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BACHELOR THESIS

Formation Flight for Unmanned Aerial Vehicles

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I want to thank all my colleagues that have made the Autonomous UAV project possible.
Special regards go to my mentors for guiding me in elaborating this thesis.

I also want to thank Nistor Mot for managing to combine my two favorite fields , aviation and computer science, by saying:

“Software that almost works is like airplanes that almost fly!”

Abstract

Here goes the abstract about UAV Formation Flight.

TODO:

Write abstract

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Notations and Abbreviations

ACS – Faculty of Automatic Control and Computer Science

CAN – Controller Area Network

Controller Area Network – .

FG – Flight Gear Instance

FGMS – FlightGear Multi-Player Server

ORCA – Optical Recognition Collision Avoidance

QGC – QGroundControl

RC – Remote Control

RPI – Raspberry PI

SO – Self Organized

TNI – Teamnet International

UAS – Unmanned Aerial System

UAV – Unmanned Aerial Vehicle

Chapter 1

Introduction

1.1 Domain Description

In the last 3 decades the aeronautic industry has focused on creating methods of flying that does not involve a human factor inside the airplanes, developing solutions for unmanned flight. The necessity for advancements in UAV domain is powered by the desire to keep human pilots out of harms way. UAV systems are useful in military missions, and high risk search and rescue missions. Along the military missions, UAVs can be used in civil context for missions like: traffic surveillance, cartography or animal tracking. An UAS or drone is a vehicle that doesn't have a human pilot on board and can be either controlled by a RC, a ground control system (Control Tower) or be fully autonomous. The concepts of unmanned vehicles emerged a couple of years after the first mechanized flight in 1903 by Orville and Wilbur Wright [13]. In 1915 Nikola Tesla had a vision about a fleet of unmanned military aircrafts and in 1919 was developed the first UAV by Elmer Sperry, that was used for sinking a captured German battle ship. The first two countries that saw the high potential of unmanned vehicles were U.S.A and Israel. In 1960 the U.S. Air Force started a research program for developing UAVs, and in 1964 is the first documented use of an UAV in a real war scenario, during the Vietnam War. Israel started using UAVs for reconnaissance and surveillance mission. As a result, Israel reported no downed pilot during the Lebanon War in 1982. In the present, drones are intensively used in the war theaters from Afghanistan and Iraq [5]. The development of the autopilot is strongly correlated to the with the developed of the UAV. The company of Elmer Sperry was the first to produce an autopilot that was able able to fly autonomous for three hours in a straight line without being supervised by a human. By 1933 Sperry's autopilot was able to flight on true heading and maintaining the altitude, compared to the gyroscopic heading of the first version. The current evolution of autopilots is in close relation with the development of reliable communication systems. Although the first UAVs were controlled remotely by a human operator, they are now able to receive a flight plan and based on that to calculate the flight path and follow it to complete the mission. In moder autopilots the human factor the secondary role of supervising the system and controlling the on board equipment, like cameras and sensors.

1.2 Motivation

When I was a child I received my first toy airplane and became fascinated by the idea of moving freely like a bird. A couple of years later I first stood near a MIG-21 Lancer at my fathers garrison. The passion with witch the pilots talked about being in the air close to the clouds inspired me the love for moving freely in 3 dimensions.

The high number of human casualties reported in war theaters and training missions determined me to explore the field of autonomous fling. The necessity for reducing the loss of human lives gives autonomous great potential for evolution.

My motivation is to help create a next generation of autopilots capable of accomplishing difficult missions where it is the risk for a human pilot would not be affordable.

In Romania the UAV fields is still unexplored. The main fields where a UAV platform would be useful are interest points detection and monitoring, border patrol, search and rescue team and imagery intelligence.

1.3 Objectives

Although a single UAV is already able do accomplishing various mission by it's own, an interesting, and in my opinion mandatory, field is the one of fling in formation. A mission where the objective is to track multiple targets becomes very hard for a single drone, thus emerging the necessity for a swarm of UAVs. There are situation where the risk of loosing an UAV due to hostile conditions is to high, being more affordable to deploy multiple, cheaper UAVs in contrast to an expensive drone. Another use case for a formation would be a search mission where we can't equip a single aircraft with all the sensors necessary for success and choosing to use multiple specialized drones.

Usually a human pilot is able to fly in formation using a combination of cognitive and reactive behavior, always making small adjustments to maintain a coherent formation.

