Autonomous Navigation of a Flying Vehicle on a Predefined Route

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Abstract

In this paper a flying platform and its navigation algorithm are presented. The proposed system is composed by the commercially available model airplane "Arising Star" by SEAGULL, and an additional component that carries all the electronics suitable for the autonomous navigation. This is an additional custom-made box, the main advantage of which is that it consists of off-the-self parts, exclusively. Therefore, it can be adjusted to any airplane. The proposed navigation algorithm can be tailored as well. The whole system can be easily reprogrammed in order to comply with the aerodynamic constraints of the airplane in hand, to define speed and altitude safety levels as well as to define different target co-ordinates each time.

1 Introduction

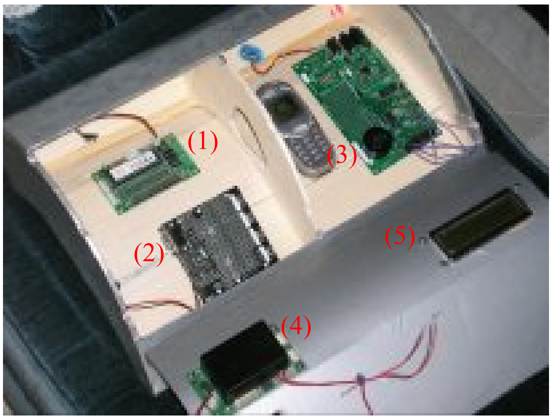
Unmanned Aerial Vehicles (UAV) is a well-established branch of aeronautics (Chiesa *et al.*, 2000), (de La Parra and Angel, 2005). Over the last decades, under top-secret projects and in special facilities, the pilot sits in the cockpit, just for emergencies. However, the research in this field is still active. French military air-force has ordered 160 close range UAVs and the Greek military air-force has founded a special branch, whose specialty is the construction of unmanned aerial vehicles. These are going to be used during peace for border and agricultural surveillance or during war for preparation operations under limited communication control, espionage and, of course, in both defensive and offensive situations. Nowadays, UAV research involves not only militia but academia and industry as well (van Blyenburgh, 1999). Moreover there are many magazines and web pages that give out instructions on how to create a "do it yourself" UAV. Recently, what is mostly mentioned is UFAV, which stands for "unmanned fighting aerial vehicle", that in the near future is going to replace the usual air-fighters and their pilots. New promising technologies are being developed for launching, recovering and refueling unmanned high altitude airborne platforms. Numerous techniques have been developed also for urban environments: from vision-based autonomous helicopters using optic fibers and neural networks (Muratet *et al.*, 2005), to mission planning using A* graphics engine (Vachtsevanos *et al.*, 2005) and performance prediction using multi-agent systems (Lian and Deshmukh, 2005). Last but not least, a preliminary design of low speed, long endurance remote piloted vehicles (RPV) for civil applications has also been proposed (Martinez-Val and Hernandez, 1999). Today there are many UAVs that cover any need for autonomy: from close range UAVs with a wing span of 1.5m to long range UAVs that can cross the Pacific completely autonomously. The UAV technology has never been more popular than nowadays. In the last few years, the development of UAV market has been a top priority both in European Union and in USA. Unmanned air-vehicles are also taking off in NATO's priorities and DARPA is the main sponsor of most American academia UAV projects (Fielding and Jones, 2000).

The main thrust of our project is to produce a generic navigation system, based on several different types of sensors, portable to any kind of airplane. The proposed system is easily reprogrammed, so that it complies with the aerodynamic constraints of any arbitrary airplane. The experiments and the demonstrations were carried out on an experimental UAV setup, which is also presented in this paper. The proposed air-vehicle has a wing span 1.7m and its autonomous flight operation lasts 40 minutes. Onboard there is an aerodynamic box, inside which is placed the navigation system of the UAV. This is comprised by two subsystems. The first one is the system responsible for the navigation control of the airplane. It includes a GPS (global positioning system), a basicX microcontroller and an LCD. The second subsystem is responsible for the safety of the airplane. It contains an OOPic microcontroller, a magnetic compass, a sonar, a speech recognition system and a battery check system. Whenever the airplane does not navigate automatically via the GPS, we take over control through a receiver-transmitter system. The navigation algorithm for the system in hand is also presented. This is mainly based on two comparisons, i.e. comparisons between the instant latitude and longitude, to the constant latitude and longitude of the target, respectively. Depending on which co-ordinate is bigger, the airplane turns to the left or to the right, respectively. The distance that the airplane covers, depends on the magnitude of this difference. Secondary comparisons are also made to control the speed and the altitude of the airplane.

