

ROBAIR: MOBILE ROBOTIC SYSTEM TO INSPECT AIRCRAFT WINGS AND FUSELAGE

Tariq P. Sattar, Shuwo Chen, Bryan Bridge, Jianzhong Shang
Center for Automated and Robotic Non-Destructive Testing
South Bank University, 103 Borough Road, London SE1 0AA
sattartp@sbu.ac.uk; chens@sbu.ac.uk; bridgeb@sbu.ac.uk

The ROBAIR project is developing a robotic system for the non-destructive testing of rows of rivets and surfaces on the wings and fuselage of commercial aircraft. The system can climb on the outside surfaces of aircraft wings and fuselage and deploy a payload of sensors with a scanning arm. The payload of sensors consists of ultrasonic phased arrays and compression probes, an acoustic camera, eddycurrent sensors and a thermographic camera. This paper focuses on the climbing robot that carries a Cartesian scanning arm and payload of sensors while walking on the topside and underside of wings and on varying surface curvatures presented by the fuselage of different types of aircraft.

1. INTRODUCTION

Around the World, a great variety of fixed wing aircraft carry more than a billion passengers each year. To ensure passenger safety, an enormous inspection and maintenance effort is required on aircraft structures. It is estimated that inspection and maintenance accounts for 12% of the cost of flying a Boeing 747 from London to New York. Regular inspection and maintenance of wing joints and fuselage is a salient feature of the maintenance schedule of airlines as failure in these regions can be catastrophic. Most of this inspection is done manually with visual inspection backed up with limited area coverage using nondestructive evaluation techniques. The common techniques used are eddycurrent, ultrasonic and X-rays.

Manual inspection performed over large areas, for example rows of hundreds of rivets holding the skin together, is time consuming and leads to fatigue induced errors. There is the problem of providing operator access to some parts of the aircraft during maintenance. Also, airlines now want a hardcopy of inspection data, and 100% inspection of vital structures e.g. aero-foils, wings, etc. This is very costly if done manually.

To reduce the cost of inspection and to improve the quality of non-destructive evaluation (NDE), a number of projects are developing mobile robotic devices to automate the inspection [Bar-Cohen and Backes, 2000; Siegel, 2000]. The other more expensive approach to automated inspection is a total structural inspection with a car wash type of robot [Bridge and Sattar, 2001].

Mobile robots that can climb on aircraft structures and deploy suitable NDE techniques are probably the most cost effective way to automate aircraft inspection as

they combine the advantages of transportability from aircraft to aircraft and the ability to carry out the inspection while other maintenance work is being carried out in a busy schedule.

The next section describes the ROBAIR European project that is developing a mobile inspection robot capable of deploying a range of NDE techniques to carry out the following inspections on aircraft structures:

1. Inspect along fastener lines for:
 - Cracks from fastener holes in both outer skin and inner skin or structure.
 - Corrosion between layers.
 - Lack of bonding between layers.
2. Carry out localized inspections on metallic and composite structures for:
 - Lack of bonding.
 - Impact damage.

2. ROBAIR ROBOTIC INSPECTION SYSTEM

2.1 Overview of the Inspection System

The robotic inspection system consists of the following sub-systems:

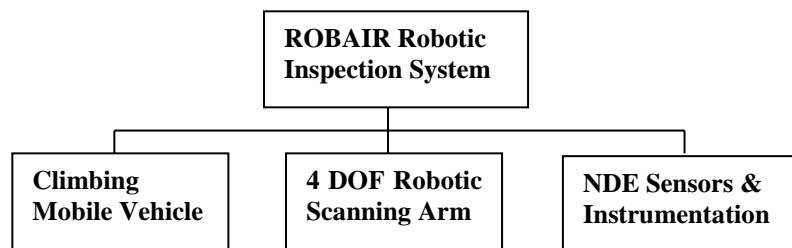


Figure 1 – Main modules of the ROBAIR inspection system

Climbing Mobile Vehicle

Access to the top-side and under-side of aircraft wings and fuselage is provided by a climbing vehicle that uses vacuum adhesion to adhere to a surface. The vehicle is a compact, fully pneumatically actuated climbing vehicle that is designed to:

- Climb on the topside and underside of aircraft wings and on all areas of the fuselage.
- Carry an 18 kg payload of scanning arm plus NDE Sensors with a safety factor of 4.
- Move over all surfaces with curvatures less than 0.3m^{-1}
- Travel with a maximum speed of 1m/min.

