POSITIONING NDT SENSORS WITH A MOBILE ROBOT FOR EFFICIENT AIRCRAFT INSPECTIONS

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Abstract. Non Destructive Testing is one of the major tasks in Maintenance, Repair and Overhaul (MRO) processes in the aircraft industry. For MRO companies as well as for the airlines it is important that NDT is performed both thoroughly and efficiently.

Currently, NDT processes are mostly performed manually. To increase efficiency and to minimize the risk of errors, automation of NDT processes is desirable.

The Institute of Aircraft Production Technology (IFPT, Technische Universität Hamburg-Harburg) and the innovation management department of Lufthansa Technik are developing a mobile robot which is able to perform automated NDT inspections on aircraft fuselages. The robot has a universal tool platform on which a wide range of NDT sensors can be mounted.

For performing automated inspections, an accurate localisation system for the robot is required. This system needs to take into account that airplanes are affected by significant dimensional tolerances. This paper presents a localisation concept with which the robot's position on airplanes can be determined. It involves a thermographic identification of local airplane structure and a matching to a prebuild map.

The development of the universal inspection robot and its localisation system is an important step to increase the automation and efficiency of NDT processes in the aircraft industry.

1. Introduction

To keep aircraft save and airworthy, the aviation authorities and aircraft manufacturers specify MRO checks of different intensity. Every commercial airplane has to undergo these checks regularly. A major part of them is based on NDT processes. Since there is a variety of potential damages (e.g. cracks, scratches, dents) nearly all kinds of NDT technologies are used for the inspections. [3] gives an overview of 8 NDT technologies and their applications in aircraft maintenance.
Because of the complexity of NDT tasks, also caused by the dimensional tolerances of airplanes, NDT tasks are currently mainly performed manually. To increase efficiency and to minimize the risk of errors, automation of NDT processes is desirable.

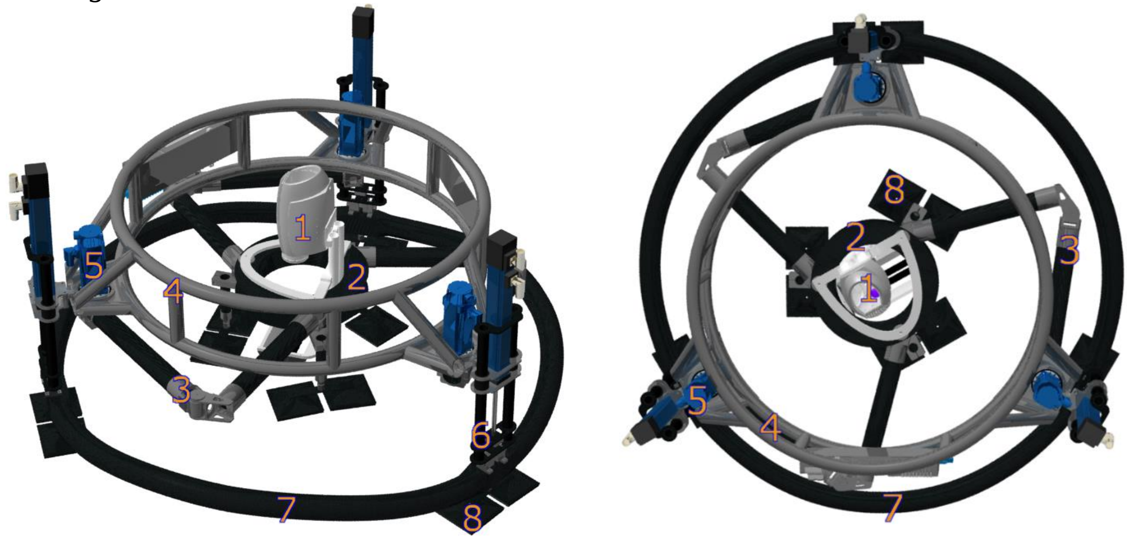
First approaches of the use of mobile robots for automation in the aircraft industry have been made [1, 6]. But it is further on a topic of current research. Boeing has recently developed a mobile robot for Non Destructive Examination [2]. This robot adheres to the aircraft by vacuum elements. The movement is performed by four mecanum wheels. In [7] another robot is presented which is able to position an NDT sensor for aircraft inspections. This robot adheres to the aircraft by multiple vacuum chambers. Its movement is performed by two differential controlled wheels.

