

The AIRobots (Innovative aerial service robots for remote inspections by contact) Project

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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 to support 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 project, the paper shows the first technological outcomes obtained during the first year of activity.

1 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 [8], to synchronize with other vehicles to form coordinated fleets [14], to perform acrobatic maneuvers [7], to reconstruct unknown environments [3], 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 [10,4] as well military [5] 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 [17], Chapter 44), a terminology inspired by “ground robots”, the latter identifying vehicles moving autonomously on ground (see [17], Chapter 17).

[†] The European project AIRobots (ICT 248669) is supported by the European Community under the 7th Framework Programme.

An observed trend of the international research, however, shifts the attention to applicative domains where UAVs are not merely used as vehicles capable to fly 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 [1], [6], [11], [13], [12]. 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 to support human beings in all those activities which require the ability to interact actively and safely with environments not constrained on ground but, indeed, airborne. The objective of this paper is precisely to present the main ideas of AIRobots and the research challenges addressed within the project.

2 The AIRobots Project

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

From a graphical viewpoint the aerial service robot inspiring the AIRobots activities is sketched in Figure 1. 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 priori 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 she were directly on the site, allowing a remarkable level of interaction between the human and the environment.



Fig. 1. The AIRobots vision.

2.2 Driving Industrial Applications

The spin-off business ALSTOM Inspection Robotics, jointly founded by ALSTOM and ETH Zurich, is the industrial partner of AIRobots. ALSTOM 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 (Figure 2). 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 have 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.



Fig. 2. Some industrial environments inspiring AIRobots.

2.3 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.

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.

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 with in 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. In fact classical control strategies synthesized without explicitly considering the interaction cannot deal with the situations in which an aerial service robot may incur due to the remarkably different dynamics underlying the system behavior in free flight and in presence of contact with the environment. Hybrid Automata, nonlinear control theory, path following strategies, discrete event system theory, are some of the theoretical tools that are under investigation to succeed in the above goal.

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.

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 she were directly on the site.

To obtain this objective, the project is expected to make significant contribution in this research area also from a methodological point of view. The algorithms to be developed are in fact expected to take into account for the aerial robot uncertain and underactuated dynamics in the formal analysis of the human-robot loop.

Compared to current state of the art UAV systems which mainly transmit image data from analog cameras and possibly GPS and IMU information to a ground control unit, a significantly higher communication load is expected for aerial service robots. High-quality digital images, force and tactile information, data collected by non-destructive testing equipment, as well as others navigation information need to be transmitted to the ground control unit. This fact necessarily requires highly efficient communication architecture and suitable protocols that are currently under study.

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.

2.4 Technologies

The operational scenarios that characterize aerial service robotics suggest the employment of aerial platforms with a high level of manoeuvrability 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 3, 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).

3 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.

3.1 Ducted-Fan UAV

The first prototype relies upon a ducted-fan aero-mechanical principle [9]. 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 3. 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 a contact sensor. Additional Hw and avionics details can be found in Table 1.

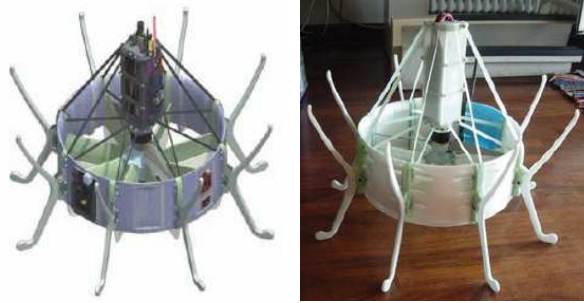


Fig. 3. The Ducted-Fan AIRobots first prototype.

Table 1. Ducted-Fan AIRobots first prototype: features and Hw components.

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

3.2 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 4. 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 com-

ponents. 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 [2]. In Table 2 additional details on Hardware and avionics components used for the first prototypes are shown.



Fig. 4. The coaxial rotor AIRobots first prototype.

Table 2. 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, custom carbon fiber structure
Servo Motors	3 x WK-7.6-6
BLDC-Motor	1 x Scorpion HK-II 2221-6 KV 4400, 525 W cont. power, 81 g
LiPo Batteries	1 x Thunder Power Pro Lite V2, 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

3.3 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 consist 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 it 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 5



Fig. 5. The AIRobots Manipulator: preliminary designs.

