Defence Science Journal, Vol. 65, No. 4, July 2015, pp. 319-329, DOI : 10.14429/dsj.65.8631

Unmanned Aerial Vehicle Domain: Areas of Research

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ABSTRACT

Unmanned aerial vehicles (UAVs) domain has seen rapid developments in recent years. As the number of UAVs increases and as the missions involving UAVs vary, new research issues surface. An overview of the existing research areas in the UAV domain has been presented including the nature of the work categorised under different groups. These research areas are divided into two main streams: Technological and operational research areas. The research areas in technology are divided into onboard and ground technologies. The research areas in operations are divided into organization level, brigade level, user level, standards and certifications, regulations and legal, moral, and ethical issues. This overview is intended to serve as a starting point for fellow researchers new to the domain, to help researchers in positioning their research, identifying related research areas, and focusing on the right issues.

Keywords: Unmanned aerial vehicles, UAV research, UAV domain

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have recently become an important element in military operational environment. In addition to military purposes, today UAVs are being used for scientific, commercial, and public purposes. Depending on different user needs, many types of UAVs are under development. Therefore, the research areas in UAV domain are evolving as the types and number of UAVs increase.

The evolution is being shaped by the increasing and varying expectance of the UAV users. Currently, many universities, government agencies, technology companies, public and private R&D organisations conduct research depending on their interests. This UAV research overview is divided into two areas. The first deals with the operational research areas centered on the theme of effective use of UAVs. This area is mainly researched by government agencies, companies in defence sector, universities, and public research institutions. The second area focuses on the issues related to the development of the unmanned vehicle systems. The private sector is quite active in this area. Naturally, universities and research institutions conduct a portion of the research in this area. Even though, these two areas may seem non-overlapping, an issue in one area may have significant impact on the other. For example, the autonomy level of the UAV will determine the types of missions that the UAV can accomplish. In essence, research efforts in both areas serve a common purpose, that is to benefit from these machines to the maximum extend for both military and civilian uses.

An important portion of this study is the result of an in-depth analysis of roadmaps and master plans of defence agencies[1-10]. The rest is the result of a broad academic literature review. However, since the scope is an overview rather than a literature review, only certain reference studies are highlighted to guide fellow researchers.

2. UNMANNED AERIAL VEHICLES

2.1 History of UAV

The frontiers of UAVs were used in American Civil War in 1916. The first examples are balloons with explosives used to attack enemy. Naturally, the military showed an interest and researchers conducted studies. During World War II, Germany developed an attack UAV known as Buzz Bomb. Substantial developments occurred over the years. In Vietnam (1964-1972), Israel/Lebanon Conflict (1982), Operation Desert Storm and Operation Desert Shield (1990-1991), Operation Enduring Freedom and Operation Iraqi Freedom (2001-2006), these vehicles executed various missions.

2.2 UAV Classification

Classification of UAVs provides a common terminology for communication and knowledge sharing among organisations with different perspectives[18]. Although, each organisation or government has a different categorisation, a NATO classification is presented in Table 1. The classification of the UAVs is based on their maximum gross take-off weight and operating altitude. Categories[18] start with weight classes,

Received 03 April 2015, revised 05 July 2015, online published 30 July 2015

that are further divided on the basis of the UAVs operational altitude.

Many countries developed UAVs for both military purposes and civilian applications. There is a detailed list[40] of UAVs developed and operated all over the world.

2.3 Main Components in a UAV System

The various components[18] in a UAV system can be grouped into various elements such as payloads, control elements, data links, support elements, system users, etc. Even though most researchers focus on the unmanned vehicle, in a UAV system, the vehicle is only one of the elements. The main components are shown in Fig. 1.

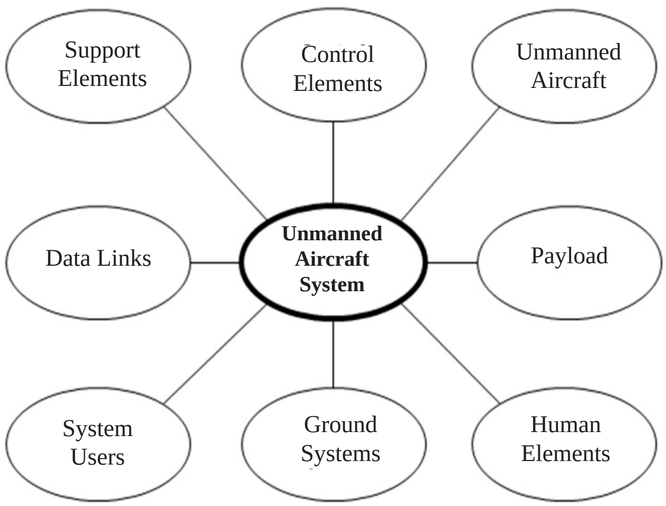

Figure 1. Main components in a UAV system.

