YAP (Yet Another Paparazzi)

Pascal Brisset, Murat Bronz, Michel Gorraz and Jeremy Tyler
ENAC, Toulouse, France
mailto:drones@enac.fr
http://paparazzi.enac.fr

March 2008

Abstract

When attending Micro Air Vehicle (MAV) competitions, one notices a majority of teams concentrating on the vehicle itself, be it from an aerodynamics, structures, propulsion or control point of view. A total system approach is not often seen, though MAVs pose a very unique challenge to the system designer who must propose a platform and architecture to support the autopilot, the communications, user interface, simulation, analysis and tuning tools, flight plan management and many other details. Since it's inception, the Paparazzi team considered the MAV as a system and used a bottom to top approach focusing on safety, robustness and usability of the system as a whole.

This paper tries to show how this usability has been applied to the MAV08 challenge. New agents are introduced in the system, an helicopter, the ground vehicle and the commando, all equipped with a Paparazzi board and its communications. A unique ground control station is used to monitor all these heterogeneous agents. The reduction of the size of the vehicles and related difficulties are also presented. Building methods of the 30cm Slicer plane and control laws for the Twisted Logic helicopter are detailed.

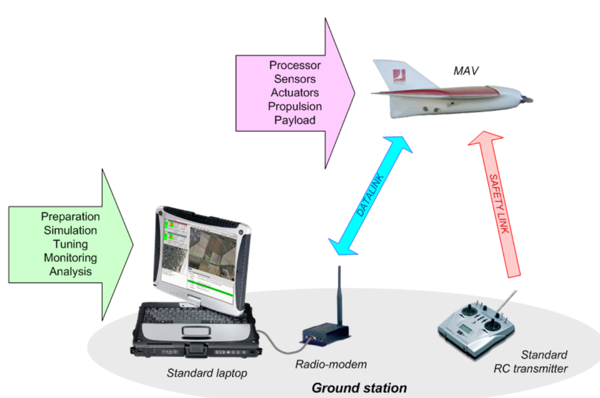

Figure 1: Paparazzi System base components

1 Introduction

Paparazzi is an open-source autopilot system oriented toward inexpensive autonomous aircraft of all types. The project began in 2003 and has enjoyed constant growth and evolution ever since. The system has been used on dozens of airframes and implemented by several teams around the world. Thousands of hours of autonomous flight have been successfully achieved with the Paparazzi system.

The Paparazzi system includes the airborne processor with its required sensors, the airborne autopilot software, a ground control station, the communication protocols linking the different components and a simulation environment.

Safety and reliability have been the primary goals throughout all phases of the Paparazzi system development. The critical airborne code has been carefully designed to be as simple and short as possible for reliability and robustness.

The system has been designed to be easily adapted to any type of airframe and is currently used in both fixed and rotary wing systems. The airborne software is also supported by several microprocessor architectures and many hardware configurations.

The powerful flight plan language allows the operator to define complex autonomous missions and create a logical tree of autonomous decisions for the system to make while in flight to perform any task or adapt to any scenario. The ground station operator can also manually navigate the aircraft at any time using video, real-time GPS data, and/or visual contact while relying on the autopilot to perform only the flight stabilization.

The ground control station utilizes a powerful and flexible client/server architecture which allows the operator to control one or more aircraft from a single location or from multiple locations.

Source code, hardware schematics and thorough documentation are released under the GNU Public License and are freely available for anyone to download from the project website. This open source license was chosen in the hope that our work will be used by and improved by the great number of people interested in this technology.

The MAV08 mission is a lot more challenging than the previous MAV competition because of the complexity of the scenario and because of the strong size constraint. This size constraint required to design an appropriate aircraft. The scenario required to propose, first to use a new vehicle able to stop and perch 1km away from the launch point, second to be able to navigate a remote ground vehicle, third to control all the different agents from a single ground station.

We detail in this paper our answers to these different questions. We first give a brief overview of the Paparazzi system and its evolutions during the last months. Then we show how the system can be used to make the different agents cooperate to achieve the mission, taking into account the expected global safety. In the next section, the air vehicles, fixed wings and rotorcraft, are described. A specific section is dedicated to the payload, a mobile camera which has been designed to fit the 30cm airplane. Guidance of the simulated UGV inside the Paparazzi environment is presented and we conclude with the ground control station operations description.

The overall preparation for the challenge is based on the experience accumulated through the previous competitions. It is also the result of an international cooperation between some of the main active members of the Paparazzi project. This cooperation was finalized through a

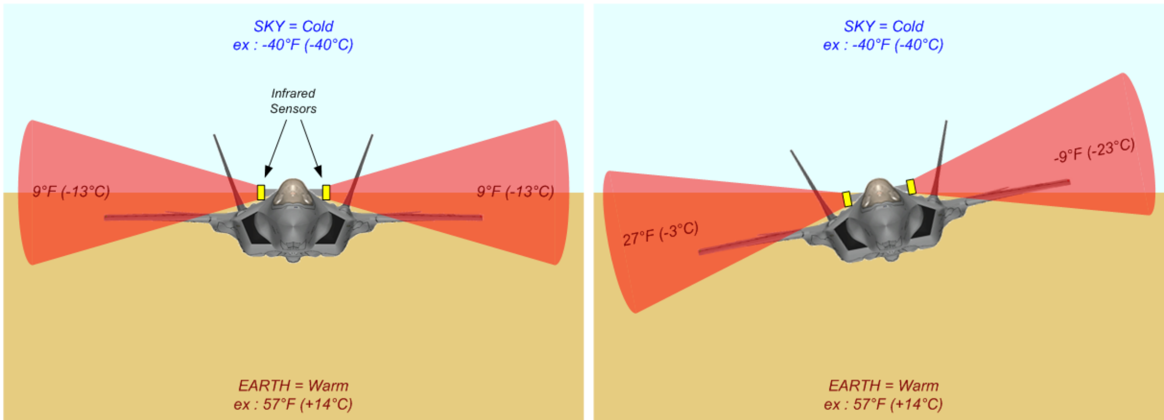

Figure 2: Infrared sensors for attitude estimation. Roll angle is deduced from the difference of temperature measured on right and left sides.

