Human-robot collaboration to perform aircraft inspection in working environment

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Keywords: Human-Robot Interaction, Collaborative Robot, Non-Destructive Testing, Autonomous Navigation, Human Follower, Artificial Intelligence, Aircraft Inspection, Aircraft Maintenance.

Abstract: The Air-Cobot project aims to develop a collaborative mobile robot to obtain a human-robot inspection of an aircraft during maintenance operations before takeoff on an airport. In working environment with security protocols and time constraints, the duo of inspectors, made of a cobot and its human operator, has to cope quickly with environment variability. The robot is able to perform autonomously navigation and routinely inspection tasks. The human operator supervises its mission, checks its non-destructive testing results and intervenes if the robot is in trouble. Meanwhile, the human operator checks visually the aircraft. In case of a default, the robot helps him to evaluate the default and register the intervention. This robotic solution improves aircraft maintenance and traceability.

1 INTRODUCTION

Airplanes are inspected periodically during maintenance operations either outdoors on an airport between flights, or in a hangar for longer-duration inspections. The reduction in inspection time is a major objective for aircraft manufacturers and airlines. If maintenance operations are faster, this will optimize the availability of aircraft and reduce maintenance operating costs. Nowadays, the inspection is performed by human operators mainly visually, sometimes with some tools to evaluate defects. The multi-partner Air-Cobot project aims to improve aircraft maintenance and traceability.

Figure 1: Air-Cobot platform evolving under an A320 aircraft in a hangar of Air France Industries.

Previous robotic solutions for aircraft inspection focus on aircraft surface skin inspection with robot crawling on the airplane surface (Siegel, 1998) (Shang, 2007). The Air-Cobot projet chooses a different path which leads to a collaborative mobile robot with cameras and a three-dimensional scanner, see Figure 1. Thanks to its acquisitions, a database dedicated to each airplane containing images and scans, will be updated after each maintenance check.

Researches have been made on three main problematics which are:

- autonomous navigation;
- Non-Destructive Testing (NDT);
- Human-Robot Interaction (HRI).

To navigate in the airport, the robot can go to an airplane parking thanks to geolocalization data, or by following its human operator. To autonomously navigate around the airplane, the robot is able to use laser and vision methods to localize itself compared to the aircraft (Frejaville, 2016) (Jovančević, 2016b) (Tanguy 2016). Obstacle recognition and avoidance are also use in navigation mode (Futterlieb, 2014).

The robot can inspect visually some items of the aircraft such as probes, static ports, trapdoors, latches and scan some fuselage parts (Jovančević, 2015) (Jovančević, 2016a). It has a tasks checklist to follow. The human operator controls the inspection diagnoses on its tablet. He also checks visually the aircraft and can request additional NDT checks.

This article introduced HRI and security measures taken into the Air-Cobot projet. See (Goodrich, 2008) and (Heyer, 2010) for introductory material on the HRI research field. Working in a proximate interaction, the two operators, robot and human, have to communicate and, in some way, rely on each other to improve their team work. The aim is an efficient collaborative duo of inspectors. To make it safe in such a working environment, security protocols are of major importance. The robot uses different localization approaches. Geofencing is performed. The human operator is always at proximity to check the conduct of the robot mission.

This article is organized as follow. The mobile platform, its remote control, the sensors and the tablet interface are described in Section 2. The autonomous robot tasks for navigation and inspection are introduced in Section 3. In Section 4, the collaboration between human and robot is explained by describing some of their interactions.

2 ROBOT AND CONTROLS

2.1 Platform and remote control

The electronics equipment is carried by the 4MOB mobile platform manufactured by Stéréla, see Figure 2. Equipped with four-wheel drive, it can move at a maximum speed of 2 meters per second (7.2 kilometers per hour). Its lithium-ion battery allows an operating time of 8 hours. Two obstacle detection bumpers are located at the front and the rear. They stop the platform if they are compressed.

Figure 2: 4MOB platform manufactured by Stéréla.

Figure 3: Remote control of the 4MOB platform.

On the remote control, see Figure 3, it is possible to follow the battery level and receive 4MOB platform warnings.

In case of a problem, two emergency shutdown devices are accessible on the platform and another is present on the remote control. The duo human-robot is supposed to work at a relative close range. If the platform moves away too much from the remote control carried by the operator then there is an automatic emergency shutdown.

