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Low Cost Sensing and Communication System for Rotor-Craft

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Abstract— **Local communication and sensing between individuals are frequently used for control in multi-robot systems. However, in current flying multi-robot systems, such as swarms of quadrotors, these abilities are often only emulated using global communication and global position sensing. This is mainly due to the complexity, cost, weight, or power requirements for such sensors. Here we present a system that can allow for more natural swarming behaviors by enabling direct bearing and elevation sensing, as well as communication between nearby rotor-craft. This system takes advantage of the existing motion of the vehicles propellers, is low power, and can be adapted to existing vehicles with only simple modifications. We describe the system, present a working prototype, show performance of this prototype, and conclude by describing future work integrating the system into a rotor-craft swarm.**

I. INTRODUCTION

The ability to sense and communicate with neighbors is an integral and widely used capability for all types of multi-robot systems. It can be used to exchange maps and measure relative pose for multi-robot SLAM [1], build relative coordinate systems [2,3], efficiently route messages [5], coordinate self-assembly [6,7], coordinate group motion [8], etc. Communication and local sensing, such as distance and bearing, are commonly found in ground-based multi-robot systems; however, it is often lacking in flying multi-robot systems especially with smaller vehicles, due partly to complexity, weight, and power constraints. Here we present a system capable of sensing and communication for flying rotor-craft, such as quad-rotors, that is low-cost, uses very little power, and is easy to adapt to most systems.

Currently, flying swarms have shown impressive demonstrations of multi-robot behaviors such as collective construction [9,10], group formation control [11], flocking [12], etc. However, the communication and sensing systems used are, for the most part, fundamentally different from those believed to be used in natural systems [13], or envisioned in simulated flying swarms [14]. Natural systems are thought to rely on local sensing, such as bearing and elevation to neighbors, whereas most existing work in this space only emulates this kind of information by deriving it from global information, such as external motion capture systems, beacons, and centralized controllers.

For example, in the flocking of virtual “boids” [14], and in fish schooling [13], individuals within the group directly sense, for example using vision, the bearing and elevation of neighboring individuals, and use this information to control their motion and interaction with others in the swarm. This works without global position knowledge, is scalable, and does not require centralized control. There are examples of similar behavior found in flying robotic swarms, such as using fixed wing vehicles to flock in tight formation [12] or in competitive swarming [15]. In these examples, robots make use of bearing and elevation, but this is not directly sensed. Instead they transmit their position from beacons such as GPS or ultra-wideband transmitters [16] to other vehicles using wireless communication, and use the position of neighbors and their own position to compute the bearing and elevation information. This indirect sensing may have scalability issues as in some examples messages are broadcast to the entire swarm, even though the information is only used by nearby neighbors. Relying on GPS also constrains the swarm to operate outdoors.

Another negative effect of using position to indirectly sense bearing and elevation is that noise in the sensed position is independent of the distance between two individuals. This noise in sensed position will cause noise in the indirectly sensed values, such as bearing or elevation, between two individuals to increase as the distance between them decreases. This is the opposite of the desired noise behavior, since it is most critical to have accurate sensor information when individuals are in close proximity, closely interacting, and with increased risk of collision.

Other approaches to swarming vehicles use external tracking systems, such as VICON [17], to detect the absolute pose of individuals and then either emulate the required sensed information indirectly, or directly use positions of all robots for trajectory following [18] that gives swarming behavior without collisions. While these external systems offer very good pose sensing at high frequency, they are expensive, inherently centralized, and constrain swarm operations to areas already outfitted with such systems.

In this paper we will present a system for sensing and communication between flying rotor-craft, such as quad-rotors, which allows individuals to directly communicate to and sense the bearing and elevation of neighboring robots in a fully distributed way. This system takes advantage of the existing motion of the vehicles’ propellers, is low power, and can be adapted to existing vehicles with only minor modifications. In addition, this system can easily be scaled to large robot swarms without relying on centralized control infrastructure. We describe the system, present a working prototype, show the performance of this prototype, and conclude by describing future work integrating the system into a rotor-craft swarm.