There are two ways that formation flight could be achieved. One would be a centralized method, where all the drones report the telemetry data to a central authority like a ground control system and the later would make the necessary decisions for all the involved actors and then relay the data back to the aircrafts. Although in theory this approach could give an optimal flight path, problems like delay in communication and sensors reporting faulty data could jeopardize the success of the mission. Another approach would be a decentralized method, inspired by swarms of animals, like ants or bees. In the second approach each UAV would decide what actions to execute based on the actions of the others.

The main goal of this thesis is to design an decentralized algorithm responsible for maintaining a flight formation based on the leaders actions. The leader will not share the flight path or mission plan with the other drones, it will share only the current position, speed and direction. Based only on this data, the drones must be able to maintain a predefined flight formation. Thus each drone, except the leader, is modeled as an reactive agent that has the mission to approach the leader and mimic his actions.

The secondary goal of this paper is to design a management platform for a fleet of airplanes that are able to execute different missions. The platform has the role of programming the mission for each drone, manage the in flight performance for each UAV and if necessary to send commands, inserted by a human supervisor, to the drones and by this modifying the current state of the mission execution.

The platform developed is possible thanks to a collaboration between the TNI company and ACS, University Politehnica Bucharest.

This thesis present a possible solution for achieving UAV Formation Flight.

Chapter 2

Related Work

A large number of articles describe the work done to solve the problem of autopilots UAV swarms, communication and coordinate systems. In the following paragraphs I will describe the main ideas and trade-offs for each described solutions.

The autopilot problem is well covered in the literature and from real life practice it is considered that the best architecture is one that is stratified. Each layer is responsible for receiving commands from the superior layer, deciding if the the command would put the UAV in a state of imbalance, or danger in general, and forwarding the command to the layer below. If a possible imbalance state is detected the layer either discards the received command and does not send any command to the next layer, or it tweaks the command so that a incoherent state would not be induced.

The architecture as proposed by Borges de Sousa et. al [4] would have the following layers:

Platform

The UAV vehicle with all the hardware

Maneuverer controller

Controller that decides what hardware action is executed (roll, pitch, yaw)

Vehicle supervisor

Basic autopilot capable to make simple decisions (setting the target speed, setting the heading)

Mission supervisor

Artificial Intelligence System that plans the mission based on a template and the rest of the drones. It forwards the commands to the Vehicle Supervisor for validation

External controller

Human factor that can interfere between the Mission Supervisor and Vehicle Supervisor to override or even deactivate the first one.

The architecture imagined by Borges de Souse can be seen in [Figure 2.1](#).

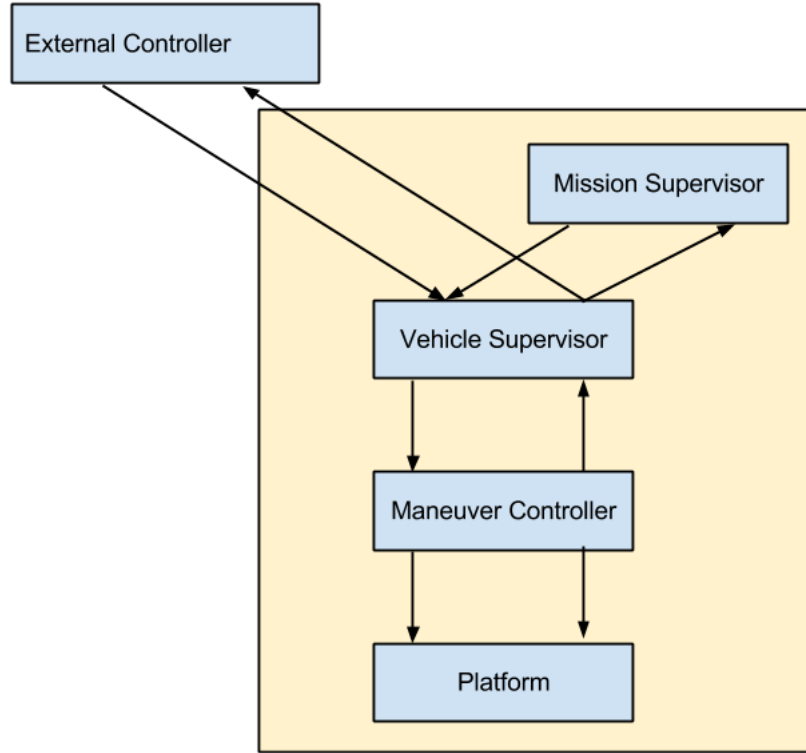


Figure 2.1: Vehicle Control Architecture.