2.2 Sensors and operating systems

The robot is equipped with navigation sensors:

- four Point Grey cameras;
- two Hokuyo laser range finders;
- Global Positioning System (GPS) receiver;
- Initial Measurement Unit (IMU);

and non-destructive testing ones:

- Pan-Tilt-Zoom (PTZ) camera manufactured by Axis Communications;
- Eva 3D scanner manufactured by Artec.

Figure 3: Air-Cobot is equipped with many sensors.

The open source framework Robot Operating System (ROS) has been used for integrating device drivers and navigation algorithms (Quigley, 2009). The robot has two industrial computers, one running on Linux for the autonomous navigation module and the other on Windows for the non-destructive testing module. The whole cobot weighs 230 kilograms.

2.3 Tablet interface

The tablet interface provides several control panels to perform different actions: changing the mission tasks or the navigation mode; checking the pose estimations or the NDT results; reading robot warnings or interaction requests. Figure 4 presents a view of the control panel for the NDT sensors.

At the end, the robot provides its diagnoses and asks the human to validate or refute them. The operator can easily manipulate the pictures or the 3D scans for zooming or rotating, see Figure 5. Color representations of the results are put on the pictures or the 3D scans to help the user comprehension.

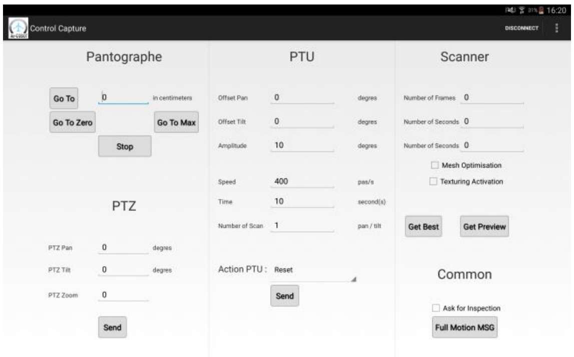

Figure 4: View of the control panel for the NDT sensors.

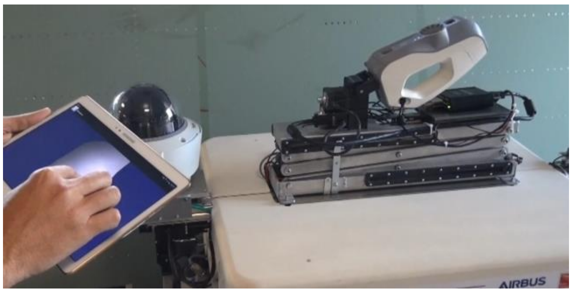

Figure 5: 3D scan visualization on the tablet.

3 AUTONOMOUS ROBOT TASKS

3.1 Autonomous navigation

The robot has two different types of navigation to perform: in the airport to reach the aircraft parking and around the aircraft to reach the checking positions. For safety measure, two methods of localization have been considered in each type of navigation. Air-Cobot is also able to detect, track, identify and avoid obstacles that are in its way.

3.2.1 Navigation in the airport

In the airport, the robot navigates in dedicated corridors and has to respect speed limits. The first time, the human operator has to teach the trajectory to the robot by moving it in remote control mode or follower mode. Waypoints are built from this trajectory. Georeferenced maps of the facility with areas (forbidden, limited speed …) are also provided and taken into consideration.

In an outdoor environment, the robot is able to go to the aircraft parking by localizing through GPS data. The GPS device developed by M3 Systems allows the use of geofencing. A visual localization based on Simultaneous Localization And Mapping (SLAM) approaches to propose a complement to the GPS one is currently evaluated.

3.2.2 Navigation around the aircraft

To perform the inspection, the robot has to navigate around the aircraft and go to checkpoints. The position of the aircraft in the airport or factory is not known precisely; the cobot needs to detect the aircraft in order to know its pose (position and orientation) relative to the aircraft. To do this, the robot is able to locate itself, either with the laser data from its laser range finders, or with image data from its cameras (Frejaville, 2016) (Jovančević, 2016b) (Tanguy 2016).

