MINIATURE UAVS CONCEPTS FOR OUTDOOR MISSIONS

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ABSTRACT

The Unmanned Aerial Vehicles (UAVs) are the next step of the aeronautics evolution. They can be divided into several categories, depending on their size and missions: from the High Altitude Long Endurance (HALE) ones, as large as airliners, to the micro-UAVs, that can stand in the palm of your hand. On the lower end of this very large scale of UAVs types are the miniature UAVs. They are the category which use seems the most “accessible”. Indeed, the large HALE are technically achievable but are facing the integration into the airspace problem. The micro-UAVs are very (too much?) challenging, from a mechanical and miniaturization point of view, to be used for near to mid term operational missions. Miniature UAVs are big enough to use COTS (Commercial Off The Shelf) subsystems and small enough not to have insurmountable regulatory problems.
In addition, the potential spectrum of activities to be performed by mini-UAVs is very wide: from military support for infantryman to civil power lines inspection. Each application induces specific constraints to be considered when designing a UAV and a lot are requiring two driving capabilities: stationary flight and outdoor use.

The stationary capability constraint impacts the vehicle configuration. Indeed, stationary flight, as vertical take-off and landing, can only be performed by rotary wing (or flapping wing) aircraft. The most common rotary wing UAV concepts are the conventional helicopter, composed of a main rotor and a tail-rotor, the two contra-rotative rotors and the four-rotor configuration. Each one has advantages and drawbacks. The conventional and contra-rotative helicopters are very well known (from a dynamics point of view) and can reach pretty high speeds. Nevertheless, to have a good agility, they require a mechanically complicated rotor hub (variable cyclic and collective pitch). The four-rotor configuration is mechanically much simpler: the rotors are connected to the motors in direct-drive and can be controlled through the motor rotation speed. Nevertheless, the controls along all degrees of freedom are coupled.

The outdoor flight constraint has a strong impact on the guidance and control of the vehicle, mainly due to wind and turbulences. Indeed, because of their small dimensions and weight, such miniature vehicles are very sensitive to aerologic perturbations. Adaptive control techniques have been widely applied to design guidance and control laws for the outdoor use of miniature UAVs, by taking into account an estimate of the perturbation. To also deal with physical constraints such as actuators limits, adaptive control can be used in combination with model predictive control (MPC), as presented in this paper. By that approach, stabilization of the vehicle at a given reference point can be achieved as well as trajectory tracking.
Measurements required for guidance and control are commonly provided by IMU (Inertial Measurement Unit) and/or GPS. Nevertheless, for outdoor flight in a constrained environment, for example in an urban canyon, the UAV can also be equipped with a vision based sensor to estimate the location of possible unknown obstacles. The ability of MPC to deal online with constraints can then be used for obstacle avoidance, without requiring the generation of a new collision-free reference trajectory.
In order to accommodate the payload, the number of embedded sensor may be limited on miniature vehicles. Assuming that the UAV is uniquely equipped with a vision based sensor, only position and attitude angles measurements may be available for guidance and control design. Observers, Kalman filter or other filtering strategies can be applied to estimate the non-measured velocities of the vehicle.
Hence, the constraints imposed by an outdoor use of mini-UAVs must be directly taken into account in guidance and control design.

Therefore, miniature UAVs are very interesting and promising systems. Nevertheless, numerous challenges are still to be faced before they can be fully operational.

1. INTRODUCTION

The purpose of this introduction is to give a brief overview of the categories and capabilities of UAV systems (UAS) in general.

1.1. UAS architecture

When speaking about UAVs, the first thing to remind is that a UAS is not limited to the vehicle. A UAS is composed of three parts:

- The Aerial Vehicle (AV): this is of course the most visible part of the system. This is also the main part of the system as it carries the payload, without which the system is useless… The role of the aerial vehicle is to enable the use of the payload in the most efficient way, depending on the mission;
- The Ground Control Station (GCS): this is the interface between the operator and the AV. The operator sends order to the AV (position, altitude, manoeuvre, etc.) using the GCS. But it is also used by the operator to get the data collected by the payload;
- The Data Link (DL): it is the way to link the AV and the GCS. Without DL, it would not be possible for the operator to send order to the AV, as it would not be possible to get data from the payload.

Each part of the system has an equivalent importance, as if only one of them is missing, the UAV operation is not possible.

This UAS architecture is illustrated by FIG 1.

