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State of Technology Review of Civilian UAVs

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Abstract: Background: Unmanned Aerial Vehicle (UAV) technology has exploded in recent years. Presently UAVs are beginning to be major in roads into geographical mapping, site inspection, agriculture, and search and rescue. **Methods:** This paper reviewed patents and papers worldwide related to both hard-ware and software for the construction and deployment of UAVs and is intended to provide a snapshot of currently available UAV technologies, as well as to identify recent trends and future opportunities in affiliated hardware and software. **Results:** Basic components related to self-designed units are explained (e.g. plat- form selection, autopilot control comparison and sensor selection), and current applications and research areas are discussed. Since autonomous navigation is a key technology in UAV applications, concepts about this are also explained. **Conclusions:** Both in the self-designed and commercial markets, UAV components are becoming modularized. By following a standard components list, it is no longer difficult to make a customised UAV. In this way, commercial products are becoming cheaper and more standardized in their performance. Current limitations of UAVs have also become more readily detectible. Extending the flight time, im- proving autonomous navigation abilities, and enriching the payload capacity will be the future research focus to address these limitations.

Key words: Unmanned Aerial Vehicles, Drone, Multi-rotor, Navigation, Remote Piloted Airborne Systems.

INTRODUCTION

A Unmanned Aerial Vehicle (UAV) is defined by the U.S. Federal Aviation Administration (FAA) as an aircraft flown with no pilot on board [1]. Drones, Remote Piloted Airborne Systems (RPAS) are also terms that are commonly used. UAVs were first introduced for American military usage in 1950's [2]. Such efforts continue in transport, surveillance, and combat. However, in recent years, UAVs have gained great popularity in civilian usage. Improvements in sensor and control technology have enabled UAVs to gain unprecedented prominence in a wide range of non-military applications. This is especially true for multi-rotor units because of their low cost and significant flexibility (due to their small size). Their popularity is further promoted by remote control capabilities that can reduce the aircraft operator's exposure to dangerous environments for various forms of documentation and investigation. Potential applications include search and rescue [3-5], civil engineering [6], agriculture [7-9], wildlife conservation[10-12], and infrastructure inspection [13-17], as well as transportation [18]. More use cases are shown in figure 1. According to a survey made by the Association for Unmanned Vehicle Systems International (AUVSI) on 3136 exemptions in the United States, the top three applications in UAVs industry are construction, infrastructure and agriculture (fig. 2) [19]. Notably, in many jurisdictions usage is restricted by aviation authority regulations, as opposed to commercial viability.

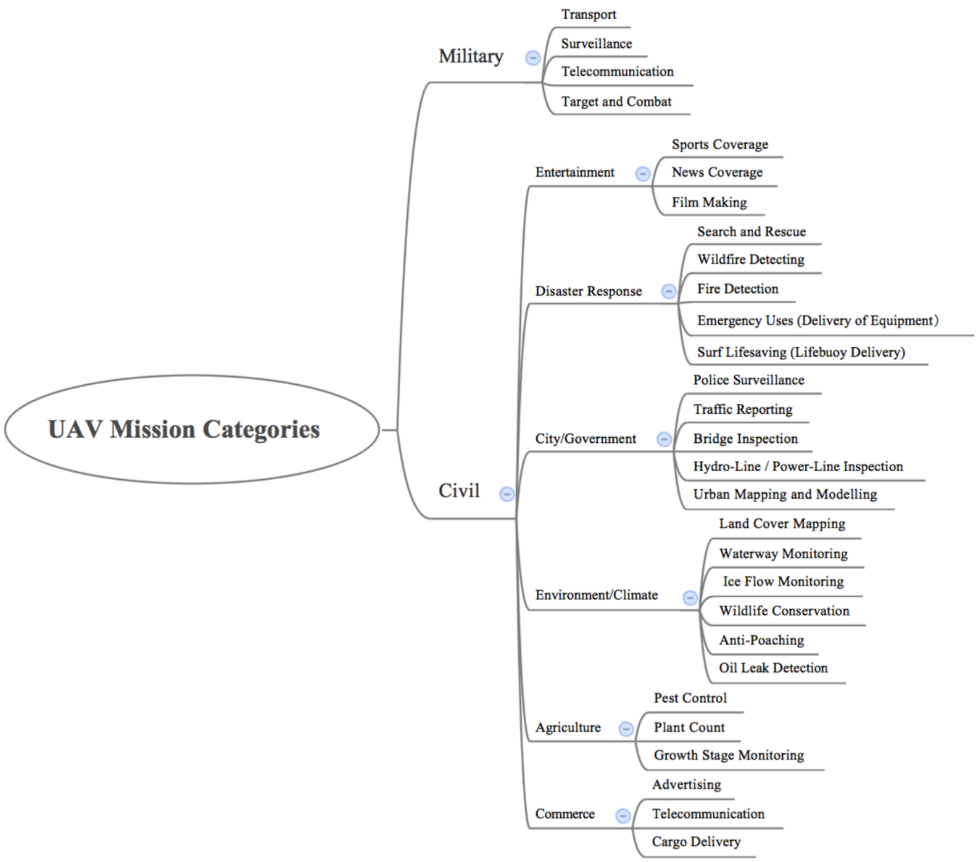


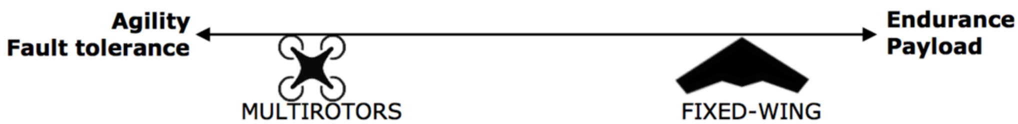
Fig. 1. UAV Usage Categories

Fig. 2. UAV application distribution based on the first 3,136 exemptions granted in the United States, as per January 20, 2016 [19]

UAV TYPES

UAVs can be classified in many ways such as usage (civilian vs. military), maximum take-off weight (MTOW), and lift style (fixed-wing vs. multi-rotor). The relative capabilities between fixed-wing and multi-rotor UAVs were recently summarized by Brien et al. [20]. According to that division, the fixed-wing UAVs are more stable and larger and have higher flying capabilities, greater payload capacity, and better endurance but at the expense of a certain level of agility and cost.