3. RESEARCH AREAS IN UAVs DOMAIN

The research areas are examined under two headings: Technology and Operations. Research areas in technology are related to the development processes of these systems. Research areas in operations deal with how these systems are used and the issues related to effective deployment of these systems. Figure 2 shows an overview of the research areas in the UAV domain.

3.1 Research Areas in Technology

Research areas in technology are divided into onboard technologies and ground technologies. While most researchers new to the domain only focus on the unmanned vehicle itself, ground technologies are as important as onboard technologies. Although these systems are called unmanned, most of the current UAVs are remote controlled by a human operator. Therefore, ground technologies play a significant role in the domain.

3.1.1 UAV Onboard Technologies

The first line of studies deals with the physical structure of the UAV. These studies are similar to manned aircraft design studies. The second line of research studies includes the development of various devices and sensors. In manned aircraft research, autonomy-related issues are investigated to a certain extent. However, autonomy is at the heart of UAV research. An important difference between manned and unmanned aerial vehicle research is the need for human support systems in manned aircraft design, which is unnecessary for UAVs.

3.1.1.1 Physical Structure

Research on the physical structure may be divided into platform design, payload configuration, and battery technologies.

Platform Design: Platform design consists of aero structure and coating of UAVs. Both research areas affect the reflection ratio, energy consumption, and strength of UAVs. To achieve long endurance, UAVs are coated with self-healing coating materials such as biopolymer and isomers[10]. In addition, advanced structural design techniques are used. Although, these technologies are not mature yet, long-endurance flights will be achieved in the near future via these technologies. For military UAVs, stealth technology is important for evading enemy radars and systems. Similar to research on long-endurance, stealth capability can be achieved via platform design and using better coating materials[23].

Payload Configuration: Many UAV types have payload limitations. Payload configuration is a limiting factor in endurance. Developers have to make trade-offs between payload configuration and endurance while satisfying user needs. For example, in a mini-UAV, there is no need to use

Table 1. NATO UAV classification[18]

Class	Category	Employment	Operating altitude	Mission
Class I (less than 150 kg)	Micro < 2 kg	Tactical Pl, sect, individual (single operator)	Up to 200 ft AGL	5 km (LOS)
	Mini 2-20 kg	Tactical sub-unit (manual launch)	Up to 3000 ft AGL	25 km (LOS)
	Small > 20 kg	Tactical unit (employs a launch system)	Up to 5000 ft AGL	50 km (LOS)
Class II (150 kg to 600 kg)	Tactical	Tactical formation	Up to 10, 000 ft AGL	200 km (LOS)
Class III (more than 600 kg)	Male	Operational / Theatre	Up to 45,000 ft	Unlimited (BLOS)
	Hale	Strategic/ National	Up to 45,000 ft	Unlimited (BLOS)
	Strike/combat	Strategic/ National	Up to 65,000 ft	Unlimited (BLOS)

