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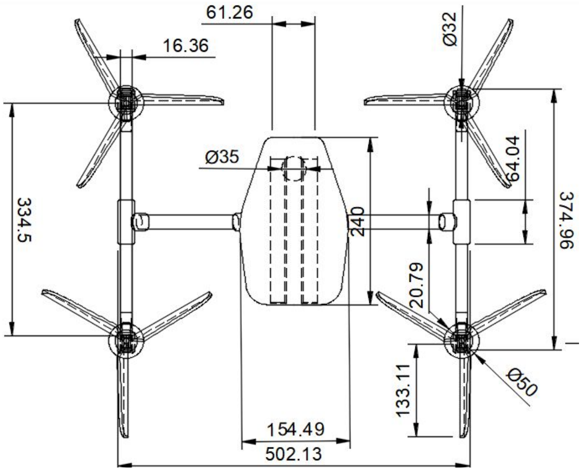
Introduction

To fulfill the brief, we propose two concepts which work together to exploit recent developments in the commercial aerospace and communication sectors. We have developed a lightweight, compact autonomous drone, to be operated in a 'swarm' of 14 in an attempt to significantly enhance the RAF's reconnaissance capabilities. The operation of these drones (referred to as HIVE drones) in a swarm will maximise opportunities for data collection, increasing the probability of success of later missions. To facilitate the use of the swarm drones, we have also developed a flight-data analysis system (referred to as F-DAS) with the aim of intelligently processing and analysing the data retrieved by the swarm to make actionable information available as soon as possible after collection.

In recent times, manned aircraft have increasingly become a financial burden on the RAF: an investigation conducted by The Times reported that the total unit cost of Lockheed Martin's F-35B Lightning II Joint Strike Fighter may reach £150 million[1]. By contrast, our swarm drones would be inexpensive to manufacture, maintain and operate across the globe. This, alongside the vulnerability of larger drones (such as the REAPER) to fighter jets and air defence systems, was a key factor in our decision to explore the commercial drone sector. With the recent surge of commercially-available drones, many in smaller, more nimble frames, we are entering the golden age of UAVs (unmanned aerial vehicles). We believe that the RAF, in order to remain at the forefront of military technology, should further its information-gathering capabilities through the use of smaller-scale autonomous surveillance.



HIVE drone design

1. Propulsion system!

Each drone has four independent bladed rotors, which enable three-axis flight. In order to maintain a net angular momentum of zero during vertical motion and stationary flight, one pair of rotors (across the drone's lead diagonal) rotate clockwise, and the second pair rotate counter-clockwise. All four rotors are driven by individual brushless inrunner DC motors with neodymium magnet cores. Brushless DC (BLDC) motors have a high efficiency and power density, and have no voltage drop across brushes (a downside of using brushed DC motors). Inrunner motors, which use fixed coils mounted to the outer casing and magnets on the drive shaft, were chosen because of the greater stability they afford. Moreover, their low inertia compared to outrunner motors enables rapid acceleration and deceleration. We suggest a relatively low motor KV rating of 1200 rpm/volt, which will ensure greater stability during flight, especially with the larger propellers that we intend to use. As is standard in commercial quadcopters, each drone will contain a digital flight controller and four electronic speed controllers (ESUs) to manage power distribution to each of the four motors. The flight controller is responsible for processing information generated by the inertial measurement unit (which contains an accelerometer, gyroscope and magnetometer). This allows the flight controller to make adjustments to the position and heading of the drone dynamically.

2. Takeoff, landing and cruising at altitude

The drones utilise a VTOL (vertical takeoff and landing) system, allowing them to enter flight on rough, uneven terrain, in environments where space is not available for a runway-based takeoff. HIVE drones can also hover before landing, which enables them to land on moving platforms (and vehicles) by matching their speed to the target prior to setting down. On the base of each motor, there is a landing leg that ensures greater stability for HIVE drones when landing and taking off. We have developed the base of these legs so that they cover a wider area: this is to reduce the pressure on a landing surface, enabling the drone to land in unstable terrain (such as sand dunes). During flight, the highly agile drones can control their velocity in all three axes of flight, allowing them to navigate complex terrain, including buildings and other structures. In terms of navigation, a general flight route should be pre-programmed before launch, taking into account the maximum range and power requirements for a round trip. Due to their small form-factors and their aerodynamically-designed central bodies, HIVE drones experience minimal drag. We expect the cruising speed