4 Vision Based Navigation System

A new vision-based obstacle avoidance technique for indoor navigation has been presented for MAVs applications. The planned vehicle trajectory is modified according to a repulsive force field generating on the basis of the *Absolute Depth Map* ADM of the surrounding environment computed online using the *Optical Flow* (OF). A single onboard omnidirectional camera is assumed to be available and calibrated. In particular, a new formulation of a closed-form solution for the absolute-scale velocity estimation problem, which are required for the ADM estimation, is presented. Starting from the solution proposed in [19], where in addition to inertial measurements the correspondences of an image feature between three image frames

are required, a new compact formulation is adopted, also providing a generalization to the case of multiple visual station and image features. Once estimated the vehicle velocity, the distance of each feature observed in the scene and associated to an OF element can be evaluated and collected together with the corresponding optical rays. The result is a temporary environmental map, namely (Absolute) Depth Map, which can be fully exploited for lateral obstacle avoidance during the navigation.

4.1 Optical flow computation

The Optical Flow can be defined as the motion of a particular image feature between two consecutive camera frames. It is usually expressed in units of angular velocity, i.e. radians per second or degrees per second. It is known that the motion of obstacles observed in an image sequence depends on the distance of the object with respect to the camera, and thus the OF can be profitably exploited estimating the distances of surrounding obstacles. For this reason, OF is often employed in non-stereo visual based obstacle avoidance. However, the estimation of the absolute distance of an obstacle requires the knowledge of the vehicle translational velocity, which is evaluated with a new proposed closed-form solution based on image correspondences and IMU measurements.

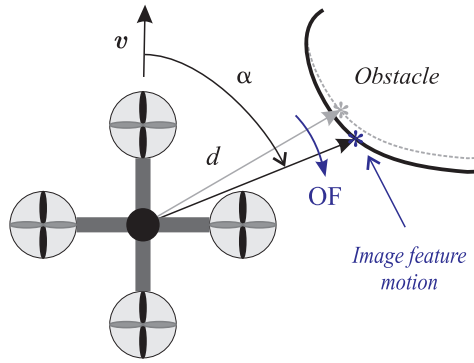


Fig. 6. Optical flow during a translational motion.

In the case of a purely translational motion of the vehicle, assuming that all the objects in the scene are stationary, the translational Optical Flow ω_T of an image feature of an observed object depends on the relative velocity between the camera and the object itself v and on the angle between the direction of motion and the observed feature α , as shown in Fig. 6, with the following rule:

$$d = \frac{\|v\|}{\omega_T} \sin(\alpha), \quad (1)$$

where d is the distance between the object feature and the camera, and the computation of the ω_T component is performed applying a compensation of the rotational

effect. Therefore, if the vehicle velocity is available, the distance and so the position of the observed obstacle can be estimated. However, in a general case, the motion of the vehicle is composed of a translational part and of a rotational part, namely ω_T and ω_R , each of which produces a rate of the OF.

4.2 Dynamic region of interest

The OF computation requires, as explained before, an image feature extraction algorithm and a matching algorithm, that can be computational expensive for the typical processor units available on a MAV. In the case of an omnidirectional camera, the adoption of region-of-interest (RoI) for the image elaboration processes may provide a large benefit in terms of computational requirement, while the main drawback is that the systems becomes “blind” outside the RoI. However, the adoption of a dynamic RoI that is smartly adapted online to the real environmental and navigation conditions may reduce the risk of an unpredicted impact. Observing that, due to the inertial of the system, an obstacle can be avoided only if it is detected as early as possible with respect to the vehicle velocity, the solution proposed is to adopt a RoI that “looks” more forward as the vehicle is moving quickly.

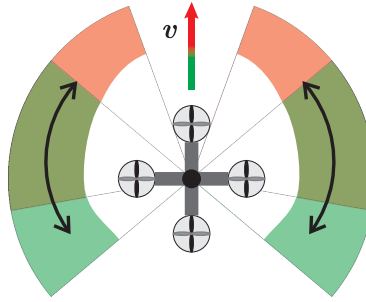


Fig. 7. Dynamic region of interest.

In the proposed approach, the RoI is composed of two regions, namely left and right RoI, which are symmetric with respect to the direction of motion. Both regions have a fixed total extension around the vertical axis, but they are rotated in view of an angular offset θ_{of} with respect to the navigation velocity (see Fig. 7). Notice that the forward region in the direction of motion is discarded due to numerical inconsistency of the OF along this direction. Also the vertical extension of the RoI is shaped in view of the offset, symmetrically reducing its range with the increase of θ_{of} . This behavior is required for omnidirectional cameras, that compresses objects extension in the image as far as they are along the direction of motion.

