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MODERN METHODS FOR DETECTION OF UNMANNED AERIAL VEHICLES

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Abstract. Most recent Unmanned Aerial Vehicle (UAV) detection methods are discussed in the article. Detection of UAV principles are pointed out during the overview. Brief advantages of each technique is covered and compared in between. Key technological limitations of each technique is pointed out and discussed. Several most recent and actual UAV threat accidents are presented with the indication of the used counter UAV systems. New upcoming threat of "Kamikaze" (self-destructive) UAV and their detection limitations are presented. Case studies on the hybrid counter drone technology interactions are covered.

In this article, important civil and military types of UAV propulsion are covered. Design features and future consumer demands, are analyzed, aiming at UAV components which are mandatory to perform a flight. Using recently published articles energy sources and thrust power plants are analyzed. UAV detection principles, that include audio signal signature analysis, aerial object video tracking, thermal heat signature analysis, radar systems, radio frequency spectrum and data packet communication detection are covered, pointing out their advantages and limitations.

Conclusions are drawn taking into account future perspective of the UAV technology developments and upcoming future threats of the highest impact. Evaluation of most actual recent articles is made in order to overview weak points of the counter UAV system development techniques. Finally future UAV technology development is analyzed and main safety related threats are indicated. Slowly developing UAV components are indicated, putting more attention on possible UAV detection methods, where UAV mandatory components will not become obsolete.

Keywords: UAV detection, anti drone system, counter drone, C-UAS systems.

Introduction

Unmanned Aerial Vehicles (UAV's) are lightning fast getting in our everyday life by solving complex tasks never available before. The most active sector in UAV development is in the field of military, scientific research, agriculture and recreational use.

The state of the art intelligent autonomous technologies used in UAV's are capturing information data, performing search and rescue, military missions, fire fighting and medical help operations.

Recent situation based on UAV threats show, that UAV's can perform devastating precise attack's on remote infrastructure and make a high volume global impact on essential supplies worldwide. Last high volume UAV attack launched on 14 September 2019, cut Saudi oil production by 50%, precision impacts are shown in Figure 1. The oil processing plant closure had an impact almost on

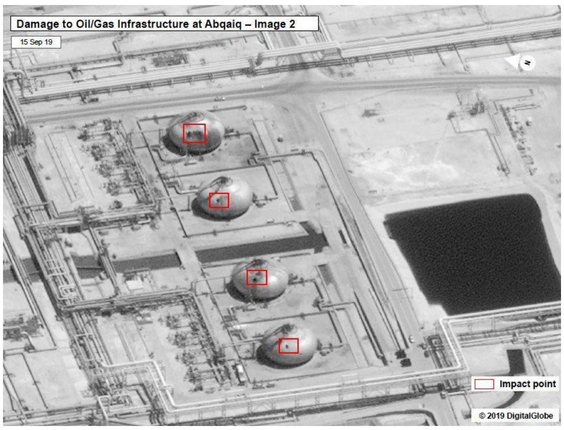

Figure 1. Results of high impact UAV attack on Saudi oil processing plant infrastructure. Red square rectangles indicate a precise hit and UAV positioning control possibilities (CNBC News, 2019)

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5.7 million barrels of crude production per day, about 5% of the world's daily oil production (CNBC News, 2019).

It is worth to mention the arising threat of "kamikaze drone" (a type of UAV packed with lethal explosives and shrapnel), that is becoming widely available to construct and show no practical technological detection solutions from terrorist attacks, especially in highly populated and dense urban areas. Usually such UAV's are handmade and use specialized remote control equipment, which is not mass produced and easily discovered in urban areas (Russell et al., 2019). The detection of UAV's is even more complicated, when fully autonomous flight autopilot systems take care of the flight control, without the need of any radio communication and navigation.

On 5 August 2018 Venesuela's president N. Maduro was attacked using civil UAV's, where two serial made DJI M600 UAV's, packed with C4 explosives were involved (BBC News, 2018b).