Table 1. Capabilities of fixed-wing/multi-rotors (adapted from [20])



	MULTIROTORS	FIXED-WING
POWER SOURCE	**Electric**	**Electric / Combustion**
ENDURANCE	**10'** to **50'**	**45'** to **10+ h**
PAYLOAD	up to **15 Kg**	**0,5 Kg** to **50+ Kg**
GROUND SPEED	0 (hovering) to **75 km/h**	**45 km/h** to **200+ km/h**
ALTITUDE (ceiling)	Up to **3000 m**	Up to **5000+ m**
SIZE	**6 cm** to **1,6 m** (frame diameter)	**1 m** to **20+ m** (wingspan)

UAV COMPOSITION

Amongst civilian UAVs, typical components include the following: a frame, a driving system, a power system, and a pilot system. To remotely control it and to obtain real-time video, a controller, camera, camera gimbal, and monitor are also required. Figure 3 illustrates the basic components for a camera-equipped UAV. Table 2 shows the electronic components used in a typical system.

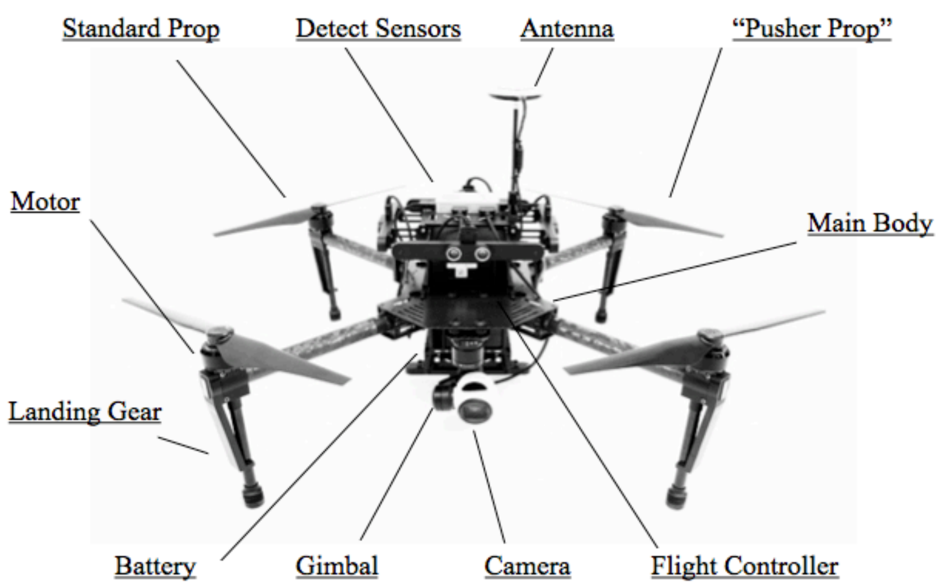
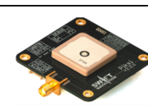
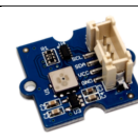
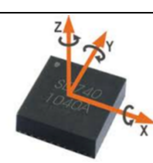
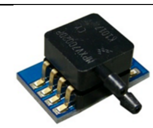
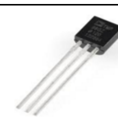


Fig. 3. Typical components of a Multi-rotor UAV (adapted from [21])

Table 2. Components

Function	Equipment	Use	Picture
Driving	Coreless Motors	Drives the prop in small multi-rotors	 [22]
	Brushless Motors	Drives the prop and controlled by the Electronic speed controller	 [23]
	Electronic speed control (ESC)	Regulates the electrical power supplied to the motors, which is managed by the flight controller	 [24]
Power	LiPo Battery	Provides energy to the driving system, pilot system, and payloads	 [25]
Control & Communi cation	Antennas	Receives commands from the ground station (receiver antenna) and sends telemetry and other data (e.g. video) from the on-board system (transmitter antenna)	 [26]
	Ground Station	Sends operator commands to the UAV and receives real-time flight data	 [27]
Autopilot	Flight Controller	Controls the power of each motor and other systems depending on the data received from the sensors, as well as the commands from the ground station; can be a commercial standard device with open software or something developed for a specific solution	 [28]
	GPS	Establishes the geographic position of the RPAS	 [29]
	Barometer	Determines the distance from the sea level	 [30]
	Inertial measurement unit （IMU）	Integrated accelerometers, gyroscopes, and magnetometers. Determines the current rate of acceleration, changes in rotational attributes and orientation drift	 [31]

Function	Equipment	Use	Picture
	Airspeed sensors	Determines the relative speed between the air and the RPAS	 [32]
	Positioning Camera	Points towards the ground to keep its position over a specific area over the ground; also records images.	 [33]
	Ultrasonic Sensors	Determines the distance from ground and various obstacles	 [34]
	Infrared Sensors	Ranges and detects static/moving obstacles	 [35]
	FPV Camera	Gives a first person view of the flight and can be used to take pictures or record video	 [36]
Payloads	HD Camera	Produces photographs; usually stabilized with a gimbal device	 [37]
	Thermography Camera	Produces thermal images	 [38]
	Laser Sensors	Generates a point cloud of the built and natural geometry	 [39]
	Gas Sensors	Detects chemical substances and concentration in the air (e.g. CO2)	 [40]
	Temperature Sensors	Determines environmental temperature	 [41]
	Radioactivity Sensors	Measures radioactivity	 [42]
	Other	Many other systems (physical and electronic) and sensors can be easily integrated	