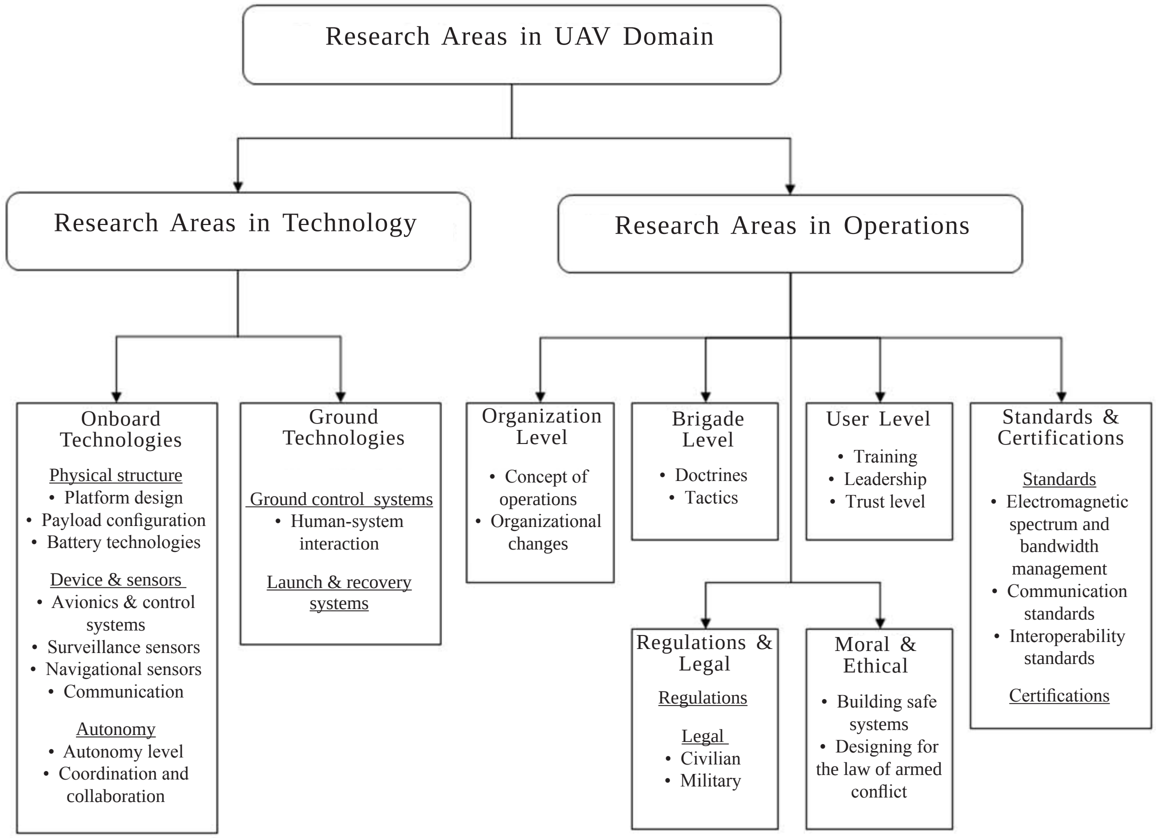

Figure 2. Research areas in the UAV domain.

specialised detection sensors or improved onboard processing devices. Data link systems and imaging sensors would be adequate for such vehicles[24].

Battery Technologies: Battery is the energy source for UAV sensors and impulsion systems. Long endurance is defined as the ability to fly with an unpleasant or difficult situation, experience, or activity over a long period of time. Today, UAV endurance is limited due to current energy technology limitations. Studies[20-22] discuss the developments in energy sources for UAVs. According to an unmanned systems roadmap[1], longer endurance will be possible by next generation power sources in 2015 and bio mass reactor power in 2035.

3.1.1.2 Devices and Sensors

UAV onboard devices and sensors vary depending on the missions that the UAV is designed for. In some cases, if the design allows, the vehicle may be equipped with extra devices and sensors in addition to the ones onboard. The UAV devices and sensors are quite different in size and capability for different UAV types. For example, the sensor and device requirements for a HALE UAV will be quite different than the requirements for a micro UAV. Payload of a UAV should be as light as possible to have a long endurance.

The main sensors and devices on UAVs can be categorised[26] as:

- Avionics and control systems
- Surveillance sensors
- Navigational sensors
- Communication systems

Avionics and Control Systems: Avionic systems implement the automatic flight control of UAVs. It consists of an onboard flight computer that collects data from sensors and executes flight control rules via the actuators. Since an avionic system constitutes the central component of a UAV, it should meet important requirements[44] including safety, robustness, determinism, and real-time. Hence, the research on avionic systems architecture mainly focuses on reconfiguration capabilities and integrating COTS processing equipment[44]. The embedded intelligent behaviour is another important research area. The necessary intelligence level is determined based on the UAV tasks. However, more research is required to accomplish systems autonomously performing complicated tasks. The trends are discussed[45].

Surveillance Sensors: One of the main purposes of UAVs is to collect data and perform imaging by sensors measuring radiation over wavelengths in visible and infrared ranges of electromagnetic spectrum. Common sensors used in surveillance include electro-optical and video cameras. Main research issues in sensing and imaging technologies are two fold. The first is the high resolution imaging by increasing the sampling rate. The second is the sophistication of cameras capable of sensing a wide range of electromagnetic spectrum. Various surveillance sensors are listed[46].

