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# State of the Art in Rotorcraft UAVs Research

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*Abstract— An unmanned aerial vehicle (UAV) is an aircraft equipped with an on-board flight controller, data processing units, sensors, and communication system, which make it capable of performing autonomous flight missions based on a pre-programmed flight data or driven remotely from a ground control station. This class of vehicles offers greater benefits over manned aircraft when used for high-risk tasks or in missions requiring high confidentiality. Rapid development witnessed in the research and development of UAVs can be attributed to a number of factors, such as technological advancements, political and economic factors among others. UAVs can be classified into fixed-wing and rotorcraft. This paper presents a comprehensive review of literature related to rotorcraft UAV design and development.*

*Index Terms— Aircraft, fixed-wing UAV, ground control station, on-board flight controller, rotorcraft UAV and Unmanned aerial vehicle (UAV).*

## I. INTRODUCTION

A Rotorcraft UAV commonly called a vertical take-off and landing (VTOL) UAV exists in numerous rotor configurations. The most common configurations are main and tail rotors (conventional helicopter), coaxial rotors, tandem rotors and multi-rotors. The rotorcraft UAVs are better suited for military and civilian applications requiring low altitude flights owing to their hover capabilities and excellent manoeuvrability. Recently, there is a growing interest in the development of small-scale rotorcraft UAVs, usually equipped with advanced on-board autonomous capabilities and commonly used as experimental platforms within the academic research circle. The rotorcraft UAVs can be categorized further into five groups based on size, payload, endurance and range [1].

### A. Group I – Full Scale Unmanned Helicopters

The unique feature of this group of rotorcraft is the provision of an on-board safety pilot. It has high capabilities of payload capacity, endurance and range. A good example of this group is the K-MAX UAV (Fig. 1), a transformational technology jointly developed by Lockheed Martin Corporation and Kaman Aerospace Corporation [2], enabling the vehicle to deliver supplies to precise locations. The vehicle is capable of autonomous or remote controlled cargo delivery by either day or night. It is can fly at higher altitudes with a larger payload can also deliver more cargo to more locations in one flight. The vehicle has been used in a number of military and civilian roles, including demolition work by having a wrecking ball as sling load, logging and power-line construction.



Source: <http://www.lockheedmartin.com/us/products/kmax.html>

**Fig. 1 The Group I UAV: KMAX UAV**

### B. Group II – Medium Scale Unmanned Helicopters

This group is available in autonomous and semi-autonomous platforms, popular amongst them include Rotomotion SR-500 and Schieble S-100 shown in Fig. 2(a) and (b). The Rotomotion SR-500 is a low cost medium-scale rotorcraft UAV developed by Rotomotion Helicopter systems [3]. The vehicle is equipped with on-board attitude stabilization and navigation sensors and supports up to 50 kg of payload with optional payloads such as camera and agricultural implements. It is powered by a 28 HP gasoline fuel injection 2-stroke engine and supports three

piloting modes: autonomous, semi-autonomous and remote piloting. The Schiebel S-100 is a product of Austrian company Schiebel Corporation [4], it is capable of pre-programmed autonomous missions and has a maximum take-off weight of 200 kg, a six hour endurance, a maximum speed of 220 km/h, and a ceiling of 5,500 m. The Schiebel is powered by a 55 horsepower internal combustion engine and can carry various payloads, such as electro-optical and infrared sensors.



Source: UAVDronesFor.com

(a)



Source: www.militaryfactory.com

(b)

Fig. 2 Group II UAVs: (a) Rotomotion S-500 (b) Schiebel S-100

The main advantage of these platforms is their significant payload that allows them to carry heavy and high-quality navigation and mission sensors.

### C. Group III – Scale-Scale Unmanned Helicopters

This group comprises remote control (RC) based UAVs powered by either a small-scale single-stroke internal combustion or a DC motor with an option to incorporate an autopilot. They are cheaper, featuring low-cost off-the-shelf components, and usually weigh less 25 kg and support up to 10 kg of payload. They incorporate on-board orientation and navigation sensors that enable autonomous and semi-autonomous flight modes. Example of vehicle in this group include the Align Trex 600 Fig. 3(a) and Raptor 50 Titan Fig. 3(b), and both are available with an IC engine or electric DC motor option.



Source: <http://rc.helicopterfly.com/nitro-helciopter-p-1424.html>

(a)



Source: www.ruberkon.com

(b)

Fig. 3 Group III UAVs: (a) Trek 600 (b) Raptor 50 Titan.

### D. Group IV – Mini-Scale Unmanned Helicopters

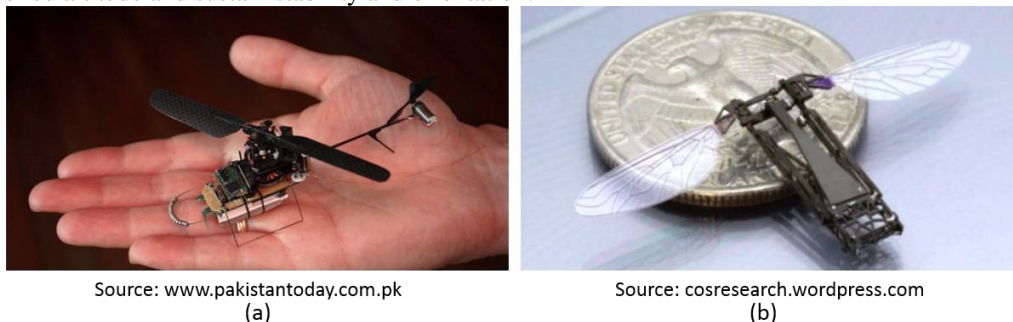
This group comprises mini rotorcraft, weighing less 3 kg, DC motors powered, RC-operated, and portable enough to be carried. They are equipped with orientation and navigation sensors, and can be autonomous or semi-autonomous. The vehicles are also capable of flight in both indoor and outdoor environments, having flight time ranging between 5 to 45 minutes depending on the payload. Their low-cost, ease of maintenance and safe operation make them excellent platforms for academic research. Some example of vehicles in this group includes Syma S107C Fig. 4(a) and MikroKopter quadrocopter XL Fig. 4(b).