The advantages provided by this kind of architecture is the separation of concerns for each level and the fact that the repair in case of failure can be easily detected and fixed. The only draw-back of this approach is the fact that in the case of poor implementation it could introduce a latency in communication losing the possibility of having a real time system.

The autopilot system presented in this thesis is similar to the one described above because the Hirus drone [14] provided by TNI already contains a maneuver controller, vehicle supervisor and an external controller. Thus the system described in these thesis would act as a mission supervisor.

In the terms of UAV teams, Mark D. Richards and his colleagues [12] identify two main groups of strategies. The first one, called **Behavior-based Control Systems**, uses a mesh of interacting high-level behaviors to perform a task. The second one, **Deliberative System**, acts by creating a specific flight path for each individual UAV to follow. This second behavior is a generalization of the search path optimization that Ablavsky proposes in [1]. Ablavsky approaches the problem by following the following steps:

1. Restrict the search area based on the mobility of the target.
2. Divide the search area in to the smallest number of sub-regions keeping in mind the constrains of the aircraft.
3. Determine a search pattern for each sub-region with the property of assuring full coverage with a minimized path length.
4. Combine the individual results into an optimal global path.

The deliberative approach used by Richards is based on dividing an area for each UAV and generating inside the designated zone a flight path to be followed. For achieving some degree of

flexibility, Richards opted not to use an adaptive replanning where a central controller computes a specific flight path for each agent and then broadcasts it to the team. The drawbacks of this approach are represented by the fact that there would still be a single point of failure and the fact that by the time the plan is sent to the UAV it may be already be deprecated. The approach that was used was a reactive one. The initial path is computed and if an hostile condition is generated each UAV has to determine a way to exit that state. By these means Richards managed to sweep an area that is divided in sub-zones with different degrees of danger and even a no fly zone. The reactive behavior was useful for avoid collision with a friendly unit or for escaping a danger zone.

Although Richards proposal uses a long range unsynchronized flight team, in this thesis I used a similar approach for obtaining a synchronized formation.

Gaudio and his team research the possibility to explore a zone based on the strategies used by schools of fish, flocks of birds and swarms of insects. The research they published in [6] and [7] is based on mimicking the pheromones left behind by the swarms of insects. To be able to replicate the insects behavior, Gaudio assumed that each UAV is aware of the terrain geometry, is equipped with a sensor that provides a forward code of vision able to detect elevation and distance, has a sensor to detect the other UAVs in a given sphere, is positioned using GPS-like coordinates and has a sensor that mimics the pheromone detection. The later sensor detects, within a rectangular region centered on the UAV, the coverage of the current cell. In their simulation they have used a global communication system that was able to assure data flow between each two UAVs. The strategy to control the UAVs is implemented in a decentralized way where each UAV can decide what action to execute. Gaudio tested 5 strategies to explore an area:

Baseline

Each UAV starts with a different heading, flies in a straight line until the area limit is reached and then turns so that it doesn't leave the area.

Random

Is similar to the baseline implementation but at each time step, the UAV will change it's heading by a small random angle.

Repulsion

An UAV can detect the other UAVs on a given radius and it changes it's heading so that they do not intersect.

Pheromone

Each UAV is able to detect the already explored cells and changes it's heading so that it heads in the direction of unexplored cells.

Global

The area is divided in smaller regions and an UAV knows how many UAVs are in one region and based on that it decides what region to explore.

Based on their experiments they have discovered that the most efficient way to obtain a higher coverage is the pheromone strategy. Compared to the repulsion strategy that obtained a 44% coverage the the pheromone strategy obtained a 60%. These coverages were obtained using 10 UAVs. The same experiments showed that scaling to larger UAV swarms presents a drawback represented by the fact that although the coverage efficiency increases with the number of UAVs, their relative efficiency decreases. While on a very large area 10 UAVs would cover 6%, 110 UAVs would cover only 33%.

In contrast with the approaches form above, Nowak centered his research on creating a self organized swarm. To achieve this he created a three-tiered architecture for a SO System Model that separates the implementation details from the real world agents behavior. This architecture (as presented in [10]) can be seen in [Figure 2.2](#).

