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Accessible Synthetic Aperture Radar System for Autonomous Vehicle Sensing

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***Abstract*—The usage of autonomous vehicles is rapidly expanding on both the ground and air. With more autonomous vehicles in close proximity to humans, new and better sensors need to be developed to manage these relationships, both good and bad. This new age of autonomous activity will bring both new opportunity and new threats to people and property. One of these threats will be from cheap, very functional unmanned aerial vehicles (UAV). Currently, there is very little we can do to detect and track these vehicles, without expensive and typically unaccessible military grade sensors, such as radar. To provide a response to these threats, in a ubiquitous manner, low cost, accessible systems capable of detecting and tracking dubious UAV activity must be developed. This research effort is to develop a low cost, accessible sensor system with sufficient power and accuracy to be utilized in a number of task domains throughout the robotics and autonomous systems field, including for UAV detection and tracking. To make these systems accessible, the systems are flexible in terms of power and range, but a fully functioning radar system that anyone, such as local first responder organizations can afford. Given these requirements, we started with a design for a low cost synthetic aperture radar (SAR) and built the components. The basic design was modified to specifically address the challenges of being autonomous, low cost and mobile and to detect objects with minimal cross section. In the end the result is a promising system that can detect very small objects in an acceptable range.**

I. Introduction

The expansion of autonomous robots and vehicles in terms of number, spread and usage creates opportunities, challenges and problems. An example of the challenges, new autonomous vehicles are in closer proximity to other autonomous vehicles, as well as humans, than ever before. While we look at new breeds of unmanned ground vehicles (UGV) and unmanned aerial vehicles (UAV) that can help us with everyday tasks such as logistics and low level labor, the vehicles must be able to work in similar ways as humans can, with similar capabilities. To work together in close proximity, groups of autonomous vehicles must sense each other and their environment successfully, to avoid collisions, as an example. To do this, we need appropriate sensing capability. In this paper, we propose a sensing technology, while not completely new in concept, but much more accessibility to all due to requirements and cost. We propose a low cost synthetic aperture radar (SAR) system capable of detecting objects with precision and ease, at acceptable range, for use in detecting small class UAV's.

Fig. 1. DJ Phantom shown at the White House in Washington, D.C.

An application for this type of low cost SAR is the detection of UAV's. In January 2015, a dubious UAV landed on the front yard of the White House in Washington, D.C. Given that this is one of the most protected spaces in the world, the fact that a low cost UAV could easily penetrate the air space undetected and land successfully, alerted many security agencies to a growing potential threat caused by the potential use of UAV technology for harassment, criminal behavior or terrorism. Due to low cost, ubiquitous access and minimal barriers to entry, UAV's have become enabling technologies for good and unfortunately bad behavior.

One of the key challenges of dealing with a UAV threat is the initial detection and tracking of a small, class 1 UAV. Examples of this type of technology are the IRIS [1], DJ Phantom [2] , shown in Fig. 1, and the Parrot AR Drone [3].

As shown, a class 1 UAV weighs less than 55 pounds. Typically, it is much smaller as in the case of the DJ Phantom as shown in Fig. 1. An issue is the size and the cross section of detection. A small, plastic, non-ballistic craft is a unique challenge in several ways. The greatest challenge is the detection at a distance to prepare time for tracking and remediation, if there is dangerous intent.

Another challenge is creating a detection mechanism with enough range and capability, that is also accessible to first responders on the front line of detection and remediation of these type of threats, at the local level. As a commercial or military grade radar system typically does not fit the budget profile of a local police or first responder jurisdiction. For example, if a system is to be set up for a stadium protection

Fig. 2. Purdue University football stadium, top view

protocol, such as shown in the Purdue University football stadium, shown in Fig. 2, then several of these detectors must be used, multiplying the cost greatly. The cost to create this system is not feasible with current hardware, but with a low-cost functional SAR, the ability to detect and track small UAV's [4] will become very realistic and usable for almost anyone, regardless of budgetary constraints. While using multi-modal systems, such as RADAR and acoustic systems [5] that work well on ground platforms, this current model of RADAR can also work as a mobile sensor mounted on a ground-based robot or UAV.

The organization of this paper shows the realization of near-field object detector in section 2. In section 3, we show a set ofexperiments and results using a common automobile and then comparing that with at class 1 UAV. In section 4, we discuss the promising conclusions of this work and the future plans to make the technology functional and with the ability to field the SAR.