**Fig. 4 Group IV UAVs: (a) Syma S107C (b) MikroKopter Quadrocopter XL.**

**E. Group V – Mini-Scale Unmanned Helicopters**

This group comprises remarkably small form factor UAVs, usually inspired by the biology of flying insects. They weigh less than 100 g and carry a payload of less than 20 g. In most cases, the vehicle's size constraint prohibits mounting on-board orientation and navigation sensors. Research in these vehicles has led to the development of tiny UAVs able to fly around corners, fly into buildings and can relay information to the ground control station. An example of vehicle in this group includes the Black Hornet PD100 Fig. 5(a) and RoboBee Fig. 5(b). The Black Hornet is a tiny battery-powered surveillance helicopter developed by Norwegian firm Prox Dynamics [5]. The RoboBee was developed at Harvard University and flies by flapping its two wafer-thin wings 120 times a second to attain desired altitude and sustain stability and orientation.



**Fig. 5 Group V UAVs: (a) Black Hornet (b) RoboBee.**

The UAVs in groups I, II and III are dominated by the conventional helicopters having single main-rotor and tail-rotor configuration mainly used for outdoor applications, requiring a suitable provision for launch and recovery. Whilst, group IV and V are multi-rotor platforms capable of operating in the indoor and outdoor environments owing to their size advantage and can be launched by hand or in confined spaces and do not require special provision for recovery. This study focuses on the UAVs in class IV and V, as they are mostly adopted as research platforms within the academic circle.

**II. ROTORCRAFT UAVS RESEARCH AND DEVELOPMENT**

There are numerous research centres around the world working to develop or improve the existing UAV autonomous technologies. These centres cut across universities, military and industries each with special interest on the different aspects of the technology. This section describes the efforts of some of these centres, although it is not exhaustive.

**A. Commercial research centres**

Over the last few years, several private companies and government research centres have engaged in research and development related rotorcraft UAVs technologies with the view to exploiting their capabilities. For instance,

- **Laboratory for Autonomous Flying Robots (LAFR):** Based in Berlin, Germany, the Laboratory has worked on different subjects connected with practical applications of autonomous aerial robots with a level of on-board intelligence. The LAFR's main research areas include mathematical modeling and



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control of small scale aerial robots; sensors and data processing for autonomous navigation; collision detection/avoidance for small scale aerial robots and control of multiple coupled helicopter distributed real-time systems. Target application areas for the laboratory researches are cargo transport with multiple helicopters, deployment of sensor networks using small-scale aerial robots as well as monitoring and observation. The laboratory developed a modular control system that can be used to operate different types of vehicles. Platforms used by the Laboratory are Aero-Tec CB-5000 helicopter weighing 16 kg and Mikado Logo14 a quadrotor weighing 5 kg. The modular control system used by this vehicle consists of hardware for autonomous navigation, real-time software for control and communication [6].

- **Autonomous System Laboratory (ASL):** Part of the Mechanical Engineering Department of the College of Engineering at the University of Hawaii at Manoa, USA, the laboratory conducts a number of research and development in the field of rotary-wing UAVs with the goal of developing aerial vehicles capable of operating autonomously in complex and diverse environments. The laboratory has a specific interest in the design and control of systems that can autonomously adapt to different situations and cope with uncertain and dynamic environments with an emphasis on novel methods and tools for perception, abstraction, mapping and path planning. Some of the projects the Laboratory worked upon include myCopter, a Personal Aerial Transport, muFly, a 50 g Micro-Helicopter and sFly, a Swarm of Flying Robots [7].
- **Australian Research Centre for Aerospace Automation (ARCAA):** This is a world-leading research centre based in Brisbane, Australia. ARCAA conducts research into all aspects of aviation automation, with a research focus on autonomous technologies and safer utilization of airspace. The centre is also involved in design and development of autonomous aircraft and on-board sensor systems for a wide range of commercial applications [8].

#### **B. Military research centres**

The military in many nations have set up UAV research centres with the view to developing indigenous UAV technology. However, in some industrialized nations where UAV technology has been developed, the military is running a number of UAV systems, from the Reaper [9], which can carry Hellfire missiles and laser-guided bombs, to the Black Hornet mini-helicopter [5], which can fit in the hand. Some popular amongst the military UAV research centres are detailed below:

- **West Wales UAV Centre (WWUAVC):** This is a unique environment created in the UK to facilitate and accelerate the growth of the UAV industry, with safety, management and operational infrastructure delivered by QinetiQ. The centre is supported by the Welsh Government-supported project that enables: UAV R&D integrated UAV operating environments, expert technical and operational support, outstanding infrastructure and test facilities, development and demonstration flight trials as well as training. In addition, the WWUAVC is acting as the platform upon which UK and European UAV developments are promoted, it serves as an avenue that facilitates the commercialization of research and acts as a facilitator for the development and proving of UAV policies and regulations. The WWUAVC provides all aspects of the infrastructure, support and administration required to operate a UAV [10].
- **Israel Aerospace Industries (IAI):** The IAI is the largest aerospace and Defense Company in Israel and is globally recognized leader in development and production of military and commercial aerospace and defense systems. For over five decades, IAI has been the sole provider of advanced aerospace systems for the Israel Ministry of Defense and many demanding customers worldwide. The company invests substantially in research and development, thus providing unique systems solutions for a broad spectrum of needs in business jets, UAV, radars, mission aircraft among others. The IAI other areas of expertise include upgrading and conversion of military aircraft and helicopters to UAVs, maintenance and conversion of commercial aircraft, including conversion to aerial refueling navigation systems [11].
- **Defense Advanced Research Projects Agency (DARPA):** This organization is saddled with the funding and managing majority of the UAV researches in the United States. Under this arrangement, the United States





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Military Services have multiple training, operations, research and development programmes related to UAVs under an inter-service memorandum of understanding (MOU) between the USAF, US Army and US Navy. Project planning and policies enactments relating to UAV technologies lies with the US Department of Defense. The Department periodically publishes its Roadmap for UAV development. The current publication being UAV Roadmap 2010-2035 [12].

