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Review on Unmanned Aerial Vehicles (UAVs) Control Systems

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Abstract

Recently, the great interest in using robots in various applications has led to great advances in using unmanned vehicles in highly expensive, risky and tedious work. So far, a lot of unmanned vehicles have been developed to accommodate various applications in different working environments, such as unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs).

The use of UAVs has been increased in various applications for replacing human, especially in those tasks that threat human life. UAVs can be used in civilian applications as well as military ones, as in emergency situations such as in nuclear disaster, volcano, flood, forest fire fighting and rescue. Among all types of UAVs used, mini helicopters and quadrotors are the most used vehicles due to their low cost, maneuvering capability and vertical take-off and landing (VTOL) characteristics. These types of aerial vehicles can be easily used in hovering position, which enable us to use these vehicles easily in search, exploration and monitoring missions.

For complete use of these vehicles, UAVs should have a high level of autonomy and mostly preferred to work cooperatively in groups rather than working individually. Using cooperative UAVs allow them to share information for rapidly and effectively accomplishing their mission.

This report aims to make a critical review on the development of UAVs guidance, navigation and control (GNC) techniques. Control is mainly used in trajectory tracking, obstacle and collision avoidance, and is responsible of calculating actuator dynamics to reach desired position and velocity of the UAV (or UGV, USV, UUV etc.) for mission completion.

This report is organized as follows. In Section 1, an introduction, historical review and different UAVs categories are illustrated. In Section 2, general structure of UAV is explained with its guidance, navigation and control functions. In Section 3, control of UAVs is discussed containing quadrotor mathematical model, various control methods, vision-based control systems and obstacle avoidance control. In Section 4, review on different coordination and formation strategies for multiple unmanned aerial vehicles and an example of UAVs cooperation are given. Finally in Section 5, the conclusion of the reviewed work is provided.

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1 Introduction

1.1 History of Unmanned Aerial Vehicles (UAVs)

In the last century, various types of unmanned vehicles have been receiving growing attention and have been used for various military and civilian applications in air, space, sea, and on the ground. They are developed to be capable of working without human assistance in complicated and uncertain environments, which enables longer endurance [6, 7].

Moreover among various types of unmanned vehicles used, the importance of UAVs appeared earlier in several military applications. Their developments started during the World War I and increased more in the World War II, when they have been used in attacking naval, land targets and in aerial reconnaissance [6]. UAVs are also known as drones, remotely operated aircrafts (ROAs), remotely piloted vehicles (RPVs), and unmanned aerial systems (UASs). UAVs are continuously developed very rapidly and becoming an important assistant to human beings. However, difficulty in controlling trajectories and communication of UAVs is still a challenge till now.

1.2 UAVs Classification

Based on their shapes and geometric structures, UAVs can be roughly characterized into the following four categories [8]:

- Fixed-wing UAVs
- Rotory-wing UAVs
- Flapping-wing UAVs
- Other unconventional UAVs

Among them, the fixed-wing and rotory-wing UAVs are currently the dominant in most of practical applications [7]. Furthermore, most of the major research interests are focusing on small UAVs which called miniature aerial vehicles (MAVs). This type of UAVs has several advantages when used in air surveillance, search and rescue missions in complex environment after disasters, such as earthquakes, explosions and fires. MAVs are capable of flying in narrow places, searching for victims, and sending their coordinates for rescue [5].

Moreover, an important type of UAVs is the vertical take-off and landing (VTOL) vehicle, which are considered very important because of their challenging control problems and their broad fields of applications. As widely known, VTOL vehicles have specific characteristics like flying in very low altitudes and easy for hovering. These characteristics make them suitable for a lot of applications compared to other types as fixed-wing vehicles. Table 1 presents a short comparison between different types of mini VTOL vehicles. Letter A stands for Single rotor MAVs, B for Axial rotor, C for Co-axial rotors, D for Tandem rotors, E for Quadrotor, F for Blimp, G for Bird like and H for Insect like. From this table, quadrotor and coaxial helicopter are among the best configurations when used as UAVs [5].

1.3 Quadrotor UAV

A quadrotor is a rotary-wing UAV composed of four rotors laid up symmetrically around its center. It is capable of hover, forward flight and VTOL. Hence, it is classified as a rotary-wing VTOL aircraft. Although the term “Quadrotor” is the most common, other terms are used to refer to this vehicle, such as “Quadrocopter” (German). Other terms are trademarked, like “quad copter” [9]. This configuration is relatively rare amongst helicopters, most helicopters are fitted with one main rotor and a tail rotor to compensate the reaction torque.

Table 1: VTOL vehicles comparison [5]

Item	A	B	C	D	E	F	G	H
Power cost	2	2	2	2	1	4	3	3
Control cost	1	1	4	2	3	3	2	1
Payload/volume	2	2	4	3	3	1	2	1
Maneuverability	4	2	2	3	3	1	3	3
Mechanics simplicity	1	3	3	1	4	4	1	1
Aerodynamics complexity	1	1	1	1	4	3	1	1
Low speed flight	4	3	4	3	4	4	2	2
High speed flight	2	4	1	2	3	1	3	3
Miniaturization	2	3	4	2	3	1	2	4
Survivability	1	3	3	1	1	3	2	3
Stationary flight	4	4	4	4	4	3	1	2
Total	2.2	2.5	2.9	2.2	3	2.5	2	2.2

Key: **1**=sufficient, **2**=good, **3**=very good, **4**=excellent

There are two basic reasons for the quadrotor not widely used previously. First, the majority of the usual payloads can be lifted using one or two main rotors, hence there is no need for more rotors, which increase the weight and the complexity of the vehicle. The other reason is the lack of experience in designing helicopters of this type. However this trend has been changed recently, and quadrotor is now used in a lot of applications because of its advantages compared to other configurations as shown in Table 1.

