Using mmWave sensors to enhance drone safety and productivity

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Overview

Aerial drones have taken flight, from package-delivery trials, to entertainment, sporting events and their generous availability at any electronics store. By 2022, the global unmanned aerial vehicle (UAV) market is forecasted to reach more than USD $21 billion[1] and drive a global market economy for business services valued at over $127 billion[2]. Industries that will be rapidly disrupted by drones include infrastructure, agriculture, transportation, security, entertainment and media, insurance, telecommunications and mining.

Designing and customizing drones for specific industries optimizes productivity, enhances safety and lessens the environmental impact of current methods. Drone designers do face a myriad of design challenges to realize real-world deployment, however, including:

- **Operation in all conditions.** Grounding drone flights because of weather, lighting conditions, visibility obstructions caused by smoke or fog, or literal obstruction caused by trees and other objects can significantly impact the actual productivity of drone systems in deployment. Designing drones that can work accurately across environmental conditions is necessary.
- **Lightweight design.** In its simplest terms, decreasing the weight of the drone platform increases the time of flight on a given battery. The lighter the drone system, the easier it is to deploy. Reducing weight in a drone platform also enables more payload budget, which can then be dedicated to onboard application-specific tools. All of these considerations greatly enhance the productivity of the drone platform.
- **High speed.** The faster drones fly and perform, the higher the productivity—but designers must balance speed against safety considerations. Drones can achieve maximum horizontal velocities over 70 kph; two drones flying directly toward one another represent a closure rate of 40 m per second and create a significant challenge to sense-and-avoid functions.
- **Intelligent operation.** The most dangerous times of drone operation are when it is close to the ground during takeoff or landing, because of the reduced error margin with the ground. Operator error here can result in damage or loss of the drone, drastically impacting productivity and introducing many safety concerns. A key factor is the speed as the drone approaches the ground, so the ability to accurately detect distances at the centimeter level is critical. Another must-have feature is for the drone to be able to detect the type of surface it intends to safely land on, and whether it is wet or dry.
- **Object detection and avoidance.** Drone platforms operate in environments with physical obstacles. The ability to detect obstacles and then take avoidance measures reduces the potential of damage or loss of the drone and damage to surroundings. Combined with high speeds these measures must be taken quickly with calculations in real-time.