II. Realization of near-field object detector

Radio detection and ranging (RADAR) has been widely implemented in various fields, in which a system needs to detect an object appearing in front of it. RADAR technology provides a significant level of accuracy and robustness against most environmental constraints (e.g., humidity, weather, day or night) such that the technology has also been applied to field robots such as autonomous driving vehicle [6], under water robot [7], unmanned aerial vehicle [8]. Unlike such robots, macro and micro size robots (i.e., iRobot Create, class 1 type commercial UAV's) are likely to have less power, less computation capability, and be simpler and smaller. In addition to this, the paradigm of multi-agent system has accelerated the use of multiple smaller and simpler robots. In order to support and provide the charming function of RADAR to such macro and micro robots, existing RADARs have to 1) consume less power, 2) be smaller, and 3) be lighter.

The radar system in [8] uses the FMCW technique and operates at 35 GHz center frequency with 800 MHz bandwidth

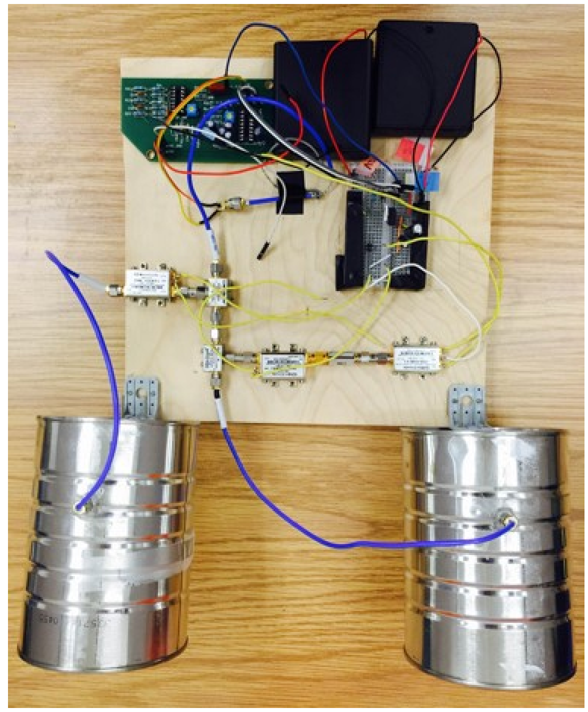

Fig. 3. The appearance of the system: two coffee can antennas are used. 2.4 GHz oscillator generates signal through the antenna and mixed signal of original signal with the signal received from low-noise amplifier (LNA) is processed through three stages of amplifiers and a band-pass filter at 15 KHz.

radar to perform as a SAR radar, for a side-looking and a nadir-looking sensor. The radar was loaded on a motor glide which has 23 m wing span and can load up to 320 kg to image the downside of the flying motor glide. Our RADAR uses a 2.42 GHz center frequency with bandwidth 260 MHz. The weight of RADAR is less than 1 kg which makes it possible to load on a class 1 UAV to reconnoiter.

The proposed low-cost RADAR system is originated from the design introduced in [9]. The RADAR uses frequency modulated continuous wave (FMCW) centered at 2.4274 GHz with less than 10 mW of transmission power in order to detect an object's approaching speed and distance to the system. As shown in Fig. 3, the system consists of three parts: pre-processing component, radio frequency (RF) components, and post-processing component. The pre-processing component generates continuous ramp signal with 20 ms of up-ramp time. The ramp signal oscillates actual FMCW signals in the RF components. The FMCW signal is then amplified and mixed with the received signal that comes from the object as the amount of reflection. The mixed signal goes to post-processing component and it is amplified by 10 times and finally filtered by 4^{th}, order low-pass filter.

The radar system designed at MIT [9] uses the similar FMCW technique to ours and operates at about 2.4 GHz with 93 MHz bandwidth. This research has specifications where the RADAR operates at a similar center frequency of 2.4274 GHz with larger bandwidth of 260 MHz, which is approximately 3 times larger than the bandwidth that the MIT radar operates.