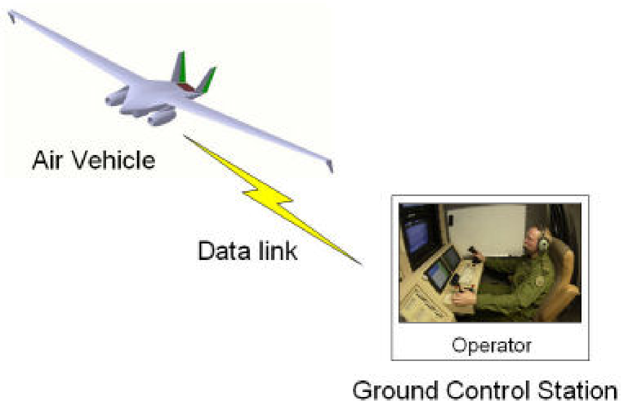

FIG 1. The three parts of a UAS

1.2. UAV categories

Even if a UAS architecture is always the same, the AV can be divided in several categories. The main ones are:

– The HALE;
– The MALE;
– The tactical UAVs;
– The MAVs;
– The micro UAVs.

1.2.1. HALE UAVs

The High Altitude Long Endurance (HALE) UAVs are the largest ones: the American Global Hawk (Northrop Grumman) has a wingspan that is even bigger than the one of the Airbus A320! HALE UAVs are designed to fly at high altitude, above FL600 (60,000 ft), for several tens of hours for the “conventional” ones, or even several weeks for the solar ones.

They are also the most expensive. This is mainly the reason why today, only a few HALE exist.

FIG 2. Example of a HALE UAV: the Global Hawk (Northrop Grumman)

1.2.2. MALE UAVs

The Medium Altitude Long Endurance (MALE) UAVs are designed to fly at medium altitude, FL250 to FL400 during several tens of hours, like the HALE. Lots of Ministries of Defence are interested by this type of UAV, because of its abilities and cost, compared to the HALE.

FIG 3. Example of a MALE UAV: the Eagle 1 (EADS)

1.2.3. Tactical UAVs

The tactical UAVs are used for military purpose, on conflict theatres. They are used to gather data on the battlefield, mainly visual information. They fly at low to medium altitude and are designed to be operated even without specific infrastructure, like airport or runway. It is possible to take-off using a catapult and to land using a parachute.

FIG 4. Example of a tactical UAV: the Sperwer (SAGEM DS)

1.2.4. UCAVs

The Unmanned Combat Air Vehicles (UCAVs) are also used for military purpose, but in this case they are designed for attack missions, like bombing. They can be easily recognized as they are designed to be stealth, which gives them a characteristic look.

FIG 5. Example of a UCAV: the X-45C (Boeing)

1.2.5. MAVs

The Miniature Air Vehicles are UAVs that wingspan (or main dimension) is around 1 m. Their potential configurations are more varied that the previous categories: fixed wing or rotary wing configurations are commonly used.

FIG 6. Example of a MAV: the Dragon Eye (AeroVironment)

1.2.6. Micro UAVs

The Micro UAVs are the smallest ones: their main dimension does not exceed 15 cm. They are particularly adapted to indoor flight.

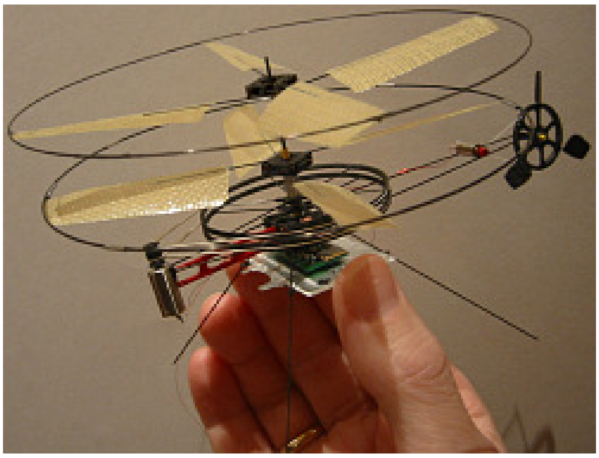

FIG 7. Example of a micro UAV: the Microflyer (Proxflyer)

1.3. Potential applications

The potential applications of the UAVs are very dependant of their categories. Indeed, a HALE application will obviously be very different from a MAV one! Civil and military missions can be envisioned, whatever the type of UAV.