### C. Academia research centres

A number of research groups in different universities are involved in researches related to various aspects of UAVs. Their contributions are itemized under the following: flight control and navigation; attitude control; path planning and obstacles avoidance; performance optimization.

- **UAV flight control and navigation system:** Various groups relating to UAV flight control and navigation reported many contributions, few amongst them include; Institute of Control and Computational Engineering, University of Zielona Gora, Poland demonstrated a UAV cascaded nonlinear flight controller with high accuracy and easy implementation for indoor application in [13]. A cost-effective indoor UAV navigation system was reported in [14], where three laser beams fixed to the underside of the UAV body were used to overcome GPS signal limitation in indoor application. An indoor navigation system was demonstrated for mini flying vehicles in [15]. The OS4 project [8], focused on micro VTOL vehicles evolving towards full autonomy in indoor environments. In another development, [16], demonstrated a Real-Time Indoor Autonomous Vehicle Test Environment for unmanned vehicle systems technologies for autonomous multi-agent mission platforms. Similarly, [17], explored a method that integrates three-dimensional (3D) point cloud data, two-dimensional (2D) digital camera data, and data from an Inertial Measurement Unit (IMU) with the view to providing accurate position and attitude determination of UAV for indoor application. A georeferenced satellite was used [18] to augment GPS outages for UAV navigation system.
- **UAV attitude control:** Various centres contributed in the aspect of UAV attitude control, e.g., an on-board attitude stabilization controller for a quadrotor was developed for indoor applications [19]. Similarly, in [20], a controller was designed using the Active Disturbance Rejection Control technique to regulate the velocity and attitude of a UAV in various wind turbulence conditions, simulation results show that the UAV velocity and attitude can be maintained well under various wind turbulence conditions.
- **Path planning and obstacle avoidance:** Numerous contributions are reported under these aspects of the UAV, e.g, an evolutionary algorithm based framework was utilized in [21] and [22], to design an intelligent path planner for UAV autonomous navigation. A real-time path-planning algorithm was demonstrated in [23] for a quadrotor UAV base on Rapidly-exploring Random Tree (RRT). In [24], probabilistic road-maps and D\* Lite were combined with a stereo vision for obstacle detection and dynamic path updating for path planning to developed a UAV navigation algorithm through unknown environments interspersed with obstacles. Similarly, a low-complexity, accurate and reliable scheme for motion field estimation was developed using UAV navigation videos in [25], and used to determine the range map for objects in the scene, with the view to designing control and guidance laws to navigate the UAV between waypoints and avoid obstacles.
- **Performance Optimization:** in the same vein, the computational engineering and design research group at University of Southampton UK have reported a number of contributions related to the UAV performance optimization. Amongst their contributions, include design and deployment of minimal protective system for a multi-rotor UAV [26] to cater for changes in legislation and provide for greater use in both in and outdoors. In [27], the group developed a test rig to highlight salient aerochemical components and variables that dictate the coaxial rotorcraft flight performance geared towards the optimization of the propulsion systems of HALO coaxial rotorcraft UAV designed by the Autonomous Systems Lab. In addition, the group in [28] demonstrated the application of weighted matrix method in the design optimization of a reconfigurable perching element for rotorcraft UAV. Similarly, in [29] the length of touring time a UAV requires to navigate defined waypoints repeatedly was minimized using a model built by solving the traveling salesman problem (TSP) problem.

### III. BUILDING BLOCKS OF A ROTORCRAFT UAV SYSTEM

An autonomous UAV system comprises five main elements as depicted in Fig. 6: including the vehicle mechanical structure, which provides the platform upon which other elements are mounted; the flight control system, responsible for coordinating and controlling the functionalists of the on-board electronic systems; navigation system, provides means of regulating the vehicle position, orientation and sometimes altitude; guidance system, provides means of directing the vehicle to the target position and ground control station provides a friendly and realistic interface for the vehicle operator to monitor the performance and state of the vehicle in flight. The subsequent section provides detailed description of these elements.

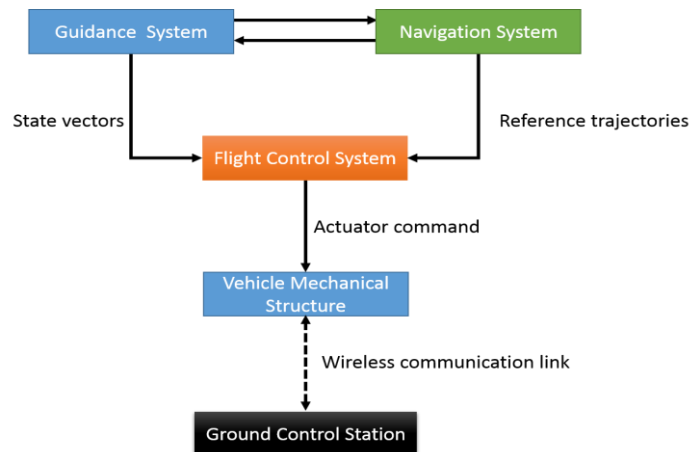


Fig. 6 Elements of RUAV autonomy

### IV. FLIGHT CONTROL SYSTEM

An autonomous Flight Control System (AFCS) manipulates the inputs to a dynamical system to obtain the desired effect on its outputs without a human in the control loop. Design of an AFCS for a rotorcraft UAV consists of a synthesizing algorithms or control laws that compute inputs to the vehicle actuators that produce torques and forces that act on the vehicle for controlling its 3D motion (position, orientation and their time-derivatives). An AFCS integrates hardware, such as IMU, camera, sonar sensor, with software to ensure the accomplishment of the desired flight task. A number of UAV flight control system architectures and algorithms have been developed and implemented on some vehicles as reported in the literature [30]-[37]. Rotorcraft AFCS incorporate velocity/position and heading control, as well as 3D trajectory tracking. Although rotorcraft UAVs control systems are often based on the control methodologies used for manned aerial vehicles, in the last decade various other control techniques have been developed in the academia specifically for rotorcraft UAVs [38]-[41]. The rotorcraft UAVs flight controllers can be classified into three main categories: (i) learning-based control methods, (ii) linear flight control systems, and (iii) model-based nonlinear controllers as shown in Fig. 7.