One of the UK busiest Gatwick's runways has been shut on 20 December 2018, since UAV's have been repeatedly flying over the airfield, causing about 110,000 passengers on 760 flights to be late (BBC News, 2018a).

It is evident, that UAV's threats are one of the major unresolved safety concerns of the nearest future. The arising task for detection of an UAV's in a no-fly zones is getting highly demandable but hardly solved tasks (Bunker, 2015). Each country has their own UAV no-fly zones for airport and strategic infrastructure security, but due to the development of intelligent UAV control technology, upcoming high capacity communication links, it tends to be less reliable instruments to achieve the desired safety (Solomitckii et al., 2018).

1. UAV propulsion types

In general all UAV's need propulsion energy to perform their take-off, flight and landing. Thrust engines are used to power any UAV for a flight, with exception for gliders and lighter than air systems. Glider type construction UAV's do not need propulsion energy as they can perform their flight using rising air streams, but they do need to be lifted or towed in the sky. Main UAV propulsion energy and engine types are as follows:

1. Chemical or nuclear energy powered engines
   1.1. Thermal engine;
   1.2. Nuclear reaction powered engine;
   1.3. External combustion engine;
   1.4. Internal combustion engine;
2. Kinetic energy powered engines
   2.1. Spring loaded thrust engines;
3. Electric energy powered engines
   3.1. Battery operated electric engine;
   3.2. Hybrid liquid fuel-electric power plant powered electric engine;
   3.3. Hybrid solar power-battery powered electric engine;
   3.4. Hydrogen power cell powered electric engine.

Electric thrust engines tend to be the best choice for recreational UAV propulsion. They can be small, lightweight, reliable and easily controlled in flight. Nevertheless, it is the batteries what limits flight duration and range. Figure 2 shows a solution of a petrol-electric power plant, powered by a small gas engine for longer UAV flight range (Hung & Gonzalez, 2012).

2. Types of engines for UAV propulsion

Propulsion is mandatory for all UAV to perform their flight. Main thrust engine types for UAV flight performance, are introduced briefly, focusing on internal combustion and electric engines. A piston engine, also commonly referred to as a reciprocating engine, is an internal combustion engine that uses one or more reciprocating pistons to convert pressure into a rotational motion in order to obtain thrust power from a liquid fuel. An electric engine (motor) is an electrical machine that converts electrical energy into mechanical energy. A motor shaft rotation force is achieved through the interaction between the motor's magnetic field and electric current in a motors wire windings.

Two-stroke engine is a kind of an internal combustion engine, which performs two cycles in one shaft revolution. In a two-stroke engine, the end of the combustion stroke and the beginning of the compression stroke happen simultaneously, with the intake and exhaust functions occurring at the same time. The high power achieved in this way leads this type of engine to a high power to weight ratio in comparison with other types of internal combustion engines. Simplicity of construction makes these engines relatively lightweight and widely used for the UAV propulsion.

Four-stroke engine has four stroke working cycle. They are: intake stroke, compression stroke, power stroke and exhaust stroke. Four stroke engines tend to be heavy as they use an oil pump and oil storage for the lubricating of the engine. Valve system is present in the engine which also gives more weight. A four stroke engine deliv-

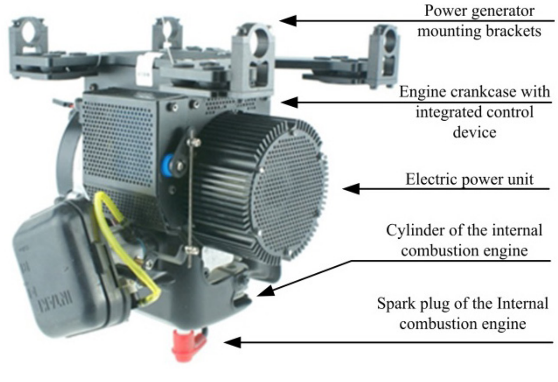

Figure 2. Modified picture of UAV hybrid petrol-electric power plant H2. System weight 3.5 kg, electric power of 2.0 kW (H2 Richen Power Ltd, 2018)

ers one power stroke for every two cycles of the piston (or four piston strokes), this is why it has less coefficient of power to weight ratio. Nevertheless this type of engine, due it's built in oil lubricating system is far more reliable and energy efficient that the two-stroke engines. Four-stroke engine usually are used for long endurance military type UAV propulsion. Wankel engines are redesigned for a use in UAV propulsion as hybrid power generating units.