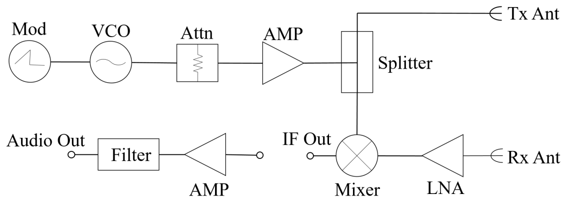

Fig. 4. Functional block diagram of the proposed system. The PCB contains modulator, amplifier located after mixer, and filter parts shown in this diagram.

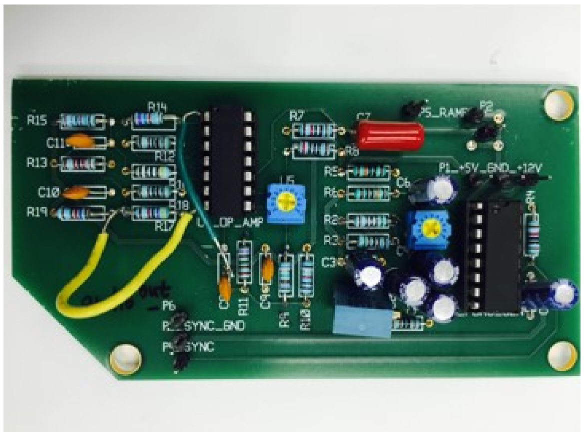

Fig. 5. An electric circuit board designed on a PCB for the RADAR system. Ramp generator, amplifier, and low-path filter are loaded on the board. Basically 5 V and 12 V inputs are needed to perform these subsystems loaded on the board.

When the operating bandwidth becomes larger, the maximum ranging distance becomes shorter but there is better range resolution.

We designed a PCB which contains electric parts of the RADAR system as a step to make the RADAR lighter to carry. The electric parts (see Fig. 5) are ramp generator, amplifier, and low-path filter. The board basically needs 5 V and 12 V inputs for powering the electric components, and receives the mixed signal to amplify and filter. The triangular ramp signal from the board to RF component is needed when the RADAR detects range of a moving object. Post-processed signal passed through the amplifier and the low-pass filter is transmitted and recorded as an audio signal.

In this experiment, we changed bandwidth generated from the modulator of the system because our targeting range of detection was closer than 100 m. The oscillator swept from 2.2973 GHz to 2.5576 GHz with bandwidth of approximately 260 MHz.

III. Experiment and Results

In this section, we look at the basic experiment set up using an automobile and a class 1 UAV as targets. Then we show some basic results for the range and velocity for the car and just range for the UAV. Finally, the outcomes on accessibility are briefly described, as that is a key element of this work.

A. Validation of the RADAR

To verify the detection range and accuracy of the RADAR built with the PCB which we designed, we performed Doppler and ranging experiments. A moving target for these experiments was a medium sized sedan to prove the design works and indicate good tracks. The car was standing by 180 m away from the RADAR, and moved toward the system. We did experiments with two different velocities, and the car gradually reduced its speed and stopped beside the RADAR because of safety and regulatory reasons. However, before we reduce speed of the car, we assume that the velocity of the car was stably maintained, because we could not use cruise control under 40 mi/h. We gathered reflected signal, concentrated it into an audio file, and analyzed the audio data using a Matlab script performing FFT within both frequency and time domain.

Fig. 6 illustrates results of ranging measurement. Velocities of the car were 10 mi/h and 20 mi/h, which are approximately 4.5 m/s and 8.9 m/s, respectively. The velocities are common velocities of class 1 UAVs. Although there are significant harmonic noise in both plots, light yellow lines which show the distance from the RADAR are distinguishable. While the car was coming from 180 m away from the RADAR, it could capture when the car was in the range of 50 m from the RADAR. Arrows in the plot indicate where the RADAR first saw the car in experiments.

Velocity of the moving target was calculated based on the Doppler Effect. Fig. 7 shows results of velocity measurement. For these experiments, velocities of the car were 10 mi/h and 30 mi/h to see obvious difference between the two experiments, which are approximately 4.5 m/s and 13.5 m/s, respectively. Although results showing in Fig. 7 have significant harmonic background noise, a light sky blue points at the bottom left side of each plots. The points start to appear from 20 seconds in Fig. 7 (left), and 14 seconds in Fig. 7 (right), where the car was in the range of 50 m as we explained above (see Fig. 6).

