TOTAL INTEGRATED ROBOTIC STRUCTURAL INSPECTION FOR ENHANCED AIRCRAFT LIFE AND SAFETY (TIRSIEALS)

B. Bridge and T.P. Sattar
South Bank University
School of Electrical, Electronic and Information Engineering
Centre for Automated and Robotic NDT
103 Borough Road
London SE1 0AA
Bridgeb@sbu.ac.uk, Sattartp@sbu.ac.uk

ABSTRACT

Aircraft life can be extended, safety standards and passenger confidence enhanced, and structural inspection costs dramatically reduced, by establishing at major airports specialised 'Total Inspection Centres' that would be open 24 hours a day. Aircraft would be flown to these centres. Here every relevant type of Non Destructive Testing (NDT) sensor would be deployed by multi-axis robots moving on Cartesian gantries to cover the wing, fuselage, tail and rudder. Each inspection would produce a defect map of 100% of the aircraft surface. This is very unreliable if done manually because of operator fatigue.

A gantry robotic system has the advantage that very heavy NDT sensors such as X-ray tubes and SQUID magnetometers can be deployed in addition to all the more common sensors such as ultrasonic and Eddy current probe arrays. Acoustic emission monitoring of an entire airframe can be achieved with robotic scanning without the need for a vast and expensive array of sensors. This would be most useful for fuselage pressure testing.

At present NDT of aircraft is carried out in many relatively small units attached to individual airports that cannot possibly afford the whole range of NDT equipment and robotic deployment facilities. A specialised centre can do so and in addition achieve complete data fusion of the results from different sensors.

KEYWORDS: Aircraft Inspection, Aircraft NDT & NDE, Integrated Robotic NDT

INTRODUCTION

Regular Non Destructive Inspection (NDI) of civil aircraft is a mandatory requirement. Currently 90% of routine aircraft inspection is visual [1]. An inspector armed with a powerful flash light, using experience, intuition, doggedness and minute examination of surface dents, and bubbles etc. can find most types of flaw e.g. cracks and corrosion. Only in ambiguous cases are eddy current techniques employed (an estimated 90% of the 10% inspection that is instrumented). Ultrasonic inspection is used as a last measure. This NDI is mostly manual and restricted to limited area coverage. X-ray techniques are rarely used because they are expensive and require component removal.

However, this is not true for composite materials used in fighter aircraft where impact damage is nearly invisible and ultrasonic scanning of the entire surface becomes necessary.100% inspection performed manually is unreliable due to operator fatigue. There is therefore a requirement to automate this type of inspection.

In addition, pressurisation and de-pressurisation during takeoff/landing cycle causes stress fatigue at the rivets that hold the surface skin to its frame and results in growth of radial cracks. There are in excess of 2,000 rivets in a typical aircraft wing. Manual inspection of so many rivets once again becomes a problem and this task would benefit from automated inspection. Also, with increasing use of composites there is the requirement to test the full surface of aircraft wings and fuselage for bond quality (disbonds and delaminations), corrosion, impact damage, cracks around fastner holes, and to test fuel tanks internally.

While some tools have been developed to aid the inspection of aircraft, full automation has not yet been achieved. Portable Scanners for manual and semi-automated inspection have been around for some time e.g. the Portable C-scanner Bridge, fixed by straps or suction cups, has enabled semi-automation of ultrasonic field inspection using advances in microelectronics and PC development.

Flexible bridges have been introduced in recent years to deal with the complex geometry of aircraft structures e.g. PANDA (Tektrend, Quebec), MAUS (Boeing, St Louis), ISCAN (Fraunhofer Institute, Germany).

AUTOMATED INSPECTION

To advance the automated inspection of aircraft, two developments are needed:

- Thorough, correct & recordable NDE via automation. These are precisely the three operational and economic advantages of robotic deployment of NDE.
- New NDE methods (e.g. acoustic camera able to scan a large area in 1/10 time), phased arrays and fusion of techniques to obtain better detection e.g. combination of eddy current/ultrasonic/impedance matching.