FRAMES AND BOOMS

Frame materials are highly varied and may include wood, plastic, metal, glass, or carbon fibres. Traditional and innovative manufacturing processes, such as injection moulding, laser cutting, computerized numerical control (CNC) processing, 3D printing technology have all been applied to UAV's construction. For example, in 2013, engineers from the Advanced Manufacturing Research Centre (AMRC) at the University of Sheffield cooperated with the Boeing company to design and manufacture a fixed wing UAV constructed entirely of acrylonitrile butadiene styrene (ABS), a common plastic in 3D printing. Specifically, the application of Computational Fluid Dynamics (CFD) analysis and 3D printing technology were able to improve aerodynamic performance [43]. Specifically, CFD was used to optimise the chosen design and to assess the lift, drag, pitching moment, and other characteristics over a range of angles of incidence. The application of 3D printing technology resulted in smooth leading and trailing edges over each half-span, which was suited to the low Mach number flight regime under which the UAV would operate.

In contrast to fixed-wing UAVs, multi-rotors UAV do not have high geometric requirements for their frame design, except for the booms' number and layout (fig. 4). The layout could be of an X-shape, Y-shape, or V-shape along with the general quad-rotor, hexa-rotor, and octo-rotor arrangements. The number of booms is usually 3, 4, 6, or 8. Additionally, each boom may support one or two layers of props. More booms and more props tend to improve stability and enhance payload capabilities but at the expense of battery efficiency and, thus, flight time. More props also provide enhanced redundancy, in case of the loss of one or more rotors [44].

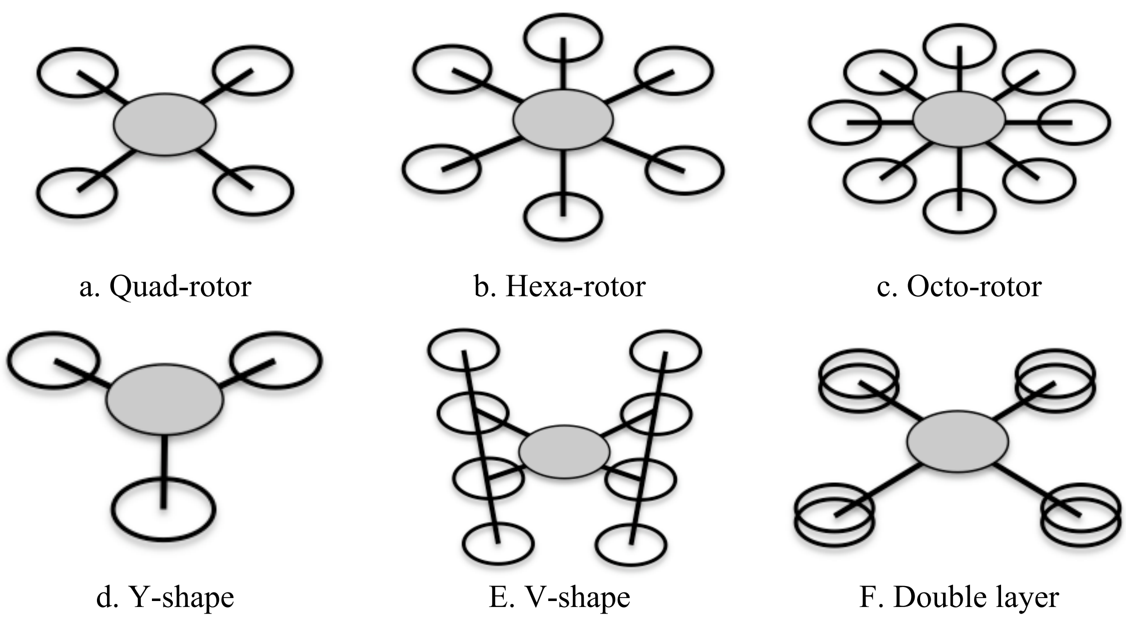


Fig. 4. Multi-rotors Layout

DRIVING SYSTEM

Electronic motors are widely used as UAV driving systems. As shown in the Table 3, coreless motors and brushless motors are favoured, because they can provide a higher rolling speed and bigger torque, as well as being more efficient and durable when compared to traditional DC motors. However, to transform DC power into AC power and control the motor speed, an electronic speed controller (ESC) must be connected with a brushless motor, which will increase the weight and system complexity.

Fuel engines and hybrid engines are also sometimes used in UAVs. A German company recently launched Yeair, the first UAV with a combustion engine. The UAV has a 60 minute flight duration and can support a 5 kg payload [45]. The American company Top flight developed the Airborg H6 1500, which has a 5000W rated (6000W peak) hybrid engine, with a 11.3 litre tank and a 16,000 mAh LiPo battery. With this, more than 2 hours of flight time can be achieved with only 1 gallon (3.8 litre) of gasoline, even with a 9 kg payload [46].

POWER SYSTEM

The power system provides energy to the driving system, pilot system, and even payloads. Fuel and LiPo batteries are the most commonly used energy sources in UAVs. However, a power cable has also been utilized to provide a constant power supply. This was introduced by the Israeli company Skysapience, as part of their HoverMaster series of UAVs to host payloads of up to 18 kg including CCD/IR cameras, radars, lasers and hyperspectral sensors. A cable serving as a power supply and wideband data link secures them (fig. 5). A similar method was also used in CyPhy's products under the following patents [47,48]. Only last year, the Canadian company Energy Or Technologies developed a proton exchange membrane (PEM) fuel cell system and with it achieved the world's longest multi-rotor UAV flight of 3 hours and 43 minutes [49].

In addition, new charging technologies are coming onto the market. They address the short battery life issue. One option is an outdoor wireless charging system developed by the German company Skysense (fig. 6). Alternatively, using solar energy is an environmentally friendly way to extend the flight time. Berry [26] patented a UAV with a wide fuselage equipped with a solar turbine and external solar film to extend flight time. An alternative approach is a charging pile combined with solar energy and wireless charging panels [50].