Basically speaking, the HALE and MALE UAVs are designed for long endurance missions and are able to carry heavy payloads. Potential civil applications are such as observation, surveillance or communication relay. Concerning military applications, observation (visible and radar) but also signal or communication intelligence (SIGINT, COMINT) are possible.

Tactical UAVs are designed for military applications, where infrastructures are limited (no airport). They are used for short range optical observation (visible, infrared).

UCAVs are designed for attack missions, such as objective bombing. Their stealth design enables to penetrate the enemy's defence in order to strike critical objectives.

MAVs spectrum of activities is maybe the largest of all the categories. Indeed, it goes from the military support for infantryman to civil power lines inspection.

Micro-UAVS are intended to be used in narrow spaces, for example indoor missions. They are also easily brought by a single person to the place where the mission has to be performed.

2. FOCUS ON THE MAVS

The purpose of this chapter is to focus on one specific category of UAVs: the MAVs.

MAVs are very interesting for several reasons. The main one is that the MAV category seems to be the most "accessible". Indeed, the large HALE and MALE UAVs are technically achievable but are facing the problem of their use in non-segregated airspace. The micro UAVs are very (too much?) challenging from a mechanical and miniaturization point of view. MAV are big enough to use COTS subsystems and small enough not to have insurmountable regulatory problems.

2.1. Vehicle configurations

As mentioned previously, the potential spectrum of activities to be performed by MAVs is very wide. And this wide spectrum of applications induces a wide spectrum of configurations. Indeed, maybe more than for all the other UAV categories, the mission to be performed has a high impact on the vehicle concept and aeroshape.

Two main families of MAV concepts can be defined:

- The fixed wing configurations;
- The rotary wing configurations.

2.1.1. Fixed wing configuration

A fixed wing MAV is more or less a model airplane (of course with more autonomy). Its main advantages are its endurance, compared with rotary wing, and its ability to fly relatively fast.

Nevertheless, the manoeuvrability is limited, as well as the possibilities of speed variations, i.e. minimal speed pretty high.

When considering MAVs, the fixed wing configuration is the less frequent type of vehicle. Indeed, as its use is understandable for infantryman (necessity to quickly see “above the hill”) who has to carry the UAS on his own, its limitations in terms of operational use (manoeuvrability and speed) make the rotary wing more attractive for most of the applications.

FIG 8. Infantryman hand-launching a fixed wing MAV

2.1.2. Rotary wing configurations

Most of the applications for the MAVs require a capability that dramatically drives its design: the stationary flight.

Such a requirement has obviously a very strong impact on the MAV design. Indeed, stationary flight, as vertical take-off and landing (VTOL), can only be performed by rotary or flapping wings aircraft.

As mentioned previously, even considering only rotary wing configurations, a lot of concepts can be envisioned, such as double coaxial rotors, tilt rotor or tail-sitters (see FIG 9).

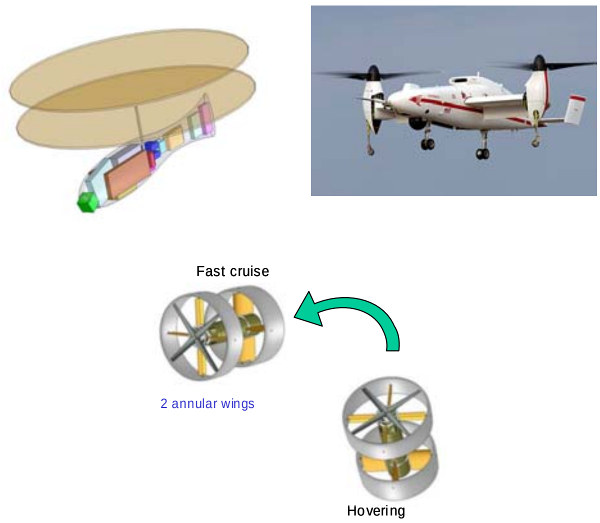

FIG 9. Various configurations of rotary wing MAV: double coaxial rotors (MAVDEM), tilt rotor (Eagle Eye, Bell) & tail sitter (ENSAM)

Nevertheless, the most common rotary wing UAV concepts are the conventional helicopter and the four-rotor configuration. This is mainly due to the complexity of the previously mentioned concepts: mechanical complexity of the rotor hub for the coaxial rotors and guidance and control during the transition phase for the tilt-rotor and tail-sitter concepts.