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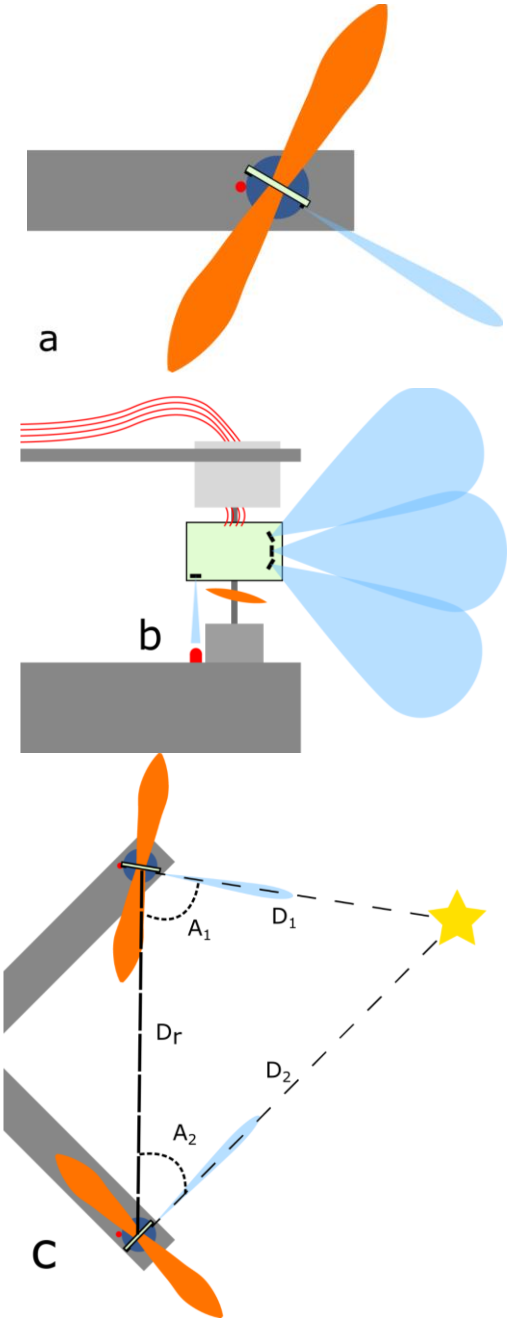

Figure 1: Conceptual drawings of sensor on rotor-craft. A) top and B) side view of a single sensor showing pickup LED (red), PCB (green), propeller (orange), slip ring(grey), and a depiction of the angular sensitivity of the receivers (blue). Side view shows three receivers depicting their angular sensitivity in the elevation direction. C) Diagram showing computation of distance using parallax between two sensors on the same quadrotor.

II. DESCRIPTION

The following describes a sensor attached to the rotating portion of the rotor-craft, such as the propeller. This sensor is capable of sensing the bearing and elevation to an omni-directional remote transmission source within line-of-sight. This transmission source could be stationary in the environment, such as a navigational beacon, or mobile, such as affixed to the chassis of another rotor-craft. As the sensor rotates with the propeller, it measures the intensity of the received signal in its current bearing direction and the elevation direction for that signal. This information, coupled with knowledge about the angular position of the sensor, allows the system to determine the bearing and elevation with the highest received intensity, and therefore the bearing and elevation to the transmission source. Instead of just emitting a constant signal, the transmitting source can modulate this signal to encode information. This will allow the receivers to detect the direction to the transmitter as well as receive a message from it, also allowing for communication. This communication will enable the receiver to easily distinguish from multiple transmission sources (for example using an ID encoded in the message). If each vehicle has a transmitter affixed to itself, then vehicles can sense and communicate with neighbors. For this paper and the sake of simplicity, the communication medium is chosen to be infrared light; however, a number of other media with directionally sensitive receivers such as radio, visible light, etc. are viable.

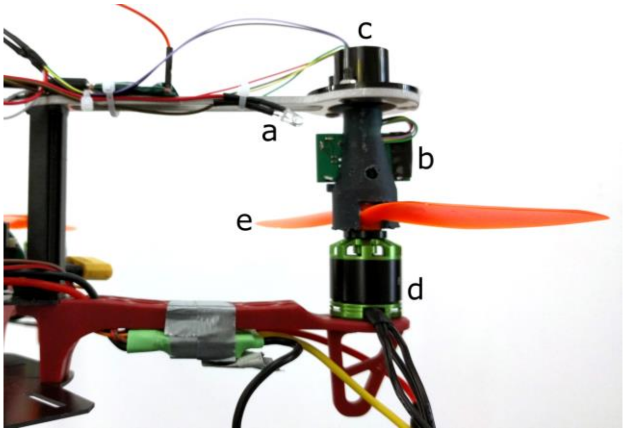

Figure 2: Prototype sensor on a quadrotor vehicle, showing pickup LED (a), PCB with receivers (b), slip ring (c), motor (d), and propeller (e).

