Doppler micro sense and avoid radar

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ABSTRACT

There is a need for small Sense and Avoid (SAA) systems for small and micro Unmanned Aerial Systems (UAS) to avoid collisions with obstacles and other aircraft. The proposed SAA systems will give drones the ability to "see" close up and give them the agility to maneuver through tight areas. Doppler radar is proposed for use in this sense and avoid system because in contrast to optical or infrared (IR) systems Doppler can work in more harsh conditions such as at dusk, and in rain and snow. And in contrast to ultrasound based systems, Doppler can better sense small sized obstacles such as wires and it can provide a sensing range from a few inches to several miles. An SAA systems comprised of Doppler radar modules and an array of directional antennas that are distributed around the perimeter of the drone can cover the entire sky. These modules are designed so that they can provide the direction to the obstacle and simultaneously generate an alarm signal if the obstacle enters within the SAA system's adjustable "Protection Border". The alarm signal alerts the drone's autopilot to automatically initiate an avoidance maneuver. A series of Doppler radar modules with different ranges, angles of view and transmitting power have been designed for drones of different sizes and applications. The proposed Doppler radar micro SAA system has simple circuitry, works from a 5 volt source and has low power consumption. It is light weight, inexpensive and it can be used for a variety of small unmanned aircraft.
Keywords: Doppler, radar, micro, sense, avoid, drone, array, directional antenna

1. INTRODUCTION

Over 430 companies around the world such as Google, Intel, Amazon, Sony, and DJI are involved both in intensive investigations as well as the production of Unmanned Aerial Systems (UAS) also known as drones or Unmanned Aerial Vehicles (UAVs). In order for a UAS to safely navigate in the already crowded aerial environment of the modern world, the U.S. Federal Aviation Administration (FAA) and other international organizations have mandated that unmanned aircraft must have an on-board system to help prevent collisions between aircraft. There are many approaches to this problem including very elaborate SAA systems on the Global Hawk and Predator drones as well as experiments with optical, ultrasound, infrared and various combination systems. These systems are complicated, expensive and large when compared to the drone's size as illustrated below in Figure 1.

Figure 1. Sense and avoid systems presented on the market today are large compared to drone size, and expensive.

2. DOPPLER RADAR APPROACH

A Doppler radar approach to the problem of Sense and Avoid offers many benefits. Doppler radar produces velocity data about objects at a distance by reflecting a microwave signal off a desired target and analyzing how the object's motion has shifted the frequency of the returned signal.

A practical, less expensive, miniature Doppler radar SAA system has been designed for small drones by combining Doppler radar with the "Fly Eye" radar concept [1-2]. This system consists of an Array of Directional Antennas (ADA) coupled to radar sensors and distributed around a drone as presented in Figures 2, 3 and 4 below.

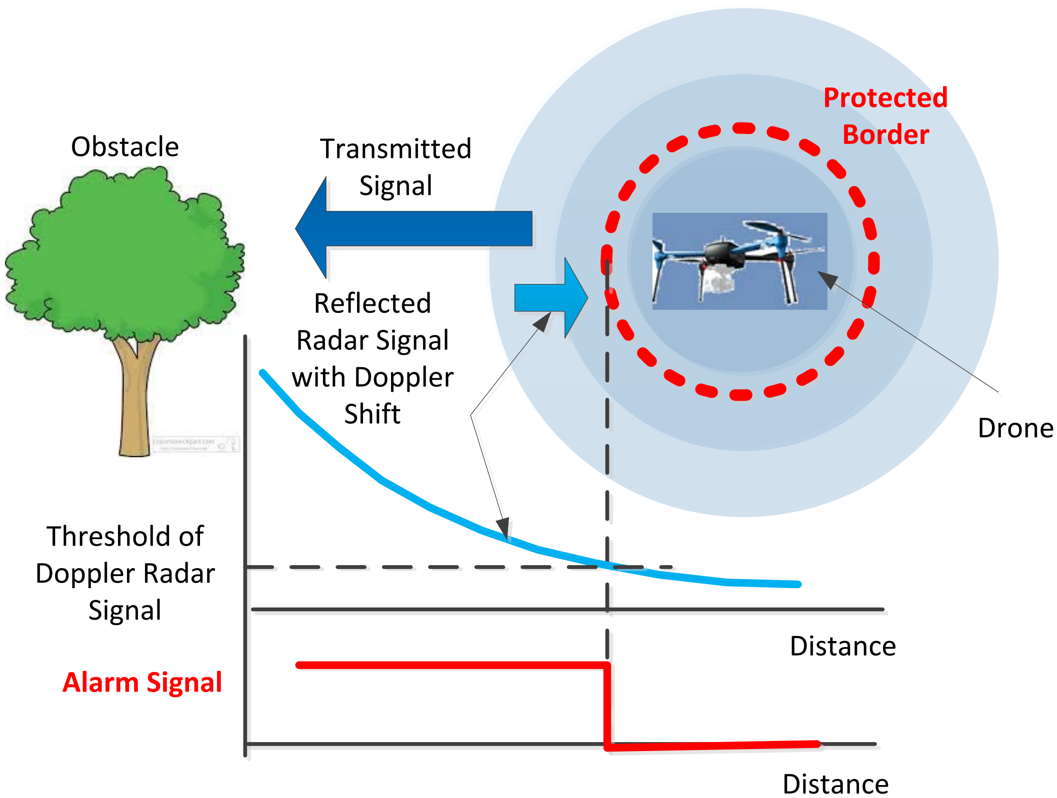


Figure 2. Concept of micro sense and avoid system based on Doppler radar for small drones.