2 Unmanned Aerial System (UAS) Structure

UASs consists of two basic components. The first one is the UAV with its subsystems while the other is its ground control station (GCS), as well as communication devices for UAVs and GCS. The GCS receives from and sends data to UAV for safe flight, assigning mission and monitoring their position and velocity. The overall UAS structure is shown in Figure 1.

For a UAV, it is normally loaded with more than five subsystems, three of them are responsible for its autonomy which are guidance, navigation and control (GNC). While other systems are needed for regular operation of any UAV, as vehicle avionics, communication equipment, mission payload, etc. [1].

2.1 Navigation System (NS)

Navigation in UAS can be defined as the process of data analysis and extraction about vehicle's states, position and its surroundings in order to perform its mission successfully. The main autonomy-enabling functions (AEF) of a navigation system from lower to higher level are sensing, state estimation, perception and situational awareness [1].

Sensing system which includes one or a set of similar or different types of sensors such as cameras, accelerometers, gyroscopes, and light detection and ranging (LIDAR), which provide the vehicle with sensing information about its surroundings. These signals can be used and analyzed by state estimation and perception algorithms to get useful information about vehicle surroundings.

State estimation is the process of tracking 3D position and velocity of vehicle's state, this state estimation can be absolute or relative to a fixed position. State estimation algorithms collect

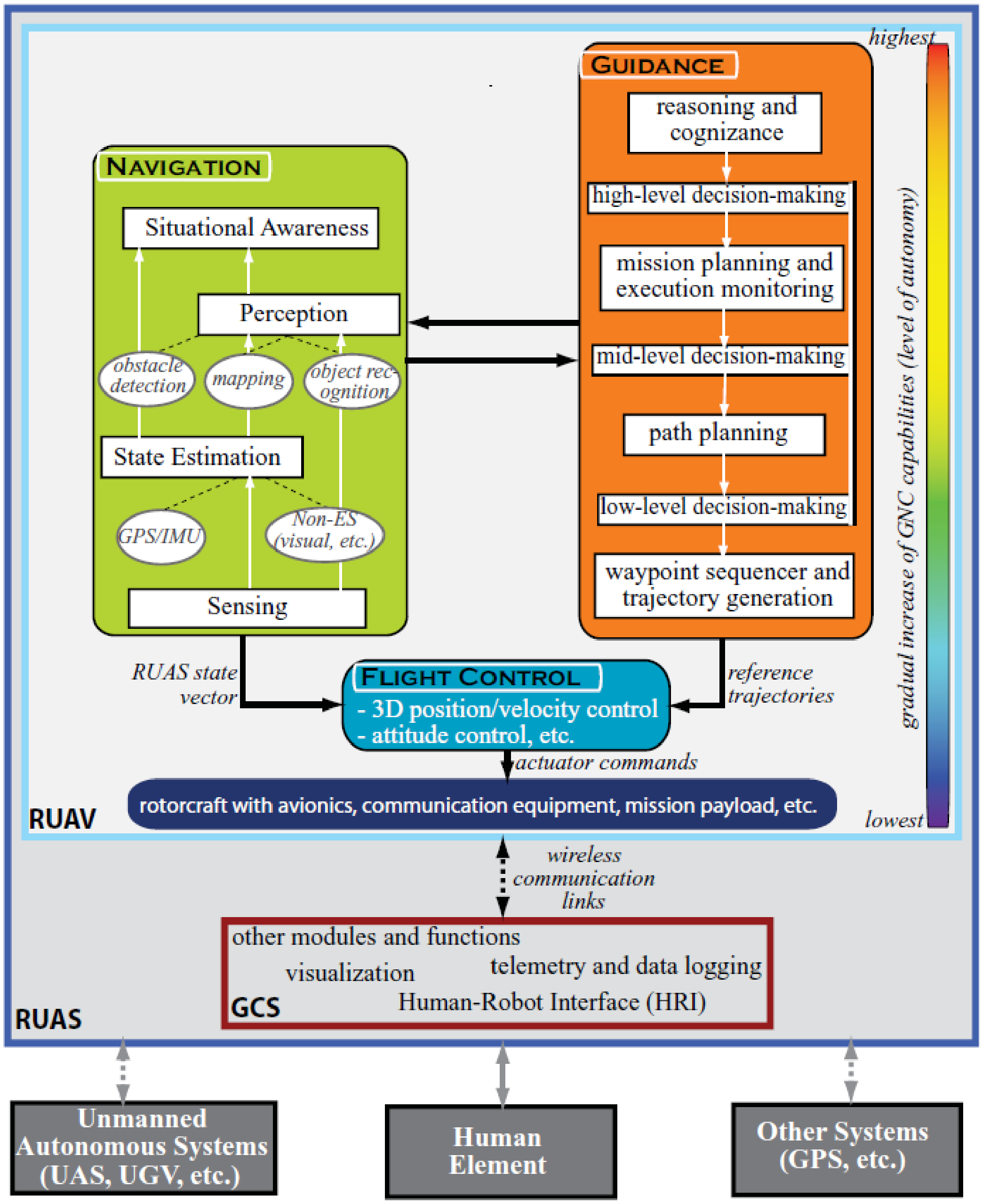

Figure 1: UAS structure [1]

their information from various types of sensors, so it can be classified into three main categories according to sensors types. First category is the conventional systems that use global positioning system (GPS) and inertial measurements unit (IMU), second is the vision-based systems (cameras and stereo cameras) and finally, systems relying on active ranging sensors (radars, infrared (IR) sensors and LIDAR).

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Perception is UAV's capability to use sensors signals and inputs to perform its mission in real life. Its function is to build an internal model of the environment to map it, avoid obstacles and track targets. This model is used to compare new observation with prior environment knowledge. Perception systems can be vision (passive) or LIDAR based perception (active).

