3D scanner positioning for aircraft surface inspection

Marie-Anne Bauda, Alex Grenwelge, Stanislas Larnier
AKKA Research, Toulouse, France
Marie-Anne.Bauda@akka.eu

***Abstract*—The French Air-Cobot project aims at improving preflight maintenance as well as providing a traceability of the performed checks. A collaborative mobile robot has been built in order to carry out those tasks. The robot is able to navigate autonomously around the aircraft and perform non-destructive testing thanks to several sensors. More precisely, in this paper we focus on how to obtain a correct position of the 3D scanner fixed on a scissor with respect to the aircraft. It acquires 3D data which is analyzed to process surface inspection. The functional safety of the scissor is based on automatic visual checking of some cues. The full process demonstrates the feasibility of integrating 3D sensor on a mobile platform in safe conditions.**

Keywords — collaborative mobile robot; embedded systems; non-destructive testing; position control system; structured-light three-dimensional scanner

I. Introduction

Surface automatic inspection is a new challenge in large industrial context. Indeed, industrial applications are expecting automatic process in order to keep human operator far from hazardous environment. However, collaboration between human and robot is still necessary while decision making remains complex.

Increasingly, mobile platforms are helping the human operator in various and different operational contexts. Among many examples, we can outline 3 concrete solutions:

- Sensabot [9] from Shell, in offshore oil and gas industry. It is designed to inspect in hazardous environment. To enforce safety moving, it is fully remote controlled via joystick through a wireless link and sensors providing perception (360° cameras, lidar, etc.)
- Riana [10] from Areva, used for waste dismantling. This robot has two navigation modes (remote and autonomous navigation with optional software) in order to map the environment, to take samples and to measure the radioactivity. It is a modular platform on different sensors (3D and thermal cameras, etc.) can be plugged.
- Oz [11] from Naïo Technologies, in agricultural robotics. This autonomous robot is designed to follow precise trajectories in order to garden weed market. It resists to dust and water projections.

Fig. 1. Air-Cobot platform.

In the considered context, airplanes are inspected periodically during maintenance operations on an airport between flights (pre-flight inspection) or in a hangar for further deeper inspection. Reducing inspection time is a major objective of aircraft manufacturers and airlines. If maintenance operations get faster, it will optimize the availability of aircraft and reduce costs. Nowadays, the inspection is performed mostly visually by human operator and sometimes with the aid of some tools to evaluate defects.

As mentioned, many robots can perform industrial inspection [1][2]. In the 90's, the first research programs on robotic maintenance applied to aircraft servicing were published, firstly based on concepts for skin automating inspections [3], and then stripping and painting concepts [4][5]. In particular, preliminary conceived robots were crawlers [7][6] such as Automated Non-Destructive Inspector (ANDI) [3] and Crown Inspection Mobile Platform (CIMP) [3].

ANDI is a fully-automated system dedicated to aircraft wing rivets inspection based on ultrasonic and eddy current sensors. It is a multi-axis robot with a dripless bubbler system which is able to test almost any surface of any contour. CIMP mobility and range of inspection is limited to the fuselage crown. It has a 3D-stereoscopic video system that provides the inspectors with remote binocular inspection capability.

In January 2013, the French multi-partner Air-Cobot project started. It aims to improve maintenance tasks by accelerating them through the reduction of dedicated time and meanwhile increasing inspection outcomes traceability with a mobile collaborative robot on the ground [8]. During the following years, some approaches using drones were also born such as [12][13]. Most of them use laser range finders for navigation and camera for Non-Destructive Testing (NDT). In Air-Cobot case, our concept concentrates the analysis on ground robot due to the fact that most (around 70%) of the items to inspect are visible from the floor.

Operationally thinking, Air-Cobot (Fig. 1) needs to be an extension of the human operator. To navigate in the airport or in the hangar and reach aircraft parking zone, Air-Cobot uses either geolocalization data [14] or marks on the floor [15]. It can also follow its human operator. Based on a planned maintenance mission, see Fig. 2, the robot can visually inspect some items of the aircraft such as probes, static ports, trapdoors, latches, tires and scan some fuselage parts [19][20][21][22]. It follows a tasks checklist. The human operator can in parallel (real-time) control the inspection diagnoses on its tablet. He can also check visually the aircraft and request additional non-destructive testing checks [14].

Fig. 2. Planning a maintenance mission.

In addition to its camera sensor used for visual check, the robot has a structured light scanner to perform 3D analysis of some parts of the fuselage. Details on scanner are given in section III.B. For more information on this technology regarding robot perception, please read [23]. This article focuses on how to bring this tool safely to the correct position and perform correctly the acquisitions. It also illustrates how the human operator checks and collaborates with the robot for this specific non-destructive testing task.

