A SURVEY OF FLIGHT CONTROL SYSTEMS AND SIMULATORS OF AERIAL ROBOTS

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Abstract: Unmanned Aerial Vehicles (UAVs) are used for wide range of applications in both military and civil operations. Flight control systems (FCS) and simulators are used for the control and analysis of UAV performance and behavior. Various components are integrated to implement both FCS and simulators. Simulators are used to evaluate the flight performance, controllability and handling quality of aircraft. As such, they are an integral part in FCS design. This paper provides a thorough review of the modelling techniques, communication systems, sensory devices, control algorithms and simulation methods that are used for the implementation of FCS. The paper discussed the role of the various components of an FCS, as well.

Keywords: Flight control system, flight simulators, unmanned aerial vehicle

Introduction

The advancement of technology has led to the deployment of Unmanned Aerial Vehicles (UAVs) in wide range of military and civil applications. For civil applications, UAVs are used in agriculture, products delivery, infrastructural development and so on (Mualla *et al*., 2019). On the other hand, UAVs are used for search and rescue missions, reconnaissance, logistics and other military applications (Peng *et al*., 2019). Flight control system (FCS) and simulators are vital systems that are used to ensure the safe operation of UAVs (Lv *et al*., 2013; Moud *et al*., 2019). Various methods and components are integrated to implement these systems. Acquiring a good understanding of these methods and techniques is crucial for the design of robust FCS. Although a review on this subject has been made in other literatures (Chao *et al*., 2010; Ebeid *et al*., 2017), based on the authors research, none has encompassed all the necessary methods and components required for designing an efficient FCS. This paper would provide a detailed review on these components and methods for readers to know the current and projected trends of FCS and simulators.

The review is presented as follows. Section two discusses various modelling approaches that are used in developing UAV models. Essential models in designing UAV systems such as FCS, provide a platform for analyzing the behavior of the UAV. Section three reviews the various communication links that are used for data transfer between the subsystems of an Unmanned Aerial System (UAS). This section also explains how the referenced UAV's controlled variables are sent to the FCS. It further describes the communication protocol that guides the exchange of data between UAS' subsystems. Section four examines the various sensory devices that are used for measuring the actual values of the controlled variables. The accuracies of the sensory devices are key to the efficiency of the FCS. Section five discusses various control algorithms that are used for controlling UAVs; this includes the advantages and disadvantages of each algorithm.

Furthermore, the section gives a suggestion on how to achieve optimal control of UAVs. Section six states the importance of simulation and simulators to FCS and UAS design. Section seven discusses the several autopilots that are used in implementing the adopted control algorithms, and other algorithms such as the mission and mode transition algorithms. Section eight provides an insight into the future of FCS, while concluding remarks are presented in Section nine.

The Communication (Telemetry, GCS), Sensor components and Flight Controller (which involves the System Modelling and the Control Algorithm) embedded on the FCS are shown in Fig. 1.

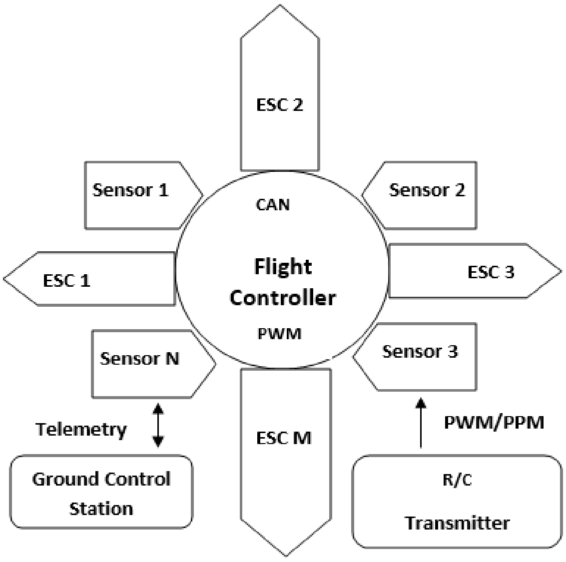

Fig. 1: UAV flight control system (Ebeid *et al*., 2017)

FCS Modelling

Design and analysis are the bedrock of any well implemented system. A good representation of any proposed system, based on its requirements, is used for analyzing its behavior under different operating conditions. One of the ways of representing a system is through mathematical modelling (i.e. representing the system using a set of mathematical equations). With the advancement of technology, models of a system can be developed by providing user specifications to software that is meant for modelling such type of system. Models of aircraft are used for designing their flight control systems (FCS), especially FCS that are developed based on model-based control algorithms. Furthermore, the models are used in simulating the overall behavior of an aircraft, as well as observing the performance of an FCS in terms of the variables (attitude, velocity, position, etc.) that are being controlled. Various methods have been used in modelling an aircraft. This paper provides a review of different approaches to modelling UAVs.