Fig. 5. Power cable used in HoverMaster [51]

Fig. 6. Wireless charging system [52]

CONTROL AND COMMUNICATION

To remotely control a UAV and obtain a First Person View (FPV) from the camera, a ground station is required. A typical ground control station [53] includes a management unit, a telemetry module, a user control module, a graphical user interface (GUI), and a wireless data link subsystem. The wireless data link subsystem is used for remote communication with a UAV. The telemetry module is coupled to the ground control station and is configured to download on-board data from the UAV to the ground station and is configured to upload commands from the ground station to the UAV. Control is often assisted through the use of a GUI, which includes a display module that is configured to display an FPV from the UAV's camera.

Communication frequency between the ground station and a UAV can occur at different rates. Typical ones are 5.8 GHz, 2.4 GHz, 1.2 GHz or 900 MHz. While 900 MHz has great obstacle penetration, a setting of 5.8 GHz has good range per watt and is well-suited for open areas. Most Remote Control (R/C) circles used in UAVs operate at 2.4 GHz [54]. Wi-Fi, Zigbee and 3G/4G all work around this frequency. Wi-Fi and Zigbee can be used for short distance communication (usually less than 100 m), while 3G/4G can be used in long-distance communication but with a short delay.

AUTOPILOT SYSTEM AND OPEN-SOURCE PROJECTS

The autopilot system is the brain of a UAV. A typical autopilot system includes a flight controller board, a gyroscope, an accelerometer, a barometer, a magnetometer, and a global positioning system (GPS). In the last few years, autopilot systems have greatly benefitted from open-source projects (OSPs) and online communities. The OSPs constantly optimize the autopilot system by integrating different sensors and increasing reliability and stability. This was particularly notable in 2014, when the Linux Foundation, a non-profit organization dedicated to accelerating the growth of Linux and collaborative development, announced the founding of the Dronecode Project, a common, shared open-source platform for UAVs [55]. Founding members included 3D Robotics, Baidu, Yuneek, DroneDeploy, and Intel, amongst others. Dronecode includes the APM/ArduPilot UAV software platform and associated code from 3D Robotics. It also incorporated the partner PX4 project led by Lorenz Meier from ETH [56]. Based on the PX4 and APM projects, 3D Robotics published the Pixhawk autopilot platform at the end of 2014. This portion of UAV control, especially as it matures into some form of autopilot system, is one of the most rapidly changing aspects of the technology. A sampling of available OSPs and their URLs are listed in Table 3 [57].

Table 3. Open-source Projects (adapted from [57])

Project Name	Features	URL
ArduPilot	Has a set of autopilot products including hardware, firmware, and software and is supported by the Linux Foundation DroneCode effort	http://ardupilot.com/
Openpilot	Focuses on developing two hardware platforms: the CopterControl (both Original and CC3D) and the Revolution and is an autopilot platform with a full INS unit onboard	http://www.openpilot.org
Paparazzi	Was designed for multi-unit control with autonomous flight as the primary focus and manual flying as secondary	https://wiki.paparazziuav.org
Pixhawk	Supports PX4 and APM flight stacks and is supported by the Computer Vision and Geometry Lab at ETH Zürich, as well as the Linux Foundation DroneCode effort	https://pixhawk.org
MultiWii	Is general-purpose software to control a multi-rotor RC model; first designed to control a tricopter	http://www.multiwii.com

Dronecode	Is an open source, collaborative project that brings together existing and future open source UAV projects under a non-profit structure governed by the Linux Foundation	https://www.dronecode.org/
DIY Drones	Has created the world's first "universal autopilots", ArduPilot Mega (APM) and partakes in the Pixhawk development.	diydrones.com
Erlerobotics	Is a Linux-based open source project for UAVs and robots that is combined with Robot Operating System	http://erlerobotics.com/
Robot Operating System (ROS)	Is an open-source, meta-operating system, which provides services from an operating system, hardware abstraction, low-level device control, message passing between processes, and package management	http://www.ros.org/

COMMERCIALLY AVAILABLE MULTI-ROTOR UAVS

Initially, most companies aimed at penetration in the consumer market and focused on making UAVs cheaper and more reliable. These efforts are reflected in refinement of the structural design, improvement of flight control system, and enhancement of camera resolution. In contrast, in the last two years, with the maturity of the civilian, professional UAV market, there has been a shift towards greater functionality and the development of more user-friendly devices. More specialized UAVs have been marketed for sports photography, filmmaking, sites investigation and agriculture application. In the early years, there were three well-known consumer UAV manufacturers – Parrot, SZ DJI Technology Co. (DJI), and 3D Robotics (3DR). After that, further companies entered the market, such as Yuneec, SenseFly and Ehang. According to UAVGLOBAL, there are currently 240 commercial UAV manufacturers around the world [58].

Parrot

In 2010, the French company Parrot released their first generation quadrotor, AR.Drone 1.0. It had an ultrasonic altimeter (thereby providing vertical stabilization up to 6 meters), 15-watt brushless motors, an 11.1 volt lithium polymer battery, and a forward-facing camera. With a self-generated Wi-Fi hotspot, the UAV can be remotely controlled by an iOS device and is equipped to send live video streams to mobile devices [59]. These features make it quite popular. About half million of units have been sold to date [60]. Their new product Bebop is equipped with a fish-eye lens camera that can take photos at 90 degree without loss in image quality.