workshop organized in California in February 2008, where integration of airframes, electronics, control and ground software was achieved.

2 A Brief Overview of Paparazzi

A extensive description of the Paparazzi system has been given in the MAV06 technical paper[1]. The main components of the system are recalled in figure 1. One originality of the system is that the attitude estimation can be done with a simple set of infrared sensors ([6], figure 2). Accuracy of the roll rate measurement may be improved with a gyroscope and the hardware supports the addition of a full set of inertial and magnetic sensors. Such sensors have been mounted on the helicopter prepared for the MAV08 challenge.

The control architecture is detailed in figure 3. All these controllers can be used together or separately and the choice can be done from the flight plan.

Paparazzi have been improved in different ways during the last year:

- The GUI (figure 4) which provides to the operator a versatile and complete monitoring and control of the system has been simplified to be used by non-experts. It has been used to train operators in a couple of hours. This has been successfully demonstrated to US Army people in November 2007[2].
- A new hardware has been developed[1]. Easier to build and assemble, it should help the beginners to start with the system.
- Intelligent navigation[2] taking advantage of chemical sensors use has been developed to achieve a complete autonomous search of a chemical source (or a smoke source). Time can also now be used as a parameter in the flight plan language and rendez-vous navigation strategy is provided.

The Paparazzi system has been extensively used by many users:

[1] `http://paparazzi.enac.fr/wiki/index.php/Tiny_v2`

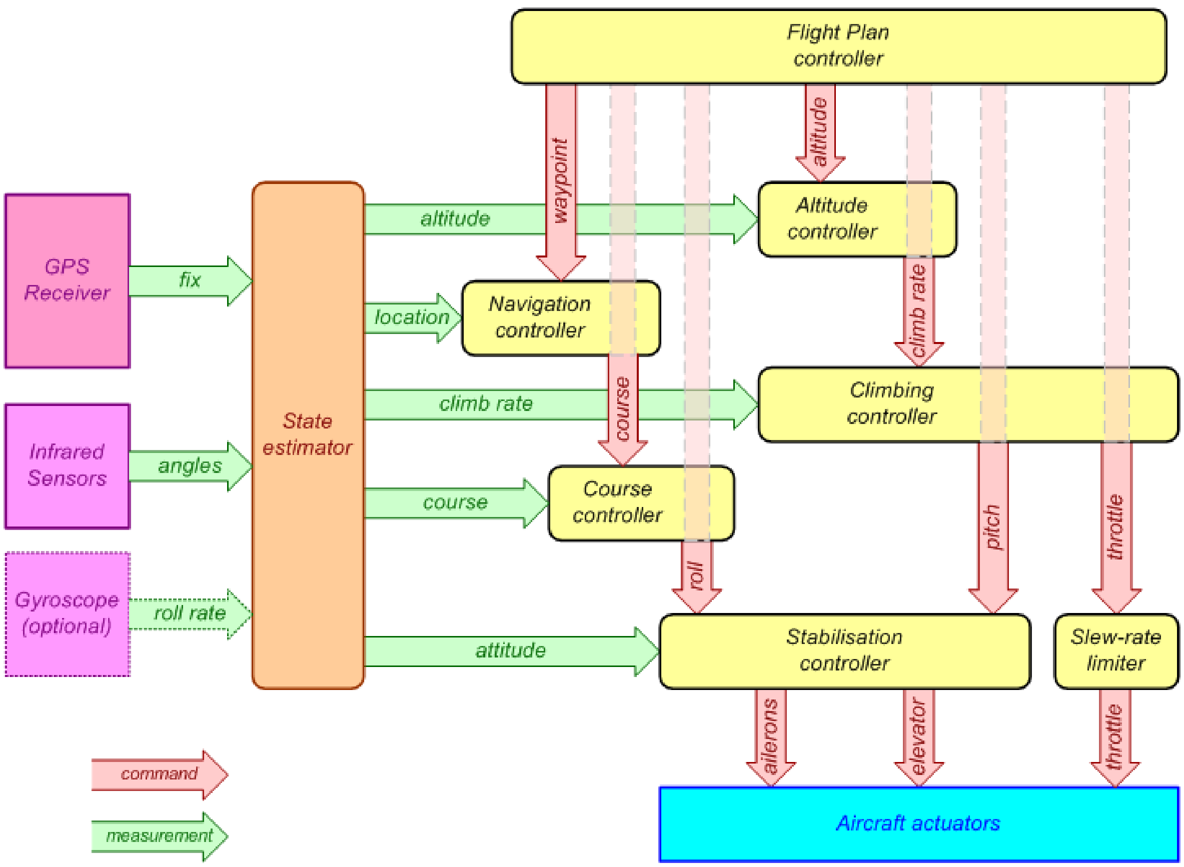

Figure 3: The stack of controllers in the Paparazzi autopilot for a fixed wing aircraft. Different navigation modes allows the autopilot to run these loops independently. They are all accessible to be user through the flight plan language.