An adjusted Particle Swarm Optimization (PSO) method was used for a small UAV longitudinal parameter identification (Jiang *et al*., 2015). The mathematical model of the UAV longitudinal parameter was developed using a PSO that incorporates selective particle regeneration PSO (SPRPSO). Simulation results showed that the developed mathematical model produced better results in terms of identification of aerodynamic parameters and coefficients of the propeller than the models developed based on PSO and SRPSO alone. Also, linear longitudinal and lateral mathematical models of a fixed wing UAV were developed (Ea *et al*., 2015). In this work, the nonlinear equations depicting the motion of the vehicle were obtained. The equations were then linearized based on steady state flight conditions. The linearized model was found to provide a good representation of the nonlinear dynamics of the aircraft. The work by Sushchenko & Goncharenko (2016) performed the triaxial modelling of a UAV, which involved kinematic transformations. A matrix weighting transfer functions that ensure the design of the UAV with required amplitude-frequency-altitude were utilized. A dynamic model of a quadrotor UAV was developed using Newton-Euler approach (MohdBasri *et al*., 2015). The model was developed based on the following assumptions;

1) The quadrotor is a rigid body with a symmetric architecture.
2) Its center of mass coincides with the body-fixed frame.
3) Its aerodynamics can be neglected at low Mach numbers.
4) Its fast rotor dynamics can be neglected.

The developed model was used to design a robust control system for the quadrotor. In an effort to increase the efficiency of UAV plant protection, a three-dimensional model for a six-rotor UAV was developed (Yang *et al*., 2018). The model was developed based on Navier-Stokes equation and SST K-ε turbulence model. The model was used for the numerical analysis of the droplet problems that is faced by multi-rotor UAV, while spraying pesticides in farmlands for plant protection. In a research work conducted on attitude control (Oosedo *et al*., 2015), the dynamic model of a quad tilt rotor UAV was developed using the translational and rotational dynamic equations that fits the aircraft. The model was used in developing the FCS that controls a large attitude change of the vehicle.

A UAV with electrostatic spraying feature for crop protection was modelled by Zhang *et al*. (2017). The 3D model of the six-rotor UAV was developed using Unigraphics (UG) software. The parameters that were used for modelling the vehicle are; maximum flight velocity, maximum load, number of rotors, rotor diameter, vehicle dimension, flight duration, water pump power, water pump flow rate, number of nozzles and nozzle mast length. In consideration of crop protection operational requirements with regards to different UAV models, the six-rotor UAV was found to have better stability than a four-rotor UAV, and consumes less energy than its eight-rotor counterpart. In a similar work (Zheng *et al*., 2018), a plant protection multi-rotor UAV was developed using Solid Works. The model was used to study the features of downwash airflow as well as observe the static wind area of multi-rotor UAVs in hovering state. The main parameters that were used for the development of the physical model are; flight height, main rotor diameter, size, weight, maximum load and effective remote-control distance.

The reviewed UAV models were used for analyzing the behavior of the vehicle and/or for the design of a system that is required for the operation of the vehicle, such as the FCS. For effective analysis of a system's behavior and the design of a robust controller, a nonlinear model that captures almost all of its dynamics would be the ideal option (Katz *et al*., 2018). Such models could be obtained by using first principles derivation (Hermann *et al*., 2017; Rohr *et al*., 2019). However, development of models from first principles is computationally expensive, especially for complex systems (Katz *et al*., 2018). Experimental methods such as black-box and grey-box system identification techniques are an alternative of easing this difficulty, but at the expense of having some dynamics uncaptured since they are based on approximations (Gill & Andrea, 2019). A summary of the pros and cons of the two-modelling technique discussed is summarized in Table 1. Therefore, proper trade-off between the degree of accuracy required and the complexity involved should be made while developing a model.

Table 1: Advantages and disadvantages of different modelling techniques

Modelling Techniques	Advantages	Advantages
First Principle	Accurately captures the system dynamics.	A prior knowledge of the system is required.
System Identification	Prior knowledge of the system is not required when this technique is employed.	The fidelity of the model developed depends on the appropriateness of the input signal used in the modelling process.

Communication Systems

Communication systems for UAV entail selection of suitable spectrum and protocol for data exchange. It is analyzed based on the operating distance, required bandwidth and interface to other systems (Yan *et al*., 2019). Communication systems are used for sending radio transmitted digital commands to the FCS from ground control station (GCS) (Koubaa *et al*., 2019). These commands serve as reference values to a UAV's controlled variables. Since the radio control (RC) transmitter and GCS influence the operational performance of UAVs, it is therefore necessary to establish a reliable communication link for the systems to interact. This section categorized communication links between UAV subsystems based on criticality; then analyzed the structure and suitability of different communication protocols already developed for UAV (Agriculturae *et al*., 2016). Depending on the criticality and the user's intent, communication link is grouped into essential and complementary data link. Essential link is the one required for safe flight control, video link could also be essential where reconnaissance is desired, other links used for obtaining weather parameters, monitor onboard sensors are complementary links, usually as a separate or redundancy for the essential link. Fig. 2, shows a general model containing the essential (command and control link), and the integration of other links such as the payload and video system to make a complete air- ground. Table 2 in Okcu (2016) highlight the classification of communication link with common designed frequency range, data and connection type. The data in the table varies in some countries based on the law and dedicated spectrum for UAV communication. The command-and-control link allows UAV to be directed by the pilot, with a feedback for monitoring, therefore it is required to be duplex, while the video and payload are downlink for telemetry data and video feed with higher bandwidth. The essential link includes:

