Electromagnetic Susceptibility of COTS Control Systems

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***Abstract*—COTS control systems used on small UAVs were investigated for EMC vulnerabilities. Electronic speed controllers, autopilots, and inertial measurement units were electromagnetically disrupted, by modulating RF signals with waveforms that were rectified by nonlinearities. These disruptions had catastrophic effects on the functionality of the devices, without physically damaging them.**

***Index Terms* – COTS, EMC, susceptibility, UAV.**

I. INTRODUCTION

Both the commercial and hobbyist communities make use of common off-the-shelf (COTS) control systems for robotics applications. These devices can range from Arduinos to more purpose built embedded systems. While COTS equipment is typically tested for electromagnetic compatibility (EMC), many of these inexpensive devices were not designed to be robust to harsh electromagnetic environments, and therefore have electromagnetic susceptibilities that can alter their functionality [1]. These vulnerabilities are exacerbated when subjected to intentional electromagnetic interference (IEMI) [2], which has been an emerging threat in recent years [3]. Characterizing these electromagnetic vulnerabilities can lead to more robust electromagnetic compatibility design techniques.

Specifically, the electromagnetic susceptibilities of COTS control systems were investigated, that are commonly found on small unmanned aerial vehicles (sUAV). These sUAVs are ubiquitous in society, and are commercially available, as well as custom built by hobbyists. Some of the COTS components typically found on these platforms include electronic speed controllers, autopilots, and inertial measurement units.

II. ELECTRONIC SPEED CONTROLLER

Electronic Speed Controllers (ESC) are typically brushless DC motors, which consist of electronics that convert a pulse-width-modulation (PWM) control signal into three-phase voltage for a delta or wye-wound motor. Two ESC examples are shown in Fig. 1, i.e., the DJI 420 Lite (bottom) and a BL Heli (top). The wires entering the right side of the ESCs are power and PWM control-signal wires. The three conductors on the left side of the ESDs in Fig. 1 provide the motors with their three-phase power. Increasing the pulse width increases the three-phase voltages, speeding up the propeller motors.

By modulating an RF signal with PWM, the radiated signal can couple into the ESC, where it can be rectified to baseband, by the various nonlinearities that all electronics possess, if driven hard enough. If this rectified PWM voltage is great enough, the ESCs will respond by speeding up or slowing down, depending on the pulse width.

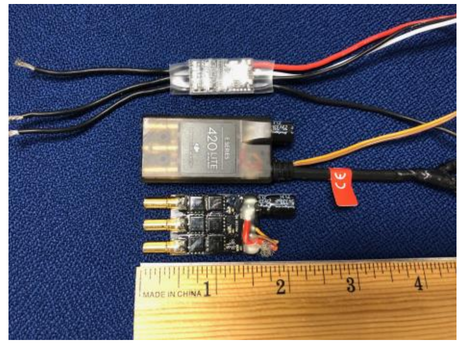

Fig. 1. Electronic speed controllers (ESC), BL Heli (top) and: DJI 430 Lite (middle and bottom).

The DJI ESC in Fig. 1 was connected directly to a function generator that provided a 400-Hz PWM signal to the ESC, with a 1.55-ms pulse width (46% duty cycle). This control signal fixed the propeller to a steady speed that was used as a reference. Then a 1.581-GHz signal was modulated with a similar PWM signal and transmitted with an EIRP of 19W, using the setup in Fig. 2. As the pulse width of the modulated RF signal was increased/decreased, the propeller speed increased/decreased proportionally, as would be expected if the wired PWM controlling signal had been varied.

III. PIXHAWK AUTOPILOT

The Pixhawk PX4 autopilot, shown in Fig. 3 was similarly disrupted by modulating a 2.001-GHz signal with a 300-Hz PWM waveform, and a pulse width of 1.3 ms (52% duty cycle). The autopilot was configured to control the ailerons of a fixed-wing sUAV, using servos that were attached to the ailerons. As soon as the modulated RF signal began to transmit onto the autopilot, the servos snapped the ailerons to their neutral positions, preventing control by the autopilot. As soon as the RF transmission was turned off, the autopilot regained control.

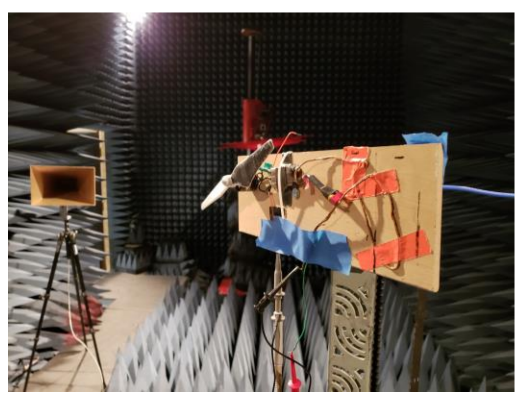

Fig. 2. DJI ESC experimental setup.

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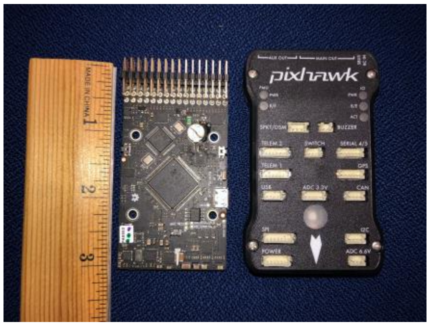

Fig. 3. Pixhawk, PX4 autopilot.