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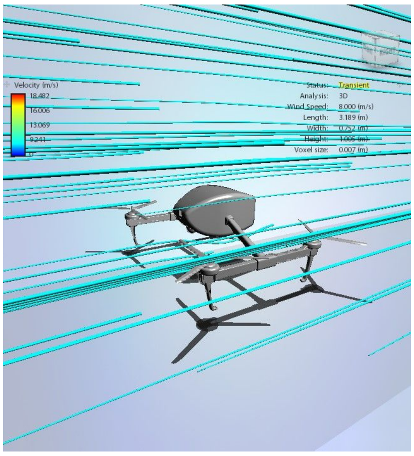
[1] Press Association (2017) *Ministry of Defence facing 'hundreds of millions in hidden costs' for new fighter jets* [online]. Telegraph Media Group Limited. Available from: https://www.telegraph.co.uk/news/2017/07/17/ministry-defence-facing-hundreds-millions-hidden-costs-new-fighter/ [last accessed 21st May, 2018].

to be about 12 ms^{-1} (about 27 mph, 43 kph) which is on the lower end of typical commercial drone velocities given HIVE's greater size and weight. The *DJI Mavic Pro*, a commercially-available drone which is smaller and lighter to HIVE drones, has a top speed of 65 kph [2] (about 40 mph). HIVE drones will usually operate at an altitude of 60 meters.

3. Central body and aerodynamics!

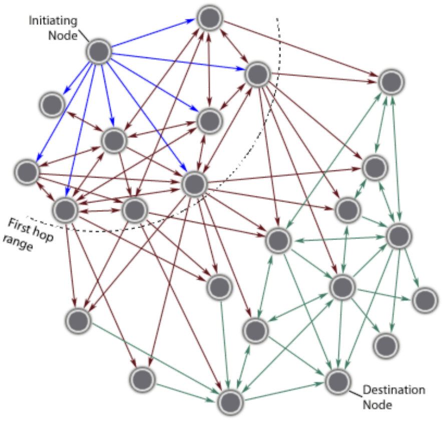


The central body has been developed to reduce drag by maximising laminar flow around it, and reducing any turbulent flow at the front and rear of the shell. Drag has been reduced by rounding off the edges of the shell and curving the front face, as demonstrated in the air flow diagram to the right: the drone experiences minimal drag at a wind speed of 8ms^{-1}. The central body will contain all the necessary hardware for the drone to function, including the flight controller, Arduino-based secondary controller, power source and PCB. As seen in the images above, each drone is equipped with a LiDAR (light detection and ranging) system on the curved base of the shell and above this, there are 2 small air vents to ensure that all internal components do not overheat, enabling the drone to fully function in warmer climates.

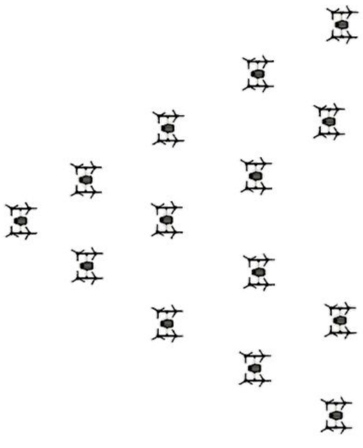
4. Swarm communication and behaviour

HIVE drones will fly in a swarm, arranged in a V formation. In the standard proposed arrangement, 14 drones will fly in a V formation (as illustrated in diagram below and to the right). In the swarm, the drones will be spaced out with roughly 3 meters between each drone. Depending on the mission, the number of drones in a swarm may vary greatly.

HIVE drones utilise modulated ultrasound to communicate within the swarm. Drones can communicate in both directions at any pre-assigned frequency in the ultrasound range (above 20 kHz, the limit of human hearing). The greatest advantage to using ultrasonic communication is that, if the carrier frequency is varied often, the signals are near-impossible to detect without high-sensitivity directional microphones, making them effectively impossible to jam. For inter-drone communication, we propose that the swarm utilises a 'flooding' technique, as opposed to a traditional 'routing' method. Ultrasound generation is more energy efficient than RF transmission, and equally does not interfere if unique frequencies are used, making ultrasound appropriate for flooding. The flooding mechanism is illustrated in the diagram[3] to the left, where each drone is represented as a node. Flooding has a number of advantages over routing, the most important of which is redundancy: in the event of one or more members of the swarm being damaged or destroyed, communication between other drones is uninterrupted. Secondly, routing requires that routing tables and additional overhead be transmitted alongside any message, which would require a more complex transceiver and introduce additional points of failure. Flooding also reduces the effects of local interference and obstructions, making it a more robust mechanism for transferring information. In addition, simpler flooding controllers consume less power and less real estate on a PCB, increasing efficiency. Robust communication between drones is essential to maintaining the swarm - the drones must be able to propagate information about nearby obstacles and other relevant sensor data quickly. During flight, HIVE drones will regularly scan their surroundings for oncoming obstacles using active SONAR in the ultrasound frequency range. In the event of object detection, the drone will 'flood' information about the obstacle to all other drones in the swarm, causing the pack to split around and avoid the obstacle.