These Doppler radar modules transmit a Continuous Wave (CW) microwave signals from the moving drone. Any obstacle will reflect part of the radar signal back to the drone as soon as the obstacle enters into the range of the Drone's radar. The reflected radar signals will be inversely proportional to the square of the distance to the obstacle, as shown in Figure 2 and consist of a Doppler frequency shift because the drone is moving in the obstacle's direction. The Doppler frequency is calculated as shown in Equation 1:

$$\mathrm{Fd} = 2\mathrm{V}\left(\frac{\mathrm{Ft}}{\mathrm{c}}\right)Cos\theta \qquad (1)$$

Where: Fd - Doppler frequency; V - Velocity of the target;
Ft - Transmit frequency; c - Speed of light (3×10^8 m/sec);
θ - The angle between the target moving direction and the axis of the module.

Doppler radar signals are detected by the sense and avoid system. As soon as the Doppler signal exceeds the preset threshold level of the protection border, the processor circuit will generate an alarm signal and the drone's autopilot will stop the drone or generate an avoidance maneuver command. The preset threshold level determines the radius of the protected border around the drone and can be adjusted by the analog processing circuit or by the autopilot program.

With a reliable way to sense and avoid obstacles, the number of applications for drones can be dramatically increased as they become more independent of the controller and can, therefore, reach areas that were once unreachable. After an obstacle is detected and the data is processed, it is then sent to the drone's autopilot which generates the necessary avoidance command for the drone to follow.

The Fly Eye radar concept presented in Figure 3 can cover the entire sky (360 degree by azimuth and elevation) without mechanically scanning the sky or a complicated phase array.

Fly Eye Radar Concept [3-7]:

- An Array of Directional Antennas (ADA) covering the entire sky;
- Each directional antenna is coupled with a separate Radar Receiver Module;
- The ADA may be loosely distributed over the perimeter of the UAS or between separate UAS in a swarm;
- The radar receivers are connected to a radar signal processor for 3D intelligent processing;
- The ADA is not phase dependent and can be multi-band (multi constellations) or multi-function.

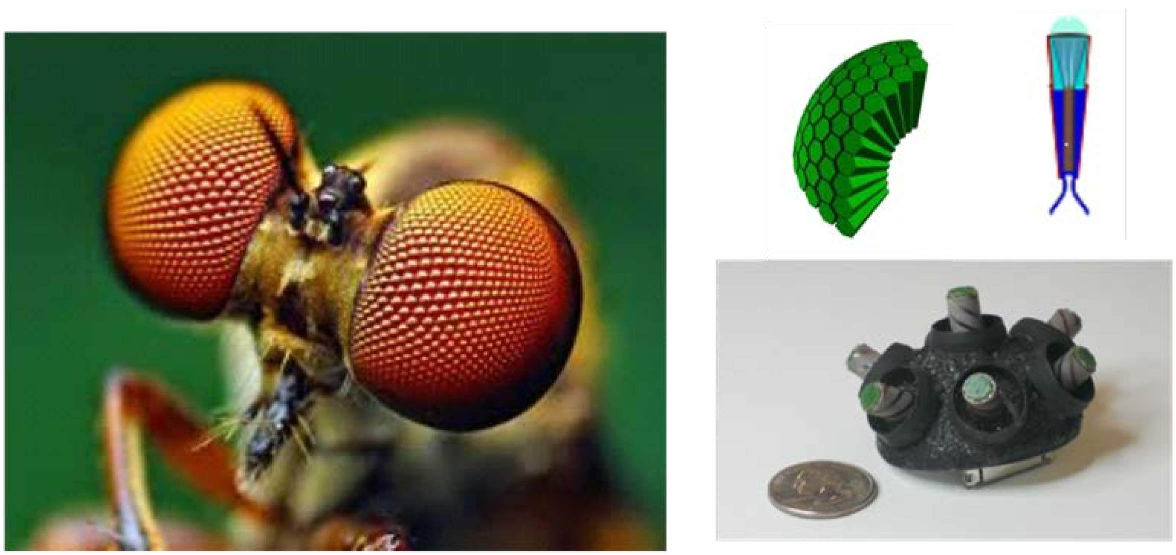


Figure 3. To compensate for its eye's inability to point at a target, the fly's eye consists of multiple angularly spaced sensors which give the fly the wide-area visual coverage it needs to detect and avoid the threats around him. Each sensor is coupled with a detector and connected separately to memory. This same concept is used in the Fly Eye radar. Multiple angularly spaced directional antennas are coupled with microwave receivers and separately connected to a processor by a digital interface.

Optical and Infrared (IR) cameras and Laser Radars (LIDAR), which work at optical, IR, IF frequency or even with short wavelength microwave frequency electromagnetic signals, have a significant degradation in rain or snow conditions. Only radar systems which have electromagnetic signals with a wavelength larger than hail, snow and dust particles (approximately a few mm in size) provide good enough visibility in harsh conditions. Microwave signals within a 3 GHz (wavelength 10cm) - 30 GHz (wavelength 1cm) frequency range are optimal.