1. **GCS – UAV link:** This could be a specially designed hardware and software or a software running on an operating system. It provides a visual data on GCS interface for drone operator to monitor live UAV operation, set waypoints, execute new commands through a telemetry hardware radio unit attached to radiate and intercept UAV signals (Ebeid *et al*., 2017).
2. **RC – UAV link:** A designed and portable hardware used to control UAV's 3-axis of movement (pitch, roll, and yaw), and throttle settings. The pulse width modulation (PWM) and pulse position modulation signals are mapped with control commands, and transmitted to the onboard FCS to activate the motors and control surfaces based on the received command (Ebeid *et al*., 2017).

The necessity of complementary links depends on the field of application, which may include:

1. **Video link:** This is a dedicated link for real-time monitoring of event, airborne video image to give a continuous view of the UAV onboard system in the most intuitive and accurate form. This link is used for disaster management, surveillance and tracking of a ground target, which may require live video stream. It is separated from essential link to prevent unnecessary delay and interference it may incur.
2. **Payload link:** the payload link is mission critical but not essential to the flight. Data including battery voltage level, temperature, pressure and humidity are payload data to ensure the success of the mission (Vasile *et al*., 2019).

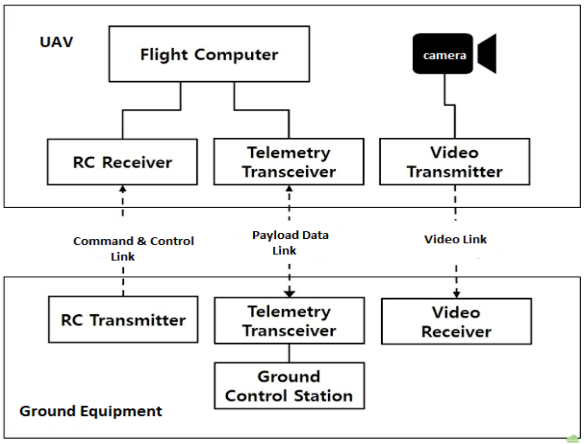

Fig. 2: Air – Ground communication architecture for UAV

To exchange any form of data between subsystems e.g. the GCS and RC communication with the onboard flight controller, the subsystems involved must agree on a common principle known as communication protocol, which specify the format of data exchanged between both parties. Protocol makes it easy to encode and decode information needed for control and monitoring of UAV operation. It basically contains the header, payload and footer. The header precedes the message and contains sender/receiver data length and type. The payload is the actual message, while the footer carries control and information fields to ensure error-free reception of the information. Most attacks on modern UAS are usually on its communication links. Hence, it is necessary to emphasize on the structure and vulnerability of data exchange protocol, to ensure improvement from developers and consideration for potential users. Some of the commonly used protocols on UAV includes Uranuslink, UAVCAN and MAVLink protocol.

- The Uranus link is one of the early protocols designed for radio systems to facilitate both reliable and unreliable packet-oriented protocol (Kriz & Gabrlik, 2015).
- Uranus link is a lightweight protocol having its bytes varied between 6 to 258 for empty and full payload, respectively. To have a balance between overhead and robustness, an optimum preamble and checksums row are selected.
- **UAVCAN** was developed to provide connectivity for vehicular networks such as CAN (controlled aerial network) and buses for avionics equipment. It supports multiple nodes and performs well on publish-subscribe architecture and having all the nodes with the same level of priority. As a result, the chances of failures are rare since the nodes transact payloads that are accommodated on a single CAN frame (Khan *et al*., 2020).

MAVLink protocol is one of the most widely used protocol on modern UAVs. MAVLink messages are exchanged between the onboard controller and GCS. It is a binary-serialized protocol, that communicated using bits to achieve light weight. The MAVLink 1.0 has now been upgraded to version 2.0 by replacing the starting frame of the former 0XFE with 0xFD, one of the significant changes is the MSGID header of 1 bytes that is increased to 3 bytes with appended signature field of 13 bytes to enforce more security on the link against tamper. Hence, all MavLink messages are verified before it is being parsed (Koubaa *et al*., 2019).

