2 shows the normalization results. The unnormalized directional gain patterns are all similar, but differ greatly by a scale factor. The normalized patterns do not differ by this scale factor. Furthermore, all normalized patterns have a peak gain of roughly 9 dBi and a beam-width of roughly 60°, matching manufacturer-provided values for the Yagi. The similarity of the normalized patterns to each other and the nominal values validates the proposed normalization procedure.

The unnormalized patterns shown in Fig. 2 do not fully match expectations. There is nearly a 5 dB difference between the patterns measured at 100 and 120 feet. Increasing the distance by a factor of 1.2 should lead to a drop of 1.58 dB, according to Eq. (2). This disparity between expected and measured strength exists for most of the unnormalized patterns shown, suggesting that there are other factors affecting the

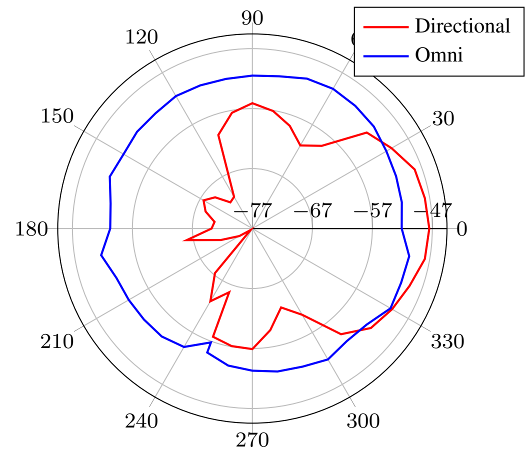

Fig. 1. The mean power measurements made at a distance of 30 feet from the router. The omnidirectional antenna's gain is fairly constant.

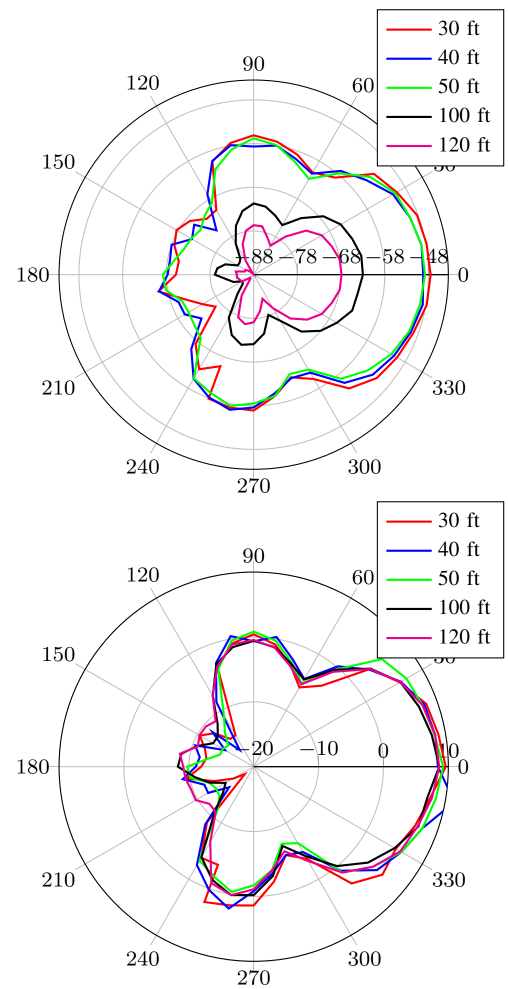

Fig. 2. Strength measurements made by the directional antenna yield similar but scaled patterns depending on distance (top). This scale factor is eliminated with the use of the omnidirectional antenna, resulting in the gain induced by the directional antenna (bottom). The peak directional gain is roughly 9 dB at all distances, which is the nominal value for our antenna.

measured strengh values. Despite this, normalization still yielded the expected results.

The robustness of normalization to these unknown factors hints at an advantage our architecture has when tracking non-cooperative RF sources. If a non-cooperative RF source varied its transmitted power to confound a tracker, a single, rotating, directional antenna would not be able to separate the effects of relative bearing and the changing transmitter power. Normalizing with a full rotation would not resolve the effects. Because the omnidirectional and directional antennas can take measurements simultaneously, changes in RF source strength over time have no effect.

IV. LOCALIZATION

In the last section, we generated a normalized gain pattern for our directional antenna. This pattern relates measured strength and relative bearing to an RF source. These measurements are noisy, so Bayesian filtering is applied. We also show the effect of using information-theoretic control.

