Flight patterns for clouds exploration with a fleet of UAVs

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Abstract— Modeling the cloud microphysics processes is essential to improve our understanding in climate changes and reduce the uncertainties in weather predictions. Aircrafts, remote sensing and ground-based infrastructures provide either sparse or coarse spatial measurements that are not sufficient to develop fine cloud models. UAVs have shown their ability to collect relevant cloud in-situ measures, and can be even more efficient when deployed in fleets. However, collecting relevant cloud data call for specific trajectories: this paper introduces a series of flight patterns dedicated to cloud exploration by a fleet of UAVs. The patterns definition comprise both a priori geometric information and real-time reactions to collected data. Results in simulated clouds assess their relevance for cloud in situ data collection.

I. Introduction

The precise understanding of the clouds micro-physical properties is still a challenge for atmosphere scientists. The complexity of the involved physical processes calls for thorough models, whose relevance and adequacy require dense and precise data to be assessed. For this purpose, ground-based and satellite measurements can be complemented by in-situ measurements provided by instrumented research aircrafts. Yet, the observations collected by aircraft are localized in space and time [1], which limits the understanding of clouds evolution.

The use of UAVs is now significantly spreading within the atmosphere scientists community. For instance, recent experimental campaigns have been conducted to analyze air-sea interactions [2], to track and estimate gaseous pollution plumes [3], [4], or to compare measures of cloud extinction profiles with air parcel models [5]. Large UAVs are also used to collect data in the upper atmosphere [6].

Yet, dense data are required to precisely assess the physical phenomena that take place in the atmosphere. For this purpose, the use of a fleet of UAVs is very relevant [7]: a fleet can acquire synchronous data over large extents of space, allowing for instance the assessment of fluxes, which no single measurement system can provide. Moreover, intelligent fleet control strategies can be developed so as to optimize the data collection, while autonomously adapting to the situation at hand.

This paper presents on-going work on the development of a fleet of UAVs to explore clouds, in the context of the NEPHELAE project, whose purpose is to develop and actually deploy a fleet of autonomous UAV to collect data within and around cumulus clouds. The project involves atmosphere scientists from the Meteo France research lab GAME, the drone team of ENAC, and roboticists from LAAS/CNRS, and builds upon prior exploratory work [8]. Various axes of work are carried out, that span from the conception of a dedicated UAV and the development of on-board atmospheric sensors, to the definition of individual UAV flight control laws and overall adaptive fleet control schemes. We focus on the two latter points, and depict in details the specific flight patterns developed to achieve adaptive data collection.

Outline: The next section presents the overall approach retained for the fleet operations, which relies on the assembly of sequences of dedicated flight patterns. Section III depicts the defined flight patterns, which are evaluated in section IV, and the paper concludes with a roadmap of developments towards actual flight experiments.

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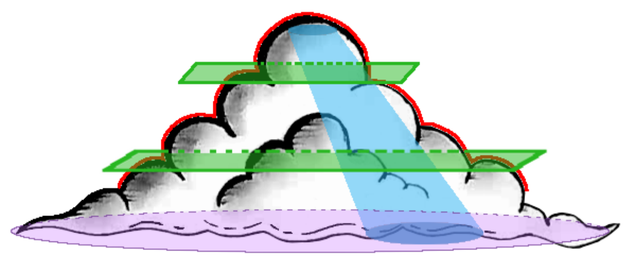

Fig. 1. The different zones in which UAVs will gather data: the cloud base (purple), its body (green), the internal updraft (blue) and the cloud borders (red).

II. Problem statement and approach

A. Mission definition

Numerous discussions have been conducted with atmosphere scientists in order to understand their needs. Thanks to intensive atmosphere microphysics simulations, they have established a first conceptual (macroscopic) cloud model for continental cumulus clouds, that links key meteorological parameters (e.g. updraft, entrainment) to basic cloud geometry (e.g. width, height, aspect ratio) [9]. For instsance they assessed linear relationships between the cloud base diameter, the cloud height and vertical fluxes. On the basis of these observations, they defined basic data collection needs to assess the model validity. The variable of interest to collect are:

- The pressure, temperature and humidity
- The wind field and turbulences
- The liquid water content (LWC), which represents the mass of liquid water in a cloud for a specified

amount of dry air, an essential information in cloud microphysics [10].

The atmosphere scientists have defined a series of information to collect so as to track and monitor the various stages of a cumulus cloud life, from cloud formation (dominated by updraft air flows) to dissipation (dominated by entrainment at the cloud borders). These information define zones to be mapped by the UAVs, that are illustrated in the Fig. 1.