Table 2: Classification of UAV data link

Communication Link	Direction	Connection type	Data type	Frequency (MHz)	Data rate (Kbps)	Priority
GCS- UAV	Uplink& downlink	Full duplex	text	136–2400	Low < 30	Essential
RC – UAV	Uplink	Simplex	text	136– 2400	Low < 30	Essential
Video Link	Downlink	Simplex	video	433-5400	High < 1000	Complementary
Payload Link	Downlink	Simplex	text	136– 2400	Low < 30	Complementary

Table 3: Comparison between UAV communication protocols

Protocol	Weight	Application	Multiple Language support	Supported network	Error detection	Scalability
UranusLink	Light	Aerospace/ robotic	No	Wi-Fi	Yes	No
UAV CAN	Light	Real time systems	No	Wi-Fi	Yes	No
Mavlink	Light	All application	Yes	Wi-Fi, IP network, Ethernet	Yes	Yes

One of the merits of MAVLink protocol over others is its adaptability to different transport layers and multiple language. It supports Wi-Fi, Ethernet data transmission, as well as serial telemetry channels operating at sub-GHz frequencies (433 MHz, 868 MHz and 915MHz). Sub-GHz frequencies allow large communication ranges for the control of UAV remotely up to 250 kbps, its footer contains 2 bytes for the checksum (CKA and CKB). Cyclic redundancy check (CRC) calculated with seed values A and B to ensures that the message has not been changed during its transmission (Khan *et al*., 2020). MAVLink supports most wireless networks, its application includes robotics, aerospace and control systems, other protocols such as UranusLink are developed primarily for aeronautics while UAVCAN was developed for real time systems. MAVLink support for multiple language gives it edges over others in the market, new radios and equipment being designed can now be easily interfaced with others using MAVLink protocol. The comparison between the discussed protocols UAV based on application and scalability is shown in Table 3.

Since UranusLink was purposely designed for radio ways where incorrect or data loss are much expected, the checksum only validates whether the received message is altered or not. It is therefore risky to exchange confidential data over it. On the other hand, the developer of UAVCAN has categorically stated that no provision was made for shielding and it is not intended for mission-critical and safety-critical systems. The remaining and most widely used protocol is the MAVLink. Since the initial frame STX value is aimed at verifying the MavLink messages, the appended signature of the enhanced version MAVLink 2.0 supports multiple language with minimal latency and can verify or discard messages with altered signature, thus the data integrity is guaranteed. However, since there is no direct encryption mechanism in MAVLink, as encrypted message would change the header value and make it difficult to recognize whether it is a MAVLink packet or not.

Sensory devices

Sensory information is crucial for the control and navigation of UAVs. The technology of sensors used on UAVs is mostly based on the UAV size and the type of data that is to be measured (Arfaoui, 2017). Critical to the creation and realization of small unmanned air vehicles has been the development of small, lightweight solid-state sensors. Based on microelectromechanical systems (MEMS) technology, small but accurate sensors such as accelerometers, angular rate sensors, and pressure sensors have enabled the development of increasingly smaller and more capable autonomous aircraft (Beard & Mclain, 2012).

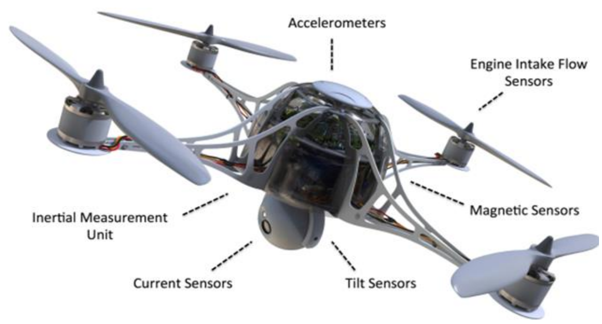

Fig. 3: Sensor technologies for modern UAVs (Chris Winkler, 2016)

There are many categories of sensors, among which are; the speed and distance sensors that measures the speed at which the UAV moves and its distance away from another object, respectively. The distance sensors measure the distance of a detected object without physical contact with the object, and this can be achieved in many ways. For example, the measurement is achieved through Sonar-pulse distance sensing, light-pulse distance sensing and the magnetic-field change sensing. The data obtained from speed and distance sensors are also used to compute for UAV's collision avoidance, navigation, and altitude measurement. Another category of sensors are the infrared and thermal sensors, which are used for surveillance and obstacle detection. Furthermore, there are image sensors that detect and give information about what has to do with image, and this is achieved by converting attenuation of light waves into signals. Also, there are chemical sensors, which are self-contained devices that can be attached to UAVs to extract data relating to chemical properties of a body or environment. The transducers connected to this device send signals when a change occurs (Ebeid *et al*., 2017). Fig. 3 shows the various sensor technologies that are used on UAVs. Table 4 highlights the most important sensors commonly on UAVs with their characteristics and application.

Accelerometers

Accelerometer is a sensor used to determine the position and orientation of a UAV in flight. They are small silicon-based sensors that are used for flight control to ensure safety. The technology senses the micro displacement of small structures that are in the small integrated circuit. The displacement of these structures changes the amount of electrical current flowing through the structures, showing a change in position relative to the gravitational force.

Inertial measurement unit and global positioning system (GPS)

The Inertial Measurement Unit and GPS (Global Positioning Systems) are sometimes combined for maintaining direction and paths of flight. As UAV development increases and becomes more autonomous, they became essential for air traffic control and adherence to flight rules. An inertial measurement unit uses multiple axis magnetometers that are relatively small with accurate compasses. These data are fed to the central processing unit when it senses changes in orientation, it ultimately shows direction, speed and orientation.