A. Bayesian Filtering

The measurement y_t measured at time t is

$$y_t = g_{\text{dir}}(\theta_t) + w_t, \tag{6}$$

where θ_t is the relative bearing to the target and $w_t \sim \mathcal{N}(0, \sigma)$ is the noise. The function $g_{\text{dir}}(\theta)$ provides a directional antenna gain for bearing θ and was estimated as the mean of normalized patterns shown at the bottom of Fig. 2.

Using the measurement model in Eq. (6), we can apply standard filter techniques to maintain a belief, or probability distribution over RF source locations. Resulting beliefs tend to be multimodal and highly non-Gaussian, as can be seen in Fig. 6. This non-Gaussianity makes Kalman filters unsuitable for this problem. We use a discrete Bayes' filter, discretizing the search area into cells that might contain the RF source; the belief is a probability distribution over these cells.

B. Motion Model and Control

We fix the UAV to a constant altitude, because altitude has little effect on the gain received. Because our multirotor UAV is agile, we can approximate it reasonably well with single integrator dynamics. For simplicity, we assume the UAV travels at a constant speed and can rotate in either direction at a fixed angular rate (or not rotate at all). We use discrete time steps equal to the interval between successive RF measurements. Therefore, a control policy effectively selects the next UAV pose from which to make a measurement, subject to the speed and rotation constraints.

There are many ways to choose the next measurement location. A popular option is a greedy, information-theoretic strategy that has been used often on UAVs [2], [4], [12]. This control policy picks the next UAV pose that minimizes the expected belief entropy after the next measurement. Entropy is a measure of disorder in a system—a uniform distribution maximizes entropy. This method has been covered extensively in prior work, so we do not cover the details here.

TABLE I
TIME REQUIRED TO ATTAIN A CONCENTRATED BELIEF.

sensing modality	policy	localization time (s)
directional	greedy	95.3
directional + omni	greedy	11.11
directional + omni	random	108.1

C. Simulations

To test our sensing modality, we simulated localization of a stationary RF source in a $100\,\mathrm{m} \times 100\,\mathrm{m}$ search area. The UAV starts in the center of this area, and the RF source is initialized to a random location. We assume the UAV travels at 5 m/s and can rotate at 15 °/s. Bearing estimates from the rotate-for-bearing modality are assumed to have zero-mean Gaussian noise with a standard deviation of 5°, comparable values in the literature [12]. In the pseudo-bearing sensing modality, measurements are made at 1 Hz with 2 dB noise. We ran 1000 localization simulations for each of three UAVs: a rotate-for-bearing UAV that selects rotation locations according to greedy information gain, a pseudo-bearing UAV with greedy information control, and a pseudo-bearing UAV with random control. The belief is represented as a 21×21 grid and the RF source is considered localized when some target cell has a probability greater than 0.7.

Table I shows the mean time for each of the three setups to localize the RF source. The two-antenna sensing modality performs much better than the directional-only modality, localizing roughly an order of magnitude faster when both modalities use greedy information control. Localization occurs in roughly half the time it takes to make a single rotation, if we use the fastest rotation in the literature [12]. Even when using random control, the two-antenna modality performs roughly as well as the directional-only modality with greedy control. Although not a rigorous bound, the random policy is likely worse than any policy to be used.

Because pseudo-bearing measurements are limited by the RF sensor sampling rate, it is beneficial to sample at a higher rate. To explore the effect of sampling rate and measurement noise on pseudo-bearing localization, we ran 1000 simulations for different combinations of noise values and sampling rates. Greedy policies were used. The results are shown in Fig. 3. Even when sampling at 1 Hz with 6 dB noise, the pseudo-bearing measurements lead to localization much faster than the rotate-for-bearing equivalent.

V. FLIGHT TESTS

In Section III-C, we validated the normalization procedure on the ground. Here, we present validation of the method in flight tests. Flight introduces additional measurement challenges such as interference and vehicle stability. We use a UAV to localize a stationary WiFi router.