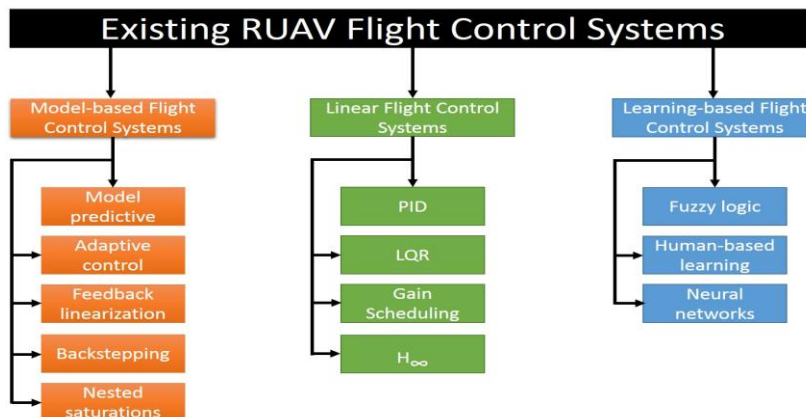


Fig. 7 Categories of rotorcraft UAV flight control systems



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### A. Learning-based flight controllers

The learning-based control scheme does not utilize the vehicle dynamic model, instead several trials and flight data are required in order to train the system. In this scheme, the most popular methods are fuzzy logic, human-based learning and neural networks, e.g., given a task to solve and a class of functions, learning means using a set of observations to find which solves the task in some optimal sense. This entails defining a cost function such that, for the optimal solution, i.e., no solution has a cost less than the cost of the optimal solution. The cost function is a fundamental concept in learning; it is the measure of how far away a solution is from an optimal solution. Learning algorithms search through the solution space to find a function that has the smallest possible cost. The use of these methods has been reported by several researchers [42]-[45] and applied on many platforms [46] and [47]. The idea in fuzzy logic implementation is to translate the information and knowledge used by human pilots into rules that can be used by a fuzzy control system. A neural network controller is essentially a simple mathematical representation associated with a particular learning algorithm or learning rule defining a function or a distribution or both and has been reported in [48], [49] and [39].

### B. Linear flight controllers

These are referred to as the classical controllers and are more application-orientated compared to other control methods. This control scheme disregard the multivariable nature of the vehicle dynamics and the strong coupling which exist between the vehicle states and its control inputs. Thus, implying that each vehicle control input is responsible for the control of an individual vehicle's output. Control system design of this type is known as Single Input Single Output (SISO). The majority of flight controllers implemented on rotorcraft UAV platforms are based on the linear controllers such as PID [50], linear quadratic regulator (LQR) [51] and H-infinity [52], etc.

### C. Model-based flight controllers

To overcome some of the limitations of linear controllers' architecture, a variety of nonlinear flight controllers have been developed and applied on rotorcraft UAV systems. The nonlinear flight controllers are based on the nonlinear model of the vehicle dynamics derived from the first-principles technique or system identification. Popular amongst these includes feedback linearization [53], adaptive control [54]-[57] and model predictive control algorithms [58]-[60]. Other control techniques such as back stepping [61] and [40] and nested saturation [62] have also been demonstrated for the control of small and mini rotorcraft UAVs. However, unlike the linear controllers, nonlinear controllers are mostly valued for their theoretical contribution to the UAVs control problem and rarely implemented to actual platforms.

## V. NAVIGATION SYSTEM

Navigation in rotorcraft UAV systems is the process of monitoring and controlling the movement of the vehicle from one location to another. It simply implies the process of data acquisition, data analysis, and extraction and inference of information about the vehicle's states and its surrounding environment with the objective of accomplishing assigned missions successfully and safely. This information can be metric such as distances, topological, such as landmarks or any other attributes that are useful for mission achievement. A navigation system for a RUAV comprises three enabling functions: sensing, state estimation and perception as shown in Fig. 8.

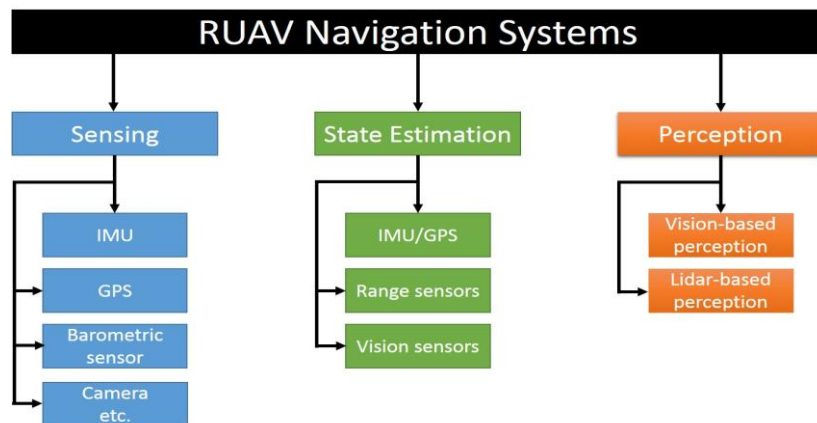


Fig. 8 Composition of RUAV navigation system



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#### **A. Sensing**

A sensing system is a collection of devices referred to as sensors that respond to a specific physical phenomenon or stimulus, and generate signals that reflect some features or information about the state of a physical phenomenon. Sensors such as gyroscopes, accelerometers, sonars, magnetometers, static and dynamic pressure sensors, cameras and LIDARs are commonly used on-board UAVs to provide raw measurements for state estimation and perception algorithms.

