RF Techniques for Motion Compensation of an Unmanned Aerial Vehicle for Remote Radar Life Sensing

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***Abstract*—Unmanned Aerial Vehicle (UAV) platforms are ideal for remote life sensing applications including military, humanitarian and post-disaster search and rescue operations. Doppler radar sensors can remotely detect human vital signs to assess triage but any sensor motion will corrupt the signal. The vital signs signal fidelity can be improved by using the Received Signal Strength Indicator (RSSI) and Radio Frequency Direction of Arrival (DOA) to compensate for the platform motion and drift via a closed loop control system that modulates the UAV Electronic Speed Controller (ESC). The measured average RF DOA error was 0.004 degrees. Motion compensation with an ultrasonic sensor was also successfully demonstrated.**

Keywords— motion compensation, remote sensing, radar, RF DOA, RSSI, UAV

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have the potential for post-disaster search and rescue missions where triage can be conducted on victims using an on-board radar sensor to detect respiratory motion [1]. Vital signs measurements using a stationary Continuous Wave (CW) Doppler radar sensor have been previously demonstrated [2]. This research project attempts to compensate for the motion of the radar sensor on the UAV platform through the use of RF techniques to minimize signal distortion from the UAV motion. Other papers describe motion cancellation techniques for vital signs sensing when the subject motion interferes with the measurement [3].

Since the radar return signal corresponds to the phase modulation resulting from the range variation between the radar and the subject, any sensor platform motion will induce an undesired phase component to the baseband signal. For our concept of operations, the assumption is that the human subject is stationary, as is likely the case for a post-disaster scenario where victims are prone on the ground and the primary component of signal distortion is from the UAV motion.

Hover and loiter modes of existing drones that rely on GPS or barometric and ultrasonic sensors to maintain a stationary position are prone to drifting and are inadequate for radar life sensing. Supplemental motion compensation using RF techniques include tracking the Received Signal Strength

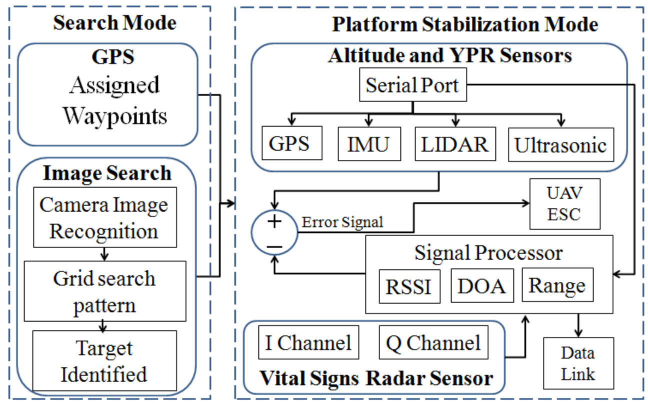

Fig. 1. System block diagram for the search and stabilization modes for the UAV radar sensor platform. Conventional sensors (GPS, IMU, LIDAR, barometric and ultrasonic sensors) that determine altitude and yaw, pitch, roll (YPR) are supplemented with RSSI and DOA for motion compensation.

Indicator (RSSI) and the RF Direction of Arrival (DOA) of the vital signs radar baseband signal. The RSSI and DOA outputs are used to generate an error signal for a closed loop feedback system that can be used to adjust the on-board Electronic Speed Controllers (ESC) that control the propeller speed for each quad-copter motor, thereby stabilizing the platform.

The operational concept is for the system to have a search mode and an acquisition mode as shown in Figure 1. In the search mode, the UAV navigates to the area of interest using GPS waypoint coordinates. At the waypoint station, an onboard camera with image recognition identifies potential victims (targets). In the stabilization mode, a suite of sensors, including GPS, IMU, LIDAR and/or ultrasonic range sensors, are used to adjust the UAV Electronic Speed Controllers (ESC) to maintain a steady altitude and fixed Yaw, Pitch and Roll (YPR) attitude. In the target acquisition mode, the UAV autonomously converges above the subject and uses the RF techniques described in this paper to maintain signal lock on the target.