Section II provides a global view of the chosen equipment of the platform, sensors, actuators and user interfaces. Section III presents functional part of the platform with related work. The control system for scanning is detailed in Section IV. Positioning of the robot as well as scanner positioning system are both needed to perform autonomously the scanning task of an element. Indeed, the robot needs to reach the correct pose compared to the aircraft and bring the scanner to the desired height. The contribution of this paper focuses on the relative position of the sensor on the robot and how the system provides the correct height. Section V introduces the security and checking measures put in place on the elevation system. Finally, section VI illustrates the 3D acquisition data and treatment capabilities.

II. AIR-COBOT OVERVIEW

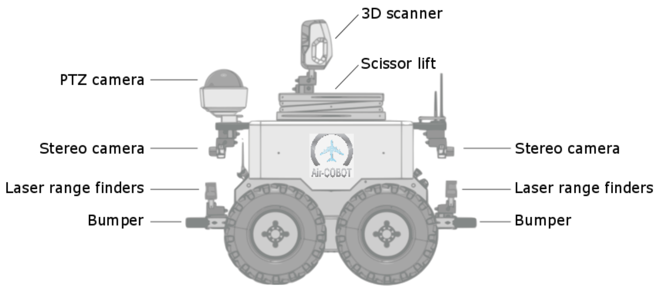
An overview of the platform and of the available sensors is given in Fig. 3. All the electronics equipment is carried by the 4MOB mobile platform manufactured by Stéréla, see [24]. Equipped with four-wheel drive, it can move at a maximum speed of 2 meters per second (7.2 kilometers per hour). Its lithium-ion battery allows an operating time of 8 hours. Two obstacle detection bumpers are located at the front and the rear. The platform stops automatically when they are compressed.

The full robot, is equipped with navigation sensors: four Point Grey cameras separated in two stereo sets, two Hokuyo laser range finders, Global Positioning System (GPS) receiver, Initial Measurement Unit (IMU); and non-destructive testing sensors: Pan-Tilt-Zoom (PTZ) camera [25], Eva 3D scanner [26] respectively producted by Axis Communications and Artec 3D.

Front and back of the platform have both a camera stereo set and a laser range finder. They are mounted on Flir Pan-Tilt Unit (PTU) D46 [28] to be able to change the fields of view or types of acquisition when needed. The 3D scanner is also moveable thanks to a PTU and a scissor lift.

The collaborative robot, Air-Cobot, supports three different main tasks:

- Navigation;
- Non-destructive testing;
- Human-Robot Interface.



Overall length	1540 mm	Non Destructive Testing Sensors : • Pan-Tilt-Zoom camera • Stereo cameras • 3D scanner • Laser range finders	
Overall width	800 mm		
Overall height	1400 mm		
Ground clearance	150 mm		
Boom reach scissor lift	2707 mm		
Weight	230 kg		
Speed	2 m/s (max 5 m/s)	Battery	Li-ion battery 48V
Mobility	4 wheel drive, all terrain	Charging power	48V AC, 10A, 1200W max
Maximal permissible slope	30%	Autonomy	8 hours
Security	Bumpers, emergency shutdown	Communications	Wi-fi, Ethernet

Fig. 3. Air-Cobot specification.

III. RELATED WORK

Related work focused on the cobot main tasks. For a better understanding of our contribution following sub-sections describe each main task.

A. Navigation

Air-Cobot, integrates three modes of navigation with increasing autonomy : the remote mode enables the operator to decide where to go, the following mode enables to follow the human operator and finally the automatic mode upon which an autonomous motion can be executed based on a predefined mission.

The first navigation mode enables the human to take the full control of the robot with the remote control or with the Android tablet. The remote control gathers information from the battery level and 4MOB platform received warnings. In case of a problem, two emergency shutdown devices are accessible on the platform. One additional 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 far from the remote control carried by the operator then the robot shuts down automatically.

The following mode commits the robot to follow the human operator. The robot is robustly enslaved behind the guide, thanks to the Lidar data [33]. The position of the guide is predicted depending on the speed of his movement even if he gets hidden by an obstacle. It means that the algorithm deals with occult data and enables to avoid obstacle.

Third and last navigation mode is the fully automatic mode. Air-Cobot is able to execute a set of tasks previously planned. It can localize itself on its own with different approaches, wherever he is inside or outside. To navigate autonomously around the airplane, the robot is able to use laser and vision methods to localize itself with regard to the aircraft [16][17]. Obstacle recognition and avoidance are also implemented in navigation mode [18]. More details on the relative positioning and on the 3D servoing based on lidar information are given in section IV.A. During its mission the robot performs Non-Destructive Testing acquisitions and processing.