Robotic Scanner

A scanning arm is mounted on the climbing vehicle. It deploys NDE sensors in a work envelope of volume 400 x 400 x 180 mm. It is designed to have:

- Light construction
- 4 degrees of freedom (X,Y, Z and Roll)

- Control systems that will adapt to the changing dynamics of the inspection device as it operates on different structures e.g. on a fuselage or top or bottom of aircraft wing
- Control systems with real time surface profile functions
- An anti-collision mechanism

Non-Destructive Evaluation Sensors and Instrumentation

The climbing vehicle and scanning arm carry a Flaw Detector and Sensor Payload that comprises of:

- Acoustic Camera Sensor
- Ultrasonic Phased Array Sensor
- Eddy Current Sensor
- Thermographic Camera and display software
- Interfaces for video images with other NDE displays
- Ultrasonic Dry Contact Wheel Probes
- NDE Sensor Holders
- Defect Visualization Software

3. THE CLIMBING VEHICLE

3.1 Previous Designs of Climbing Robots

The Center for Automated and Robotic NDT has developed a number of climbing robots over the past ten years that use vacuum adhesion and permanent magnet adhesion forces to climb on vertical surfaces. The vacuum adhesion climbing robots have invariably used a stepping gait to walk with each step requiring a set of vacuum suction cups to be alternatively lifted and placed on the surface. Typically, these designs require at least five linear actuators to lift or lower the suction cups while another two actuators are required for forward/backward motion, and a rotary actuator is required to change direction of motion. The speed of these robots is quite slow and structural vibration during release of the vacuum cups is usually a problem. Building these robots to cope with surface curvature adds more complexity to the mechanism as now the suction cups have to be oriented correctly for a normal presentation to the surface. Flexibility in the suction cup materials is also required which militates against the requirement for structural rigidity to reduce over-turning moments. Hence, the design has to trade-off payload carrying capability and adaptability to surface curvatures against increased dimensions /weight of the robot due to rigid and increasing number of complex mechanisms.

3.2 The ROBAIR Climbing Vehicle

The design of a vehicle that can provide access to aircraft outer surfaces is again that of a stepping robot that alternately picks and places suction cups while moving forward through actuation by linear pneumatic cylinders. The main research focus in this development was to

- decrease the mass of the robot with the re-engineering of components with

- lighter materials and modified structures.
- provide sufficient passive compliance in the suction feet to enable suction cups to adhere to surface curvatures that will vary during motion of the vehicle and whose direction of curvature would also change during this motion.
- reduce structural vibrations due to the flexibility provided in the adapting feet.
- reduce structural vibrations caused by residual vacuum in suction cups when lifting them off a surface.

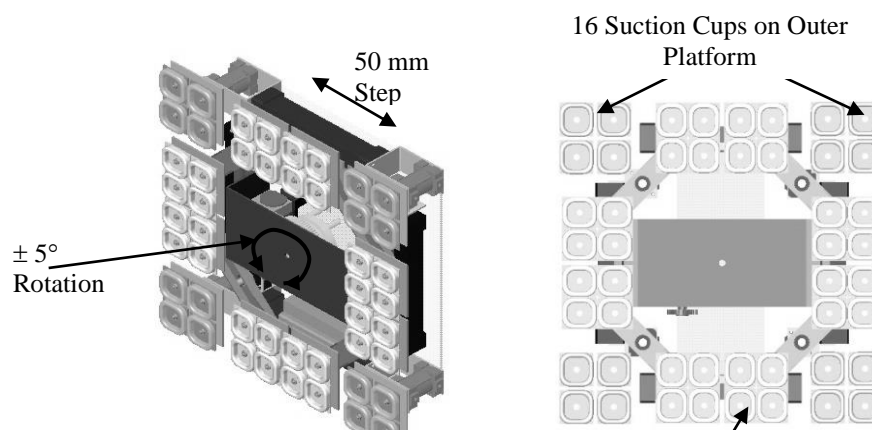
Figure 2 shows the design of a stepping, pneumatically actuated climbing vehicle. This arrangement of suction cups, actuating cylinders and motion axes allows the vehicle to move forward/backwards in 50 mm steps and to move sideways left/right with the same step. Hence, the orientation of the vehicle remains the same once it has been presented to the aircraft. Loss of orientation due to positioning errors and slippage is corrected by rotating the two platforms. A rotation axis is provided that can rotate each platform through $\pm 5^\circ$.

Figure 3 shows the plan and side views of the actual construction. The photograph on the right shows the climbing vehicle on a curved surface. In this picture only the inner platform of the vehicle is shown. A universal joint at the "ankle" of each foot allows the foot to adapt to a surface. In addition four suction cups mounted on each foot have a similar joint to permit each cup to present itself normally to the surface.

All actuators are pneumatically controlled by an on-board controller. The controller communicates with the operators console on the ground via two RS485 twisted pairs. Teleoperation of the vehicle from the ground is performed by sending high level commands to the vehicle where the controller interprets them to obtain the correct motion sequence.