These robots are not able to position their inspection devices with 6 DOF. This limits their cases of applications. If an NDT sensor is to be guided precisely with a specific angle along the fuselage, a 6 DOF-positioning is required. Besides NDT tasks there are various other tasks in aircraft maintenance which require 6 DOF-positioning, for example drilling rivet holes or scarfing processes.

This paper presents the development of a universal inspection robot which is designed to climb on an aircraft surface to position NDT sensors with 6 DOF and perform fuselage inspections automatically. The paper covers a description of the robot's design and its positioning of the inspection device on the airplane. For automated positioning of the inspection device, an accurate localisation of the robot is required. This paper presents a new approach which involves a two-staged localisation concept for precise positioning on tolerance affected airplanes.

2. Mobile inspection robot

2.1 Design



Pic. 1: design of mobile inspection robot

The robot consists of a serial link-up of two parallel mechanisms. The first mechanism enables a movement of the tool platform (2, see *Pic. 1*) which contains the NDT sensor (1) within the outer frame (4). This is performed by rotary motors (5) which power three to the tool platform connected arms (3). The second mechanism enables vertical movements of the first mechanism as well as tilting movements. This is performed by linear motors (6) which can be independently controlled. On the tool platform as well as on the base frame (7) of the second mechanism there are vacuum cups installed (8) by which the robot adheres to the aircraft surface.

This specific design enables the robot to move along the aircraft surface on the one hand, on the other hand it enables the positioning of the NDT sensor with six degrees of freedom.

The movement is being performed by alternating the attachment of the robot by the vacuum cups of the base frame and moving the tool platform, and its attachment by the vacuum cups of the tool platform and moving the base frame.
Further information about the robot concept is described in [5].

2.2 Application

The first application of the robot was the crack detection in airplane skin. This was done by an active thermographic system installed on the robot's tool platform.
The robot has been developed as a universal inspection robot. Thus, on its tool platform there can be installed various other inspection tools. The additional payload which the robot can carry is 20kg. For the NDT inspection device there is power supply and compressed air supply available, as well as an Ethernet connection for real-time data transfer.

The robot has been tested under real conditions on the aircraft. Its attachment to the aircraft surface with its vacuum cups and the movement of NDT sensors with regard to the fuselage curvature was successful. *Pic. 2* shows a picture of the aircraft tests.

Pic. 2: Testing of the mobile robot

3. Localisation

To perform automated aircraft inspections, the determination of the position of the robot on the aircraft is required. As for nearly every mobile robot the internal odometry system, which determines the position by adding up the controlled movements, is not accurate enough. This is because with the movements little errors sum up to not acceptable position errors. Thus a localisation concept for the robot is being developed.

3.1 Related work

The above mentioned Boeing robot is localised with the in-house developed 'Local Positioning System' [2]. This system uses a camera which is installed on a motorized pan-tilt system which is positioned on the ground next to the airplane. With an attached laser-range-meter the distance to the robot is being measured. The information of the distance to the robot, the angles of the pan-tilt mechanism and the taken images of the targets on the robot is used to determine the coordinates of the robot. This system is patented under US8447805 B2 [4].

In [7] a mobile robot for NDT inspections of airplane structures is described which uses a laser tracker for localisation. A pan-tilt mechanism is installed on the robot which focuses the reflector target to the laser tracker at any time. By fusing the laser tracker data and the angle data of the pan-tilt mechanism a precise absolute position of the robot is determined.

These methods of external absolute localisation have two main disadvantages. The first is that they do not take into account that airplanes have significant dimensional tolerances. Their dimensions vary for example with the current payload, but also with the number of flight cycles due to mechanical stress. On an airplane with these tolerances there might be a significant difference between the robot's actual position and the position which is determined by the external absolute localisation system.