Situational awareness (SA) is higher than perception and it is related to understanding the situation and then analyzing this information, to see its effect on the flight in future. Till now nothing has been published about autonomous situational awareness [1].

2.2 Guidance System (GS)

A *guidance system* is defined as the UAV driver which is responsible of planning and decision making to perform the assigned mission. This system can replace human pilot's decisions by taking its inputs from navigation system and can request new information if needed, then generate general trajectories and commands for the control system. Guidance system for UAV contains trajectory generation, path planning, obstacle avoidance, mission planning and reasoning and high level decision making [1].

Trajectory generation is responsible of calculating motion functions and trajectories that can be performed by UAV considering both kinematics and dynamics. Thereafter, flight controller can use this trajectory as its reference trajectory for tracking.

Path planning is the process of finding the optimum route from the UAV's current position to a destination point ignoring its dynamics, and it refers to either path or trajectory planning [10]. Dynamic path planning refers to onboard, real-time path planning.

Mission planning is the process of generating tactical goals, a route, a commanding structure, coordination and timing for a UAV or a team of them. The mission plans can be generated either in advance or in real time, by operators or by onboard software. Systems can be called "*dynamic mission planning*" if this will be done in real time and onboard of the UAV [1].

Decision making is the capability of UAVs to take an action or a set of actions among set of predefined scenarios, based on the available information from the navigation system to achieve its mission successfully.

Path planning algorithms designed to solve the dynamics-constrained problem relying on a decomposition approach. The steps of this approach are: solving a path planning problem, applying smoothing constraints, forming a trajectory that corresponds to the planned path, and finally using a control loop to follow this trajectory [10]. Once a mission is assigned for a UAV to move between two points, the UAV will first find the best route to reach the destination while avoiding all obstacles. Thereafter, the required velocity to achieve the generated trajectory is calculated. Now the UAV has to compute all the required forces and torques exerted by its actuators to track the required trajectory. UAV mission execution is illustrated in Figure 2. Furthermore, lot of works have been done using several motion planning techniques such as graph search methods, potential fields, quadtrees and fuzzy logic. A three degrees of freedom mobile UAV motion planning in partial and full unknown environment can be found in [11], traditional work assuming prior knowledge of the environment can be found in Latombe [2].

Path planning techniques implemented on UAVs can be classified into six main classes, road maps [12], potential fields [13], optimization methods [14], heuristic search algorithms [15], planning under uncertainties [16] and reactive and bio-inspired obstacle avoidance methods [17]. The above-

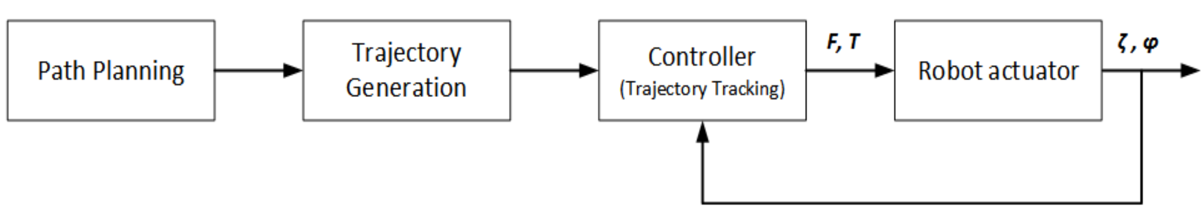

Figure 2: Robot mission execution flow chart [2]

mentioned first five path planning techniques can be global, local or both. *Global path planners* assume prior knowledge of the surroundings and generate a complete path from the start to the destination point before moving of the UAV, regardless of any change that may happen in the environment. *Local path planning* monitors UAV with its surroundings while moving via sensory data extracted from the vehicle. The *reactive path planning* method generates UAV path depending on the sensory data obtained from its own sensors. This method allows UAV to avoid both static and dynamic obstacles that UAV may face during mission execution. Therefore to obtain a robust practically applied path planning algorithm, a combination between local and global types with the reactive one will give acceptable results. More information and references on path planning techniques and algorithms are available in [1, 10].

Optimization methods are the mostly used techniques because they use vehicle dynamics while providing an optimal solution for the problem. Among optimization methods, MPC (model predective control) is the mostly used technique in UAV guidance applications, it has often been used with mixed integer linear programming (MILP) solver. However, it is not restricted to use other types of numerical solvers with MPC [10].

2.3 Flight Control System (FCS)

Control of UAVs has become recently a great attraction for researchers around the world in a lot of universities and academic institutes because of its importance, potential applications and development of new challenging control methods. Control of UAVs is often based on the control methodologies of manned aerial vehicles, they both include the same control outputs as position, velocity, heading control, etc. Flight control systems can be classified into three main categories as shown in Figure 3 [1]:

1. Learning-based flight controllers
2. Model-based linear flight controllers
3. Model-based nonlinear flight controllers