B. Non-Destructive Testing

The selected camera for inspection is an AXIS Q6045- E Mk II PTZ Dome Network Camera [25]. It offers HDTV 1080p and 32x optical zoom. The PTZ camera is oriented towards desired direction through the control of pan and tilt angles. Zoom capability is essential for inspection. Moreover, as mentioned, the camera is used for visualization check of the scissor lift deployment.

Many 3D sensors exist and can be used to collect the 3D data necessary to check the surface. After comparing the specifications, costs and analysis of data quality from various types of scanner, Eva structured-light 3D scanner manufactured by Artec 3D [26] has been chosen as best compromise. It offers appropriate specifications to achieve the required objective, please refer to Table I. In particular, it enables to acquire 3D information between 40cm and 1meter.

TABLE I. EVA 3D SCANNER SPECIFICATIONS [26]

3D resolution, up to	0.5 mm
3D point accuracy, up to	0.1 mm
3D accuracy over distance, up to	0.03% over 100 cm
Texture resolution	1.3 mp
Light source	flash bulb
Working distance	0.4 - 1m
Linear field of view, HxW, closest range	214 x 148 mm
Linear field of view, HxW, furthest range	536 x 371 mm
Angular field of view, HxW	30 x 21°
Dimensiosn HxDxW	261.5 x 158.2 x 63.7 mm
Weight	0.85 kg
Power consumption	12 V, 48 W

C. Human-Robot Interface

Air-Cobot is a collaborative robot. Interactions are possible in both ways: from human to robot and from robot to human.

On first hand (from human to robot), the tablet interface acts as a remote control. It provides several control panels to perform various actions: changing the mission tasks or the navigation mode; checking the pose estimations or the NDT results. Fig. 4 illustrates a view of the control panel for the NDT sensors.

On the other hand (from robot to human), the tablet is used to visualize information provided by the cobot such as reading robot warnings messages or to define interaction requests.

At the end of the process, the robot provides its diagnoses and requires human collaboration in order to validate or refute them. The operator can easily manipulate the pictures or the 3D scans thanks to zooming or rotating capabilities, see Fig. 5.

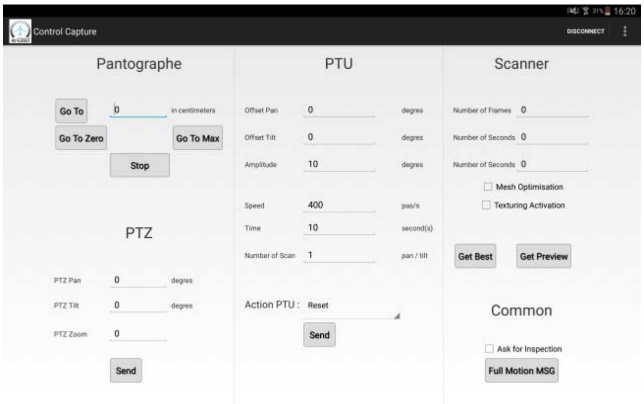


Fig. 4. View of the control panel for the NDT sensors.

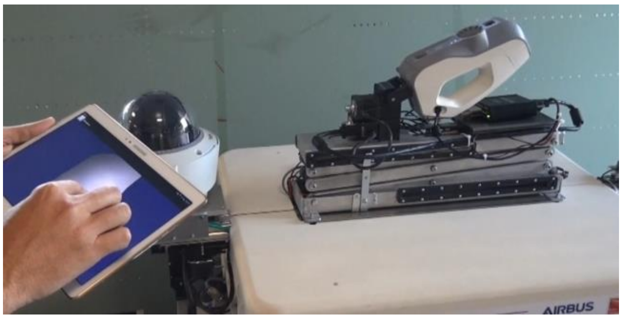


Fig. 5. 3D scan visualization on the tablet.

IV. Control system for scanning

The control system for NDT scanning can be split in two parts: the robot positioning and the scanner positioning which depend on the height of the elevation system.

Firstly, it is obviously prohibited to hit the whole aircraft structure (fuselage, wings, power plant, etc.) in order to avoid any potential damage onto the aircraft structure, paintings or exterior equipment such as probes. Hence, safety requirements have been defined with threshold distance in the global geodetic referential, in order to protect the item to inspect. If the 3D sensor has not reach the required/adequate position, then it may either prevent the system from acquiring data, or it may lead to acquire inexploitable or erroneous data such as false negative results.

A. Robot positioning

To perform the inspection, the robot has to navigate around the aircraft and reach predefined checkpoints. Indeed, the position of the aircraft in the airport or factory is not precisely known prior to the inspection. As a consequence, the cobot needs to detect the aircraft in order to calculate its pose (position and orientation) relative to the aircraft. To cope with such requirement, the robot needs to be able to locate itself, either with the 3D point cloud from its laser range finders, or with image data from its cameras [17], depending on sensors system availability and captured data precisions.