The second disadvantage is that in the maintenance documents positions are mostly not given absolutely but in relation to a structure element. Usually stringer and frames are used as references for relative positions.

The next section describes the developed localisation concept with which both these disadvantages can be avoided.

3.2 Concept description

To compensate the issues of absolute external localisation systems described above, the developed localisation concept for the addressed robot consists of two stages. In the first stage an external localisation system estimates the approximate position of the robot. This stage will further be referred to as <u>approximate localisation process</u>. As described such a system can only provide position information of limited use.

Thus, in the second stage, an on the robot installed thermography system identifies structural elements of the airplane and determines its position in relation to these local references. The acquired thermographic images of the structural elements will not be unambiguous so after the identification of structural elements there might still be several possible positions of the robot on the airplane. With the information of the approximate localisation process the structures can be unambiguously allocated so that the position of the robot is precisely known. This stage will further be referred to as <u>precise localisation process</u>.

For this concept it is assumed that even for airplanes with significant global tolerances, the tolerances of local positions in relation to near structure elements are negligible.

3.3 Approximate localisation process

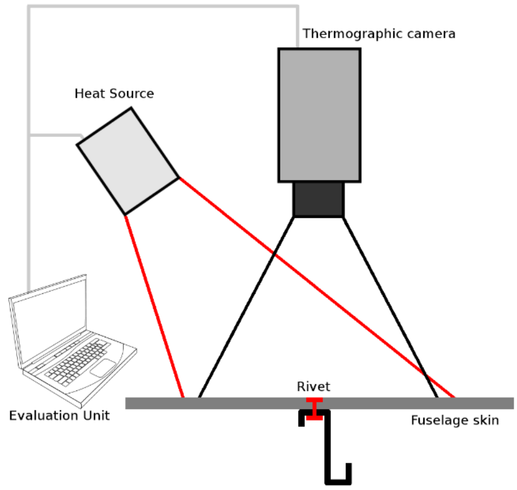
The determination of the robot's approximate position can be done by an external localisation system, for example by using one of the systems described in 3.1. There are various other applicable systems, e.g. radio-based indoor positioning systems. With this system the robot's approximate position on the airplane is estimated. The information is used in the precise localisation process to correctly allocate detected structures. The required accuracy of the approximate localisation system depends on the minimum distance of near structure elements which are used in the precise localisation process.

3.4 *Precise localisation process*

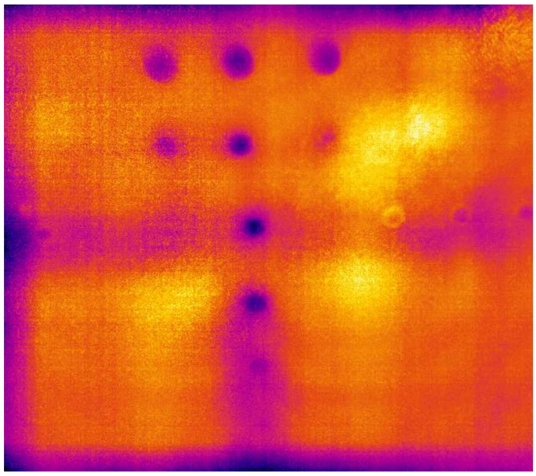
For the precise localisation of the robot on tolerance affected airplanes it is necessary that the robot uses local references on the aircraft surface to determine its position in relation to the references. These references can be structural elements of the airplane.

As described in 3.1, positions in maintenance documents are mainly given in relation to stringer and frames. Since these elements are underneath the airplane surface and thus difficult to detect, it has been chosen to use the rivets, which connects the elements to the skin, as local references.

The first step is to detect the rivets. Since they are installed into the aircraft skin and covered with paint, visual techniques, for example with cameras, are not reliable. Thus, for the detection it has been chosen to develop a thermographic camera system. This system consists of a thermographic camera, a heat source and an evaluation unit.
The principle is shown in *Pic. 3*.



