UAV Operations: From Autonomous Navigation to Multi Platform Cooperation Achievements in the ReSSAC Project at ONERA

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FROM AUTONOMOUS NAVIGATION TO MULTI PLATFORM COOPERATION

In the ***ReSSAC*** project, two Yamaha RmaX remote control rotorcraft have been equipped with an autonomous control architecture and algorithms providing capabilities of autonomous flight, navigation, take-off and landing in known areas. The project is now working on the problem of autonomous landing in an unprepared area, which requires autonomous reactive flight and navigation capabilities in order to react to obstacles on the one hand, and some autonomous decision making capabilities in order to cope with environment uncertainties on the other hand. The aircraft actions may have uncertain results due to noisy measurements, wind or turbulence, but also because the terrain is ill-known, potentially obstructed by obstacles. The ReSSAC rotorcraft are using flight and navigation sensors (GPS, compass, accelerometers and gyrometers) to estimate the current navigation state, but it can also perceive the surrounding environment thanks to an embedded image acquisition and processing vision system (from camera to decision computer). Additional experiments have been conducted in order to simulate in flight the decking of a rotorcraft on a virtual mobile point, the motion of which is emulated and measured by a distant moving device including an hybrided GPS and Inertial Measurement Unit. Relative localization of potential obstacles is achieved by monocular stereovision at higher altitudes and optic flow based algorithms at lower ground heights. The ReSSAC autonomous rotorcraft adapt to the environment according to a conditional action strategy, obtained as the optimal solution of a structured Markov Decision Process (MDP), using also the initial mission definition and an itinerary graph generated from the a priori numerical terrain model. The aircraft control and supervision architecture is justified by dependability concerns. Experiments of landing in the vicinity of artificial obstacles have been performed, leading to improve the robustness of the system, using a progressive exploration of the environment in three phases, including different vision algorithms and online mission planning which have been demonstrated in flight. This work opens the ways for cooperative decision making for multi platform cooperation.

1. INTRODUCTION

1.1 Autonomy: what for ?

Network centric operations of multiple UAVs and platforms, require higher levels of autonomy (Figure 1) in order to play a significant role in future warfare operations, homeland security or risks management applications (see references [3] to [11]). UAV mission planning tools have been developed in recent years in the Systems Control & Flight Dynamics Department of ONERA. Specific mission planning algorithms have been developed and integrated in the ReSSAC project's mission planning decision aid software of the ground control station (see references [14] to [19]). However, the resulting decision aid tools do not really solve the safety problems.

The management of safety issues via ground operated fail safe procedures is prone to lead to undesired mission interruptions. Situation awareness problems may lead the security operators to immediately apply unnecessary drastic measures (false fault detection, temporary loss of control data link, …). More flexibility and time for analysis would be required. This in turn requires safe and efficient capabilities of on-board fault detection, identification and autonomous reconfiguration.

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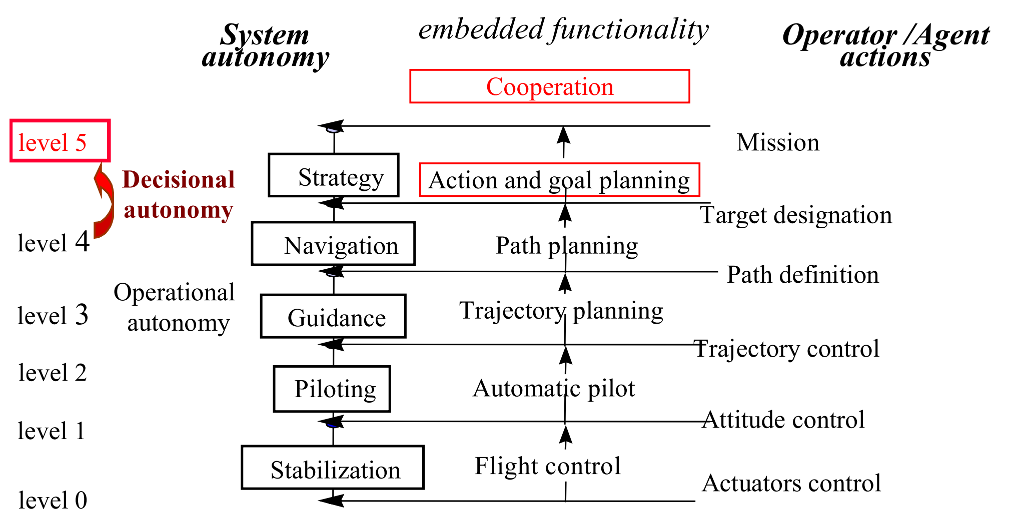


Figure 1 ***Autonomy levels hierarchy***

1.2 ReSSAC Project

The ReSSAC project at ONERA ([1], [2], [13]) aims at demonstrating the feasibility of enabling uninhabited systems with embedded perception and decision making capabilities.

Two remote control Yamaha RmaX helicopters (Figure 2) have been bought as experimental platforms.

Figure 2 One of ONERA's two autonomous RmaX rotorcraft

Both ReSSAC uninhabited helicopters (one of which is shown on Figure 2) are equipped with onboard avionics systems providing them with the capabilities of autonomous take-off, autonomous flight, autonomous navigation and autonomous landing in known areas and known environments. Their control architecture, including the security ground pilot, the ground station and data links have been developed with strong safety and security requirements. Such capabilities do ensure a maximum level of operational and functional autonomy throughout the successive flight phases of most possible missions, but only under the close supervision of operators. In such a context, all the mission reconfigurations have to be managed by human decision makers. Since the possible conditional alternatives may rapidly become unmanageable in case of an emergency, their number must remain limited. The aircraft flight plan is bound to be constrained within strict boundaries, obtained via rigid authorization processes favoring simple and robust safety procedures.

This paper presents our current efforts to propose a generic approach toward UAV decisional autonomy and safety within the ReSSAC project [13][14] and is organized as follows.

- We first recall the autonomous flight, guidance and navigation capabilities of the ReSSAC uninhabited RmaX rotorcraft.
- We then describe the experiments conducted with one of these rotorcraft, experiments that allowed us to demonstrate in flight a series of simulated decking on a virtual mobile point. This demonstrate the ability of our rotorcraft to apply a reactive strategy conditional to its dynamic external environment.
- This reactive strategy can be designed to perform other missions: we present the waypoints and path planning algorithms and tools of the ReSSAC project. These tools allow us to automatically plan an exploration mission in a partially known region.
- The rotorcraft then needs to perceive its environment, prior to deciding and reacting: our vision algorithms and landing site characterization image processing experiments are described. These algorithms are then used for the automatic selection of a landing spot : autonomous landing on a partially known terrain obstructed with obstacles was demonstrated in flight.
- Finally, we describe the on-going work in order to provide the rotorcraft with the capability of mission re-planning : the UAV should be able to automatically generate the reactive strategy in order to explore its environment in successive phases, re-plan its exploration strategy and act conditionally to its environment : land on the terrain if appropriate and go elsewhere if appropriate.

2. AUTONOMOUS FLIGHT AND NAVIGATION

In the ReSSAC project, two uninhabited Yamaha RmaX helicopters have been equipped with an autonomous navigation and guidance architecture: this core flight, guidance and navigation architecture is authorized to fly autonomous under the supervision of a security pilot. This architecture is presented with more details in [14] and we only recall some features here.

The ReSSAC rotorcraft are able to fulfil any mission described in terms of :

- a flight plan associated with procedures (phases and flight states transition to comply to)
- a reactive action strategy, conditional to external events or perception .