DJI

In 2006, DJI was founded in China and started to design a flight control system for helicopter like UAVs. In 2013, DJI produced their first, small-sized, ready-to-fly quadrotor, the Phantom 1.0. With a built-in GPS sensor, it has a position-holding function making it useful for inspection work. The unit also comes with a GoPro Hero action camera and an adjustable-angle mount. The overall design provides significant stability in windy environments and improved remote sensing data acquisition. This product helped DJI enter the market. According to a survey from AUVSI, DJI now manufactures 65% of the platforms in the United States market [61] and

70% worldwide [62]. In the last two years, they have shifted their focus to the professional market and invested in autonomous flight system development. Their latest product, the Phantom 4 combines advanced computer vision and sensing technology and was lunched in March of 2016. The Phantom 4's obstacle sensing system features two forward-facing optical sensors that scan for obstacles and automatically directs the aircraft around any impediments [63]. Furthermore, they also designed an octocopter named MG-1 for agriculture applications, a quadrotor named Inspire for filmmaking [64] ,and a quadrotor platform named Matrice 100 for research use [65]

3DR

3D Robotics was founded in 2009 in the United State. In 2014, they introduced their first ready-to-fly, consumer products: IRIS and IRIS+. The products are distinguished by the inclusion of the Follow Me technology [66], which enables a UAV to follow a moving target and keep its camera automatically centred on it. In 2015, they lunched a more advanced model, named Solo, equipped with two on-board computers marketed for both consumer and professional aerial photography [67]. Later, as strong proponents of open source technology, 3DR announced that they would no longer produce any other legacy models except Solo and released all of the 3D printable files for the IRIS+ exclusively to the MyMiniFactory community [68]. With a 3D printed frame, users only need to purchase the electronic components from 3DR, and they can build their own IRIS+ drone.

OTHERS

In 2015, Lily Robotic introduced their Lily quadrotor, which can be launched by being thrown into the air. The waterproof body allows flying in the rain or snow, thereby making it more suitable for sports photographing [69]. In the autonomous flying areana, Intel invested $60 million in the Chinese drone-maker Yuneec who recently released their Yuneec Typhon H UAV, which is equipped with an Intel RealSense camera and an Intel CPU for obstacle detection and collision avoidance [70]. For site investment applications, with the requirement of covering a large survey area, SenseFly launched their fixed wing UAV-ebee that can cover 12 km^2 in a single flight [71]. Moreover, the move towards multiple functionality is evidenced by the German company Microdrones' md4 series drones with its wide range of remote sensing accessories including a laser scanner, thermal camera, and miniature, multiple camera arrays [72].

TYPICAL UAVS IN THE MARKET

Some typical UAV products are demonstrated in Table 2. The lower end of the market starts a bit over the $200 mark, with a lot of choices between $800 and $1,500. This level of UAV typically has 4 props with a built-in camera or an electronic gamble with a Gopro camera. This class of products rarely has extra payload capability. The upper portion of the market starts at $3000 and more commonly has 6 or 8 props with a carbon fibre, foldable frame and powerful payload expansion mounts. The payload capability can range up to 5,000g. They are usually equipped with a professional camera or multifunction cameras and a gamble. The flight time is still a bottleneck for UAVs. Especially with payloads, it is hard for most consumer-based UAVs to fly longer than 30 minutes. Flight time is largely independent of cost, but highly dependent upon payload and self weight.

Table 4 Typical Commercial Drones

Product	Company	Price	Locale	Flight Time/ Payload	Camera/ Operation Range/ Features	Image	Reference
AR Drone 2.0	Parrot	$249	France	12 min/ 100g.	Built-in 720p Cameras 200m/ Supports multiple controlling devices		[73]
Bebop 2	Parrot	$799	France	22 min/ 20g.	Stabilised 1080p Cameras 180° vision HD 2000m/		[74]
Iris+	3D Robotics	$599	US	22 min/ 400g.	GoPro Camera/ 1000m/		[75]
Solo	3D Robotics	$919	US	25 min/ 420g.	GoPro Camera/ 805m/ Powered by twin computers Ballistic parachute system		[76]
HEXO+	Squadrone System	$999	US	15 min/ 200g.	GoPro Camera/ 100m/ 2-second battery swap		[77]
Phantom 4	DJI	$1,399	China	28 min/ 300g.	Built-in1080p Camera, 4K resolution video/ 5000m Automatically avoid obstacles.		[78]
Inspire 1 Pro	DJI	$3,899	China	18 min/ 1700g.	Built-in1080p Camera, 4K resolution video/ 2000m/ Independent camera controller		[79]
MATRICE 100	DJI	$3,299	China	40 min/ 1000g.	External camera stabilization gimbal/ 5000m/		[65]
QR X900	Walkera	$4,399	China	25 min/ 3000g.	External camera stabilization gimbal/ 1000m/ Parechute protection device		[80]
Typhoon H	Yuneec	$1,299	China	25 min/ 600g.	Built-in1080p Camera/ 800m/ Integrated autonomous flight models		[81]

Product	Company	Price	Locale	Flight Time/ Payload	Camera/ Operation Range/ Features	Image	Reference
Tornado H920	Yuneec	$8,000	China	25 min/ 5000g.	Gimbal for Panasonic Lumix GH4/ 2000m/ Integrated autonomous flight models		[82]
MD4-1000	Microdrones	$2,000	Germany	45 min/ 1200g.	External camera stabilization gimbal/ 500m		[83]
eXom	SenseFly	￥44，000	Switzer-land	22 min/ 1200g	Built-in HD camera and thermal camera/ 2000m		[84]
eBee	SenseFly	$12,000	Switzer-land	50 min/ 150g	Sony WX or thermoMAP/ 3000m		[71]