For example, when the robot is close to the aircraft, a 3D point cloud is acquired through the laser scanning sensors fixed on PTUs. Then, matching between the model of the aircraft and the scene point cloud is performed to estimate the static pose of the robot [16]. Fig. 6 and Fig. 7 provide an example in an outdoor context. When the 3D model of the aircraft is available and stored into the cobot memory, the relative localization is mastered using lidar captured data, otherwise only visual servoing can be used [21].

More precisely, there are two ways to locate the robot using the 3D information. On the first hand, without any movement, 3D features are compared between reference 3D model and captured data in order to determine the best potential matching of identical part. Such static localization enables also to know the height of the aircraft which can change upon payload weight. On the other hand, when 3D data is acquired in a 2D plane, the RANSAC algorithm is used to associate geometrical templates. Fig. 8 shows items used for the 2D pose estimation with respect to the aircraft position. The process also computes a maximal error distance in order to know the confidence that we can provide to the measurement.

Some feature-based visual servoing approaches [22] are available on Air-Cobot but the description of those approaches is out the scope of this paper since we choose to focus on the 3D data.

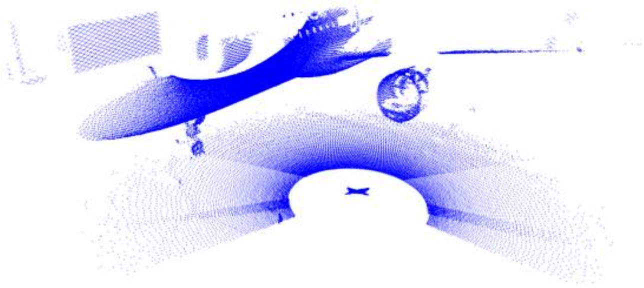


Fig. 6. Robot is located in front left of the aircraft in an outside environment. 3D data is acquired with a laser range finder moved thanks to a PTU.

Fig. 7. The matching result is made of data (blue) with model (red).

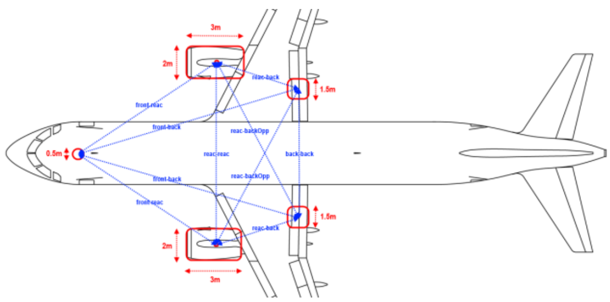


Fig. 8. Items used in the 2D pose estimation process.

Fig. 9. Deployement of the positioning system after an human operator request in order to scan an A320 aircraft at Air France Industries.

B. Scanner positioning system

The elevation system deployment can be activated through the mission plan or on human operator request, see Fig. 9.

With regard to the sensor position itself, the goal is to reach the highest position on the robot to maximize height potential. It is also required to optimize stability by positioning the scissor at the upper surface center and comply with installation constraints. In addition, such position minimizes the complexity of the transformation matrix.

The chosen scanner positioning system is made of a scissor lift [27] to reach the correct height, and a PTU [28] to orientate the scanner and provide a movement during acquisitions. This combination of elements provides 3 degrees of freedom to the 3D scanner with respect to the robot.

Compared to robotic arms, lifts are simpler to construct, easier to control and maintain the load charge in a fixed planar location. There are different types of lifts: elevator, four bar, forklift, and scissors. A trade-off has been performed to compare various solutions and the most appropriate was chosen given the main following reasons:

- Lowest weight,
- Longest elevation with minimum retracted height,
- Simplest mechanics.

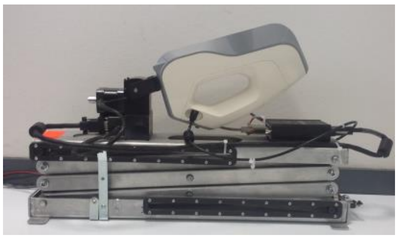


Fig. 10. Folded scanner positioning system.

Fig. 11. Unfolded scanner positioning system.

Nevertheless, during experimentations, we have noticed that tightening torque should also be verified during preventive maintenance tasks of bolt tightening in order to prevent any distortion of axis orientation.

The elevation system is moved by an IG42 gear motor. The gear motor specifications are the following : 24VDC, reduction ratio of 1:24, rated torque of 9.5 kgf-cm, rated speed 240 RPM and no load current is inferior to 500mA.