The reflection from the target decreases in low frequency radars where the frequency wavelengths are longer than the target's size. As a result, the minimal size (radar cross-section) of detectable targets will be increased and the radar will therefore sense only larger targets. Proposed Ku-band (12-18 GHz) Sense and Avoid systems provide good sensitivity for obstacles with small cross-sections (0.25 sq. ft. at distance 5 y.). In contrast to ultrasound and optical systems, they dramatically increase the sensitivity to even very thin obstacles such as overhead electrical wires because of the sensitivity to the change of the electromagnetic waves.

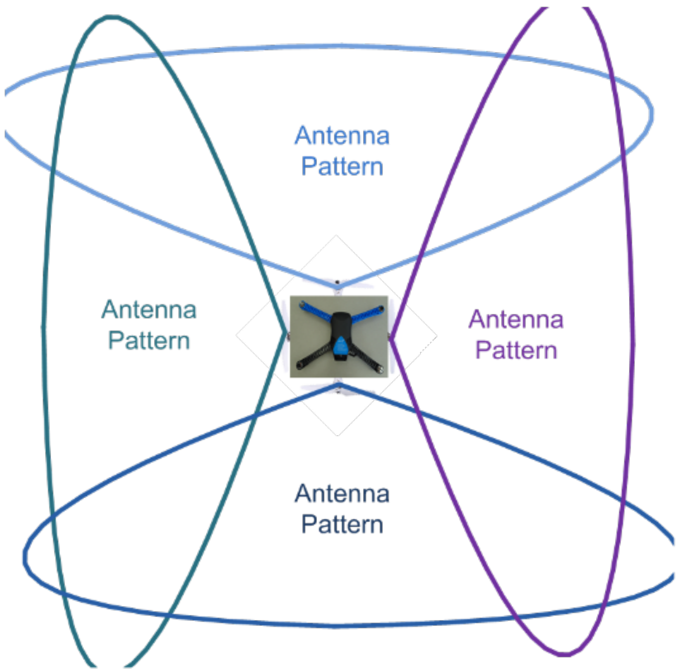


Figure 4. Distribution of directional antennas around the drone allows entire sky coverage without application of a heavy mechanical scanner or a complicated expensive phase array.

The Doppler radar structure is presented in Figure 5. It consists of a continuous wave oscillator, transmit and receive directional antennas, mixer and an intermediate frequency processor with a video amplifier and band pass filter. The oscillator generates a continuous wave Ku band (12-18 GHz) microwave signal, which is transmitted through directional antennas. In the Figure 4 example, the oscillator transmits in four directions, where antenna patterns can partially overlap. Received signals with Doppler shift mix with part of the transmit signal. Intermediate Frequency (IF) signals received go through the analog input of the autopilot after amplification and filtering; the amplitude of these incoming IF signals is used to determine the drone's distance to the obstacle. The protection border threshold is adjusted to the intermediate frequency signal level of the desired protection border size or distance.

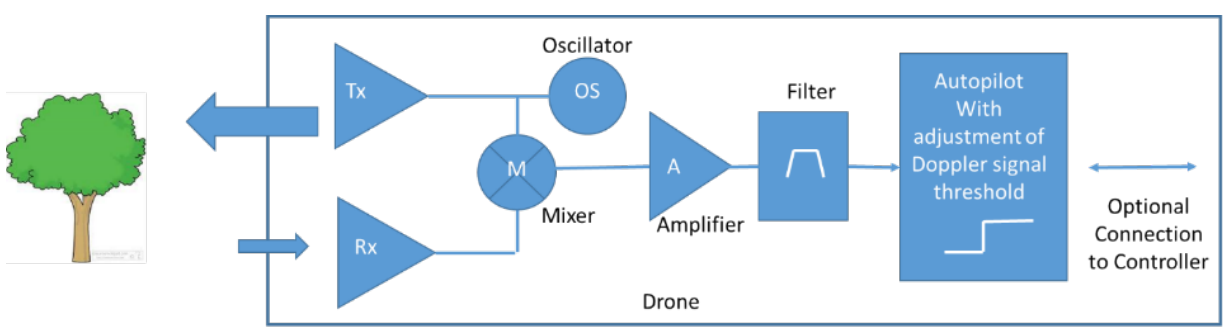


Figure 5. Block diagram of Doppler radar sensor with mixer and adjustment of threshold level by program in autopilot.

3. STRUCTURE OF A SENSE AND AVOID SYSTEM

Direction to an obstacle is determined by the direction of the antenna. Alarm signals are activated if an obstacle is in an angle of view of the sensor and the Doppler signal exceeds the set threshold level. The angular accuracy of the SAA's obstacle detection is determined by the angle of incidence of the radar sensor to the target.
The number of radar sensors selected depends upon the radar's range, accuracy and area of coverage required. Long range radar sensors usually have narrow angles of view (incidence) so the number of sensors to cover a given area of observation may be increased.

Radar sensors are connected to analog inputs A1 thru A4 of the autopilot, as shown in Figure 6. The Threshold of the Doppler signals can be created in the analog processing circuit connected to the sensors, or in the autopilot through software. When the Doppler signals from the radar sensors exceed the selected threshold, the autopilot will send stop or maneuver commands to the Engine Servo Controllers (ESC) and to the control panel via the Servo Connectors.