2.1.2.1. Conventional helicopter

The conventional helicopter concept is composed of a main rotor and a tail rotor.

FIG 10. Conventional helicopter MAV configuration (Micro Star)

The main advantage of the conventional helicopter configuration is that it is very well known from a dynamics point of view. So this is the simplest configuration to apprehend when creating control laws. Another advantage is that its big main rotor enables pretty high efficiency of the propulsion set, leading to good performances in terms of endurance and cruise speed.

2.1.2.2. Four-rotor configuration

The four-rotor concept is so-called because it is composed of… four rotors! In fact, these rotors can be replaced by propellers.

FIG 11. 4-rotor MAV configuration (DraganFlyer)

These four rotors (or propellers) are used to control the UAV along all axes.

The fuselage of the vehicle can be located between the four rotors (see FIG 11), or under (see FIG 12).

FIG 12. 4-rotor MAV configuration with the fuselage located under the rotors (MAVDEM)

The main advantage of the four-rotor concept is its mechanical simplicity. In addition, a lot of papers can be easily found about its control laws.

2.2. Mechanical considerations

2.2.1. Conventional helicopter

The conventional helicopter is controlled through its main and tail rotors.

The role of the main rotor is two-fold:

- To create the lift and to control the altitude, through the collective pitch;
- To control the vehicle pitch and roll through the cyclic pitch.

The role of the tail rotor is to counter the torque created by the main rotor, and so to control the yaw.

The consequence of this architecture is a pretty complicated main rotor hub. Indeed, this hub has to manage variable cyclic and collective pitch. In addition to its intrinsic mechanical complexity, the rotor hub has to be very small.

2.2.2. Four-rotor configuration

The four-rotor concept is controlled through a combination of the lift of its four rotors.

When using rotors, the lift is controlled through the collective pitch. But rotor blades can be connected to the motors in direct-drive and so the lift is controlled through the motors rpm. This last solution makes the four-rotor a configuration that is very simple from a mechanical perspective: no mobile parts (except the propellers!), only motor control.

The attitude control of the four-rotor is explained in FIG 13.

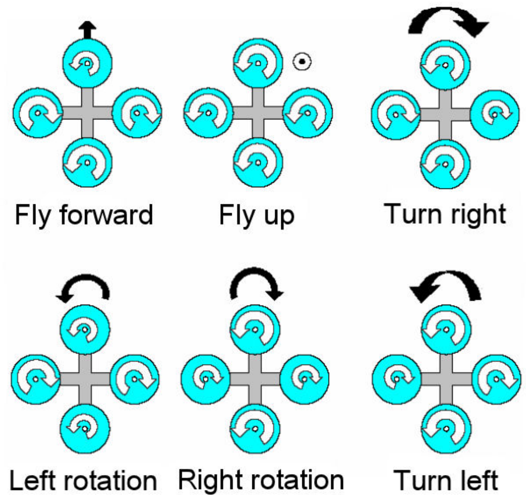

FIG 13. Attitude control of a 4-rotor MAV

Nevertheless, even this configuration is mechanically very simple, the controls along all degrees of freedom are coupled, which has to be taken into account when defining the control laws.

3. GUIDANCE AND CONTROL OF MINIATURE UAVS FOR OUTDOOR MISSIONS

3.1. Guidance, Navigation and Control

Since UAVs may be used to replace manned aircraft for specific missions where the presence of a human operator is considered to be dangerous or inadequate, a decision and control system must be developed to achieve the required autonomy.

A hierarchical decision and control system is classically used. Its structure is presented in 0FIG 14.
A mission can be defined in terms of objectives and constraints or, for example, in a lower level of representation, by desired Way Points (WP). That parameterization of the mission can be specified by an operator before the start of the mission and updated during the flight. A path planner layer generates a reference trajectory, or intermediate Way Points, to be tracked by the UAV. A guidance algorithm is then used to make the centre of gravity of the UAV converge to the desired reference, whereas the attitude stabilization of the vehicle is handled by the control layer. Control inputs computed by the guidance and control layers are then applied to the vehicle actuators. In a navigation layer, the measurements delivered by the embedded sensors (e.g. Inertial Measurement Unit, GPS, vision based sensor) are used along with the values of the applied control inputs to estimate the state of the UAV (position, linear velocities, attitude angles, angular velocities). A localization layer can also be designed to determine the location of the UAV with respect to its environment. This information is sent back to the path planner and to the guidance and control layers.