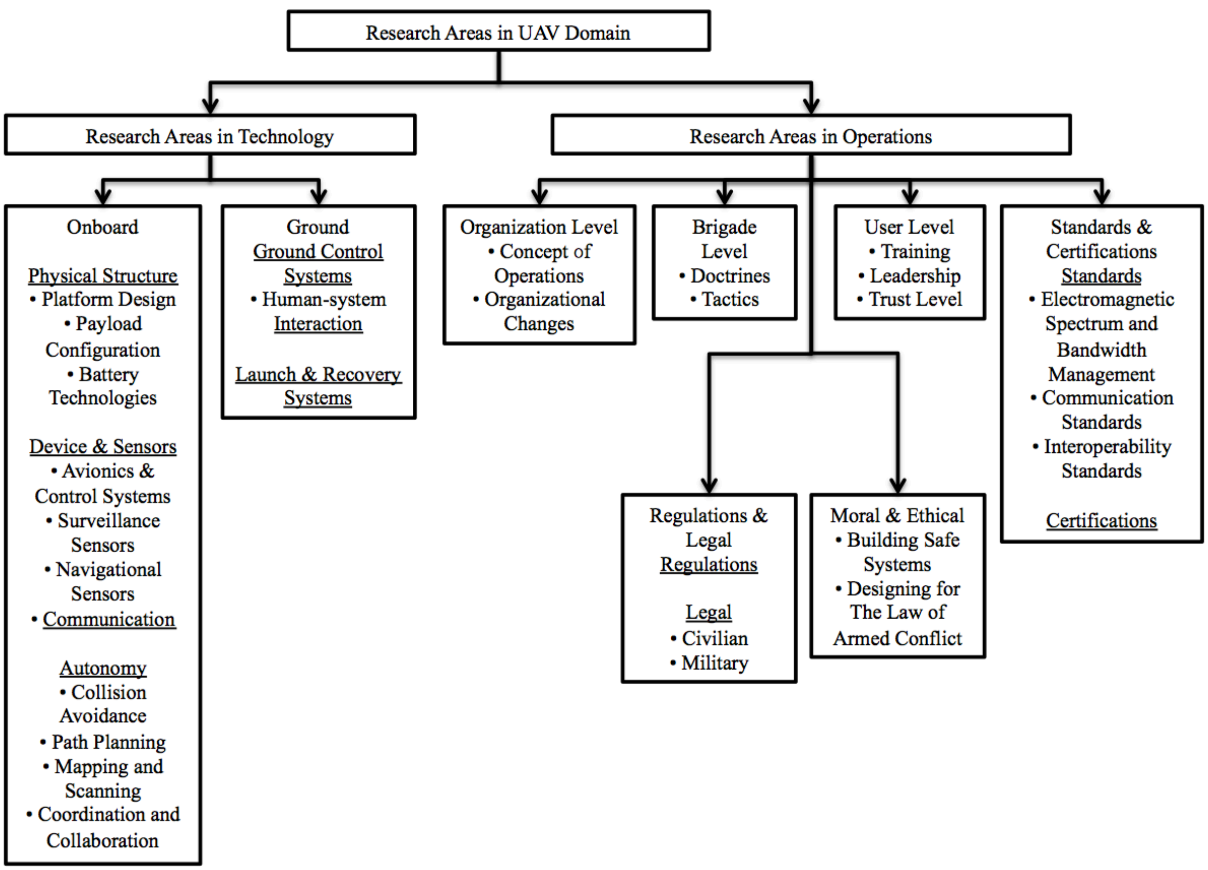


Fig. 7. Research areas in the UAV domain (after [85]

CURRENT UAV RESEARCH

According to a survey by Demir [85], UAV research can be classified into two aspects: technology and operations. Technology research is related to the development of all UAV systems, while those in operation address how UAV systems are used and are geared towards their effective deployment. Fig. 7 shows an overview of the main research areas in the UAV domain. Here, only the technology part is presented. In this aspect, autonomy is the most active topic. Because UAVs have 6 degrees of freedom and are moving at a high speed, effective manual remote control is challenging when working in geometrically complex environments. In such scenarios, autonomous navigation technologies are a great support to operators. As mentioned above, UAV companies (e.g. DJI, Inter, and Yuncee) invest significantly in this function. Academic research groups are also interested in this field. For example, MIT's group employed a stereo camera with fixed-wing UAVs to avoid collisions at speeds of 30 Km/h [86], while Carnegie Mellon University's group presented an imitation learning strategy for high-speed UAV autonomous flying through dense forest environments [87]. In that project, they applied the DAgger (DAtaset aggregation) algorithm [88] to train the flight controller system. By iteratively mimicking a human expert's behavior, the controller performance improved. During a flight test, the UAV avoided more than 680 trees when travelling 3.4km at speeds up to 1.5m/s. Despite this notable success, to achieve full autonomous navigation, there are significant issues to be resolved besides collision avoidance. These include path planning and automatic mapping and scanning. While topics can be studied individually, they are typically addressed in composite solutions. One major example is the simultaneous localization and mapping (SLAM) problem. This topic has merged sensor application, obstacle detection, pose estimation, and map generation. These elements are discussed below.

SLAM

SLAM is widely used in UAV navigation systems for the simultaneous tracking of an UAV and the updating of the detection information in an unknown environment. SLAM has long been studied for ground-based robots in two-dimensional (2D) situations and is now being introduced into the more complex three-dimensional (3D) context required of UAVS. Hardware used in a SLAM process could be classified into two groups: (1) environment detection sensors and (2) positional estimation sensors. Environmental detection sensors give the on-board computer obstacle information about the immediate environment, while positional sensors help to estimate the UAV's movement and register it in the same coordinate system (Fig. 8).

OBSTACLE DETECTION SYSTEM

The critical factor for collision avoidance is obstacle perception. Because UAV payloads and computing abilities are typically quite limited, detection devices to improve obstacle perception must be lightweight (e.g. monocular camera[89], stereo cameras [86], RGB-D cameras [90], Light Detection and Ranging (LIDAR) sensor [91], and ultrasonic distance sensors [92]). A typical UAV object detection system is shown in Fig. 9 and includes two stereo camera pairs (one pointing forwards, one pointing backwards) and a tilted, continuously rotating, 3D laser scanner for perceiving the environment in all directions [93]. Depending upon the direction, the measurement density of the 3D laser scanner varies and has its maximum in a forward-facing cone. Only a small portion above the UAV's back is shadowed. In addition, eight ultrasonic sensors are mounted in a ring around the UAV. For localization and state estimation, a downward pointing optical flow camera is mounted (in addition to the two stereo camera pairs and the 3D laser scanner).

