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A Combined Approach for 3D Formation Control in a Multi-UAV System using ROS

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ABSTRACT

Formation control in multi-UAV systems can be obtained through different strategies, each one with its own advantages and disadvantages. In order to minimize the weaknesses of each technique, this paper proposes a combined approach to drive a group of three quadrotor UAVs in a time varying formation, using a virtual structure, a leader-follower strategy and two behavioral rules. To each UAV is assigned a position in a formation that is represented by a virtual structure. The UAVs then have to compute their desired positions in order to achieve the formation. This is done using one of two possible methods, one based on a leader-follower approach and another based on waypoints received from a ground station. Two behavioral rules are then used to move the UAVs towards their goal while avoiding collisions with each other. The algorithm was implemented in C++ using the ROS platform and was tested in simulations using the Pixhawk SITL simulator. Results show that the UAVs are able to move in formation and also to change the formation without colliding with each other.

1 INTRODUCTION

Recently there have being a growing interest in the use of UAVs (Unmanned Aerial Vehicles) in a wide range of applications. This is due to the development of inexpensive and easy to build UAV models that can carry powerful sensors and even miniature computers. The number of proposed applications is large, ranging from civil uses such as forest fire monitoring and fighting [1][2], buildings and bridges inspection [3], crop dusting [4] and search and rescue of survivors after a disaster [5], to millitary uses including surveillance and monitoring of an area [6] or even air strikes [7]. One of the most popular model both in commercial use and in academic research is the quadrotor, thanks to its simplicity and great mobility.

Since the control of one UAV is already well understood, a new problem that is attracting attention is the use of a group of UAVs to perform missions. There are many advantages that come from this approach: a group carries more sensors and so is able to acquire more information about the environment; the number of UAVs in the swarm can be altered to tackle missions of different levels of difficulty; if one UAV fails the remaining ones can continue the mission without it. All these advantages however come with the drawback of being more difficult to control a swarm correctly than a single unit.

There are many examples of successful attempts in controlling groups of UAVs, using techniques proposed in the swarm robotics field. Kushleyev et al. developed an impressive flock of 20 minature quadrotors capable of assuming many different formations, using a centralized control strategy [8]. Bürkle et al. created an outdoor quadcopter swarm also using central processing at a ground station [9]. Vásárhelyi et al. used flocking rules to fly a remarkable swarm of 10 quadrotors in an outdoor environment [10]. And in [11] a group of simulated UAVs is used to monitor an area.

Most of the control algorithms proposed in the literature can be classified as three types: leader-follower [12][13], virtual structure [14][15] or behavior based [16][17]. In the leader-follower strategy, one of the UAVs in the group is chosen as the leader. The others have to follow it and position themselves according to its position. This approach has the advantage of being easier for a human operator to drive the group, having to control only the leader. However one disadvantage is that if the leader stops working, the whole group also stop. The virtual structure strategy consists in treating the whole group as a single fixed structure, with each UAV representing one point that composes it. The controller is designed such as each UAV is moved to create the structure's desired behavior. Finally, in the behavior-based strategy the UAVs are programmed to follow some desired behavior, such as avoiding collisions or move closer to one another. In most of the cases, these kind of strategy is based in real phenomena observed in nature, and so is classified as bio-inspired.

To control a group of three UAVs while avoiding collisions with each other and keeping track of a time varying formation, we propose an approach that combines elements from the three mentioned strategies. The formation is treated as a rigid structure, composed by an array of poses that will be assigned to each UAV in the group. The leader is the only robot that can move freely, being controlled by an operator at a ground station or navigating autonomously. All the other

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UAVs will try to move autonomously to their assigned poses in the formation, relative to the leader. The position control is behavior based, using two behavioral rules to move the UAVs: formation and separation.

The rest of this paper is structured as follow. Section 2 presents our multi-UAV system and describes our hardware and software platforms. Section 3 describes the design of the formation control strategy and the pseudocode implementation of the behavioral rules. Finally, Section 4 presents the simulation environment and the obtained results.