B. Evaluation of UAV

Fig. 10 and Fig. 11 show the practical set up of the experiment. DJ Phantom 2 was the target that the RADAR tracked. The UAV was manually controlled in an indoor environment and was flying back and forth in front of the RADAR. The shortest and longest distances of the flying UAV in front of the RADAR were approximately 1 m and 6 m, respectively. It was difficult to record the velocity and actual position of the UAV while it was flying because of the manual control. According to the RADAR design, we expected about 65 degrees of the beam width of the can-antennas so that the UAV was always flying within the line of sight of the RADAR.

Fig. 9 depict the measured distance of the flying UAV from the RADAR. In order to compare the intensity of the detection, we covered the surface of the UAV with reflection tape (See Fig. 10) and performed two experiments with reflection tape (right) and without reflection tape (left). While testing the drone with reflection tape, we put the tape on the head of the battery and one side of body of the drone to prevent increase of

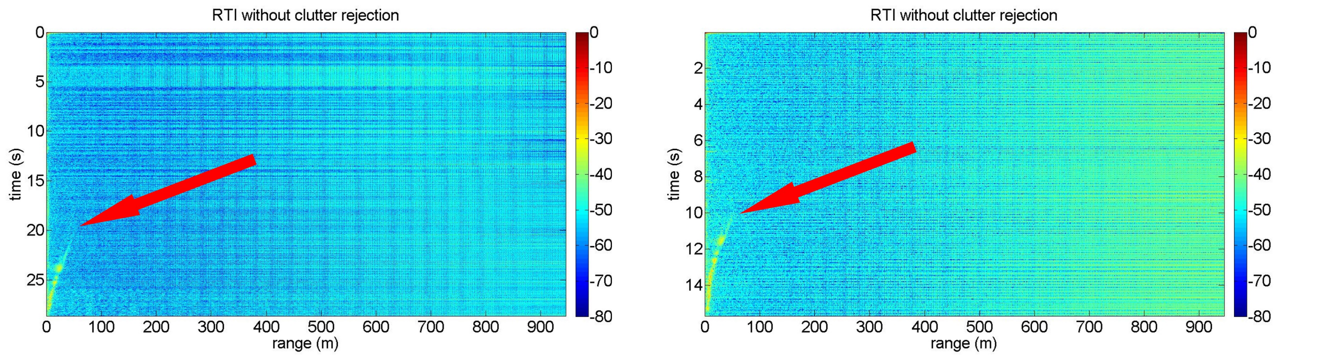

Fig. 6. Experiment result to verify ranging capability of the RADAR using a car with 10 mi/h (left) and 20 mi/h (right), which are approximately 4.5 m/s and 8.9 m/s, respectively. Both results have obvious background noise, however lines which red arrows point where the RADAR started to detect the car are distinguishable. The points are approximately 50 m from the RADAR.

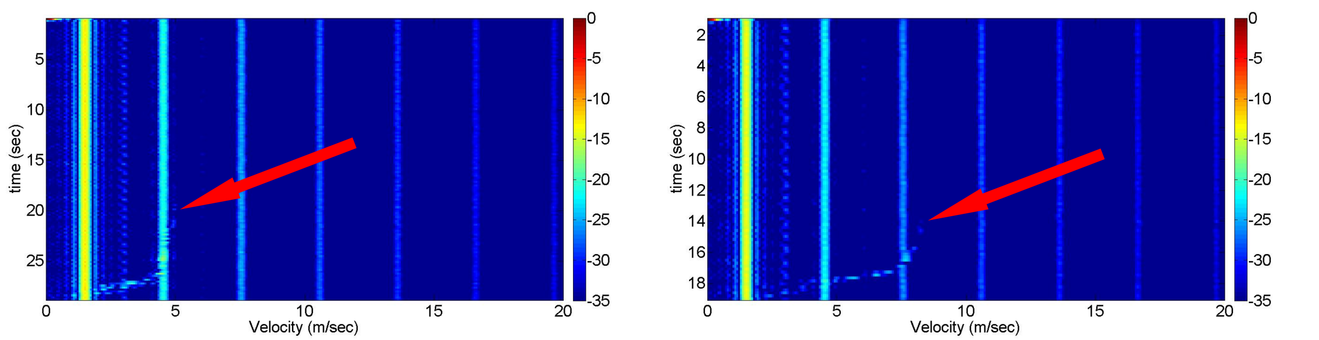

Fig. 7. Experiment result to evaluate velocity detection capability of the RADAR using a car with 10 mi/h (left), and 30 mi/h (right), which are approximately 4.5 m/s and 13.5 m/s, respectively. Both results have significant harmonic background noise, however the lines which the red arrows point where the RADAR started to detect the car are also distinguishable. The time where the blue line starts in each plot is when the car was in the range of 50 m.