Pic. 3: Principle of rivet detection



Pic. 4: Thermographic image

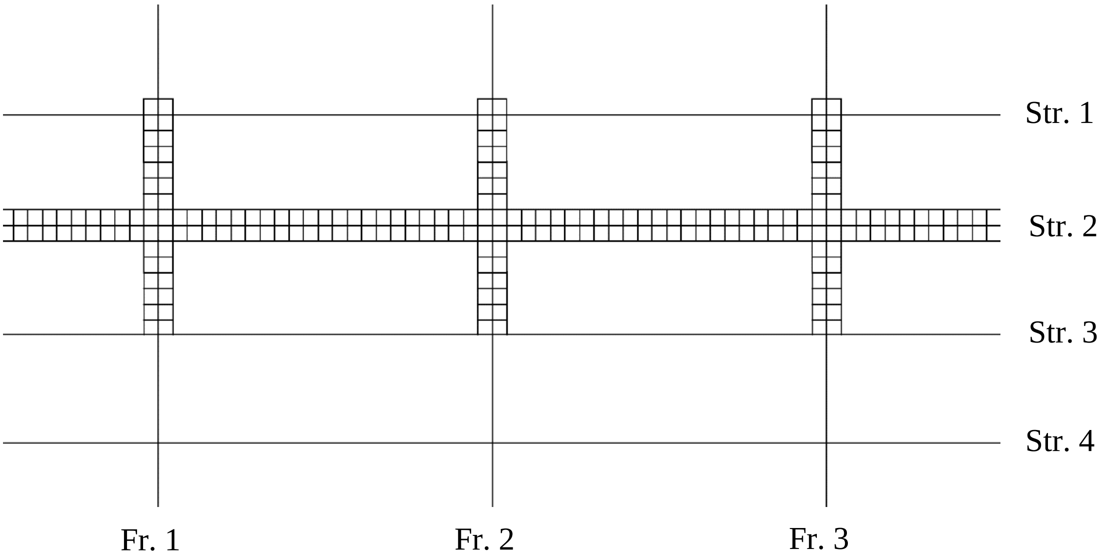
For the detection of rivets the heat source heats up the fuselage skin. Since the rivets have different heat transfer properties than the skin they heat up slower at the surface. Thermographic images are taken and transferred to the evaluation unit for viewing and further processing. An example of such a thermographic image is shown in *Pic. 4*. The bright areas indicate warm, the dark areas indicate comparatively cold surfaces. The dark circular spots show rivets.

3.5 Rivet map

For the localisation of the robot the detected rivets need to be associated with their actual positions. Therefore a map has been developed in which the rivet positions are registered. By matching the detected rivets with this rivet map, it is possible to determine the robot's position.

Since there is a large quantity of rivets installed in an airplane, and not every position of every rivet is precisely known, it is very difficult to match single rivets correctly. It seems to be a more reliable approach to match lines of rivets, so that irregular distances or a slight offset of single rivets can be compensated. The developed rivet map for this approach consists of lines which show where rows of rivets are located. An additional advantage of this map is that the map building is simple in comparison to other robot map building methods, which involve for example an entire sensorial acquisition of the robot's environment.

The figure below shows the visualisation of the rivet map for a surface area of an Airbus A-300 aircraft. This aircraft type is being used for testing and evaluation of the presented concept.



Pic. 5: Rivet map for robot localisation (schematic view)

