Remote and Automated Inspection: Status and Prospects

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1. INTRODUCTION

Since 1989 at least five experimental "robots" for remote (and to some extent automated) inspection of aircraft have been built in the US. Three were built at universities (one at Wichita State[1][2] and two at Carnegie Mellon (CMU)[6][8]), one at a NASA facility (JPL)[11], and one privately (AutoCrawler LLC)[14]. These efforts have been supported by the FAA[1][2][6], the Air Force[11], the State of Pennsylvania[8], Boeing[1], private entrepreneurs[8][14], and, in kind if not in cash, by US Airways[6][8] and Northwest Airlines[8]. Outside the US, the Singapore Air Force is currently supporting a substantial local effort for robotic underwing inspection of F-5 aircraft[15], and there are persistent rumors of one or more ongoing efforts, particularly in Japan, that are not being reported in the open literature. In addition, several university and commercial groups have designed and built robots for specific or generic "wall climbing" applications and mentioned aircraft inspection as possible future uses of their devices.

In the aggregate, the five US prototypes have demonstrated all of the technical capabilities needed to implement a robotically assisted inspection system: measurement (NDI sensors, and cameras for remote visual inspection), manipulation (actuators that can place, guide, and scan the sensors), mobility (a vehicular platform that can negotiate the aircraft surface), and monitoring (signal acquisition, data processing, and information display). However no one has demonstrated all these "4M-s" at once. Probably only one of the robots (the second of the two developed at CMU) has actually delivered to an aircraft inspector in the field anything that could with a straight face be called useful inspection data.

This paper focuses, more sharply in hindsight than was possible in foresight, on why building an aircraft inspection robot that actually delivers useful data has proven so difficult. In the course of reviewing the rationale for robotic deployment of NDI equipment for aircraft inspection and describing the major research efforts to date, it elucidates how universal issues in teleoperation and automation are manifest specifically in the aircraft inspection environment. In describing the five major and several minor efforts, CMU's contributions of necessity emphasized, as they are best known to the author personally, and also most thoroughly documented in print; however it is my goal to be as comprehensive as openly available knowledge permits. The paper concludes by outlining a path to a comprehensive, economical, and culturally acceptable system for remote automation-assisted deployment of NDI and enhanced visual inspection equipment.

2. WHY USE ROBOTS FOR AIRCRAFT INSPECTION?

Numerous hypothesized advantages of computer controlled mobile remote deployment platforms (for short, “robots”) for aircraft inspection instruments and remote cameras for visual inspection have been expounded at length elsewhere, so here I will mention, briefly, only the arguments my personal experience has led me to believe are most realistic and realizable. The key arguments relate to *thoroughness*, *correctness*, and *recordability*. Some early arguments that I and others offered, particularly those relating to allegedly increased bodily safety of the inspectors and other advantages of “getting the man off the airplane,” I have come to think are less important as the likely deployment scenario (primarily during heavy maintenance) and the personalities of the inspectors (they enjoy being on the airplanes) have been clarified by probing discussions and actual field experience.

2.1. THOROUGHNESS

The robot will cover the programmed inspection path or area completely, with a uniformly high level of concentration, and it will remember the result faultlessly.

2.2. CORRECTNESS

The robot will deploy the correctly set up inspection instrument using exactly the programmed deployment protocol.

2.3. RECORDABILITY

The robot will faultlessly see and remember the outcome of every observation. Thus the correct data will always be available for interpretation (by computer software or by human experts), the location on the airplane where the data were obtained will always be known exactly (enabling advanced “C-scan” image-accumulation-and-display whatever the sensor), and precise trend analysis over arbitrary time periods will be possible (enabling better understanding of the development and evolution of problems, and allowing the operator and the regulatory authorities to choose statistically appropriate inspection intervals).[1]

3. DESIGN SCENARIOS FOR ROBOTS FOR AIRCRAFT INSPECTION

3.1. THREE BASIC DESIGNS

Imagining systems that could bring the advantages of robots and automation technology to the field of aircraft inspection, especially skin inspection, leads to three scenarios to which I attach the pictorial labels “*car wash*,” “*cherry picker*,” and “*skin crawler*.”