The UAV used in these experiments is a DJI F550 hexcopter. It carries an ODROID-XU4 computer that takes RSSI measurements, performs normalization and filtering, and provides commands to the vehicle. This small computer

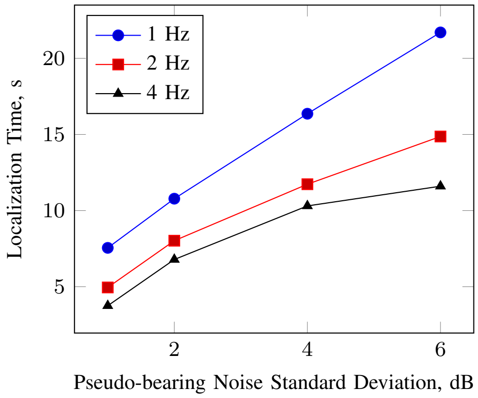

Fig. 3. Effect of sampling rate and noise on pseudo-bearing localization.

Fig. 4. The UAV during flight tests. The directional antenna is housed in the white cylinder in front of the UAV. The omnidirectional antenna hangs from the UAV, lying flat on the ground until takeoff.

weighs 60 grams and has 2 GB RAM. Measurements from both antennas are made at 1 Hz. The UAV is shown in Fig. 4.

The directional antenna is fairly robust to interference from the UAV. Its most sensitive gain lobe sits in front of the vehicle. Measurements made when the vehicle points away from the source are obstructed and degraded by the UAV body. However, the degradation is acceptable because the resulting patterns are similar to nominal (antenna alone) patterns and directionality is preserved.

In contrast, we rely on the omndirectional antenna having similar gain in all directions and cannot allow its measurements to be degraded in some directions. Preliminary flight tests showed a 5–10 dB degradation on omnidirectional measurements blocked by the UAV body. This uneven degradation ruins the normalization presented in Eq. (5).

Properly placing the omnidirectional antenna is difficult on a small UAV. To mitigate interference from the body, we hung the antenna under the body. Before flight, the antenna lies flat on the ground. When the UAV takes off, the antenna cable pulls taut and the antenna hangs. Hanging introduces some problems: the antenna swings somewhat during flight, adding noise to the measurements and changing vehicle dynamics. However, the antenna seemed mostly stable in flight and the significant reduction in noise makes the trade-off profitable.

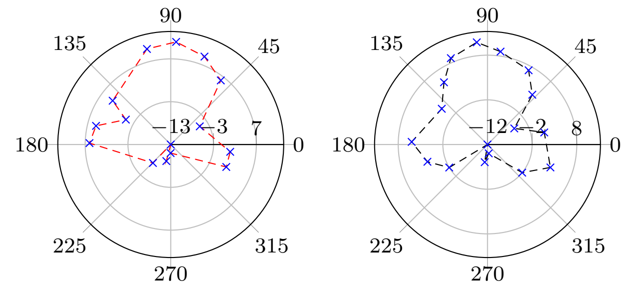

Fig. 5. Two example patterns at a range of 40 meters and relative bearing of roughly 90° to the router.

A. *Gain Patterns*

We tested the impact of flight-induced factors on measurements to determine whether the resulting patterns matched the ground-based results from Section III-C. The UAV performed several rotations in place at 15 °/s while collecting and normalizing measurements to generate gain patterns.

Fig. 5 shows two patterns measured in flight. The patterns are visually similar to the ground-based patterns in Fig. 2—the side and main lobes are present, and the maximum gain is near the nominal value of 9 dB. The patterns are relatively sparse, making a more analytical comparison between the ground and airborne patterns difficult. The sparsity could be mitigated with a higher sampling rate, but the WiFly receivers struggle to produce measurements at greater than 1 Hz. Additionally, sometimes one of the WiFly receivers fails to make a measurement. When this happens, normalization cannot be performed and we throw out the measurement from the other receiver. However, the ground and airborne patterns are visually similar enough to validate aerial normalization.

B. *Localization*

Three flight tests were flown in a $110\,\mathrm{m} \times 110\,\mathrm{m}$ search area. After takeoff, the UAV flew a fixed path at 10 m/s and constantly rotated at 15 °/s. This path was chosen so the resulting measurements would have good geometric diversity. The sensor model used in the filtering and estimation had a conservatively large standard deviation of 6 dB.

At the end of each flight, the Euclidean error of the mean target estimate was under three meters. Fig. 6 shows the results of one flight test. The entire flight took 50 seconds, whereas previous bearing estimation methods reportedly spent 45 seconds [2] or 24 seconds [12] for a *single* bearing estimate. Despite the simple trajectory and low sampling rate, the flight test results validate the pseudo-bearing concept.