cross-section comparing with the case of using a drone without reflection tape. As the result, the figures show the detection of the UAV in a short distance (less than 7 m) over time. For both experiments, the RADAR could be able to successfully detect the UAV although we had a very strong harmonic noise at the distance of about 2.3 m. In addition to this, in the noise zone we could not distinguish the reflection signal of the UAV from the noise. The experiment without reflection tape (left) detected the UAV with the maximum intensity of -20 dBm at 5.5 m while the other experiment with reflection tape (right) measured -11 dBm at the same distance.

Fig. 8 illustrates the details of the measurements from the experiments. The V-shape patterns in the Fig. 8 are the measured movements of the UAV. Because the UAV was controlled by a human pilot, the velocity of the UAV varied. The horizontal line at 2.3 m shows the harmonic noise. As can be seen, the two latter V-shaped result in the Fig. 8 are sharper than the first V-shape, which indicates that the latter flights were faster than the first one. When it is seen in the Fig. 9, the reflected signals were higher on the latter two flights than the first approach due to the fact that faster movement of the UAV makes it more tilted which increases the cross-section when the UAV comes closer to the RADAR.

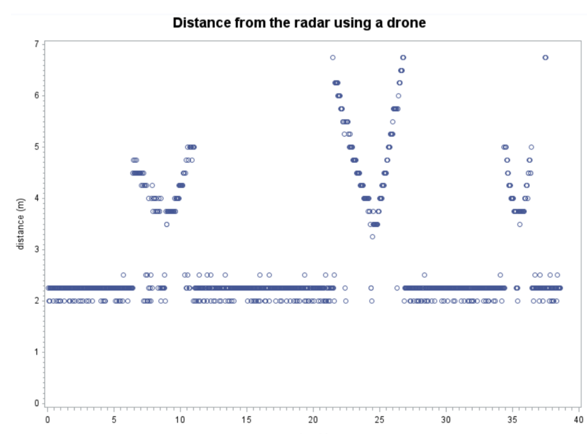

Fig. 8. Scatter plot of distance from the RADAR using a UAV with reflection tape. V-shape points are the position recorded by the RADAR, however positions around 2.3 m are strong harmonic noise.

C. Accessibility

While the range and power of this system are flexible, the PCB designed is the system core. Anything from coffee cans to professional crafted transducers can be used depending on what the user wants to get in terms of performance or to pay in price. To provide maximum accessibility the system has been

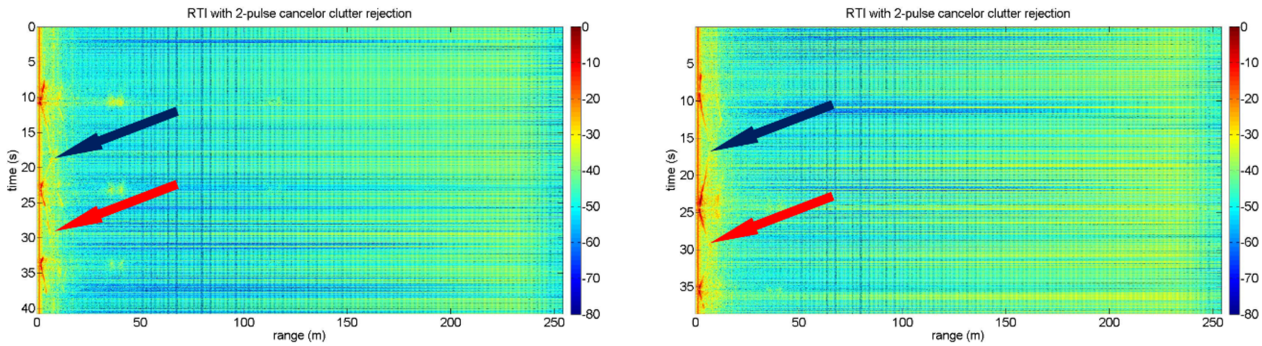

Fig. 9. Intensity spectrum of the track with a class 1 UAV (Phantom 2). The spectrum at the right side is the experiment result with reflection tape and the left side is the experiment result without reflection tape. The UAV flew back and forth in front of the RADAR three times with different velocities. Arrows in the figure points the farthest distance where the UAV detected. Blue arrow (upper arrow) shows the starting point of the track and Red arrow (lower arrow) shows the end point of the track. Even though background noise is strong, there are noticeable red lines illustrating distance of the UAV. V-shaped lines are distinguishable in both plots, however the line at the right side stronger (longer red line) then the left side. The strength of the experiments were different because of existence of reflection tape.

