Extremely-Low Frequency (ELF) Radio Sensing of Unmanned Aerial Systems

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***Abstract*—This paper describes RF-based detection of unmanned aerial systems (UAS) without using transmit signals. The proposed scheme uses a sensitive magnetometer and digital signal processing algorithm to enable robust detection of high-torque/weight ratio rare earth magnet-based electric motors that are the enabling technology in electrical UAS. Preliminary experimental results with a 1 m^2 receive coil show reliable detection of a small UAS at distances of several meters.**

I. Introduction

The commercial and recreational use of small unmanned aerial systems (UAS, also known as drones) is rapidly increasing. The use of electrically-powered micro-UAS for terrorism is also a fast growing concern. As a result, there is a growing need for improved drone detection and classification methods [1]. Homebrew versions of UAS threats will likely be remotely-operated via radio-control, and such remote controlled UAS are easy to detect using a RF receiver. However, a technologically advanced foe will use autonomous UAS, thereby rendering RF control-link detection schemes useless.

One way of detecting autonomous UAS is to use radar, in which the detector uses either signals of opportunity (such as nearby radio/TV stations or cell towers) or its own transmit signal to detect unique radar signatures [2], [3]. However, both cases require a transmit signal to generate the radar signature. This emitted signal (e.g., a single tone for continuous-wave radar) reveals the location of the UAS sensor, thereby increasing risk of electronic countermeasures/attacks. Thus, a clandestine surveillance unit must maintain radio silence, which makes radar-based detection impractical in many scenarios. Several passive detection methods have been proposed to avoid this problem, e.g., by using machine learning to analyze data from video cameras [4], [5] or acoustic sensors [6], [7]. However, these methods suffer from limited detection range due to weather conditions and/or ambient noise.

In this work, we propose to passively sense the low-frequency magnetic fields ($\mathbf{B}$-fields) generated by the UAS motors and motor controllers for remote UAS detection. While relatively little work has been done in this area, some preliminary experiments by Blažek et al. demonstrated that both fluxgate and inductive magnetometers can detect very low frequency (VLF) $\mathbf{B}$-fields (in the 5-20 kHz range) generated by UAS motor controllers at distances up to 1.5 m [8]–[10].

II. Theoretical Analysis

Motivated by our work on generating extremely-low frequency (ELF) $\mathbf{B}$-fields via rotating high-strength permanent magnets for low-rate data communications [11], here we use a magnetometer-based receiver to detect the unique ELF signatures of UAS. All types of UAS emit such signatures, since these devices contain several electric motors based on rare-earth magnet rotors. The permanent magnets in the motors spin at the rates of the UAS propellers, resulting in a mechanical rotation of the magnetic fields. The use of high-strength magnets thus generates a detectable receive signal at significant distances d that is proportional to both the rate of rotation as well as the number of poles in the rotor.

UASs typically use high-speed brushless DC (BLDC) motors for propulsion. Such motors use stationary current-carrying coils and rotating permanent magnets (PMs), and are electronically commutated by an on-board electronic speed controller (ESC). Two common motor configurations are used: inner-rotor and outer-rotor. Inner-rotor designs place the PM rotor in the center, where it is surrounded by the stator windings. By contrast, outer-rotor designs place the stator coils within an outer PM casing, as shown in Fig. 1(a). The latter are favored for UASs due to their smaller magnet sizes, reduced copper losses, greater rotor inertia, and lower cost [12].

As shown in Fig. 1(a), the PM outer-rotor contains P alternating poles and is surrounded by a soft-magnetic shield ("back iron") that provides a low-reluctance return path for the $\mathbf{B}$-field. For example, typical UAS motors use $N = 12$ stator coils (and teeth) to drive a rotor with $P = 14$ poles. While the shield is designed to confine the field within the motor, in practice some external "stray" or "leakage" field is inevitable. Let us define f_0 to be the rotation rate. Since there are a total of $P/2$ north and south poles in the rotor and each dipolar field has 2-fold rotational symmetry, we expect the external magnetic field to vary periodically with a fundamental frequency of $f_0 P$. In addition, any asymmetry or mismatch between the poles will break the P-fold rotational symmetry of the system, resulting in a lower-frequency component at f_0.