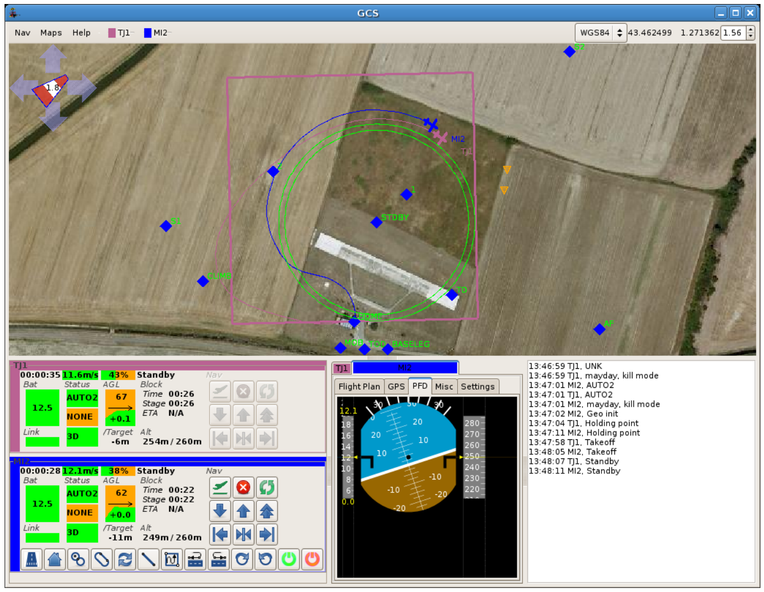

Figure 4: Ground Control Station (GCS) graphical user interface. Top-left: aircraft labels (strips); Top-right: 2D maps; Bottom-right: flight plan trace; Bottom-left: Alarm window; Left-center: real-time video.

- Experiments for forest fire surveillance have been conducted in France in June 2007. Atmospheric measurements have been done in Iceland using Paparazzi equipped aircraft during the FLOHOF campaign[4], August 2007.
- G. Hattenberger has validated a navigation strategy for UAV formation flight with three autonomous planes[3]
- In December 2007, From the 24C3 conference in Berlin[5], Paparazzi aircraft operated in Hildesheim, Germany and in Toulouse, France were remotely controlled in real time in front of the audience. This demonstration showed that the system is ready for operations distributed around the world.
- Most of the teams taking part at the MAV07 (September 2007, Toulouse) competition were using the Paparazzi system ...

3 Mission

The scenario complexity of the MAV08 challenge lead us to imagine a solution involving many agents and intelligent communications.

3.1 Operations

The initial planned approach involves:

- Two fixed wing aircraft for mine detection, obstacles, covered position and armed vehicle localization. Two is a minimum since the endurance of one 30cm aircraft (about 20 minutes) does not cover the complete mission duration (40 minutes). However, the two airplanes can fly in the same time and can be controlled by the same GCS.

- One rotorcraft to look for the hostage in the building. The helicopter does not have the endurance to fly for a long time so it perches next the building.
- One simulated UGV.
- One controller. It is the operator responsible for monitoring the UAVs and the UGV tracks.
- One planner. This operator is responsible for interpreting the video transmitted by the UAVs and planning the track for the UGV and the commando.

All these agents are connected inside the Paparazzi environment through wireless (UAVs, UGV and commando with the GCS) and wired communications (planner with the GCS).

Figure 5 give an overview of the planned operations. Radio communications with the ground agents have been omitted. They will allow to temporarily cut the datalink communication in order to free bandwidth for the UAVs. When they are close to the launch point, the UAVs can also be piloted directly with a standard hobby RC link.

3.2 Safety

Safety and reliability have been the primary goals throughout all phases of the Paparazzi system development:

- The system provides a complete simulator which allows the operator to precisely prepare its mission. Failures also can be tested: The simulated environment can simulate a loss of GPS coverage, drop the battery to a low level, add strong wind, ...
- The GCS graphical interface gives concise and precise information to the operator to help him to monitor the system. Graphical and audible alarms are also provided.
- The autopilot can operate in several failsafe modes:

  Home If the aircraft flies too far from the launch point or if the RC link is lost in manual mode, the autopilot switches to a basic navigation, circling around the HOME waypoint at a safe altitude.

  NoGPS If the GPS coverage is lost, the autopilot switches to a basic attitude control with a fixed throttle and a fixed roll attitude.

  Kill If the aircraft flies too far and is not able to come back closer too home, the throttle is cut.

  All these behaviors are configurable by the user according to the desired mission. For example a custom zone can be specified in the flight plan and actions can be triggered when the aircraft get out of the zone.