There are three possible strategies for automating the inspection of aircraft:

The Surface Crawler

This approach uses a climbing mobile robot that can attach itself to the skin of the aircraft using pneumatic suction cups. It deploys NDT sensors by crawling over a surface or by using a multi axis arm to scan the surface. This is the most acceptable method to airlines provided the robot can be made friendly and easily operable by aircraft inspectors. Its main disadvantage is the management (in a cluttered environment) of the umbilical required to supply power, communication and control signals, compressed air for the suction cups of the crawler. A schematic diagram of such a crawler is shown in figure 1. Figure 3 shows an actual robot that could be used for aircraft inspection. The climbing robot (developed at the South Bank University, London) uses pneumatic suction cups and actuators and carries a seven degrees of freedom scanning arm (developed by ANSALDO, Italy). The robot can climb on curved surfaces such as a fuselage. A force sensor in the wrist of the arm allows specified contact forces to be maintained between the NDT probes and the skin surface (developed by the

University of Genoa, Italy). This is useful for maintaining good probe coupling with the surface. See [2] for an extensive review of Wall climbing robots.

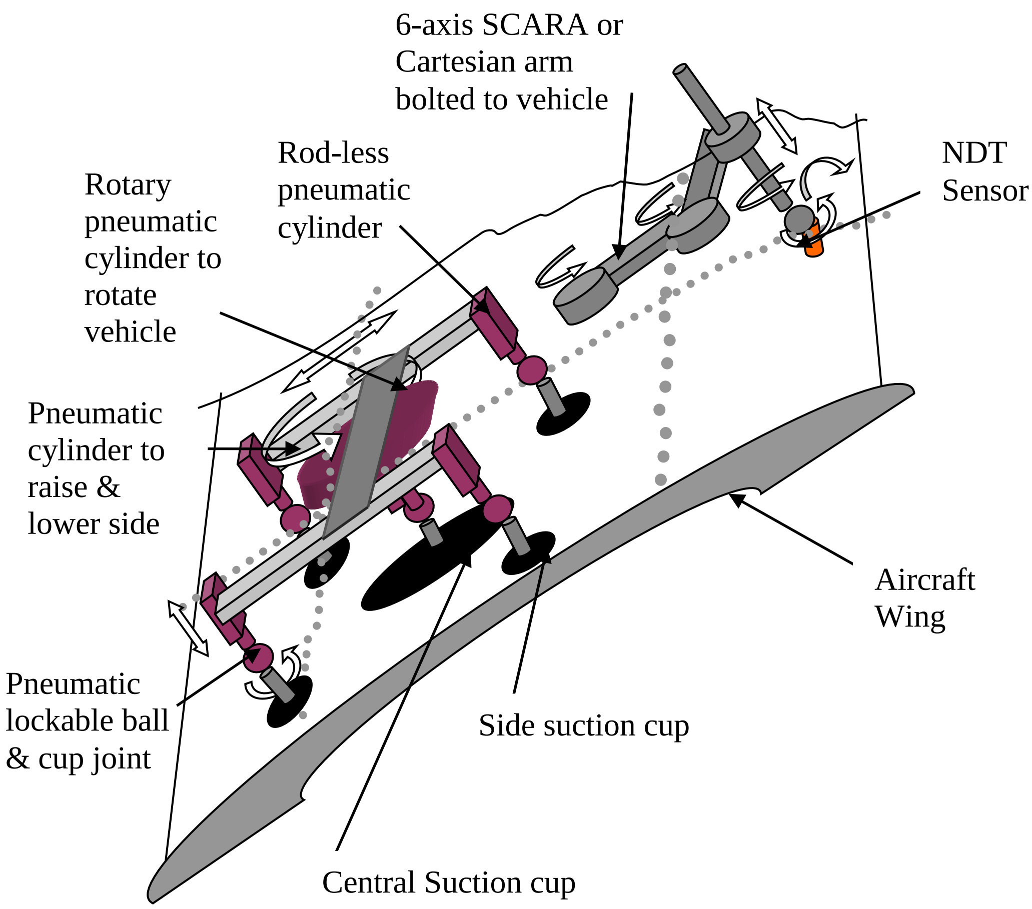

Figure 1: Schematic of Aircraft Skin Climbing Robot.