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II. QUADRATURE RADAR MOTION COMPENSATION

In addition to the platform stabilization, baseband signal processing is also used to compensate for residual phase artifacts in the radar in-phase (I) and quadrature (Q) channels. While the platform stabilization techniques remove the majority of the motion noise, additional signal processing is required to remove the remaining phase distortion. These errors can be determined by the phase components measured by the ultrasonic and lidar sensors and removed from the I and Q signals to yield the respiration waveform. The I and Q channels are represented by the following equations:

$$I = kA\cos[(\boldsymbol{\omega}_1 t) + u(t - \varphi_u - \tau_u) + l(t - \varphi_L - \tau_L)] \qquad (1)$$

$$Q = kA\sin[(\boldsymbol{\omega}_1 t) + u(t - \varphi_u - \tau_u) + l(t - \varphi_L - \tau_L)] \qquad (2)$$

where $\boldsymbol{\omega}_1$ is the respiration signal modeled as a sinusoid, the measured ultrasonic sensor signal is

$$U(t) = u(t + \varphi_u + \tau_u) \qquad (3)$$

and the lidar sensor signal is

$$L(t) = L(t + \varphi_L + \tau_L). \qquad (4)$$

The terms φ_i and τ_i are the measured sensor phase and sensor delay for each sensor i, respectively. These values are the contribution from the platform motion and are subtracted from the composite signal so that the resulting signal is the original respiration waveform.

A. *Motion Compensation Simulation*

A Matlab Simulink program was written to simulate the effect of the UAV platform motion on the respiration signal of interest. An example with sinusoidal respiration and platform motion is shown in Fig 2.

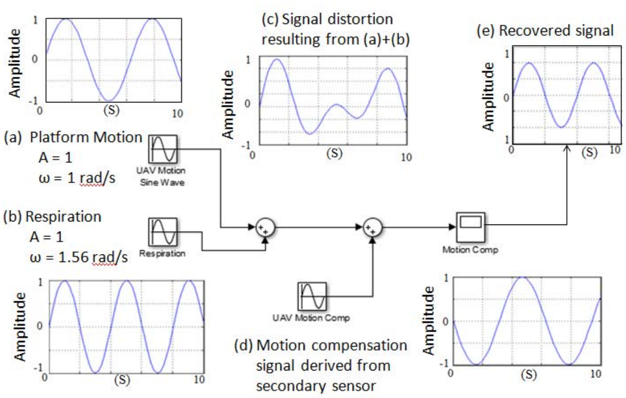


Fig. 2. Motion compensation simulation using Simulink: (a) UAV sinusoidal platform motion at 1 rad/s (b) respiration sinusoid signal of interest at 1.56 rad/s (c) motion distortion of signal of interest (d) motion compensation error signal (e) recovered signal.

B. *Received Signal Strength Indicator (RSSI) and Phase Monopulse*

The received signal strength indicator (RSSI) is a measure of power in a received signal. In our case, we compute the RSSI as $I^2 + Q^2$ from the baseband radar signal. For a radar platform situated above a target, RSSI would be useful to determine how far off center the radar is relative to the target. Therefore, if the UAV hover is maintained at a constant altitude, the average target RSSI should also remain constant (in the absence of multipath). Given the near vertical slant range, multipath is expected to be minimal. In this case, any additional RSSI variation would be due to the off-axis drift of the UAV relative to the target and can be used to compensate the drift.

Phase comparison monopulse is a technique used to find the angle at which the radar sensor is relative to the target. This technique uses an N element antenna array with a single transmitter and dual receivers. The relative phase delay, φ, between adjacent antenna elements N and N-1 follows the relationship

$$\varphi = kD\cos(\theta), \qquad (5)$$

where $k = 2p/\lambda$ and D = antenna element separation, from which the off axis angle, θ, of the incident signal can be computed.