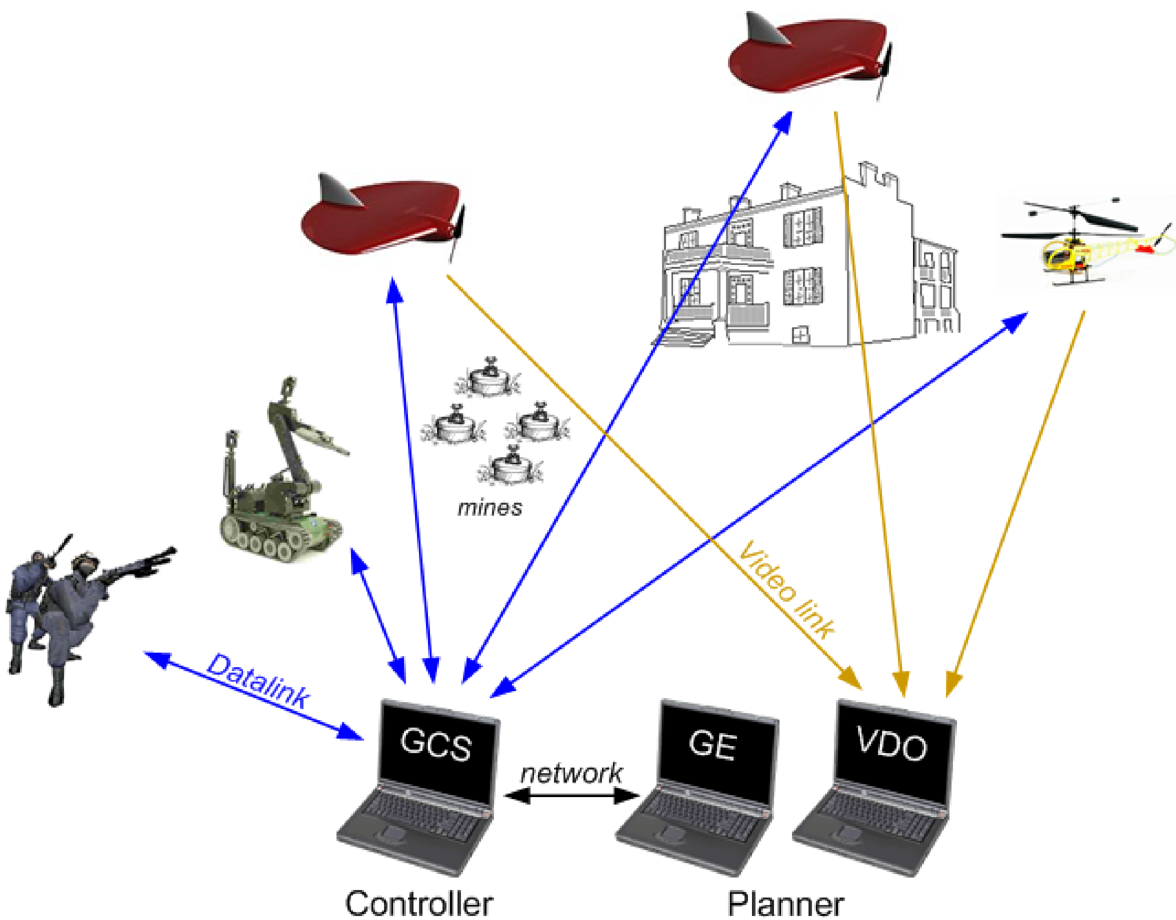

Figure 5: Agents for the MAV08 mission. Two operators are required to control and plan the mission. Wireless digital communications are used between the controller and the mobile agents. The planner monitors the video and uses a Google Earth editor connected to the Ground Control Station to draw obstacles, mines, tracks, ... on the map.

Table 1: Slicer's Weight Breakdown

Part	Description	Grams
Airframe	Kevlar skins + EPP core	65
Propulsion	Brushless motor + Lipo battery + controller	85
Avionics	Autopilot + sensors + modems	45
Payload	Pan tilt camera + transmitter	30
Total		225

4 Air Vehicles

4.1 The Plane

The Slicer is a special-purpose evolution of the successful 33cm Dragon Slayer UAV. The rules of this year's competitions impose a maximal dimension of 30 cm. Furthermore, a reduction of the flight speed was desired in order to improve the quality of the video footage as well as to allow shorter landing distances. Compared to the Dragon Slayer, an improvement in ease of throwing was desired while keeping the good robustness qualities of the original aircraft. In the light of the previous years competitions, a modular payload bay with unobstructed field of view and mechanical protection was desired in order to increase the vehicle versatility.

The Slicer utilizes similar structural and manufacturing principles as the Slayer, as well as a combination of airfoils developed specifically for this airframe using computational analysis tools. The airframe was entirely CAD designed with CNC machined molds and major structural components. It was designed around the Paparazzi autopilot system, incorporating the electronic hardware into the fuselage and wing structure. The modular payload bay occupies most of the volume in the center of the wing, allowing for field-interchangeable payloads to be installed in a well protected location on the bottom center of the aircraft. The shape of the fuselage was specially designed to provide an unobstructed 360 degrees field of view as well as protection during landings for the payload bay.

The bottom part of the fuselage part is used as a handle during launch and contains the infrared thermopiles in a protected yet unobstructed location. The propulsion is assured by an electric brushless motor. A sealed cooling system was designed with no external mechanical part, rendering the aircraft completely dust proof. It allows the aircraft a little over 30 minutes endurance at a cruise speed of 12m/s.

A particular care was given to the design of antenna which are part of the aircraft structure.

Table 1 shows the repartition of mass between the different subsystems of the vehicle.

4.2 The Rotorcraft

Rotorcraft control is a complex matter and typically requires the availability of a complete, fast and accurate state estimation of the vehicle. Such a state estimation can only be obtained through the use of an extended set of sensors (inertial and absolute references such as magnetometer, barometer, rangemeter, GPS or vision sensors) and a computationally heavy estimation filter algorithm to hybridize them.