2 Materials and Methods

2.1 Multi-UAV System

Our system consists of a group of robots that fly over an area and a ground station with which they communicate through a telemetry link. The ground station is responsible for collecting flight data from each robot and sending information about the desired formation, but not controlling them. The control algorithm is distributed and runs in each UAV. The objective is to move the group to a desired point, avoiding collisions between the UAVs and keeping a formation that can be changed over time.

The quadrotor is a simple machine, capable of vertical take-off and landing (VTOL) and moving with six Degrees of Freedom (DoF). It consists of a center body with four individual rotors attached, as illustrated in Figure 1. By controlling the thrust generated by each rotor, we can lift the quadrotor and move it in the air. As shown in Figure 1, rotor i rotates anticlockwise if i is even and clockwise if i is odd. By adjusting the speed of the clockwise and anticlockwise rotors we can control the Yaw angle.

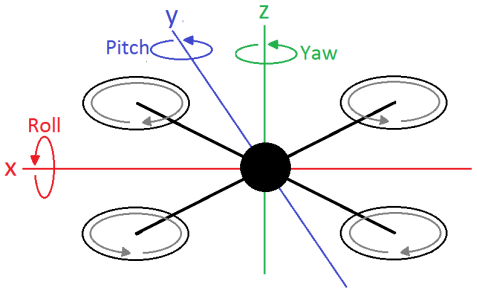

Figure 1: Degrees of freedom achieved by the quadrotor and rotation direction of the rotors

2.2 UAV Hardware

The robots we are developing the algorithm to control are small quadrotors with 250mm diameter, each one using a Pixhawk as a flight controller board. The Pixhawk is an open-source device [18] equipped with many sensors such as gyroscope, accelerometers, magnetometer and barometer and can also be connected to a external GPS module. It runs a powerful software that implements the basic controller routines of the quadrotor, along with many other useful functions. In our application, the main function of the Pixhawk is to provide the low-level stabilization and height control of the UAV. Figure 2 shows a photo of one of the UAVs used in our laboratory.

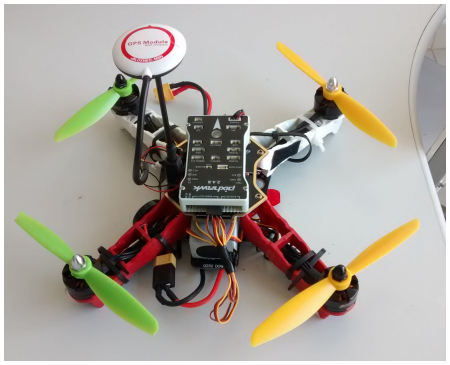

Figure 2: UAV used in the laboratory

Originally the Pixhawk is intended to be controlled by a human operator via radio controller or receive commands from a ground station. However, it is also able to communicate with other devices via a protocol called MAVLink. We use this protocol to send commands from an embedded Linux computer (Raspberry Pi) which is also carried by the UAV. in this way we can program the UAV to fly autonomously, while still being able to regain manual control at any time. Figure 3 shows a schematic view of the UAV components.

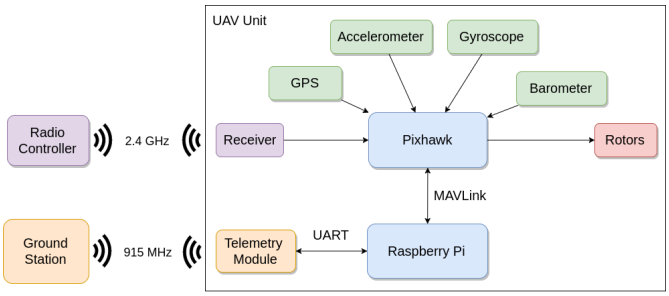

Figure 3: UAV components

2.3 Robot Operating System

Our algorithm was implemented in C++ and runs on the ROS platform. ROS (Robot Operating System) is an open source framework created to aid researchers in developing robotic applications [19]. ROS provides us with many tools and facilities that were very useful in our work.

A ROS application is a network of independent programs, called nodes, that communicate with each other. This network is managed by another program called ROS Master. The communication works in a message passing way. Nodes that generate data publish this information in topics in the form

of messages, while nodes that need that data subscribe to the corresponding topics and receive the published messages. The types of messages represent common data structures used in robotics, such as sensor readings or velocity commands.