Navigational Sensors: GPS, high power radar, inertial, altimeter, and magnetometer are some of the sensors a UAV has. The sensors are used to measure attitude and position accurately and to stabilise the UAV body in different payload orientations, even in high G manoeuvers. One research area is to increase the accuracy of sensors. However, since no single sensor can reliably provide a high performance without a ground base support, the research in this area also focuses on the fusion of data gathered by all UAV navigational sensors.

Communication: Communication is the exchange of commands and data between onboard systems and ground systems. This research area mainly deals with issues related to bandwidth management, network architecture, and link security. Bandwidth management is related to data links. As commercial and military UAVs are on an increase in the airspace, the current bandwidth management policies limit the effective use of UAV systems. There is an increasing need for the development of novel techniques to increase the throughput for C2 and data link signals[1]. Frequency-hopping RF, non-RF, or bandwidth-efficient modulation methods are considered as the novel approaches for future UAV related projects[1-10].

Network architectures including protocols and interfaces must be flexible enough to allow inter operability. For example, there may be a need for transfer of command (also called handoff) between a ground station and a ship command and control system depending on the mission. To efficiently incorporate the use of UAVs into national network-centric warfare capabilities, the network architectures and related technologies must be redesigned.

Another important research area is ensuring the link security. Today, there are cases of UAV hijacks reported in the media. Therefore, the command and control links must be secure and robust enough to control the UAV[7]. To reduce interference and intrusions, optimised frequency spectrum allocation, management and encrypted networks must be used[7].

3.1.1.3 UAV Autonomy

Autonomy Level: The autonomy of unmanned systems is defined[19] as an unmanned system's ability of integrated sensing, perceiving, analysing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned. So, the autonomy level can be defined as the level of ability to perform the functions[27] listed in Table 2.

Table 2. Research areas on UAV autonomy

Sensor and other information fusion
Communication management
Optimal path planning
Collision avoidance
Trajectory motion and path following
Target idendification and threat evaluation
Engagement decision
Weapons deployment
Abort decision-making/ response
Task scheduling
Co-operative tactics

The main advantage of UAV autonomy is to provide a capability of performing long flights such as for weeks without any operator inference[1]. Another advantage is ability to timely control multiple UAVs by a single operator. So, the technology focus should be on the enhancement of the autonomy level during UAV operations[7]. However, increasing UAV autonomy level poses additional challenges in reliability, maintainability, and logistics. Developers must have to find a balance between the autonomy level and related challenges in UAV design. The autonomy levels are determined by the complexity of missions, environmental difficulties, and required support or intervention from the operator[49]. ACL[48] and ALFUS[49] are the example studies addressing the evaluation of autonomy levels in unmanned systems. One framework[28] for automation levels is provided in Table 3.

Table 3. Automation levels[28]

Automation level	Description
1	No computer assistance; the operator must make all decisions and take actions.
2	Computer offers a complete set of decision/action alternatives.
3	Computer narrows the selection down to a few.
4	Computer suggests an alternative.
5	Computer executes a suggestion if the operator approves.
6	Computer allows the operator a restricted time to veto before the automatic execution.
7	Computer executes automatically, then informs operators when necessary.
8	Computer informs the operator only if asked.
9	Computer informs the operator only if it decides to.
10	Computer decides everything and acts autonomously, ignoring the operator.

Coordination and Collaboration: In real world, many operations such as search and rescue (SAR) and space explorations[29] may be achieved by a team of robots rather than by a single robot. Therefore, use of multiple UAVs in coordination to accomplish a task is an active research area. UAV teams are better equipped to complete tasks faster and more efficiently[30]. Furthermore, some operations necessitate more than one vehicle.

Although, developing such a coordination and collaboration framework depends on the environmental factors and unexpected outcomes of actions[29], autonomy level is the main criterion affecting the framework. Various studies[29-35,47] were conducted to construct a framework on coordination and collaboration between UAVs.

3.1.2 UAV Ground Systems

Ground systems consist of ground control systems (GCS) and launch and recovery systems (LRS).

3.1.2.1 Ground Control Systems

A overview of issues related to the development of GCSs can be found in the work by Anderson[39]. Research studies[36-38] are just a few examples of the studies focused on developing GCSs.