2.1 Flight plans

Flight plans are defined by "enriched waypoints" to be reached, each waypoint being defined by :

- its 3D location (x,y,z) in earth reference coordinates
- the desired velocity vector Vc and
- the desired heading of the aircraft at this point.

In order to determine the trajectory between each of those waypoints, we apply the Principle of the Maximum, with a minimum time criterion under the constraint of saturation imposed on the yaw rate. In the horizontal 2D plan, this problem can be solved by geometric considerations, because of the optimality of a “bang-bang” control. This gives trajectories formed successively by a first arc of circle, a straight line and a final arc of circle, as shown in Figure 7: the determination in real time (at each guidance step) of the flight parameters allows the real time computation of the control input in terms of yaw rate to be given to the above control loops.

2.2 Guidance, obstacle avoidance and navigation

The SNAKE ("Système de Navigation Autorisant une Kyrielle d’Evitements") navigation system adds to the above guidance law the capability of avoiding forbidden or dangerous (even moving) areas.

This function must be compatible with the guidance algorithm and with its use in real time. For that purpose, forbidden areas or obstacles, are considered as circles, or pairs of circles, to be geometrically treated one by one by the iterative navigation algorithm.

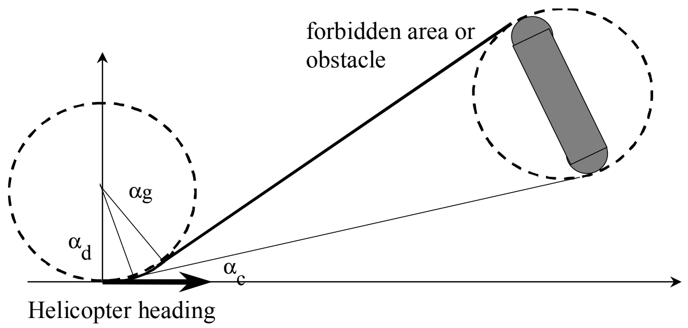


Figure 3 Avoidance of an obstacle or a forbidden area

For each obstacle, two possible avoidance trajectories are considered, respectively defined by the α_d and α_g angles (respectively right hand side and left hand side obstacle avoidance heading as in Figure 3). These two angles could soon be measured in real time by an obstacle detection sensor, but it is not the case yet. The two angles are computed from the map and compared to the current heading control order α_c to conclude on a possible collision and define a new route with minimal turn :

If $\alpha_d < \alpha_c < (\alpha_d + \alpha_g)/2$ then $\alpha_c = \alpha_d$

If $\alpha_g > \alpha_c > (\alpha_d + \alpha_g)/2$ then $\alpha_c = \alpha_g$

Forbidden areas (Figure 4) and obstacles are treated by order of decreasing distance to the aircraft (the most faraway obstacle is treated first and so on). The final heading control order α_c is given when all the forbidden areas and obstacles between the next waypoint and the current position of the aircraft have been treated. This warrants a real time behavior and a local optimality of the area avoidance trajectory, even with moving forbidden areas or obstacles: it does not always provide a globally optimal (shortest) trajectory to the next waypoint, depending on the avoidance areas configuration.

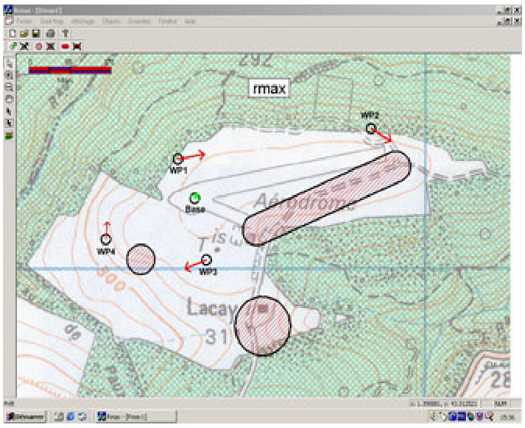


Figure 4 ***Terrain map and forbidden areas***

3. PROCEDURES AND SAFETY

3.1 Operations

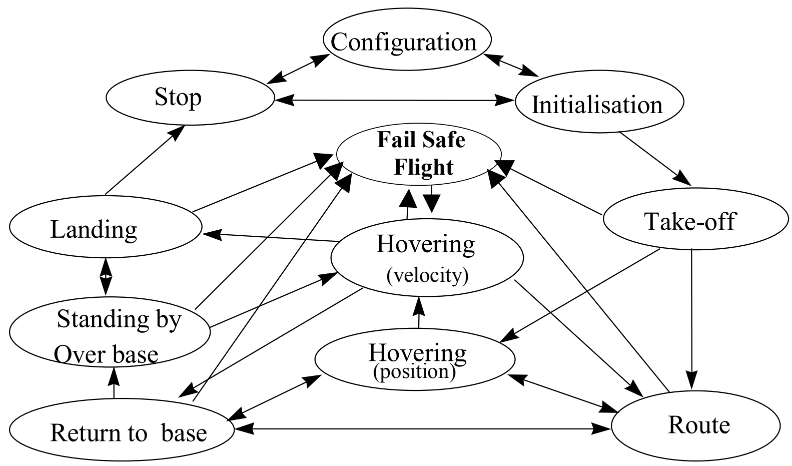


Figure 5 ***Autonomous flight states***

The behavior of the rotorcraft in its different operation mode is bound to follow a strict procedure for transiting between the different possible operation modes and mission phases: this is encoded by the flight state automaton described in Figure 5.

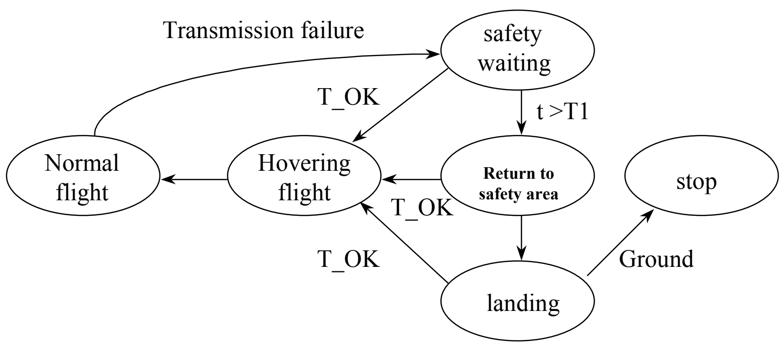


Figure 6 ***Fail safe procedure***

Other such state automata describe the overall operation rules. The automaton presented in Figure 6 presents the fail safe procedures of the rotorcraft.

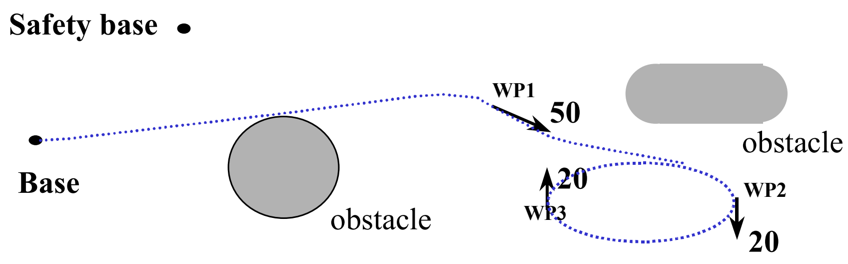


Figure 7 Example of generated flight plan using SNAKE

The 2D mission in Figure 7 can either be generated automatically as explained below, or be designed by the operator: three waypoints, linked in two ways for a final loop realization, and two forbidden areas.