In our application, the ROS system, containing all the control algorithms, runs on the Raspberry Pi. We used a node called mavros which connects to the Pixhawk via a serial connection and is able to translate MAVLink messages into ROS messages and vice versa. In this way the control node can get data from the Pixhawk and send commands to it. This architecture is represented in Figure 4.

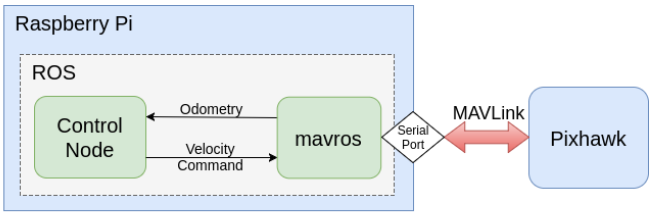

Figure 4: System architecture overview

3 Development

3.1 Formation Control Strategy

We define a global reference frame S_G with X, Y and Z Cartesian coordinates, fixed on the ground. The position of each UAV i in the S_G frame is given by:

$$p_i^G = (X_i^G, Y_i^G, Z_i^G) \tag{1}$$

Each robot uses its embedded sensors to locate itself in the global frame. Considering the Earth's geometry and the origin of the S_G frame, the latitude and longitude information from the GPS sensor can be converted to values in meters in the X and Y coordinates. This gives us the robot's initial position. From this moment on, the position will be obtained from the Pixhawk's internal state estimator, which uses an Extend Kalman Filter to fuse the measurements from its embedded sensors, including gyroscope and accelerometers. The Z coordinate is obtained from the GPS and the barometer information fused together.

Each UAV receives an unique ID, which is a positive integer number starting at 0 and increasing in increments of 1. The formation is defined as an array of positions relative to a formation reference frame, S_F. The assigned position to each UAV is the one whose index in the formation array is equal to the UAV's ID. In our experiments we defined three formations: a horizontal line, a vertical column and a triangle.

Each UAV has to compute its desired position relative to the formation frame. We defined two methods to make this calculation:

- **Leader-follower method:** In this method, one UAV is considered the leader of the group (the one with ID 0). The leader ignores its position in the formation and instead is able to move freely, being controlled by an operator or following a sequence of waypoints. The other UAVs calculate their desired position relative to the leader, considering it the origin of the formation frame.
- **Waypoint method:** In this method, all UAVs receive a waypoint to follow and treat it as the origin of the formation frame. There is no leader in this method. As such, this approach is more tolerant to UAV failure than the first one, however is more difficult for a human operator to drive the group.

The position of each UAV i in the S_F frame is represented by p_i^F. In the first position calculation method, the origin of the S_F frame is the position of the leader, and then the desired position of each UAV i in the global frame is given by:

$$p_{iD}^G = p_0^G + p_i^F \tag{2}$$

where p_{iD}^G is the desired position of UAV i in the S_G frame and p_0^G is the leader's current position in the S_G frame. In the second method, the S_F frame is centralized at the next waypoint, so the desired position of UAV i in the global frame is given by:

$$p_{iD}^G = p_w^G + p_i^F \tag{3}$$

where p_w^G is the position of the next waypoint.

3.2 The ROS Application

Two nodes are executed by each UAV: mavros and the control node, called formation_controller_node, which is our main control program. This node subscribes to some of the topics where mavros publishes data received from the Pixhawk. Using information from the GPS sensor and the internal state estimator of the Pixhawk, the formation_controller_node determines the position of the UAV in the global reference frame. It then publishes this information in a topic called /uav_positions. The node also subscribes to this same topic, but since all UAVs are publishing their positions in this topic, the node receives the position information of all other UAVs. This data will be used by the behavioral rules to move the UAV.

The formation_controller_node also subscribes to a topic called /formation, where the ground station publishes messages of type geometry_msgs/PoseArray. These messages contain an array of positions representing the formation virtual structure. Each time a new message arrives, the formation_controller_node updates an internal formation array variable, which means that the formation can be changed during the flight.