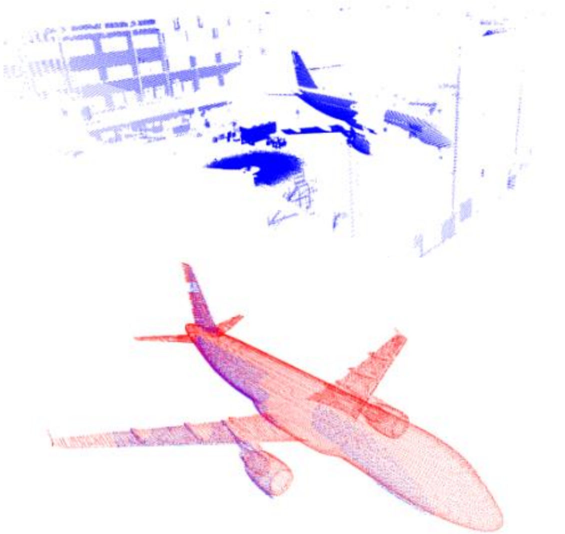

Figure 6: Robot is located in back left of the aircraft in an inside environment. At top, 3D data is acquired with a Hokuyo laser range finder moved thanks to a pan-tilt unit. At bottom, the matching result is made of data (blue) with model (red).

Near the aircraft, a point cloud in three dimensions is acquired thanks to the laser scanning sensors fixed on pan-tilt units. Matching between the model of the aircraft and the scene point cloud is performed to estimate the static pose of the robot, see Figure 6. The robot moves and holds this pose by considering the IMU, the wheel odometry and the visual odometry (Frejaville, 2016).

Laser data are also used horizontally in two dimensions. Pose estimation of the robot is computed when enough elements from the landing gears and engines are visible (Frejaville, 2016).

For visual localization, the robot estimates its pose relative to the aircraft using visual elements (doors, windows, tires, static ports etc.) of the aircraft. Pattern recognition or extraction of features are used to detect those visual landmarks (Jovančević, 2016b) (Tanguy 2016). By detecting and tracking them, see Figure 7, in addition to estimating its pose relative to the aircraft, the robot can perform a visual servoing (Futterlieb, 2014).

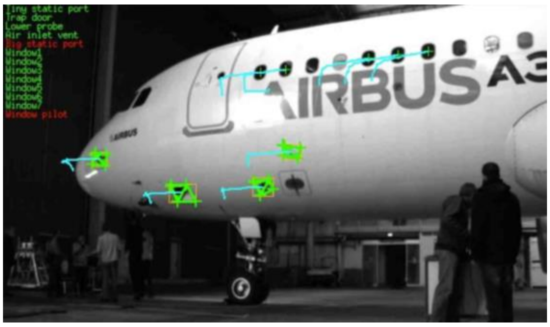

Figure 7: Tracking of visual features for pose estimation.

A first confidence index is computed based on the number of items visible in laser data. A second confidence index is computed based on the number of visual features. If good data confidence is achieved, the pose is updated. Artificial intelligence arbitrating between those pose estimation results is in developpement (Frejaville, 2016) (Tanguy 2016).

3.2.3 Obstacle avoidance

The laser data coming from laser range finders and visual data coming from the cameras are used for detection, classification (moving, motionless) and recognition (human, vehicle, other) of the obstacles (Futterlieb, 2014). The detection and the classification are easier in the two-dimensional laser data, while identification is better in the images. The two methods are complementary. Three kinds of avoidances are considered:

- stop and wait for a free path;
- spiral obstacle avoidance;
- path planning trajectories.

The chosen avoidance approach depends on the robot's surroundings (navigation corridor, tarmac area without many obstacles, cluttered indoor environment etc.) at the time of the encounter with an obstacle.

3.2 Non-destructive testing

At the start of the project, the NDT tasks were based on the PTZ camera and the 3D scanner. They require image analysis for the first sensor and point cloud analysis for the second one. During the project, it has been put into evidence that the navigation cameras and the laser range finders could also provide data useable for NDT tasks.

3.2.1 Image analysis

At given positions, the robot performs a visual inspection by analyzing acquisitions made with the PTZ camera. Before the image analysis of the acquisition, several steps take place: pointing the camera, detecting the element to be inspected, if needed repointing and zooming with the camera and finally, image acquisition.

Image analysis is used in different cases: doors to determine whether they are open or closed; on the presence or absence of protection for certain equipment; the state of turbofan blades; the state of the probes; or the wear of landing gear tires (Jovančević, 2015) (Jovančević, 2016a). Figure 8 provides some examples of items to inspect.

Figure 8: Examples of items to inspect. From left to right, static port with its protection, open air inlet valve, AOA probe. Light conditions are very different.

The detection uses shape recognition with regular shapes (rectangles, circles, ellipses) or more complex shapes obtained with the projection in the image plane of the 3D model of the element to be inspected. The evaluation is based on indices such as the uniformity of segmented regions, convexity of their forms, or periodicity of the image pixels' intensity. (Jovančević, 2015) (Jovančević, 2016a).