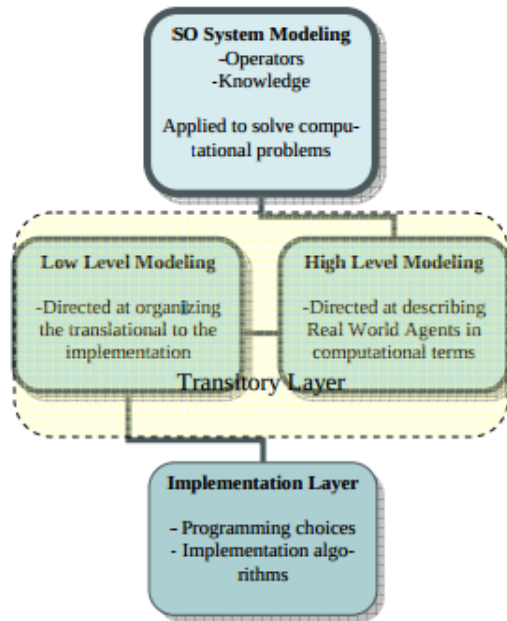


Figure 2.2: Three tier SO architecture.

The behavior of many cooperative agents in the same way is a behavior that has been studied in detail by many researchers. Reynolds proposed in 1987, three fundamental rules for swarming: [11]

Separation

The UAV must steer away from the nearest neighbors to avoid crowding.

Cohesion

The UAV must steer towards the average position of its neighbors.

Alignment

The UAV must steer towards an average heading of the neighbors.

A visual representation can be seen in [Figure 2.3](#)

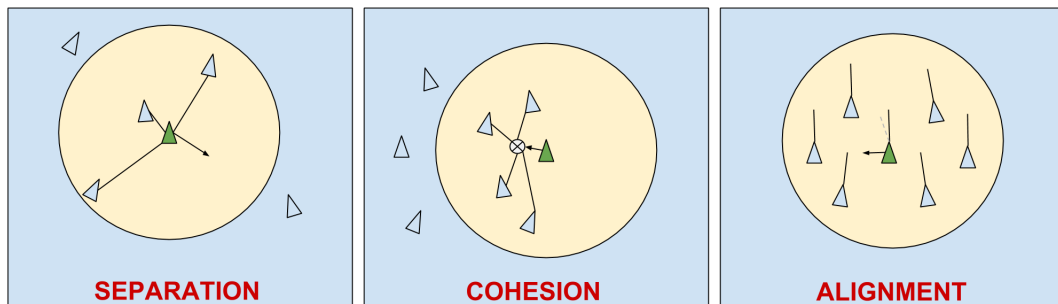


Figure 2.3: Fundamental Swarming Rules.

Based on Reynolds rules, Nowak implemented, in SWARMFARE 10, rules for a coherent formation flight [10]:

Flat Align

vector align neighbors

Target Orbit

orbit target at safe distance

Cluster Range Towards

cohesion

Cluster Range Away

separation

Attract

towards center of mass of all targets

Weighted Attract

towards closest target

Target Repel

repel if within 90% of UAV sensor range

Weighted Target Repel

repulsion based on proximity to target

Evade

Apriori collision detection and avoidance

Obstacle Avoidance

Real time obstacle avoidance

The difference between the previous approaches and Nowak's is that the later considers that at no point an agent will give commands such as "Slow down", "Turn" or "Dive". Each UAV is responsible for computing what action to execute based on a minimal set of data received from the other UAVs. A possible set of data is formed from:

- GPS coordinates
- altitude
- speed
- heading

To test the SWARMFARE framework, Nowak opted to paralyze the computation using a Master-Slave architecture. The resulting parallel time calculation results from the equation:

$$T_p = k(t_s + t_w m)(p - 1) + \frac{n^{ck}}{p} \quad (2.1)$$

k = number of generations
 t_s = setup time
 t_w = transfer time
 p = number of processors
 n = number in population
 p = constant defining the variable
 n^ck = linear calculation time

The time obtained by using a initial population of 2 per node is 540 minutes for one node and 80 minutes for 16 nodes.

The SWARMFARE is a work in progress and the trade-offs that could appear only from the implementation of the 10 rules.

