2012 2nd International Conference on
Applied Robotics for the Power Industry (CARPI)
ETH Zurich, Switzerland. September 11-13, 2012

# Aerial Service Robotics: the AIRobots Perspective

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*Abstract*— **This paper presents the main vision and research activities of the ongoing European project AIRobots (Innovative Aerial Service Robot for Remote Inspection by Contact, www.airobots.eu). The goal of AIRobots is to develop a new generation of aerial service robots capable of supporting human beings in all those activities that require the ability to interact actively and safely with environments not constrained on ground but, indeed, airborne. Besides presenting the main ideas and the research activities within the three-year project, the paper shows the first technological outcomes obtained during the first year and a half of activity.**

## I. INTRODUCTION

Nowadays Unmanned Aerial Vehicles (UAVs) represent a research domain able to attract the interest of many fields of engineering, including, among others, control, aerospace and aeronautics, electronics, science of materials. As far as the area of control engineering is concerned, the research interest has been mainly focused on the development of control laws able to govern the vehicle, fully autonomously or with a partial human supervision, to fly through pre-specified paths ([1]), to synchronize with other vehicles to form coordinated fleets ([2]), to perform acrobatic maneuvers ([3]), to reconstruct unknown environments ([4]), and others. Indeed, the focus of the research attempts has been driven by domains of application where such vehicles are typically employed, such as surveillance and data acquisition in areas that are dangerous for human operators and inaccessible to ground vehicles. A number of civil ([5], [6]) as well military ([7]) applications show their use in these contexts. The ability of flying, in a fully or partially autonomous way, within possibly unstructured environments is the main reason why UAVs are also referred to as “flying robots” (see [8], Chapter 44), a terminology inspired by “ground robots”, the latter identifying vehicles moving autonomously on ground (see [8], Chapter 17).

An observed trend of the international research, however, shifts the attention to applicative domains where UAVs are not merely used as vehicles capable of flying autonomously, but rather as vehicles able to physically interact, in a non-destructive way, with the surrounding environment in order to accomplish real robotic tasks, such as manipulating objects, data acquisition by contact, sample picking, objects repairing and assembling, all that in air and not constrained on ground. Examples of this research trend can be found in [9], [10], [11], [12], [13]. Within this research scenario, the European project AIRobots (innovative aerial service robots for remote inspections by contact, www.airobots.eu), supported by the European Community within the seventh framework programme, is also placed. The goal of AIRobots is, in fact, to develop a new generation of service robots capable of supporting human beings in all those activities, which require the ability to interact actively and safely with environments not constrained on ground but, indeed, airborne. Given the new ability of these robots a number of application is possible. AIRobots concentrates on industrial inspection where the contact with the environment might be due to the cluttered and unstructured space but mainly because the robot actively get in contact with surfaces. The contact is essential for precise measures (e.g. ultrasonic). Studied scenarios are inspection of big boilers and high chimneys involved with energy production in power plants. The objective of this paper is precisely to present the main ideas of AIRobots and the research challenges addressed within the project.

## II. THE AIROBOTS PROJECT

### A. Main Objectives and Ideas

The goal of the project is to develop an aerial robotic vehicle able to interact with the human world in order to accomplish typical robotic tasks airborne rather than constrained on ground. The goal is to develop a new generation of service robots able to support human beings in all those activities requiring the ability to interact with environments that are un-accessible by ground robots. The step forward with respect to the ”classical” field of aerial robotics is to realize aerial vehicles not only able to fly autonomously but rather to accomplish a large variety of applications, such as inspection of buildings and large infrastructures, sample picking, aerial remote manipulation, precise or long lasting measures, etc.

The starting point is an aerial platform whose aeromechanical configuration allows the vehicle to interact with the environment in a non-destructive way and to hover close to operating points. Rotary-wing aerial vehicles with shrouded propellers represent the basic airframes that are then equipped with appropriate robotic end-effectors and

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This work was supported by the European project AIRobots ( Innovative Aerial Service Robots for Remote inspections by contact, ICT 248669) supported by the European Community under the 7th Framework Programme.

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978-1-4673-4587-3/12/$31.00 ©2012 IEEE

sensors in order to transform the aerial platform into an aerial service robot, a system able to fly and to achieve robotic tasks.