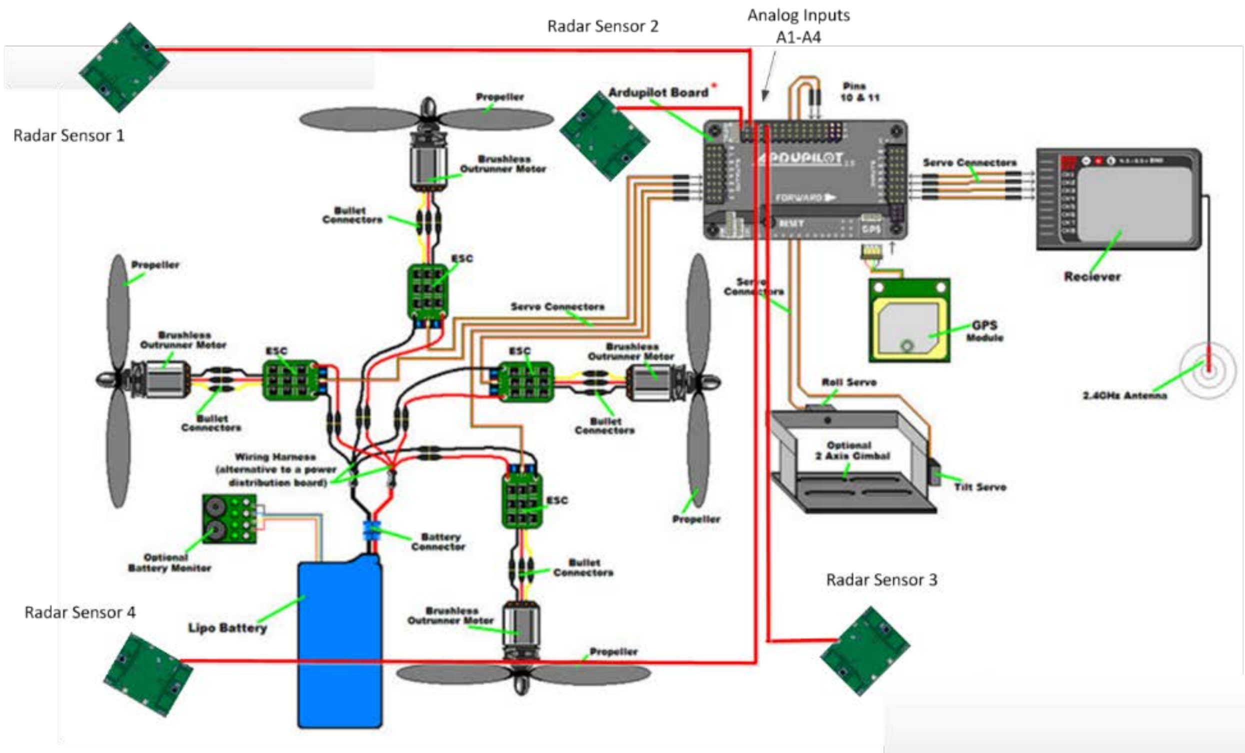


Figure 6. Samples of connections of the four Doppler radar sensors to the autopilot in a four propeller drone. Doppler radar modules are installed on different sides inside or outside the drone cover. Modules need to be installed with clear vision of observation areas and with minimum interference between modules. The drone's cover will not normally attenuate the transmitted radar signals. Metallized foil and metal drone construction parts can create re-reflections and interference and need to be avoided.

Sense and Avoid systems can be designed with four separate Doppler radar sensors as shown in Figure 7, or on one board, consisting of all four directional antennas, microwave Doppler sensors and an Intermediate Frequency processor. The block diagram of a Sense and Avoid system with four directional antennas on one board is presented in Figures 8 & 9.

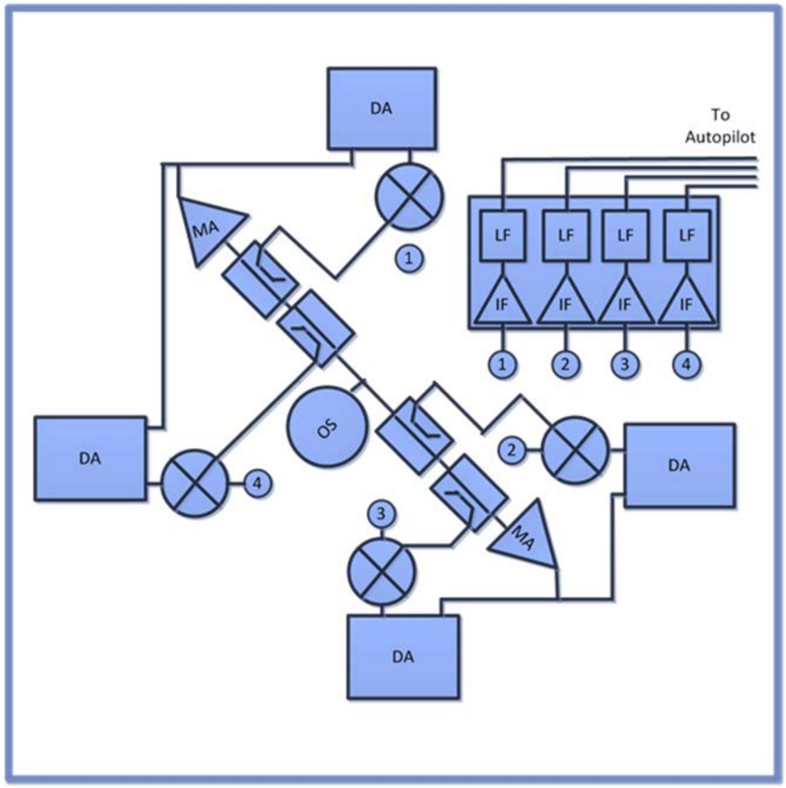


Figure 7. Block diagram of sense and avoid system with four directional antennas. Where: DA – directional antennas; MA – microwave amplifiers; LF – low frequency filters; IF – intermedia frequency amplifiers; OS – oscillator.