Human-System Interaction: The main goal of the human-system interaction is aiding the operator to accomplish the desired goals in an application domain[25]. The interaction between the UAVs and human operators is established via ground stations. A good human-computer interaction (HCI) design enables the control of multiple UAVs. Implementing common or open architecture control station interfaces allows modifiability and extendibility. There are a number of studies[11-13] addressing the human-system interaction issues.

3.1.2.2 Launch and Recovery Systems

UAVs classified as high altitude and long endurance (HALE) or medium altitude and long endurance (MALE) use their own landing gears. However, in medium-size and mini UAVs, different techniques are required for launch and recovery. Launch systems provide an initial velocity for these UAVs and recovery systems assist in landing. These systems should perform under all required operational environments. Especially in military operations, such as in shallow waters and high sea states, improved launch and recovery systems are required[1]. Moreover, these systems may be deployed on different platforms such as on ships that have limited runways for launch and recovery for UAVs. Therefore, physical design of these systems becomes an important issue.

There are ongoing studies to enable UAVs to launch and recover in space-limited areas. Currently, medium-sized UAVs can be launched from many platforms. Some of the launch and land-off methods are:

- Pneumatic and hydraulic-pneumatic launching systems,
- Parachute systems,
- Vertical and near-vertical systems,
- Hand-launch and hand-land-off systems.

3.2 Research Areas in UAV Operations

Research areas in UAV operations consist of UAV employment considerations. These areas are among the main challenging research areas in the current operational environment. To address defence needs with existing technology limitations, novel employment strategies must be developed. Besides the employment of UAV teams, teaming manned-unmanned systems is also important. The research areas on UAV operations are discussed based on the hierarchical operational considerations, as shown in Fig. 3.

3.2.1 Organisational-Level

The research areas at this level deal with satisfying organisational needs. These areas are determined by organisations or governments. Concept of operations (or concept of employment) and organisational changes are among the main organisational issues.

Concept of Operations: A concept of operations (CONOPS) is a document describing the characteristics of a proposed system from the viewpoint of an organisation using the system[15]. CONOPS documents are developed by agencies or military forces. Developing an integrated CONOPS satisfying all stakeholders is a challenging task. But developing a CONOPS for UAVs is crucial in addressing all stakeholders needs for a coordinated deployment of UAVs. The first CONOPS[16] on UAVs was published in 1996 by U.S Air Combat Command. The next CONOPS focuses on High-Altitude Long-Endurance Unmanned Aerial Vehicles in the U.S. National Airspace System. The most extensive one[18] was published by NATO Joint Air Power Competence Centre (JAPCC) in 2010. It describes a capability-based approach to UAS employment, which enhances the operator's ability to execute given missions and tasks. Naturally, agencies and military forces in other countries are developing their own CONOPS.

Figure 3. Hierarchical operational considerations.

Organisational Changes: To manage and employ UAVs, re-structuring of current organisations is inevitable, especially in Armed Forces. Developing trained and specialised forces equipped with necessary knowledge is a necessity. Therefore, organisational changes are due for organisations employing UAVs.

3.2.2 Brigade-Level

Although, 'brigade' is a term originated from military, it can also be used for civilian organisations. It defines the middle-level which is between the organisational-level and user-level. The research areas at this level deal with satisfying departmental needs. Every department has to determine its own needs in line with organisational needs. Developing necessary specialised doctrines and tactics are among the main research areas at this level. Developing both tactics and doctrines provide a guideline on how to use these vehicles in an operational environment for decision makers.

Doctrines: Doctrines are the guidelines addressing how to appropriately manage a number of platforms in a given environmental situation. The difference from a concept of operations is that doctrines are more related to the missions and tasks rather than UAV related issues. The focus of these documents is to develop techniques and procedures. Most doctrines are not in public knowledge domain due to their confidentiality.

Tactics: Tactics are specific tasks such as an approaching manoeuver of a UAV taking pictures in a search and rescue (SAR) operation. Like doctrines these are not released to the public. The most appropriate tactics may be developed using simulations in dynamic and realistic operational environments[71-76]. Furthermore, using UAV simulations, the most suitable sensor configurations[74] can be investigated for better tactics development.