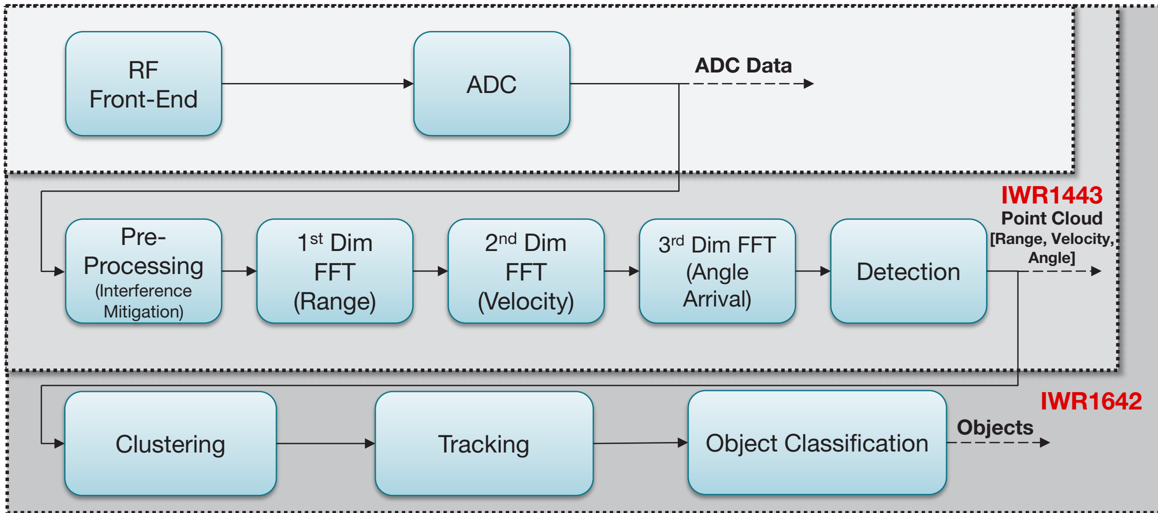


Figure 1. mmWave signal processing

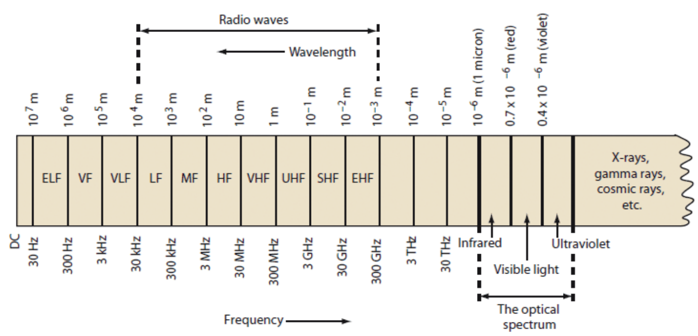
The application of millimeter wave (mmWave) silicon sensors

TI's millimeter wave (mmWave) sensor, integrates RF processing, calibration, high-speed ADC, microcontroller (MCU), digital signal processing (DSP) and memory on a single complementary metal-oxide semiconductor (CMOS) monolithic chip, which accurately reports range, velocity and angle between the sensors and objects around the drone. The resulting level of integration allows for a scalable family of devices that address different processing outputs, shown in **Figure 1**, which can be used in a variety of system architectures to output real-time intelligence to the drone-control system about the surrounding environment and potential obstacles.

This real-time intelligence enables designers to make drone systems that can operate with high productivity in real-world deployments and meet the design challenges listed above. Deploying multiple sensors and sensing modalities adds safety redundancy, and mmWave sensing has unique attributes to address these challenges.

Operation in all conditions

Radar technology is not new; British physicist Sir Robert Watson–Watt created the first practical system in 1935[3]. Similar to microwave radar used in modern aviation, mmWave devices in the 30 GHz–300 GHz spectrum operate in all weather conditions. Looking at the frequency spectrum in **Figure 2**, mmWave sensors operate in the spectrum between photonics and microwaves.



Courtesy of Electronic Design, http://www.electronicdesign.com

***Figure 2**. Frequency spectrum*

Operating in this spectrum makes mmWave sensors interesting because they:

- Can penetrate materials and see through plastic, drywall and clothing

- Can see through sleet, rain, snow, fog and other hazardous conditions
- Feature highly directional compact-beam steering with 1-degree angular accuracy
- Offer small wavelengths with submillimeter range accuracy
- Employ standard optical techniques for focus and steering
- Offer large absolute bandwidths with the ability to distinguish between two objects

Lightweight design

Using CMOS silicon technology to integrate most required functions on a monolithic die just the TI millimeter wave device, power management and boot prom integrated circuits plus a PCB board antenna are all that are required to implement the full sensor. **Figure 3** shows the size of an existing module from D3 Engineering using the TI mmWave sensor in a 3 transmit and 4 receiver antenna configuration. **Table 1** compares the mmWave module dimensions and weight with a state-of-the-art LIDAR rangefinder showing an almost 3× reduction in size at less than half the weight.

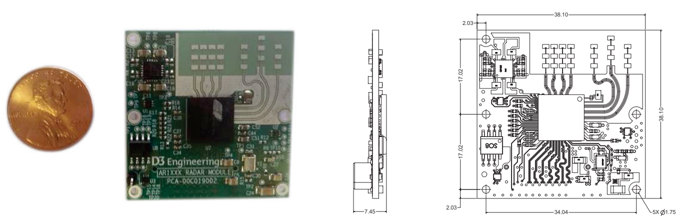


Figure 3*. Typical mmWave module design*

	mmWave Module	LIDAR rangefinder Module	Reduction %
Module size	38 × 38 × 7.5 mm	20 × 48 × 40 mm	72%
Module weight	7.5 g	16 g Note 1	53%

Note 1–includes optics and housing

Table 1. *Comparison of size and weight of D3 mmWave sensor module with LIDAR module*

The compactness of the solution allows easy placement of the sensor behind plastic enclosures, enabling a rugged design that adds minimal weight. Contrast this with an optical or an infrared (IR)-based solution that requires lens housings, tooling and calibration during manufacturing test and a lower assembly cost is suggested.

High speed

Drones can fly very fast, with maximum specifications of 72 kph. Thus, any sensing technology must be able to measure velocities at these speeds. The V_{max}, or maximum measurable velocity (maximum relative velocity if both the sensor and the object are moving) is related to the total chirp period of the mmWave transmit signal, as shown in **Equation 1**:

$$V_{max} = \lambda/(4T_c) \qquad (1)$$

where T_c is the chirp duration/period total, λ is the distance traveled in one cycle and V_{max} is in meter/sec.