Fig. 10. Drone with reflective tape

designed to be inexpensive and easy to build. The PCB can be made available easily with a total functional system cost of less than \$100 with functional tracking distance of up to 1 km in an ideal situation. While the functional specifications of the system are crucial, the accessibility of this system is equally important. In comparing this to commercial-based systems, the price is a great differentiator. In comparing this with military grade systems, availability is the great differentiator. While there are cheap radar systems which are available to consumers, the basic function of detection and tracking is not available in either form, function, capability or mobility, compared to this system, at anywhere comparable to the cost. An example of this is by Stalker [10]. Similar efforts to this functionality are starting to appear, such as with low cost by Hackaday [11].

IV. Conclusions and Future work

In this section, we discuss conclusions about the currently completed preliminary work and also the planned work to extend this technology into a usable and highly functional system.

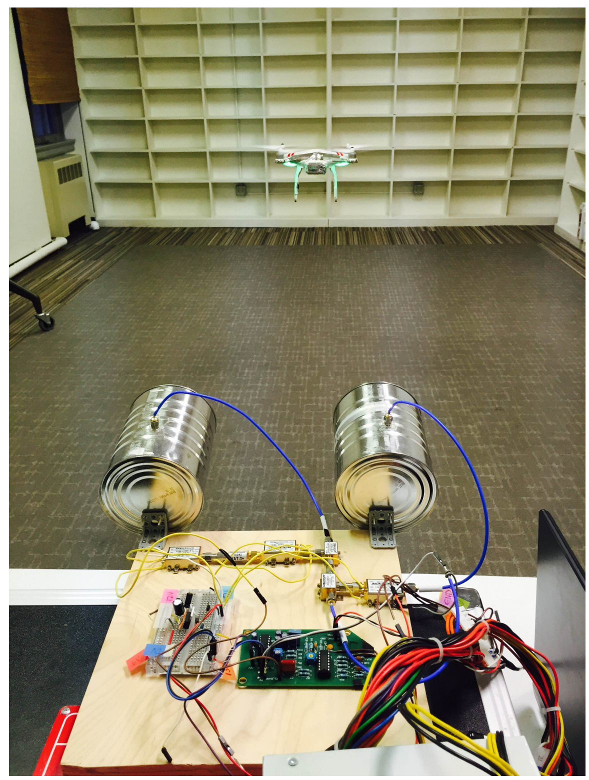

Fig. 11. Drone with Radar

A. Conclusions

This work is to develop a low cost radar system with sufficient power and accuracy to be utilized in a number of task domains throughout the robotics and autonomous systems field. The main issue with radar is the cost and accessibility, typically not feasible for a university lab, first responder jurisdiction or a small company, such as a robotics start-up.

In this paper, we show the design and the basic capability to track an object. We use an automobile as it is a topical object to track, given the interest in autonomous cars. But, the real intent will be tracking smaller objects such as a small, class 1 UAV. The cross section of a small UAV is a real challenge, but the benefit will be the realization of a system that can be used to detect, track and remediate dangerous UAV activities over public or private spaces, which is a high priority goal for many government agencies.

B. Future Work

While the current iteration of the radar system can detect and form a track for the desired objects, there is still a great number of enhancements and requirements to make it usable, in a general sense, for a number of task domains, such as tracking of small, class 1 UAV's. Some of the further work will be in a human interface, deployable on any computing device, such as a smart phone, tablet or personal computer, that can interpret the object and show it to a human user. Basically, an interface that can show the relation of the object to the tracking source. Another desire is to create a completely autonomous interface which can be used with a UAV remediation system, for local police and first responder jurisdictions. Finally, we will improve the accuracy and number of tracks the system can provide at any given time.

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