The selected motor controller is the SDC2160. Various actions are possible to control the elevation. The encoder mode has been chosen for its capacity to improve the accuracy of the elevation system. Two motors are connected to the controller with 20A per motor. A voltage of 48V is needed for powering the controller. The communication with the computer is released by a RS232 connector.

The 3D scanner is mounted on a PTU-D46 powered in 12V and 1A. This system enables either to orientate the scanner to the optimal targeted axis or to perform an acquisition in movement.

As one can notice by looking at the positioning system in folded and unfolded configurations (see Fig. 10 and Fig. 11), the top of the elevation system does not move linearly. In the figure representing the unfolded scanner, the elevation system reaches almost 70 percent of its maximal position. The top of the scissor system moves slightly forward along elevation. Thus, an equation is required to calculate the height from the number of motor rotation cycles. Different heights have been measured. A polynomial approximation has been computed to estimate the number of rotations required to reach the desired height. Fig. 12 provides the curve diagram resulting of this analysis.

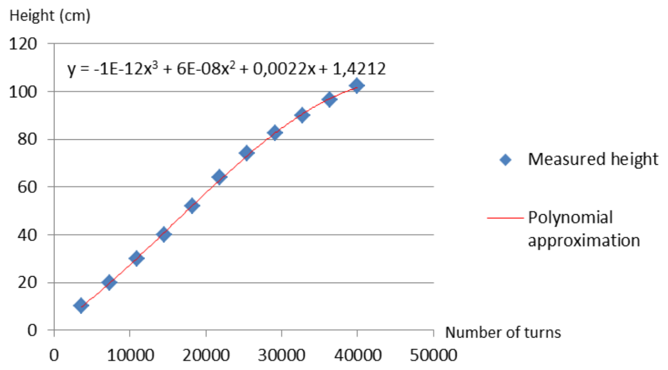


Fig. 12. Curve representing the elevator height in function of the number of motor turns.

The safety threshold distance has also been considered but such enhanced solution would require additional sensor such as depth sensor that could increase payload and distort cobot performance (physical and computational capabilities).

V. Security and Measurement Checking

A. *Security stop devices*

Stopping devices are used to avoid further motor rotations if the system reaches its top or bottom limits. An emergency shutdown device, dedicated to the scissors, is easily visible and accessible on the robotic platform and acts as the top railing. In case of failure or contextual hazard, the human operator can immediately stop at any time the movement of the lift.

When the robot is going to deploy the elevation system, an alert is sent to the human operator requesting him to send back a confirmation when he is at reasonable distance from the robot. That seems to be a system's limitation but in fact it atcs as an overall safety check to ensure that the operator has visually checked scissor movement hull with regard to aircraft structure. In case of software dysfunction, the human operator can also change the elevation mode to manual and perform an emergency unfolding.

One of the prospects is to integrate obstacle avoidance sensor modules at the top elevation system to shut it down automatically when required. It will act as a safety protection when an acquisition has to be performed in some risky cases, for instance when the robot is under the aircraft wings.

B. *Visual movement checking*

To provide a second security measure and a stability check, green stickers have been positioned on the scissors at visible locations for the PTZ camera. The stickers are easily recognized by the camera due to the chosen color and the perfectly known location. Detection, tracking and pose estimation algorithms are available in ViSP library [29] [30].

An additional, red sticker has been put on the tip of the elevator. The robot sees it when the PTZ camera looks in the back, see Fig. 13. The integrated software of the camera adapts itself automatically to the lighting conditions. Presence and recognition of the red sticker is checked at each start of the deployment and at each end. If it is not found at the expected position, an alert is sent to the human operator and the robot stops all its tasks, waiting for further instructions from the operator. Inversely, if it is found at the expected position, the robot keeps processing and performs its next sequential action.

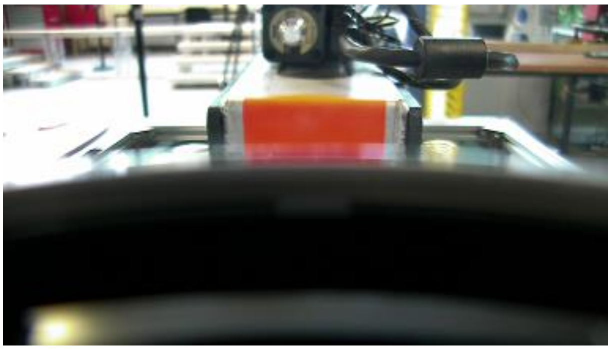


Fig. 13. Visual checking of the folding elevation system with its red sticker.