As an example, consider the DJI Phantom 3, a popular small quadcopter. The four BLDC motors used by this device have stators with double-layer windings ($N = 12$ coils, each

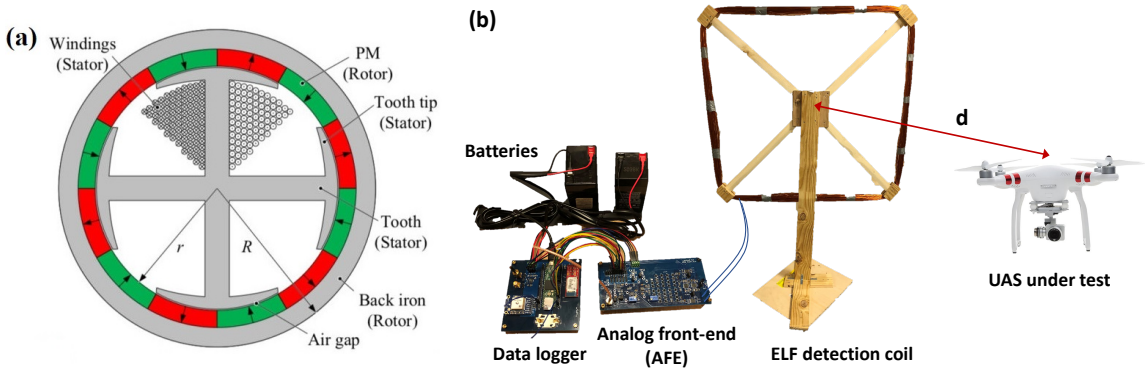


Fig. 1. (a) Cross-section of a typical outer-rotor BLDC motor. (b) Experimental setup used for $\mathbf{B}$-field based UAS sensing. The data logger includes an on-board GPS receiver for time-stamping the acquired ELF waveform. The entire system is powered by two sealed lead acid (SLA) batteries.

23×12 mm in size) and a rotor with $P = 14$ poles. The rated motor voltage, current, and speed constant are 17.4 V, 20 A (steady-state) or 30 A (peak), and $K_v = 960$ rpm/V, respectively, resulting in a maximum possible rotation rate of $f_0 \approx 16,200$ rpm (270 Hz). Thus, the fundamental frequency of the external $\mathbf{B}$-field may reach values as large as $270 \times 14 = 3,780$ Hz, although it will typically be much smaller. During flight, the ESC controls the rotation rate using pulse-width modulation (PWM) at a switching frequency $f_{sw} \gg f_0$ (typically, $f_{sw} = 8$ kHz or 16 kHz).

III. Experimental Results

Initial experiments to verify the proposed concept were performed using a homemade magnetometer (160 turns of AWG 18 magnet wire wound on a square 1 m^2 wooden frame) and JFET-based low-noise ELF receiver. The experimental setup, which is shown in Fig. 1(b), includes a battery-powered data logging unit that can continuously record several hours of ELF data (at 10 kS/sec) to an on-board SD card.

Experiments using the proposed setup show that a small quadcopter (DJT Phantom 3) can be reliably detected at distances up to ∼5 m without any sophisticated signal processing; an example is shown in Fig. 2. The detection distance can be significantly improved by using non-linear signal processing methods. In addition, the signatures detected by our experimental ELF sensor suggest a large number of features that make automated detection and classification of UAS type using machine learning a likely possibility.

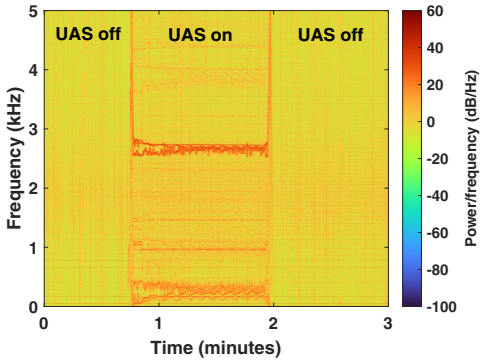


Fig. 2. Spectrogram of a typical experimentally-measured UAS signature at $d = 1.5$ m. Both the fundamental rotation frequency at $f_0 \approx 175$ Hz (10,500 rpm) and the expected harmonic at $14f_0$ are clearly visible when the UAS motors are "on". Doppler shifts due to UAS motion are also visible.

Acknowledgement

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