The mission progress is monitored through the state evolution in a state graph, according to the operator requests and the safety reports. A fail-safe flight is engaged by the safety mechanisms in case of a system failure. The possible flight states corresponding to the "autonomous flight" are organized as in Figure 5:

- three ground phases: "stop", "maintenance" and "initialization", which correspond to the states of the helicopter when it is on the ground. The initialization phase includes all the automatic check-list procedures before take off.

- two transition phases: "take off" and "landing".

- five flight phases: “route” and “return to base” which use the SNAKE navigation and three other phases linked with hovering flight ("position hovering flight", "velocity hovering flight", "stand by before landing").

In the flight state "fail-safe flight", the safety procedures, imposed by the use of autonomous vehicles, are described by Petri nets, such as for example in Figure 6 for the case of a transmission failure. The autonomous flight capabilities of the helicopter allow an easy definition and execution of these procedures.

For example, it is able to return to a safety landing zone without any operator intervention nor predefined trajectory, provided that the map of known obstacles is up-to-date and sound: some verification of the map is useful.

The verification of the map is made at mission planning time and should be redone as often as the mission is re-planned : SNAKE is not an optimal path planner and obstacles must not overlap in the map it uses.

3.2 Automatic flight authorizations

The mission is always conducted in full compliance with the safety and operation procedures. This is the basis on which the rotorcraft receive their automatic flight authorizations from the French Civil Aviation

Authorities.

According to these authorities, the first step toward decisional autonomy in the ReSSAC projects was made through our attempts to improve our fail safe procedures in case of a loss of data link. The aircraft was given the capability to automatically re-plan its trajectory toward a predefined safe landing area. The French civil aviation authorities considered it as a major mission reconfiguration, leading us to further work in the direction of improving both autonomy and safety guarantees for the behavior of the ReSSAC autonomous aircraft.

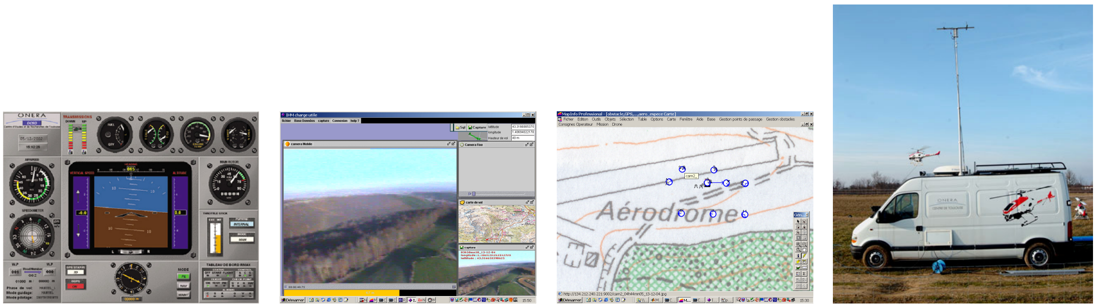


Figure 8 ReSSAC control screens for flight control, navigation and geo-referenced image capture

Current flights are still performed with a "line-of-sight" security pilot, and authorized on the basis of the autonomous navigation architecture (described in the following). The project also developed a mobile ground station allowing future "out-of-sight" autonomous flights with a "inside" security pilot enabled to control the flight of the aircraft from inside the mobile ground station thanks to a number of instrument flight screens and a front camera view (Figure 8).

The step to "out-of-sight" flight authorizations only depends on the choice of a military flight zone, or on the development of an independent fail safe device enabling the security operator to rapidly land the aircraft in a bounded perimeter in case of an emergency. Such a device is available only in "line-of-sight" operation for the moment and we don't really need more for our current work.

4. MISSION AND ACTION STRATEGY

4.1 Mission data necessary for the action strategy

From the ground station, the operator can re-define the mission by providing the necessary data to be taken into account by the autonomous navigation system :

- Waypoints : location coordinates (x,y,z), velocity vectors, aircraft headings
- Forbidden areas : position of circles centres (one or two circles if they are combined), radius

- Base : ground station for a normal landing
- Safety base : area for a fail safe landing
- Path : list of waypoint numbers to reach successively with possible loops on the waypoints and actions to apply on these waypoints, conditionally to external events or perception.

This allows the uninhabited helicopter to coherently perform two possibly incompatible tasks:

- comply to the established mission and safety procedures
- adapt to its environment, thus showing some autonomous behaviors.

A first example of such conditional action strategy is of course the SNAKE navigation and obstacle avoidance strategy.

4.2 Execution of an action strategy:

Flight simulated decking on a virtual point moving approximately like a "ship at sea"

We implemented another reactive action (decking) strategy in experiments conducted in order to flight test a ship decking strategy based on GPS-IMU measurement made on both the air vehicle and the ship. SNAKE was still active (it is thus shown compatible) for obstacle avoidance.

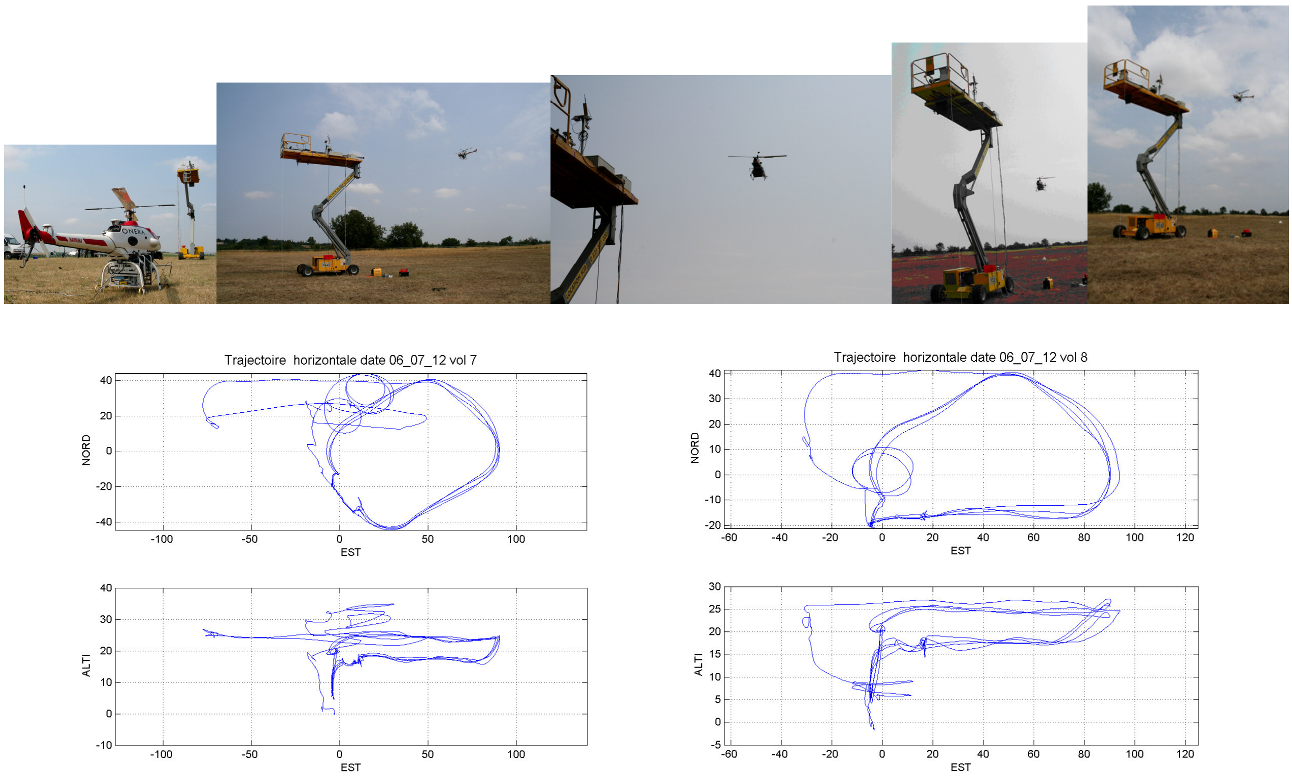


Figure 9 ReSSAC flight experiments and demonstrations images and trajectories records of simulated ship rotorcraft decking on a designated virtual mobile point

The experiment shown in Figure 9 is a simulated ship decking.

