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Coherent Doppler Lidar for Human Motion Detection Under Dense Foliage Obscuration

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Abstract: Heavily foliated environments pose challenges for aerial surveillance systems because dense tree canopy obscures the view from airborne sensors. While direct detect foliage penetrating airborne lidar systems have proven effective at locating fixed structures (trails, buildings, stored vehicles, etc.), these systems struggle to detect moving targets such as humans hidden under heavy foliage. To overcome this challenge, MIT Lincoln Laboratory is investigating the feasibility of an airborne coherent lidar for detecting humans under canopy by sensing the Doppler signature caused by human motion (e.g., walking or working). Toward this end, a two channel 1.5 µm pulsed coherent lidar was constructed and tested in a static downward-looking configuration in a foliated environment. Results from this field test are presented along with system simulation, analysis, and a path toward a fully operational airborne design.

1. Introduction

Much of Earth’s land area is covered by thick tree foliage. There is interest in being able to locate persons who may be obscured by this foliage. People may be inadvertently obscured, as in the case of lost hikers in a search-and-rescue operation, or they may be attempting to conceal illicit activities. Penetrating the tree cover to reveal the activity below requires carefully designed airborne systems.

To date, direct-detect 3D lidar systems have proven effective at revealing the location and characteristics of fixed objects such as buildings, trails, and stationary vehicles by utilizing canopy “peek-through”. A random distribution of small holes in the canopy allows some photons to penetrate down to ground level. By viewing a scene from a variety of angles (via a moving aerial platform), a large number of peek-through windows are interrogated, each revealing a small portion of the underlying scene. In time a 3D point cloud of the scene is developed, allowing for detection of human-made structures underneath nearly impenetrable canopy obscuration. This foliage penetration capability has been used to identify man-made structures under thick canopy in both defense and archeological areas of interest [1-3].

One major drawback of the direct-detect peek-through method is its inability to directly indicate the presence of persons on the ground. Due to the requirement for a variety of look angles, a peek-through system can only identify fixed structures. The presence of structures is an indication of human activity, but in many cases it is impossible to know whether a particular site is being actively used for illicit activity or whether it has been previously abandoned.

In order to enable the detection of humans under canopy directly, MIT Lincoln Laboratory researchers have proposed a coherent Doppler lidar system capable of detecting velocities on the scale of human motion. Like a direct-detect peek-through system, this coherent system would utilize small holes in the canopy to penetrate to ground level. However, this system would be sensitive to the Doppler shifts caused by human movements such as foot swings, head bobs, and hand gestures. This Doppler sensitivity would allow the system to identify human movers with a single look, enabling rapid detection and geolocation of movers on the ground.

2. Methods

In order to better understand the phenomenology of human motion detection under foliage, a dual-pixel coherent lidar system was developed and deployed from an elevated platform in order to simulate airborne operation.

A block diagram of the lidar system is shown in Figure 1. It uses a pulsed transmit beam that has been frequency shifted relative to a continuous wave local oscillator (LO). When signal photons return from a moving target, the Doppler shift imparted by the target on the signal photons manifests as a beat note on the balanced photodiode. Additionally, range-to-target is measured using the time of flight of the lidar pulses. In this way, both line-of-sight velocity and range-to-target are measured simultaneously. A list of pertinent parameters is given in Table 1.

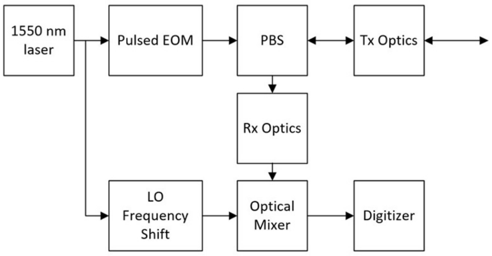

Figure 1. Simplified lidar block diagram. A frequency-shifted, continuous wave local oscillator is mixed on a balanced photodetector with pulses reflected from the target. The resulting beat note is recorded by a digitizer.

Table 1. Lidar system parameters

Parameter	Value
Wavelength	1550 nm
Pixel Count	2
Average power	1 W/px
Spot size @ target	10 cm 1/e^2
Pulse repetition frequency	5 MHz
Pulse duration	2 ns
Unambiguous velocity	±96 cm/s
Unambiguous range	30 m

The system is built entirely of off-the-shelf components and housed in waterproof containers for outdoor storage at the field site.

The field site consists of a 20 m steel weather tower near a grove of oak trees (see Figure 2). The laser amplifier and free space optical components were placed on the uppermost platform of the tower whereas the pulse-shaping, frequency shifting, and digitizer components were placed at ground level.

Once the lidar system was deployed at the field site, the beams were directed toward different areas with varying levels of foliage obscuration. With the beams held steady, human subjects were directed to walk through the beams while the system recorded their Doppler signature. A synchronized IR context camera provided images of the positions of the beams on the subject during the test. Additional data were gathered on the natural movement of foliage due to wind as well as non-walking human motion, such as rising from a sitting position.

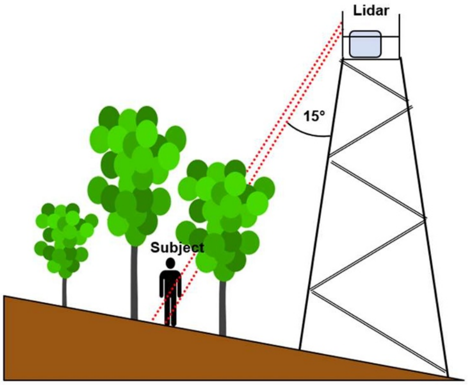

Figure 2. Site diagram. The lidar beams were directed at a steep down-looking angle through foliage.