4.3 Obstacle avoidance and cruise control

The safety of the vehicle during navigation within an indoor environment depends on its capability to avoid unplanned lateral obstacles. With respect to the dynamic

left and right RoI presented above and for each available ADM, the distances of the vehicle with respect to the left and right side of the surrounding environment are computed. Then, the vectors of distances from the left and the right sides of the navigation direction are composed using as sorting criteria the position along the motion direction. Finally the minimum of each distance vector is found and a local spacial average is applied resulting in the minimum mean lateral distances. Hence, the course correction is obtained through a PD controller with respect to a suitable safety lateral distance.

The proposed navigation control considers a *cruise velocity* of the vehicle along the direction of motion in the case of free space, i.e. the maxim velocity that the vehicle could reach. However, for the safety of the vehicle, when an obstacle is detected or when the dimension of the space that is free for the motion is reduced, i.e. the minimum distance with respect to the environment becomes less than a safety distance, a reduction of the navigation velocity is commanded. On the other hand, to avoid obstacles without penalizing excessively the velocity also the motion direction has to be locally corrected. For this purpose, a correction of the planned motion direction is achieved taking into account the presence of lateral obstacles. To reduce noise effects, the obstacle position vectors, which are computed using the ADM, are elaborated performing a filtering in the time and a spatial mean of a certain number of measurements.

4.4 Simulation results

The performance of the proposed ADM construction algorithm and of the navigation control has been tested with simulations using the MATLAB/Simulink environment.

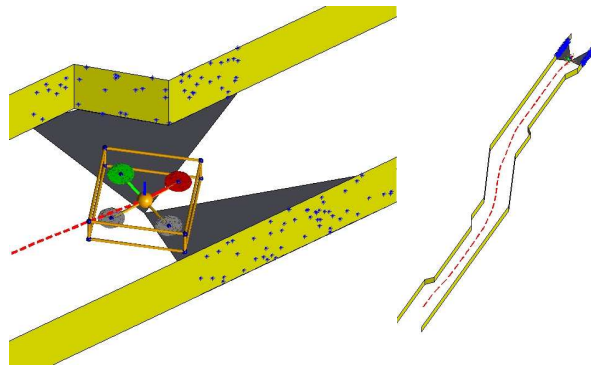


Fig. 8. Simulated indoor environment.

In Fig. 8 a sketch of the employed simulator is showed. The considered indoor environment is similar to a corridor of a total length of 25 m and with a longitudinal shape that changes along the path. In particular the width of the free navigable space varies several times from 2 to 1 m, and vice versa, also changing in its middle

line position. A random occurrence of image features has been considered on both sides of the environment. Gaussian white noise has been added on image and IMU measurements.

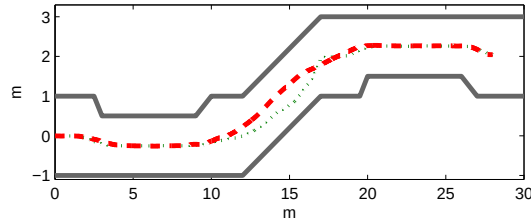


Fig. 9. Course correction during navigation, with (red dashed line) and without (green dotted line) the motion direction correction, in view of the detected obstacles and of the path deviations (gray lines).

The course correction achieved during the navigation is shown in Fig. 9, where also the shape of the environment has been reported. The vehicle starts from the home position that is near to the left side of the environment. The path followed by the vehicle is almost centered in the middle of the available free space left to the vehicle as desired.

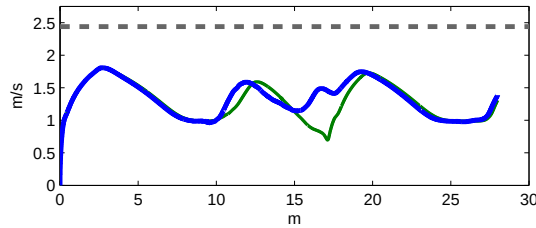


Fig. 10. Navigation velocity modified in view of the detected obstacles and of the current free space, with (blue line) and without (green line) the motion direction correction, and adopted v_c (gray dashed line).

In Fig. 10 the navigation velocity modified in view of the detected obstacles and of the available free space is shown. As expected, the velocity is reduced when the vehicle is near to obstacles or in a small area. In turn, the velocity in the narrow part of the environment is decreased, depending on the chosen parameters, to about 1 m/s. When the available free space increases also the velocity increases towards the maximum value.