For miniature UAVs, the outdoor flight constraint has a strong impact on the design of the guidance and control layers, mainly due to wind and turbulences. Indeed, because of their small dimensions and weight, such miniature vehicles are very sensitive to aerologic perturbations. Therefore, specific methods must be used to design the guidance and control layers in the case of perturbed environments.

In addition, in outdoor missions, the UAV flies in an environment that may be not exactly known. In fact, for exploration missions, the UAV may be used to build a map of unknown areas. For missions in urban or constrained environments, the location of obstacles that the UAV is likely to encounter may be badly known or dynamically varying. Therefore, for such missions, guidance and control algorithms must be able to deal with that uncertainty.

Finally, for payload reasons, the number of embedded sensors may be limited on miniature vehicles. Depending on the nature of available sensors, measurements may not be sufficient to give information on the whole state of the UAV, composed of the values of the position, the linear velocities, the attitude angles and the angular velocities. In that case, this lack of information must be compensated by an estimation algorithm or directly taken into account in the design of the guidance and control algorithms.

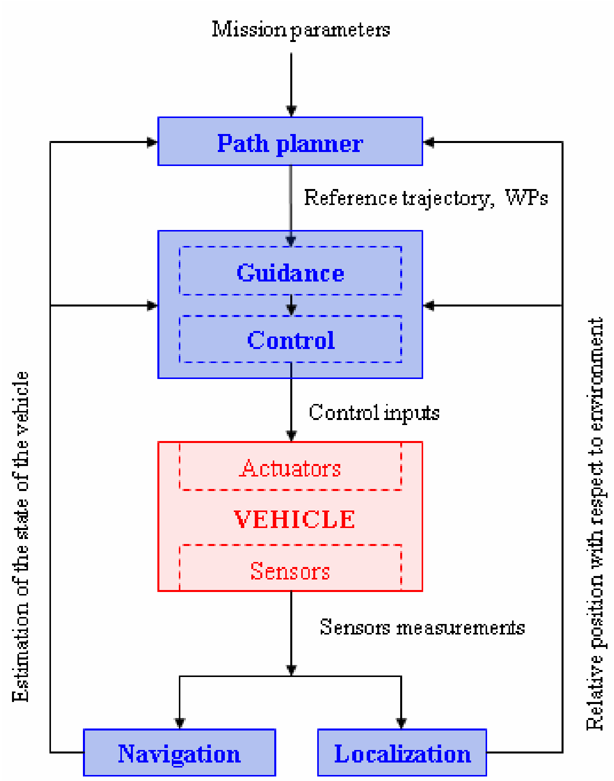

FIG 14. Structure of the hierarchical decision and control system

To deal with these three issues, related to outdoor flight, specific methods for guidance and control of rotocraft-based miniature UAVs will be presented in the rest of this paper.

3.2. Perturbed environments

The design of guidance and control laws for miniature UAVs must take into account aerologic perturbations to allow the vehicle to achieve outdoor missions.

A solution consists in developing an adaptive controller. In adaptive control, an estimation of the perturbation is taken into account to design the control laws. The estimator and the controller can be designed separately or simultaneously. Adaptive backstepping is an example of such a method that has been applied to guidance and control of miniature UAVs for outdoor missions [1].

To enhance the performances of adaptive control, Model Predictive Control (MPC) has been simultaneously applied to a miniature UAV model [2]. In MPC, the control is computed by solving online an optimization problem over a finite time horizon. A prediction of the behaviour of the vehicle is hence taken into account. By adding control constraints in the optimization problem, the physical limitations of the actuators can also be handled by that approach.

An application example of that adaptive-predictive control scheme is presented in 0FIG 15 where the stabilization of the UAV around a reference trajectory (black dashed curve) is achieved despite a wind perturbation leading to a unknown constant force F_{ext} on the UAV. In comparison with the adaptive controller (blue dotted curve), the speed of convergence is increased by the adaptive-predictive approach (red solid curve) which also makes the UAV anticipate the change in the reference.