Another set of stickers has been put under the top plate of the elevation system. The robot sees it when the PTZ camera looks up, see Fig. 14. It is checked at the end of the deployment. Thanks to the known pattern of stickers, the height can be computed and checked with the expected one. If there is an issue (absence of sticker cues, divergence between the calculated and expected heights), the human operator is warned. System stability can also be checked. Any issue, such as excessive wind for example, drives folding of the elevator and warnings generation and sending to the human operator through tablet or remote station human-machine interfaces.

Fig. 14. Visual checking of the deployed system with its green stickers.

VI. Performing and Analysing Scans

A. *PTU movements for correct acquisitions*

The PTU enables different kinds of movements: static, horizontal, vertical or even a mix. The optimal PTU movements are preregistered for usual acquisition such as Radome (radar in the nose fuselage) or static port. When the operator requests to add a check on a fuselage part, he is responsible for finding an accurate acquisition to achieve it successfully. Thanks to the tablet interface, he can control the acquisition system and have direct and real-time 3D visualization feedback [14].

Figures provide different scan acquisitions such as scans of radome (Fig. 15), static port region (Fig. 16) and surface fuselage (Fig. 17). The radome has the most significant curvature. The static port part is the most textured region. One can notice that static port paintings are visible in the scan Fig. 16.

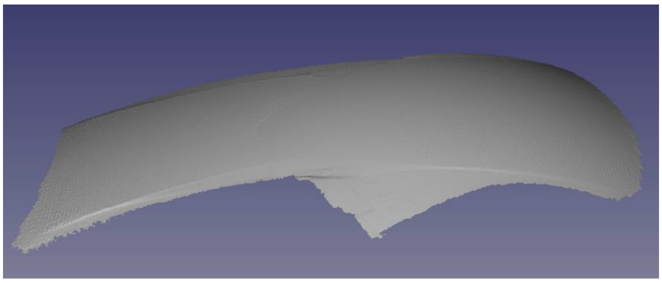


Fig. 15. Tridimensional scan of the radome, the curvature is well acquired.

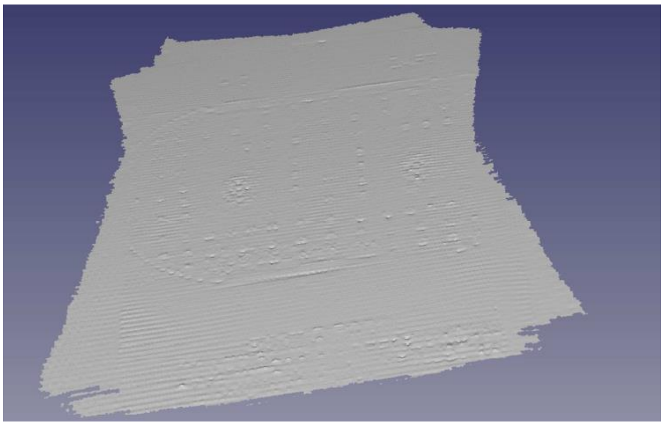


Fig. 16. Tridimensional scan of the static port area, the texture is visible.

B. *Scan analysis for defect detection*

The acquired point cloud is smoothed by moving least squares algorithm. Then, the normal and curvature information of each point in the point cloud is computed. A region-growing approach is used with this information to segment the point cloud defected regions and non-defected regions [31]. Fig. 17 provides a tridimensional scan of the aircraft. A crack and a bump are visible. Please refer to Fig. 18 for results. Bounding boxes encompass the defected regions to provide sizes and orientations. The depth is computed with a comparison between the ideal smooth surface and the actual inspected one.

The tests performed in [31] show that the total processing time varies between 20 s and 120 s. There is some place for code improvement regarding computation time. One can note that, thanks to its two redundant computers, the robot can in parallel navigate to continue the mission and compute the results at same time.

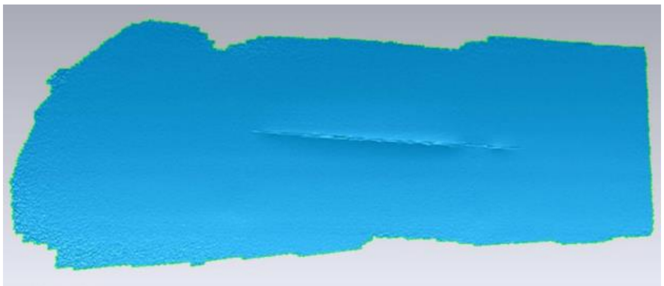


Fig. 17. Tridimensional scan of the aircraft, a crack and a bump are visible.