3.2.3 User-Level

Training: As the number of UAVs increase, the need for UAV operating teams will increase. Training large number of operation teams for the deployment of UAVs will be essential in the future. Selection of these team members based on their ability and skills is a critical issue[17]. Training these teams wrt to strategies, doctrines, and CONOPS, ensures efficient use of these systems in large-scale joint operations in a net-centric environment. Furthermore, using interactive 3-D software-based UAV simulations leverage the operator's capabilities and skills[2].

Leadership: Although the autonomy level in UAVs has been increasing rapidly, human intelligence is still indispensable. In many cases, uncertainty can be reduced by UAVs, but it cannot be completely eliminated. Therefore, flexibility and leadership of decision makers or commanders need to deal with diverse circumstances.

Trust Level: In automated systems, system performance is affected by the level of operator's trust on the system[41]. UAV designers should ensure that operators have the right level of trust on the UAV system. As exhibited in the past studies[42,43], over reliance or under reliance on the UAV systems have consequences. Over reliance on the UAV automation may result in damage or loss of vehicle, therefore, resulting is mission failure. Under reliance on the UAV systems may result in not being able to use the system to its full capacity, leading to mission ineffectiveness. As a result, development of appropriate trust models, and designing the system accordingly, is crucial in UAS developments[42].

3.2.4 Standards and Certifications

Developing necessary standards may be considered as one of the most critical issues for UAS research, since UAVs should be interoperable with the other existing systems.

Electromagnetic Spectrum and Bandwidth Management: This research area is critical as UAVs are going to operate in a crowded frequency and bandwidth spectrum[2]. Therefore, a central authority to coordinate frequency and bandwidth assignment is essential in reducing the interference in the communication systems[2].

Communication Standards: NATO has published standardisation agreement (STANAG) documents for UAVs. STANAG 4586 defines standard message formats and data protocols. It provides a common interface between the UAVs and the ground stations. STANAG 4559 defines the coalition-shared databases that allow sharing of information between the intelligence sources[2].

Interoperability Standards: Interoperability standards enable systems-both manned and unmanned-to operate together effectively. The ongoing NATO standardisation projects are listed in Table 4.

Table 4. NATO standardisation projects[10]

Network standards
Internet standards
Internetworking standards
Data link standards
Data standards
Flight operation standards
Operation standards

Certifications: The goal of airworthiness certification is to validate that a UAV meet the minimum requirements to conduct a specific operation or flight. In USA, the Federal Aviation Administration regulates each type of UAV operation including public operations, civil operations, and hobby/recreation usage[50]. For UAVs used in public operations, FAA issues a Certificate of Waiver or Authorisation (COA) that permits public agencies and organisations to operate a particular aircraft, for a defined purpose, in a particular area[50]. For the operations that do not meet the criteria to conduct public aircraft operation, several types of authorisation methods are determined. Additionally, FAA regulates the model aircraft operations for hobby or recreational purposes. The statutory parameters of a model aircraft operation are outlined in Section 336 of Public Law 112-95 (the FAA Modernisation and Reform Act of 2012)[51].

3.2.5 Regulations and Legal Issues

These issues are discussed in two parts. The first part is about aviation issues, the second part focuses on regulations on social issues.

Regulations: Aviation regulations determine the rules and minimum flight requirements that a UAV should meet when used for a specific purpose. These regulations[54] are generally discussed in three parts: (i) Integration into Airspace, (ii) Airworthiness Certification, and (iii) Operator/Pilot Licensing.

Currently, in most countries, UAVs are only used in separated airspace zones. Integration of UAVs into the airspace is a critical issue under discussion. Since, this integration has consequences at many levels as the use of UAVs expand.

International Civil Aviation Organisation (ICAO) co-ordinates and regulates international air travels. The organisation has released a document[55] 'to provide a fundamental international regulatory framework with supporting procedures for Air Navigation Services and guidance material, to underpin routine operation of UAV throughout the world'. There are also several national regulations[56-58] aiming to ensure safe operations of different UAV types in national airspaces.

In Canada, if the aircraft weighs less than 35 kg, and is only used for recreational purposes, a permission from authorities is not required. If the unmanned vehicle is used for work or research and it weighs 35 kg or more, UAV users must apply for a special flight operations certificate before operation. Once granted, the operation of the UAS will be subject to the rules set by Transport Canada. Depending on the industry and intended use of the system, different rules apply. Restrictions may include locations, time of day, and other operating and safety parameters. In addition to USA and Canada, Australia and Germany also unites the rules governing all UAVs into one body of legislation.