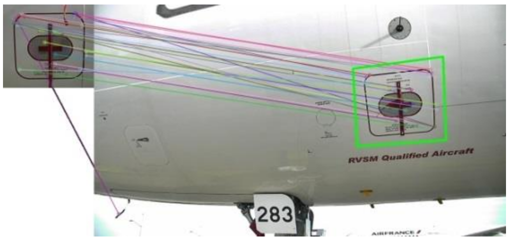

Figure 9: Static port inspection with SURF method.

Feature extraction using Speeded Up Robust Features (SURF) can also be applied to perform the inspection of certain elements having two possible states, such as pitot probes or static ports being covered or not covered, see Figure 9. For such items, in order to decrease the mission time, visual inspection with the navigation cameras during displacements around the aircraft is under consideration (Villemot, 2016).

3.2.1 Point cloud analysis

At given positions, the pantograph elevates the 3D scanner at the fuselage level. A pan-tilt unit moves the Eva scanner to acquire the hull. Figure 10 shows a 3D scan. By comparing the data acquired to the 3D model of the aircraft, algorithms are able to diagnose any faults in the fuselage structure and provide information on their shape, size and depth.

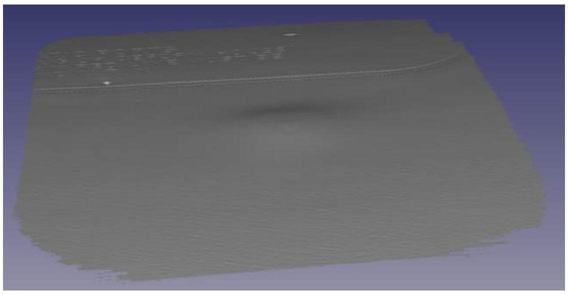

Figure 10: Tridimensional scan of the aircraft surface, a bump is visible in the middle. The writing, visible in the top, helps to locate precisely the default.

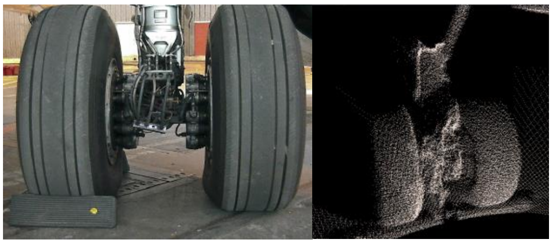

Figure 11: At left, a picture from PTZ camera of a landing gear with a chock in front of the left tire. The task is the detection of the chock. At right, an example of laser data acquisition of a landing gear.

As explained in Section 3.2, by moving the pan-tilt units of the laser range finders, it is also possible to a obtain a point cloud in three dimensions. It is planned to make targeted acquisitions, simpler in terms of movement, to verify, for example, the absence of chocks in front of the landing gear wheels, or the proper closing of latches.

Figure 11 illustrates the interest of using the laser range finders on landing gear inspection when the chock is not easily distinguishable from the tire (Frejaville, 2016).

4 COLLABORATION

4.1 Three navigation modes

The robot has three possible navigation modes:

- Autonomous mode;
- Follower mode;
- Remote control mode.

The level of robot autonomy is decreasing between this three modes and the human-robot interactions are adapted in consequence.

In the autonomous mode, like explained in the previous section, the robot performs a list of tasks autonomously such as moving to a pose in the airport frame or in the aircraft frame, inspects an item or avoids obstacles. The human operator has to stay at proximity of the robot and check sometimes the robot behaviour but he can perform his own inspection tasks in the meantime.

In the follower mode, the robot follows the human operator until a change of mode. The robot has to be able to avoid obstacles and recognize its human operator between other humans.

In the remote control mode, the human operator can displace the robot to a specific location thanks to the remote control (Section 2.1) or specify an NDT task thanks to the tablet interface (Section 2.3). The human operator is completely in charge of the mobile platform and the NDT sensors.

4.2 Robot to human interaction requests

4.2.1 Classical warnings

Classical warnings of the robot can emerge if there is a crashing code problem, or a material dysfunction. If possible, it continues the mission with its reduced capacities and skips tasks linked to these problems until someone intervenes.

One example during navigation tasks, if the GPS signal is too weak, then the robot send a soft warning to the human operator and move a bit updating its pose with odometry measurements. But at some point, it has to receive the GPS signal otherwise its confidence level of its pose estimation would be too low and the robot would stop and send a strong warning to the user.

Second example during inspection tasks, if the elevator of the 3D scanner has a mechanic malfunction and it is not elevating correctly then the human operator has to check it.