The information to gather in these zones are the following:

- At the basis of the cloud (purple), the information to gather are the shape of the cloud contour, and the distribution of the LWC and the vertical wind at the elevation of the basis. The latter information in particular define the "center" (or core) of the cloud, where the updraft is the higher.
- Cumulus clouds exhibit a column where updrafts take place (blue), which can be coarsely described as a slanted truncated cone. The main interest of gathering information within this zone is to follow the evolution of the vertical wind during the life of the cloud.
- By mapping vertical winds on thick sections of the cloud (green), the scientists can estimate air fluxes.
- And finally, measuring the vertical wind, turbulences and the evolution of the LWC at the borders of the clouds frontier (red) is essential.

Once the zone to gather data have been defined, the life span of the cloud will determine the frequency of exploration of each part. The cumulus clouds life extent is of the order of 30 minutes, which imposes constraints on energetic autonomy, attainable horizontal and vertical speeds, weight of the UAV, ... Cloud exploration is a highly constrained problem, that actually requiress the development of specific UAVs (see chapter V).

B. Approach to fleet control

The UAV fleet is to be tasked by high level commands such as "assess the entrainment at the cloud edge" or "quantify the updraft at the cloud base". This calls for deliberative approach that explicitly models (maps) the environment on the basis of in-situ measurements and that builds actions plans (trajectories) based on aircraft performance models and sensing capacities.

But instead of directly planning trajectories in space and time, the deliberative layer assembles trajectories defined as a sequence of specific flight patterns, each pattern being adapted to the acquisition of one of the information listed above. The flight patterns can partly be parameterized geometrically (e.g. specifying at which elevation a horizontal section of the cloud is to be mapped), but are also defined as adaptive trajectories which execution is servoed on acquired data (e.g. the perceived LWC can be used to detect the cloud boundaries when mapping a cloud section).

The specification and development of the overall planner is still under way. A centralized architecture will be used: all UAVs transmitting their data down to the ground station, where data are processed to build cloud maps using Gaussian Processes regression techniques [11], and where the task allocation and primitive assembling processes are also executed. Such a centralized architecture can be easily disturbed by loss of communication and does not scale up with the number of UAVs. Evolving towards a distributed architecture can balance these issues and is on our research agenda – and is actually also a reason why we chose to specify flight plans as sequence of patterns, thus easing the decision processes.

Finally, note that initial information on the cloud can help the scientist to specify the task to be achieved, and the central planner to decompose the tasks into sequences of primitive patterns. For instance [12] have developed a method to assess coarse geometric parameters of a cloud using a network of all-sky cameras, such as its base height, size and horizontal velocity. Atmospheric Lidars and radar can also provide similar data to initialize the sampling strategy of the UAV fleet.

III. Flight patterns

This section presents the concepts of the flight pattern primitives that have been developed to gather efficiently atmospheric data. The idea is to create several flight plans that are easily executable for the UAV with limited processing power. The computational complexity of these algorithms is limited by the possibility to embed them on a dedicated electronic card such as a Raspberry Pi. The implemented solution is not an optimal path planning method driven by an utility criterion but rather a set of adaptive shapes triggered by sensor readings in real-time.

Schematic illustrations are shown for a better understanding of the patterns. The shape of the cloud is displayed in black, the UAV is represented in orange, the theoretical trajectory in green, the calculated points and circles in blue and finally, in red, the parameters.

Observation: The basic parameters are directly given by the design of the UAV. That's the case of the cruise speed, the max roll angle and the minimum curvature radius deduced from the first two parameters with the following equation :

$$R_{min} = \frac{V^2}{g\tan(roll_{max})} + R_{margin} \tag{1}$$

where R_{min} corresponds to the minimum radius, V the cruise speed, g the gravitational constant, $roll_{max}$ the maximum roll angle and R_{margin} a margin to warrant the execution of the curve even in harsh condition.

A. The lace

The lace pattern is inspired by [13] that develops a method to estimate the boundaries of an dynamic environment with a team of robots. They prove that with a swarm of several agents it is possible to collect data, communicate them to the others and perform the required calculations to estimate the frontier. The interesting part of their work is that they succeed to distribute all the processing part and to deploy their team of robots in a cooperative way.