A. *Prototype Sensor*

The prototype sensor consists of a printed circuit board (PCB) that has multiple infrared receivers with a narrow angle of sensitivity in the rotation (bearing) direction, and wide but varying angle of sensitivity in the elevation direction (up and down), see Fig 1,2. In addition, there is an infrared pickup receiver which can measure when the sensor passes over an LED attached to the stationary frame of the rotor-craft. The receivers are connected to a small microcontroller which can poll the sensor values 75 thousand time a second. The PCB is rigidly attached to the rotating motor shaft and rotates with it. During flight, the PCB and its mounting hardware are subject to high angular velocities, approximately 300-600 radians/second. To prevent damage to the PCB and unnecessary vibrations, the PCB and mounting hardware are designed to be rotationally balanced and remain as close as possible to the axis of rotation. The transmission source is a cluster of IR LEDs which are pointing in various directions, emulating an omni-directional source.

While the sensor system on the PCB is passive (not emitting), it does require some power to operate, on the order of a few milliwatts. While a small battery might be sufficient, concerns about balance led us to transfer power from the quadrotor's main battery pack to the propeller-mounted sensor using an electrical slip ring mounted co-axially and above the motor. The use of a slip ring allowed for easy prototyping of the system; however, other methods to transfer power may be more practical, such as passing a coil in the propeller over a magnet in the quadrotor arm, solar power, inductive power, etc.

B. Bearing Sensing

As the sensor sweeps with the propeller, each receiver can measure the intensity of light in the direction of the bearing angle it is currently facing. The narrow angle of sensitivity for the receivers in the bearing direction means that the sensor can only detect the transmitter when the PCB is directly facing it. By comparing this intensity for all bearing angles in a full rotation of the propeller, the sensor can detect angles of maximum signal intensity, and thus the bearing direction to a transmission source. For some platforms, certain angles may be blocked by the robot's own structure, such as the chassis, creating blind spots for a single sensor. These blind spots can be removed by placing sensors on multiple rotors which can sense angles that are in other sensors' blind spots.

C. Elevation Sensing

On each sensor PCB there are multiple receivers pointing in the same bearing direction, but at different elevation directions, see fig. 1. Similar to [4], by knowing the elevation each receiver is facing and comparing the intensity detected by each receiver at the same bearing, the elevation angle of the transmitter can be computed.

D. Distance

In the case of a multi-rotor vehicle, two sensors can be placed on two adjacent propellers, with a fixed and known distance D_r between the two sensors, fig 1. By using two sensors on two rotors for the same vehicle (with a known distance between the sensors), the parallax between sensed angles can allow for the distance to the source to be computed for short ranges. If the transmitter is at the same height as the sensors, i.e. elevation is zero, then the distance between the sensors and the transmitter can be computed using the law of sines as follows (shown in fig 1),

$$D_1=D_r\sin(A_2)/\sin(\pi-A_2-A_1) \quad (1)$$
$$D_2=D_r\sin(A_1)/\sin(\pi-A_2-A_1) \quad (2)$$

Where D_1 and D_2 are the distance between the sensors and the transmitter, and A_1 and A_2 are the bearing angles measured by the sensors. If the elevation angle is non-zero, then the distance between the sensors and the transmitter can be computed as:

$$D_1=(D_r\sin(A_2)/\sin(\pi-A_2-A_1))/\cos(E_{a1}) \quad (3)$$
$$D_2=(D_r\sin(A_1)/\sin(\pi-A_2-A_1))/\cos(E_{a2}) \quad (4)$$

Where E_{a1} and E_{a2} are the sensed elevation angle for sensors 1 and 2, respectively.

E. Sensor orientation

In order to determine the bearing angle at which data is received and intensity is measured, the sensor must have a way to measure its current angle with respect to the vehicle reference frame. In practice, this can be done in multiple ways, such as using an encoder, a pickup sensor to measure when the propeller passes over the frame, using feedback from the motor controller, etc. In this prototype system we use a pickup sensor on the rotating PCB which looks for a light source that is fixed to the frame of the quadrotor and registers when the sensor passes over the arm, see figure 1,2. This allows for the sensor to measure the speed of the propeller during the previous rotation, which together with the time since last passing over the arm, allows the sensor to estimate the current orientation. This method was chosen as it is low cost and requires very little modification to existing vehicles.