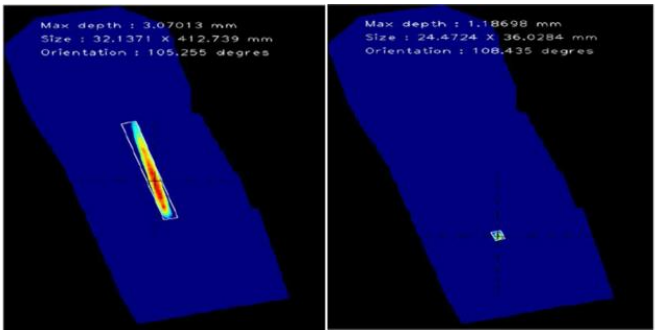


Fig. 18. The algorithm provides shape, size and depth of surface imperfections with visual color representation to help the human operator.

Conclusions and Prospects

The Air-Cobot project provides new automatic and accurate capabilities to support human operators during aircraft maintenance operations. The present work proposes a robust approach regarding safe autonomous positioning of a 3D acquisition device for surface analysis by managing the scanner position system simultaneously through the robot position and the height of the scissor.

The elevation system brings the scanner at the correct height to scan the region of interest. Safety measures avoid involuntary contact between the top of the system and the fuselage. Rotary motion of the motor enables to check the elevation system at the start and end of its movement and compare it to the task order. Moreover, the PTU control system is able to perform various kinds of movements to provide accurate acquisitions for different part of the aircraft. The scan analysis enables to detect defects such as bumps, hollows and rifts, which could have significantly impact on aircraft operability.

In the chosen inspection contexts, the localization was sufficient to avoid a collision between the top of the system elevation and the fuselage. Further hardware and software investigations will be made for more complex situations considering specific pose under the aircraft or under the wings.

With the proposed independent, low-cost and easily replaceable visual cues and associated automatic checking methods, the scissor lift is visually checked at the beginning and ending of each of its movements. In the future development, the deployment will be analyzed in real time with the video data coming from PTZ camera.

The fundamental part of the proposed method does not need to be changed if other types of lift or 3D scanner are used. The actual control system is fully operational in indoor conditions. It is only useable outdoor in correct weather conditions with low wind speed. The current presented robot is a prototype and further development investigations are on-going to increase the robustness of the system to cope with more extreme weather conditions.

Prospects of the whole project deal also with increasing the use of intelligence algorithm in airport and hangar in order to benefit from a more efficient global environment implying autonomous vehicles, drones, cobots to help human operators, video monitoring… [32]

Acknowledgments

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

References

[1] L. E. Parker, and J. V. Draper, “Robotics applications in maintenance and repair”, in S. Nof (Eds.), Handbook of Industrial Robotics, 2nd Edition, John Wiley & Sons, 1999.

[2] A. Kroll, “A survey on mobile robots for industrial inspection”, proccedings of the 10th International Conference on Intelligent Autonomous Systems (IAS), 2008.

[3] M. Siegel, P. Gunatilake, and G. Podnar, “Robotic assistants for aircraft inspectors”, IEEE Instrumentation Measurement Magazine, 1998.

[4] S. Birch, and L. E. Trego, “Aircraft stripping and painting”, Aerospace Engineering, 1995.

[5] J. E. Baker, J. V. Draper, F. G. Pin, A. Primm, and S. Shekhar, “Conceptual design of an aircraft automated coating removal system”, proceedings of 6th International Symposium on Robotics and Manufacturing (ISRAM), 1996.

[6] T. S. White, R. Alexander, G. Callow, A. Cooke, S. Harris, and J. Sargent. “A Mobile Climbing Robot for High Precision Manufacture and Inspection of Aerostructures”, International Journal of Robotic Research, 2005.

[7] J. Shang, T. Sattar, S. Chen, and B. Bridge, “Design of a climbing robot for inspecting aircraft wings and fuselage”, Industrial Robot: An International Journal, 2007.

[8] N. Colin and F. Guibert, “Collaborative robot for visually inspecting and aircraft”, Patent WO2015059241 (A1), 2015.

[9] SensaBot Inspection Robot. Robotics Institute, Carnegie Mellon University. http://www.rec.ri.cmu.edu/solutions/energy/sensabot-inspection-robot.html [Accessed: Oct. 24, 2017].

[10] RIANA http://www.new.areva.com/EN/news-10553/nuclear-facility-dismantling-areva-delivers-first-riana-robot-to-the-cea.html [Accessed: Oct. 24, 2017].

[11] OZ Weeding robot, Naïo Company, Toulouse https://www.naio-technologies.com/en/agricultural-equipment/weeding-robot-oz/ [Accessed: Oct. 24, 2017].

[12] UAV aircraft inspection, Donacle Company, Toulouse, https://www.donecle.com/technology/ [Accessed: Nov. 22, 2017].