The *car wash* scenario imagines a central facility dedicated to inspection: aircraft are flown in specifically for inspection “with a fine tooth comb.” In this scenario inspection can be carried out without interference from operations, maintenance, or anything else. Under these ideal circumstances, the technically most excellent job can probably be accomplished by a *gantry robot* arrangement, like a huge automatic car wash, from which extremely precise deployment of a variety of inspection devices can be carried out unhurriedly and thoroughly. The conflict that this scenario presents for economical operation in the civilian sector (and perhaps for mission

1. It will of course not escape the reader that the legal departments of commercial airlines may not regard recordability and recording as desirable features; in the military aviation sector, however, they are usually regarded positively.

readiness in the military sector) probably makes it impractical despite its technical superiority over all alternatives.

The *cherry picker*, in contrast to the car wash, imagines bringing the inspection apparatus to the airplane rather than the reverse. In this scenario a vehicle-mounted cherry picker, of the sort used for a variety of operations in typical maintenance and inspection hangars, is used to deploy inspection devices in much the same manner as in the car wash scenario: in both, mobility and manipulation use separate mechanisms and operate at substantially different scales. In the big picture, the cherry picker is much less disruptive of normal operations than is the car wash. However discussions with responsible individuals in the civilian sector uncover substantial objections to this method. Objections are primarily on two grounds, first the fear that an automatically or teleoperated cherry picker will collide with and damage the aircraft under inspection, and second the complaint that the floor space around an airplane undergoing heavy maintenance and inspection is too busy and too cluttered to tolerate the routine intrusion of a cherry picker. I don’t yet know whether the same objections exist, or exist as strongly, in the military sector.

Given the substantial operational and economic objections to the car wash and the cherry picker, we are left with only the *skin crawler*: a small self-mobile device that adheres to the aircraft skin and maneuvers under some mix of teleoperation and autonomous control to carry out a sequence of inspections at a sequence of locations. In this scenario the line between mobility and manipulation may be fuzzy, as some actuators may be used both to move the vehicle and to scan the sensors. From the operational perspective a small skin crawler, particularly one without a tethering umbilicus, is ideal: an inspector affixes it, at shoulder height, to the airplane at any convenient ground location, it crawls wherever it needs to go and does whatever it needs to do, then it returns to the original or another ground accessible place where the inspector removes it. Everyone likes this idea. The problem is that building a crawler that will be practical in the aircraft inspection environment is easier said than done!

3.2. WHY SKIN CRAWLERS ARE HARD, AND THE CONSEQUENCES

It is not easy to make a skin crawler because a crawler needs to adhere to the airplane, and the only practical way to make it both adherent and mobile is to use suction cups. Although passive suction cups are a possibility, operational and safety considerations demand active suction cups, i.e., suction cups that depend on a vacuum supply. Elementary analysis shows that the power required to obtain the necessary vacuum pumping speeds for a reasonable operating time exceeds what is available from any practical on-board energy storage system. So the only alternative is an umbilicus carrying a vacuum hose or, better, an air hose that can generate vacuum on board via venturi-effect “ejectors”. The problem is that the umbilicus gets in the way of the easy mobility contemplated in the previous paragraph. Even worse, managing the umbilicus becomes a frustrating, expensive, often simply intractable problem: the umbilicus literally becomes the tail that wags the dog.

As a consequence I can say with reasonable confidence that no group anywhere in the world has succeeded in building a generally mobile skin crawling robot for aircraft inspection that has actually delivered useful inspection data: all the effort has gone into the mobility, leaving no time or resources for developing a useful inspection capability. The efforts that I know about, which I believe are all that have occurred, are summarized in Section 4.

3.3. An interim way out

In particular, recognizing the difficulty of the general mobility-with-umbilicus problem, yet wanting desperately to demonstrate the value of remote inspection technology (in part as a rationale for continuing to work on the mobility problem), my group recently built a robot of limited mobility, restricted to the crown of a DC-9 or 737 (or larger) aircraft, minimizing the mobility problem so we could concentrate on the inspection problem. The project and results, yielding a robot called CIMP, the Crown Inspection Mobile Robot, are reported in Section 4.5.