Jet type engines are being used in large scale UAV's. The propulsion in the jet type engine is created by discharging liquid fuel combustion products with a high rapidity, inducing the thrust, which acts as a pushing power for a UAV.

Rocket engines are powered by liquid or solid fuels. As a result of burning fuels the propulsion power is obtained. This type of engines has a limitation for using in UAV propulsion, as the there is no mechanism of thrust power control. There is no option to shut down the engines before all fuel is burned.

Jet engine with a compressor has different stages of rotating vanes. Air in the engine enters each stage and each stage incrementally compresses the air. The flow path the air takes gradually reduces in area as it makes its way to latter stages. At the end of the compressor is a diffuser that slows the airstream down as well as further increases its static pressure.

Turboprop or turbofan engine is a turbine engine that drives an aircraft propeller or a turbofan incased in enclosure. Some of the power generated by the turbine is used to drive the compressor, while the rest is transmitted through the reduction gears to drive the propeller or a turbofan. The main difference from a turbojet engine, is that the engine's exhaust gases do not contain enough energy to create powerful thrust, that is why almost all of the engine's power is used to drive the propeller or a turbofan.

Electric thrust motors are being widely used to perform take-off, flight, positioning and landing of an UAV. A fixed wing UAV can be powered even with one electric motor, as for performing its take-off, flight and landing, controlled flight surfaces are used. A generally called "copter" UAV can be powered minimum with three thrust engines in order to perform take-off, flight, positioning and landing procedures. Positioning of the copter is realized by varying thrust power of the electric motors and maintaining the position and flight path of the UAV.

Brushed direct current (DC) electric motor can be used as a thrust motors for a tiny copter UAV. It can also power a fixed wing UAV, as it does not need to produce the lifting force due to airfoil type wing presence. To operate a DC motor there is no need to use complicated electronic speed controller circuits, they can be powered by DC current or controlled using pulse width modulation.

Brushless direct current motors (BLDC) are advanced electric motors widely used in general purpose electrically powered small UAV's. The main advantage of the motor are:

- Elimination of brushes, commutator and slip rings makes the design compact and robust;
- Simple, light weight and lossless rotor construction lead to low inertia and high efficiency;
- Low rotor inertia leads to quick dynamic response;
- High efficiency allows a reduction in frame size of the machine;
- High life cycle, in special cases more than 30.000 hours;
- Motor windings are a part of the fixed stator, that is why no moving electric parts and mechanical commutation is present;
- High reliability, as the bearings are the only part which take friction force.

BLDC motor consists of the permanent magnets rotating around the fixed stator with windings (Figure 3). Power to the stator windings is controlled with the electronic speed regulator circuit, which also senses the rotation speed and direction of the rotor. For the control of the motor speed, high current pulse width modulation is used, as a result, stator windings are energized at a different fraction of time but at a constant frequency.

Due to motor's weight, acceleration momentum and the lack of mechanical thrust control possibilities, internal combustion engines are not used on copter type UAV's. Up to date there is no mass produced solution for using an internal combustion engines in recreational type copter UAV's. The majority of recreational copter type UAV's are powered by electrically powered thrust power plant. Hybrid internal combustion engines, as electric energy generators, are likely to be the only internal combustion engines, which could be used in copter type UAV's together with the BLDC electric thrust motors.