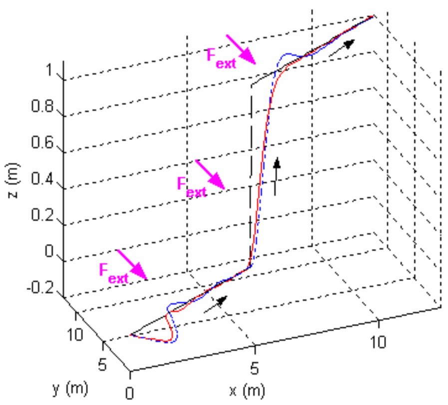

FIG 15. Adaptive-predictive guidance and control in a perturbed environment

3.3. Uncertain environments

For exploration missions, or for outdoor missions where the environment is badly known, the single use of a pre-planned reference trajectory may lead to collisions between the UAV and obstacles, the location of which were unknown. Therefore, the UAV must be equipped with a set of sensors (vision based sensors, telemeters, laser scanners) that can be used for online detection. Given the position of the detected obstacles, the trajectory of the UAV must be modified with respect to the initial reference.

A first solution consists in generating a new collision-free reference trajectory. However, the real-time generation of a reference trajectory may be prohibitive. A "reactive layer" can be introduced, between the path planner and the guidance and control layer, to modify the reference by taking into account the location of the detected obstacles.

Another way to deal with that uncertainty is to simultaneously achieve obstacle avoidance and guidance. This approach is studied in [3] by taking advantage of the faculty of MPC to consider new information as it becomes available.
A contractive MPC algorithm based on [4] is used for the design of the guidance and control layers. In the optimization problems used to compute the control inputs, a constraint is introduced to impose a norm contraction on predictions of the state of the vehicle, and hence guarantees stability for trajectory tracking. An example is presented in FIG 16 to illustrate the stability of the vehicle (red solid curve) for trajectory tracking of a reference (black dotted curve), as controlled by the proposed approach.

In the optimization problem used to compute the control, additional state constraints are then activated to represent the detected obstacles by a set of coordinates that the UAV must avoid.
An example of scenario is presented in 0FIG 17, where the vehicle has to follow a linear reference trajectory (black dotted curve). This pre-planned reference does not take into account the presence of possible obstacles. If only the first spherical obstacle is detected, the trajectory of the vehicle (blue solid curve) is vertically deviated from the reference. If both the spherical and cylindrical obstacles are detected, the trajectory of the UAV (red dashed curve) is deviated from the reference so that avoidance of both obstacles is achieved.

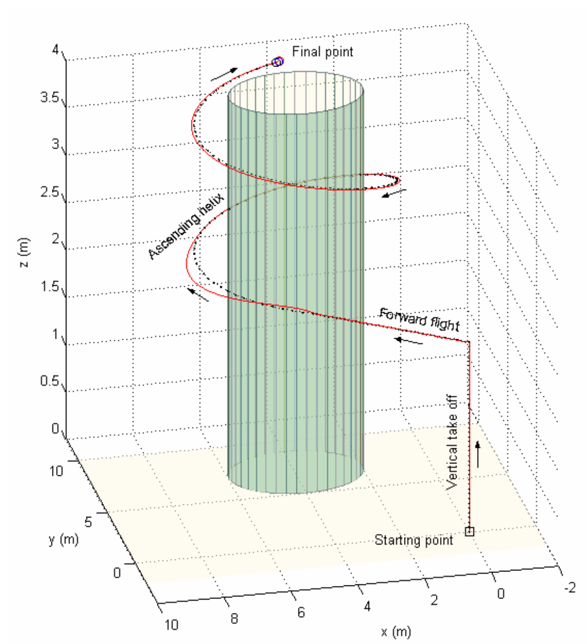

FIG 16. Trajectory tracking using contractive Model Predictive Control

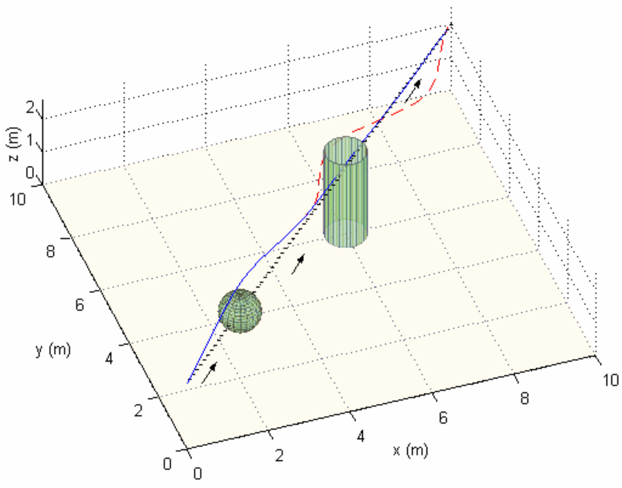

FIG 17. Obstacle avoidance using contractive MPC guidance and control

3.4. Measurements

For miniature vehicles, payload is a critical issue. Therefore embedded sensors are limited in number, size and mass.
For constrained or uncertain environments, as it may be the case for outdoor missions, a vision based sensor can be used to estimate the position of the UAV with respect to its environment. Optical flow methods, for example, can then be used to estimate both position and attitude angles of the vehicle [5]. In that case, no measurement of the linear velocity, nor of the angular velocity, is directly available.