From the data sheet of the IWR1443 device, λ = 3.9 mm for a start frequency of 76.5 GHz.

For a V_{max} of 72 kph, the value of T_c = 48.75 µs.

Based on inverse proportionality, as long as T_c is less than 48.75 µs, then a V_{max} greater than 72 kph is detectable. Calculating the T_c across a range of V_{max} values generates the curve shown in **Figure 4**.

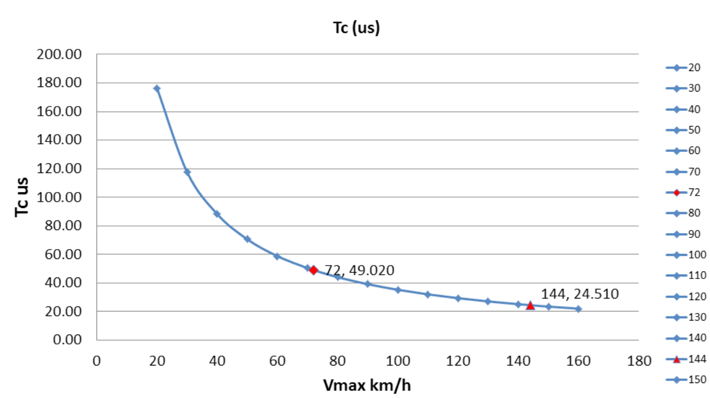


Figure 4*. Maximum measurable velocity vs. chirp duration/period total*

Intelligent operation

To maximize drone productivity in real-world applications, it is important to assist operators with intelligence from the sensors on the drone. As we discussed earlier, the most perilous time for a drone is when it is in close proximity to the ground, such as in landing scenarios. mmWave technology can provide navigational information during landing and assess the suitability of the landing surface. The sensors are not susceptible to wind buffeting or dust generated from the drone propellers when close to the ground, as is the case with other sensor technologies.

Using the [IWR1443 mmWave evaluation module](#) (EVM) a 2-cm accuracy can be achieved with an altitude range from the ground to 40 m, at speed from hover to exceeding 25 cm per second. **Figure 5** shows a screen capture of a drone landing demonstration, capturing the drone at a 19.73 cm altitude and a speed of 22.55 cm per second from the ground.

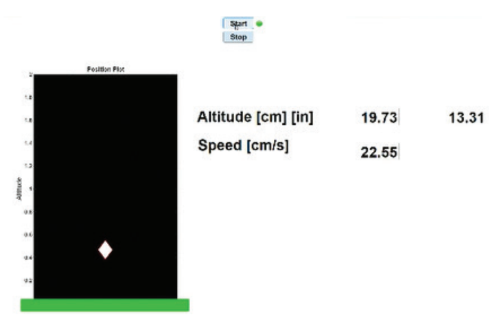


***Figure 5**. Screen capture of a drone landing demonstration*

The accuracy of mmWave sensors also has the potential to determine the type of landing surface based on surface movements generated from the drone propellers during hover with the drone stationary right before final touchdown. Experiments conducted at TI using the IWR1443 mmWave EVM (under static conditions without the drone flying) show that the ground was distinguishable from water, based on the differences in reflectivity and by measuring microvibrations from the material surface, as shown in **Figure 6**. In case it does detect water, the drone can abort its landing and thus avoid damage or total loss of its cargo, or of the drone itself.

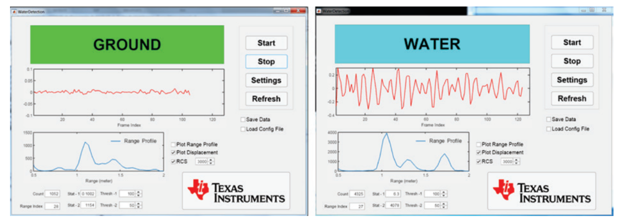


***Figure 6**. Using mmWave to detect ground or water surfaces*

Object detection and avoidance

At the core of an intelligent sense-and-avoid operation is a drone's ability to detect likely obstructions that it will encounter in its line of flight, which could result in total loss or damage to the platform, negatively impacting productivity. Beyond the ability of mmWave sensors to detect objects in conditions without regard to lighting, smoke, dust or fog, they are uniquely positioned to detect objects that are difficult using other sensor technologies.