The unmanned aerial vehicle, equipped with appropriate sensing devices and end effectors, is remotely controlled by means of haptic devices, which allow the operator to remotely supervise the task. Advanced automatic control algorithms are developed to govern the aerial platform. In this respect, the focus is both on the development of completely unmanned control governors and on the study of control architectures relying upon a cooperative and adaptive interaction between the on-board automatic control and the remote operator. The latter is assumed to be a specialist in the specific application rather than a pilot. In this scenario, integrated design schemes between the remote operator and on-board automatic control are studied according to schemes, which are not fixed a priory but modified according to evolving needs and objective conditions. In this way a real co-operation between the robot and the human is established: this is achieved by employing the state of the art in term of virtual reality and sensing technology, such as augmented reality and haptic devices, to allow the operator to be aware of the tasks that are accomplished and subsequently to guide the robot in the actions to be achieved. Ideally the aerial service robot represents a ”flying hand” that allows the human to act as if he/she were directly on the site, allowing a remarkable level of interaction between the human and the environment.

### B. Driving Industrial Applications

The spin-off business ALSTOM Inspection Robotics (www.inspection-robotics.com), jointly founded by ALSTOM and ETH Zurich, is the industrial partner of AIRobots. ALSTOM Inspection Robotics plays the role of end-user of the outcomes of the project and it brings to the consortium attention industrial needs and expectations.

Maintenance industry offers facility services to a large set of customers working in business fields such as power production, oil and gas transportation and processing. Within the power industry very large structures such as boilers (80 to 100 m in height), cooling systems (50 to 150 m in height) or environmental filter systems (10 to 30 m in height) have to be inspected. Nowadays, during repair and inspection sessions of these facilities, different components have to be shut down at least partially to avoid damage of inspection equipment and injuries of personnel. Furthermore, scaffolding and climbing utilities have to be installed within and around these structures in order to perform first visual and later detailed inspections using non-destructive testing methods (eddy current, ultrasonic, electromagnetic acoustic, radiographic technology, etc.). The plant production and processing capabilities are therefore significantly stalled for the duration of servicing. As the achievable profit per year is also related to the outage duration an industrial facility has to undergo during inspections, plant managers are likely to choose a service provider, which can guarantee short but reliable and efficient maintenance.

In this scenario, the benefits that an aerial service robots of the kind envisioned in AIRobots can introduce are enormous. The inspector has the possibility to perform a first visual inspection of industrial plants without any scaffolding or climbing utilities. Furthermore, more detailed inspection of the system can be achieved by docking directly to the structure for cleaning and non-destructive evaluation.

A catalogue of possible applications has been established in collaboration with Alstom Inspection Robotics. Some of the envisioned industrial scenarios are inspection of power plant structures, inspection of structures within oil and gas industry such as large scaled chimneys, flare systems, refining columns, pipelines and pipewebs, tanks, sequential payload lifting with a docked aerial vehicle, deployment and collection of sensor networks, inspection of civil structures such as bridges, cleaning of infrastructures, and others.

### C. Research Challenges

The development of the aerial platform envisioned in AIRobots hides many research challenges that are now faced in the project. The most relevant issues are presented in the following paragraphs.

*1) Aerial service robotics best practice and performance measures:* The first research attempt has been to define a series of performance measures both for general aerial service robotic applications and for the robotic inspections scenarios of interest for the end-user. In this respect, the system has to be designed to be robust, flexible, adaptable, portable, safe, intelligent, effective and economic in achieving the desired operations. Robust and flexible in the accomplishment of the task, which is generally obtained in an unstructured and potentially cluttered environment; adaptable in the interaction with the environment and the humans; portable in order to be carried easily and safely in the inspected areas; safe while flying and while performing the desired task close to humans and infrastructures; intelligent enough to be largely autonomous in achieving the applications goals; effective in the performance and economic due to the expected reduction of human intervention and mission duration.

*2) System design and control strategies for aerial robots physically interacting with the human world:* The design of the entire system addressing the interaction with the environment represents one of the main contributions of this project to the field of aerial robotics and control systems design. The features characterizing the AIRobots aerial platform require the design of innovative control strategies and advanced technologies integration. In this respect, both theoretical and technological issues are dealt within the project. From theoretical viewpoint, the objective is the design of innovative control algorithms showing formal proof of robustness with respect to uncertainties affecting both the model of the environment and the dynamical model of the robot. From a technological viewpoint, new methods in vehicle design and integration have to be established as well. All acting and sensing components need to be integrated into the vehicle in a way that they do not substantially influence its dynamics and yet provide full functionality during flight, during aerial manipulations and when docked to various structures. Currently, UAV system design has largely focused on integrating mechanics and electronics to achieve autonomous flight. Adding system components, which physically interact with the vehicles environment is another challenge that is addressed in this project.