The rotorcraft applies a decking strategy, which is a reactive decision rule using information from both:

1. the GPS-IMU measurements and estimation of the ship location and motion
2. the GPS-IMU measurements and estimation of the air vehicle location and motion.

SNAKE is used in order to avoid collision with the simulated ship : the experimental platform was not virtual.

The ship motion is simulated by a pointing device moving along an axis on the experimental platform. This device is actuated along the axis and along two rotation degrees of freedom. It is distantly pointing a virtual point which is bound to move approximately like a ship at sea, under sea conditions theoretically up to level 5.

The decking strategy performs:

- an analysis of the current motion of the virtual point, on the basis of the information provided by the GPS-IMU measurement unit moving on the experimental platform (not by the pointing device motion emulator) ;
- a 5 seconds in advance prediction of the next best decking "window", which is a period of calm motion appropriate for decking ;
- a decision to go for decking : "appontage" if appropriate
- then a decision to abort decking : "repli" if the ship observed current motion (during the air vehicle manoeuvre) becomes incompatible with decking condition (thus in contradiction with the prediction, which remains only a prediction).

What is interesting here for us is the ability of the rotorcraft to act dynamically and conditionally to external events.

The hardest task was for the rotorcraft, which had to act according to :

- the virtual ship
- the virtual wind
- the decking strategy
- the true safety procedures
- the actual wind ("vent d'Autan" near Toulouse)
- the absence of true decking platform (both easier and harder because it had to stop its descent).

After our experimentation campaigns, we performed a full day (16^{th} July 2006) of demonstrations, taking into account various possible orientations and approach trajectories for the rotorcraft relative to the virtual ship, under different relative wind hypothesis.

5. WAYPOINT AND ITINERARY PLANNER

5.1 Mission planning tools

Our flight experiments and demonstrations show the ability of the ReSSAC rotorcraft to act and adapt to its environment using reactive, or conditional, decision strategies. We now present general tools developed in order to design the aircraft mission.

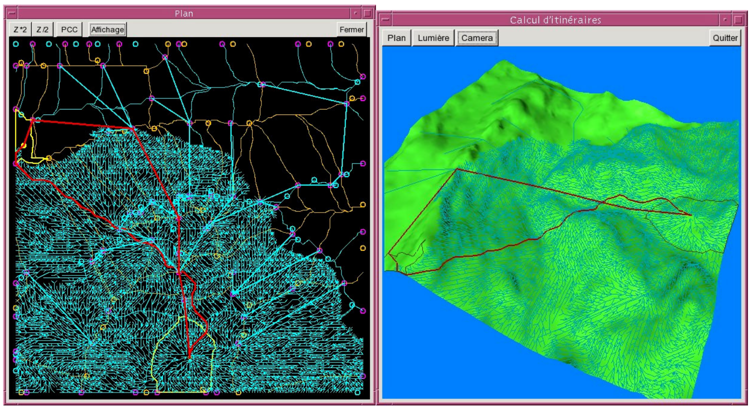


Figure 10 Trajectory optimization and itinerary planning based the initial terrain map and rough numerical terrain model

Mission planning tools were developed in the ReSSAC project. In the current implementation, this software is running on the ground station computers, as shown in Figure 10 and Figure 11, but we may very soon have sufficient on-board computation capabilities so as to have it embedded.

This mission planner is dedicated to provide a set of automatically generated possible waypoints, linked to each other by a set of possible itineraries following feasible trajectories between the waypoints.

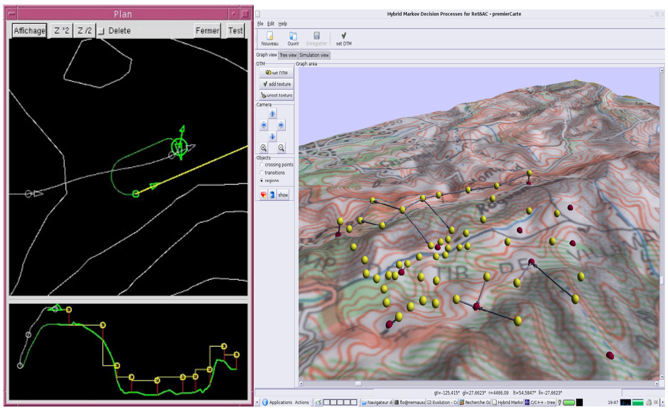


Figure 11 Automatic waypoint generation (left) and global mission planning interface (right).

A geometric algorithm is first applied in order to automatically search for crests and valley on a 3D numerical terrain model. The crests and valleys lines are populated with a number of waypoints. The itinerary planner then generates a **graph** of time (or fuel) optimal itineraries between these waypoints, by taking into account the flight dynamics and the fuel consumption model of the aircraft.

A path planner applies standard Heuristic Dynamic Programming (Moore-Dijkstra) algorithms in order to generates a graph of itineraries combining shortest path itineraries and low altitude itineraries.

The waypoint and itinerary planner is connected by an interface with the SNAKE obstacle avoidance strategy: they communicate by exchanging flight plans, as described previously in this paper, as shown in Figure 12.

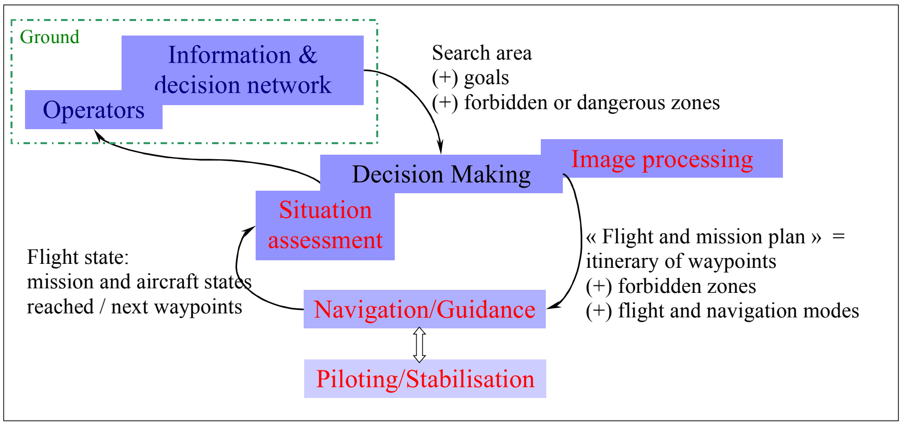


Figure 12 Autonomous information processing and decision architecture

5.2 Mission planning and action strategy

However, the SNAKE navigation and obstacle avoidance strategy is only one possible decision strategy for safe and optimal navigation missions. Our optimal itinerary planner needs to be connected to a more global mission (and perception) planner in order to address more complex missions.