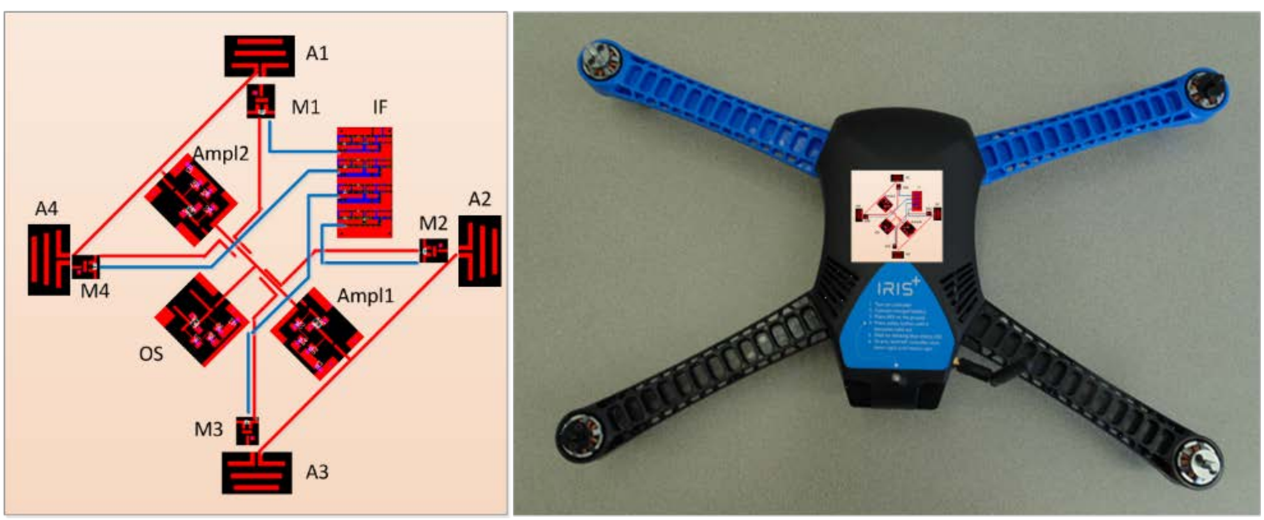


Figure 8. Sample topology of a sense and avoid system on one board shown positioning the sense and avoid system board inside of a 3DR Inc. IRIS drone.

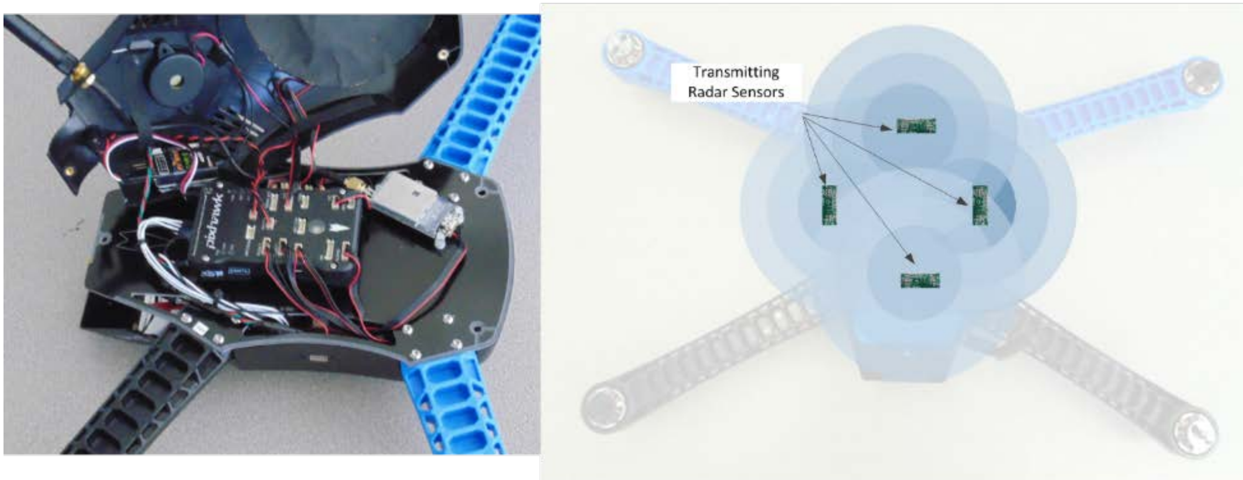


Figure 9. Position of autopilot inside IRIS drone and proposed optional sample of installation of transmitting Doppler radar sensors inside IRIS drone.

Testing of interference signals of four Doppler sensors as they would be installed on one drone platform has been done using the setup presented below in Figure 10. Outputs of the four Doppler radar sensors were connected to LEDs for visualization of the alarm signals.