Lidar data and co-collected IR context imagery were analyzed to identify time points when the beam was incident on the human subject.

3. Results

Lidar data were processed into range/Doppler diagrams (see Figure 3), indicating the simultaneous range and line-of-sight velocity measurements. A coherence processing interval (CPI) of 100 µs was used in order to estimate the Doppler spread characteristic of human motion as seen from above. Across 233 unique measurements, the mean Doppler spread was 24 kHz, with a 90th percentile spread of 192 kHz. Carrier to noise ratios (CNR) were typically in excess of 20 dB for unobscured targets.

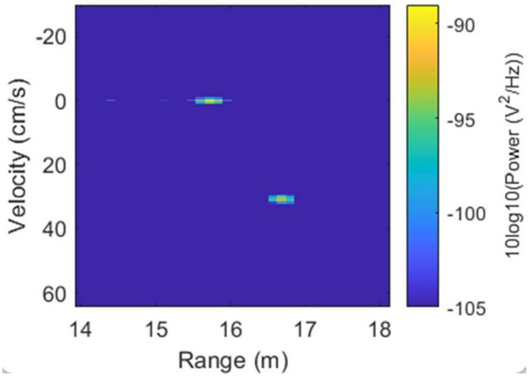

Figure 3. Example range/Doppler diagram with partial obscuration. The return on the left is from an overhead leaf and shows zero line-of-sight velocity. The return on the right is from a human mover and shows a positive velocity.

Due to the likelihood of partial obscuration due to branches and leaves in the target scene during an aerial collect, it was important to demonstrate the system's ability to collect Doppler signatures from multiple range-resolved targets, each of which may only be encountering some fraction of the beam. As shown in Figure 3, the lidar was able to range resolve the human mover from overhead canopy, measuring unique Doppler signatures from both. Additionally, the lidar was frequently able to range resolve multiple parts of the subject's body, i.e., the hand and leg simultaneously. Collecting returns from multiple range bins of the same target will be helpful for distinguishing human movers from other confusers such as animals.

4. Discussion

The system demonstrated a clear capability to detect the Doppler signature of human movers on the ground. Using the data gathered from this lidar system, we can make a prediction about the performance of a similar system deployed on an aircraft. Assuming a worst-case 90th percentile Doppler spread of 192 kHz and a reasonably short measurement time of 25 μs (5 incoherent averages of 5 μs CPI), we can expect a CNR of 26 dB and a minimum detectable velocity of 2 cm/s [4]. This velocity is consistent with some of the more subtle human movements such as head turning. Normal activity associated with working or walking around an area yields velocities of up to about 1 m/s as seen from above.

High CNR predicted here, and verified by the present field test, allows overhead for signal quality degradation due to fast scan rates and/or partial obscuration during aerial operation. For operational effectiveness, ground coverage rate will need to be maximized, potentially reducing the number of incoherent averages possible at each point.

Another important consideration for airborne operation is to reject clutter. Clutter may be present in the scene in the form of wind-blown foliage, or may be introduced by the motion of the airborne platform. Our results show that foliage movement due to wind action decreases at lower heights above ground. This is consistent with measurements of wind speed in the dense foliage environments the system is intended for [5]. Overall, wind-driven clutter is not expected to be a major confuser.

In order to test the effectiveness of these mitigation techniques, as well as account for any other phenomenology risks associated with flight, it will be necessary to conduct an airborne test of the lidar. The airborne test will aim to address three interrelated technical risks: pointing control, velocity clutter mitigation, and decoherence effects.

Pointing control is provided by a fast-scanning mirror previously deployed with other MIT Lincoln Laboratory lidars [6]. Pointing capability determines not only the accuracy of geolocation as in direct-detect lidars, but is also required for holding a spot on a target for the duration of a single coherent processing interval. If the spot moves appreciably during a coherent processing interval, new scatterers will be illuminated, leading to signal decoherence. Thus, inadequate pointing capability will degrade velocity estimation.

The motion of the aircraft carrying the system will add velocity clutter to the measured signal as well. Aircraft motion is measured in real time by an inertial navigation system, and combining these data with pointing knowledge will yield a corrective line-of-sight velocity value. As an additional mitigation, we tested a common mode rejection (CMR) scheme. The goal of CMR is to use a fixed reference in order to measure the line-of-sight velocity due to the motion of the aircraft and then subtract that reference velocity from the measured velocity of the signal, yielding the true line-of-sight velocity of the target. In order to accomplish

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this, the lidar must be measuring from both the target and a fixed reference simultaneously. This can be accomplished two ways: either by measuring the target with one beam while measuring the reference with another beam, or by measuring the target and a fixed reference such as the ground with a single beam that is only partially incident on the target. The advantage of the multi-beam method is improved CNR due to the lack of partial obscuration. However, it may be difficult to identify a suitable reference point. The small holes in the canopy that the beams must penetrate may prevent multiple beams from reaching the ground, thus forcing the use of some point in the canopy as the reference. Canopy foliage may have a higher velocity than ground-level foliage, creating a poor reference. On the other hand, single-beam CMR suffers from low CNR due to a splitting of the incident energy between two different range bins, but the improved ability of a single beam to penetrate to ground level could result in a high-quality ground velocity reference. In practice, both methods of CMR will likely be necessary to overcome velocity perturbations from the aircraft.

Finally, operating a coherent lidar from a moving aircraft presents several challenges due to potential decoherence mechanisms. The motion of the aircraft through the speckle field, Doppler spread due to pointing mirror movement, and atmospheric effects all need to be carefully considered. Preliminary analysis indicates that signal coherence is likely to be limited by the target motion.

The system is currently undergoing upgrades and hardening with a flight test planned for Summer 2025.

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