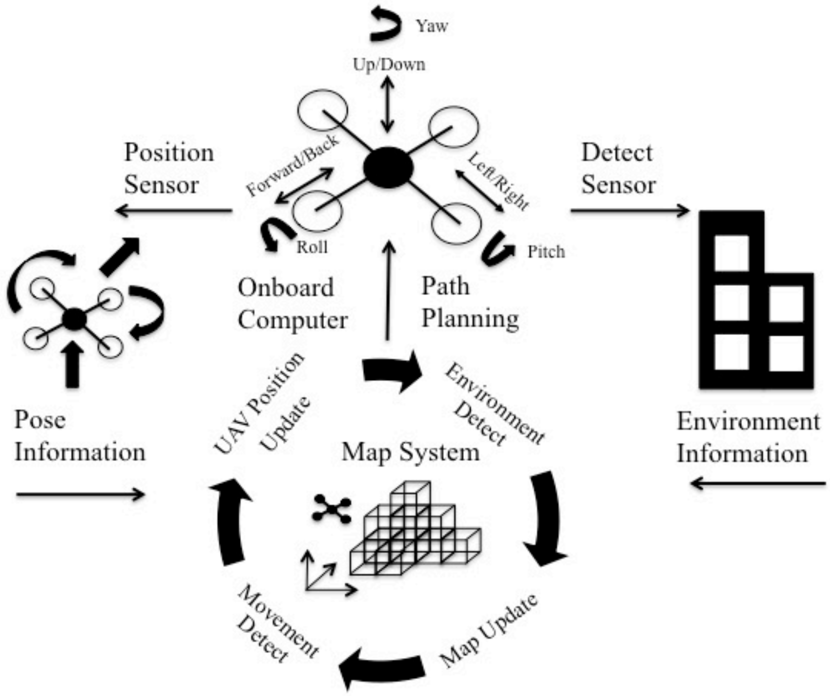


Fig. 8. SLAM Process Steps

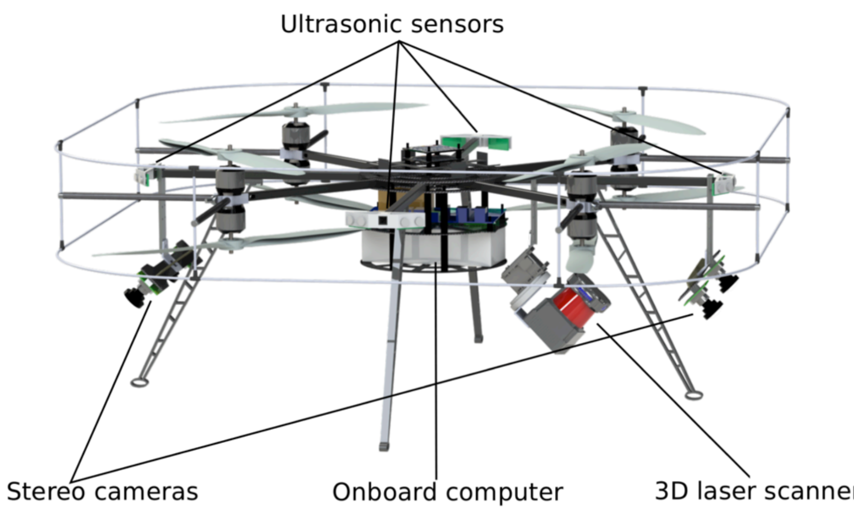


Fig. 9. Typical UAV objects detect system setup [93]

POSE ESTIMATION SYSTEM

Sensors included in the autopilot controller, such as a barometer, a magnetometer, GPS devices, can help locate the absolute position of a UAV on a map system (see section 6.3). Unlike ground robots that only move in 2D, UAVs move in 3D space and can have 6 degrees of freedom. To address this, an inertial measurement unit (IMU), which integrates accelerometers, gyroscopes, and magnetometers is used to track a UAV's movement in 6 degrees of freedom (rotational attributes like pitch, roll, and yaw, as well as linear movement up/down, forward/back and left/right shows in Fig. 8). Those data are used to calculate the relative position of the vehicle within a mapping system.

MAPPING SYSTEM

Environment and self-position information are processed in the on-board computer or sent back to a ground station computer. All location and geometric information are presented in a single coordinate, map system. Obstacles, collision-free areas, and unknown spaces are presented in this map. Depending upon the processing capabilities and the task requirements, different map models could be applied (e.g. point cloud, polygonal model, and surface element model). To help address the limited computing power of a UAV, an octree-based map [94] is widely used in SLAM-based processing.

An octree-based map represents obstacles in an octree structure – a hierarchical data structure for spatial subdivision in 3D (fig. 10). In such a data structure, each node in the octree represents the space contained in a cubic volume, usually called a voxel. This volume is recursively subdivided into eight sub-volumes until a given minimum voxel size is reached [95]. To accommodate limited UAV computing ability and on-board memory constraints, Droeschel [96] introduced a multi-resolution octree map into a collision avoidance system. In that work (fig. 11) closer obstacles have higher resolutions and more distance obstacles have lower resolutions (i.e. represented by bigger voxels).