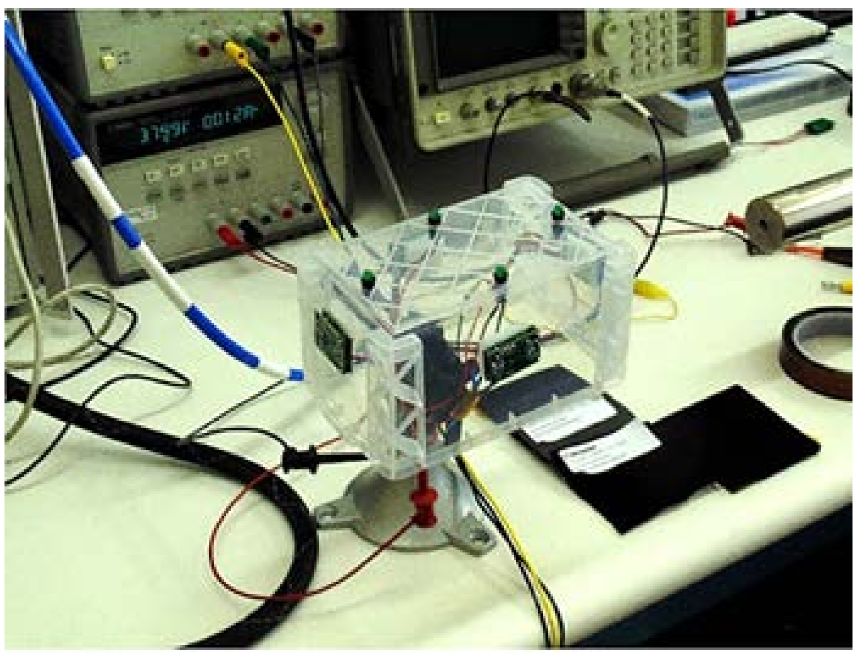
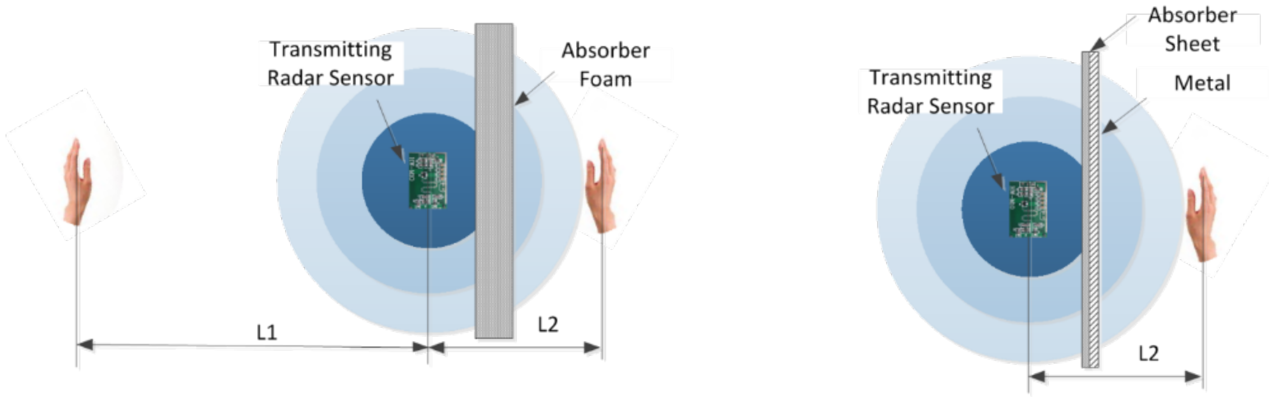


Figure 10. Setup for testing interference between Doppler sensor modules inside drone. Doppler sensors are installed around the perimeter of a plastic frame, which simulates a drone. The frame size corresponds to the drone size. All Doppler sensors are connected to LEDs for visualization of alarm signals. The space inside frame has been used to test different absorber material sheets.

Different absorber materials and combinations with metal shielding has been tested to exclude interference between sensors. The threshold Doppler signal was measured on front and back sides of the transmitting radar sensor as shown in Figure 11.



(a) (b)

Figure 11. Test of carbon based microwave absorber C-RAM MT with high dielectric loss over a very broad range (a). Test of C RAM FDSS thin magnetically filled silicone rubber sheet stock (b).

The Doppler radar range is equal to the detectable distance for a minimal radar cross-section target size. Detectable distance on the front and back side of Doppler sensor was measured with a sample of absorber material positioned behind the Doppler sensor. The distance was measured by using an approaching hand as shown in Figure 11. Decreasing radar range (sensor sensitivity) was determined by comparing the detectable distance with the absorber material to the detectable distance without absorber material.

A few different thickness samples of microwave absorber foam with high dielectric loss over a very broad frequency were tested. The absorber foam absorbed microwave signals omnidirectionally and dramatically decreased sensor range. A combination of the metal shield with the thin sheet of high magnetic loss absorber attenuating RF surface currents created better protection and smaller attenuation of microwave signals.

The test results are provided below in Table 1.

Table 1: Test Results

Material	Distance on front side (no absorber) (Meters)	Distance on back side L1 (Meters)	Distance on back side L2 (Meters)
C-RAM MT-26/PSA 0.25” Carbon loaded foam	3	2	0.5
C-RAM FDSS 30/PSA0.01 Absorber sheet	3	2	0.5
C-RAM MT-30/PSA 0.125”	3	2.5	1
C-RAM GDSST-30/PSA 0.030”	3	2.5	1.5
C-RAM RGD-S-30/PSA 0.01”	3	2.5	1.5

Conclusion of tests of absorber materials:

- Absorber foam creates attenuation of electromagnetic energy transmitted by the sensor on both sides of the sensor. Positioning the absorber foam on the back side of the sensor sufficiently decreased the range of the sensor.