The Autonomous UAV project proposes to implement an autopilot that integrates the behaviors depicted by the rules proposed by Nowak. The formation flight module implement in this thesis will integrate with the obstacle avoidance module and surveillance modules developed by my colleagues.

Based on the communication mode, there are two main methods for implementing UAV formation flight: coordinated or cooperative. Bourgault et. al. depict the difference between the two

modes in [2]. According to them in coordinated approach each agent decides what actions to execute based on the current knowledge of the world but there is no possibility that the actions of an agent to influence the decisions of another. The cooperative mode has the advantage that agents negotiate what actions to execute, thus obtaining a global optimal solution. On the other side the coordinated mode obtains a suboptimal solution, but has the advantage that the individual computation time does not increase with the number of agents.

For a close range formation there are necessary both these modes. The coordinated mode is useful for computing the position in the formation for each aircraft and the cooperative mode is useful for a collision avoidance module so that the aircrafts do not collide. Similar to Bourgault, in this thesis is presented a coordinated mode with a one-step look-ahead.

For obtaining obstacle avoidance it's necessary to have a reactive system combined with a cooperative decision making algorithm. Call et. al tried to implement such a system by obtaining data from video cameras. The cameras are preferred because they are passive, lightweight, simple and inexpensive sensors. The drawback for these sensors is represented by the fact that under low-visibility, such as fog, smoke or night, have reduced efficiency. Also the processing of the information could have high computation time. In the research paper [3], they have managed to obtain three dimensional data from cameras either by using a stereo vision system or by using multiple frames from one camera. They have found out that the relative position of an object can be obtained with an enough amount of information by using a single camera and multiple frames. The main problem with detecting obstacles is that most of the existing algorithms are based on detecting a texture variation or the detection of corners. Problems in detecting obstacles appear when the objects are described by parallel lines with no visible endpoint or have no texture. Another case when the algorithm could fail is when the obstacles have reflective glass surfaces.

The results published in [3] can be seen [Figure 2.4](#)

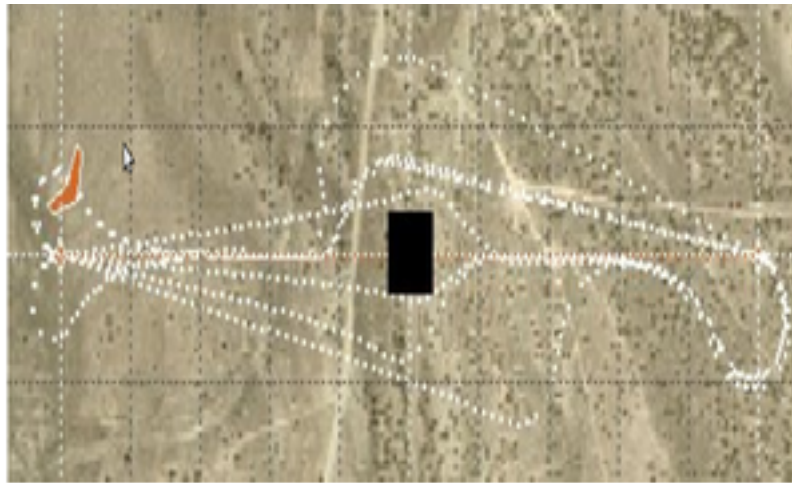


Figure 2.4: Overhead view of the flight path of the UAV as it avoids an obstacle indicated by the black box.

When using cameras to detect obstacles, the angular velocity of gyroscope often has a large amount of noise, mostly because of the yaw angle or wind. Thus the angular velocity has to be estimated using another type of on-board sensor.

He approaches this problem by following the following steps [8]:

1. Classify the image blocks in structural and non-structural blocks
2. Find multiple "best" motion vectors instead of a single one and chose the optimal one using a predefined metric
3. Using the data about structural motion, estimate the camera motion to reduce uncertainty in the motion for non-structural blocks.