The 30cm maximum overall dimension sets a hard constraint on the possible configurations for the vehicle. The lift required to carry the above described set of sensors and

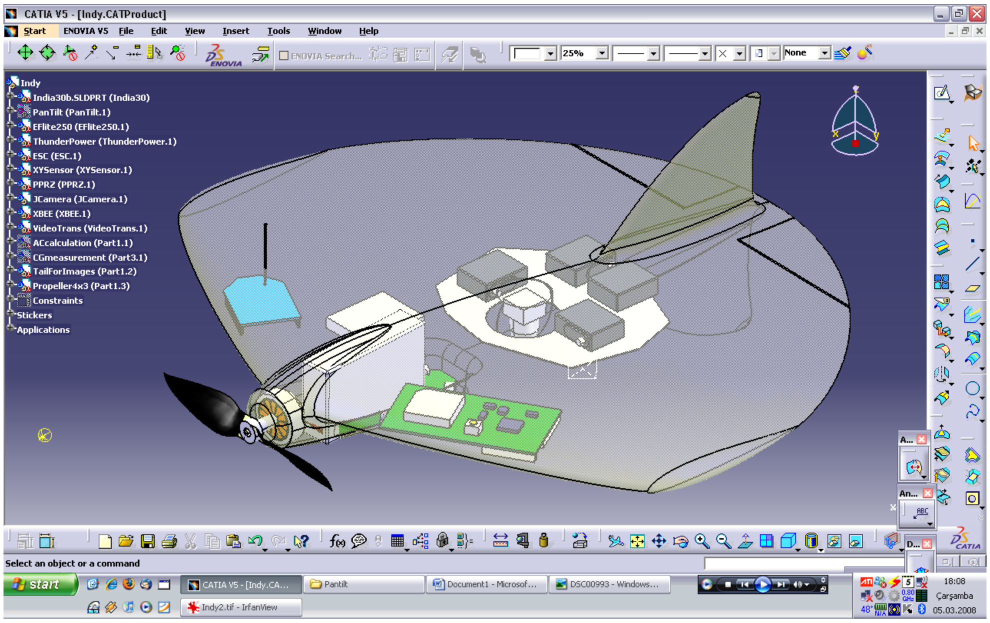

Figure 6: The new 30cm Slicer has entirely been designed under CAD.

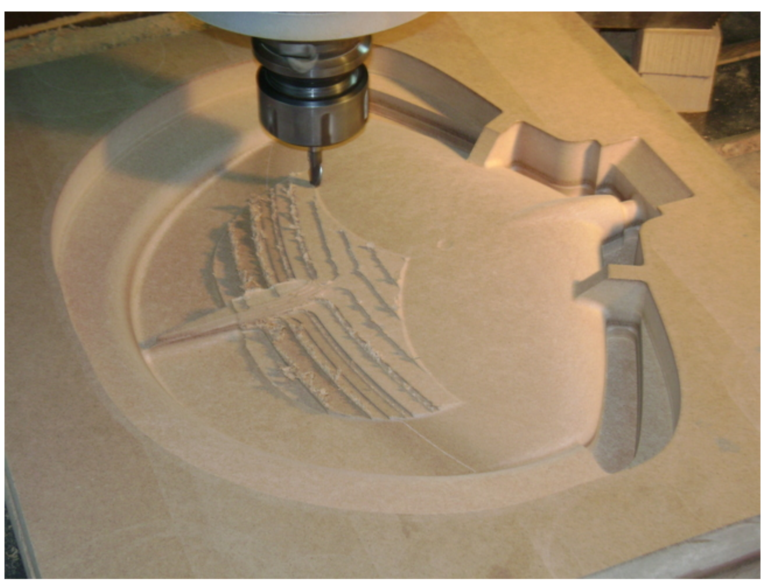

Figure 7: The Slicer male plug has been machined with a CNC directly from the CAD files.

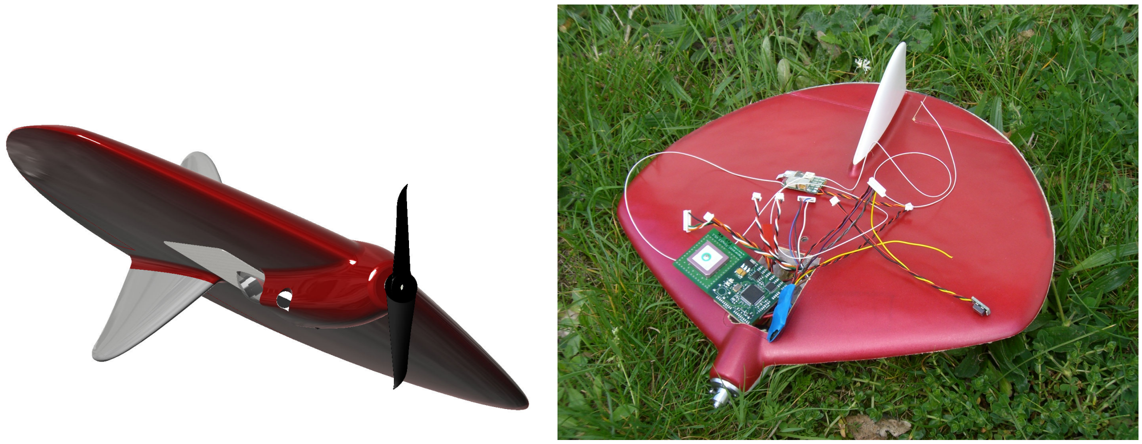

Figure 8: The 30cm Slicer: Artview and finished model with its electronic components.

associated computational means, added to the limited rotor area, naturally leads to coaxial rotors configurations and forbids configurations such as classical helicopters or the popular fixed pitch quadrirotor.