IV. Waveform Determination

This same technique could be used to disrupt several makes and models of autopilots and ESCs. The relatively low power levels that were required to disrupt these devices was achieved by finding resonances on their respective PCBs. As a first-order approximation, the fundamental resonant frequency can be estimated by:

$$f = \frac{n*c}{2*\sqrt{\varepsilon}*(Length\ OR\ Width)}\ , \qquad (1)$$

where ε is the effective permittivity. Since 'n' represents an infinite number of half wavelengths, (1) can lead to several convenient resonant frequencies. The challenge is predicting ε. Ansys SIwave provided several resonant frequencies, as illustrated in Fig. 4. However, a detailed CAD model was required for this simulation, which may not always be available. Another method is to probe for unintentional emissions. It was discovered that radiating frequencies often led to electromagnetic susceptibilities at those same frequencies. Furthermore, some system-level emissions data can often be found in FCC EMC reports, simply by searching for the FCC ID number. Known resonant frequencies can lead to many more susceptibilities from intermodulation products, such as the third-order product:

$$2f_1 \pm f_2 \quad \text{and} \quad 2f_2 \pm f_1\ . \qquad (2)$$

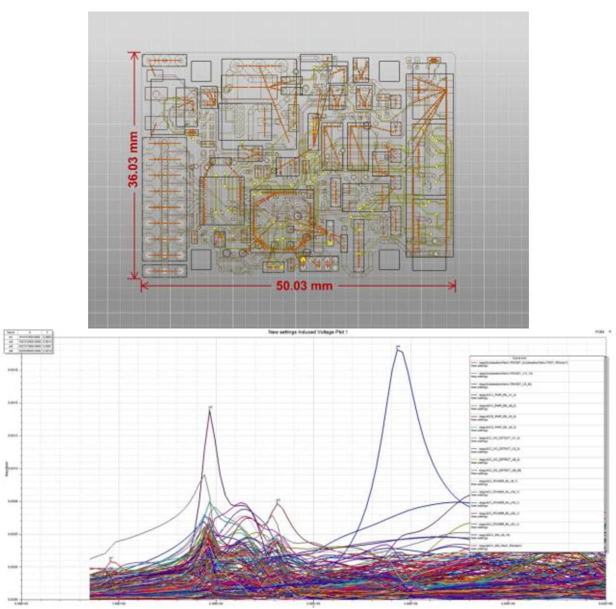

Fig. 4. SIwave simulation (bottom) of a Pixhawk PCB (top).

V. Inertial Measurement Unit

Many sUAVs use an inertial measurement unit (IMU) for stability control, as well as a navigational supplement to GPS. Several IMUs are commercially available for less than $100. They consist of accelerometers and three-axis gyros, on integrated circuits, mounted to a PCBs, exemplified in Fig. 5. The gyros are made of arrays of micro-electromechanical systems (MEMs). As inherently mechanical devices, each gyro axis has an acoustic resonant frequency. By modulating an RF signal to the same frequency as the acoustic resonant frequency, the rectified electrical signal is transduced to a mechanical wave on the MEMs array. The result can be seen in the Betaflight software display in Fig. 5. The actual IMU was stationary but appeared to be shaking violently every time the modulated RF signal transmitted. Each axis could be individually disrupted, by selecting the corresponding modulating frequency.

VI. Conclusion

COTS control systems that are commonly found on sUAVs were disrupted by modulated low-power RF signals, using selected waveforms. These COTS control systems included electronic speed sensors, autopilots, and inertial measurement units. A variety of techniques were used to determine the modulating waveforms and resonant RF frequencies that had the most disruptive effect on these devices. Understanding these vulnerabilities could lead to more robust EMC protection.

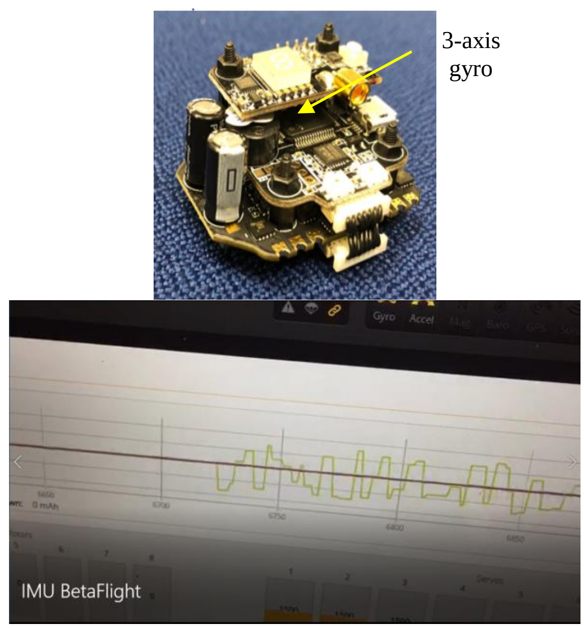

Fig. 5. Magnum Mini F4 IMU (top). Betaflight display of IMU appearing to be shaking violently, even though it was stationary.

References

[1] E. L. Kirchner and B. D. Salati, "An EMC Design Approach for Integrating COTS Equipment into an Existing Military Aircraft," IEEE International Symposium on EMC, Seattle, WA, pp. 986-991, 1999.

[2] R. Thottappillil and M. Backstrom, "Intentional Electromagnetic Interference and Critical Infrastructure," 2019 URSI AP-RASC, New Delhi, India, pp. 1-1, Mar. 2019.

[3] C. Kasmi and J. Lopes-Esteves, "Functional Susceptibility of COTS Devices to IEMI at Local and Large-scale Levels," Int. Conf. on Electromagnetics in Advanced Applications, Cairns, pp. 300-420, 2016.