2. Hardware description

The proposed system is depicted in Figure 1a. This is the commercially available airplane "Arising Star" by SEAGULL, carrying the additional custom-designed and manufactured aerodynamic component (the silver box on the wings of the model), that bears all the electronics suitable for the autonomous navigation. An internal view of the components is illustrated in Figure 1b.

(a)



(b)

Figure1: (a) The experimental setup and (b) the electronics for its navigation

The box was carefully designed by taking under consideration the airplane's aerodynamics (wing span, wing width etc) as well as the maximum payload of the plane (i.e. 1.5 kgr). On the left half of the aerodynamic component, one can see the two microcontrollers, namely the OOPic (1) and the BasicX (2). These control the safety and the navigation systems, respectively. On the right half the speech recognition system (3) is located. This along with a cell phone comprises the safety system. The role of the cell phone is to transmit safety commands (in ring-tones format) to the former speech recognition system. Below the BasicX one can notice the GPS module (4). This passes geographical coordinates to the BasicX that makes the proper comparisons and adjusts the trajectory of the airplane, by moving the ailerons. Next to it, an LCD (5) is located, that is used for functional test of the BasicX while the airplane is on the ground. Apart from these, there are also seated a magnetic compass, which adjusts trajectory to the North, and a sonar that turns off the engine of the airplane just before landing.

3. Navigation algorithm description

The whole system is designed so that the take off of the airplane is done manually, whilst afterwards the navigation is switched to autonomous mode. This mode is described in the current section. It is based on the data acquired through the GPS system and it is performed by the BasicX microcontroller. In order to perform navigation on a predetermined route, an array named route_data is defined. The array elements from route_data(11) to route_data(17) are used to describe the latitude of the target spot. Similarly in-between elements route_data(18) to route_data(26) the corresponding longitude is stored. According to the elements being assigned at places 18-26 of the array, we modulate the co-ordinates of the target spot. The route_data elements are assigned via the keyboard. There is another array defined though (instant_data), which is used as a temporary storage of the instant co-ordinates obtained automatically by the GPS. The elements of instant data array are updated with a frequency of 1Hz (one second is required for the GPS register update). We use the positions 3-18 of the instant_data array to temporarily store the respecting co-ordinates of the longitude and the latitude. The instant_data(20) element is used to check, on a constant basis, whether the GPS receives signals from at least three satellites. In case that instant_data(20) equals zero, the quality of the GPS signal is poor or nonexistent, and thus the airplane control is transferred to OOPic, i.e. the secondary microcontroller. This controls the signals acquired by the sonar, the speech recognition system, the magnetic compass and the battery check system.
When the GPS receives a good quality satellite signal, the comparison of the co-ordinates of the instant_data and the route_data array elements starts. A block diagram of this process is shown in Figure 2. Initially, the comparison of latitudes takes place. More specifically the first element of the instant_data array is compared with the first element of the route_data array. In case that it is bigger, the servo that controls the ailerons rotates towards right and the airplane flies left for approximately three seconds. This time is enough to change the former trajectory to a new perpendicular one. Due to this three second turn, the airplane loses some altitude. In order to regain the altitude lost, the servo that controls the elevation slightly rotates to the right. This rotation also lasts three seconds. By the end of this time, the servo is centered back to 1.5 ms, so that the airplane flies at a steady altitude with a steady heading perpendicular to the former one. The next servo being controlled is the one corresponding to speed. Unlike the others, it is not centered to 1.5 ms but it covers a range

from 0° to 120°. We have programmed it to rotate in a range of 60°, corresponding to approximately 60 km/h. If the latitude of the target spot is 00:00:00000 and the airplane's latitude is 10:00:00000, then the difference between the current latitude and the one of the target is 1. Since these are the first digits of the co-ordinates sequence the difference between them equals a distance of 60 miles (60×1.8 km/h = 108 km/h). If this difference is α, then the distance that has to be covered is α×60 miles and so on.