One such example is the detection of wires such as power lines, telephone lines, aerial antennas or wire fencing strung in the drone's path. TI ran a series of experiments in its anechoic chamber to evaluate the detection of different types of wire. **Figure 7** shows the lab setup.

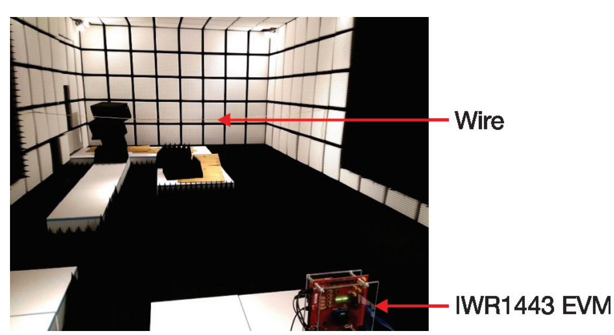


***Figure 7**. Anechoic chamber test setup for wire-line testing*

The types of wire tested included an electrical extension cord, a Category 5 Ethernet cable, a line of nonmetallic (rubber) cabling, two 30-gauge copper wires twisted together and a single 30-gauge copper wire shown in **Figure 8**.

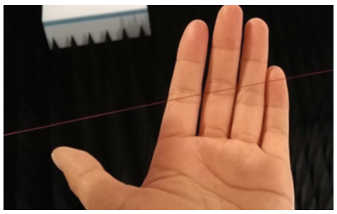


***Figure 8**. 30-gauge copper wire*

The IWR1443 mmWave EVM antenna collected measurements in the vertical and horizontal position (with suffix flip) at a distance of 1 m. **Table 2** shows the test results. Compared to a vertical orientation, the horizontal orientation achieved higher signal-to-noise (SNR) figures. The higher SNR was due to lower clutter in the test chamber in that orientation, especially for the thin wire, which was a single non-twisted strand.

We also observed a 6-dB gain by applying RX digital beamforming (BF) using the four-reciever antenna on the IWR1443 EVM.

Parameter	Value
Start frequency	77 GHz
Frequency slope	33 MHz/µs
Sampling rate	10 MHz
ADC samples_3.3G	1000

	CFAR SNR	
Test	no BF	BF
ethernet_1m	21	24
ethernet_1m_flip	21	28
extend_1m	12	14
extend_1m_flip	21	33
rubber_1m	21	31
rubber_1m_flip	8	18
thin_1m	–4	–6
thin_1m_flip	10	18
twist_1m	17	24
twist_1m_flip	14	23

***Table 2.** SNR analysis with the IWR1443 EVM*

Besides the IWR1443 mmWave EVM, we used an internal characterization board with a horn antenna for the wire test. The horn antenna has a much narrower antenna beam to reduce clutter significantly. During this test, we placed the wire at 4.5 m and measured the Constant False Alarm Rate (CFAR) SNR for each type of wire. **Equation 2** calculates the maximum detectable range of the wire as:

$$SNR \sim 1/R^3 \quad (2)$$

Figure 9 highlights the expected maximum detection range for each wire type if the CFAR detection threshold is 15 dB.

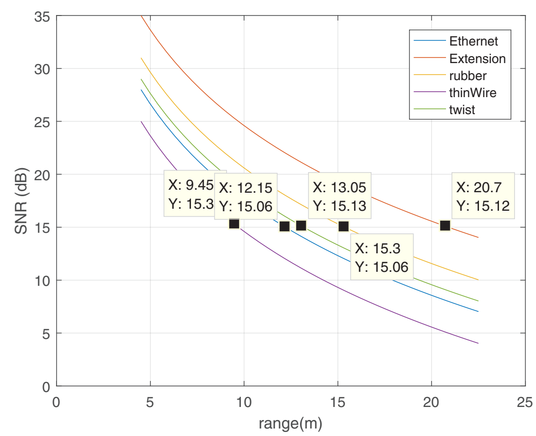


***Figure 9**. Detection range extrapolation by wire type*

The analysis showed that TI's mmWave sensors can detect all tested wire types, with the very thin and most challenging 30-gauge single-strand wire from an extrapolated distance of 9 m, up to 21 m for the largest gauge tested, in our case an extension cord.

The IWR1443 mmWave EVM—with multiple input/multiple output (MIMO) enabled—took outdoor data of actual overhead power lines. As **Figure 10** on the following page shows, the EVM can robustly detect power lines from 25 m up to 38 m for the smaller-diameter power line barely visible in the photo (fourth wire from the red arrow). This actual data highlights the aggressive nature of the lab wire-line sample types selected and the conservative extrapolation results.