The advantage of the swarm is two-fold. Firstly, it vastly increases the probability of mission success. Simulations run by the United States Navy to investigate the threat of swarm drones to naval vessels equipped with the Aegis air defense system demonstrated the overwhelming strength of swarms. The results showed that if 8 drones attack a vessel, on average, 3 are able to penetrate its defenses[4]. Given that we propose a swarm of 14 drones, it is plausible to imagine that on average, 5 will bypass some of the most advanced air-defence systems. For the most part, HIVE drones will rarely encounter such advanced air defense systems and hence, far fewer drones will be shot down on a standard mission (given that the primary function of HIVE drones is reconnaissance). The second advantage of using a swarm is that information gathering potential for any mission is maximised. With each drone carrying a total of 16 environment sensor payloads, there are 224 sensors in a swarm available for data collection. By individually controlling each drone at the mission staging site, the 16 payloads can be dropped at different locations, ensuring that drones maximise their coverage of any location to generate the most useful multi-variable map.



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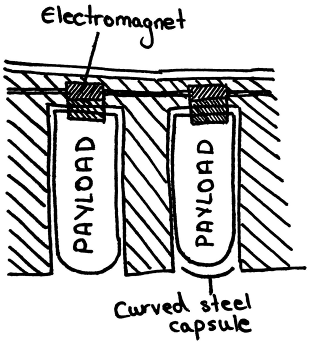
[2] *DJI Mavic Pro specifications* [online]. DJI. Available from: https://www.dji.com/mavic/info#specs [last accessed 28th May, 2018].

[3] Image credited to Aaron Sempf (2015), *Swarm Communication* [online]. Medium Publishing. Available from: https://medium.com/cælus-concept/swarm-communication-33cffc47db6d [last accessed 23rd May, 2018].

[4] Hambling, D (2016), *U.S. Navy Plans to Fly First Drone Swarm This Summer* [online]. Military Advantage. Available from: https://www.military.com/defensetech/2016/01/04/u-s-navy-plans-to-fly-first-drone-swarm-this-summer [last accessed 28th May, 2018].

5. Payload system

Every drone is equipped with a remote-releasing payload system, using a circuit-controlled electromagnetic locking system. These payloads are held magnetically in 2 rectangular 'magazines' (each of which can contain up to 8 payloads, 4 on each side of the central arm), which slide into the hollow casings that join the bow and stern motors on the left and right sides of each drone. This magazine can be quickly exchanged with another at base once emptied, using a magazine-style latching mechanism. By simply removing and replacing the magazine in the hollow casing, the payloads can be quickly reloaded or alternatively, the type of payload may be changed. Fewer payloads can be carried to reduce drone weight and increase maximum range. As seen in the diagram below, the payloads are held from the top using a low-profile electromagnet made using low-gauge magnet wire around a thin steel core. The electromagnet will operate at a very low wattage (around 1 watt) to minimize energy use while engaged. Payloads are locked into position until the circuit powering the electromagnet is broken and the payloads are released under gravity (the lower surface of the hollow casing and magazine is open).



HIVE drones are very versatile: they can be equipped with a range of payloads, varying from sensors to small plastic explosives. The first payload we have developed is the environment sensor payload, which when deployed relays information about surface vibrations, nearby electromagnetic signals and sound. When these sensors are deployed en masse over a target area, the data returned to the drones can be processed using F-DAS to create a multi-variable map, revealing hotspots of human or electronic signal activity. In a later section on F-DAS, we will outline the data processing methods the system employs. The data collected by the environment sensor payloads will be routed back to a parent drone in the vicinity using microwaves on a unique frequency band, which will then forward the data to a local F-DAS installation via satellite uplink.

The payloads themselves will contain a small lithium-polymer cell with a capacity on the order of 100mAh at a nominal voltage of 3.7V powering all the various components. They will also contain a printed circuit board, low power GPS/GLONASS chipset and RF transmitter conforming to the Bluetooth 4.0 Low Energy standard, allowing transmission in the 2.4-2.6MHz frequency range with a power consumption below 100mW. This ensures that the sensors can communicate with their parent drones up to 100 meters away (with an unobstructed line of sight). Given that HIVE drones operate at an altitude of 60 meters, communication between the parent drone and payload can always be maintained. The transceiver power usage can be reduced if the required range is less, which can double sensor uptime. For data collection, the payload contains a piezoelectric vibration sensor, which can be used to locate nearby personnel, machinery and vehicles. It also contains a RF signal detector based on the IEEE 802.15.4 standard, which when combined with triangulation using other nearby payloads, can be used to identify EM radiation sources, including mobile phones and personal area networks (Wi-Fi activity). In total, these components will consume power on the order of 800 mW, which corresponds to a payload communication uptime of up to 30 minutes with a 100mAh cell operating at 3.7V.