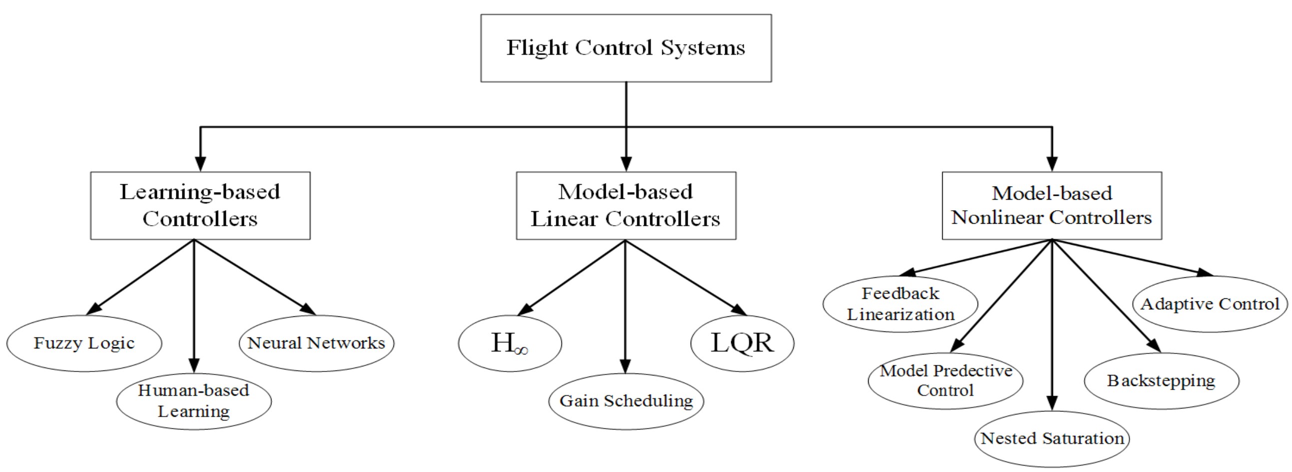

Figure 3: Flight control systems architectures for UAVs [1]

3 UAVs Control

In order to get new robust control theories. At least, availability of system model which describes system dynamics is required, with higher levels of model details and with also some approximation.

However, it is not practical in most control techniques to use complex system models. Control principle and configuration of the used UAV should be known before applying the required control technique.

3.1 Quadrotor Control Principles

The quadrotor configuration as illustrated in Section 1.3 consists of four motors laid up symmetrically around the quadrotor center in a cross configuration. The front and rear rotors turn in the same direction while the right and left rotors turn in the opposite direction to balance the body and cancel torques. But some quadrotors use different configuration, they can use two rotors on the right side and two on the left. However, the attitude control is basically identical [9].

The quadrotor is controlled in six degrees of freedom (DOF) which include three translational motions X, Y and Z and three rotational motions roll, pitch and yaw represented by ϕ, θ and ψ, respectively.

3.1.1 Attitude Control

Pitch control θ

To change the pitch angle, thrust in propeller 1 increased in a certain quantity while thrust in propeller 3 decreased in the same quantity. This results in a pitch moment caused by rotor speed variation while the whole quadrotor torque remains the same, changing the pitch angle in both directions is shown in Figures 4-a and b.

Roll control ϕ

Roll control is achieved in the similar way as the pitch control, but by increasing thrust in one of the side rotors and decreasing the other as shown in Figures 4-c and d.

Yaw control ψ

Yaw control is performed by breaking the balance of torques that has been mentioned before. For example to yaw to the left, thrust and torque are increased in both rotors rotating clockwise and decreased in rotors rotating counter clockwise as shown in Figure 4-g. Yawing to the right is shown in Figure 4-h. But to maintain stability, the total thrust must be maintained as constant.

3.1.2 Translation Control

For ascending or descending, thrust is modified equally in the four rotors as shown in Figures 4-e and f, as the quadrotor in a steady hovering condition.

To move forward or backwards a certain pitch angle has to be reached and maintained. While moving to the sides is achieved by obtaining certain roll angle. Translational motions are shown in Figures 4-a to d.

3.2 Quadrotor Model

UAVs belong to the group of underactuated mechanical systems (non-holonomic), which have less control inputs than their output variables to be controlled. Dynamic model of rotary-wing UAVs is a mathematical representation which relates outputs with inputs. Generally it can be divided into four different subsystems, rigid-body dynamics, force and torque generation mechanism, rotor aerodynamics and dynamics, and actuator dynamics.

In order to build a model to predict the dynamics of any mechanical system, the first step is to write down the equations of motion of the system. Same concept is done on the quadrotor. Newton-Euler dynamical model is presented in previous researches in order to achieve good control of the quadrotor [18, 19], and is applied also on a tilt wing quadrotor by Oner et al [20]. While a

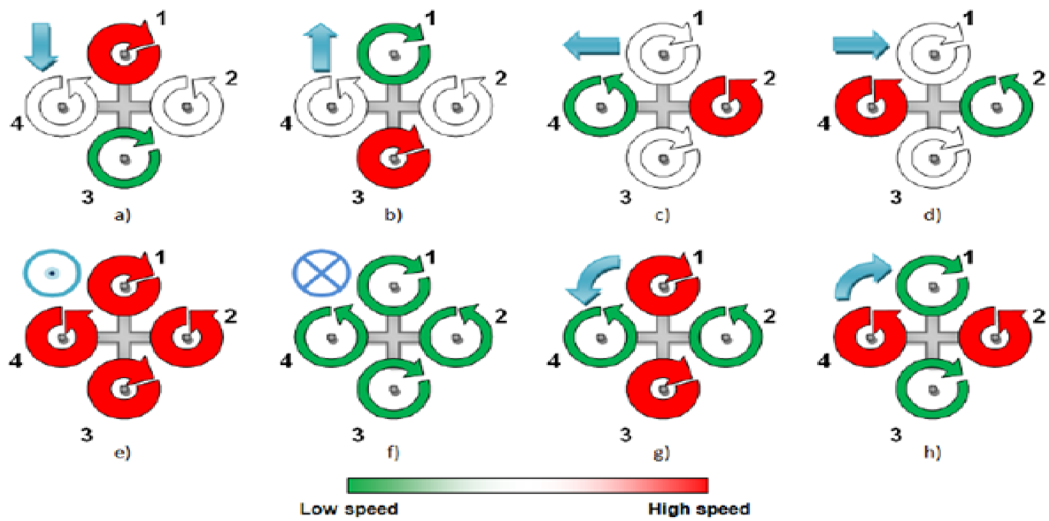

Figure 4: Translation and attitude control of a quadrotor UAV [3]

quaternion dynamic model is represented by Tayebi et al [21].