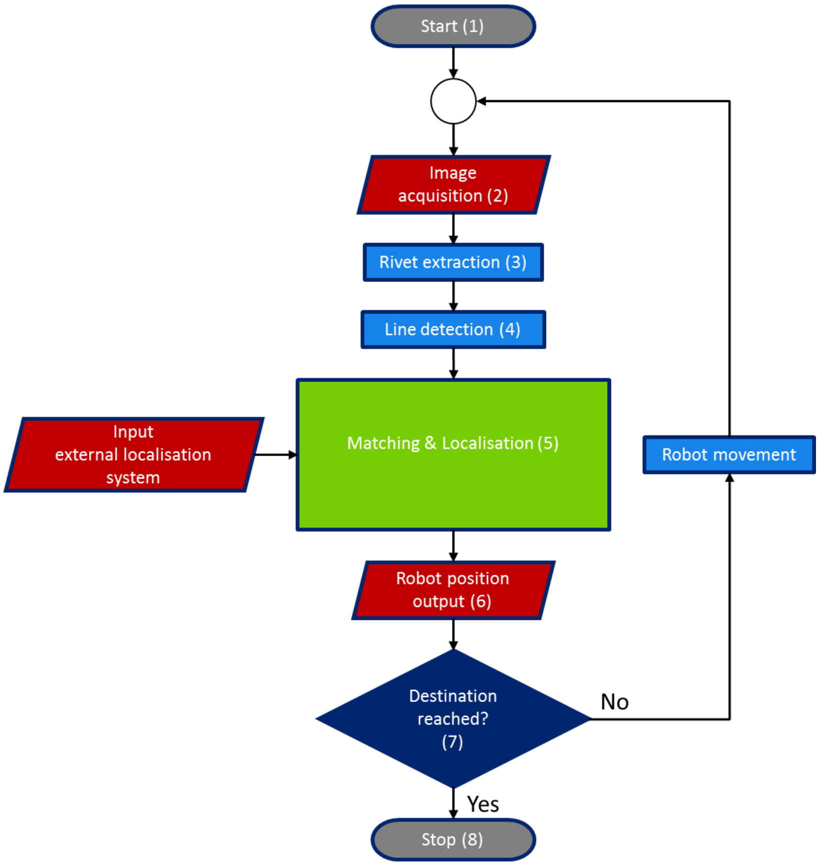
The horizontal lines in *Pic. 5* show the position of stringers, the vertical lines show the position of the frames. These structure elements are generally joint with the skin by a single row of rivets. At specific locations there is more than one rivet line. As shown at stringer 2 there are 3 parallel rows of rivets. In that area is a lap joint of the skin. At any intersection of a lap joint to a frame there is on each side of a frame a row of 16 rivets in total.

The localisation of the robot is most accurate in horizontal and circumferential direction if the intersection of a stringer rivet row and a frame rivet row is detected and correctly referenced. Due to the workspace of the robot there is at least one of these intersections at any position of the robot. The correct referencing of an intersection to the actual stringer-frame intersection is ensured by the external localisation system described in section 3.3. This system needs an accuracy of the minimum distance between two next to each other located rivet rows. In this application it is the distance between two stringers which for Airbus A-300 aircraft is 185mm.

3.6 Localisation process

The localisation process, also shown in *Pic. 6*, consists of the following steps:

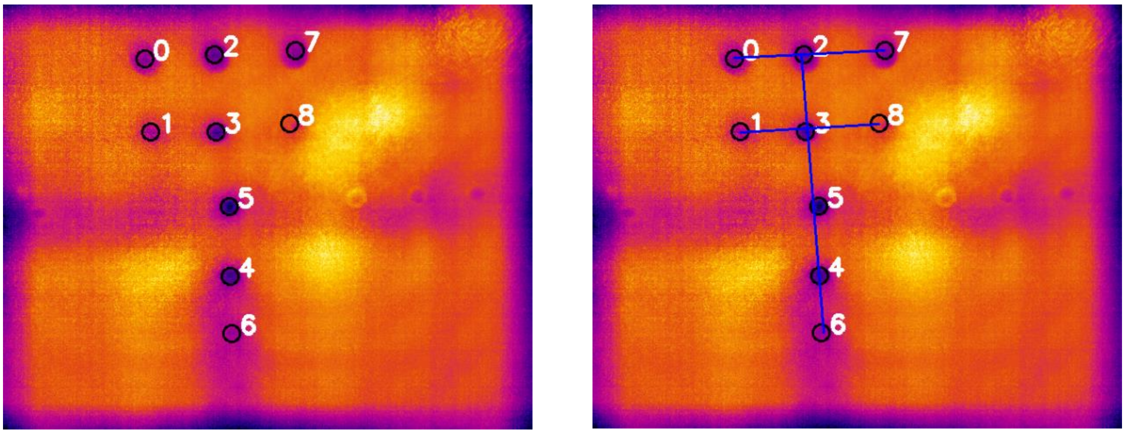
(1) At the start the robot is attached at an arbitrary position on the aircraft fuselage.
(2) With the thermography system a thermographic image of the surface structure is acquainted.
(3) From this image the center points of the rivets are extracted.
(4) Lines are fitted through the center points to determine rivet rows.
(5) Matching and localisation algorithms are applied to determine the position of the robot.
(6) The determined robot position is output.
(7) If the robot's destination is reached the localisation was successful and the process stops (8). Otherwise the robot is moved according to the results of step 5 and the process starts again.