6. Sensors and data transmission

To enable HIVE drones to operate autonomously, gather information and travel in a swarm, they must be equipped with a number of different sensors and data transmission components. Firstly, each drone must have a GPS/GLONASS chipset to be used in tandem with the flight controller, to allow the drone to follow pre-assigned waypoints to a destination and report its position to F-DAS. A programmable Arduino-based secondary controller will be used to manage data collection and transmission, regularly transmitting relevant data to F-DAS. This might include positional data, heading, altitude and speed information collected from the IMU, or information about the swarm itself collected by inter-drone ultrasound. In addition, the controller will be responsible for relaying information gathered from environment sensor payloads back to F-DAS. All communication with F-DAS will be via satellite, using a microwave transceiver which operates on the International Telecommunication Union (ITU)'s X band. Satellite-to-drone communication will be in the 7250-7750 MHz frequency band, and drone-to-satellite in the 7900-8400 MHz band, in accordance with the NATO Joint Civil/Military Frequency Agreement[5]. An ultrasound transceiver will manage active SONAR to detect nearby objects and maintain information about the position of nearby drones for use by the flight controller to adjust course if necessary. It will also manage the inter-drone flooding system when key messages need to be communicated across the swarm. A Bluetooth 4.0 Low Energy RF receiver will be used to collect data from transmitting payloads when released. Finally, each drone will have a LiDAR (light detection and ranging) sensor on its underside to measure distance to the ground. By measuring reflected laser pulses and finding differences in laser return times and wavelengths, high-resolution 3D representations of terrain can be created. LiDAR has a number of advantages over conventional and infrared cameras, chief of which is its ability to calculate depth, which allows the relative heights of ground-based structures and other objects to be directly measured (even at night). Furthermore, by avoiding the use of cameras, HIVE drones further reduce their energy consumption: the recording and transmission of data using cameras consumes large amounts of energy.

7. Power and energy consumption

In any drone, the largest energy consumption comes from the motors. We expect that each motor will draw a current of about 6A at maximum RPM, giving a maximum total current draw from the motors of 24A at their greatest speed. The remainder of the

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[5] *Official NATO Joint Civil and Military Frequency Agreement (NJFA)* (2002) [online]. Available from: http://www.akos-rs.si/files/Zakonodaja/Direktive_in_priporocila/mednarodni_sporazumi/CM-Ag.pdf (see page 9 of enclosure 1) [last accessed 28th May, 2018].

communication and sensor equipment is unlikely to draw more than 2A in total, and the electromagnetic locking system another 2A. This gives a total maximum current draw of 28A. We suggest that a lithium-polymer cell with a capacity of about 20000mAh is used in each drone, with a C-rating of 10C. This gives a maximum output current of 20Ah multiplied by 10, giving a maximum current of 200A, which is much greater than the current draw requirements of the drone. These batteries are not exotic, and are commercially available owing to recent developments in the hobbyist drone sector, making them relatively inexpensive. We estimate that, in total, the power consumption of all components will be on the order of 620 watts (about 28A multiplied by a nominal voltage of 22.2V for a typical battery with 6 cells), where the vast majority of power use is a result of the motors. 20000mAh at 22.2V is 444 watt-hours, giving an average flight time of 43 minutes.