*3) New contribution to human-robot interaction and communication:* One of the objectives of AIRobots is to develop an advanced human-robot interface. Inspection and, more generally, service robotics in fact often require an important role played by the humans in order to evaluate the information collected by the sensors and to take decisions accordingly. This fact suggests the design of an architecture, which allows a human operator to concentrate only on high level tasks, hiding the complexity behind the accomplishment of the task itself, which is instead addressed by the robot. In this way a real co-operation between the robot and the human is established: this is achieved by employing the state of the art in term of virtual reality and sensing technology, such as augmented reality and haptic devices. Ideally the aerial service robot represents a ”flying hand” that allows the human to act as if he/she were directly on the site. This fact necessarily requires highly efficient communication architecture and suitable protocols that are currently under study.

*4) Aerial navigation in loosely structured and densely cluttered environments:* During the inspection of the desired infrastructure the robot is required to fly in an environment that is uncertain and only partially structured because, usually, no reliable layouts and drawings of the surroundings are available. In this scenario the robot has to be supported by the human operator only for the high level inspection tasks while it has to be autonomous for what concerns the stabilization, both in contact with the objects or not, and navigation.

To support these features, advanced cognitive capabilities are required, and in particular the role played by vision is of paramount importance. In fact standard navigation techniques for aerial systems rely upon the GPS measures, which precision is often compromised by the fact that the vehicle might operate indoor.

Moreover the system is required to understand actively the characteristics of the environment in order to detect autonomously potential obstacles to be avoided, prohibited areas, in which the flight is potentially hazardous or instead areas that can be suitable for landing or docking in order to better execute high level operations. These characteristics require an advanced awareness of the operational environment, which is obtained through the development of suitable algorithms for advanced sensing and adaptive environmental modelling.

### D. Technologies

The operational scenarios that characterize aerial service robotics suggest the employment of aerial platforms with a high level of maneuverability together with the ability to safely interact with the human world, including both infrastructures and humans, without the risk of damages or accidental crashes. This fact justifies why AIRobots focused on shrouded propellers rotorcraft systems as aerial platforms. As better explained in Section III, ducted-fan and coaxial rotor UAVs have been developed within the project.

The aerial platforms integrates different sensors that are used for navigation, like inertial sensors and magnetometers, and also vision and force sensors that are mounted in additional moving arms placed on the device. Installation of task specific sensors such as non-destructive testing equipment and the interaction thereof with the aerial service robot is also considered in a modular fashion.

For the communication part, the system totally rely on the already existing technologies. Compared to state of the art UAV systems a higher data exchange is expected between an airborne service robot and its ground control unit. Besides data containing the vehicles current and desired state, information collected by the task specific sensors will have to be transmitted wirelessly as well. Most recent wireless communication technologies are exploited (e.g. UWB, 802.11 n).

## III. FIRST PROTOTYPES

During the first year of AIRobots two aerial prototypes have been developed. They represent preliminary platforms that, suitable developed, will constitute the aerial service robot envisioned in the project. Two different mechanical principles underly the two prototypes as explained in the following two subsections.

### A. Ducted-Fan UAV

The first prototype relies upon a ducted-fan aeromechanical principle [14]. Ducted-fan UAVs showed remarkable features in terms of simple mechanical design, robustness and reliability. In fact, the mechanical layout of a ducted-fan aircraft is essentially characterized by three main subsystems. The first one is represented by a fixed-pitch rotor. This subsystem has the fundamental role of generating the main thrust that is necessary to actuate the overall dynamics and counteract for the gravity force. The second subsystem is composed of a set of actuated flaps, namely profiled moving surfaces, that are positioned below the propeller in order to properly deviate its air flow. The flaps are governed to achieve full controllability of the attitude of the vehicle, playing the role that the tail rotor and the cyclic pitches have in classical helicopters. The third subsystem is given by the shroud and the fuselage that contains all the avionics and application dependent hardware.