III. EXPERIMENTAL RESULTS

The test platform was based on the DJI Phantom quadcopter with a payload box attached to the undercarriage. The payload comprised a 10 GHz and a 24 GHz radar module, a signal conditioning amplifier and filter, an Arduino analog to digital converter and a XBee downlink data transmitter. The ground station comprised a XBee receiver and a PC for signal recovery and processing. The test platform block diagram is shown in Fig. 3.

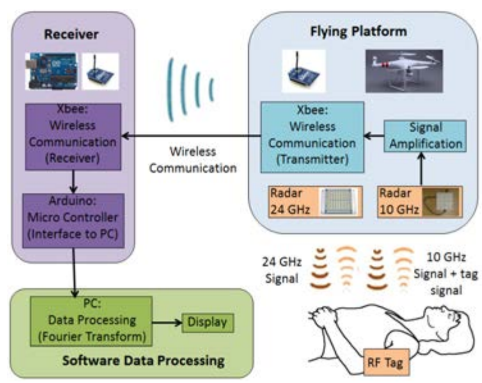
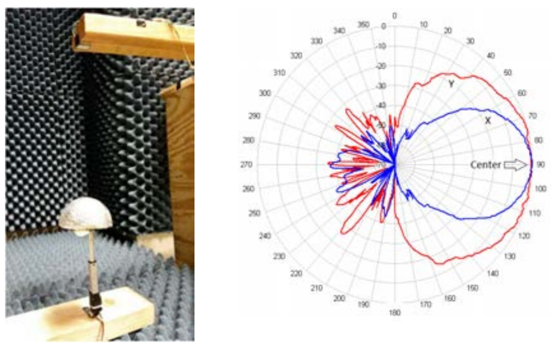


Fig. 3. System test bed block diagram showing radar payload, signal conditioning, data downlink and ground based baseband signal processor.

The experimental test chamber used to characterize the radars is shown in Figure 4. A 24 GHz K-band miniature I/Q radar transceiver, the RFBeam Microwave K-LC2 was used to measure the average power of a signal reflected from a phantom mover. The phantom mover was controlled by an Arduino Uno microcontroller, which was programmed to move at a frequency of 1 Hz and displacement of 1 cm. The radar was attached to a wood arm and placed at a height of 39cm above the respiration phantom mover. The radar antenna test setup and antenna array pattern for the cross range axes is shown in Fig. 4.

Experimental results show that the cross range RSSI levels correspond to the beam pattern as expected. The K-LC2 radar transceiver was powered by a 5VDC power supply, which also powered the Arduino controller. The I and Q outputs from the K-LC2 antenna amplified and filtered with a gain of 40dB. AC coupling was used to remove the DC component of the signal. The amplified and filtered signals were then sent to an analog to digital converter and recorded using a data acquisition program, which sampled the data at a rate of 40 Hz. Given the monotonic behavior, a peak tracking error signal that maximizes the RSSI for a fixed altitude can be used to keep the UAV bore sight on the target.



(a) (b)

Fig. 4. (a) Test setup for RSSI experiment with the 24 GHz RFBeam Microwave K-LC2 radar transceiver and phantom mover simulating the respiration of a prone victim. (b) K-LC2 antenna beam pattern.

For the DOA measurements, a RFBeam Microwave K-MC4 radar module with a two channel receiver was used. At a height of 39.5 cm, the radar transceiver was centered above the phantom mover. The I and Q output for each receiver was separated and the phase for each receiver was calculated using Matlab functions. The angle of arrival was calculated by dividing the phase difference by 6.7 (a constant calculated from the parameters and dimensions of the radar transceiver). The angle of arrival for each position was then plotted and compared with an ideal curve. The average error in measurement was less than 0.004 degrees. Maximum error in measurement was 1.6 degrees.