In our case, the UAVs use LWC data as the information to detect the cloud boundary. This boundaries being not sharp, a wider space around it has to be covered to ensure its detection: the chosen pattern is adapted to cover enough distance each time a threshold on the LWC data is crossed.

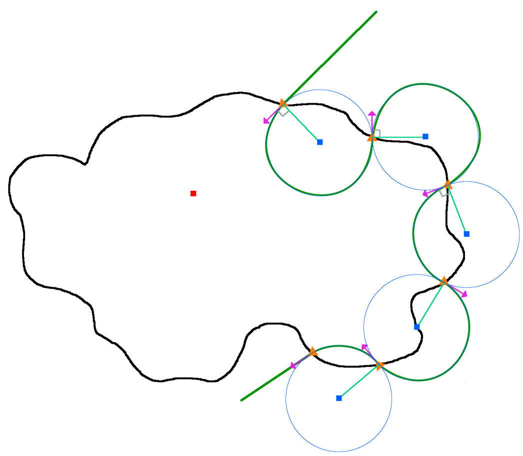

Fig. 2. The lace pattern

The Fig. 2 illustrates the path followed by the UAV in a 2D horizontal plane. It only needs a 3D starting waypoint (in red) which is inside the cloud. To extend the exploration to the 3D volume of the cloud, an extra vertical speed can be specified.

TABLE I

Algorithm of the lace sensor based pattern

```
procedure Lace(Point A, vert_speed)
    GoTo(A)
    in_out_cloud ← 0                          ▷ 0 out; 1 in
    way ← 0                    ▷ 0 to the left; 1 to the right
    ListBorderPoint
    while UsePattern = True do
        in_out_cloud_old ← in_out_cloud
        in_out_cloud ← DetectBorder()
        if in_out_cloud ≠ in_out_cloud_old then
            ListBorderPoint.add(ActualPosition())
            dir_uav ← GetDirection()
            A ← CalculateNextCenterCircle(dir_uav, way)
            Circle(A, way, vert_speed)
            if way = 1 then
                way ← 0
            else
                way ← 1
            end if
        end if
    end while
    EstimateBorder(ListBorderPoint)
end procedure
```

Table I depicts the algorithm that achieves this pattern. Every time the UAV crosses the cloud border based on LWC threshold, it exploits its position and heading (purple arrows on Fig. 2) to compute the center of the next circle that it will track, depending on the minimum turning radius R_{min} and an angle set to $\pm\frac{\pi}{2}$ (in grey). The aim is to collect as much points of the border as possible to better estimate the outer shape of the cloud.

B. The rosette

This pattern is designed for multiple purposes. As the lace pattern, it can be used to estimate the cloud border, but its role is to mainly collect information in the core of the cloud by crossing several times its central part. This provides valuable information for measuring the air mass flow when flying two UAVs at two different altitudes.

Table II presents the associated algorithm. The only parameter required to initialize the path is a 3D position inside the cloud. After reaching this point along a straight line, the UAV will continue until the border is crossed. Once outside the cloud it will initiate a turn around according to the minimum radius and estimate a new center point from the data gathered during the last segment inside the cloud. This operation is repeated as many times as required to complete the map of the data with a satisfying coverage.

TABLE II

Algorithm of the rosette sensor based pattern

```
procedure Rosette(Point A)
    GoTo(A)
    in_out_cloud ← 0
    nb_line ← 0
    nb_turn ← 0
    ListBorderPoint
    while UsePattern = True do
        in_out_cloud_old ← in_out_cloud
        in_out_cloud ← DetectBorder()
        if in_out_cloud_old = 0 & in_out_cloud = 1 then
            ListBorderPoint.add(ActualPosition())
            StraightLine(A)
            nb_line ← nb_line + 1
        else if in_out_cloud_old = 1 & in_out_cloud = 0
then
            ListBorderPoint.add(ActualPosition())
            Circle()
            nb_turn ← nb_turn + 1
        else
            if nb_line = 1 & nb_turn = 1 then
                EstimateBorder(ListBorderPoint)
                A ← EstimateCenterPoint()
                nb_line ← 0
                nb_turn ← 0
            end if
        end if
    end while
end procedure
```

Fig. 3 illustrates the path of the UAV at different times when following the rosette pattern. The red point corresponds to the point to go through and in the final picture, the purple zone is the estimation of the cloud center. A future improvement will consist in incorporating the measured updraft winds in the definition of the cloud center point by the updraft.