8. Cost, materials and feasibility

Commercially-available drones of a similar size and weight to HIVE are typically priced anywhere from £800 to £1000. The *DJI Mavic Pro*, which has a smaller form factor than HIVE, retails for £899[6], and includes an expensive 4K camera which is unnecessary in our design. The low cost of HIVE drones ensures that the development of HIVE swarms is a feasible proposal. When compared to the $12.5 million[7] price tag of the MQ-9A REAPER, the cost to manufacture, maintain and operate HIVE swarms is almost non-existent. We would minimize the cost of HIVE drones by utilising the latest 3D printing technology to print as many parts as possible. For instance, we propose that the drones' arms, along with the rectangular magazines and the hollow casings, are 3D printed from ABS plastic. The central body will be made using G10, a high-pressure fiberglass laminate. Despite being more expensive that plastic, G10 will be used for its extremely good electrical insulating properties and its high strength. Furthermore, G10 retains these properties under moist or humid conditions, enabling HIVE drones to operate in various environments. Moreover, G10 has the advantage that it does not interfere with the transmission of ultrasounds waves, whilst carbon fibre does. For the propellers, we suggest carbon fibre is used instead of plastic. Although carbon fibre propellers are more expensive, the advantages of carbon fibre vastly outweigh this drawback. Firstly, due to the stiffness of carbon fibre, the propellers will produce less vibration, reducing the amount of sound and heat generated. This makes the energy conversion process more efficient, so less energy is wasted and power is better conserved. Furthermore, quieter drones will make it harder for the swarm to be heard, further protecting them from detection. Secondly, carbon fibre is significantly stronger than plastic, making the propellers more durable and long-lasting. A further benefit of carbon fibre is the fact that it is lighter than plastic: lightweight propellers have less inertia. As a result, control of HIVE drones will be more responsive.

9. Proposed RAF use

Our proposal for HIVE drones was developed in an attempt to redefine the RAF's reconnaissance capabilities. The RAF currently employs 6 aircraft for ISTAR (intelligence, surveillance, target acquisition, and reconnaissance). Whilst these aircraft have their advantages, all 6 aircraft are relatively large, with the smallest being the MQ-9A REAPER (length: 10.97m)[8]. The size of the REAPER, and other surveillance aircraft, makes them vulnerable to both detection from RADAR and anti-aircraft weaponry. Whilst REAPERs have been successfully used in Afghanistan and Iraq, in neither environment were the REAPERs challenged by advanced air defence systems[9]. In contrast, the swarm nature of HIVE drones adds a crucial extra dimension to the RAF's ISTAR capabilities. HIVE drones will be able to gather information in hostile environments, much safer from air defence systems and RADAR detection due to their small form-factors. To further protect the swarm from attack, we suggest these further measures. Firstly, to protect the drone from oncoming weapon fire, evasive flight patterns, which can be generated on-the-fly using the onboard flight computer (or remotely uploaded from F-DAS to reduce power consumption), can be employed. Flight patterns can be stochastic (i.e. randomly generated) to make the drones more difficult to target. Secondly, HIVE drones could be later developed so that the rotors are encased in an upwards facing cone (not shown on earlier diagrams). This cone would funnel blade noise upwards and away from any ground-based microphones. FInally, we considered ways of protecting the swarm from ground-based jammers which might interfere with both inter-drone communication and communication between the swarm and F-DAS. To tackle this threat, inter-drone communication will solely use ultrasound, which it is extremely difficult to jam.

HIVE drones can either be launched from the ground or be dropped by planes closer to the target. With a maximum cruising velocity of 12 ms^{-1} (about 27 mph, 43 kph) and an expected flight time of roughly 43 minutes, the maximum range of HIVE drones for a round trip would be 36 km (before taking into account takeoff and landing, as well as the necessary amount of stationary hovering at a mission staging area to drop payloads and collect data). With a combined landing and takeoff time of roughly 2 minutes, and a minimum 10 minutes for collection of data, HIVE drones will travel for a maximum of 31 minutes during a mission. At a velocity of 12 ms^{-1}, the swarm can be expected to cover a maximum of 22.3 km, allowing the swarm to be launched over 11 km from their target. HIVE missions will primarily centre around gathering information prior to an offensives on a target, such as an army base or a city under occupation. A swarm of HIVE drone could also carry out offensive missions, if equipped with small plastic explosives as payloads. The drone has been designed for use in hot, arid climates as well as temperate areas: the air vents in the front of the shell provide plenty of ventilation. Furthermore, the use of G10 for the central body ensures HIVE drones can function in humid or moist environments. However, the drones may not operate effectively in heavy rain or snow due to their small stature. In dry regions such

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[6] *DJI Mavic Pro* [online]. DJI. Available from: https://store.dji.com/product/mavic-pro [last accessed 28th May, 2018].

[7] Unattributed (2012) *Unnamed article* [online]. Time Magazine. Available from: http://nation.time.com/2012/11/06/12548710-60/ [last accessed 29th May, 2018].

[8] *MQ-9A REAPER* [online]. Royal Air Force under UK Crown Copyright. Available from: https://www.raf.mod.uk/aircraft/mq-9a-reaper/ [last accessed 29th May, 2018].

[9] Brooke-Holland, L (2015), *Overview of military drones used by the UK Armed Forces* [online]. Available from: http://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN06493 (page 29) [last accessed 30th May, 2018].