Using all the information obtained, the formation_controller_node then uses the behavioural rules to drive the UAV by publishing a geometry_msgs/TwistStamped

message in the mavros/setpoint_velocity/cmd_vel topic. The mavros node receives this message, creates the corresponding MAVLink message and then sends it to the Pixhawk, which will follow that command accordingly.

Since each UAV runs instances of the same nodes, it is necessary to run them under different namespaces to avoid causing conflicts. To each UAV is assigned a namespace in the form of /uavn where n is that UAV's ID. A simplified diagram of the resulting system is shown in figure 5.

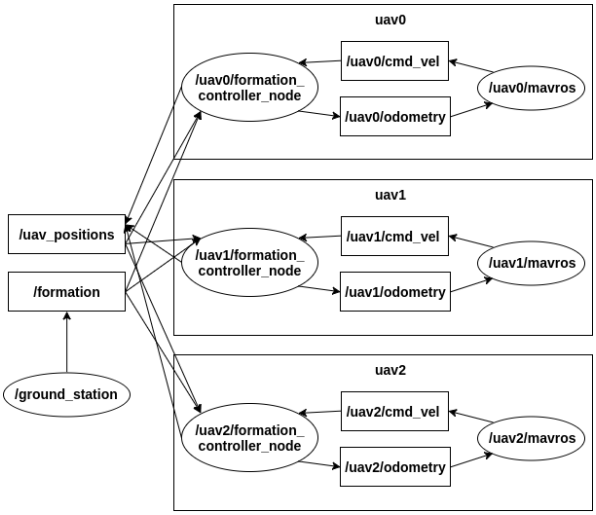

Figure 5: Simplified diagram of the ROS application generated by the program rqt_graph.

3.3 Algorithm Implementation

In this section we will describe how we implemented the two behavioral rules that move the UAVs together in a formation.

In each loop of the control algorithm, it follows the following steps: *i.* Obtain the UAV's own pose from the Pixhawk's internal state estimator; *ii.* Determine the position of the neighbors based on the position messages received from the other UAVs; *iii.* Obtain the formation array from the /formation topic; *iv.* Use the behavioural rules for Cohesion and Separation to determine the direction which the UAV should move. The main loop of the algorithm is given in Algorithm 1.

First the program calls the function *getPose()* which calculates the pose of the UAV and sets the variable *this.position* representing the UAV's position in the global frame. Then, the program calls another function *getNeighbors()* that gets the positions of the nearby robots from the received messages and stores this data in an array called *neighbors*.

Then the program starts calling the functions where the actual behavioral rules are implemented. Each function returns a vector that represent the direction that rule tells the UAV to go. For example, the Separation rule urges the UAV

Algorithm 1 Main loop of the formation control algorithm

```
1: procedure SWARM
2:     getPose()
3:     getNeighbors()
4:     getFormation()
5:     v1 ← separation()
6:     v2 ← cohesion()
7:     vres ← r1 ∗ v1 + r2 ∗ v2
8:     move(vres)
9: end procedure
```

to move away from its neighbors, so the *separation()* function will return a vector pointing to the opposite direction of the other UAVs. Each function will be explained in detail ahead.

In line 7 the two vectors are combined trough a weighted sum to generate the final resulting direction the robot should move. The weight applied to each rule determines how much that rule influences the final result. The values of the weights can be changed to obtain different results. Rules can be even completely removed from the calculation by setting its weight to zero.

In line 8 the calculated resulting direction is passed to another function that moves the UAV. This function publishes velocity commands to the mavros package, which in turn send MAVLink messages to the flight controller board, instructing it to move the UAV.

The implementation of each rule and its corresponding function will be explained in detail:

Separation Rule: This rule urges the robot to move away from other robots to avoid collisions. This is done creating a vector for each one of the detected neighbors pointing to the exactly opposite direction of that neighbor. These vectors are then combined into a resulting vector and returned to the main program. The implementation is shown in Algorithm 2.