An example of the intensity measured by the pickup sensor is shown in fig 3, and can be used to demonstrate how the sensor orientation is computed. The PCB is assumed to be at zero degrees bearing when the pickup sensor value has a positive crossing of the value i_1. The value i_1 was chosen to be halfway between the min and max values seen by the pickup sensor, which increases the resilience to noise on the pickup sensor. By measuring the time between these i_2 crossings (t_3-t_1), the time per rotation is computed, t_3-t_1. The orientation of the sensor, θ_s, at anytime, t, between t_1 and t_3 is then computed as

$$\theta_s=2\pi(t-t_1)/(t_3-t_1) \quad (5)$$

The time between t_1 and t_2 in which the outward facing sensor detects its highest value is also stored (t_2 in figure 3). By knowing the time when the outward facing sensor was highest, and therefore pointing towards the transmitter, we can compute the bearing angle to the transmitter as $2\pi(t_2-t_1)/(t_3-t_1)$. If the PCB is not at a true bearing of zero when it has a positive crossing of i_1, then a calibration constant C can be used to correct the sensed angle to the true angle as $2\pi(t_2-t_1)/(t_3-t_1)-C$.

For the sake of this paper we assume the propellers have no acceleration, which for stable flight may be enough of an approximation. However, aggressive maneuvers such as in [19] use quick acceleration of propellers, which if undetected could impact the accuracy of the sensor. This could be addressed in the future by using an accelerometer or gyro on the sensor to integrate and compute the current position based on previous measured propeller speed and detected acceleration, or using an open loop prediction on how changes in commanded motor speed effect propeller velocity.

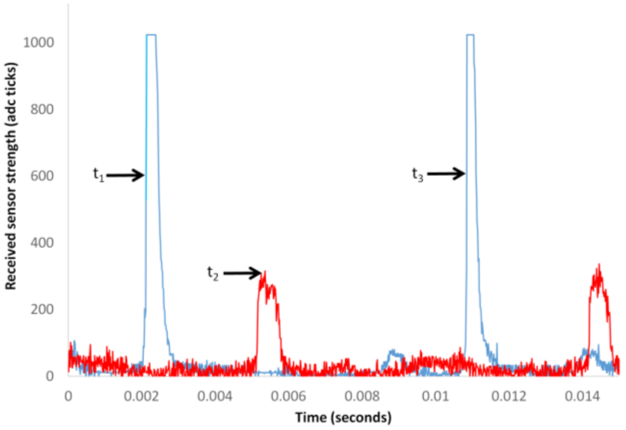

Figure 3: Data from the pickup sensor (blue) and a receiver (red) during a rotation of the PCB.

III. EXPERIMENTAL TESTS

To demonstrate the prototype sensor experimentally, we affixed sensors to two adjacent propellers of a quadrotor vehicle. These sensors were used to measure the relative pose of the quadrotor to an infrared light source, and in turn use that sensed information to feedback into the quadrotor's pose estimator for stable autonomous flight without drift. Videos of these experiments can be found in the supplementary video uploads.

Figure 4: Flight hardware with two prototype sensors.

A. Flight Hardware

The overall system architecture of the UAV uses a customized quadrotor based on the DJI F450 frame powered by off-the-shelf brushless D.C. motors and standard 8 inch propellers. Mechanical mounts were added to support the slip ring co-axially above two of the motors. The UAV is controlled by an off-the shelf Pixfalcon autopilot running the PX4 flight stack [20]. The autopilot is interfaced to an onboard Raspberry Pi 2 via a serial interface and communicates using the Mavlink message protocol [21]. The Raspberry Pi 2 is connected to the propeller sensors via a serial port and runs ROS with 3 separate nodes that read, filter, transform, and forward the sensor's information to the Pixfalcon using the open-source mavros package. For the prototype system, the information is sent to the Raspberry Pi over a serial port using the same slip ring that powers the sensor. However, this could be replaced with other forms of wireless communication such as RF (bluetooth,wifi), infrared, across inductive coupling, etc.

Upon receiving the sensor data, the flight controller's internal Extended Kalman Filter uses the propeller sensor's information as update measurements, similarly to how visual position estimates are fused in work such as [22]. This sensor fusion takes advantage of the high precision information from the IMU and combines it with the high accuracy information from the prototype sensor, filtering out drift from the IMU and noise from the prototype sensor.