Finally, in Fig. 11 the motion direction correction which is applied during the navigation is shown. Clearly, the presence of lateral obstacles and an unexpected corridor deviation require suitable corrections to keep the vehicle in the middle of

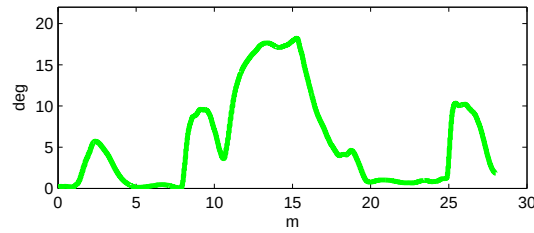


Fig. 11. Motion direction correction during navigation in view of the detected obstacles and of the path deviations.

the available space without reducing drastically the velocity. Figures 9 and Figure 10 show the improvements provided by the adoption of the proposed approach.

5 Visual Motion Estimation Algorithm

The estimation of the 3D absolute motion of a UAV is an open issue in the research community. In the outdoor navigation this problem is solved adopting suitable sensor fusion techniques for the GPS data with the IMU data, both available with very cheap solutions. Indoor scenarios are more complex due to the absence of the GPS signal and to the limited volume available for the vehicle maneuvers. In this case, the adoption of visual (and/or laser) information are crucial to estimate the absolute motion of the vehicle with respect to an absolute (e.g. base station) or a relative (target surface) reference frame and to reconstruct/update a 3D map of the environment.

It is well known that in the case of a single camera system observing an unknown environment the linear components of the motion can be estimated up to a scale factor. Some recent studies propose solution estimating the scale factor in the case of mobile robots under some specific conditions (e.g. nonholonomic constraint). However, an extension of these methods to the case of UAVs is not yet available. On the other hand, the adoption of a more complex (in the sense of computational and payload costs) stereo visual system allows an accurate and more robust estimation of the vehicle motion also when the scene is completely unknown.

One of the main issues related to the 3D motion estimation from visual data is the evaluation of robust matches between consecutive pairs of images avoiding outliers (i.e. false matches), that may produce a noisy estimation in the short term and large errors in the long term. Moreover, the robustness of the stereo matches strongly depends on the choice of the image descriptors, which may have a strong impact on the computational cost, and on the statistical processes adopted to discard the outliers.

The 3D motion estimation algorithm tested during the IW1 is based on the SURF image descriptors, which currently represent a good compromise between the robustness and the computational cost of the solution. Further solutions based on more recent descriptors as BRIEF will be also provided during the next period.

In order to detect robust points suitable for a 3D localization based on triangulation, first a robust stereo matching starting from two (synchronized) images, which are provided by a stereo camera system, is required. The stereo robust-matches algorithm (in the image plane) can be summarized, for a given pair of images, as follows:

1. detect keypoints and relative descriptors in each image;
2. match features between images;
3. reject outliers in order to minimize the transformation between keypoints in the image plane.

The first step is achieved by means of *Speeded-Up Robust Features* (SURFs). SURF descriptors are invariant to common image transformations including image rotation, scale changes, illumination changes, and small change in viewpoint. The descriptors computed on keypoints extracted from two images of the target panel employed during the IW1 are shown in Fig. 12.

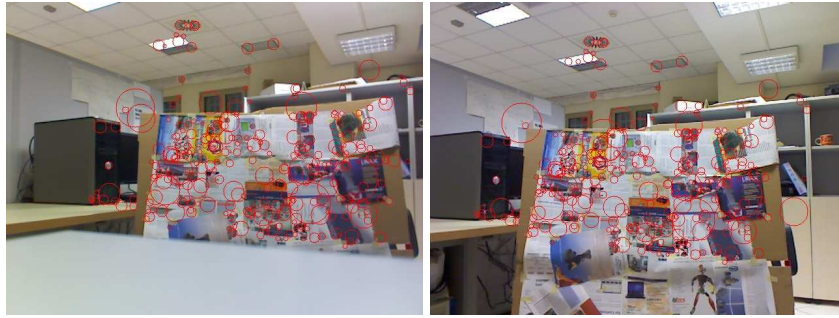


Fig. 12. SURF descriptors extracted from images of the target panel employed during the IW1.

In the second step of the tested robust matches algorithm, descriptors between two images are paired by means a k -Nearest Neighbor (k -NN) algorithm. The last step of the algorithm tries to compute a robust point transformation given by the essential matrix E between 2D keypoints y of the first image and 2D keypoints of the second image corresponding to the same 3D point of the scene $y^T E y = 0$ by means of the *Random Sample Consensus* (RANSAC) algorithm. In particular this last part consists in

- randomly selecting 8 candidate points,
- estimating E transformation by means of the eight-point algorithm,
- computing how many keypoints fit the model E within a given tolerance,
- repeat the first three steps until a desired tolerance is reached.