The following climbing robot developments for aircraft skin inspection and the motivation for their development are reviewed in [3]:

- Automated Non Destructive Inspector (ANDI) [Carnegie Mellon University].
- The Crown Inspection Mobile Platform (CIMP) [Carnegie Mellon University]. This is the only robot to have delivered field data to an aircraft inspector in the field.
- The Autocrawler [AutoCrawler LLC].
- Multifunction Automated Crawling System (MACS), NASA JPL [4].

Experience from the above developments indicates that the automation of Non Destructive Inspection will be acceptable to the industry only when the visual inspection can be automated to produce equivalent or better results than human inspectors. The automation should be lightweight and free of umbilical cables. On-board power sources will last for any length of time only if manipulators are discarded and phased arrays, electronic steering and miniaturisation of the NDT probes, magneto-optic techniques, etc are used to compensate for inexact vehicle positioning. Methods that accurately deploy a single probe should be scrapped.

Figure 2: Example of a 'Cherry Picker'

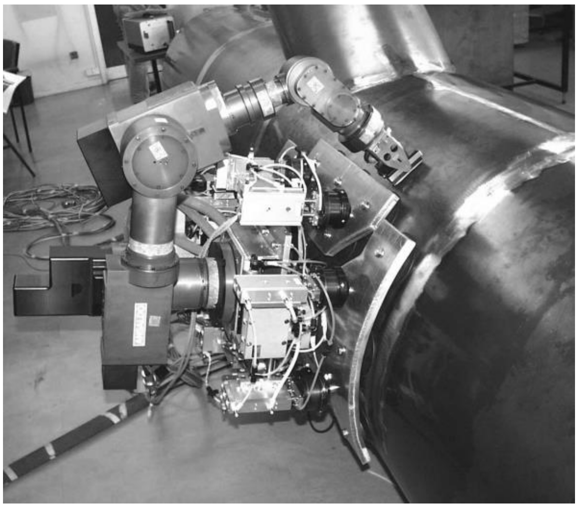

Figure 3: Climbing Robot with 7 DOF Arm and a Payload of NDT sensors

The "Cherry Picker" Approach

Technically this is considered to be a better solution. A teleoperated vehicle with a large arm is used to deploy inspection devices (see figure 2). This approach meets resistance from maintenance and inspection managers (collision fears for automatic or teleoperated cherry pickers and the floor space is too cluttered and busy).

The "Car Wash" Approach

An aircraft is flown in for inspection to a specialised testing facility. A gantry robot arrangement is technically the best solution to total aircraft inspection. For routine and regular inspection this approach conflicts with economical operation in the civilian sector where a quick turnaround of the aircraft is required and maintenance workers, cleaners and inspectors are required to work on the aircraft at the same time. However, aircraft needing total inspection with the view to life extension could be flown to such specialised centres which would be in use 24 hours a day. This seems a much more realistic future for aircraft NDT than a continuation of what has happened until now. At present NDT of aircraft is carried out in many relatively small units attached to individual airports, often with an NDT service company being called in. Such small units and service companies cannot possibly afford the whole range of state-of-the-art NDT equipment and any associated robotic deployment facilities that is affordable by specialised centres. Therefore such small inspection units cannot hope to provide such a comprehensive inspection service than could our proposed specialised centres. A specialised centre can achieve complete data fusion of the results from different sensors whilst smaller inspection units cannot do this.