Another issue caused by the required extreme miniaturization is the difficulty of mounting sensors in a proper way. For example, it will not be possible to properly isolate a magnetometer from the high intensity currents used by the propulsion. Hence the measure of the earth magnetic field will be severely biased. The same goes for the pressure sensor which will be strongly influenced by the rotor flow.

The work of enhancing Paparazzi to support rotorcrafts is underway at ENAC. The vehicle currently used for those developments consists in a draganflyer-like quadrotor helicopter weighting 500 grams and having a maximal dimension of 60 cm. A dynamic model of the vehicle as well as a model of the sensors have been developed. A navigation filter and control algorithms are being developed on the simulator and qualified on the real vehicle. The rotorcraft share most of its software with the existing Paparazzi system, only the state estimation and control being specific.

As this vehicle didn't meet the dimensional constraints imposed by the organization, a new vehicle was developed using the coaxial contrarotative formula. A mechanical stabilization device is used to account for the reduced sensor set (single gyroscope, single accelerometer, magnetometer, barometer and GPS receiver) and the limited achievable computational power. Simplified estimation and control algorithms have been developed and tested.

However, the dynamic and accuracy achieved with this system didn't prove sufficient to allow for a satisfactory use in the potentially turbulent and windy outdoor conditions of the competition. In this regard, the team has decided to retarget its strategy toward a fixed wing only solution.

5 Automatic Mobile Camera

In order to see the targets from a 30cm aircraft which is maneuvering extremely, it is compulsory to have a two axis pan-tilt camera system. Also as a matter of weight concern, the system needs to be as light as possible while being as well as robust.

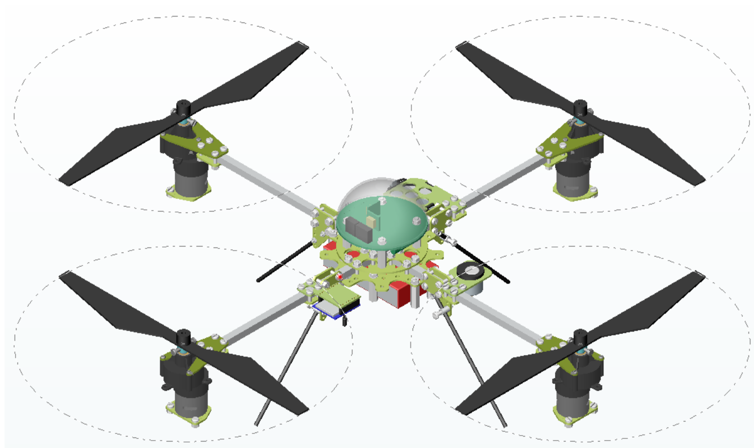

Figure 9: The 60cm VTOL testbed

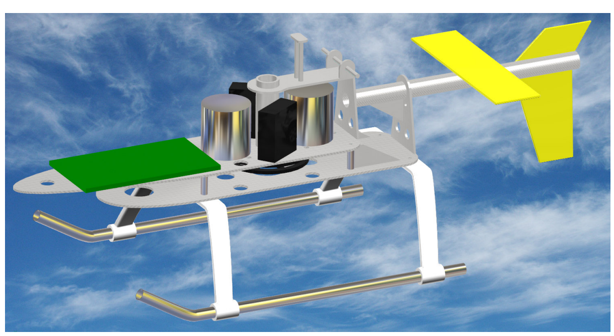

Figure 10: The 30cm Twisted Logic coaxial helicopter has also been designed with CAD.

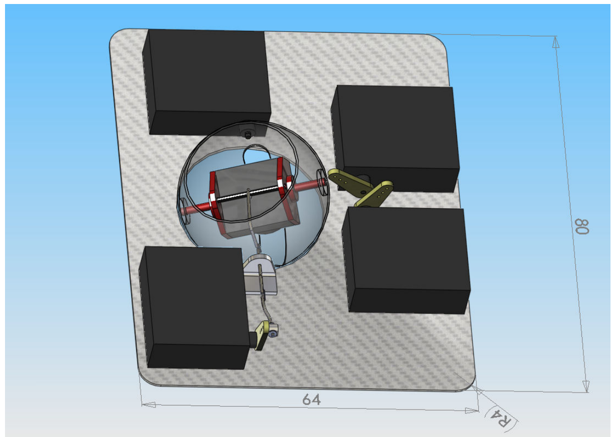

Figure 11: Artview of the two axis mobile camera. The lens is mounted in a sphere and rotates around two perpendicular axis. Micro-servos are used as actuators of the system.

5.1 Camera Mechanics

The system consists of two servos, driving the Pan and Tilt motions, one servo is directly connected to the tilt axis and the other servo has a flexible cable that gives the pan motion and also doesn't prevent the tilt motion. Custom molded one piece carbon fiber ball is used to protect the camera from harsh environment and hard landings. It has entirely been designed with the Katia CAD tool (figure 11). The weight of the different parts is detailed in the followed table:

Part	Grams
Servos	2×2.6
Carbon fiber ball	2
Hatch wall	1
CMOS camera	3.3
Bearing mechanism	2.5
Wires	1
Total	15

5.2 Camera Control

The Paparazzi autopilot provides support for a camera gimbal, allowing the operator to choose among different control modes. This has been already demonstrated with the Glotzer aircraft in MAV04 by Martin Mueller's team. The different modes provide different levels of automation:

Raw The operator directly commands the angles of the camera relatively to the aircraft.