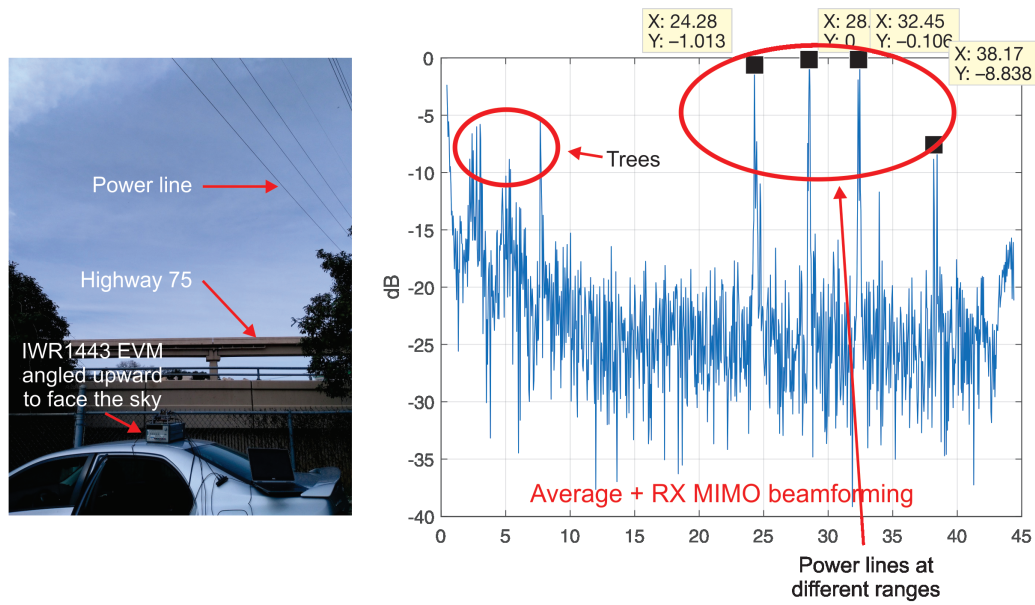


Figure 10*. Outdoor power-line detection with the IWR1443 EVM*

As a side observation, the tree foliage seen in the test pictures also showed up in the sensors' field of view. TI's mmWave sensors can detect trees with leaves regardless of moving foliage or shadowy conditions, and without excessive computational requirements that consume power.

mmWave sensors can robustly detect wire lines, from very fine single-strand wire to standard overhead power lines at distances approaching 40 m.

We selected this use case for analysis because of its sensing difficulty and calculation complexity with other sensing technologies. It also illustrates a real-world deployment of industrial drones, which must detect and then navigate around objects to produce the expected productivity and safety levels.

Summary

TI's integration of mmWave sensors on a monolithic piece of silicon is enabling designers to create drone platforms that disrupt industries and increase economic productivity. These sensors offer superior performance to operate in all conditions, at high rates of speed, with landing and takeoff intelligence and the ability to detect objects such as power lines. Realizing this performance in sensors that are small, lightweight, rugged and easily encased in drone plastics has brought TI's mmWave sensor devices to the forefront of sensing solutions for drone manufacturers.

Texas Instruments has introduced a complete development environment for engineers working on industrial mmWave sensor products that includes:

- **Hardware EVMs** for IWR1443 and IWR1642 mmWave devices.
- An mmWave software development kit (SDK) that includes a real-time operating system (RTOS), drivers, signal-processing libraries, the mmWave application programming interface (API) and security (available separately).
- mmWave Studio offline tools for algorithm development and analysis that include data capture, a visualizer and a system estimator.

To learn more about the mmWave sensor portfolio, tools and software, see www.ti.com/mmwave.

References

1. *Markets and Markets*. [“Drones Market by Type (Fixed Wing, VTOL, STUAS, MALE, HALE, UCAS), Payload (Up to 25 Kg, Up to 150 Kg, Up to 600 Kg, Above 600 Kg), Application (Precision Agriculture, Retail, Media & Entertainment), Component, and Geography – Global Forecast to 2022.”] October 2016.
2. *PwC*. [“Clarity from above. PwC global report on the commercial applications of drone technology.”] May 2016.
3. [Invention of the Radar – Obstetric ultrasound].
4. RobotShop.com. [LIDAR-Lite 3 Laser Rangefinder].