Quadrotor is assumed to be a rigid body which is subjected to external forces and torques applied at its center of mass. This system of forces and torques is expressed in its body-fixed reference frame and is represented in Newton-Euler as [5]:

$$\begin{bmatrix} mI_{3\times 3} & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \dot{V} \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} \omega \times mV \\ \omega \times I\omega \end{bmatrix} = \begin{bmatrix} F \\ \tau \end{bmatrix} \tag{1}$$

where I is the inertia matrix, V is the body linear velocity and ω is the body angular velocity. F and τ are, respectively, the body forces and torques, while m is the system mass. Consider the earth-fixed frame E and the body-fixed frame B as seen in Figure 5. Using Euler angle parameterization, the airframe orientation in space is given by a rotation matrix R from B to E.

State vector defining the attitude dynamics is given below:

$$\begin{bmatrix} \phi & \theta & \psi & p & q & r \end{bmatrix}^T$$

State vector defining the position and velocities is given below:

$$\begin{bmatrix} x & y & z & u & v & w \end{bmatrix}^T$$

3.3 Trajectory Tracking and Control Methodologies

Trajectory tracking process is responsible of calculating the actuators inputs periodically to get the exerted forces and torques required to achieve the desired path, this process may use the vehicle dynamics [4]. Due to model imperfection and other disturbances, feedback is necessary to determine and reduce the actual deviation between the current position and the planned position of UAV. This trajectory tracking problem is still a challenging research problem for researchers. These challenges come from operating conditions and nonlinear and underactuated nature of the UAV dynamics [22]. The three categories of control systems used in UAVs flight control which mentioned before in Figure 3 are discussed in this section.

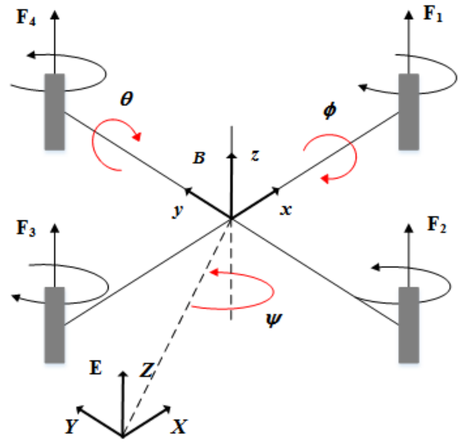

Figure 5: Quadrotor coordinate system

3.3.1 Learning-Based Flight Controllers

The main characteristic of this control scheme is that the UAV dynamic model is not used, but several trials and flight tests data are needed to train the system. Among the used methods, fuzzy logic, human-based learning, and neural networks are the most popular [1].

Fuzzy-Logic-Based Controllers It is used without vehicle dynamic model, just transform human pilot's actions into rules which can be used by a fuzzy control system. Coza et al [23] designed fuzzy control for a quadrotor which is robust to wind buffering, while Santos et al [24] developed an intelligent system based on fuzzy logic to control a quadrotor in simulation only. Coza et al [25] designed a new method for adaptive-fuzzy control which achieves stabilization of a quadrotor in the presence of sinusoidal wind disturbance. Developed fuzzy flight controller was validated in outdoor experiments over 300 autonomous flights including hovering, takeoff and landing, forward flight, and waypoint flight [1].

Human-Based Learning Techniques This technique is based on the analysis of pilot's execution of aggressive maneuvers. Gavrilets et al [26] used this technique on collected data of a small-scale acrobatic helicopter. Experimental results obtained using this technique, succeeded in performing a lot of maneuvering motions. This technique seems better than complex control theories to achieve these complex motions. Meanwhile, it failed in achieving repeatable trajectory tracking [1].

Neural-Network-Based Controllers Artificial neural network (ANN) is a method of learning-based control. A lot of researchers use this method to identify rotary-wing UAVs dynamic models offline or online. Dierks et al [27] implemented a novel controller for a quadrotor using ANN to learn the complete dynamics of the quadrotor online but it was in simulation only. Johnson et al [28] developed ANN technique to identify some unknowns and then combined with standard control techniques, while Buskey et al [29] used an ANN control for helicopter hovering, achieving partial hovering for several seconds with a small helicopter.

Learning-based approaches have been succeeded in flight maneuvers and because they are model free, they have the flexibility to be applied to different systems. This type of control algorithms allows direct mapping between navigation data and UAVs actuator as in the ANN-based controllers, which result in fast reactive behavior and performance.

3.3.2 Model-Based Linear Flight Controllers

Linear control techniques such as LQR and H_∞ achieved autonomous helicopter flight. Since 1960s and early 1970s, the CH-53A full scale helicopter achieved autonomous waypoint navigation using these classical control techniques [1].

Linear–Quadratic Regulator (LQR) or Linear–Quadratic Gaussian (LQG) is also a popular optimal control technique that has been used in controlling several UAVs. How et al [30] used the LQR for controlling MIT's RAVEN quadrotor. LQR technique was used in addition with some of the learning-based techniques by Abbeel et al [31] to design their controller.

$\mathbf{H}_\infty$ The H_∞ control approach is a model-based robust control design methods which deals with the problem of unmodeled dynamics. It has already been used for the control of a full-scale helicopter as well as Yamaha R-50 unmanned helicopter [32]. It is also used in commercial autopilots from the Swiss company "weControl". H_∞ controllers used recently in [33] without experimental verification.

Gain Scheduling These controllers are the mostly used technique in designing controllers for aerospace systems, and it is based on splitting nonlinear dynamics model to a set of linear models with each model doing a specific task [1]. Gillula et al [34] succeeded to perform aerobatic maneuvers on a STARMAC quadrotor experimentally.