The goal of such an integration is :

1. to enable the system to plan its mission according to the known 3D map of the environment and known obstacles on the one hand, and

2. to plan for information acquisition in order to update the current map on the other hand.

Safe exploration and landing on an unprepared and ill-known terrain, potentially obstructed with obstacles, is a motivating challenge. First it has potential applications for manned rotorcraft. Second, it requires to provide the aircraft with safe reconfiguration and decision capabilities.

This work is part of a cooperative research with NASA/Army ARP project [5][6].

6. PERCEPTION : VISION ALGORITHMS

6.1 Perception

Perception is obviously a crucial issue for the system to be able to act in appropriate interaction with its environment. Tools and algorithms for the perception of the environment and the updating of an unknown map of the exploration area have been developed in the ReSSAC project.

The goal is to obtain information on the presence or absence of obstacle on the terrain, and if possible update an elevation map.

The terrain map is based on an "a priori" numerical terrain model. This terrain model is bound to be embedded, which means that we are using a very coarse model today : triangulation with 40 meters long edges on average, with corresponding elevation errors in the middle of the triangles.

In any cases, we suppose that the *a priori* embedded terrain model is very likely to be correct only with a coarse granularity, which means that the precision in terms of terrain elevation is not compatible for autonomous landing

In matter of vision algorithms, three main approaches have been explored and combined:

dense stereovision from motion

sparse stereovision from motion

texture based zoning.

All three can be implemented in different ways, with more or less refinements and subsequently more or less computation cost.

6.2 Stereovision from motion

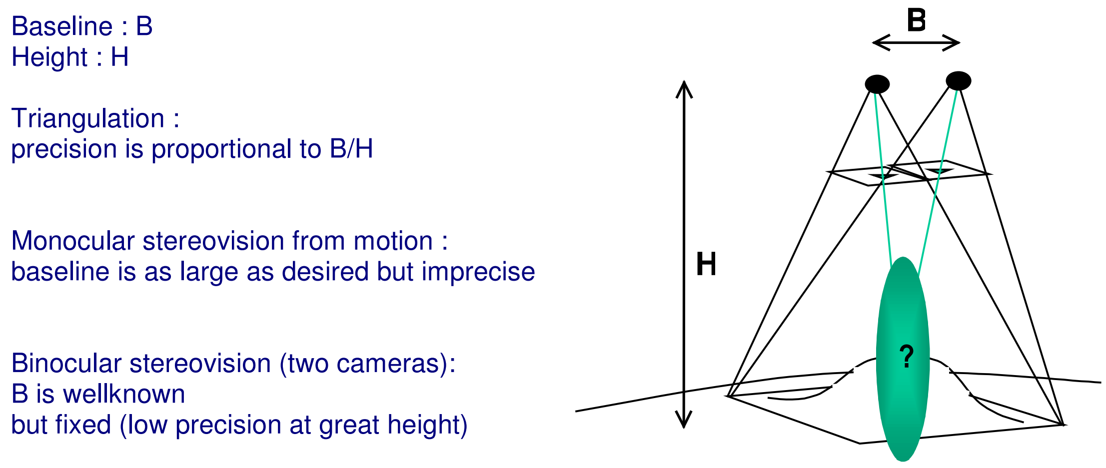


Figure 13 Principles of stereovision : binocular (2 cameras) and monocular (1 moving camera)

The basic principle of "stereovision from motion" is that the distance of observed features in the images is estimated on the basis of the way they move from an image to the next one in the video sequence. Pairs of images are correlated, in order to match a point in the first image with the corresponding point in the following image : the distance of that point from the camera is obtained by triangulation as in Figure 13.

A camera is mounted on the ReSSAC rotorcraft in "nadir" orientation, which means that it is pointing downward, vertically when the rotorcraft's attitude is calm and horizontal. In such a configuration, the estimated distance, if obtained, corresponds to the altitude of the camera relative to the obstacles on the ground.

Depending on the way this principle is applied in the image matrix, the method should be called dense or sparse.

Both methods need some hypotheses to be made:

- the scene is mostly planar, except for obstacles,
- the camera and scene models can be approximated by a homographic or quadratic 2D model,
- the speed of the aircraft and gross height above the ground can be roughly known.

6.2.1 Dense stereovision from motion

Dense "stereovision from motion" (Figure 14) algorithms roughly work as follows:

- correlation of a pair of successive images in order to compute a field of pixel speed vector (optic flow) or in order to separate the main scene motion from residual motion of "outliers" that do not move as the main flow (so the importance of the "mostly planar scene" hypothesis),

- computation of a point scoring according to the norm of the optic flow or according to the intensity of the gradient in the images themselves and in the displaced frame difference between images,

- computations and estimation of the relative location of supposed obstacles,

- projection of a dense set of points identified as obstacles or not on the terrain map: the result is a dense map without "holes", but longer to compute.

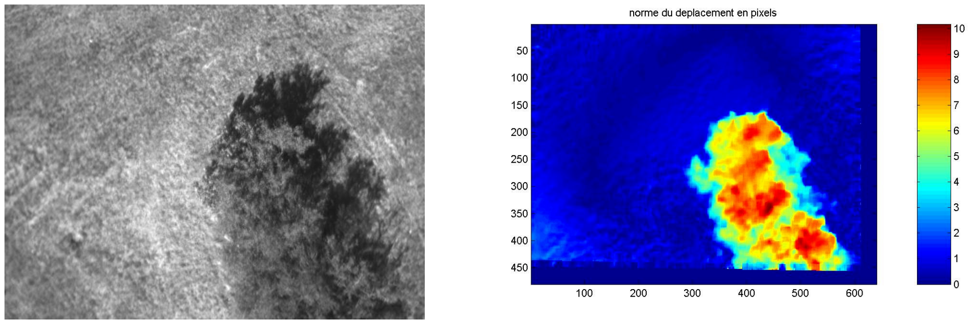


Figure 14 Monocular Stereovision obstacle detection and dense elevation estimation using optic flow

6.2.2 Sparse stereovision from motion

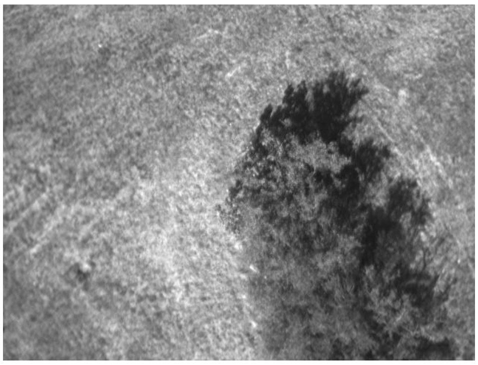
Sparse "stereovision from motion" (Figure 15) algorithms roughly work as follows:

- selection of interest points in the image by Harris filtering using the image texture, which is related to local variations of pixels' intensity,

- tracking of these interest points from an image to the next,

- computations and estimation of the relative location of supposed obstacles,

- projection of a sparse set of points identified as obstacles on the terrain map: the result is only a sparse map, i.e. with potential "holes", so the importance of the "mostly planar scene" hypothesis.