- A small metal shield creating reflections and re-reflections of transmitted signals increased the interference between the sensors. The size of the metal shield must exceed half a wavelength (15 mm for 10 GHz) for direction of the transmitted signals.

- A combination of a metal shield with a magnetically filled silicone rubber microwave absorber sheet results in decreased surface currents and attenuates the microwave signals without sufficient attenuation in forward directed signals, but still must exceed half a wavelength and also decreases the sensor range.

- The use of directional antennas will increase the sensor's range and at the same time will decrease the interference between Doppler sensors.

A Phased Array would normally be used to increase the antenna's directivity and gain. But this would also increase the size of the array. The distance between the antennas inside the array of approximately half a wavelength combined with increasing the number of antenna elements dramatically increases the antenna array size. However, the application of an antenna array can be recommended for larger drones.

An array of directional antennas was designed and investigated for application in sense and avoid systems for small drones [8-13].

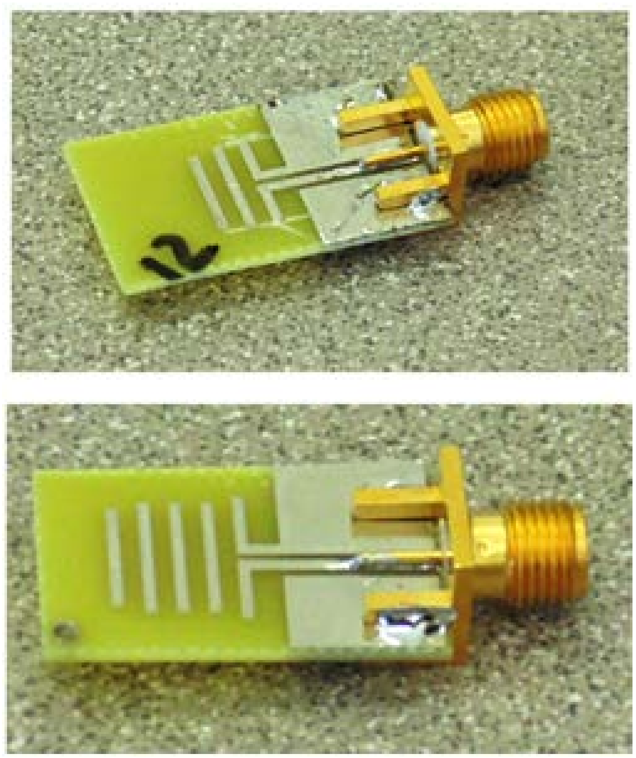


Figure 12. Directional antennas connected to coplanar line on PC board designed for a small sense and avoid system.

Ku band directional antennas connected to a coplanar line on a PC board designed for small SAA systems are presented in Figure 12. Different constructions of directional antennas have been investigated. Logarithmic periodic dipole antennas on PC boards with two and four directors are presented in Figure 12. The test results are presented in Figure 13. Increasing the number of antenna directors increases the antenna's directivity, gain and separation between antennas, directed to different sides. Increasing the number of directors in antenna can be recommended until it will no longer fit inside of the drone cover.

A Dielectric Resonator Oscillator (DRO) based on an Infineon transistor was designed and tested for Doppler radar. The schematic, topology of the test board and the test results are presented in Figure 14. The oscillator can be very small and it has a relatively simple schematic as shown in Figure 14.

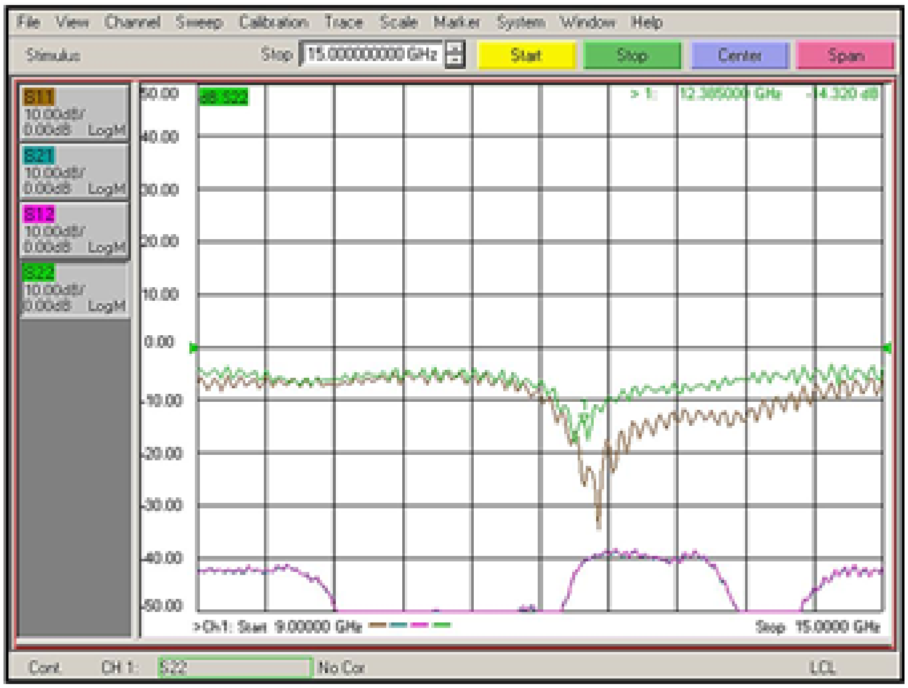


Figure 13: Test results of Ku band directional antennas designed for sense and avoid system based on Doppler radar.