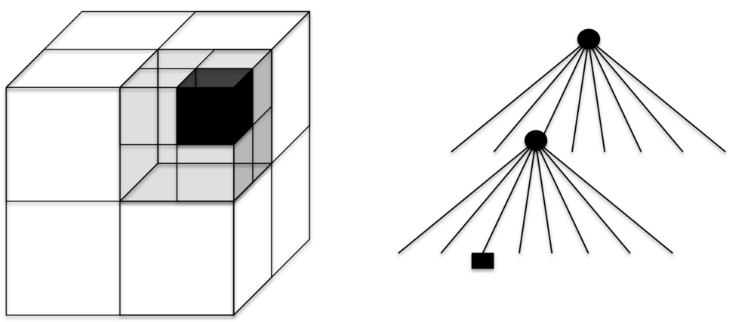


Fig. 10. Octree Structure Identifying the Location of a Single Data Point

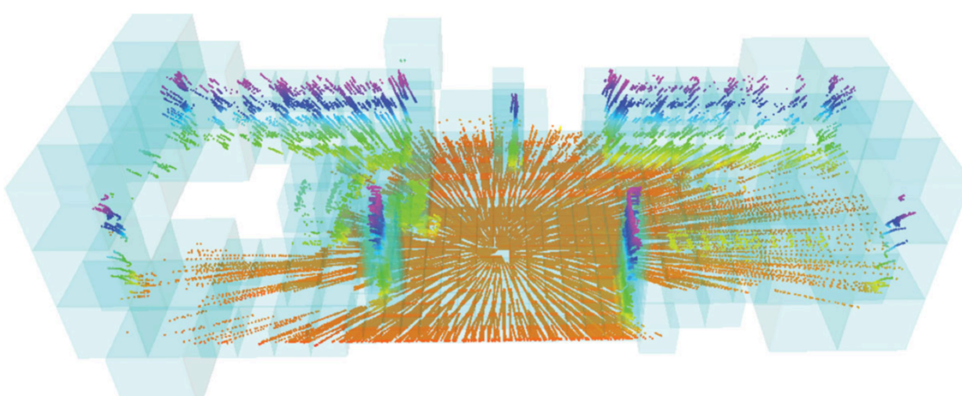


Fig. 11. Multi-resolution Octree Map [96]

As the position of UAVs is always changing, obstacles will be detected from different angles and distances. To correlate and align scan results taken from different positions is a challenge for the mapping process. For this, an alternative data index was adopted by Andreas in the form of a k-d tree [97] as part of the 6D SLAM process [98]. As explained in detail by Bentley, a k-d data index is a binary tree that has a node representation for every k-dimensional point (Fig. 12). In this data index, each node can be considered as generating a borderless plane that divides the space into two parts, known as half-spaces. In that data structure, if the sensor finds an obstacle and wants to compare it with previous data, the on-board computer only needs to search points in some specific branches, not the whole map. This process (commonly referred to as a nearest neighbour search) can significantly accelerate the SLAM process [98].

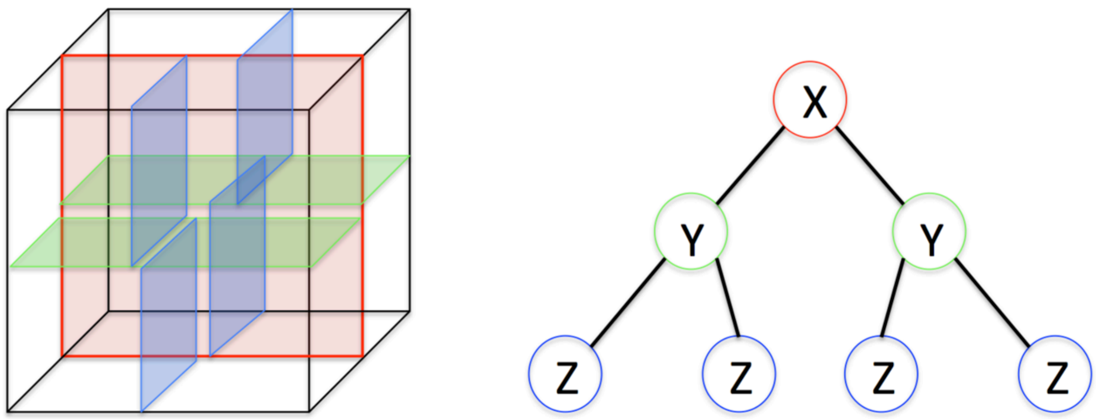


Fig.12. K-d Tree in 3D space

CURRENT & FUTURE DEVELOPMENTS

In the current market, users can easily find UAVs with live video and autopilot functions within a $500 budget. For the professional user, at around $5000 there is a lot of choice, such as UAVs with 6 or 8 props, a 1-3 kg payload, multiple sensors, and attachment options for detailed data acquisition. According to the data firm CBinsights, drone startups raised just over $450M in equity financing across 74 deals in 2015. That's up more than 300% over 2014 [99]. Those investments will continue to make civilian UAVs even cheaper，easier to use, and more functional in the coming years. The overall UAV market may be further subdivided by application areas, as UAV companies try to distinguish themselves with respect to extended flight time, improved device control for autonomous navigation, and water/wind resistant capabilities. Developers are also attempting to explore new fields for UAVs by enriching the payload composition.

In recent years, the hardware technologies supporting UAVs have improved significantly. Most patents have been in these areas, especially in hardware design and system direction control, as the software side has been largely dominated by the open source community, where notable advances have occurred in autopilot system research. Currently, flight time is the major UAV limitation. In support of this, new power supply schemes are being studied. Further areas where notable advances are likely are in swarm technology to allow the simultaneous operation of multiple drones or new UAV designs to improve flight stability and energy efficiency.

CONCLUSIONS

Despite the huge and rapidly growing popularity of civilian UAVs, there is not presently a single reference that shows the current state of the technology. This paper addresses this deficit by comparing currently available commercial with respect to hardware, software and peripherals. Considerations for cost, payload, and flying time are also addressed. The present market is spit into professional and hobby level equipment with the cost break point being around $3,000. While companies are presently striving for improved navigation and durability (including water-proofing) there are also significant attempts being made to divide up the market by developing (or at least marketing) specific UAVs for particular applications. Future UAVs are likely to show significant advances in payload capacity, flight time, functionality, and enhanced autonomous flight capabilities.

CONFLICT OF INTEREST

The authors have no commercial interest in any of the products discussed herein.

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