So supposedly that:

A1B1:C1D1:E1F1G1H1 (current latitude)

A2B2:C2D2:E2F2G2H2 (latitude of the target)

The distance that has to be covered in order to get to the target spot from the current location is:

$X=|(A2-A1)\times 60+(B2-B1)\times 6+(C2-C1)\times 0.6+(D2-D1)\times 0.06+(E2-E1)\times 0.006+(F2-F1)\times 0.0006+(G2-G1)\times 0.00006+(H2-H1)\times 0.000006|$ nautical miles of latitude.

If the value of X is positive, then the target spot lies at distance X to the right, otherwise it lies the same distance to the left..

The same goes for latitude:

A1'B1'C1':D1'E1':F1'G1'H1'I1' (current longitude)

A2'B2'C2':D2'E2':F2'G2'H2'I2' (given longitude)

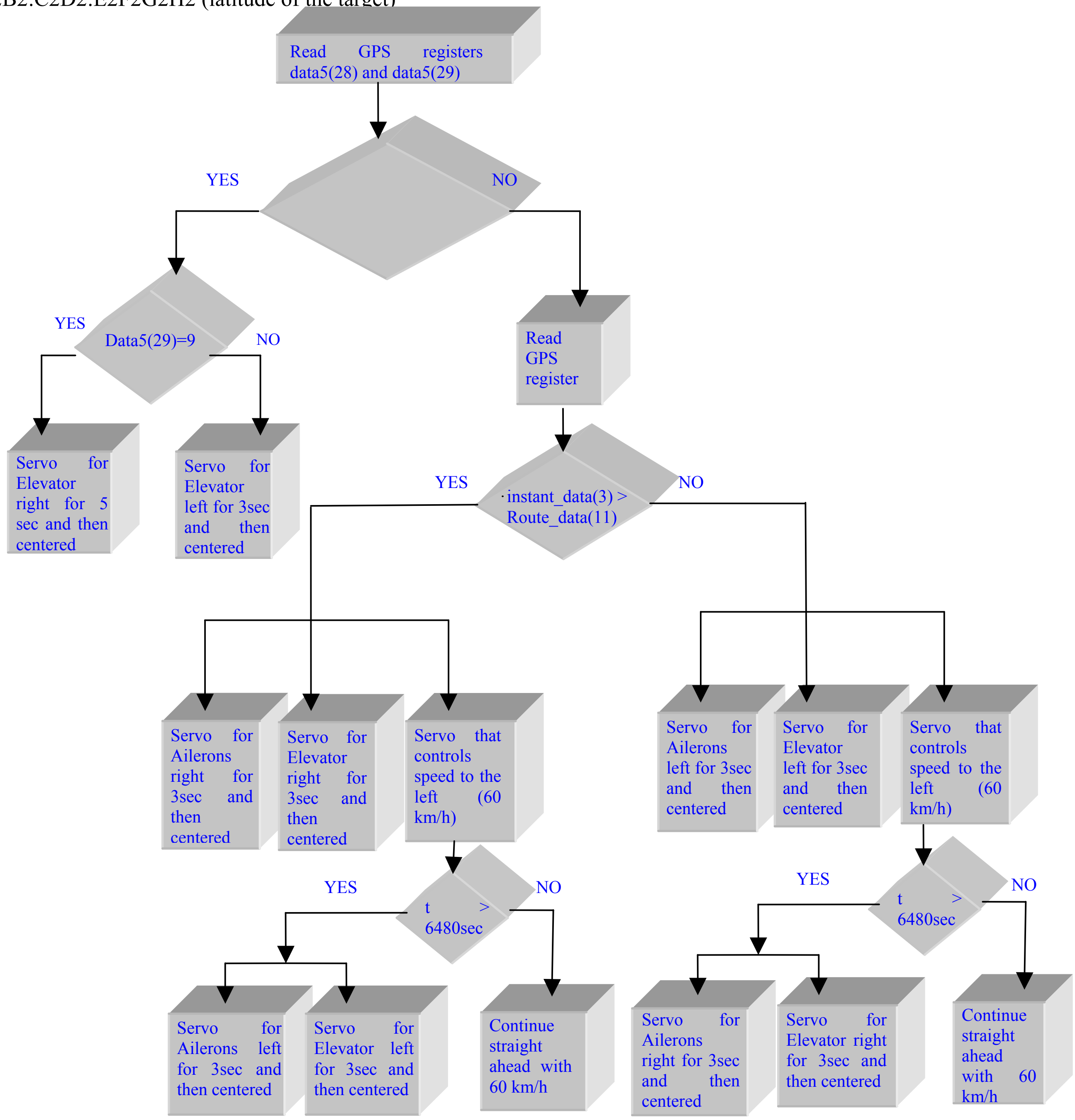


Figure 2: Decision diagram according to the signal from the GPS.

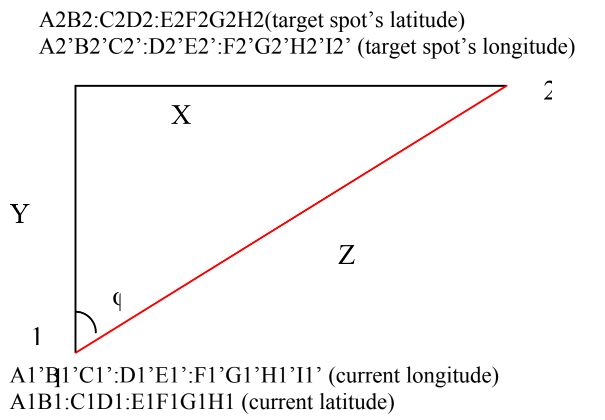


Figure 3: In order for the airplane to fly from waypoint (1) to waypoint (2), it has to cover a distance Y+X and not just Z.

This is graphically illustrated in Figure 3. In order to fly from point 1 to point 2, we analyze the resultant trajectory in two components, the first in X-axis and the second in Y-axis. Someone might wonder, since the distances X and Y are known, why we do not just calculate φ angle and turn the ailerons in such a way to cover Z distance. This could happen only if the relationship between the ailerons turn and angle φ of the airplane route concerning its former trajectory is known. However, the transfer function between the two angles is highly non-linear and, therefore, the recommended successive approximation method is a satisfactory trade off. We continue by analyzing the rotation of the servo that controls the speed of the airplane. Let us suppose that the airplane has