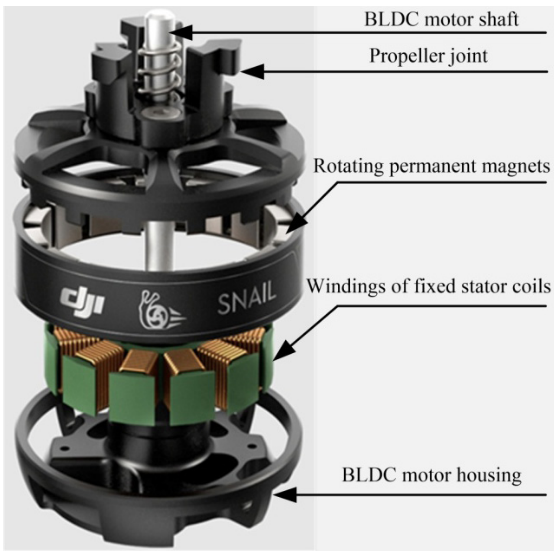

Figure 3. Main components of a BLDC thrust motor widely used in small UAV's (DJI Inc., 2019)

3. Common methods for UAV detection

There is an increasing number of different methods for solving UAV detection task. Each method differs in reliability, range, working conditions, accuracy and many more parameters. Main escalated and highly developing methods for UAV detection are:

– Acoustic signal footprint analysis

Microphone or microphone array receives an acoustic signal of UAV thrust motors, which in real time is analyzed and compared to the known UAV signal pattern. If signal patterns match, a UAV is detected.

– Optical footprint analysis

Single video camera or camera array is used to capture surrounding image. Image data is processed real time for flight path signature recognition.

– Heat signature analysis

Thermal camera or camera array is used to capture the surrounding image. Image data is processed real time for flight path signature recognition.

– Radar signature analysis

UAV is detected by the presence of their radar signature, which is generated when the UAV body encounters RF pulses emitted by the detection element. Signal, reflected from UAV is processed in real time for flight path detection.

– Radio communication

Radio frequency spectrum is received and analyzed in real time for modulation, video, telemetry and control data decoding. Known communication data packets are decoded and valuable data retrieved.

– Combined methods

Any of more than one detection methods combined, are used to increase accuracy, fail proof, stability, positioning and range for UAV detection.

4. Features of common UAV detection methods

– Acoustic signal signature analysis

Advantages:

Can be used in conjunction with many other UAV detection methods. Effectively increases accuracy of an optical detection used in combination (Liu et al., 2017). Easy to install a microphone array for securing perimeters or buildings (Pechan & Sescu, 2015; Sinibaldi & Marino, 2013). Cost effective system and installation.

Disadvantages:

Due to noise interference, not suitable for urban areas, stadium safety, mass events, airports or near any noise sources. Rain, wind and noise can influence reliability of detection. No object tracking capability.

– Optical signature analysis

Advantages:

Instant and accurate object tracking capability. Can be used in conjunction with many other detection methods. Capability for artificial intelligence interaction (Chen et al., 2018).

Disadvantages:

Under mist, fog, rain, snow and low light conditions system is not effective. Infra red light does not solve the low light problems. Gliding birds are difficult to recognize from flying UAV, they do generate false alarms.

– Heat signature analysis

Advantages:

Can be used in conjunction with many other UAV detection methods for increasing reliability.

Disadvantages:

Detection accuracy is highly dependent on weather conditions. Birds do emit thermal signature, which generate false UAV detection alarms. UAV thermal shielding and ventilation can be used as countermeasures for thermal signature detection.

– Radar signature analysis

Advantages:

High range of detection. Possible use of passive radar, when other source of transmitted signals are used (ex. TV broadcasting signal). Finding large winged drones is a task that can be performed with traditional radar products (Eriksson, 2018).

Disadvantages:

Active RF emitting system, UAV's can be programmed to overfly detection area, or fly near the surface. Small UAV's made of special material and shape are hard to detect. Small birds and UAV's are hard to differ. Not suitable in urban areas due to radiation influence on health and building shielding (Hinostroza et al., 2018). Equipment and operation prices are high.

– RF communication signature analysis

Advantages:

Software defined radio (SDR) is taking place together with the artificial intelligence for better adoption of reception in urban areas. High altitude moving UAV communication source can be used as a future detection system development with object tracking capabilities, enabling detection of swarm UAV's (Ezuma et al., 2019).