Tilt sensors

Tilt sensors combine with gyros and accelerometer to provide input to the flight-control system in order to ensure safe flight. This is much more essential for application areas where stability and surveillance are paramount. And it enables slight variations in displacement to be detected. the compensation from gyroscope allows tilt sensors to be used in mobile object applications such as UAVs and vehicles.

Range sensors

Range sensors are devices that capture the three-dimensional (3-D) structure of the world from the viewpoint of the sensor, usually measuring the depth to the nearest surfaces. The benefits of this range data is that a robot can be reasonably certain where the real world is, relative to the sensor, thus allowing the robot to more reliably find navigable routes, avoid obstacles. It is possible to acquire range information from many different sensors, but only a few have the reliability needed for most robotics applications. The more reliable ones, laser-based triangulation and laser radar (LIDAR) (Fisher & Konolige, 2008).

Magnetometers

These are sensors that give the heading of the UAVs, the senses attitude with respect to local magnetic field: the local declination is sum up in order to give the magnetic heading of the UAV. Miniaturized magnetometers are done based on the Anisotropic magneto resistance principles normally the material changes its internal electric resistance when it is open up to magnetic field.

Pressure sensors

Pressure sensors are used to estimate the altitude and airspeed of the UAVs, they are usually made out of piezoelectric materials and also miniaturized and cheap. To measure altitude, it uses absolute pressure the atmospheric pressure is smaller the higher we fly and to measure the airspeed it uses the differential pressure of the static or ambient pressure and the dynamic pressure Bernoulli's principles to capture the airspeed in flight.

Rate gyro sensor

Rate gyro is used to measure the angular rate of change of the UAV and it works with the principles of coriolis the point translating on a rotating rigid body experience and acceleration which is called the coriolis acceleration that is proportional to velocity of the point and the rate of rotation of the body.

Camera sensors

Camera sensors are used to determine size of image-low light performance, resolution, depth of field, lenses, and even the cameras physical size. An image sensor is used to convey or detect information used to form an image. It is achieved by changing the variable attenuation of light waves into signals, small burst of current that carries the information. The image sensor is a device that enables the camera to convert photons into electrical signals which are further processed to produce images. Some sensors are combined together to be used on board of the flight control system of the UAVs to reduce weight and improves the endurance and performance of the UAV, like the inertial measurement Unit (IMU) combines the accelerometer, magnetometer and rate gyro sensors to work together.

Control algorithms

Control algorithm is one of the most important aspect of FCS. It is the set of sequential steps based on which a flight controller computes the control signal that adjusts the vehicle's behavior, through actuators, to ensure stability and trajectory control. For the best flight performance of UAV, the controller requires a robust control algorithm, which would ensure optimal stability (Wang & Wang, 2020). The Autopilot system is used to generate the control signal to autonomously operate the UAV, the control signal is a function of the control algorithm that ensures excellent working performance Control algorithms could be classified into linear control and nonlinear techniques (Nguyen *et al*., 2020). Table 5 in (Nguyen *et al*., 2020) pointed out the performance of all the mentioned techniques that has been surveyed and discussed based on performance evaluation and experimental results, and each technique has advantages and disadvantages. The nonlinear techniques have better performance than the linear techniques when deployed on real UAVs.

It is clear that even the best linear or nonlinear algorithms have limitations (Zulu & John, 2014). Researchers have tackled this by combining multiple algorithms. Therefore, the combination of multiple control algorithms is the solution to achieving optimal control of UAVs. Simulation results of several control algorithms indicated that single neuron adaptive PID control algorithm had some great advantages (Li *et al*., 2010), Its response time was fast, and overshoot was small in the warp tension control system; therefore, this multi-algorithm controller are recommended in order to gain the advantage of fast response and small overshoot in UAV flight attitude and altitude control.

Table 4: Main UAV sensors characteristics

Sensors	Accelerometer	GPS	Rate Gyro	Pressure Sensor	Magneto-meter	Tilt Sensor	IMU	Range Sensor
Characteristics	Mounted near the center of mass. Can be used to measure inertial motion and acceleration in multiple directions.	Satellite-based navigation system to provide 3-D position information for objects on or near the earth's surface	Uses the Coriolis effect to measure changes in orientation and rotational motion around each of the three axes.	Measures absolute and differential pressure.	Measures the strength of the magnetic field along three orthogonal axes.	Measures tilt or slope within a limited range of motion.	Closed system that detect changes in angular rate and velocity.	obtain range data for UAV
Application	Accelerometers measure the specific force in the body frame of the vehicle. Used for motion tracking.	Flight navigation and velocity measurement,	Measures angular velocities around each of the three axes.	Altitude can be measured using absolute pressure while air speed is measured using differential pressure.	Used as a navigational aid.	Flight control	Acceleration and rate of change in attitude (roll, pitch, and yaw rates)	Used as a navigational aid and terrain characterization.