#### **B. State estimation**

This is the act of processing of raw data obtained from a sensor to estimate the different absolute or relative variables related to the vehicle's state. The variables could be the vehicle's attitude, position, velocity, etc. However, a form of state estimation that is limited to position estimation relative to some map or other location is termed as localization.

#### **C. Perception**

This involves the ability to use inputs from sensors to build an internal model of the environment within which the vehicle operates and to assign entities, events, and situations perceived in the environment to classes. The classification (or recognition) process involves comparing what the vehicle observed with a priori knowledge [63]. Perception can be further divided into various functions of different levels such as mapping, obstacle and target detection, object recognition, etc.

### **VI. GUIDANCE SYSTEM**

Guidance is a dynamic process of directing an object toward a given point that may be stationary or moving. The goal of guidance is to reach a target. When approaching a target, an object position coincides with a target position. Additional requirements to an object velocity and possibly acceleration specify various types of guidance. A guidance system exercises planning and decision-making functions to achieve assigned missions or goals. The role of a guidance system for rotorcraft UAV is to replace the cognitive process of a human pilot and operator. It takes inputs from the navigation system and uses targeting information to make appropriate decisions at its high-level, and generates reference trajectories and commands for the autonomous light control system. A rotorcraft UAV guidance system comprises a set of on-board components that measure the position of the vehicle with respect to the target and change its flight path in accordance with a guidance law to achieve the flight mission. The system usually includes sensing, computing, and control components, an operator of a mission control unit, and targets location. A guidance law is defined as an algorithm that determines the required commanded vehicle acceleration. The vehicle follows a predetermined path from the launch point to the target in accordance with the selected mission. The vehicle trajectories are defined by a series of waypoints, with latitude, longitude, and altitude, upon which the vehicle navigates. The guidance system controls the vehicles flight along preprogrammed and predetermined flight profiles between waypoints or geographical coordinates. Vehicle flight information is mostly communicated to a remote ground control station via a wireless network. A rotorcraft UAV guidance system comprises a number of autonomy enabling functions including trajectory generation, path planning, mission planning, reasoning and high-level decision-making, etc.

#### **A. Trajectory generation**

The role of a trajectory generator is to compute the physically possible vehicle's different motion functions which satisfy the vehicle dynamics and constraints, and which can be directly used as reference trajectories for the flight controller. Reference trajectories can be pre-programmed, uploaded, or generated in real-time onboard the vehicle according to the outputs of higher-level guidance modules. Numerous trajectory generation methods for rotorcraft UAVs have been demonstrated in [64]-[66].

#### **B. Path planning**

This involves the use of accumulated navigation data and a priori information to allow the vehicle to find the best and safest way to reach a goal position, or to achieve a defined task. Dynamic path planning refers to on-board, real-time path planning. The environment upon which the vehicle flies is complex and dotted with obstacles, and the vehicle may have several routes choice that lead to its target goals. Therefore, to ensure that obstacles are avoided, and shorter routes are taken, a robust path planning algorithms has to be employed. A number of path planning algorithms have been developed [67] and [68], even though there are few contributions in this regard





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related to rotorcraft UAV platforms.

### C. Mission planning

This involves the process of generating tactical goals, a route coordination, and timing for the vehicle. The mission plan can be generated either in advance or real-time, by a human pilot or by the on-board software systems in either centralized or distributed ways. The term dynamic mission planning is also used to refer to on-board, real-time mission planning [69]. There exist a number of mission planning algorithms developed and demonstrated on many rotorcraft UAV platforms [70] and [71].

The overall objective of any rotorcraft UAV guidance system is to provide the vehicle with the ability to select a course of actions amongst several alternatives and based on available analysis and information. The reached decisions are relevant to achieving assigned missions efficiently and safely, and the decision-making process can differ in type and complexity, ranging from low-level decision-making (for instance, return home if the communication link is lost) to high-level decision-making, e.g., enable hover flight when movement is detected during surveillance mission.

## VII. GROUND CONTROL STATION

Ground Control Station (GCS) is an essential part of a rotorcraft UAV system. The task of the ground station is to provide a friendly and realistic interface for users to monitor the performance and state of the UAV in flight. It is also responsible for effective communications between the avionic system and ground operators. In most cases, a GCS is a stand-alone system comprising a number of hardware and software applications harmoniously integrated to provide the requirements of the vehicle monitoring and control while in flight [72]. The features supported by a GCS include data receiving in real time; data logging; data display; displaying images captured by the on-board cameras; sending control commands to the avionic system for semi-autonomous control; displaying the reconstruction of the actual flight status in a 3D virtual environment to facilitate viewing of the vehicle when it flies out of sight as well as providing an excellent human-machine interaction. Others features include facilitating the ground piloted control or automatic control, especially in unexpected situations such as an emergency landing. Often, a secure wireless link is used for communication between the vehicle and GCS

Different methods of GCS implementation have been reported [73]. In most projects, commercial operating systems (OS), such as Window or Linux are used as the base GCS software application. Other specialized software packages, such visual basic, java, C++, Matlab, Labview, e.t.c., are normally used to develop the user-friendly graphical interface (GUI) environment for GCS. The GCS is always equipped with a wireless modem for communication with the avionic system on-board the vehicle. The software structure for the ground control station is three-layer, i.e., a GUI layer in the foreground, a data transferring layer in the background, and lastly a kernel layer acting for coordinating actions between the previous two layers. There are a considerable number of free and commercial GCS systems, each with its strength and weakness, and which can be adopted easily for scientific research. For instance, some of the commercial GCS include Portable Ground Control Station [74] and HORIZON [75] by MicroPilot Inc. Canada. The open source GCS include HappyKillmore GCS [76], QGround Control [77] and Mission planner [78].