Disadvantages:

Early detection methods were used only for communication detection in a known frequency range. UAV control data frequencies tend to be of a small power, can be used in public frequency range WI-FI, GSM, DVB or any other, where their detection in an urban area will nearly be impossible. Only pre stored sample data packet recognition was available, while newer UAV models in such systems were not detected if not uploaded to the system. Evolution of UAV autopilots, makes it possible to complete their preprogrammed flight mission in full radio silence, without any RF transmission.

– Combined detection methods

Advantages:

Any known methods combined together by integrating a variety of different sensor types in order to provide a more reliable detection capability can be used.

Audio assisted video camera array show a significant increase in detection reliability used together (Liu et al., 2017).

Table 1. UAV detection system technology comparison

UAV Detection System	UAV detection technology				Functionality		
	Radar	Audio	Video	RF	Detection	Allocation	Defense
ADS-ZIU	No	Yes	Yes	Yes	Yes	Yes	Yes
Dedrone	No	Yes	Yes	Yes	Yes	No	Yes
Ardronis	No	No	No	Yes	Yes	Yes	No
Drone Shield	Yes	Yes	Yes	Yes	Yes	No	Yes
Falcon Shield	Yes	No	Yes	Yes	Yes	Yes	Yes
AUDS	Yes	No	Yes	No	Yes	Yes	Yes
Drone Detector	No	Yes	No	Yes	Yes	No	No
Orelia Drone Dtector	No	Yes	No	No	Yes	No	No
Aronia AARTOS	Yes	No	Yes	Yes	Yes	Yes	Yes

Disadvantages:

Complicated interoperation between different UAV detection systems from different manufacturer's. There is no common interfacing standard for connection of several systems from different manufacturers.

Several common widely used passive and active UAV detection system's functionalities are compared in the Table 1. As can be seen from the table, each manufacturer of the UAV detection system has different UAV detection capabilities. There is a UAV detection system manufacturer, which includes all common UAV detection methods in one serially manufactured system. System integrates radar, video, audio and RF UAV detection technologies for improvement of detection reliability.

Using several types of different UAV detection sensors and technologies minimizes false alarm possibility for UAV detection and guarantees extremely flexible system adaptation capabilities.

5. Advantages of UAV thrust power plant detection

Analyzing history and perspective of small UAV structure development, it is obvious, that the two main components – energy source and thrust power plant are mandatory for UAV flight operation. Many other UAV operation components are developing rapidly and quickly changing to obsolete. The most frequent thrust power plant of a serially produced small UAV, is electrically powered BLDC motor. Electrically powered UAV's, due to their high motor efficiency and dense energy storage capabilities can be produced in small size and weight, which makes them hardly detectable using common UAV detection methods.

UAV's are already capable to perform a fully autonomous flights, without the need of radio communication and GPS navigation. They are easily programmed to overfly any active RF emitting radar detection system and complete the preprogrammed mission in full radio silence mode.

Due to rapidly increasing demand on payload, improving technologies of lightweight battery energy storage, UAV manufacturers are racing in between to increase maximum UAV payload mass with increase of thrust motor power. Higher thrust power of electric motors, require more powerful switching capabilities for the electric motor control, what also increases the emitted electromagnetic interference signature of electrically powered UAV (Blažek, 2015; Lipovský et al., 2018). Electromagnetic interference signature, will be increasing with increase of maximum payload of any electrically powered UAV. It is just a matter of time, when the increased payload of any electrically powered UAV will result in a noticeable electromagnetic interference for its reception.

Discussions and conclusions

UAV thrust engine technology development tendency clearly indicate, that vast majority of small recreational types of UAV's, which are mass produced, are powered electrically. This leaves a very tiny space for a mass produced small UAV's powered by any type of internal combustion engines. Because of lack of electromechanical control mechanisms for copter type small UAV positioning, high thrust inertia, direct usage of internal combustion engines used for small UAV propulsion is not developing, with the exception of a fixed wing UAV's with a high capacity of payload.