Regulations on operator and pilot licensing are in their infancy stage in many countries. There are universities and organisations offering programs on UAV pilot certification. Unmanned Vehicle University[77] issues UAV Pilot Certificates when a 42 h training is completed. The training includes 10 h of simulator, 16 h of in-class, and 16 h of flight training. Cochise College[78] offers a degree that prepares students to safely and effectively operate UASs for commercial uses in the national airspace system. There are also other training opportunities[79-80] for UAV piloting. The Air Line Pilots Association (ALPA) argues that UAV operators should have the same training and qualifications as their pilot counterparts sharing the same airspace[69]. Integration of UAVs into the airspace is discussed in depth Dalamagkidis[70], *et al*.

Legal Issues: Legal issues may be discussed under two headings: civilian-use UAVs and military-use UAVs.

Legal issues related to civilian-use of UAVs include data protection, copyright law, and private property concepts[52]. Data protection focuses on the rules to prohibit the acquisition of personal information by UAVs. In most countries, there are no regulations prohibiting the use of UAVs for image capturing. Copyright laws regulates capturing images of people in public and private areas. Although there are several regulations, there is a need for development of more comprehensive regulations. Private property rights prevent capturing images of private properties under defined conditions. In many countries, this issue is under the regulation of personal rights.

Memorandum[53] issued on 15 February 2015 by the President of USA outlines safeguarding privacy and civil rights for the Domestic use of Unmanned Aircraft Systems. Since security and economic competitiveness is necessary for the national defence, it is an executive order to complement with the existing laws to clarify and control the use of airspace. According to the memorandum, unless there is a compelling reason, such as national security or defence, any kind of surveillance conducted in National Air Space by unmanned vehicles is prohibited or limited. This memorandum also enforces an advance authorisation for data collection and protection.

Military-use UAVs are subject to a number of international laws and regulations. Laws of armed conflict (LOAC) and National rules of engagement govern how UAVs should be used in public operations[27]. There may be additional rules set by countries to regulate the use of military purpose UAVs. All these regulations aim to ensure that UAVs are not involved in illegal activities or any operation morally doubtful. The responsibility of any action is divided into two areas in terms of civil responsibility and criminal responsibility[27]. While civil responsibility handles the cases related to mistakes made by an agency or the manufacturing company, the criminal responsibility handles any death or injury cases as a result of UAV operation by an operator. There is a need for further research to tighten the rules in both areas to guarantee that the UAVs are used in a safe manner. The quality of these research studies will determine the acceptance of these systems used in operational theatre by governments.

3.2.6 Moral and Ethical Issues

Moral and ethical issues have been investigated in various studies[59-67]. Currently, the issues are far from being resolved and most of them are in debate.

According to a study[62] hold by US Surgeon General's Office, it is understood that there is an increasing ethical violation in the existing military operations and UAV operators need to be taught how to respond in such ethical situations. It is claimed that the use of autonomous systems would lead to an increase in ethical behaviour on the battlefield rather than a decrease[59]. The discussions will gather more heat as these systems cause significant human life losses on the ground in combat zones[60]. Also, despite the apparent technological neutrality, the negative ethical impacts of UAS devices are likely to fall disproportionately on marginalised populations[60].

These systems are required to adapt the current ethical implications and the UAV operators or decision makers in the battlefield must be responsible for the results both intentionally and unintentionally created by these systems[59]. And, it should consider moral uncertainties to establish ethical standards as guidelines for behaviour[61]. US officials calls for responsible use of drones, both nationally and internationally[66].

Today, most UAVs are remote-controlled. From the defence view, the moral and ethical issues are similar to the issues discussed under the debate of using long-range precision weapons. Furthermore, there also are other considerations when these systems are in fully autonomous mode. Ethical issues may be discussed under two headings[63].

Building Safe Systems: Before, it is ethical to use unmanned systems, these must be safe to operate in the field. Furthermore, these must be safe to fight alongside[63]. If these systems harm friendly forces in the battlefield due to malfunctions or other reasons, then there is no point in fielding these systems. Additionally, if the decision makers send friendly forces into the enemy land for a rescue mission to salvage an expensive UAV, then there would be a case in which machines are valued over humans. Using unmanned combat aerial vehicles (UCAVs) may cause physiological stress on remote operators. There are reported cases[63] and even a recent movie[64] on the subject. For some operators, using UCAVs may feel like playing a video game[63].