Nadir The autopilot computes the required camera angles to always look below the aircraft.

Target The operator controls the camera by moving a waypoint on the GCS and the autopilot computes the camera angles taking into account the attitude and the position of the aircraft. For the MAV08 mission, the target can be the red team armored vehicle.

Vehicle Target The autopilot controls the camera to always point it to another vehicle handled by the Paparazzi system (another aircraft or a ground vehicle). For the MAV08 mission, the vehicle target can be the UGV, to look at the mines around it.

The provided software is ready to handle different kind of mechanics, with a single degree of freedom (pitch or roll) or two degrees (yaw and pitch or pitch and roll).

6 Simulated Unmanned Ground Vehicle and Commando Control

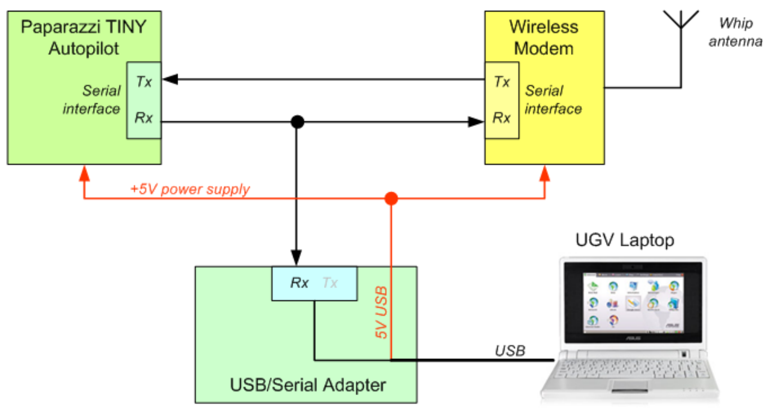

Figure 12: The UGV is equipped with a standard Paparazzi autopilot. Position and desired track are displayed on a ultraportable laptop. Connected to the main GCS, it is controlled in the same way as UAVs.

We chose to use a simulated UGV for the MAV08 mission. However, since this vehicle has to cooperate with the other agents, it has to be integrated in the complete system. The identified requirements are the following:

- The GCS operator must know the UGV position, speed and direction.
- The GCS operator must be able to give instructions to the UGV.
- The UGV operator must know its own location and be able to follow a given track.

From these constraints, we have designed a solution based on the Paparazzi autopilot, GCS and communications. We then get the integration in the system for free.

This hardware solution is displayed in figure 12: A standard Paparazzi board is connected to a modem and to a laptop handled by the UGV operator. The modem permits the bidirectional communication with the GCS operator. The laptop links allows the UGV operator, primo to know its own position, secundo to follow the track sent by the GCS operator. The Paparazzi board is powered by the laptop (no supplementary battery is required)

The UGV autopilot is loaded with a basic *flight plan* with a single target waypoint and a single simple `GoTo` instruction. The GCS operator controls the UGV simply by moving the target waypoint on the graphical interface. We have developed a basic GUI for the

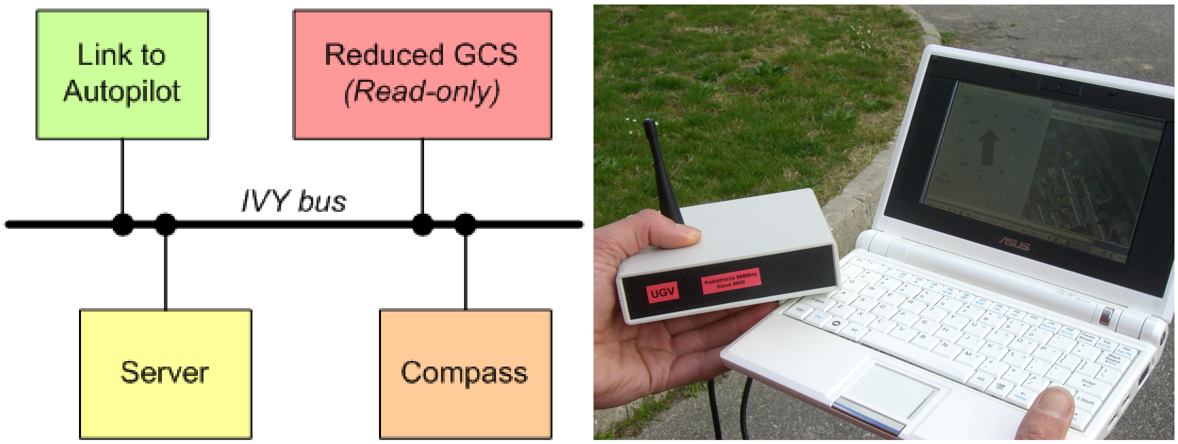

Figure 13: A new *compass* has been added to the Paparazzi software bus while the standard GCS graphical interface is used to display a map. It runs on a cheap ultraportable.

UGV operator, similar to the one found on a handheld GPS receiver, figuring a compass and displaying the distance and direction to the target waypoint. The UGV laptop also displays a reduced Paparazzi GCS with Google maps background.