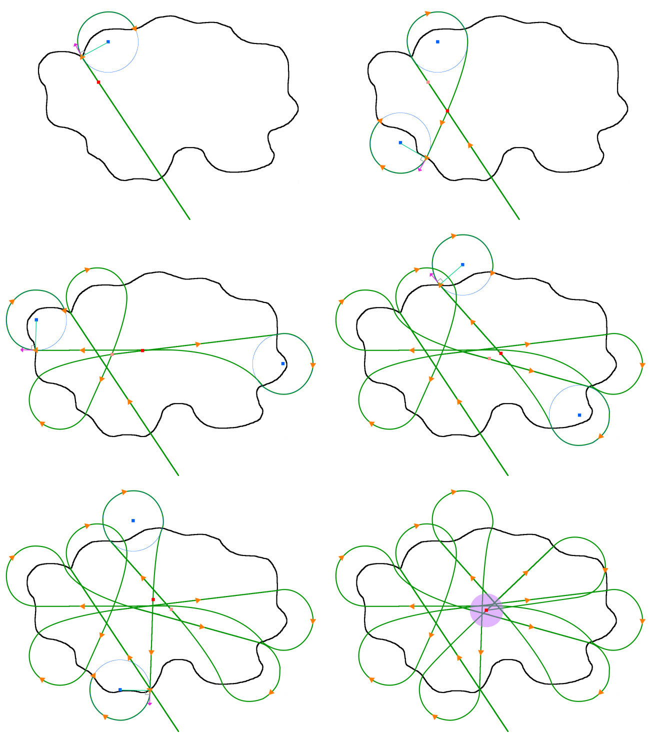

Fig. 3. Rosette path

C. The conic spiral

The main goal of the conic spiral pattern is to gather data from the cloud's core, which is where the updraft is at its maximum intensity. Starting from the cloud base, it can expend to the top of the cloud or even a bit higher. For the time being, the parameters are based on the geometry determined by other patterns like rosette at different altitudes. The resulting trajectory looks like a spiral along a slanted cone as see on Fig. 4.

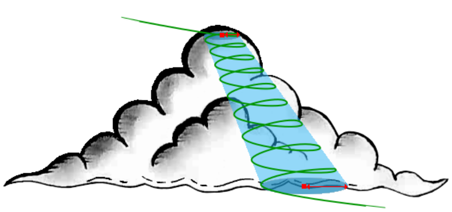

Fig. 4. Conic spiral path

A sensor based version is currently under development. It will integrate information from the vertical wind component and the UAV energy consumption to adapt the center of the spiral in real-time similarly to glider's pilots.

D. The Zamboni

The name of this pattern is coming from a manufacturer of ice rink resurfacer, who defined a geometric path to efficiently cover an area with strong constraints on the turn radius. This pattern offers a simple and fast way to cover a rectangle defined by geometrical parameters and for a large range of cloud sizes. Additionally, the coverage is more regular than the rosette pattern, which might be a mission requirement in some cases. This pattern is not driven by sensors measurements.

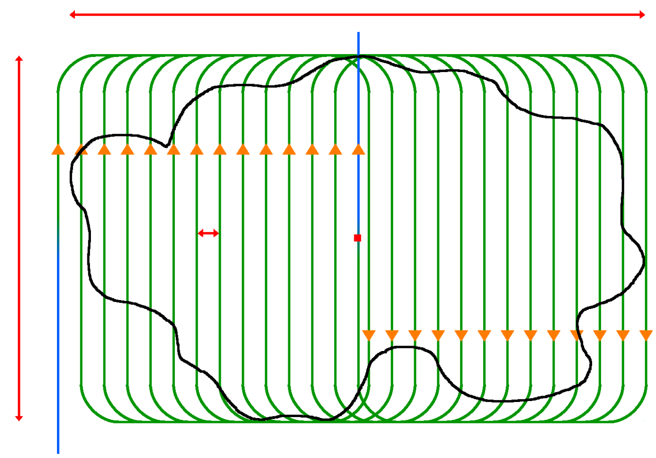

Fig. 5. Zamboni path

The Fig. 5 illustrates the execution of this pattern. Required parameters are:

- A 3D point corresponding to an estimation of the center of the cloud,
- Two distances which are the length of the cloud sides,
- A distance between two pathways.

E. Other basic patterns

In addition to the specific flight patterns that have been designed with meteorological data acquisition in mind, some standard basic patterns are also available. They can be used by the mission planing system to join the different patterns or during non measurement flight phases.

GoTo Reaching a 3D waypoint.

Path Follow a sequence of straight lines between waypoints.