4.2.2 Navigation warnings

During its navigation tasks, the robot has to follow navigation corridors and safety trajectories around the aircraft. It warns its operator if it is stuck and it cannot avoid safely an obstacle without leaving the navigation corridor or being too far safety trajectory. In that case, the operator can choose the follower or remote control modes to lead the robot away from the problem or move the obstacle that blocks its path. Alerts are also sent to the operator if the robot enters a prohibited area or exceeds a given speed.

4.2.3 Inspection warnings

During its inspection tasks, the robot can warn the human operator that something is wrong. For example, it did not find the element to inspect in the image or the 3D scan seems incorrect.

The cobot can ask for a fast human intervention for examples if there is still the chock in front of the landing gear or the protection on a pitot probe, see Figures 11 and 12. Figure 13 shows the human operator performing a zoom request with his fingers on the tablet to have a better view of the air inlet valve opening.

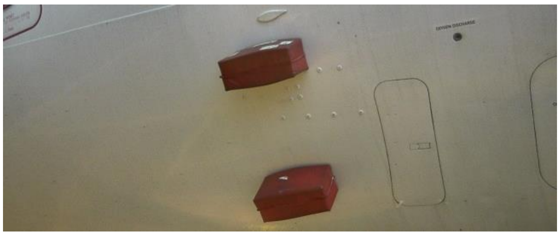

Figure 12: Pitot probe protections are in place.

Figure 13: Human operator zooming on the air inlet valve.

4.3 Human to robot interaction requests

4.3.1 Adding NDT tasks

The operator is also visually checking the aircraft. He could ask for a NDT check from the robot if he thinks there might be a problem on the aircraft which is not taken into consideration in the robot tasks. After moving the robot, he can control the sensors and asks the robot to perform some tests. In Figure 14, the human operator asks for a 3D scan.

Figure 14: Elevation of the scanner in order to perform a scan of A320 aircraft in a hangar of Air France Industries.

If the robot confirms a default for example a bump, the operator can add this check for this particular aircraft. The robot remembers its pose compared to the aircraft and the performed NDT check so it can do it the next time that it encounters this aircraft. Figure 15 presents a scan of the aircraft and the associated diagnostics.

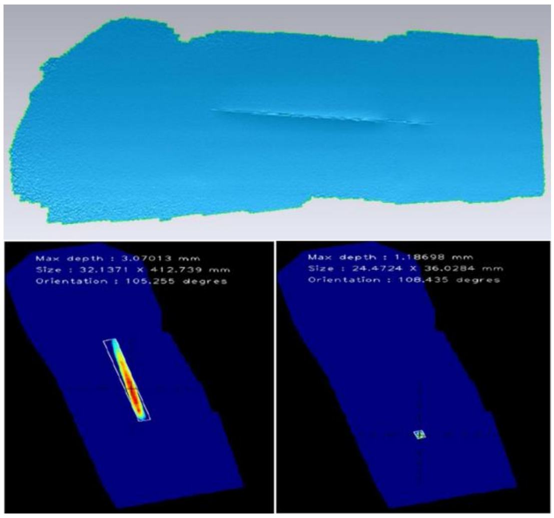

Figure 15: Tridimensional scan of the aircraft, a crack and a bump are visible. The inspection algorithms provide shape, size and depth of those imperfections with visual color representation to help the human operator.

4.3.2 Checking robot

At regular intervals, the robot sends its GPS pose estimation or its pose estimation compared to the aircraft to the tablet. The human operator can check it on a facility map for the first one, and on an aircraft representation for the second one. Three examples of the last one are given in Figure 16.

Figure 16: Three examples of poses provided on the tablet.

The human operator has an access to the mission plan status and the dignostic results in real time. He can, for example, check PTZ camera preview before image analysis to check the camera pointing.

4.3.3 Understanding the environment

Since the human operator has a better understanding of the environment, he can take the control of the robot to avoid problems before they arrived or just change the order of the list of tasks. The human is better adapted to understand if another worker interferes with the robot mission and at the opposite, to take into account whether the robot interferes with another worker. In conclusion, he is responsible for choosing which one has the priority.

5 CONCLUSIONS AND PROSPECTS

5.1 Conclusions

The Air-Cobot projet leads to a collaborative robot able to perform aircraft inspection in collaboration with a human operator. Adjustable autonomy is reached with three different navigation modes. The two agents are able to navigate in the airport and around the aircraft in an adaptive way. Various interaction requests reduce the whole mission time and improve the productivity of the duo.