Pic. 6: Localisation process

Step 5 is the core of the localisation process. The aim is to localise the robot at a stringer-frame intersection which would in most cases be two perpendicular lines in the image. Robot movements are necessary to find the closest stringer-frame intersection. The direction of these movements will also be determined within this step. For referencing correspondences to the structure, the information of the external localisation system is used, which limits the number of possible positions on the airplane to 1.

The extraction of the rivets has been implemented. Template matching and contour algorithms are used to get the coordinates of their center points. Line algorithms have been developed to fit lines through a minimum of three rivets. Applied to the image shown in *Pic. 4* the center point identification and line detection is shown in the figure below.



Pic. 7: Image processing. Left: Rivet extraction. Right: Line detection

The left figure in *Pic. 7* shows the extracted rivets. The circles visualize where the center points of the extracted rivets are located. The right figure shows the lines which are fitted through the center points by the developed algorithms.

Currently the work focuses on the implementation of the matching and localisation algorithms. So far the information about the distances and angles between the rivets rows, the involved number of rivets for each line and their distances to each other can be retrieved. In the next step this data will be used together with the data from the external localisation system to find the robot's position on the rivet map. It will be implemented that in case a localisation is not possible the robot needs to move in a certain direction according to the results to find a stringer-frame-intersection.

4. Conclusion

In this paper a new approach for the precise localisation of a mobile NDT inspection robot on tolerance affected airplanes is described.

It consists of two stages and combines an approximate localisation process with a precise localisation process. The precise localisation process uses local structure elements of the airplane to determine the robot's position in relation to the structure element. This is done by matching processed thermographic images with a developed map in which the structure elements are registered. The approximate localisation process is necessary to allocate the identified structure elements correctly to their position on the airplane.

The extraction of the structure elements from the thermographic image has been implemented. Algorithms have been developed to make them usable for the map matching.

Further work needs to be done to implement the map matching algorithms and to determine the robot's position.

The robot itself has been tested under real conditions on the airplane. The robot's attachment and the movement on the aircraft could be performed successfully. The next phase is the embedding of the localisation system into the robot.

References

[1] Bar-Cohen, Y. Scanning Large Aerospace Structures Using Open-Architecture Crawlers.

[2] Georgeson, G. 2013. Trends in R&D for Nondestructive Evaluation of In-Service Aircraft. *5th International Symposium on NDT in Aerospace*.

[3] ndt.net. 2006. *Non-destructive Testing Applications in Commercial Aircraft Maintenance*. http://www.ndt.net/article/ecndt98/aero/031/031.htm. Accessed 20 August 2015.

[4] 2013. *Patent US8447805 - Distributed operation of a local positioning system*. http://www.google.com/patents/US8447805. Accessed 30 July 2015.

[5] Schlosser, C. and Schüppstuhl, T. 2014. Numerical controlled robot crawler: new resource for industries with large scale products. *Production Engineering* 8, 6, 719–725.

[6] Shang, J., Satter, T., Chen, S., and Bridge, B. 2007. Design of a climbing robot for inspecting aircraft wings and fuselage. *Industrial Robot: An International Journal*, 34/6 (2007), 495–502.

[7] White, T. S. 2005. A Mobile Climbing Robot for High Precision Manufacture and Inspection of Aerostructures. *The International Journal of Robotics Research* 24, 7, 589–598.