Table 5: Summary of different techniques for quadrotor control

Controller	Conventional PID	Intelligent PID	LQR	H1	Feedback Linearization	Back Stepping	Sliding Mode Control (SMC)	Adaptive Control	Model Predictive Control (MPC)
Methods	Heuristic optimization and Adaptive pole placement.	Self-learning, Fuzzy algorithm and PSO algorithm.	Multi-variable control, Open loop response and Pigeon-inspired optimization.	Using two loops, State feedback and Glover-McFlane loop shaping.	Dynamic inversion method, exact feedback linearization, quasi-static feedback linearization.	Controller decom-posed into several steps. Also, combined with SMC.	Sliding mode disturbance observer approach. Adaptive SMC based on backstepping.	Adapting to parameter changes based on Lyapunov stability.	Dynamic model of system to predict the future states.
Advantages	Simple	Adaptive and quick.	Optimal, stable and robust.	High robustness and tracking ability.	Flexible with good tracking	Fast convergence and good tracking.	Robust and quick.	Robust, flexible and optimal.	Good tracking, optimal and robust.
Disadvantages	Low intelligence and optimality	Not robust and susceptible to noise.	Not simple Lack of robustness Not intelligent	Complex, slow convergence and unintelligent	Excessive modelling And poor disturbance rejection	Not robust	Not applicable to all systems, can also have high energy loss.	Requires exact modelling.	Computationally intensive.

Simulation and simulators

Simulation of systems behavior is becoming increasingly important in a design process. It helps in predicting the real behavior of a system, which could be used in adjusting unwanted responses from the system. This trend is not an exception for UAS, which need more integration of complex software systems that would improve the safety, reliability, and performance of these systems (Day *et al*., 2015). Table 6 adapted from (Ebeid *et al*., 2018) gives a description of several open-source simulation platforms, including operational characteristics, implementation language, supported operating system, and licensing terms that are used for simulating UAS.

New Paparazzi Simulator predicts the behavior of complex UAVs. Different flight dynamics models like MATLAB/Simulink can be connected to the simulator (Ebeid *et al*., 2018). It also Support rotorcraft and fixed-wing UAVs airframes. These functionalities make it closest to reality.

Aerial informatics and robotics platform (AirSim): This is a simulation platform that was developed in 2017 by Microsoft with the goal of generating algorithms for autonomous vehicle applications (Ebeid *et al*., 2018). The AirSim physics engine operates with high frequency for real-time hardware-in-the-loop (HIL) simulations, and can support renowned protocols such as MavLink. The platform supports Iris UAVs in both X-configuration, for PX4 quadrotor, and Multirotor model.

Gazebo: This is a simulation platform that was developed at the University of California in the year 2002, with the goal of providing an environment for simulating robots under different conditions (Rivera *et al*., 2019). Gazebo is a 3D simulator that has the capability of integrating various physical engines and can be used to develop and add models of robots, sensors, actuators, buildings, among other static objects (Rivera *et al*., 2019). User interfaces are used for controlling and interacting with the simulated robots (Rivera *et al*., 2019).

Java micro air vehicle simulator (jMAVSim): This is a multirotor simulator developed by PIXHAWK engineering team, and has the operational capability of supporting MAVLink protocol and visualization using the Java3D library (Ebeid *et al*., 2018).

New paparazzi simulator (NPS): is simulator that was developed at Ecole Nationale de l'Aviation Civil (ENAC) UAV Lab. It has various sensor models, and its default flight is JSBSim, which supports sophisticated airframes (Ebeid *et al*., 2018).

HackflightSim: This is a cross-platform quadcopter simulator that was developed in 2017 at Washington and Lee University Lexington, USA. HackflightSim is implemented with C++ programming, uses Unreal Engine 4, and is developed based on Hackflight firmware (Ebeid *et al*., 2018). HackFlightSim focuses mainly on quadcopter firmware.

Researchers have developed various simulations tools, which can be used at the developmental stage of a system to scrutinize and properly adjust its behavior for conformity with design specifications. The simulation platforms described in this section could serve as a guide for selecting the proper platform for simulating an UAS.

Autopilot hardware

Autopilots are systems that enable autonomous UAV operation with little or without any assistance from human operators. The UAV guidance in flight can be achieved using an autopilot (Chao *et al*., 2010; Rasi *et al*., 2020). An autopilot sits between flight control receiver and the servo that are used to operate the UAV throttle and aerodynamic control surface (Keane *et al*., 2017). A UAV autopilot system is basically a closed-loop control system; it has two parts namely the controller and the state observer. The state observer is mainly the micro inertial guidance system including magnetic sensors, gyroscope and accelerometers. Also, there are devices available that determine altitude like infrared or vision-based ones. The reading obtained from sensors in combination with information from GPS is passed to a filter, which generates the current state estimates for control use.