The first AIRobots prototype constructed according to this principle is shown in Figure 1. As clear from the picture, the airframe is characterized by 8 landing gear having multiple roles. They allow the vehicle to land safely by protecting the control vanes from undesired contacts with objects. Furthermore, they allow the UAV to detect contacts with the surrounding environment, both with horizontal (e.g. the ground) and vertical surfaces (e.g. the area to be inspected or an obstacle). This feature is obtained by designing each element in a way that it is able to pivot and then to activate

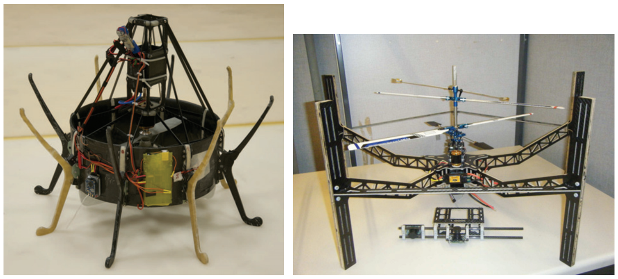

Fig. 1. The Ducted-Fan (left) and coaxial (right) AIRobots first prototypes.

a contact sensor. Additional Hw and avionics details can be found in Table I.

TABLE I

DUCTED-FAN AIROBOTS FIRST PROTOTYPE: FEATURES AND HW COMPONENTS.

| | |
|---|---|
| Weight, payload, diameter | 1500 g, 300 g, 320 mm |
| Airframe Mechanics | APC Electric 11x55E propeller,<br>custom carbon / fiberglass airframe |
| Servo Motors | 8 HG-D202HB |
| BLDC-Motor | 1 x Scorpion SII 3020<br>KV 1100, 840 W cont. power, 166 g |
| LiPo Batteries | 2 x Topfuel,<br>5S 3600 mAh Lipo, 200 g |
| Flight Time | approx. 7 minutes (with full payload) |
| MCU | Arduino MEGA, 18 MHz |
| Host communication | XBee Pro 900Mhz |

## B. *Coaxial Rotor UAV*

The second prototypes relies upon a coaxial rotor principle, a mechanical solution that already showed to be successful in the realization of miniature UAVs [15]. Inherent passive attitude stability is one of the utmost notable attributes of this class of aircrafts. This allows the system to self stabilize even after collisions with an obstacle.

The design of a coaxial rotorcraft is usually governed by a coaxial rotor configuration with one fixed-pitch and one cyclic-pitch rotor driven by two motors. Horizontal movement of the vehicle is realized using control over the main rotors cyclic-pitch, tilting the rotorcrafts thrust vector in a desired direction. Using the vehicles differential drag moment between upper and lower rotor allows simple yaw control. Depending on the design, a stabilization bar or special rotor blades can be integrated into the rotor head to enhance the passive stability of the vehicle even more.

The first prototype realized according to this principle is shown in figure 1. As shown in the figure the prototype is characterized by a pentagon shaped rigid airframe that provides flat interfaces, with which the vehicle can dock to vertical structures. The structure consists of several milled carbon and carbon - balsa wood components. All the processing devices and a mounting rig for cameras and range sensors are contained in a small box incorporating easily detachable from the structure. The current design provides space for a low-level autopilot board and an Ascending Technologies Atom computer [16]. In Table II additional details on Hardware and avionics components used for the first prototypes are shown.

TABLE II

COAXIAL ROTOR AIROBOTS FIRST PROTOTYPE: FEATURES AND HW COMPONENTS.

| | |
|---|---|
| Weight, payload, diameter | 1450 g, 300 g, 840 mm |
| Airframe Mechanics | Walkera Lama 3, 620 mm rotor,<br>custom carbon fiber structure |
| Servo Motors | 3 x WK-7.6-6 |
| BLDC-Motor | 1 x Scorpion HK-II 2221-6<br>KV 4400, 525 W cont. power, 81 g |
| LiPo Batteries | 1 x Thunder Power Pro Lite V2,<br>3S 5000 mAh LiPo, 367 g |
| Flight Time | approx. 7 minutes (with full payload) |
| MCU | ST32F103VET ARM Cortex-M3,72 MHz |
| Host communic. | XBee Pro 2.4GHz and 1 USB 2.0 |

## C. *Aerial Robotic Manipulator*

Preliminary considerations and designs have been done regarding the manipulator to be installed on the aerial platform. According to the inputs of the industrial end-user, the robotic arm should move NDT sensors along a predefined line in order to take measurements at preferred locations, as decided by the human operator. Overall, the manipulator should consists of four degrees of freedom since the necessary workspace has been estimated to be of $5 \times 5 \times 5$ cm in three translational directions and, to realize the inspection task, a roll motion is also required. The manipulator should be lightweight and the actuators used should be high in torque, speed and low in weight.