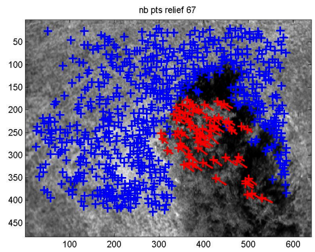


Figure 15 Monocular Stereovision obstacle detection and sparse elevation estimation using texture interest points

6.3 Action and perception coupling

In all cases, it is necessary and preferable to also use information from the rotorcraft navigation estimation and guidance (action) in order to:

- accelerate the matching algorithms that track the pixels from one image to the next
- get an order of magnitude of the aircraft altitude relative to the ground
- adapt the algorithm to the speed of the rotorcraft, which determines the distance flown between two images.

7. LANDING SITE CHARACTERIZATION : ELEVATION MAP

7.1 Dense vs. sparse

Figure 14 shows the elevation map obtained from a sequence of images using dense techniques (a sample is shown on the left). Optical flow techniques are complementary applied in order to speed up the process and identify "higher zones" more rapidly. The image and the elevation information is very nice, but takes several seconds to obtain.

Figure 15 shows the elevation map obtained using sparse techniques, which means that the number of tracked interest points is limited on purpose, in order to speed up the algorithm.

7.2 Landing site characterization experiments

Figure 16 shows the combination of dense stereovision from motion and texture detection techniques that we use in the first level exploration phase. These techniques identify the main obstacles in the scene and generate adequate sub-zones to be further explored and characterized. Based on the obstacles and terrain texture, the sub-zones are generated and assessed with respect to the probability of finding an adequate spot for landing within it.

These sub-zones are then explored according to an exploration strategy : this strategy is to be optimized on the basis of the generated obstacles and sub-zones, taking into account uncertainties in the environment and risks of fuel shortage (see paragraph below).

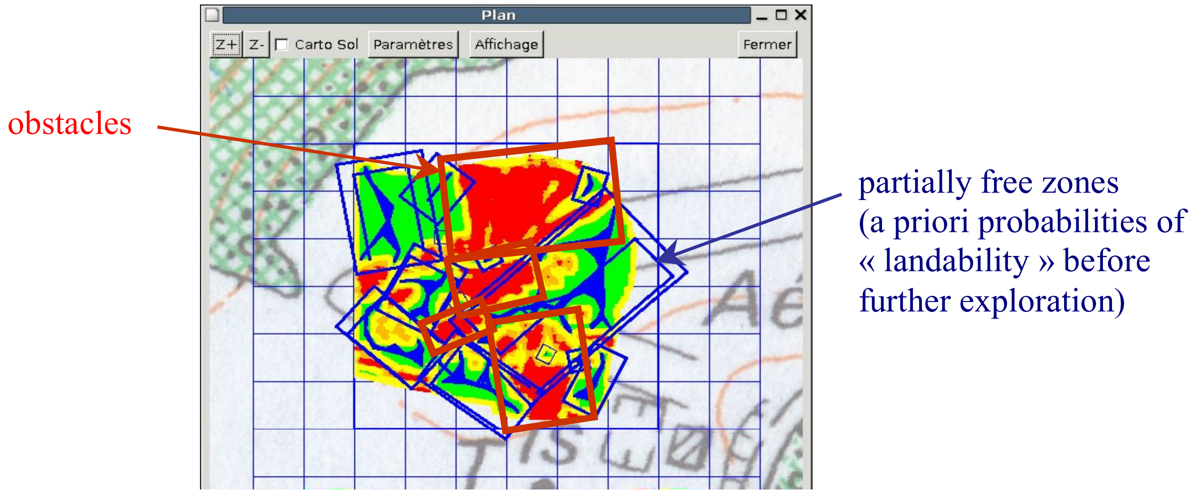


Figure 16 Obstacle detection and zoning using stereovision and texture

Figure 17 shows the combination of techniques that is currently used in real-time in the final landing phase.

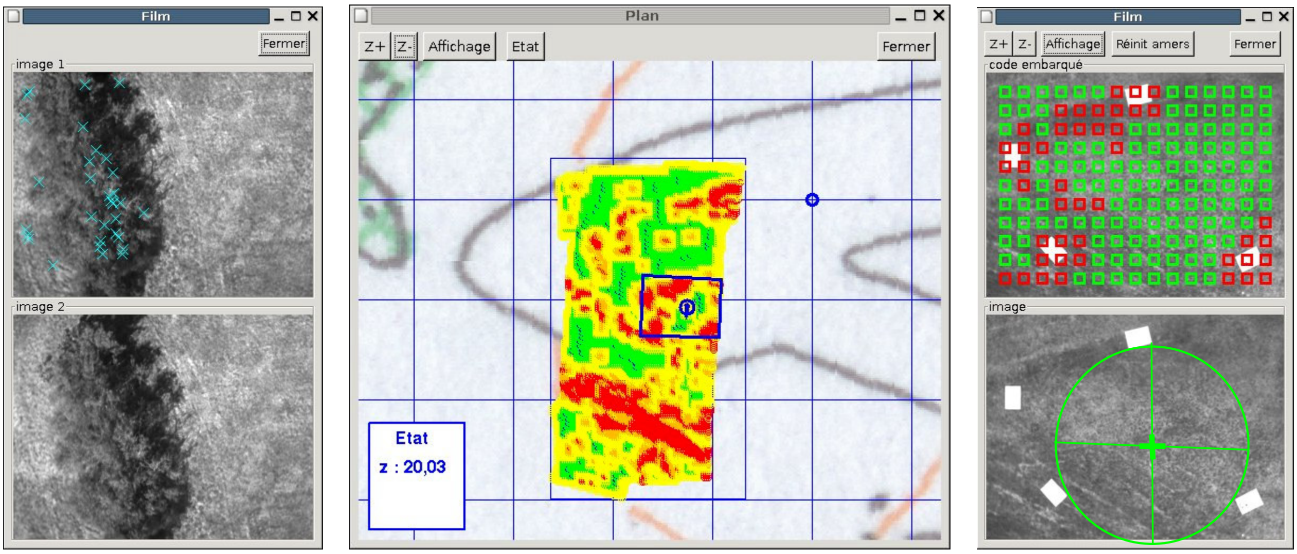


Figure 17 Onboard real-time elevation map estimation and landing spot selection

8. DEMONSTRATIONS OF SAFE AUTONOMOUS LANDING ON A PARTIALLY KNOWN NON-COOPERATIVE TERRAIN

The vision algorithms in Figure 17 were successfully applied for landing site characterization in the series of flight demonstrations performed in autumn 2006 showing the capability of the ReSSAC rotorcraft to autonomously land on a partially known terrain obstructed with (cardboard) obstacles, in the conditions illustrated in Figure 18.

These flight demonstrations of the ReSSAC aircraft have demonstrated with some success, some capabilities of autonomously deciding on the spot where to land

Indeed, it did demonstrate a full autonomous decision making capability at one precise moment of one experimentation: this when the aircraft decided by himself that the search zone that had been given to him to explore was just a little bit too narrow. The landing spot selection algorithms simply spotted a very nice perfectly free of any obstacle landing point just on the boarder of the search zone: which was absolutely clever, but unexpected.

As a matter of fact, our flight demonstration was more intended to show the helicopter acting exactly as scheduled and landing in the middle of the cardboard obstacles, rather than acting on his own with true autonomy.

The ReSSAC helicopter having taken too much autonomy was condemned to land in the middle of the cardboard obstacles during the demonstrations performed within the hours following the incident. The event was not even filmed nor publicly presented. We must state here loud and clear, for the sake of our automatic flight authorizations, that this act of independence and true autonomy was still under the tight supervision and control of our security pilot (the autonomous rotorcraft was arrested right after).