The measured phase monopulse response behaved linearly and can also be used to generate an error signal when the UAV drifts to maintain a precise position with the closed loop controller. The RSSI and phase monopulse measurement results are shown in Figure 5.

A motion controller from Galil and mover were operated using code designed in Galil Tools. The controller made the mover perform a sinusoidal motion emulating the undesired platform motion. Additional code was written for an Arduino that controlled the mover that performed the motion compensation. This code takes the output from the ultrasonic system and moves the actuator in the opposite direction by calculating the difference between the received distance value and a reference distance value.

With the motion compensation enabled, the platform motion was reduced from approximately 2.25 inches to 0.4 inches peak-to-peak. This result was based on a constant gain feedback signal. We are working on improving the compensation response with a position dependent gain factor, where the gain will be proportional to the error voltage,

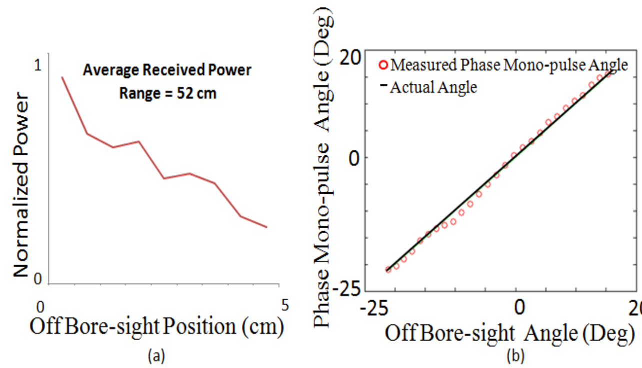


Fig. 5. Measured (a) cross range RSSI and (b) phase monopulse experimental measurements as a function of off bore-sight axis position and angle.

resulting in faster convergence of the motion compensation. Fig. 6 shows the compensation results with an ultrasonic sensor providing the error voltage. As depicted in Fig. 1, the ultrasonic sensor is one of several motion sensors and RSSI and RF DOA derived motion compensation can be similarly implemented.

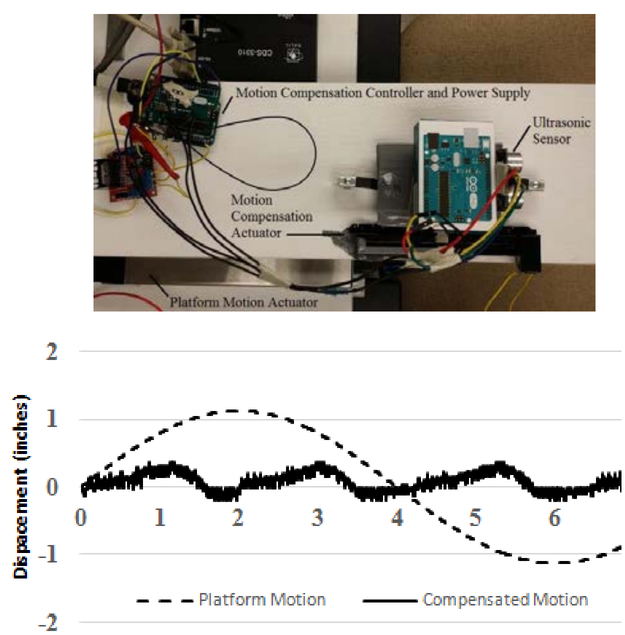


Fig. 6. (a) Experiment setup with ultrasonic sensor and motion compensation actuator mounted on platform (white plate) that are attached to a platform motion actuator. (b) Platform motion driven by sinusoidal waveform and resulting compensated motion.

IV. CONCLUSION

RSSI and DOA parameters from the baseband signal of an IQ radar were analyzed, simulated and measured to derive motion compensation signals for a UAV platform. During signal acquisition and lock, the RSSI and DOA signals can be used to generate an error signal to drive the motion feedback control system. For the UAV, the motion control can be implemented by real time inputs to the UAV ESC so that the platform altitude and attitude remain constant.

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