3.3.3 Model-Based Nonlinear Flight Controllers

These nonlinear controllers have been developed on UAVs, based on their nonlinear dynamic model to overcome drawbacks of linear controllers.

Feedback Linearization It is one of the nonlinear flight controllers which transform nonlinear state variables of the system into a new coordinate system to get linear dynamics. Then linear methods can be applied, and after that converted back into the original coordinates via an inverse transformation [1]. Koo et al [35] investigated output tracking control of a helicopter model by linearizing it through neglecting couplings between forces and moments, comparing between exact and approximate simulation results only. Kendoul et al [36] designed a nonlinear control system and validated it experimentally, same platform was used for vision based flight research in [37]. Mellinger et al [38] designed an algorithm for obtaining optimal trajectories then tracking them by a small quadrotor acting aggressive maneuvers.

Adaptive Control It is one of the robust nonlinear control techniques which deals with unmodeled dynamics and parameters uncertainties [1]. Yavrucuk et al [39] used adaptive control on GTMAX helicopter to design an envelope protection system, which estimates limits on controller commands for system protection. Further works are done also in [36, 40].

Model Predictive Control (MPC) It is also called Receding Horizon control (RHC) which deals with nonlinear systems model without dynamic inversion. MPC has a future predicting model which minimizes the objective function to decrease future errors on a certain finite horizon [1]. At each sampling time, the MPC generates the optimal control inputs by solving the optimization problem. Shim et al [41] used a real-time MPC algorithm in obstacle avoidance which is identified by an onboard laser scanner. Further works are done in [41, 42].

Backstepping Methodology This type of control technique is used for nonlinear as well as linear nonholonomic systems, and it was presented first in the adaptive control theory [1]. Theoretical work is done in [43], experimental works have been done on different types of UAVs in [17, 44].

Nested Saturation Technique This control technique is mainly used to avoid the problem of actuator saturation, which causes system instability. This problem appeared especially in mini UAVs as a result of aggressive maneuvers. Castillo et al [45] developed a nested saturation controller technique to stabilize system dynamics on a quadrotor, nested saturation technique was used with UAVs in [46].

3.4 Vision Systems

UAVs are normally operated in unknown and hazardous environments, so they have to be loaded with different types of sensors in order to perceive its surroundings, interact with environment and avoid collision. For effective collision and obstacle avoidance, moving or fixed obstacles need to be detected first. Sonar, laser range finder, radar, and LIDAR are used in UAVs to provide the perception capability. However, these sensors are energy consuming (active) and heavy, some new versions are lighter but more expensive. Vision, such as cameras are the most powerful sensors used in UAVs because of low cost and low power (passive). Cameras are used to identify UAV surroundings by extracting and implementing data from images. A camera can be installed in the workspace and keeps looking at the UAV and its surroundings as an *eye-to-hand* configuration, or it can be installed on the UAV itself as an *eye-in-hand* configuration. In complex tasks both techniques can be combined together for better performance. The eye-in-hand configuration has a partial but precise view while the eye-to-hand configuration is less precise but with global view, more details are available by Muis [47].

Cameras can act as human eyes to give information about "what" and "where" are the targets and objects surrounding the UAV. They can replace sonar and laser range finder for distance measurement to get depth sensation as done with human eyes, i.e, two different projections of surroundings are fed into the retinas of the two eyes. This difference is called *horizontal disparity*, *retinal disparity* or *binocular disparity*. These cameras are so called *stereopsis* or *stereo vision* cameras. In stereo vision two major problems are identified in [48] as, the correspondence problem and 3D reconstruction.

Moreover, visual servoing is a widely developed technique in industrial and medical applications, rescue, surveillance, firefighting and UAV navigation. Visual servoing is the principle of using one camera or more as a feedback to the controller, this technique has been widely used recently in many applications as in unmanned systems motion control [49]. It was used before in manufacturing applications such as grasping objects on conveyer belts, missile tracking cameras and aircraft landing [50]. Control systems using visual servoing can be classified into two different ways, according to the level of visual system in control loop structure and according to space of control used to estimate the camera position. Level of visual system in control loop structure can be either *direct visual servoing* or *indirect visual servoing*. While according to space of control used to estimate the camera position (Cartesian space or image space), and may be used with three types of visual servoing techniques such as *position based*, *image based* or *position-image based* (mixed) [46, 50, 51].

3.5 Obstacle Avoidance

After solving the path planning algorithm to obtain an optimal path to follow and then making decision by the control to track that path. Obstacles may be presented in this path from the beginning or appeared suddenly and can be detected by using different sensors, one of them is the vision sensor which is illustrated in the above section. Therefore, two types of obstacles are being considered, according to nature *convex* and *concave*, according to status are *static* and *dynamic*. An obstacle is considered as *static* if there is complete knowledge of the surroundings, and it is fixed in position and is *time-invariant*, while it is considered as *dynamic* if knowledge of the surroundings is not perfect and obstacle changes in position with time (*time-variant*) while executing the mission.

Many works have been done on UAVs and quadrotors in obstacle and collision avoidance. For example, Roberts et al [52] presentd a MAV quadrotor with four infrared sensors using proportional-derivative controller and distance balancing algorithm to avoid collision experimentally. Bouktir et al [53] proposed a nonlinear optimization method for trajectory generation under obstacle avoidance constraints, while Mellinger et al [54] proposed an optimal trajectory tracking algorithm for a team of quadrotors up to four using mixed-integer quadratic programs, and verified their algorithm experimentally.

Optic-flow based strategies can be used for obstacle avoidance without mapping the environment, its idea is to interpret regions with high optic-flow as coming obstacles. Translational optic flow is proportional to the magnitude of the vehicle velocity and inversely proportional to the distance to obstacles in the environment [1].