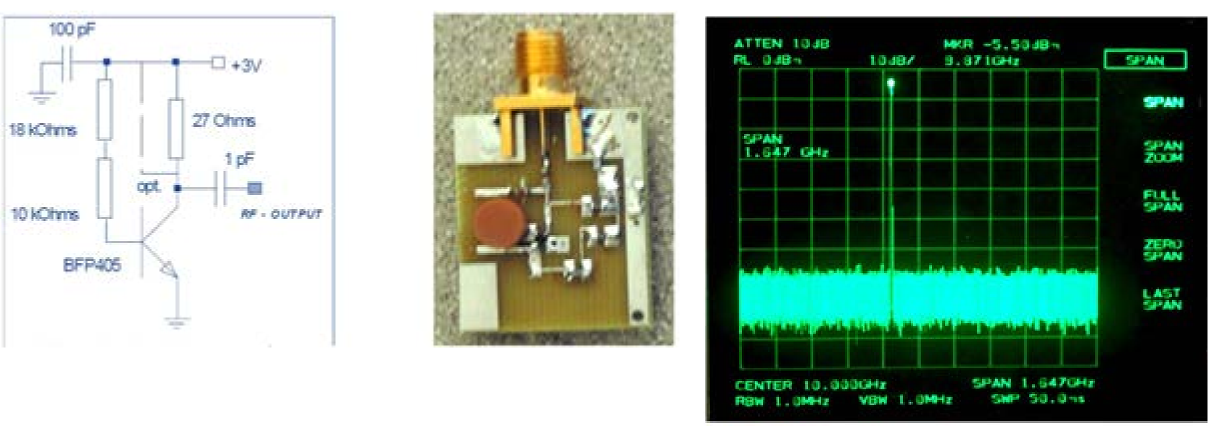


Figure 14: Dielectric Resonator Oscillator (DRO) based on Infineon transistor. Schematic, topology of test board and test result.

4. DRONE TEST RESULTS

A prototype of a Doppler radar sensor was designed and tested for the 3DR IRIS drone application. The prototype is presented in Figure 15. A collision avoidance system based on an array of directional antennas was designed and presented in a few papers [8-10].

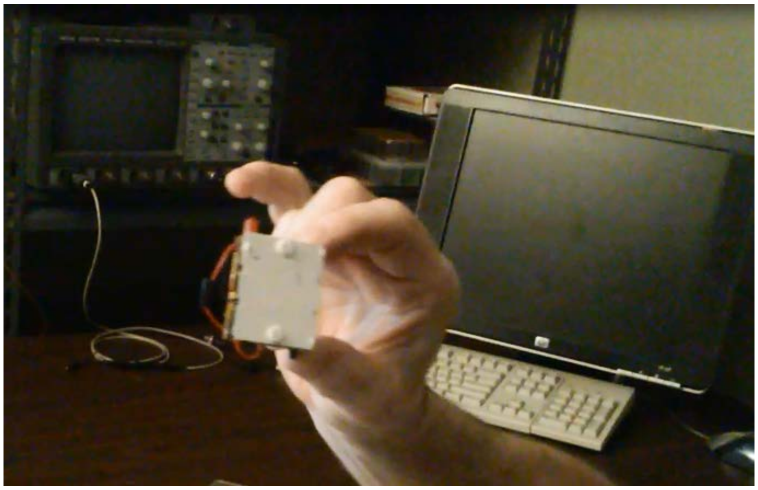


Figure 15: Prototype of Doppler radar sensor designed and tested for 3DR IRIS drone application.

The test of a drone with one Doppler radar sensor is presented at [14]. A drone with four Doppler radar sensors was tested and will be presented at the conference.

Conclusion:

- Designed and tested small (40 grams with battery) sense and avoid system based on Doppler radar for small unmanned systems;
- Proposed sense and avoid system which will give small drones the ability to “see” close up and give them agility to maneuver through tight areas;
- In proposed sense and avoid system, Doppler radar modules coupled with an array of directional antennas which cover the entire sky by being distributed around the perimeter of the unmanned system and connected to autopilot are used;
- The Doppler radar module transmitting and receiving continuous wave microwave signals can detect and track small obstacles, even wires and non-cooperative non-transmitting aircraft by receiving reflected signals;
- The Doppler radar sensors can work in any weather conditions (snow, rain, dust) and have perfect sensitivity for wires and electromagnetic fields. A combination of Doppler radar sensors with ultrasound systems will provide universal sense and avoid system for all kinds of materials and conditions.
- The Doppler micro sense and avoid radar has simple circuitry, works from a 5 volt source, has low power consumption, is light weight, inexpensive and can be used for small unmanned aircraft;
- Designed a series of Doppler radar modules with different ranges, angles of view, transmit power designed for drones with different sizes and applications and will be the base for more powerful and complicated sense and avoid systems with high-accuracy obstacle tracking, recognition and imaging.

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