[13] Paint-Stripping Robot for aircraft, USA https://www.cmu.edu/homepage/computing/2012/fall/paint-stripping-robot.shtml [Accessed: Nov. 22, 2017].

[14] F. Donadio, J. Frejaville, S. Larnier, and S. Vetault, “Human-robot collaboration to perform aircraft inspection in working environment”, proceedings of 5th International conference on Machine Control and Guidance (MCG), 2016.

[15] M.-A. Bauda, C. Bazot, and S. Larnier, “Real-time ground marking analysis for safe trajectories of autonomous mobile robots”, IEEE International Workshop of Electronics, Control, Measurement, Signals and their application to Mechatronics (ECMSM), 2017.

[16] J. Frejaville, S. Larnier, and S. Vetault, “Localisation à partir de données laser d'un robot naviguant autour d'un avion”, proceedings of Reconnaissance des Formes et l'Intelligence Artificielle (RFIA) congress, 2016.

[17] I. Jovančević, I. Viana, J.-J. Orteu, T. Sentenac, and S. Larnier, “Matching CAD Model and Image Features for Robot Navigation and Inspection of an Aircraft”, proceedings of the 5th International Conference on Pattern Recognition Applications and Methods (ICPRAM), 2016.

[18] M. Futterlieb, V. Cadenat, and T. Sentenac, “A navigational framework combining visual servoing and spiral obstacle avoidance techniques”, proceedings of 11th International Conference on Informatics in Control, Automation and Robotics (ICINCO), 2014.

[19] I. Jovančević, S. Larnier, J.-J. Orteu, and T. Sentenac, “Automated exterior in-spection of an aircraft with a pan-tilt-zoom camera mounted on a mobile robot”, Journal of Electronic Imaging, 2015.

[20] I. Jovančević, A. Arafat, J.-J. Orteu and T. Sentenac, "Airplane tire inspection by image processing techniques", Proceedings of 5th Mediterranean Conference on Embedded Computing (MECO'2016), 2016.

[21] T. Villemot, S. Larnier, and S. Vetault, "Détection d'amers visuels pour la navigation autour d'un avion et son inspection", proceedings of Reconnaissance des Formes et l'Intelligence Artificielle (RFIA) congress, 2016.

[22] J. Ramirez Leiva, T. Villemot, G. Dangoumau, S. Larnier and M.-A. Bauda, "Automatic visual detection and verification of exterior aircraft elements", IEEE International Workshop of Electronics, Control, Measurement, Signals and their application to Mechatronics (ECMSM), 2017.

[23] B. Apolloni, A. Ghosh, F. Alpaslan and S. Patnaik, "Machine Learning and Robot Perception", Springer Science & Business Media, 2005.

[24] Stéréla, "4MOB: autonomous intelligent platform", V1509, 2015. [Online]. Available: http://www.sterela.fr/ [Accessed: Jan. 2, 2017].

[25] Axis Communications, "AXIS Q6045- E Mk II PTZ Dome Network Camera: User Manual", Part No. 1463329, May 2015. [Online]. Available: http://www.axis.com [Accessed: Jan. 2, 2017].

[26] Artec 3D, "Professional 3D scanning solutions", 001-05/2016-EUR-ENG, 2016. [Online] Available: https://www.artec3d.com [Accessed: Nov. 16, 2017].

[27] SuperDroid Robots, "58 inch Electric Scissor Lift with Controls", WC-063-058, 2016. [Online] Available: http://www.superdroidrobots.com [Accessed: Jan. 2, 2017].

[28] Flir Systems, "PTU-D46", Technical Specifications, February 2009. [Online] Available: http://www.flir.com/mcs/pdf/specs-ptu-d46.pdf [Accessed: Jan 2, 2017].

[29] A. Comport, E. Marchand, M. Pressigout, and F. Chaumette, "Real-time markerless tracking for augmented reality: the virtual visual servoing framework", IEEE Transactions on Visualization and Computer Graphics, 2006.

[30] E. Marchand and F. Chaumette, "Feature tracking for visual servoing purposes", Robotics and Autonomous Systems, 2005.

[31] I. Jovančević, "Exterior inspection of an aircraft using a Pan-Tilt-Zoom camera and a 3D scanner moved by a mobile robot: 2D image processing and 3D point cloud analysis", doctoral thesis, Université de Toulouse, France, 2016.

[32] F. Donadio, J. Frejaville, S. Larnier, and S. Vetault, "Artificial intelligence and collaborative robot to improve airport operations", proceedings of 14th International Conference on Remote Engineering and Virtual Instrumentation (REV), 2017.

[33] K.O. Arras and O.M. Mozos and W. Burgard, "Using Boosted Features for the Detection of People in 2D Range Data", IEEE International Conference on Robotics and Automation, 2007.