## VIII. CONCLUSION

This paper has presented a general literature review of the rotorcraft UAVs, topics treated include: history of the UAVs, area of applications, classification, centres engaged with the research and development of rotorcraft UAVs as well as UAV autonomy enabling requirements. The study has laid a foundation for further study into the design and development of the rotorcraft UAVs that can be used for numerous tasks, such as surveillance and monitoring.

## REFERENCES

- [1] K. Farid, "A Survey of Advances in Guidance, Navigation and Control of Unmanned Rotorcraft Systems", (2012).
- [2] K-MAX Helicopter: <http://www.lockheedmartin.com/us/products/kmax.html>,(2013).
- [3] Rotomotion SR-500: <http://www.rotomotion.com/>,(2013).



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International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 1, January 2014

- [4] Schieble S-100: <http://schiebel.net/>, (2013).
- [5] Black Hornet: <http://www.proxdynamics.com/>, (2013).
- [6] K. Kondak, "Virtual Blade Model Tutorial", Laboratory for autonomous flying robots, Berlin, Germany, (2008).
- [7] R. Siegwart, "Virtual Blade Model Tutorial", Autonomous Systems Lab (ASL), Zurich, Switzerland, (2012).
- [8] ARCAA, "Australian Research Centre for Aerospace Automation", (2013).
- [9] Reaper UAV: [http://www.ga-asi.com/products/aircraft/predator\\_b.php](http://www.ga-asi.com/products/aircraft/predator_b.php), (2013).
- [10] West Wales UAV Centre (WWUAVC): <http://www.wwuavc.com/>, (2013).
- [11] Israel Aerospace Industries (IAI): <http://www.iai.co.il/2013/22031-en/homepage.aspx>, (2014).
- [12] Defense Advanced Research Projects Agency (DARPA): <http://www.darpa.mil/>, (2014).
- [13] T. Krokowicz, M. Gasca, H. Voos, and D. Ucinski, "Indoor navigation for quadrotor UAVS using schematic environment maps", pp 457 -462, (2010).
- [14] M. K. Mohamed, S. Patra, and A. Lanzon, "Designing simple indoor navigation system for UAVs", pp 1223 -1228, (2011).
- [15] S. Grzonka, G. Grisetti, and W. Burgard, "Towards a navigation system for autonomous indoor flying", pp 2878 -2883, (2009).
- [16] S. Bouabdallah and R. Siegwart, "Full control of a quadrotor", pp 153 -158, (2007).
- [17] J. P. How, B. Bethke, A. Frank, D. Dale and J. Vian, "Real-time indoor autonomous vehicle test environment", Transactions on IEEE Control Systems, pp 51 -64, (2008).
- [18] E. Dill and M. U. Haag, "Integration of 3D and 2D imaging data for assured navigation in unknown environments", in 'proceedings of the IEEE/ION Position Location and Navigation Symposium (PLANS), 2010', pp. 285 -294.
- [19] G. Conte and P. Doherty, "An Integrated UAV Navigation System Based on Aerial Image Matching", in 'proceedings of the IEEE Aerospace Conference, 2008', pp. 1 -10.
- [20] M. Alpen, K. Frick and J. Horn, "Nonlinear modeling and position control of an industrial quadrotor with on-board attitude control", in 'proceedings of the IEEE International Conference on Control and Automation, ICCA, 2009', pp 2329 -2334, (2009).
- [21] H. Xiong, R. Yuan, J. Jianqiang, G. Fan and F. Jing, "Disturbance Rejection in UAV's velocity and attitude control: Problems and solutions", in 'proceedings of the 30th Chinese Control Conference (CCC), 2011', pp 6293 -6298, (2011).
- [22] I. K Nikolos, K. P. Valavanis, N. C Tsourveloudis and A. N Kostaras, "Evolutionary algorithm based offline/online path planner for UAV navigation", The Transactions on IEEE Systems, Man, and Cybernetics, Part B: Cybernetics, pp 898 -912, (2003).
- [23] D. Rathbun, S. Kragelund, A. Pongpunwattana, and B. Capozzi, "An evolution based path planning algorithm for autonomous motion of a UAV through uncertain environments", in 'proceedings of the 21st Digital Avionics Systems Conference, 2002' 8D2-1 - 8D2-12 vol.2, (2002).
- [24] B. Hui, S. Shihuang, and W. Hongyu, "A VTOL quadrotor platform for multi-UAV path planning", in 'proceedings of the International Conference on Electronic and Mechanical Engineering and Information Technology (EMEIT), 2011', pp 3079 -3081, (2011).
- [25] S. Hrbar, "3D path planning and stereo-based obstacle avoidance for rotorcraft UAVs", in 'proceedings of the IEEE/RISJ International Conference on Intelligent Robots and Systems (IROS), 2008', pp 807 -814, (2008).
- [26] H. Zhihai, R. V. Iyer and P.R Chandler, "Vision-based UAV flight control and obstacle avoidance", (2006).
- [27] T. Irps, S. D. Prior and D. Lewis, "Development of a Reconfigurable Protective System for Multi-rotor UAS", in 'proceedings of the 9th International Conference, EPCE 2011, Orlando, FL, USA, July 9-14, 2011.', pp 556-564, (2011).
- [28] J. Bell, M. Brazinskas and S. D. Prior, "Optimizing Performance Variables for Small Unmanned Aerial Vehicle Co-axial Rotor Systems", in 'proceedings of the 9th International Conference, EPCE 2011, Orlando, FL, USA, July 9-14, 2011.', pp 494-503, (2011).
- [29] M. A. Erbil, S. D Prior and A. J. Keane, "Design Optimization of a Reconfigurable Perching Element for Vertical Take-Off and Landing Unmanned Aerial Vehicles", International Journal of Micro Air Vehicles, pp 207-228, (2013).