Circle Hold a position while flying in circle.

Flower A simplified purely geometric form of the rosette pattern.

IV. Implementation and simulations

This project is developed based on the Open-Source autopilot project Paparazzi[1]. The simulations are based on the flight dynamic model JSBSIM[2] for a better realism. A preliminary work from atmospheric scientists have built a high-fidelity model of the clouds based on Large-Eddy-Simulations (LES). The results are stored in Meso-NH files[3] containing all micro-physical properties of the

[1] http://paparazziuav.org

[2] http://jsbsim.sourceforge.net/

[3] http://mesonh.aero.obs-mip.fr/mesonh54

atmosphere, including the LWC. This last information is used to feed the UAV simulation and to test the sensor-based patterns. On this preliminary work, the data are coming from a static environment, later work will introduce horizontal wind and temporal evolution to the clouds. The first path plan implemented and tested is the Lace pattern. It has been created to detect the border of the cloud at a given altitude, so with a zero vertical speed.

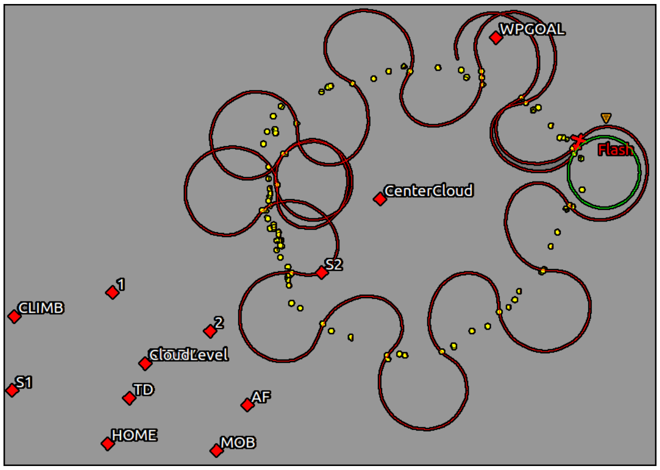

Fig. 6. Screenshot of the Paparazzi simulation of a lace pattern

The Fig. 6 shows the result of a flight simulation with sensor feedback in real-time. The plain line corresponds to the actual UAV path while the green circle corresponds to the current desired trajectory. Each yellow point is associated to a detection of the border of the cloud. With this aircraft model, the flight speed is around 18m/s, with a turn radius of 90 meters and it takes 20 minutes to get the presented result after around 7 laps.

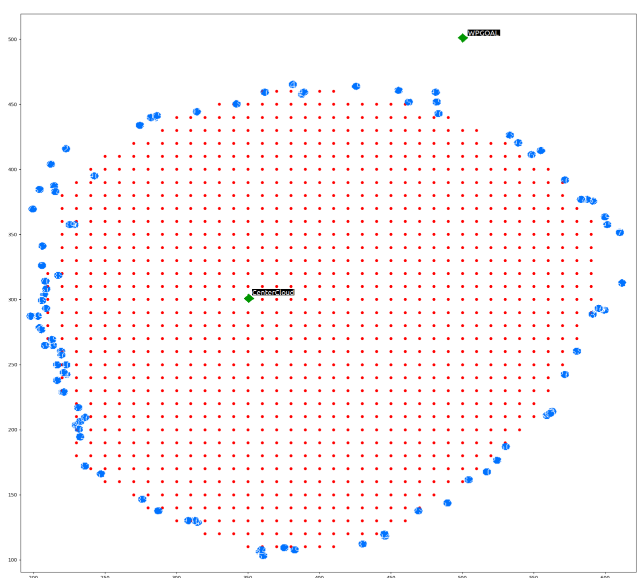

Fig. 7. Screenshot of the cloud display software

The Fig. 7 displays the LWC points above 0 from the Meso-NH file (in red). The blue points corresponding to the estimated border (yellow points in Fig. 6) are correctly matching with the shape of the cloud.

The final evaluation of the different patterns in regards of the mission objectives will be done by the atmosphere scientists. The criteria will be the feasibility to reconstruct the cloud micro and macro physical characteristics from sparse local measurements. This will be done by considering the flight time, the energy consumption and the coverage density compared to systematic survey that is traditionally used in such missions.

The PPRZ autopilot allows the creation of a simulation with multiple aircraft. The aim being to use each UAV with a particular pattern, a fleet of three UAV has been created to confirm the possibility to gather different data in several zone of the cloud. Two UAV execute the rosette pattern, based on GPS position, at different altitude and center. The last one, uses the lace pattern, with a positive vertical speed between the two 2D horizontal plan created by the others UAV.