Thanks to the distributed architecture of the Paparazzi GCS around the Ivy software bus, the integration of the new compass agent was trivial (figure 13). This has been installed on a ultraportable ASUS eeePC which is a light, cheap and convenient tool for this usage (figure 13).

7 Ground Control Station

The standard Paparazzi GCS has to be extended in order to fulfill the mission. We propose to organize the control around three screens and two operators, the controller and the planner :

1. The Paparazzi GUI: It is used to monitor the UAVs, the UGV and the commando positions. It provides an interface to control the navigation of the UAVs and the UGV.

2. The video screen: Displaying the streaming of one UAV, it allows the planner to inform the controller about interesting places and helps him to plan a track for the UGV and the commando.

3. The plan editor: Using the standard Google Earth software, it displays the Paparazzi vehicles positions and the waypoints. It allows the planner to edit directly on the map the obstacles and the planned path for the ground agents. Figure 14 is a screenshot of a simulated mission at the MAV08 site.

8 Conclusion

One of the challenges raised by the MAV08 mission consists in managing an heterogeneous multi agents fleet with a limited number of human operators to achieve complex tasks. We

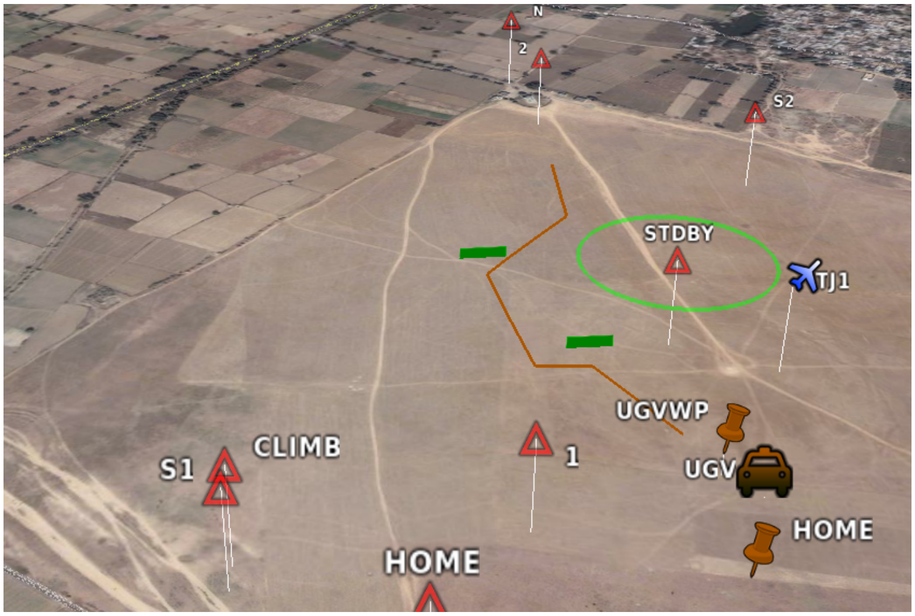

Figure 14: Google Earth, connected to the Paparazzi software bus, displays UAVs, UGVs and waypoints. It allows the planner to directly edit the obstacles, the mine places, the covered positions and the planned track.

have been able to extend the Paparazzi system architecture to fulfill those requirements, thus proving the validity of our initial conception.

We think that the introduction of the multi-agents aspect as well as the complexification of the goals present the UAV system designers with a very interesting challenge.

We are convinced that the wide spectrum of the difficulties arising from this new type of mission makes it mandatory to capitalize on existing systems and to tackle the issue as a team.

Following is a list of the hard points which we think are to be dealt with for a successful completion of the new type of mission.

- Avionics (sensor, estimation, control)
- Vehicle (aerodynamics, structure, propulsion)
- Communications (networking)
- User Interfaces (human factor, automatic planning)
- Payload (image processing)

Nevertheless, given the fact that no rotorcraft has ever been demonstrated to fulfill the autonomous navigation mission in the past editions of MAV competitions, the team regrets that the organizers of MAV08 have once again hardened the dimensional and mass constraints, thus preventing its main vehicle to enter the contest.

If the multi agents aspect was to be further pushed in a subsequent edition of the competition, the team foresees two hard points, namely the bandwidth availability associated with the required communications and the operator workload which exponentially increases with the number of agents.

References

[1] P. Brisset, A. Drouin, M. Gorraz, P.-S. Huard, and J. Tyler. The Paparazzi solution. In *MAV2006*, Sandestin, Florida, November 2006.

[2] P. Brisset, A. Drouin, M. Gorraz, and C. Ronfle-Nadaud. Intelligent surveillance with mavs, system design and navigation strategies. Technical report, ENAC, January 2007. R&D contract 1042-AM-01.

[3] Gautier Hattenberger, Rachid Aalmi, and Simon Lacroix. Hattenbergeriav2007. In *Intelligent Autonomous Vehicles*, 2007.

[4] M. Jonassen and J. Reuder. Determination of temperature and humidity profiles in the atmospheric boundary layer by fast ascending uavs. In *Geophysical Research Abstracts*, volume 10, 2008.

[5] Martin Mueller and Antoine Drouin. Paparazzi - the free autopilot. build your own uav. In *24th Chaos Communication Congress*, December 2007.

[6] B. Taylor, C. Bil, and S. Watkins. Horizon sensing attitude stabilisation: A VMC autopilot. In *18th International UAV Systems Conference*, Bristol, 2003.