With this method robust matches between keypoints (in the image plane) can be detected and an evaluation of the shift between two different positions of the aerial



Fig. 13. Final shift direction computed on robust matched keypoints of images of Fig. 12.

vehicle is provided. Figure 13 shows the final shift computed on robust matched keypoints of the images shown in Fig. 12.

Once image-space robust matches are available, a further statistical iterative test, which has been proposed and tested by UNINA during the IW1, is applied in the Cartesian-space finding the outliers that are undetectable in the image space. Using a triangulation method, the 3D points corresponding to each robust match in the image space are evaluated. For each Cartesian point, the distance with respect to the matched point of the reference images pair is evaluated. Then, within an iterative process, the standard deviation of the distances, referred to the current set of robust matches, is evaluated. All those points with a distance greater than 3 times the standard deviation are considered outliers and are removed from the set of the robust matches. Notice that it has been assumed a Gaussian distribution as the probability of occurrence of the residual outliers. This iterative process stops when no more outliers are found or when the standard deviation falls under a suitable threshold. Typically, one to three iterations are sufficient.

When a set of robust matches is available, the 3D motion of the vehicle is evaluated solving a known *absolute orientation* problem.

6 AIRobots Flight Arena and First Flight Tests

First 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.

6.1 AIRobots flight arena and control architecture

Figure 14 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.

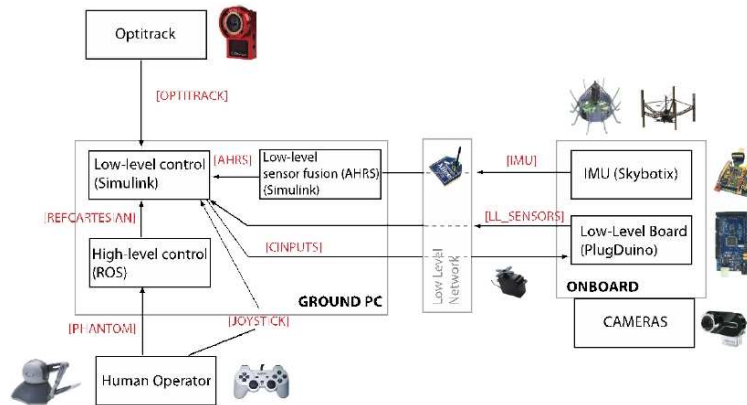


Fig. 14. The AIRobots Control Loop Architecture.

- **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 [16]. 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.

6.2 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.

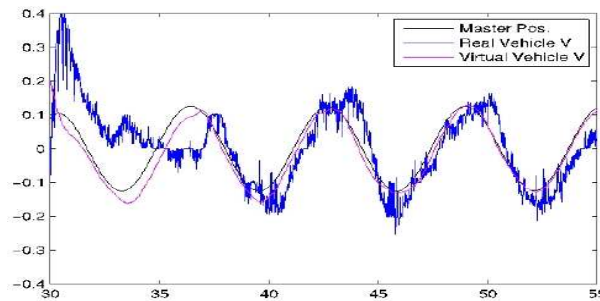


Fig. 15. Preliminary telemanipulation experiments: master position, real and virtual vehicle position.

Figure 15 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.

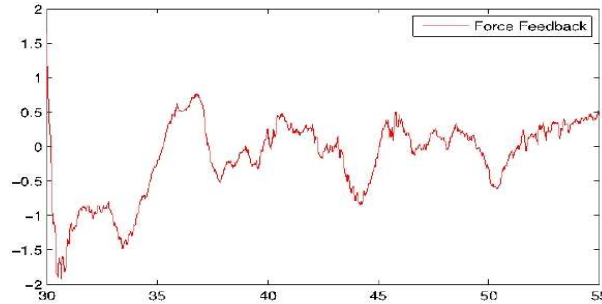


Fig. 16. Preliminary telemanipulation experiments: Force feedback.

The force feedback shown in Figure 16 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.

Finally, the visual motion estimation algorithm has been tested in several experiments. The target panel of Fig. 12 has been used as a reference structure for the evaluation of the relative vehicle motion. In particular, the couple of images acquired in the initial pose have been used as the fixed reference for the evaluation of the image matches, resulting in an estimation of the relative motion of the vehicle with respect to the initial pose.