AIMS OF THE PROPOSAL

The aim of this proposal is to extend the life of existing and future aircraft whilst enhancing safety standards and passenger confidence, with dramatically reduced aircraft structure inspection costs. This is to be achieved through the concept of specialised

‘Total Inspection Centres’ based at major airports. In these centres every relevant type of Non Destructive Testing (NDT) sensor will be deployed by a team of multi-axis robots guided by 2 Cartesian gantries arranged at right angles, one covering the wing and the other covering the fuselage, tail plane and rudder. The outcome of each aircraft inspection would be a defect map of 100% of the aircraft surface from which the number of flying hours before the next inspection and/or the overall predicted flying lifetime could be advised. Direct revenue to those exploiting the technology are estimated at 100 Million Euro per annum whilst indirect economic benefits to the airlines, passed on to their customers will be far greater, though less tangible.

A gantry based robotic system has the specific advantage over mobile robot systems in that very heavy NDT sensors such as X-ray tubes and SQUID magnetometers can be deployed in addition to all the more common less heavy sensors such as ultrasonic and Eddy current probe arrays. Robotic scanning could also achieve acoustic emission (AE) monitoring of an entire air frame without the need for a vast and expensive array of AE sensors. This would be most useful for fuselage pressure testing.

Regular and periodic non-destructive inspection is mandatory for all civil airlines in the world, large or small, for obvious reasons. Most of this inspection is presently done manually with limited area coverage. But, with economic pressures to extend the service life of every costly aircraft there is a rapidly increasing need for large inspections e.g. 100 percent inspection of large aerofoils and other central surfaces, or even whole wings, fuselages or aircraft. Such inspection is very unreliable if done manually because fatigue leads to wrong interpretation if a human operator has to spend hours and days scanning over large areas, whilst remaining mentally alert at all times to interpret the inspection measurements.

Thus there is a great need on grounds of both air travel economics and safety to provide the specialised testing centres just described in which all inspection would be automated and robotic. Such centres will eventually be in demand to inspect the entire world fleet of aircraft in a rolling programme. There are over 12000 civil aircraft in use amongst the 100 largest carriers, and this figure is projected to reach 24,000 in 20 year's time

MAIN ASPECTS OF THE PROPOSAL

Quality of Life/Safety/Health of Workers and Impact on Employment Skills. Manual inspection of aircraft is both boring and stressful, physically and mentally because of the need to manipulate inspection probes, which are sometimes heavy at awkward angles and involving bending down or lying on aircraft surfaces. These jobs would be replaced by more skilled jobs associated with the design and running of Inspection Centres. Manual operators are highly skilled and are retrainable into these positions.

Quality of Life/Safety of Passengers/Consumer Protection. The majority of the population of the developed countries and an increasing proportion of the population in developing countries regard the freedom to partake in frequent and inexpensive air travel on holidays and to visit distant relatives as an essential part of ‘quality of life’. Presently the one hundred major airlines in the world possess some 12,000 aircraft. The European Commission has estimated that some 16,000 new aircraft/aircraft life extensions globally, 3200 of them in Europe (130%

growth on present numbers to 24, 000 aircraft assuming that about 2/3rd of the present fleet is still in service then) over the next 20 years will be needed to cope with this demand. Safety in air travel is an irreducible part of this quality of life and to cope with this vast growth in air travel whilst making it feel safe to the consumer will require no increase in the present level of accidents, every one of which gets reported in the newspapers. It follows that the accident rate per flight (about 1 in 2 million) must actually decrease to 1 in 2 million and correspondingly, structural integrity inspection, the subject of this proposal, must be greatly improved. This factor of 2 improvement requirement appears much more dramatic if one takes into account increasing de-regulation and the fact that the present one in a million accident rate is an average with some airlines having much higher rates up to 1 in 100,000 at the worst end.

Community Added Value. Aircraft construction and airline operation is a key and core business in Europe and several countries, Spain, France, and England collaborate in manufacturing the Airbus range and in planning the new megaliner. It is natural, therefore, to approach future inspection needs in a transnationally collaborative manner with dissemination that is European-wide (at least).