Heinrich [55] created a robust detection scheme based on flow and depth information using stereo vision and motion analysis. Eresen et al [56] used optical flow velocities for obstacle detection, and used PID controller for path tracking and obstacle avoidance. Sarcinelli-Filho et al [57] implemented an obstacle avoidance mobile robot by visual sensing based on optical flow experimentally. Also Dev et al [58] used a camera on board to drive through a corridor deriving wall distance and orientation from the optic flow.

4 Multiple Unmanned Aerial Vehicles

Recently, UAVs, especially quadrotors, have received more attention because of their capability of VTOL. This characteristic helped them to successfully achieve their missions in reconnaissance, surveillance and firefighting. However, these tasks can only be performed with one vehicle in most existing works, multiple vehicles will be more flexible and efficient in performing the tasks. However, using multiple vehicles in various applications is limited by several constraints, as limitations in onboard computational power, communication and incomplete situation awareness due to sensing technologies [59, 60].

4.1 Control of Multiple UAVs

Cooperative UAVs can be defined as a group of vehicles having common objectives in cooperation to ensure mission execution successfully, with better performance to be achieved than a single vehicle. These vehicles can perform the task while maintaining a certain geographical shape with constant relative distances [60]. *Cooperation* control of UAVs differs from *coordination*. Coordination involves low level interactions for task or maneuver execution, mainly when sharing position information. Despite, *cooperation* or *collaboration* occurs at a higher level and may require that all UAVs work toward a common task by sharing data and controlling actions together [1]. *Formation flight* is a special cooperative operation of multiple vehicles while maintaining a specific geographical shape with constant relative distances [60].

4.2 Coordination Strategies

Centralized and decentralized are the most important classification of a group of unmanned vehicles architecture, in which UAVs can take their decision by communication via a central station or independently. In a *centralized* system, a powerful central station communicates with all vehicles during a mission, organizing their formation, coordination, adjusting faults, monitoring the whole mission execution and sometimes assigns one vehicle or more an extra mission. Its main disadvantage is that failure of central station may result in failure of the whole system. While in the *decentralized* configuration, it has no central station but all the agents can communicate and share information with each other, make decisions, perform a specific task from the whole global mission [4, 60].

Researchers have developed many strategies and algorithms for multi-vehicle coordination and control such as leader-follower, behavioral approach and virtual structure approach as follows:
1. In *leader-follower* approach, one of the UAVs are assigned as a leader while the others are followers, which should maintain certain relative position with the leader. Main advantage of this approach is its simplicity and reliability, but it has no feedback from followers to leader and it is not robust in case of leader failure due to its centralization feature [60].
2. In *virtual structure* approach, the whole team is considered as one unit and each UAV follows a certain path so it can perform only synchronized maneuvers. This coordination behavior is robust and not complex. However, due to its centralization feature, single point failure can lead to failure in the whole mission as well [60].
3. *Behavior based* method assigns several behaviors for each robot and the final decision and control is derived from a weighting of the relative importance of each behavior. Systems using this approach are able to navigate to waypoints, while avoiding obstacles and keeping formation at the same time [61]. However this approach lacks for theoretical modeling [60]. More approaches are investigated by Zhang et al [60].

4.3 Collision-Free Coordination

UAVs have been widely used in various applications, either in single vehicles or in multiple formations, this results in more research and development in multiple UAVs control. One of the main problems that facing researchers is collision and obstacle avoidance, not only between UAVs and static, dynamic obstacles, as explained previously in Section 3.5 but also between UAVs themselves as they are treated as dynamic obstacles. For example, Fujimori et al [62] presents a collision avoidance technique called cooperative collision avoidance, which navigates two robots or more towards their goals while avoiding collision between each other. It depends on controlling velocities and angles of robots to avoid collision, giving priorities for taking action according to which robot will reach the crossing point first. Others proposed stopping robots for a certain time before collision and changing their direction. More references are provided in [60].

4.4 Applications of Multiple Unmanned Vehicles

Recently, multiple unmanned vehicles have been widely used in various applications such as underground mining, cooperative vehicle reconnaissance, surveillance, search and exploration. In this section search and exploration application is discussed.

Search and exploration using multiple vehicles are recently used due to widely used applications despite of its complexity, comparing to performing same task using single vehicle. It needs novel methods for dynamic data fusion, task allocation, coverage control and cooperative path planning. Moreover, a lot of challenges still need to be solved.

For the search algorithms, they are based on the way of taking decision which may be centralized, decentralized or distributed. If the control decision of each agent is coming from its information and its neighbor's information so the control strategy is said to be *distributed*. This strategy has several advantages as it is easier to reconfigure and more robust due to decentralization without having to depend on a central station. The information flow of all types of control strategies must go in sequence through these modules, sensing, communication, decision and control. Control and decision modules sequence can be changed according to requirement. Figure 6 shows the closed-loop diagram of distributed control strategies.

In order to detect the environment, a *sensing module* has to be established to deal with raw