In the same article [8] uses the following two formulas to compensate the motion noise of the camera:

$$m(O_B, r) = \frac{1}{|C(O_B, r)|} \oint_{C(O_B, r)} I_t(x, y) dx dy, 0 < r \leq R_s \quad (2.2)$$

Where:

- $O_B = (X_B, Y_B)$ center of block B
- $C(O_B, r)$ = circle center in O_B with radius r
- R = maximum radius to search
- $m(O_B, r)$ = intensity profile of pixel O_B or block B

$$d_1(A, B) = \min_{1-\delta \leq \lambda \leq 1+\delta} \max_{0 \leq r \leq \frac{R}{\lambda}} |m(O_A, \lambda r) - m(O_B, r)| \quad (2.3)$$

Where:

- λ = scaling factor
- $[1 - \delta, 1 + \delta]$ = search range for λ

From [Equation 2.2](#) and [Equation 2.3](#) the distance between blocks A and B can be computed with the following formula:

$$d(A, B) = w d_0(A, B) + (1 - w) d_1(A, B) \quad w = \text{weighted factor} \quad (2.4)$$

The formation flight module implemented for this thesis will integrate with a module of collision avoidance based on ORCA.

Millington proposes a set of algorithms for implemented moving in [9]. In his book, he divides these kind of algorithms based on variable of speed and acceleration. The categories are:

Stationary and Running where the output is represented simply by the direction of movement. The movement imposed by this type of algorithm is called **kinematic movement** and it is not influenced by acceleration or deceleration.

Dynamic where the output is represented by accelerations or forces that are meant to change the velocity of the agent.

If the worked environment is a 2D model, the output from this algorithms would be represented by one (or both) of the two following values: *a*) clockwise angle in radians from the positive z-axis (the vertical axis being the y-axis); and *b*) acceleration needed to change velocity . The mathematical model necessary used in 3D could be very complicated, thus Millington

proposes in [9], *Chapter 3. Movement* a hybrid coordinate system with 4 degrees of freedom called **$2\frac{1}{2}$ Dimensions**. In most 3D simulations these system use sufficient because an agent is always pulled down by the gravity. Even in the cases where a character is looking up or down, the movement direction is not influenced by the viewing direction. For computational purposes it is usually more convenient to represent an orientation as a vector instead of a scalar. The transformation can be computed with the following formula (assuming a right-handed direction):

$$\vec{w_v} = \begin{bmatrix} \sin w_s \\ \cos w_s \end{bmatrix} \quad \begin{array}{l} w_s = \text{orientation as scalar} \\ \vec{w_v} = \text{orientation as vector} \end{array} \quad (2.5)$$

Millington proposes a set of algorithms for achieving kinematic movement by using only static data (position and orientation without velocity). The algorithms are described below [9]:

Seek

Based on static data about the source and destination, the direction between them is computed and movement along that line is required. If the source is static, moving at full speed could cause the agent to pass the destination and move back and forward reaching a state of **Stable Equilibria**. To avoid this, it could be considered that the target has been reached if the agent is at a distance from the target that is smaller than a predefined radius.

Wandering

The agent always moves at full speed in the direction of the current orientation and at each step the orientation could be altered by a small amount using a binomial random function (computes values between -1 and 1 with a higher probability for 0).

For these thesis a **Wandering behavior** would not be useful, but the **Seek behavior** is used for obtaining a *follow the leader* movement.

Millington also proposes a set of steering behavior based on outputting accelerations:

Variable matching One agent tries to mimic the kinematic of another agent.

Seek and Flee One agent tries to mimic the position of the target agent or move further from the target, being similar to the **kinematic Seek**

Arrive Is an improvement from **Seek**, but here the agent slows down when is close to the target.

Face Here the agent first calculates the target orientation and then tries to head in the direction of the target's next position.

For movement in 3 dimension, Millington states that the algorithms described by him have to be adapted by using quaternions.

In this thesis I used the *Variable Matching* behavior for fling in the same direction and *Seek and Flee* for entering formation.

Chapter 3

UAV Management Platform

3.1 Architecture

For the Autonomous UAV platform we have used an architecture based on multiple agents that communicate with the *Mission Supervisor* via a CAN. The CAN will also be able to route messages to other CAN buses.

The testing architecture can be seen in [Figure 3.1](#).