Table 1 - Characteristics of the Climbing Vehicle:

Mass of climbing vehicle	20 kg
Outer Dimensions	518 x 518 x 180 mm
Payload including umbilical mass	18 kg
Payload Platform size	300 x 300 mm
Speed, straight-line motion	1 m/min
Motion	X-Y Step size 50 mm, Rot $\pm 5^\circ$
Electrical Supply	24 VDC
Air supply	Supply max = 10 bars, Operation 7 bars Volume = 580 l/min
Communication between vehicle/console	RS 485
On-board Vehicle Control system	Digital I/O, One Servo system and micro-controller
Umbilical	Two 10mm air pipes, Two twisted pairs for RS 485 Communications, Two wire cable for 24VDC supply



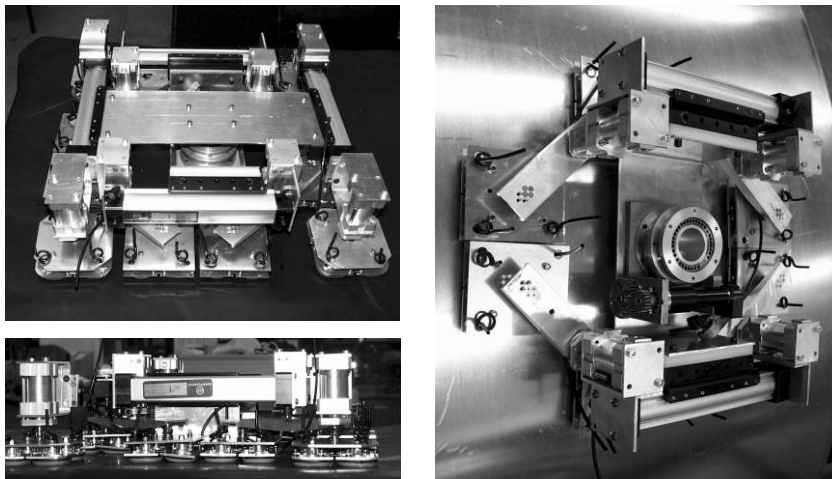


Figure 3 – Left: Top and Side Views of the Climbing Vehicle. Right: The Inner Platform of the Vehicle attached to a vertical “fuselage” section

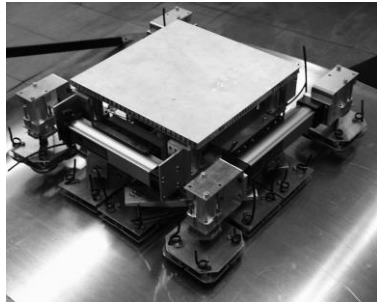


Figure 4 – Climbing Vehicle with payload platform

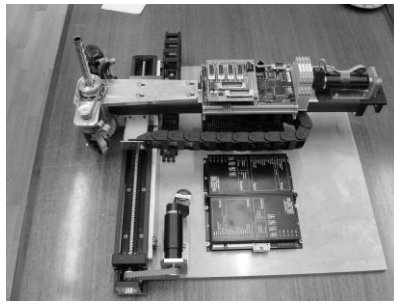


Figure 5 – 4 DOF Scanning Arm

4. THE SCANNING ARM

The scanning arm shown in Figure 5 is carried on the climbing robot shown walking on a 1.5-metre diameter pipe in Figure 4. The arm is a 4-axis Cartesian manipulator (X-Y,Z and 360° Roll) with a work envelope of 400 x 400 x 100 mm. With a current mass of 18 kg, it is within the payload capability of the climbing vehicle although further development is attempting to make it lighter. The mass includes all the servo-drives and controller which are carried on-board the vehicle. The umbilical cord comprises of a power cable and a twisted pair communications cable. The arm is equipped with sensors to detect obstacles in the way of a scanning trajectory and avoid collisions. Scanning trajectories for inspection are required to be linear scans along fastener lines, raster scans across a whole area, or pick and place movements for whole area inspection with phased arrays and acoustic cameras.

5. NDE SENSORS AND INSTRUMENTATION

The payload in Figure 6 of Non-destructive Evaluation sensors and systems is deployed by the climbing vehicle and scanning arm.

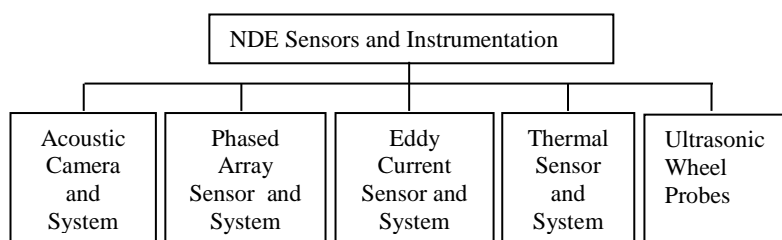


Figure 6 – NDE modules deployed by the robotic inspection system

5.1 Acoustic Camera Sensor and System

An Acoustic camera provides similar information to an ultrasonic C-scan without having to raster scan the test area with a probe. The camera can detect through thickness cracks in an aluminum component and metallic inclusions in a monolithic composite (commonly found in aerospace components) in through transmission and

pitch-catch mode. However, in most aerospace applications it is not possible to gain access to both sides of the panel or component being tested. Therefore, for practical testing purposes it is necessary to operate the acoustic camera from one side of the specimen only. Development work has been carried out to implement pulse-echo operation on an acoustic camera by employing a beam-splitter in the set-up and to increase camera sensitivity to detect typical damage in aerospace materials.