4. A zoo load of crawlers

4.1. Rostam I through IV: Wichita State University

Benham Bahr and his students at Wichita State University, Wichita KS may have been the first to describe a family of robots specifically conceived to carry NDI sensors and video cameras for aircraft skin inspection. With FAA support (Prof. Bahr spent several summers at the FAA Technical Center in Atlantic City coordinating aspects of the Aging Aircraft Research program), they built the series of wall climbing robots ROSTAM I through IV. Aircraft inspection was addressed as first among many possible applications for a generic suction-cup-based crawler.

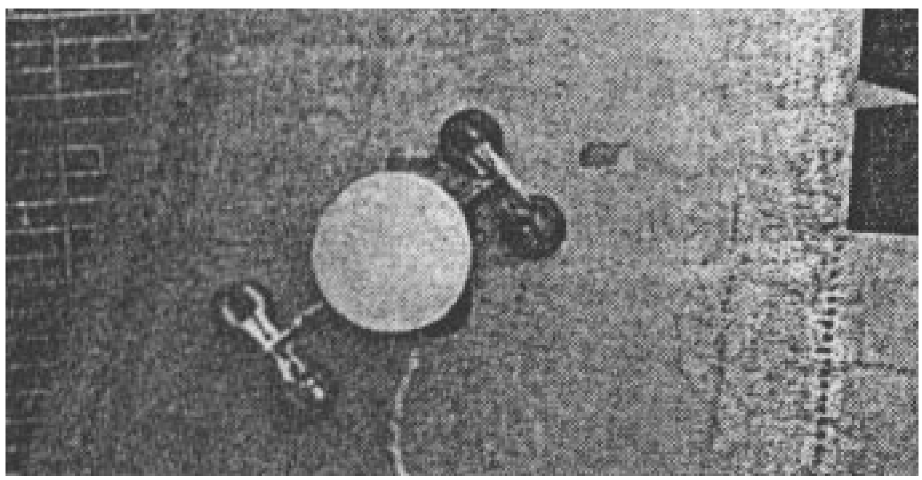

Fig. 1: ROSTAM III on a section of aircraft material.

The series is notable for a design that uses one very large diameter suction cup on its "belly" and a smaller suction cup on each "leg" (or "arm"). ROSTAM III[2] is shown on a section of aircraft material (apparently wing) in Fig. 1. Many theoretical aspects of the ROSTAM series design (suction cups[3], safety issues[2], sensory guidance[4]) and their hypothetical inspection capability (automated crack monitoring using a vision system[5]) have been reported in the technical conference and scholarly archival literature; however it does not appear that any verifiably practically useful inspection data were ever delivered in field tests of any of the series.

In support of the ANDI program at CMU (Section 4.2), Prof. Bahr also conducted analyses of the requirements and optimal designs of suction cups for aircraft inspection crawlers.

4.2. ANDI: Carnegie Mellon University

The FAA Aging Aircraft Research program sponsored the design, construction, and testing of the Automated NonDestructive Inspector (ANDI) at Carnegie Mellon University, Pittsburgh PA, in a joint project of the Carnegie Mellon Research Institute (CMRI), the university's applied research arm, and my lab, the Intelligent Sensors, Measurement, and Control Lab, in the Robotics

Institute of the School of Computer Science. ANDI's design was dictated by the FAA's state of mind and by the state of NDI technology around 1990, when the project was defined and begun. The state of mind at the time, still dominated by the Aloha incident of 1988, was that large scale eddy current "fishing expeditions" are a desirable way to head off future Alohas, and that large scale instrumented inspection could be made palatable to commercial airline operators if there were an economically acceptable automated device to deploy the sensors. The state of technology for eddy current sensors at the time was mainly manually manipulated point probes and complex impedance plane displays of their signals. These circumstances led to a design that maneuvers most gracefully along long fore-aft lines of rivets, maintaining precision alignment with them so that an eddy current pencil probe scanned parallel to the line of motion would follow the desired scanning path with little or no need for additional closed loop path control[7].