VI. Conclusion

We demonstrate a simple yet effective sensing modality for multirotor UAVs localizing an RF source. Combining directional and omnidirectional antennas, this modality is an inexpensive addition to UAVs already equipped with a directional antenna. In simulation, this modality localizes RF sources faster than traditional “rotate-for-bearing” modalities by an order of magnitude. We also validate the modality in flight tests and localize a stationary WiFi router.

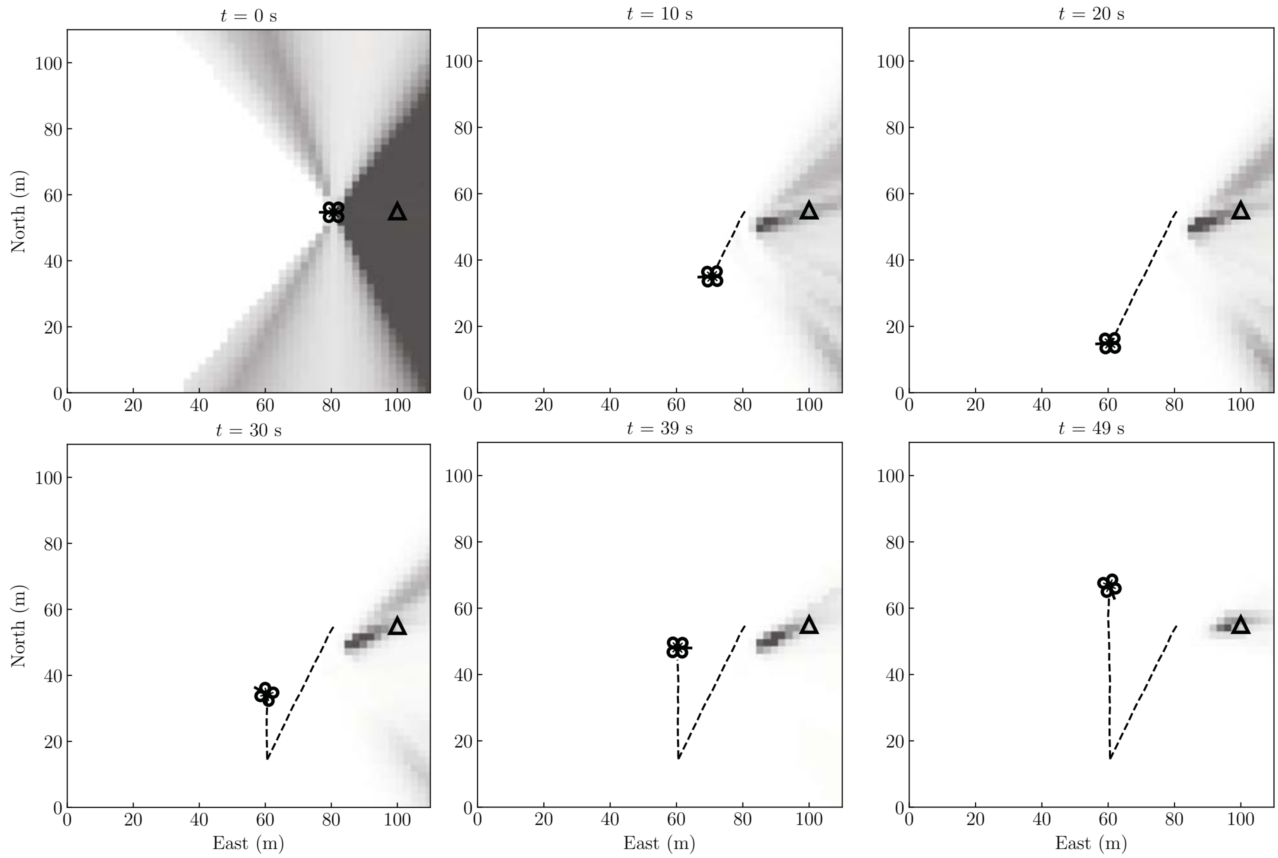

Fig. 6. Beliefs and UAV positions during a flight test. The router (triangle) is effectively localized. The dashed line shows the path flown.

Future work will improve the current system and explore other applications. We are already working on replacing the WiFly receivers with more robust sensors capable of faster measurement rates, such as low-cost software defined radios [16]. These sensors can operate at various frequencies, allowing other RF sources to be hunted. Although the hanging antenna worked well at our relatively mild speeds, we might seek a solution more robust to aggressive maneuvering.

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