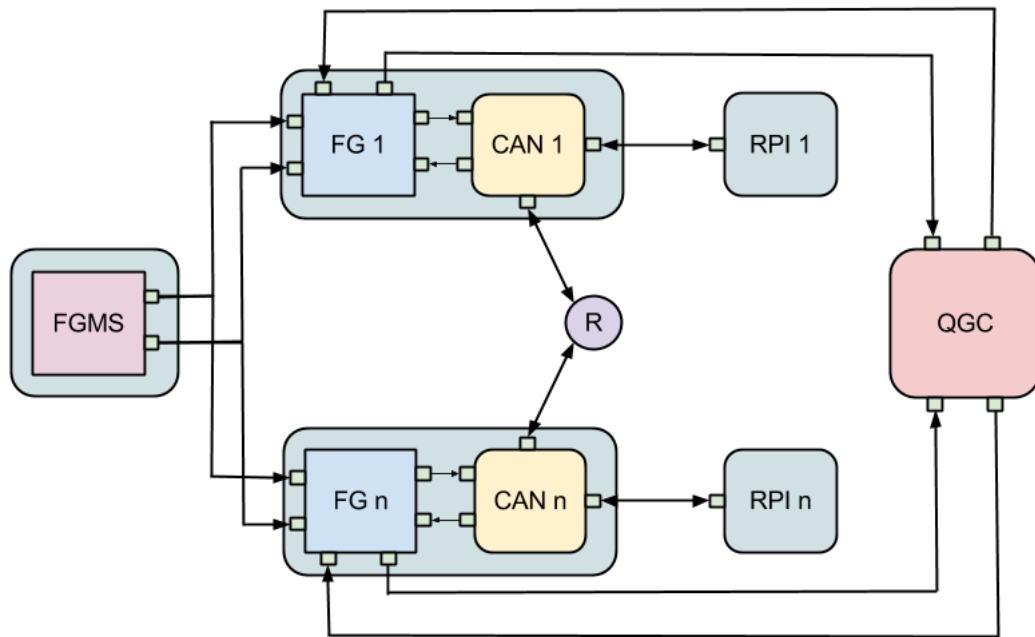


Figure 3.1: Autonomous UAV testing framework

In [Figure 3.1](#), the components are as follows:

FG_{1..n} FlightGear Flight Simulator. Simulator responsible flying a single drone.

FGMS

FlightGear Multi-Player Server. It has the role of broadcasting information about UAVs between multiple instances of *FlightGear Flight Simulator*

RPI_{1..n}

Raspberry PI Computer. Runs the *Mission Supervisor*.

CAN_{1..n}

CAN Interface Simulator. Mimics the behavior of a CAN bus and sends messages between a *Flight Gear Flight Simulator* instance a *Raspberry PI Mission Supervisor*

R

CAN Interface Router. Broadcasts the telemetry position from one *Flight Gear Flight Simulator* instance to the rest of the instances.

QGC

QGroundControl. Ground Control Software responsible of collecting data from all the UAVs and plotting them on a map for visualizing the flight path.

In the Autonomous UAV project, QGC also has the role to prepare the mission plan that will be uploaded on each UAV.

The *Mission Supervisor* architecture is depicted in [Figure 3.2](#).