And what next ? We first planned to extend the area covered with cardboard obstacles, so to suppress the nice "boarder line" landing spots.

Figure 18 ***ReSSAC experiments on*** **ONERA & US Army Helicopter Div. NASA Ames Common Obstacle Field**

9. EXPLORATION IN A PARTIALLY KNOWN UNCERTAIN WORLD

We then decided to perform the full exploration mission in several phases, including the re-planning of the mission in the middle, as described in the following paragraph.

9.1 Phase One:

- initial navigation and exploration of the search zone: planned using our waypoints and itinerary planner generating a navigation map and systematic exploration (sweeping) trajectories in order to explore the initial search zone at higher altitude (50 meters in fact)
- geometric decomposition of the search zone into obstacles and sub-zones of interest, further assessed in terms of probability of "goodness" for landing purposes
- Mission re-planning by optimizing a conditional strategy (reactive decision rule under uncertainty) for the exploration of the thus ranked sub-zones, taking into account the probabilities of failure or success in finding an site appropriate for landing, together with other probabilities coming from the changing and uncertain environment.

9.2 Phase Two:

- Execution of the exploration strategy, choice of a sub-zone to characterize and test for slope, until safe landing in the search zone, or safety landing in the safety zone, or safe return to base, …

9.3 Phase Three:

- Test, by use of a laser telemeter, of the slope of the sub-zone eventually selected in Phase Two, then if the slope is ok proceed with selection of a landing spot based on the techniques presented in Figure 17 and landing, otherwise resume exploration in Phase Two.

This approach clearly requires the system to be able to replan its mission according to the encountered situation and according to environment uncertainties.

The techniques applied for that purpose are described in the following : the algorithms are ready and efficient. The exploration planning problem is modeled in a formal way, using the Planning Problem Description Language PDDL 2.1 including probabilistic action effects description .

These algorithms have been implemented on the on-board computer and integrated in the ReSSAC decision and supervision architecture described in Figure 12 .

Flight demonstrations have been conducted between February and March 2007 and should be more officially presented by the beginning of July 2007.

The experiments shown in Figure 18 correspond to the last phase of the present ReSSAC rotorcraft autonomous exploration mission.

10. DECISIONAL AUTONOMY

Extending the autonomy capabilities of an unmanned aircraft is not a goal in itself. Such efforts are driven by the need for the aircraft to be able to manage by itself a situation were the control and supervision link is lost.

Preparing for this eventuality often appears as crucial when considering complex missions involving a mix of manned and unmanned assets, and especially the insertion of unmanned aircraft within an airspace populated with other aircraft. The loss of control can be due to a data-link failure with the ground control station, due to an excessive workload of the operators or due to the fact that the link with the information and decision network that normally supervises the mission, does not provide a sufficient level of situation awareness to the operators, or does not allow them to react in time.

For these reasons, we study the case were the pre-planned mission, should be reconfigured on-board the autonomous aircraft by its own re-planning capabilities.

10.1 Re-planning

10.1.1 Reactive replanning

The basic level of such a replanning capability is well represented with the case of obstacle avoidance. Assuming that we are able to detect autonomously the obstacle, or that we are informed by other means of the presence of this obstacles, we are able to adapt to the new situation with the SNAKE navigation system, unless the obstacles come into tricky configurations so that some obstacles overlap, which is possible with moving objects.

SNAKE is therefore more considered as a general navigation and obstacle avoidance reactive strategy, rather than a true planning tool. Higher level motion planning capabilities are thus required on top of it.

State of the art algorithms can provide good real time motion planning solutions to that problem in the case of one single aircraft (multiple aircraft flight planning and collision avoidance can be much more complex). Yet, most missions are not purely geometrical trajectory planning problems and combine other variables, some of them controllable and some of them random or unpredictable.

10.1.2 Deliberative re-planning : re-optimizing the action strategy

Figure 12 shows a classical decisional architecture for autonomous agents, which is applied to the ReSSAC aircraft. It is important to notice that all the situation assessment, decision making and image processing functions need not be fully embedded on-board the aircraft, nor in the ground control station.

There is likely to be a sharing between the functions that are required to be on-board the aircraft and those that are required to be kept under control of the operator: this possibly uneasy choice is partly studied in the ReSSAC project.

11. AUTONOMOUS EXPLORATION PLANNING PROBLEM

11.1 Planning problem

In order to get a first idea of the possible benefits of using Artificial Intelligence planning techniques for real-world autonomous aircraft, the case of an exploration mission is studied within the *ReSSAC* project. This example is abstracted from the initial Search & Rescue application scenario of the project.

An exploration mission is composed of a problem of navigation and a problem of information acquisition in a partially known environment. It can be addressed at different levels of modeling. Motion planning and information processing aspects are important when a sufficient flow of sensory information is available through the use of range or object detectors, 3D sensors, … etc. Our focus is on a more abstract level: on planning under uncertainty for both motion actions and information acquisition tasks, which is a crucial issue for autonomous systems.

11.2 Exploration planning problem

In our exploration planning problem, different regions are identified, such as in Figure 19, after a preliminary (higher altitude) exploration, the partition of the initial search zone into sub-zones and the ranking of these zones in terms of probability of "goodness" for landing purposes.

These regions require to be exhaustively or partially explored, mapped or searched for the presence of persons or objects, before continuing the mission. Information acquisition may be part of intermediate goals of the mission, and may also impact on the subsequent tasks or navigation actions.

Such missions can be modeled at a higher level of abstraction, as a sequence of mission phases, tasks, or macro-actions: for each mission phase, the system needs to achieve navigation and information acquisition goals, before proceeding with one of the possibly following phases.

The order in which the intermediate sub-goals or tasks must be achieved can be free or constrained. Thus, they can be seen as pre-conditions of other tasks: this implies that searching for a good mission plan (not even the optimal one) requires to explore the combinatory number of all possible branches in an AND-OR graph of possible states looking like a conditional version of the flight plan in Figure 7, with additional possible "information acquisition" flight phases in the middle.

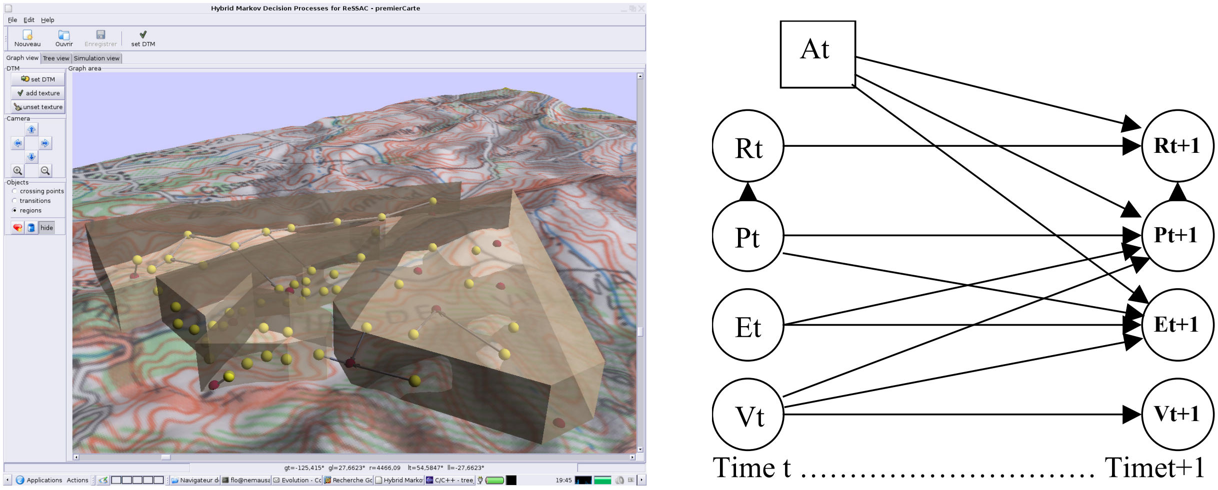


Figure 19 Exploration mission (MDP) definition interface (left) and Dynamic Bayesian Network Model (right)

Furthermore, each intermediate goal must be achieved while minimizing risks and costs and thus by optimizing the navigation and the action strategy while taking into account uncertainties on the values of a number of random or unpredictable variables.