The design developed for this scenario is drawn in Fig. 2; below the drawing is a photograph of the near-final ANDI on a DC-9 nose section at the Aging Aircraft Nondestructive Testing Center (AANC, Sandia National Laboratories, Albuquerque NM). This design, a form of what is known in the robotics literature as a "beam walker," achieves mobility by suitable motions of the bridges (arms) relative to the spine as the suction cup groups on the spine and the bridges are alternately affixed and released. The eddy current probe is scanned by one of the bridges moving along the spine while the spine's suction cups are affixed to the aircraft skin. ANDI is equipped with four cameras for navigation and alignment: one each fore and aft to align the spine with the rivet line, one adjacent to the eddy current probe to verify location and alignment, and one high mounted with a wide angle field of view for navigation, obstacle avoidance, and proprioception ("self awareness"). In contrast to CIMP, the second CMU aircraft inspection robot (Section 4.5), whose capability is focused on enhanced remote visual inspection, ANDI's cameras were not intended to have sufficient resolution to be useful for visual inspection per se.

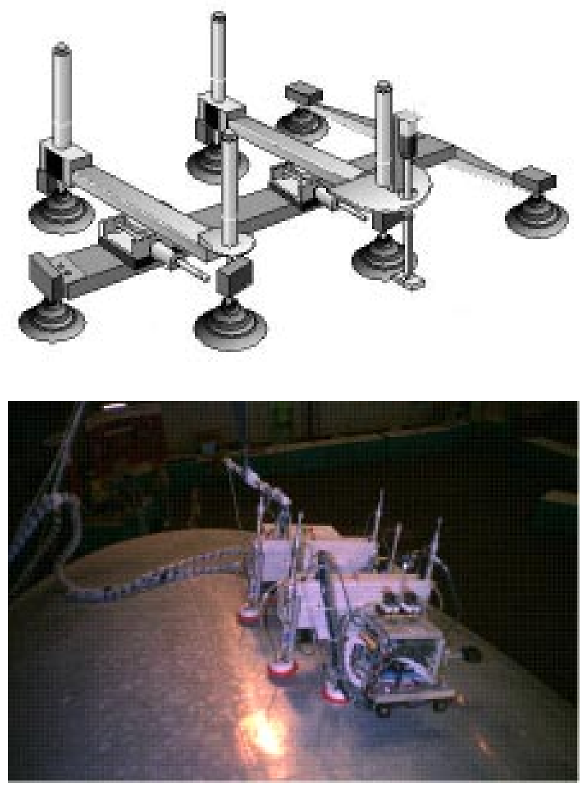

Fig. 2: (above) ANDI as a design drawing, and (below) photographed on the nose section of a DC-9. In the drawing, the eddy current sensor is seen on the near end of the far bridge (arm). In the photo the small black box (on an outrigger on the far side) contains one of the two alignment cameras (see text for camera arrangement).

Despite essential successes in mobility (getting where it needed to be), automatic alignment (using a machine vision rivet line finding algorithm), manipulation (moving the eddy current probe smoothly along the desired path), and measurement (collecting and delivering eddy current sensor data to the ground), as well as the articulation of a comprehensive system architecture for integrating robotics and automation into aircraft maintenance and inspection, unforeseeable changes in the context for ANDI led to its early marginalization.

First among these factors was a de facto return to the model that visual inspection should be the lion's share of skin inspection, with eddy current and other NDI technologies being used for backup, confirmation, and a relatively small number of directed inspections for specific flaws at specific problematic locations. A robot designed for large area eddy current inspection along rivet lines would have a hard time being economically competitive in an environment that views eddy current as a confirming technology for suspected visual flaws and as a survey technology only for a few specific fuselage locations, e.g., locations known from structural models or past experience to present specific cracking or corrosion patterns.

Simply stated, at least in the civilian sector, there is no economic interest in a robot that does the 10% of inspections that are instrumented; to make an impact with the commercial airline operators, a robotic inspection system will have to do the visual inspections that account for 90% of the inspection effort.

Another development that weighs substantially against the viability of ANDI is the recent advance in sensors and display systems for C-scan rendering of eddy current data. We now have linear and area arrays (or their equivalent in, e.g., MOI), and inspector now expect to see false-color images rather than oscilloscope traces, making ANDI's mechanical optimization for point probes somewhat pointless.