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 1, January 2014

- [30] L. N. Jerome, "Performance Optimization for Unmanned Vehicle Systems", (2008).
- [31] K. M. Passino and S. Yurkovich, "Fuzzy Control", Prentice Hall, (1998).
- [32] L. Doitsidis, K. P. Valavanis, N. C. Tsourveloudis, and M. Kontitsis, "A framework for fuzzy logic based UAV navigation and control", in 'proceedings of the International Conference on Robotics and Automation (ICRA), 2004', pp 4041 - 4046 Vol.4, (2004).
- [33] I. Sadeghzadeh, A. Mehta, A. Chamseddine, and Z. Youmin, "Active Fault Tolerant Control of a quadrotor UAV based on gain scheduled PID control", in 'proceedings of the 25th IEEE Canadian Conference on Electrical Computer Engineering (CCECE), 2012', pp 1-4, (2012).
- [34] J. Yusong, W. Xinmin and Y. Xiang, "Robust reliable gain scheduling control for helicopters", in 'proceedings of the IEEE International Conference on Automation and Logistics, ICAL 2008', pp 1721-1724, (2008).
- [35] Z. Qiang, W. Junqing, and X. Xi, "Control system design and experiments of a quadrotor", in 'proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO), 2012', pp 1152-1157, (2012).
- [36] C. M. La, G. Papageorgiou, W. C. Messner and T. Kanade, "Design and flight testing of a gain-scheduled H infinity loop shaping controller for wide-envelope flight of a robotic helicopter", in 'proceedings of the American Control Conference, 2003', pp 4195-4200 vol.5, (2003).
- [37] K. Alexis, G. Nikolakopoulos and A. Tzes, "Model predictive control scheme for the autonomous flight of an unmanned quadrotor", in 'proceedings of the IEEE International Symposium on Industrial Electronics (ISIE), 2011', pp 2243-2248, (2011).
- [38] K. Alexis, C. Papachristos, G. Nikolakopoulos and A. Tzes, "Model predictive quadrotor indoor position control", in 'proceedings of the IEEE International Symposium on Industrial Electronics (ISIE), 2011', pp 1247-1252, (2011).
- [39] P. Bouffard, A. Aswani, and C. Tomlin, "Learning-based model predictive control on a quadrotor: Onboard implementation and experimental results", in 'proceedings of the IEEE International Conference on Robotics and Automation (ICRA), 2012', pp 279-284, (2012).
- [40] T. Dierks and S. Jagannathan, "Output Feedback Control of a Quadrotor UAV Using Neural Networks", IEEE Transactions on Neural Networks, pp 50 -66, (2010).
- [41] F. Zheng and W. Gao, "Adaptive integral backstepping control of a Micro-Quadrotor", in 'proceedings of the 2nd International Conference on Intelligent Control and Information Processing (ICICIP), 2011', pp 910-915, (2011).
- [42] A. D. Rodic, and I. R Stojkovic, "Dynamic Inversion Control of quadrotor with complementary Fuzzy logic compensator", in 'proceeding of the 11th Symposium on Neural Network Applications in Electrical Engineering (NEUREL), 2012', pp 53-58, (2012).
- [43] J. W. Tweedale, "Fuzzy control loop in an autonomous landing system for Unmanned Air Vehicles", in 'proceeding of the IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), 2012', pp 1-8, (2012).
- [44] J. L. Dong and B. Hyochoong, "Reinforcement learning based neuro-control systems for an unmanned helicopter", in 'proceedings of the International Conference on Control Automation and Systems (ICCAS), 2010'.
- [45] K. M. Passino and S. Yurkovich, "Fuzzy Control", Prentice Hall, (1998).
- [46] H. Nakanishi and K. Inoue, "Development of autonomous flight control system for unmanned helicopter by use of neural networks", in 'proceedings of the International Joint Conference on Neural Networks, 2003', Vol. 3.
- [47] M. A. Dziuk, and M. Jamshidi, "Fuzzy logic controlled UAV autopilot using C-Mean clustering", in 'proceedings of the 6th International Conference on System of Systems Engineering (SoSE), 2011', pp 305-310, (2011).
- [48] H. Nakanishi, H. Hashimoto, N. Hosokawa, A. Sato and K. Inoue, "Autonomous flight control system for unmanned helicopter using neural networks", in 'proceedings of the 41st SICE Annual Conference, 2001', pp 777-782, (2002).
- [49] I. E. Putro, A. Budiyo, K. J. Yoon, and D. H. Kim, "Modeling of unmanned small scale rotorcraft based on Neural Network identification", in 'proceedings of the IEEE International Conference on Robotics and Biomimetics, ROBIO, 2008', pp 1938 -1943, (2009).
- [50] I. C. Dikmen, A. Arisoy, and H. Temeltas, "Attitude control of a quadrotor", in 'proceedings of the 4th International Conference on Recent Advances in Space Technologies (RAST), 2009', pp 722-727, (2009).
- [51] J. L. Dong and B. Hyochoong, "Model-free LQ control for unmanned helicopters using reinforcement learning", in 'proceedings of the International Conference on Control Automation and Systems (ICCAS), pp 117-120, (2011).