Support to Standardisation. The proposed inspection standards will produce a quantum leap improvement in the standard of inspection and indeed new standards could be introduced based on a number of standard robotic trajectory routines for the manipulation of the different types of inspection sensors (probes)

Time Period to the exploitation of the results. A full-scale prototype Inspection Centre could be commissioned within two years of the end of the project i.e. 5 years from project commencement. Other Centres would then be opened at the rate of 10-15 per year until a maximum of about 70 are established

TECHNICAL AND SCIENTIFIC OBJECTIVES AND INNOVATIVE ASPECTS WITH RESPECT TO THE STATE OF THE ART

1. A prototype robotic total aircraft inspection centre will be developed, based on an existing Cartesian x-y-z robot frame on which can move an existing team of multi-axis robots for sensor deployment. Figure 4 shows a schematic of the gantry arrangement and scanning robots deploying all the anticipated NDT techniques.
2. Presently available arms are a 5 axis arm built under an EU contract and a unique 7-axis arm purpose designed for NDT and just completed under a current Brite Euram contract, which can deploy sensors weighing up to 30kg and 5kg respectively. The former can handle the Compton scatter tube Squid probe, whilst the latter is ample for ultrasound and eddy current arrays.
3. The available gantry built under EU funding at a cost of 1.2 Million Euro, is large enough to accommodate aircraft sections such as a wing section up to 5x 20 m, a complete Boeing 747 rudder and undercarriage, and a one quarter cross section of a Boeing 747 fuselage – such parts, which would include some made from advanced composites, will be procured for the research.
4. All types of sensor, standard and state of the art, presently used or envisaged for aircraft inspection will be procured and robotically deployed in carefully planned scanning routines on aircraft parts such as the above, with real or simulated defects

such as cracks in or around rivets, bolt holes, fasteners, wheels and undercarriage, fuselage fatigue cracks, bond defects in adhesively bonded structuresand corrosion, particularly in fuel tanks, undercontrol surfaces and around galleys and lavoratories.

5. Sensors used would include ultrasonic and eddy current arrays, the novel Squid magnetometer probe, and an even more novel Compton Scatter tube which will permit 100% X ray imaging of a complete aircraft with access only required from one side. Accounts of the NDT techniques for aircraft currently in favour are given in references [5-9] which form a special feature on NDT in the aerospace industries published by the British Institute of NDT in March 2000.
6. A 100% defect image map of a complete aircraft would thus be compiled aided by the latest image processing and data fusion techniques.
7. Defect sizes would be determined to a precision that meets existing and future planned EU standards and which permits reliable flying life prediction, and maximisation of flying life and time between repeat inspections.
8. The specifications of a full size inspection gantry large enough to accept a taxied meggaliner or Boeing 747 would be drawn up and construction costs, aircraft throughput and financial turnover estimated as part of the exploitation plan.

INNOVATIVE ASPECTS OF THE PROPOSAL

(i) The concept of total integrated NDT of aircraft achieved through the creation of specialised centres which can function in such a way that it is economically feasible to offer every kind of aircraft inspection technique inspection.

(ii) The concept that an aircraft is a mobile object that is readily deliverable to such centres intact and that total inspection can be achieved without any dismantling of aircraft components.

(iii) Such Centres permit maximum data fusion from different sensors to maximise the predictable safe lifetime of an aircraft.

The principle has a direct analogy in medical practice where whole body scanning of patients is achieved by them travelling to special centres comprising multimillion Euro Magnetic resonance and X-Ray tomography imager's in selected hospitals.

With respect to the state of the art, objectives 1-8 and concepts (i) – (iii) are totally new and to our knowledge have never been tried before – as stated elsewhere earlier NDT is carried out at present in a very diffuse, piecemeal way.

POTENTIAL IMPACT OF THE RTD ON ECONOMIC DEVELOPMENT PERSPECTIVE/EXPLOITATION

Globally about 861 Million Euro is spent worldwide (25% of this in Europe) on the NDT of airline fleets, 26% on equipment and 74% on services, about 72,000 Euro per aircraft.

The capital cost of the installation of one novel inspection centre, including 2 gantries with sensor equipment will be around 6 MEuro. Allowing for a depreciation of the capital costs over 4 years at a fifteen percent margin (running costs including staffing would be negligible compared with this depreciation), the inspection centre will need to make 4600 Euro per day. If it is estimated that 1 aircraft a day is inspected, 4600Euro would be the structural inspection cost assuming a 15% profit.