11.3 Formal Markov Decision Process modeling

Our exploration planning problem contains a number of possible tasks, associated with rewards, each of which can be obtained once in turn, no matter the order, before reaching the goals, and final rewards. The achievement of these tasks is not certain and there are uncertainties in the results of the performed actions.

To model this, we need to introduce binary state variables depending on whether the goals have already been achieved or not, and some representation of the uncertainties. The formalism of Markov Decision Processes (MDP) can be applied in that case, but in a factored state and action representation based on state and action variables.

In our exploration planning problem, the Markov Decision Process (MDP) model is based on the following variables:

1. Action variables :
    - At: rotorcraft action choice at time step t

2. State variables
   - Et: rotorcraft estimated fuel level at time step t
   - Rt: the region being explored by the rotorcraft at time t
   - Pt: the current best landing point at time t
   - Vt : the current flight velocity of the rotorcraft at time t

11.4 Dynamic Bayesian Networks

Planning problems that are modeled with such an hybrid structure combining a navigation state space and orthogonal mission of internal state variables have been studied in [16].

Such problems of sequential decision under uncertainty can be modeled using Dynamics Bayesian Networks (DBNs) such as in Figure 19, or in many problems of the ICAPS'2004 probabilistic track planning competition in which we participated with preliminary versions of our algorithms [17].

In Figure 19, the arrows arriving to Et+1 mean that the probability distribution on the possible values of E (energy level of the aircraft) at time t+1 is given as a conditional probability depending on Vt, Et, Pt and the choice of the action At chosen at time t.

Our exploration planning problem is thus modeled in a factored form [16-18], and difficult to represent graphically, except for the interface defined in Figure 19. The underlying navigation problem is still present, but the dimension of the state space is increased. The navigation goals to be achieved depend on the values of the other variables. The level of energy autonomy is a good example of an additional state variable with a high impact on the navigation.

Flight is thus limited by energy autonomy, and the aircraft can decide to return to its base, either if all its goals have been achieved, or if it is running short of fuel, in which case it may as well go to its failsafe or emergency crash base. Other random variables may also impact the navigation decisions, such as the ground height, the presence of objects, the distance to obstacles (especially in unknown environments), the local winds and turbulence conditions which may allow an approach to landing or not, etc.

11.5 Optimization algorithms

Yet, such factored Markov Decision Process (MDP) formulations of the problem may lead to optimization problems of untractable complexity.

We tested many algorithms [17-18] and developed a symbolic focused dynamic programming (SFDP) algorithmic scheme (Figure 20 and Figure 21), which enables us to efficiently find a feasible solution for very large factored MDP [19], that optimal algorithms cannot tackle.

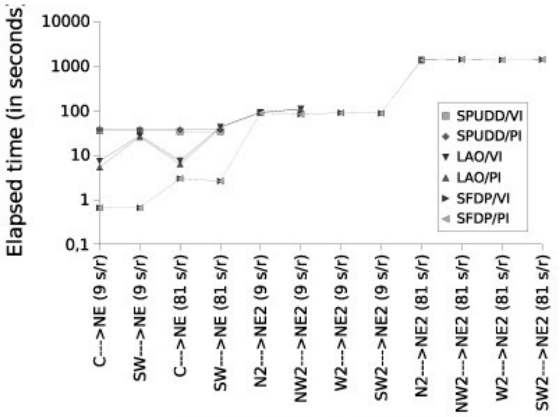


Figure 20 The SFDP algorithm can tackle the problems of size beyond N°7 (from left to right)

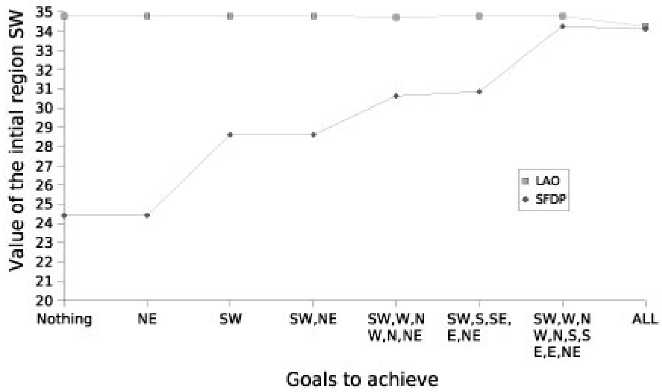


Figure 21 The SFDP algorithm can incrementally improve the reactive action strategy expected value

We developed a incrementally de-focused approach that first finds a feasible solution to the problem and then incrementally imposes increasing constraints on the optimality of the solution, until optimality [20]. Further work will be devoted to the development of optimization algorithms to tackle hybrid probabilistic planning problems including continuous state variables, time and concurrent actions, with extension to cooperative multi-agent planning.

11.6 Online replanning

The on-line "almost anytime" re-planning algorithm has been integrated on-board within the overall mission management architecture with the motion planning algorithms and navigation system. These techniques have been tested on the ground first, then experimented in flight including exploration, landing zone selection and mapping, autonomous landing in an unprepared area and flight back to the base. The official final demo is scheduled by the beginning of July 2007, which is still a challenge, w.r.t. the supervision of "autonomy".

12. CONCLUSION

We have presented the current status and achievements of the Autonomous Air Vehicle ReSSAC project at ONERA. The project has now reached a maturity stage, with two aircraft capable of autonomous navigation under the supervision of a security operator.

A large variety of experiments were conducted and real steps forward achieved within the last month which have lead to flight demonstrations of autonomous exploration and landing in an ill-known unprepared environment, with several exploration phases from coarse obstacle detection to finer site characterization, including the zoning of the search area into sub-zone and the online mission re-planning to adapt exploration to the encountered environment.

By this demonstration, the ReSSAC project achieves a true feasibility step of autonomy capabilities for uninhabited aircraft, either for Search & Rescue or for other missions. This demonstration now makes it possible to make further steps towards autonomous agents in cooperation, planning and deciding for cooperative action in the achievement of a common mission.

Of course, this also leads to work on motion and action coordination functions, which are necessary to operate multiple platform concurrently. Decisional autonomy is not required in order to perform formation flying or visual servoing. However, some adequate capacities of collective adaptation and cooperative decision making are required in order to achieve a common mission requiring the resources from several agents, some of them uninhabited, and in order to achieve cooperative work by these agents while facing unexpected events, intrusions by non-cooperative agents, pop-up threats or moving dangers, for instance.

Further work will be focused in the following directions:

- embedded decision and replanning
- improved mobility in non-cooperative environments
- cooperative embedded coordination and decision making
- dependability and safety : how to prove the safety of highly reconfigurable control architectures.

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