Collaboration between these two agents is inevitable due to the safety measures to follow in this particular working environment and the variability of the inspection defaults.

The robot is able to learn from these interactions with the human to improve its efficiency: transforming human requested checking tasks into automatic tasks for a specific aircraft; learning new obstacle to be able to perform recognition; developing its artificial intelligence.

The duo of inspectors will increase the efficiency and the reliability of inspection, reduces the risk and uncertainties, self-adapt to different types of aircrafts, service types, investigation contexts, human stakeholders, and operational circumstances.

5.2 Prospects

To improve further the robot, the tablet or the human operator's actions or reactions, feedbacks from multiple missions will be needed.

Thanks to the historical data about aircrafts of regular flights and the diagnosed issues over a longer time, it will be possible to forecast possible future happenings and provide preventive maintenance information for the technical staff.

Sharing knowledge between AKKA Research projects is in developpement. For example in navigation, the airport markings on the ground could be taken into account; and on the CoCoVeA project (French acronym for Cooperation between Driver and Automated Vehicle), see Figure 17, road markings are taken into account for autonomous car.

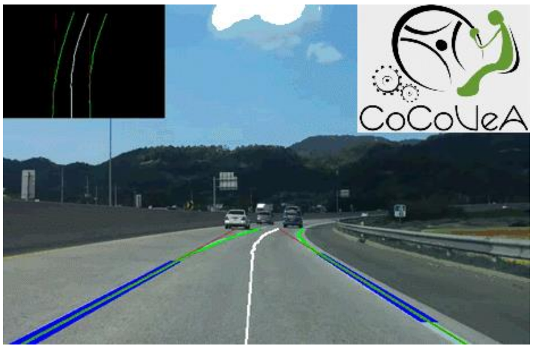

Figure 17: Illustration of CoCoVeA project. Road marking are detected in real time by the autonomous car.

It is also envisioned to employ the facility surveillance system to check the environment. In the airport context, AKKA Research has the Co-Friend project, which used video-surveillance, video-tracking and artificial intelligence to automatically detect and monitor all stopover operations (Greenall, 2012), see Figure 18. The facility surveillance system could provide, in real time, adaptive navigation plans to the robot and its human operator to avoid the other human activities.

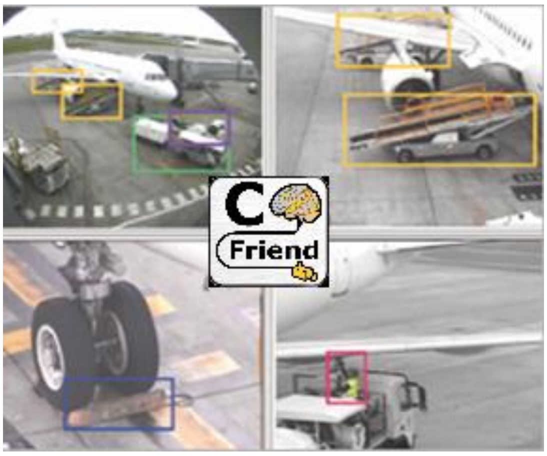

Figure 18: Illustration of Co-Friend project. Artificial intelligence automatically detects and monitors all stopover operations with video-surveillance.

The mobile platform is made for inspecting the lower parts of the aircraft. It is envisonned to use it with a drone for the upper parts. The partnerships between the robot and the drone is beneficial: complementary inspections, better robot pose estimations compared to the aircraft and better adaptability. Since the robots are inspecting different parts of the aircraft from different point of view (ground, air), the fusion of these modalities provides a better inspection process. A single robot can localize itself compared to the aircraft and sometimes can also view another robot. The fusion of the sensors data from each robot can help the group to provide a better pose estimation of each robot. Some vision NDT algorithms could be used on drones. It would provide different inspection strategies for some aircraft items and generate alternative inspection plans in case of a problem.

ACKNOWLEDGEMENTS

Air-Cobot (http://aircobot.akka.eu) is a Fonds Unique Interministériel (FUI) project from the competitiveness cluster of Aerospace Valley. We thanks the other members of Air-Cobot team from AKKA Research and the other partners of the project (Airbus Group, LAAS-CNRS, Armines, 2MoRO Solutions, M3 Systems and Stéréla) for their help and support. The partners of the project thank Airbus and Air France Industries for giving us access to aircrafts to do acquisitions and validations; and their staffs which help us during those days.

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