Generally, due to the different control strategies, the UAV autopilots can be categorized into fuzzy based autopilots, PID (Proportional Derivative Integrative) based autopilots, Neural network-based autopilots and other robust autopilots. The key advantage of PID-based controllers is they are easy to tune and to understand. Moreover, PIDs give designers a better control of the system dynamics. The major drawback of PID autopilot is that when there is wind disturbances, it need to be re-tuned by changing PID control gains, hence it lacks the capability to adapt to changes due to variation in UAV dynamics or in cases when the payload characteristics are changed (Mammarella & Capello, 2018).

A typical Commercial off the shelf (COTS) autopilot system in UAV consists of the micro inertial guidance system, the GPS receiver and the processor onboard (that is responsible for state estimation and flight control) as shown in Fig. 4.

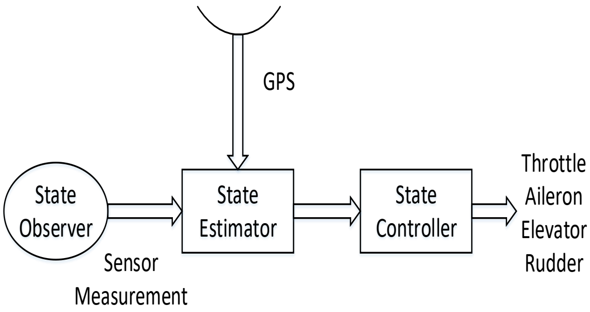

Fig. 4: Functional structure of the UAV autopilot (Chao *et al.*, 2010)

Hardware component autopilot

An autopilot system basically includes onboard processors for estimation, sensor packages for state determination and peripheral circuits for modem communications & servo. The limitation associated with small UAVs is their limited size. Consequently, the autopilot should be of small size, consume low power and should be of light weight. In addition, to obtain an accurate UAV flight control, its altitude in the air must be observed with precision. Moreover, the sensor packages should also guarantee a good performance, especially in a mobile and temperature-varying environment.

Open-source autopilot

This category of autopilot can be modified based on used requirement, and it has flexibility in hardware and software. Table 7 adapted from (Ebeid *et al.*, 2017) shows some examples of open-source hardware (OSH) platforms. Common examples of OSH platforms include the following:

a) Atmel-based platforms
b) Raspberry Pi based platforms
c) ARM-based platforms
d) FPGA based platforms.

a) Atmel-based platforms: examples of the platforms are fly maple and Ardupilot Mega (APM).

Fly Maple: Its design is based on Arduino style ARM processor, and it is normally used as control board for quadcopter. It is designed to run on Helicopter, mobile platform and quadcopter that require high-performance real time controllers and Inertial Measurement Unit (IMU) (Ebeid *et al*., 2017).

Ardu Pilot Mega (APM): This is an arduino mega based autopilot with capability to control autonomous fixed wing aircraft ground rovers, multicomputer and antenna trackers (Ebeid *et al*., 2017).

b) Raspberry Pi based platforms: example is Erle brain 3

Erle-Brain 3: This was developed by Erle robotics located in Spain, and it is Linux based (Ebeid *et al*., 2017). It combines a raspberry Pi (an embedded Linux computer) and another board (PXF Mini) that has several sensors, power electronics, input and outputs.

c) ARM-based platforms: some examples under this category includes Pixhawk autopilot, Paparazzi autopilot and CC3D & Atom.

Pixhawk autopilot

Paparazzi: The central processor is made up ARM chip. Its software can achieve auto takeoff and landing, altitude hold and way point tracking. paparazzi are indeed autonomous that hardly rely on ground control station. The drawback of this autopilot is that it lacks a good speed hold and changing function, because of lack of air speed sensor reading at its controller part.

d) FPGA based platform: Examples include octagonal pilot on Chip (OcPoC) developed by aerotenna company and Phenix Pro (Ebeid *et al*., 2017).

i. **OcPoC:** It has fully programmable ppm, pwm and GPIO pin which can be integrated with a variety of additional sensor. It has standard connectors for other peripheral like camera link, SD card and GPS. The Ardupilot software platform that runs on OcPoC has the capability of processing sensory data in real-time.

ii. **Phenix Pro:** It is equipped with Linux based robot operating system and a real time operating system. it has over 20 interfaces. Interface like Ultra vision HD, mm Wave, radar, on board sensors, ultra-vision HD video transceiver through SDN (software defined Radio) etcetera (Ebeid *et al*., 2017).