Algorithm 2 Separation Rule

```
1: procedure SEPARATION
2:     Vector v ← 0
3:     for all neighbors n do
4:         vn ← this.position − n.position
5:         vn.normalize()
6:         vn ← vn ∗ distance(this, n)
7:         v ← v − n
8:     end for
9:     return v
10: end procedure
```

We also want the robot to move faster the closer it is from its neighbor. We do this by adjusting the vector's magnitude. First we normalize it so it becomes a unit vector. Then we divide it by the distance between the two robots. As the distance between two robots gets smaller, the magnitude of the

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resulting vector becomes bigger.

Formation Rule: This rule tries to move the robot to its desired position in order to maintain the formation. The implementation is shown in Algorithm 3. Fist we test which method is being used to determine the desired position. Then we check if the UAV is the leader by testing if its ID is 0. If the method being used is the leader-follower, the leader follows the waypoint and the followers determine their desired position according to Equation 2. If the waypoint method is being used, all UAVs use Equation 3 to determine their desired position. The function then generates a vector pointing to the calculated position.

Algorithm 3 Formation Rule

```
1:  procedure FORMATION
2:      Vector v ← 0
3:      Vector DesiredPosition ← 0
4:      if leader-follower then
5:          if ID == 0 then
6:              DesiredPosition ← waypoint
7:          else
8:              DesiredPosition ← leader.position +
    Formation[ID]
9:          end if
10:     else
11:         DesiredPosition ← waypoint + Formation[ID]
12:     end if
13:     v ← DesiredPosition − this.position
14:     return v
15: end procedure
```

3.4 Computational Complexity and Communication issues

One important concern when designing a multi-robot control application is the elevation of the computational complexity with the increase in the number of robots. In special, in a behavior based approach such as the one we used, each individual has to iterate through all other individuals to compute its behavioral rules. If a centralized control is used, this represent a $O(n^2)$ computational complexity, where n is the number of robots. However, in a decentralized approach, each robot runs its own control algorithm with a computational complexity of O(n). This means that a decentralized approach can make the system more scalable, with the addition of more robots bringing a smaller burden to the process.

Another concern is the influence of delayed communications. In our application the robots must communicate with one another to be able to locate their neighbors. Since we performed our tests in simulation, the communication delay was not a problem. However, in real life implementations the system would be negatively influenced by this delay. In Section 5 we discuss how this problem could be tackled in future works.

4 Results and Discussion

We decided to run our program in simulation first as a proof-of-concept and also as a way to evaluate its performance. We used the Pixhawk SITL (Software In The Loop) simulator, a software that is provided as part of the Ardupilot project. With it we were able to interact with a simulated Pixhawk running its original firmware and generating accelerometer, gyroscope, GPS and other sensors data. Three instances of the simulator were executed simultaneously, each one using a different GPS starting position, effectively simulating three UAVs that were able to be controlled individually by our ROS application.

We defined a scenario where the three UAVs, with IDs of 0, 1, and 2, have to move together maintaining a formation. The UAVs were commanded to take off to an altitude of 2 meters. As soon as they are stabilized in this altitude, we started the control node and they start moving. Since the SITL does not generate a graphical representation of the simulation, we used the program RViz, which is a standard ROS tool to create a visual representation of the UAVs. Figure 6 shows the three UAVs in RViz screen.

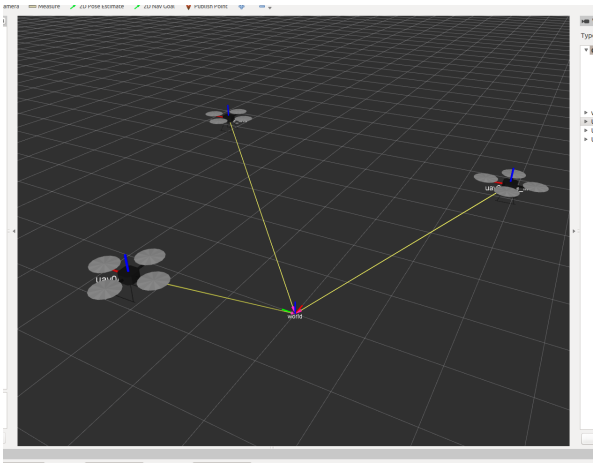

Figure 6: Visualization of simulated UAVs in RViz.