to cover a distance of 60 miles on X axis (which results if the difference between the first digit of current latitude with the first digit of the given latitude is 1) and a "for" loop from 0 to 50 equals one second. It is not difficult to calculate that we have to use a "for" loop from 0 to 324000. During this loop, the airplane moves straight ahead. The same goes for the second digit, but instead of 60 miles we have to cover just 6 miles. So, the "for" loop, which we will have to use, ranges from 0 to 32400 and so on. After the airplane has completed its trajectory on X-axis, the servo that controls the ailerons rotates towards the left, so that the airplane continues the trajectory that was interrupted before the altitude loss. The servo that controls the elevator lifts the airplane to its former altitude. These two servos that control the ailerons and the elevator are centered back to 1.5 ms. Finally, the longitude (or else the Y distance) is computed. If the difference between the current longitude and the given one lies in the first digit, then the airplane has to cover a distance counted by a loop from 0 to 324000. If the difference is in the second digit, the loop ranges from 0 to 32400 and so on. In our example, presented in the decision diagram on Figure 2, the airplane was supposed to turn left, because instant_data>route_data. If instant_data<route_data, then the airplane is going to turn right, i.e. the servo that controls the ailerons has to rotate for three seconds towards left. With this method the aircraft does not pass over the target spot immediately after the first comparison, but after as many co-ordinates comparisons as possible, so that it is more accurate (see Figure 4).