Table 6: Comparison of open-source simulators for UAVs

Platform	Characteristics	Implementation Language	Supported Operating System	License
AirSim	• Support MavLink Protocol • Used for X-configuration Quadcopter and multirotor simulation	C++	Windows, Linux	MIT
Gazebo	• Do not support MavLink Protocol. • Simulate Quadrotor and other UAV configurations.	C++	Linux, MacOS	Apache V2.0
jMAVSim	• Support MavLink protocol • Used for Multirotor simulation.	Java	Linux, MacOS, Windows	BSD 3
New Paparazzi	• Support range of relatively complex UAV airframe.	C	Linux, MacOS	GPLv2
Hackflight	• It focuses only on Quadcopter firmware.	C++	Linux, Windows	GPL

Table 7: Open source autopilot hardware platform comparison

Platform	Development	Sensors	Processor	Power Consumption (watts)	Interfaces	Weight (g)	Source/ URL
Atmel Based	a). fly Maple	IMU Barometer	STM32	$\approx$ 1.6	PWM, UART, I2C	15	www.ardupilot.co.uk
	b). APM 2.8	IMU, Barometer, LED	ATMEGA2560	$\approx$ 1.6	ADC, UART, I2C	31	http://opwiki.
Raspberry Pi based	Erle-Brain	IMU, Barometer	Raspberry Pi	$\approx$ 1.6	PWM, UART, I2C	15	www.emlid.com
ARM based	a) PixHawks	IMU, Barometer, LED	ARM cortex-M4F	$\approx$ 1.6	PWM, UART, I2C, ADC, CAN	38	www.pixhawk.org
	b) Paparazzi	IMU, Barometer	STM32F767	$\approx$ 1.6	I2C, UART, AUX, SPI, CAN	38	www.paparazziuav.org
FPGA	a). OcPoC	IMU, Barometer, GPS, WIFI	ARM Cortex-A9	4	Ethernet, SPI, JTAG, PWM, CAN	70	www.raerotenna.com
	b). Phenix	IMU, LED, HUB, GPS	ARM Cortex-A9	2.6	HDMI, CAN, LVDS, Camera Link	64	www.robsense.com

Design of autopilot controller

Controllers used by autopilot for control of flight are categorized into two distinct groups, which are;

a) Heading and velocity controllers are responsible for way point navigation guidance. Heading controllers are designed with the use of outer loop of PID controller in many UAVs. By deflecting the ailerons, the heading control could be achieved by implementing PID controller in the feedback path of the system – the yaw angle is set as input. The sideslip and yaw angle are combined in some cases to give a heading angle, but the side slip angle must be kept near zero, to have a smooth flight. Otherwise, there would be cross couplings effects between the control surfaces while on flight, except with the use of loop shaping controller as an inner loop. The velocity controller is designed from the longitudinal plane model, using pitch or throttle command. The setting for acceleration is adjusted, using a proportional derivative PD controller to smooth the velocity response based on geometric method (Xu *et al*., 2018). Also, (Kimathi *et al*., 2015) employed adaptive controller based on reinforcement learning, this is achieved by using *sarsa* algorithm for error correction, with the update of neural network weights. Reward function r(s) is then estimated as the difference between the target and desired state to compute the total value function. At each cycle, the total value function is computed as the sum of the current reward function, the current and previous state-action value for the next cycle of learning.

b) Altitude Controller: is responsible for controlling the take-off and landing process. Hence, it is primarily meant to drive the UAV to a specified altitude. The altitude controller could be designed from the longitudinal model of the UAV, using the PID controller. The controller keeps the thrust constant, and uses the velocity feedback to control the airspeed. Elevator is deflected as input to vary the aircraft altitude; thus, the altitude information is attained with the feedback of the pitch angle and the proportional gain. Also, a phase lead compensation technique could be employed, in order to improve the transient response of the system, which involves application of feed rate feedback to the longitudinal sub model. The climb rate using this approach is uniform; nonetheless, it takes longer time compared with the PID controllers (Ahsan *et al*., 2013).

Future trends in UAV control systems and simulators

The development of sensor technologies (miniaturization) and improvements in embedded computing capacity, the autonomous control capability of UAVs (autopilot) will significantly improve the performance of the UAVs – by automatically controlling the speed, altitude, position, flight path and attitude control. While most autopilots are designed using PID controllers, adaptive controller and phase-lead compensator are promising approaches for better transient response, most especial for altitude and airspeed design on the longitudinal plane. However, there is need to enhance the design of controllers to compensate for uncertainties involving sudden changes due to sensor failure and weather changes. In other words, when mission conditions change either externally or internally during flight, the UAV will have the ability to control its flight state autonomously. In essence, it can avoid the already present flight path. It will only return to its original flight path when the abnormal condition disappears, or after completing the mission.

In designing autopilots, simulation is essential for development phase of the flight control systems since they aid in visualizing the performance of the UAV. MATLAB / Simulink and X-Plane have been powerful simulation tool that have been used to implement and validate FCS. In the future it will be ideal to have an appealing standalone platform that would facilitate the study, design and simulation of various design for autopilot systems for real-time monitoring of VTOL, fixed wing and Hybrid UAV.

Conclusion

This paper presents the major components and techniques involved in the development of FCS and simulators for UAVs. It also provides insights on the future trends in the development of FCS and simulators. FCS and simulators are an integral part of UAS. These units are used to ensure stable operation and observation of UAS behavior. Advancements in UAV technology have the potential to develop transportation as well as security infrastructure in sub-Saharan Africa. More so, it could also help domesticate other enabling technologies like battery technology, micro-electromechanical systems, data communication, material technology and 3-D printing.

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