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 1, January 2014

- [52] L. Mingyun, H. Yanpeng, and L. Peng, "Attitude control for unmanned helicopter using h-infinity loop-shaping method", pp 1746-1749, (2011).
- [53] H. Voos, "Nonlinear control of a quadrotor micro-UAV using feedback-linearization", in 'proceedings of the IEEE International Conference on Mechatronics (ICM), 2009', pp 1-6, (2009).
- [54] Z. T. Dydek, A. M Annaswam and E. Lavretsky, "Adaptive Control of Quadrotor UAVs: A Design Trade Study With Flight Evaluations", IEEE Transactions on Control Systems Technology, pp 1400-1406, (2013).
- [55] M. Mohammadi and A. M. Shahri, "Decentralized adaptive stabilization control for a quadrotor UAV", in 'proceedings of the 1st RSI/ISM International Conference on Robotics and Mechatronics (ICRoM), 2013', pp 288-292, (2013).
- [56] H. Bouadi, C. S. Simoes, A. Drouin, and F. Mora-Camino, "Adaptive sliding mode control for quadrotor attitude stabilization and altitude tracking", in 'proceedings of the IEEE 12th International Symposium on Computational Intelligence and Informatics (CINTI), 2011', pp 449-455, (2011).
- [57] M. Mohammadi and S. A. Mohammad, "Modelling and decentralized adaptive tracking control of a quadrotor UAV", in 'proceedings of the 1st RSI/ISM International Conference on Robotics and Mechatronics (ICRoM), 2013', pp 293-300, (2013).
- [58] K. Alexis, G. Nikolakopoulos and A. Tzes, "Model predictive control scheme for the autonomous flight of an unmanned quadrotor", in 'proceedings of the IEEE International Symposium on Industrial Electronics (ISIE), 2011', pp 2243-2248, (2011).
- [59] K. Alexis, C. Papachristos, G. Nikolakopoulos and A. Tzes, A., "Model predictive quadrotor indoor position control", in 'proceedings of the 19th Mediterranean Conference on Control Automation (MED), 2011', pp 1247-1252, (2011).
- [60] A. Aswani, P. Bouffard and C. Tomlin, "Extensions of learning-based model predictive control for real-time application to a quadrotor helicopter", in 'proceedings of the American Control Conference (ACC), 2012', pp 4661-4666, (2012).
- [61] T. Madani, and A. Benallegue, "Control of a Quadrotor Mini-Helicopter via Full State Backstepping Technique", pp 1515-1520, (2006).
- [62] Z. Zamudio, R. Lozano, J. Torres and J. L. Rullan-Lara, "Vision based stabilization of a quadrotor using nested saturation control approach", in 'proceedings of the 15th International Conference on System Theory, Control, and Computing (ICSTCC), 2011', pp 1-6, (2011).
- [63] H. Huang, P. Kerry, A. James and M. Elena, "Autonomy levels for unmanned systems (ALFUS) framework", in 'proceedings of the International Conference on Unmanned Ground Vehicle Technology, 2005', pp 439-444, (2005).
- [64] I. Astrov, A. Pedai, and E. Rustern, "Desired trajectory generation of a quadrotor helicopter using hybrid control for enhanced situational awareness", in 'proceedings of the IEEE International Conference on Information and Automation (ICIA), 2010', pp 1003-1007, (2010).
- [65] I. Palunko, R. Fierro and P. Cruz, "Trajectory generation for swing-free maneuvers of a quadrotor with suspended payload: A dynamic programming approach", in 'proceedings of the IEEE International Conference on Robotics and Automation (ICRA), 2012', pp 2691-2697, (2012).
- [66] D. Mellinger and V. Kumar, "Minimum snap trajectory generation and control for quadrotors", in 'proceedings of the IEEE International Conference on Robotics and Automation (ICRA), 2011', pp 2520-2525, (2011).
- [67] B. Hui, S. Shihuang and W. Hongyu, "A VTOL quadrotor platform for multi-UAV path planning", pp 3079-3081, (2011).
- [68] L. W. Van, S. Bellens, G. Pipeleers, J. De-Schutter, and J. Swevers, "Time-optimal parking and flying: Solving path following problems efficiently", in 'proceedings of the IEEE International Conference on Mechatronics (ICM), 2013', pp 841-846, (2013).
- [69] H. Huang, P. Kerry, A. James and M. Elena, "Autonomy levels for unmanned systems (ALFUS) framework", in 'proceedings of the International Conference on Unmanned Ground Vehicle Technology, 2005', pp 439-444, (2005).
- [70] D. Patrick, K. Jonas, and H. Fredrik, "A temporal logic-based planning and execution monitoring framework for unmanned aircraft systems", Autonomous Agents and Multi-Agent Systems, pp 332-377, (2009).
- [71] P. Fabiani, V. Fuertes, A. Piquereau, R. Mampey and F. Teichteil-Königsbuch, "Autonomous flight and navigation of VTOL UAVs: from autonomy demonstrations to out-of-sight flights", Aerospace Science and Technology (2007), 183-193.



**ISSN: 2319-5967**

**ISO 9001:2008 Certified**

**International Journal of Engineering Science and Innovative Technology (IJESIT)**

**Volume 3, Issue 1, January 2014**

- [72] D. Miaobo, M. C. Ben, C. Guowei, and P. Kemao, "Development of a real-time onboard and ground station software system for a UAV helicopter", AIAA J. Aerosp. Comput. Inf., Commun, pp 933-955, (2007).
- [73] C. Guowei, H. L. Tong and M. C. Ben, "Unmanned Rotorcraft Systems", Springer London Dordrecht Heidelberg New York, (2011).
- [74] "Portable Ground Control Station Datasheet V2.1", <http://www.robotshop.com/media/files/PDF/datasheet-stand-gcs.pdf>, (2013).
- [75] "HORIZON Ground Control Station", <http://www.micropilot.com/products-horizonmp.htm>, (2013).
- [76] Mather, P., "Happy Killmore Ground Control Station", <http://code.google.com/p/ardupilot-mega/wiki/HappyKillmore>, (2013).
- [77] Meier, L., "QGround Control Station", <http://www.qgroundcontrol.org/>, (2010).
- [78] Osborne, M., "Mission Planner Ground Control Station", <http://code.google.com/p/ardupilot-mega/wiki/Mission>, (2013).