The fast-growing demand on UAV payload, increases the overall power of thrust engines used in small UAV's. The fast developing lightweight electrical energy storage solutions allow UAV manufacturer's to compete in achieving the maximum payload and flight endurance on any mass produced UAV. Hybrid solar, petrol-electric energy plants are taking the development race increasing UAV flight performance characteristics, while thrust engine development, due to its performance, weight and control capabilities is completely stuck on electrical energy source.

Using of fast developing artificial intelligence show a great signs of reliability and range improvement in drone detection systems development.

Present passive UAV detection technology development trends, tend to put all attention to low power RF communication detection methods. It should be noted, that, due to the highly improved autonomous flight control capabilities, UAV's can perform remote flight missions in complete radio silence, without the use of any type of radio communications or overfly zones where active radar detection is observed. RF spectrum signature analysis method are hardly effective in the highly populated urban areas, where radio communication channels are intensive and UAV can be programmed to use communication frequencies in any WI-FI, GSM, DVB-T or any other highly busy and hardly discoverable frequency range.

Early detection systems had only a variation of several types of detection methods for getting better results of UAV detection and miss alarm. At present most of UAV detection systems tend to use artificial intelligence and adapt to the environment which is monitored.

Increase in technological development for autonomous, radio silence flights makes covert low terrain flights possible. There is no widely available instruments ready to resist "kamikaze drone" attacks during mass event organization or protecting our national airports and no-flight zones. These circumstances are pushing to return to the essence of UAV flight, and to eliminate all the features without which UAV flight would be not possible. One of mandatory small copter UAV flight components is electric thrust engines and their control peculiarities during take-off, positioning and landing.

Analyzing rapidly increasing demand for UAV's payload and flight endurance, UAV manufacturers tend to compete in developing high power electric BLDC motors, innovative electric energy sources and high power BLDC motor speed regulators. The usage of these high power components increase the emitted electromagnetic interference signature of electrically powered UAV. Signature of electromagnetic interference will be increasing with increase of maximum payload of electrically powered UAV. It is just a matter of time, when the increasing payload of any electrically powered UAV will result in a noticeable electromagnetic interference signature for its reliable reception and detection.

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MODERNŪS BEPILOČIŲ ORLAIVIŲ APTIKIMO METODAI

T. Jačionis

Santrauka

Bepiločiai orlaiviai (BO) tapo XXI a. fenomenu. Jie plačiai naudojami policijos, gelbėjimo tarnybų, pasitelkiami kariuomenės poreikiams, tapo geodezijos, žemės ūkio specialistų, filmų kūrėjų ir kitų sričių entuziastų kasdieniu įrankiu. Deja, kasdien dažnėjant bepiločių orlaivių piktavališko naudojimo atvejams, sparčiai didėjant įrangos prieinamumui ir jos autonomiškumui, aptikti bepiločius orlaivius tampa sudėtingu technologiniu ir saugumo užtikrinimo iššūkiu. Vertinant bepiločių orlaivių valdymo galimybes pasitelkus dirbtinį intelektą, artimiausioje ateityje bepiločių orlaivių skrydžiai bus galimi be radijo ryšio palaikymo ar klasikinės navigacijos priemonių. Tobulėjančios autonominio išmanaus skrydžio valdymo technologijos palieka minimalias galimybes aptikti bepiločio orlaivio autonominius skrydžius, ypač kai to reikia visuomenės saugumui ar valstybės strateginių objektų apsaugai užtikrinti.

Šiame straipsnyje apžvelgiami pagrindinės bepiločių orlaivių traukos jėgainės ir energijos šaltiniai. Analizuojami populiariausi bepiločių orlaivių atpažinimo metodai, jų privalumai ir trūkumai. Atkreipiamas dėmesys į skirtingų bepiločių orlaivių aptikimo metodų taikymo galimybes ir jų apribojimus. Išvadose apibendrinamos bepiločių orlaivių aptikimo technologijų vystymosi tendencijos, artimiausi iššūkiai ir teikiamos įžvalgos moderniems bepiločių orlaivių aptikimo metodams.

Reikšminiai žodžiai: bepiločių orlaivių (BO) aptikimas, atpažinimas, UAV, C-UAS.