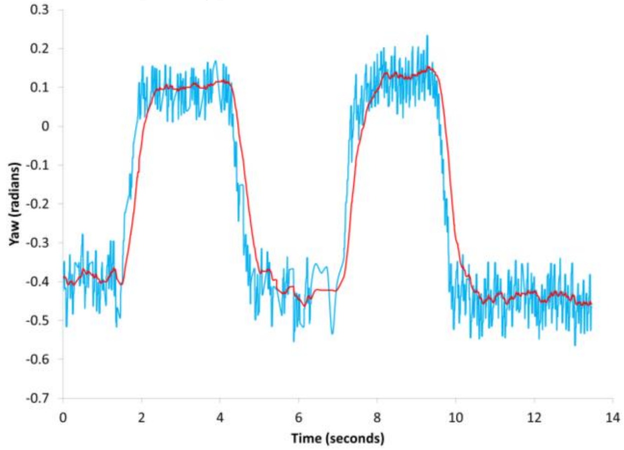

Figure 5: Data from perturbations of the quadrotor's yaw, showing output from the bearing sensing (blue), and the belief from the Extended Kalman filter (red).

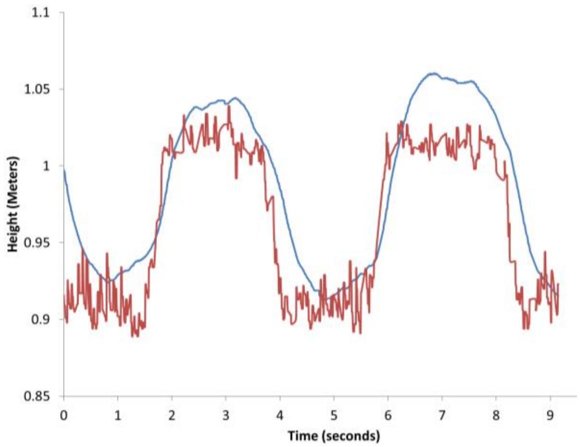

Figure 6: Data from perturbations of the quadrotor's height, showing output from the elevation sensing (red), and the belief from the Extended Kalman filter (blue).

B. Results

To test the sensor capabilities, a transmitter was held stationary in the environment, and the quadrotor was excited along two degrees of freedom, yaw and altitude. The raw sensor information and the vehicle pose estimate, a result from the Extended Kalman filter, can be seen in figure 5,6. While the graphs show that the raw sensor data contains noise, it is being sampled at a high frequency, the frequency of propeller rotation, so filtering could further reduce this noise if needed. In addition we observed that the Extended Kalman filter sufficiently damped down the noise from the sensor, giving us smooth flight autonomously controlled by the prototype sensors.

The noise on the sensor data could be the result of multiple factors. Noise and imprecision on the pickup sensor will cause noise on sensing of the PCB's position, and therefore noise in the sensor data. To improve the pickup sensor, future versions could use a narrower window between the pickup sensor and the pickup LED, or switch to a different way of sensing the pickup that is less noisy, such as an opto-electronic interrupter or magnetic sensing. Another factor that could be causing sensor noise is the vibration of the quadrotor due to unbalanced sensors. While effort was made to balance the sensor, some vibration was noticed on the quadrotor when hovering. This vibration is not necessarily synchronized to the rotation of the sensor. For example, the vibration of one sensor could cause motion in another sensor, and the motors are not necessarily running at the same speed. This could move the position and orientation of the sensors during subsequent rotations, and cause noise in the sensed bearing and elevation to the transmission source.

IV. CONCLUSION AND FUTURE WORK

Tests with the prototype sensor have shown that it can be used to sense bearing and elevation, and to control the autonomous flight of a quadrotor. The sensor shows promise in enabling a swarm of directly sensing fully distributed rotor-craft. However, there is still room for improving both the noise of the sensor as well as the physical packaging.

Future work will investigate methods to reduce sensor noise by placing pickup sensors and receivers on both sides of the PCB, to sample twice a rotation instead of once. This will double the sampling frequency and allow for better filtering of noise. Updating the pickup sensor to reduce noise in measuring the PCB position will also reduce noise on the sensed values of bearing and elevation.

One goal of this work is to create a sensor that can easily be attached to a rotor-craft, and the current prototype does not meet this goal. Future work will include transferring power to the sensor using inductive or a magnetic generator, such as a coil on the sensor passing over a magnet on the chassis to generate power. This could remove the complication of a slip ring, and allow for the majority of the sensor to be easily attached to a propeller, or even embedded into it. The data link from the sensor to the quadrotor control could be switched to wireless as well, for example using Bluetooth. These modifications could allow the sensor to easily be added to existing rotor-craft. In addition, we plan on using this system to control interaction and behavior in a swarm of flying robots.

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