Assuming only one such a complete inspection would be needed per year, this represents a vast reduction on present inspection costs. Presently the NDT costs are high because aircraft structures are inspected piecemeal with different parts being inspected at different times and often aircraft parts such as wings have to be detached for inspection, in contrast with our proposal which permits 100% inspection capability of intact aircraft.

Of course one needs to add the cost of delivering an aircraft to be tested to the nearest inspection Centre. Sometimes this might be very high but in most cases airline operation logistics would be adapted so that passengers and /or cargo were involved in a visit to an inspection centre, envisaged as being located at most or even all major international airports.

To service an estimated world fleet of some 22,000 airliners in 20 years time about 65-70 Centres would be needed to provide total inspection of all them. Thus at 6 Million Euro per Centre the potential sales would be about 100 Million Euro per annum assuming total refurbishment of each Centre every 4 years.

The Centres could also be built into the international train networks and the same principles used for inspection of the entire world fleet of locomotives.

The total economic impact is much bigger and more direct – it is a simple fact that passengers will choose to fly by airlines that show themselves committed to the total inspection philosophy and thus a certificate of inspection from one these centres will have immense cash value to that airline. Above all, the research is about providing re-assurance to and thus a better quality of life for the travelling public.

STRATEGIC CONTRIBUTION TO TECHNOLOGICAL PROGRESS

Whoever takes forward these ideas will establish themselves as clear leaders in automated nondestructive structural integrity testing, which is now a very sophisticated technology in terms of advanced sensor design, data acquisition and processing, and measurement process modelling. NDT has come a long way since 'wheel tapping'!

REFERENCES

1. Siegel Mel and Gunatilake Priyan, (2000) Robotics Critical Technologies, Chapter 2.2 in *Automation, Miniature Robotics and Sensors for Nondestructive Evaluation and Testing*, Volume 4, Topics on Nondestructive Evaluation Series, Technical Editor Yoseph Bar-Cohen, The American Society for Nondestructive Testing, pp. 31-45.

2. Sattar, T.P. (2000) Wall Climbing Crawlers for Nondestructive Testing, in *Automation, Miniature Robotics and Sensors for Nondestructive Evaluation and Testing*, Volume 4, Topics on Nondestructive Evaluation Series, Technical Editor Yoseph Bar-Cohen, The American Society for Nondestructive Testing, pp. 77-100.

3. Siegel Mel (2000) Inspection Crawlers, Chapter 3.3 in *Automation, Miniature Robotics and Sensors for Nondestructive Evaluation and Testing*, Volume 4, Topics on Nondestructive Evaluation Series, Technical Editor Yoseph Bar-Cohen, The American Society for Nondestructive Testing, pp. 61-75.

4. Bar-Cohen, Y. and Backes, P. (1999) Open-architecture robotic crawlers for NDE of aircraft structures, *Materials Evaluation*, Vol. 57, No. 3, pp. 361-366.

5. Schmidt, H.J., Schmidt-Brandecker B. and Tober, G. (2000) The Design of Modern Aircraft Structures and the Role of NDI, *INSIGHT*, 42, pp. 141-147.

6. Krause, H.J., Hohmann B., Gruncklee and Maus, M. (2000) Aircraft Wheel and Fuselage Testing with Eddy Current and SQUID, *INSIGHT*, 42, pp. 148-151.

7. Birt, E.A. (2000) The Applicability of X-Radiography to the Inspection of Composites, *INSIGHT*, 42, pp. 152-157.

8. Prassianakis, I.N. (2000) Non-Destructive Testing of Antesively Bonded Materials, *INSIGHT*, 42, pp. 158-161.

9. Cluzeau S. (2000) Neutron Radiography at the 'Institut De Maintenance A'ernautique' Bordeaux University, *INSIGHT*, 42, pp. 163-165.