Fig. 8. View in 2D of the KML path of the two UAV using the rosette pattern

The Fig. 8 shows the result getting in Google Earth with the KML path of the two first UAV. The blue path corresponds to the trajectory of the rosette pattern deploy in the base of the cloud and in green, at the top of the cloud.

Fig. 9. View in 2D of the KML path of the UAV using the lace pattern

The first picture of the Fig. 9 shows, in red, the lace pattern used to scan the border of the cloud and the second picture display a 2D view of all the trajectories of the fleet.

The Fig. 10 reveals a 3D view of the different KML path of the UAV. The rosette pattern allows the collect of data all over a 2D horizontal plan whereas the lace pattern gather data all around the frontier of the cloud in 3D.

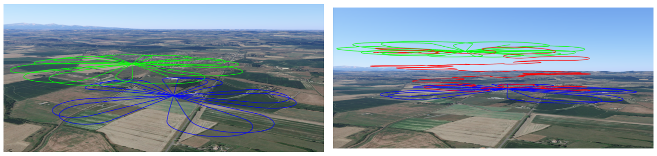

Fig. 10. View in 3D of the KML path of the fleet

The same aircraft model has been used for this simulation and it takes around 7 minutes to obtain these results. It demonstrates the feasibility to deploy the different created pattern on a fleet of UAV in a 3D environment, such as a cloud, to collect data in different position at same time.

V. Conclusion and future work

This work proposes a new approach for the exploration of clouds. The main objective is to design trajectories that will efficiently collect measures depending of the requirements of the scientists processing these data. This goal is achieved by creating adaptive flight patterns reacting to sensors in real-time.

Each pattern have been described and implemented into a realistic simulation framework, including the flight dynamic of the UAVs and the clouds modeling. The comparison of the boundary points obtained during the simulation with the reference environment proves the validity of the pattern approach.

The next step of this work will be to run the simulation over a dynamic cloud environment in order to assess the adaptability of the patterns to moving boundaries. The actual UAVs that will be used in the project are under development and will allow, once ready, to perform hybrid simulation mixing a real flight with simulated sensors. A flight management and mission planing system will be build on top of these flight patterns in order to control the fleet and perform task allocation from high level operator inputs.

Finally the atmosphere scientists involved in the project will evaluate the overall efficiency of the performed trajectories with regards to their objectives of cloud modeling.

Appendix: Development of a UAV dedicated to clouds exploration

The UAV used to explore a cloud have to answer specific constraints required to collect data over a satisfactory coverage. Here is a list of the constraints :

- Speed High flight speed to follow the horizontal motion of the cloud even in the presence of wind.
- Autonomy Enough flight time to execute the mission and collect data during the complete life time of a cumuls cloud.
- Weight Light to be easily operable (take off and land) and transportable.

Once the constraints of the plane were well defined, an optimization method has been used to define the UAV conceptual design. The picture Fig. 11 shows the first prototype of the UAV and the Table. III exposes its noticeable features.

TABLE III
Features of the NEPHELAE UAVs

Features	Values
Cruise speed	15 to 25 meters per second
Autonomy	electrical battery to fly during 2 to 3 hours
Desired altitude	1000 to 3000 meters
Curve radius	80 to 100 meters
Wingspan	1,6 meters
Payload weight	around 800 gramms
Battery weight	around 900 gramms
UAV and autopilot weight	around 800 grams
Total weight	2 to 4 kilogramms
Take off	Bungee
Landing	Net

This UAV is equipped with the autopilot Paparazzi (PPRZ). This Open-Source system developed at ENAC [14] has been used worldwide on hundreds of airframes. PPRZ's unique flight plan language allows the execution of complex procedures, navigation patterns, and event-based actions, which are not readily available in other systems. In particular, it has already been used in atmospheric studies [11].

In order to collect the desired data, the UAV embed a group of specific sensors developed by the meteorologist. The payload is composed of a humidity and temperature sensors, a 3D Pitot probe which can collect static and differential pressure and is useful to determine the airspeed (vertical and horizontal) and finally a LWC sensors based on the reflection of the light on a droplet. This set of sensors will supply all the local and punctual information useful to guide the UAV in the cloud and to construct its model.

Fig. 11. Picture of the UAV designed for the NEPHELAE project (without the payload)

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