5.2 Phased Array Sensor

An aircraft wing has many sizes of rivets within a relatively small zone so a flexible ultrasonic design is required which can cope with a range of geometries. Manual inspection of rivet holes involves moving the probe from one rivet to an adjacent rivet in a straight line, maximizing the signal from the rivet, and then skewing the probe each side of the rivet. The probe is then turned round 180° and the scan repeated. This is a complex movement for a robot and would generate a great deal of data to process.

We have replaced this complex mechanical scan with two placements of a phased array probe which creates this pattern with an electronic/software generated equivalent scan pattern. By skewing the beam it can be maintained at normal incidence to the expected defect direction. Figures 7 and 8 show images obtained with a phased array 5MHz 32 element probe with each element having a 1mm pitch. A 6MHz probe with 0.6mm pitch has been designed and developed and will provide a smaller focal spot and a higher resolution image. Using image interlacing the resolution will be doubled from to 0.3mm.

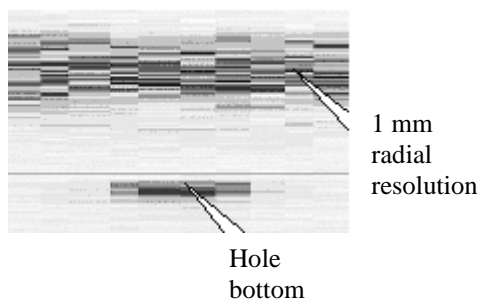


Figure 7 – D-Scan projection of defect free rivet hole with 5 MHz phased array probe

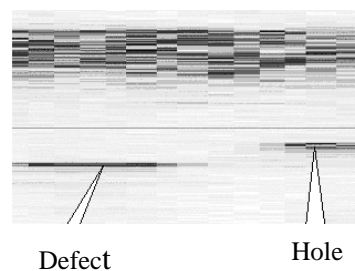


Figure 8 – Image of rivet hole with a 5mm deep radial defect.

5.3 Eddy Current Sensor

Eddy current probes scan the surface of the fuselage/aircraft wing etc to locate and determine whether or not any of the rivets have any defects. Tests are performed at two frequencies. Depth of penetration of the eddy current field increases with decreasing frequency. A high frequency test is conducted with AC applied to the test coil at MHz to detect cracks in the surface skin. A low frequency test uses AC frequencies from 100Hz to 100KHz to detect corrosion in the inner skin or sub-structure. Where an ultrasonic inspection is also required the eddy current instrument sends the co-ordinates of each rivet to a CPU, which then adjusts the unit

so that the ultrasonic phased array probe can carry out an inspection. The position of the fasteners is located with an accuracy of +/-1mm.

5.4 Thermographic System

Thermographic techniques to detect loose rivets and for other applications are potentially a very rapid process. For the technique to work, it is essential that the heat source is removed completely whilst the thermal imager scans the decay period. Our system uses a hot air source and directs the air through a nozzle for a given time and then mechanically rotates it away from the surface. Figure 9 shows the results of one test to detect a loose rivet with thermal imaging.

5.5 Solid Coupled Wheel Probe

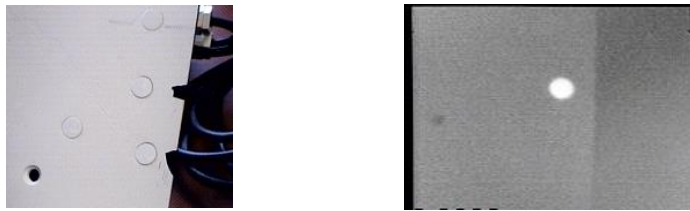


Figure 9 – Left: Loose rivet on a wing Right: Thermal image of loose rivet

Probes made of a thick hydrophilic polymer tyre that couples to the test surface and a 10 mm diameter immersion probe that is held within the fluid filled wheel are used to identify impact damage on composite wings and to measure aluminium skin thickness. The device operates in pulse echo mode. The use of hydrophilic material reduces the amount of water required to achieve consistent coupling and being a wheel of soft material it does not damage the surface.

6. ACKNOWLEDGMENTS

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