A first solution consists in designing an observer, to estimate the part of the state which is not accessible from measurement. In [6], the problem of trajectory tracking for a planar VTOL aircraft with only position and attitude angles measurements is addressed by using a full order observer. Using the certainty equivalence principle, the control is then computed taking the estimates as real values of the state.
In that case, the convergence of the observer and the convergence of the observer-based control scheme must be successively proved.

Another solution is to directly design the control laws without using the non measured states. Theses approaches are known as "partial state feedback". Most of them are based on filtering techniques used to replace the missing measurements by filtered values of the available ones.
Such a partial state feedback strategy is used in [7], where guidance and control laws are designed for a small VTOL UAV model, using no measurements of the linear nor angular velocity of the vehicle, and without designing observers. In the proposed approach, virtual states are introduced in the representation of the dynamics of the vehicle. Guidance and control laws are then designed using Lyapunov's method.
An example of trajectory tracking using only measurements of the position and attitude angles is presented in FIG 18. The closed loop trajectory of the UAV

(solid blue curve) converges to the reference helix (dashed black curve) with a satisfying closed loop behaviour, although velocities measurements are not available.

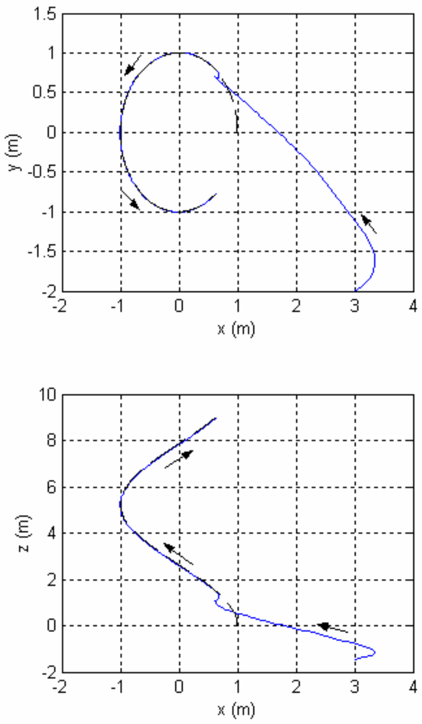

FIG 18. Trajectory tracking using only measurements of position and attitude angles

3.5. Conclusion on guidance and control

The design of guidance and control laws for miniature UAVs is a very challenging research area since all the aforementioned issues must be taken into account for outdoor missions. The implementation of guidance and control algorithms is also a challenging task due to the limitations of computers that can be embedded on miniature vehicles.
Expertise in both design and implementation is required in order to allow miniature UAVs to achieve autonomously outdoor missions.

4. CONCLUSION

As one of the main axes of development of aeronautical systems, UAVs, and especially mini UAVs, are very promising. Indeed, due to their size (and so to their cost!), numerous aeroshape configurations can be imagined, each optimized for the numerous potential applications they can perform. Indeed, each mission, whether civil or military, brings specific constraints that have a direct and strong impact on the vehicle configuration. Due to their simplicity in various areas, the conventional helicopter and the four-rotor are the most common configurations. This is also mainly due to their stationary flight ability. Indeed, this ability extends considerably the spectrum of their potential missions.

Most of these potential missions need to be performed outdoors. This requirement brings a lot of constraints, especially on the way to guide and control the vehicle. Indeed, MAVs are very sensitive to the aerologic perturbation, because of their small size and weight. In addition, MAVs are limited in payload capacity. This induces limitations on the onboard sensors. In order to manage these issues, specific control techniques have been developed, taking into account all the constraints mentioned previously.

Miniature Air Vehicles are very promising systems. But they are also very challenging! From the miniaturization of the onboard components to the development and implementation of control and guidance laws enabling their use for outdoor missions, a lot of work is still necessary before getting the full capacities of such systems.

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