In order to accomplish the requirements, a manipulator with a parallel structure has been selected. The advantage of using a parallel manipulator is that it reduces the inertia that the actuators have to move and the gravity torque the manipulator has to overcome. The actuators can be located in the same plane close to the center of mass of the UAV, creating a lower induced torque. The parallel structure also makes it easier to divide impact force over multiple actuators, giving lower requirements in their necessary strength.

The kinematic parallel structure of the Delta robot has been chosen due to its lightweight and due to the fact that is can be used for high speed tasks. In particular, it is actuated by means of revolute motors, attached to the base and that can move the end effector in three translational degrees of freedom. The Delta is endowed by a fourth degree of freedom, i.e. an adjustable length Cardan spline shaft that can compensate for the vehicle roll and can be used for the cleaning tasks.

The Delta manipulator can be mounted horizontally with respect to the vehicle so to improve the compactness and the functionality of the complete system. If none of the motors is mounted perpendicularly to the gravity axis, the stresses induced by gravity and the demands to the motors can be reduced.

Preliminary designs of the AIRobots manipulator are shown in Figure 2.

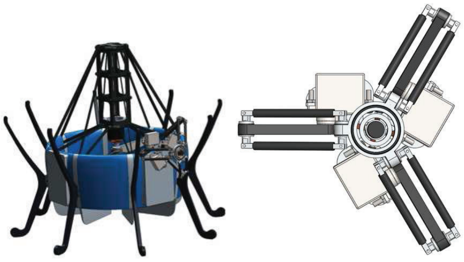

Fig. 2. The AIRobots Manipulator: preliminary designs.

## IV. AIROBOTS FLIGHT ARENA AND FLIGHT TESTS

Flight tests of the two prototypes have been carried out. As precise attitude and position reconstruction algorithms are yet to be obtained (they are planned later in the timetable of the project), a flight arena based on a commercial real-time motion visual tracking system have been set up as better described in next subsection.

### A. *AIRobots flight arena and control architecture*

Figure 3 shows the schematic diagram of the overall AIRobots control architecture set up for the first flight tests. The main components sketched in the figure are presented below.

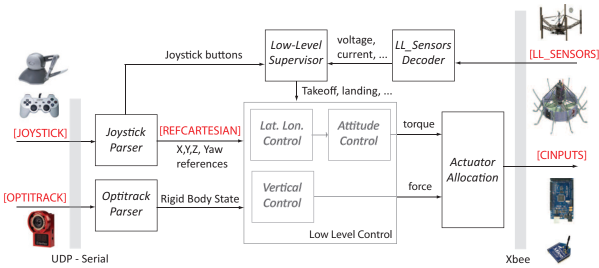

Fig. 3. The AIRobots Control Loop Architecture.

- Ground PC: It is the main computational Hw used during the first flight tests. It is used as main interface between the human operator and the UAV and to coordinate the actions of the different peripheral systems that are connected through different protocols in the communication channel. In the first flight tests both the low level and high level controllers were running on the ground PC. Off-the-shelf software packages available on the ground control station have been used in order to simultaneously develop and validate the control algorithms, by taking advantage of the software-in-the-loop capabilities.
- Optitrack System: it is a commercial real-time motion tracking system based upon infrared cameras. In combination with the software package ”Tracking Tools”, it is able to provide the attitude and the position of a rigid body once a set of round highly reflecting markers have been attached to it. For the first flight tests, a flight arena based upon the Optitrack System has been set-up by disposing 12 different cameras in order to obtain a tracking volume of approximately $4 \times 4 \times 2$ meters (flight arena). Each prototypes tested in the flight arena has been equipped with five reflective markers. Then, by using the ”Tracking Tools” software API (Application Program Interfaces), an open source library has been developed to stream over network or serial communication the position and the orientation of the UAV within the flight arena at a rate up to 100Hz.
- Joystick: It is a simple human/robot interaction interface, through which the human pilot can interact with the UAV system. During the first flight tests a standard joystick was used to interact with the low level controller, to start the UAV system, take off, landing, controller switch, velocity reference generation and others.
- Haptic Device: it is a device able to return force feedback to the pilot. The haptic interface can provide information about the current state of the UAV and about its environment. The haptic device used during the first flight tests was a Phantom Omni, constructed by SensAble [17]. It has 3 DOF force feedback and 6 DOF position sensing. It is equipped with a IEEE-1394a FireWire port interface.
- Communication devices: each component must rely on a solid, fast and reliable communication infrastructure. A wireless communication, based on UDP and Zigbee protocols, as well as standard cable RS232 protocol were used during the first flight tests. Data were streamed to and from each components at different rates according to the particular needs.