The results of two flight tests are shown in Fig. 17, while in Fig. 18 is represented the corresponding number of robust matches and detected outliers. In the first experiment the vehicle takes off and lands in a position close to the initial one, while in the second experiment the final landing position is different.

The adoption of the initial images as reference causes a strong reduction of the number of matches when the vehicle moves from the initial pose, as shown in Fig. 18. This phenomena is avoidable using the previous acquired images as dynamical reference (both solutions are currently available), i.e. when the number of robust matches decreases under a threshold a new reference images pair is acquired. This last functionality has been disabled during this tests to evaluate the robustness of the proposed matching method.

Moreover, the absence of a strong camera synchronization, i.e. an imperfect temporal alignment of the images pair in the available camera system, causes an error in the estimation and in the number of matches with a magnitude directly related to the velocity of the vehicle.

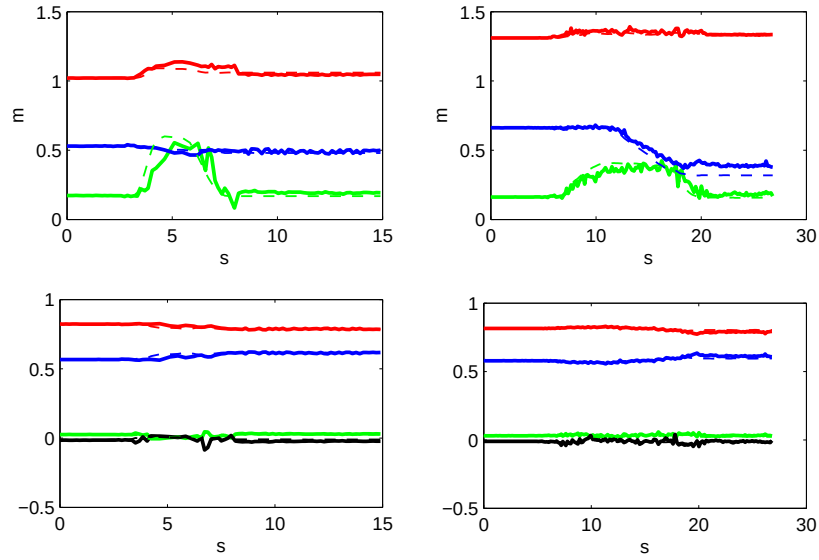


Fig. 17. Estimation of the positional (on the left) and orientational (on the right, using quaternion) components of the vehicle trajectories during experiments 1 (on the top) and 2 (on the bottom), all with solid lines, and the corresponding OptiTrack measured components with dashed lines.

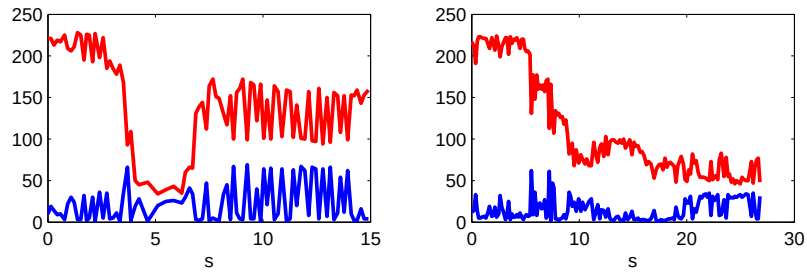


Fig. 18. Number of robust matches (red) and detected outliers (blue) of the experiment 1 (left) and 2 (right).

As a general consideration, it can be noticed that the estimation error remains quite limited along the trajectories, while a large error is quite evident in the last part of the estimation for the second experiment (see Fig. 17). This is mainly due to the poor calibration and quality of the optical system, and especially of the optical axis misalignment between the two cameras (the adopted triangulation is based on the assumption of a perfect alignment). A residual error should also depend on the rough estimation of the extrinsic camera parameters.

7 Conclusion and Future Work

In this article we presented the main ideas and first results of the ongoing European project AIRobots. The main goal of AIRobots is to pave the way for next generation of aerial service robots, able to interact safely with the environment and to cooperate with human pilots in a intuitive way. The first two aerial platforms and the first experimental results have been presented. 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. Supervisory based control architectures are under explorations in order to obtain modular and flexible design. Further attempts are directed to improve the aerial platforms according to the experiences acquired during the first flight tests. 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. Finally, a noteworthy research activity is focused on the development of sensor fusion algorithms and navigation strategies.

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