To evaluate the performance of our algorithm we defined two main tests.

4.1 Moving in Formation

The first test aims to evaluate the capability of the UAVs to maintain a formation while moving together. The robots are commanded to assume a formation and then move to two waypoints. We repeated this test for each position calculation method and for three different formations: a horizontal line, a vertical column and a triangle. In all experiments the UAVs were capable of maintaining the formation and no collision occurred. In Figure 7 we show the trajectory developed by the UAVs in the test with the triangle formation and leader-follower position calculation method.

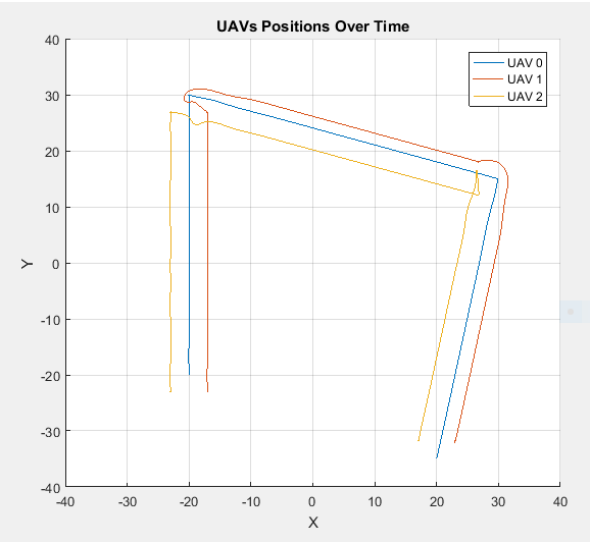

Figure 7: UAVs trajectory over time.

Another interesting feature of our solution is the possibility of formation control in three dimensions. In figure 8 the three UAVs are keeping a vertical formation, assuming different positions in the Z axis.

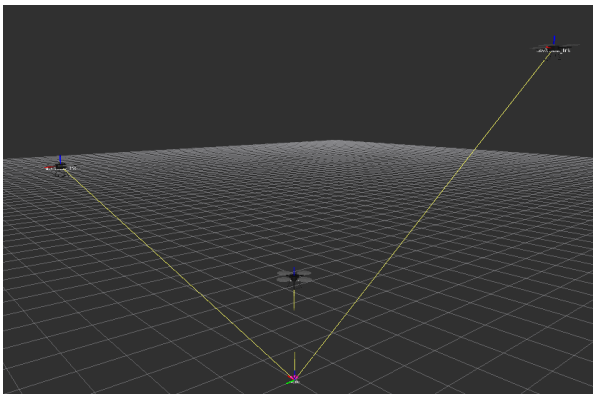

Figure 8: UAVs performing a vertical formation.

4.2 Changing Formations

In this test we tried to see if the UAVs were capable of changing from one formation to another without colliding with each other. The UAVs started at the line formation, then changed to other formations following this sequence: column, triangle, line, triangle, column and then line. Table 1 shows the time spent in each formation change. Thanks to the separation behavior, no collision was observed.

It is interesting to note that the longer times appear in the transitions to the column formation. This is caused by the fact that this formation is actually vertical, so the UAVs have to gain height in order to assume their desired positions.

Transition	**Time [s]**
line → column	7.16
line → triangle	3.66
column → triangle	4.90
column → line	4.70
triangle → line	3.53
triangle → column	7.17

Table 1: Time spent in each formation transition.

5 Conclusion

This paper presented the design of a combined approach to the formation control problem in a group of UAV vehicles. Our algorithm combined elements from three different multi-UAV control strategies: leader-follower, virtual structure and behaviour-based. The implementation was tested in simulations and presented good results. The UAVs were able to move in different formations and change from one formation to another without colliding with each other.

In future works some improvements can be studied, such as the use of cameras or range sensors to detect nearby robots. This would eliminate the need of communication between the robots, avoiding the negative influence that delayed communications would have in real systems, and enable the possibility to detect obstacles in the path.

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