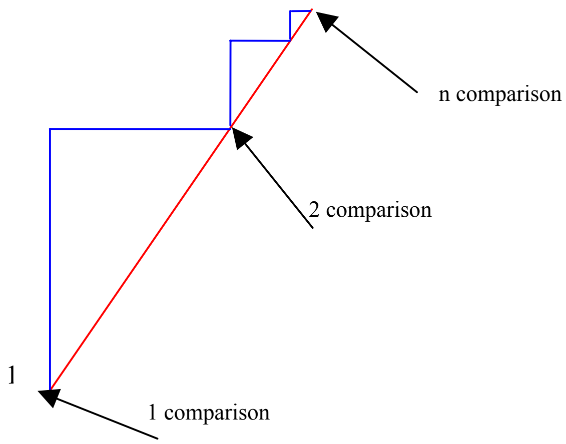


Figure 4: Successive approximation of the target with straight-line segments

4. Experiments

The above-described algorithm was programmed and tested on the proposed system. Due to the lack of inclinometers that would keep the airplane stable during take off and landing, the whole system is designed so that the take off of the airplane is done manually (first period), then the navigation is switched to autonomous mode (second period) and then back to manual (third period). During trials, the first period lasted 100sec, the second period lasted few seconds (between 3 to 10) and the final period till landing lasted another 100sec. Many trials took place for testing mostly latitude comparisons but longitude comparisons as well. The trials were mostly qualitative, since none of the microcontrollers was equipped with sufficient memory to store real flight data. Real landmarks were used and if the airplane was passing exactly above them, the GPS strings comparison were supposed to be successful. Six trials out of six were successful. As shown in Figure 4, in order for the airplane to accomplish the desired trajectory and simultaneously not to lose height that would jeopardize its safety, it has to turn towards either left or right for about three seconds. This number was varying during the trials depending on the weather conditions and the quantity of the fuel. Three seconds time is satisfactory when there is no wind interfering with the plane's trajectory (i.e. wind at most 2 Beaufort) and when the fuel carried is about 200gr. However, in most of the trials we have noticed that the airplane does not complete a full three seconds turn. This is due to the fact that the differences in compared latitudes are relatively small for the trial period. Hence, although the turn itself lasts three seconds, the comparisons last less than three seconds and, as a result, the airplane never accomplishes a full three second turn. Also in all our experiments we noticed a slight pitch with the airplane's nose up. This happens due to aerodynamic lift in the additional component on the airplane's wing.

5. Conclusions

An experimental setup was built in our laboratory to study the behavior of an UAV equipped with several different types of sensors and alternative safety systems. A navigation scheme, based on GPS, is also proposed. The proposed navigation algorithm has certain advantages in case that the predetermined flights are not going to last long. The main trajectory of the airplane is analyzed into a series of straight-line segments. That results to waste of fuel, which in UAVs is considered a very valuable asset. However, in that way, we override the flight dynamics and also the use of a wind tunnel, which is not affordable for a low-price laboratory setup, composed by of-the-self parts. The fact that the current measured co-ordinate is constantly compared to the target co-ordinate, renders the system insensitive to instant variations in measured data and thus it results in reliable navigation. Finally, the most important aspect of the project is the portability of the proposed scheme to any airplane. With minor aerodynamic adjustments to the box, which hosts the main system of the UAV, so that it fits exactly over the main wing of the considered airplane, the major advantage is that the proposed algorithm can be used by any model available in the market or even by custom made ones. Therefore, there is no reason for spending resources to build an UAV from scratch. The whole system can be easily reprogrammed in order to comply with every airplane's aerodynamic constraints, to define speed and altitude safety levels, to adjust the accuracy and the reliability of the system by defining the number of satellites that transmit signals and to define different target co-ordinates each time.

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