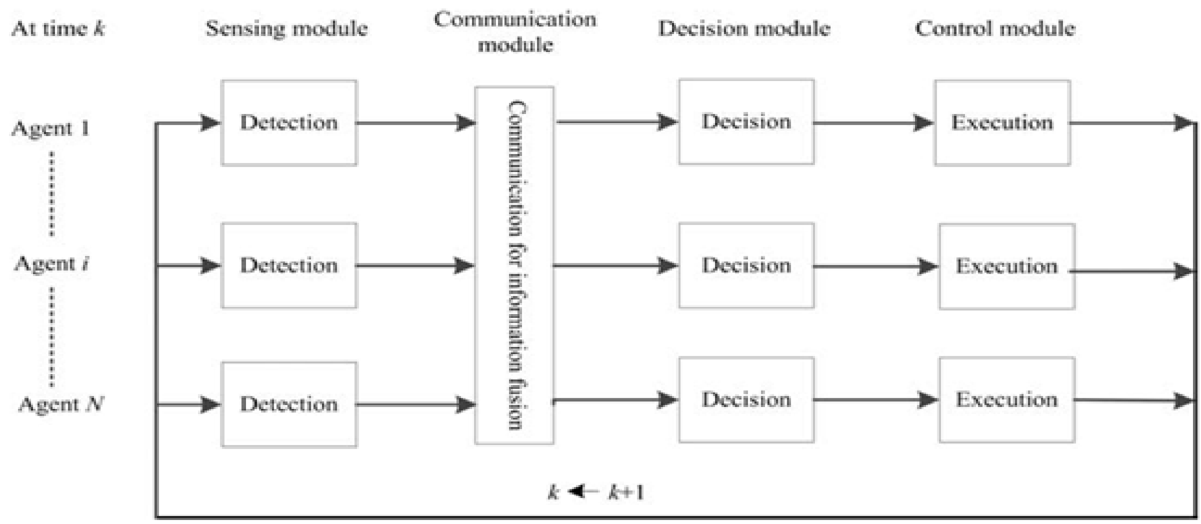

Figure 6: Closed-loop diagram of distributed control strategies [4]

data extracted from different sensors. These data should be executed for environment exploration and target detection. Therefore, two types of sensing models, deterministic and probabilistic, can be classified according to the belief of a detection result. A sensing model is said to be *deterministic* if the detection result is not a random variable given the true environment condition, otherwise it is *probabilistic*. However, in general the methods assuming *probabilistic* detections are used for universal applications and more suitable for stochastic environments in the real world [4].

Communication in multiple vehicles control is very important for sharing information between vehicles via establishing necessary communication links. Therefore two main issues should be discussed in communication between cooperative vehicles. The first issue is the determination of which information should be communicated and the second issue is the connectivity maintenance. *Determination of communication information* should be considered in order to determine the least necessary information needed to be communicated between vehicles, in order to effectively run the system according to the application needs. In some cases as in centralized control, sending only detection information between agents and central station information and commands are enough, such as 0 for no target and 1 for target detection. On the other hand, less information and communication are not suitable for decentralized and distributed control, where more information is required such as updated environment map or UAVs positions to obtain high performance. Moreover high degree connectivity should be maintained to ensure high performance robust cooperative control. High degree connectivity results in maintaining network connectivity if one or more agents move out of the network connectivity range. More references and information on communication can be found in [4] and [60].

Decision module is the module which is responsible of making decisions as explained in Section 2.2. The challenging issue in decision making is how to implement all information fusion coming from all sensors and agents [4].

Control module is the module which is responsible of realizing control decision made by decision module. This control module is divided into two main aspects especially in search and exploration problem, which is generally path planning and motion control issues. These two aspects are defined and well explained in Section 2.2 [4]. Sharifi et al [63, 64] used cooperative UAV and UGVs in the search and coverage problem based on Voronoi coverage control strategy.

5 Conclusion

This report presents a critical review for the unmanned aerial vehicles control systems. For the control part of unmanned vehicles, different types of controllers have been used such as linear, nonlinear and learning-based methods. Linear controllers have been used long time ago and nearly used by most commercial autopilots. Linear controllers can achieve stability in normal flight conditions but it lacks stability and performance guarantee while performing aggressive maneuvers. On the other hand, nonlinear control techniques are more robust than linear techniques when unmodeled dynamics and disturbances are presented. However, it did not show more flying capability experimentally comparing with linear controllers [1]. Nonlinear controllers, especially MPC are used in quadrotor control, because this technique is an optimization technique which can easily deal with multivariable systems by considering its constraints. MPC technique still needs some enhancements to increase the horizon limit while reducing computational time to be processed online without delay. Learning-based approaches are the future of control techniques because it can be used on any system due to its independency on system model. These learning approaches have been successfully used in flight maneuvers. However, stability and robustness issues are still difficult to analyze and still need more experimental work in different environments and flight scenarios.

UAVs automation depend mainly on their navigation system, so most researchers are trying to navigate and guide aerial vehicles without the use of conventional avionics such as GPS and IMU. These conventional avionics succeeded in navigation in obstacle-free environment. Recently, guiding and localizing UAVs using various sensors without the aid of GPS have been proposed, such as LIDAR, optic flow sensor, vision sensors and stereo cameras to avoid GPS signal loss. This is still a challenging open research point. Major challenge in using vision in navigation and guidance is the control method that can deal with vision data online, which needs computationally more powerful onboard processors. MPC controller is a recently used approach with visual servoing. Using optic flow in outdoor navigation without GPS lacks for experimental results and still an open research problem till now.

Controlling and guiding UAV for a certain or set of missions promoted more research interest to the guidance problem, which include path planning and decision making algorithms. However, majority of works done do not include practical implementation and sometimes ideal vehicles simulation is only provided. It is very difficult to get optimal planning algorithm with different constraints.

Challenges of UAVs vision-based control systems still need to be solved. UAVs autonomous operation using vision sensors needs high onboard computational capabilities, due to huge amount of data need to be analyzed in real time. Moreover, the widespread use of autonomous UAVs depends on the ability to learn and adapt to surroundings, while color cameras till now still need manual calibration due to their sensitivity to illumunation changes [65].

Cooperative or multiple UAVs have more advantages compared to single vehicle when used in several military and civilian applications. However, many challenges and attributes associated with cooperative UAVs decision and control. These attributes are complexity due to increasing number of UAVs participating in a mission and coupling between different tasks and heterogeneous UAVs. Moreover, lack of information shared between vehicles according to noisy, narrow bandwidth, and communication delay, also sensor fusion still a big challenge. So, decentralized matching between UAVs is very important to successfully achieve desired formation.

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