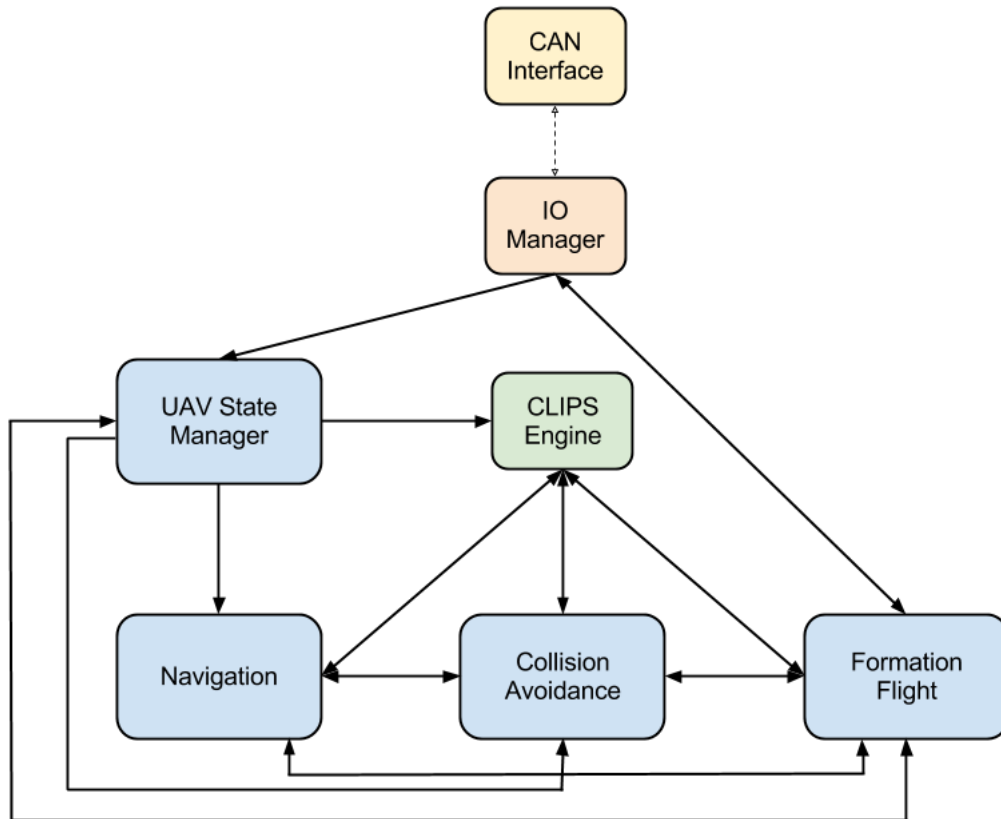


Figure 3.2: Mission Supervisor Architecture.

In [Figure 3.2](#), the components are as follows:

IO Manger

Input-Output module responsible for communicating with the UAV via the CAN bus and passing the data to the flight modules.

Clips Engine

Rules based decision engine.

UAV State Manger Module responsible for monitoring the state of the UAV. The data that it monitors includes heading, speed, position etc.

Navigation

Module responsible for deciding the flight path

Collision Avoidance

Reactive module responsible for detecting and avoiding in flight collisions.

Formation Flight

Module responsible for coordinating a fleet of UAVs for maintaining a coherent flight formation.

This thesis handles the UAV Formation Flight module that will be integrated with the other modules developed in the Autonomous UAV project to obtain an automated pilot that will be used for controlling the Hirus UAV [14].

3.2 Functionalities

The platform has the roles of:

1. Setting the flight mission objectives.
2. Selecting the flight area.
3. Selecting the aircraft types.
4. Configuring the sensors for each aircraft.
5. Based on the settings from above, generate and upload a configuration file to each aircraft.
6. After the airplanes are airborne, they will be supervised using the ground control module.
7. To control the airplanes in an autonomous way, where human intervention is needed at least as possible.
8. Override the *Mission Supervisor* or completely deactivate it, switching to a RC Controlled state.

For using the platform a will act as described below.

Using the custom widget built in QGroundControl will configure the flight objectives, selecting the number of aircrafts that will be launched, the type of sensor that will be equipped on each drone. Also the user has to create a flight path for each UAV if they are not flying in a tight formation. If the drone will fly in a close ranged formation, the user has to designate a leader and create a flight plan for him, the other UAVs will follow his path. In the case of close ranged formation, the user will specify the kind of formation that will be used (eg: V formation, Line formation). After the mission details have been set, the user will generate a configuration file that contains a rule based language that is close to the natural language and that will be interpreted by a CLIPS engine. The configuration file will be uploaded on the UAVs. When the drones are ready they are airborne and the autonomous pilot will guide to follow the mission.

From this point their mission can be overseen using QGroundControl where their flight path is displayed on the map and where their telemetry is also displayed. In case of necessity, the user will send additional commands to the drones, or it will switch the drone to RC mode and return it to base.

Chapter 4

Formation Flight

4.1 Coordinates Systems

4.1.1 Latitude, Longitude, Altitude

TODO:
describe lla

4.1.2 Earth-Centered, Earth-Fixed

TODO:
describe Ecef

4.1.3 Conversion

TODO:
describe lla-to-ecef

4.2 Formation types

TODO:
describe formation types

4.3 Entering the formation

TODO:
Describe Formation Entering

4.4 Maintaining the formation

TODO:

Describe entering the formation

Chapter 5

Implementation details

TODO:
describe implementation details

5.1 FlightGear

TODO:
talk about FlightGear

5.2 QGroundControl

TODO:
talk about QGroundControl

5.3 MY CODE

TODO:
talk about code, class-diagrams, describe methods, data-structures

Chapter 6

Use cases

TODO:
describe use cases

TODO:
captures of 3 formations

TODO:
captures of flight-path

TODO:
possible missions

Chapter 7

Conclusions and future work

TODO:
describe conclusions and future work with low priority

TODO:

Add appendixes

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