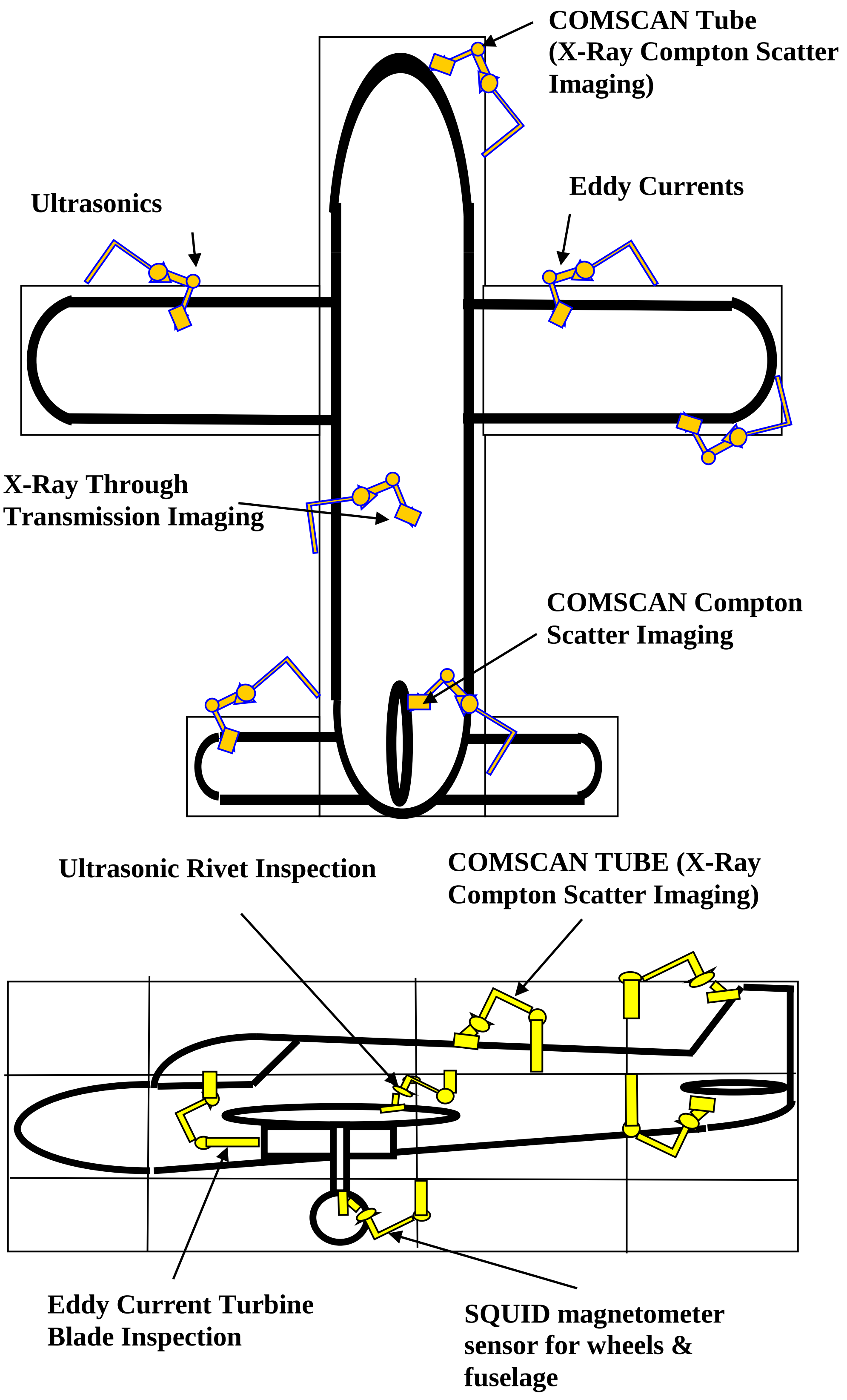

Figure 4: Each Robot and Sensor can move onto horizontal or vertical rails along the fuselage, wings, tail or fin to achieve total area coverage with each type of sensor