### B. *Experimental results*

Several flight tests were conducted by taking advantage of the flexible and reliable control architecture previously described. Videos of some flight tests can be retrieved from the project website (www.airobots.eu) in the download section.

In this part we briefly present results obtained by testing telemanipulation algorithms based on the theory developed in [18]. The implemented algorithm uses the concept of virtual slave UAV, which has an equivalent dynamics as the real UAV except that it flies in a gravity-less and frictionless environment. This algorithm is based on port-based approach, where components of the dynamic system interact with others through power ports.

We present the results obtained by testing the telemanipulation algorithm on the ducted fan UAV. In this test, only the vertical axis was telemanipulated while the low level controller controls the other DOFs. In this experiment, a switch of controller was carried out between the autonomous low level controller and the high-level telemanipulation control loop.

Figure 4 shows the position of the master device and the velocities of both the actual and the virtual vehicle, all of them along the vertical axis only. It can be observed that the desired velocity of the actual vehicle derived from the velocity of the virtual vehicle, which, in turn, was commanded by the position of the master device, were tracked with a certain lag. At the start of the telemanipulation, the tracking performance was low because of the difference between the initial velocity of the actual vehicle and the virtual vehicle. Specifically, when the telemanipulation controller was switched on, the initial velocity of the virtual vehicle was zero whereas the actual vehicle had a non zero velocity, which characterized the autonomous flight. However, later on, the tracking performance got improved as desired. The force feedback shown in Figure 5 rendered the actual environment of the UAV, based on the velocity of the actual vehicle in reference to the velocity of the virtual vehicle. It should be noted that the velocity trajectory of the actual vehicle was not so smooth as desired due to presence of noise, which emanated from various disturbance sources.

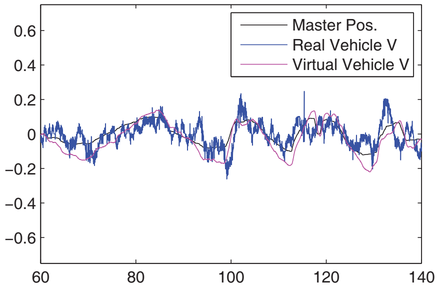

Fig. 4. Preliminary telemanipulation experiments: master position, real and virtual vehicle position.

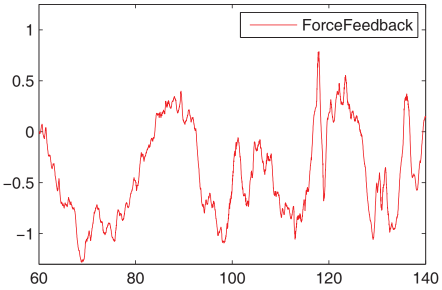

Fig. 5. Preliminary telemanipulation experiments: Force feedback.

## V. CONCLUSIONS AND FUTURE WORKS

In this article we presented the main ideas and first results of the ongoing European project AIRobots. The results presented in this paper are just preliminary achievements and several steps forward are expected in the near future. The AIRobots research attempts are now directed towards multiple objectives. One of the first crucial objectives is to develop robust control laws and control architectures that are effective in free flight and in presence of contact with the environment. In this respect the attempts are focused on modeling the UAV in the multiple operative scenarios as hybrid automata and on the development of robust nonlinear control laws. Then, several operative modes must be managed. A crucial point is to switch these control laws according to the actual operative mode. At this aim, supervisory control based architectures are under explorations in order to obtain modular and flexible design and implementation. Moreover, the robotic arm to be installed in the aerial platforms is now under construction. In this context, design principles are motivated by specific manipulation objectives and benchmarking scenarios that have been fixed in the project according to the industrial inputs, namely boiler and chimneyinspection in power plants. Finally, a noteworthy research activity is focused on the development of sensor fusion algorithms and navigation strategies.

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