Designing for the Law of Armed Conflict: The ethical use of UAVs in military context should adhere to Law of Armed Conflict (LOAC). At a minimum, these systems should meet the criteria of discrimination and proportionality[63] in armed conflicts. These principles are derived from the just war doctrine 'jus in bello'[65]. The doctrine indicates that 'UMS must be capable of discriminating between legitimate and illegitimate targets and of applying force proportionate to the pursuit of legitimate military ends'[63]. Another critical issue is the establishment of a clear chain of responsibility in the actions and results of UAV use[66]. When ethical violations occur, the responsibility should be traced back to the sources. Engineers, roboticists, operators, and maintenance personnel are among the possible responsible parties. Locating the responsibility could be quite challenging. One of the challenging research areas may be 'designing out war crimes'[63]. It is also in discussion that these systems can be designed in such a way that these do not allow war crimes to be committed. It may be possible that a clever design of user interfaces, decision-making modules, and ethics modules may prevent the unethical use of UAVs.

Table 5. Maturity level of research areas in UAV domain

Research area	Research maturity level
Onboard technologies	**Below mature**
Physical structure	**Moderate**
Battery technologies	Moderate
Platform design	Below mature
Payload configuration	Moderate
Device and sensor capabilities	**Below mature**
Avionics and control systems	Below mature
Surveillance sensors	Below mature
Navigational sensors	mature
Communication	Below mature
Autonomy	Moderate
Autonomy level	Moderate
Coordination and collaboration	Below moderate
Ground technologies	**Below mature**
Ground control systems	**Mature**
Human-system interaction	Moderate
Trust level	Moderate
Launch and recovery systems	**Below mature**
Organizational level	**Below moderate**
CONOPS	Below moderate
Organizational changes	Below moderate
Brigade level	**Below moderate**
Doctrines	Below moderate
Tactics	Low
User level	**Below moderate**
Training	Below moderate
Leadership	Below moderate
Standards and certifications	**Moderate**
Electromagnetic spectrum and bandwidth management	Below mature
Communication standards	Moderate
Interoperability standards	Below moderate
Certifications	Below moderate
Regulations and legal issue	**Below moderate**
Regulations	Below moderate
Legal Issues	Low
Moral and ethical issues	**Low**

4. CONCLUSION

In this study, an outline of basic research areas in the UAV domain is presented. The intended audience is the researchers new to the domain. With this study, new researchers will be able to quickly overview the main research areas and choose an appropriate area that interests them. Furthermore, the references provided will be starting points for their research agenda. Also, advanced researchers will have a chance to browse the areas outside of their research expertise.

Most technologies currently embedded in our daily lives followed a specific pattern of evolution. First phase is the conceptualisation. Second phase consists of development of core and supporting technologies and infrastructure. Technology acceptance among common population is next step. Finally, the technology phases out as it is replaced with newer technologies. In the technology acceptance phase, operational, regulatory, legal, moral, ethical, certification and standardisation related issues are developed and evolved when necessary. A similar evolution is being observed in the UAV domain. Currently, it can be said that the UAV domain is in between the phases of technology development and technology acceptance. Based on the literature review, an assessment of research maturity level of each area outlined in this study is presented in Table 5. The assessment scale used is as follows: Low (1), Below Moderate (2), Moderate (3), Below Mature (4), and Mature (5). While Table 5 presents an overview of current research maturity, it will help researchers in choosing an appropriate research field within the domain. An analysis of the table indicates that the necessary technologies are being developed and the current research maturity level is between moderate and mature. However, on the operational side, the research maturity level is between low and moderate. Most importantly, the research maturity level of regulatory, legal, moral, and ethical issues in the UAVs domain is low-to-moderate. Until, maturity level of operational side of UAV domain reaches above moderate level, the use of UAVs and benefit from this technology will be limited. Furthermore, the use of UAVs may be quite problematic in many aspects until legal and regulatory issues are resolved.

Another important aspect of UAV domain is that it is a frontier for autonomous robotics. The evolution, developments, and discussions in this domain will significantly affect other autonomous vehicles and the robotics field. Therefore, an in-depth understanding of this domain and its evolution will help the development and shaping of other related areas in robotics.

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ACKNOWLEDGEMENTS

The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of any affiliated organisation or government. We also thank to Prof. Coskun Bayrak, PhD, for his review on the manuscript draft.

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