4.3. AUTOCRAWLER: AUTOCRAWLER LLC

Henry R. Seemann's Seattle WA based company AutoCrawler LLC, with support from Boeing, has developed a tank-like multi-suction-cup-tracked vehicle, AutoCrawler, with a clever valving arrangement that applies vacuum only to those suction cups that are actually in contact with the surface (Fig. 3). AutoCrawler is a behemoth of a mobile platform, capable of carrying enormous loads at very high speeds thanks to its powerful air motors and high capacity vacuum ejectors. On the other hand, it demands an enormous air compressor, and it makes a hell of a racket. Although suction cups of optimized material and shape have been custom designed and

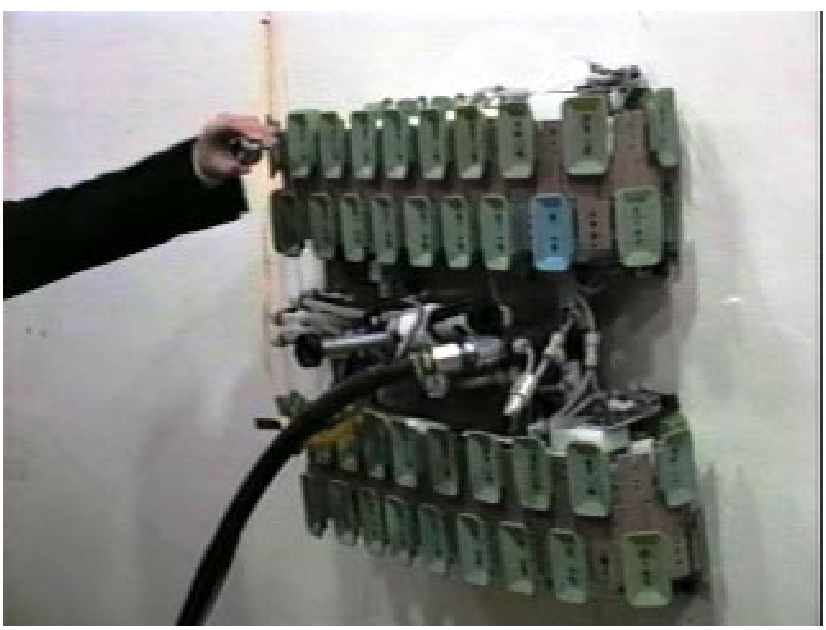

Fig. 3: AutoCrawler on the side of an airplane. The hand is about to install, on the "periscope" at the center of the AutoCrawler, a retroreflector that is part of the laser tracking system used for locating the robot absolutely relative to the hangar floor.

manufactured for the application, aluminum surface scuffing is still very evident in the AutoCrawler's wake. Boeing's experimental area array eddy current sensor and the PRI Magneto-Optic Imager have been carried by AutoCrawler on a 737 fuselage section with known defects, and images from the Boeing sensor have been exhibited in AutoCrawler's sales literature. Based on our experience (Section 4.2) with ANDI's eddy current sensor's tendency to "chatter" if not scanned with a sufficiently firm but light touch, it seems likely that a point sensor deployed by AutoCrawler would suffer from this problem in spades; however, as the described demonstrations confirm, AutoCrawler's mechanics are well suited to area-type sensors, as they do not require precise placement and scanning. The AutoCrawler has not been reported in the technical conference or archival scholarly literature; however some early work toward a window washing robot, in which project Mr. Seemann participated, is reported in the trade magazine Robotics Engineering[17].

Mr. Seemann reports in a personal communication that he is currently investigating an Air Force NDI application on a contract routed through the University of Dayton Research Institute[16].

4.4. MACS I THROUGH III: NASA JPL

The Air Force Robotics and Automation Center of Excellence (RACE)[13] at Kelly Air Force Base, San Antonio TX, funded a group led by Paul Backes at NASA's JPL, Pasadena CA, to develop a series of mobile platforms, Multifunction Automated Crawling System (MACS) I through III. Leveraging NASA's efforts in developing miniature planetary rovers, telerobotic devices, and NDE technology, the MACS team has applied the years of experience and cutting-edge innovative ideas of its members, with their state-of-the-art expertise in robotics (Backes), NDI (Bar-Cohen), mechanical design (Joffe), and ultrasonic motors (Lih), supported by NASA's

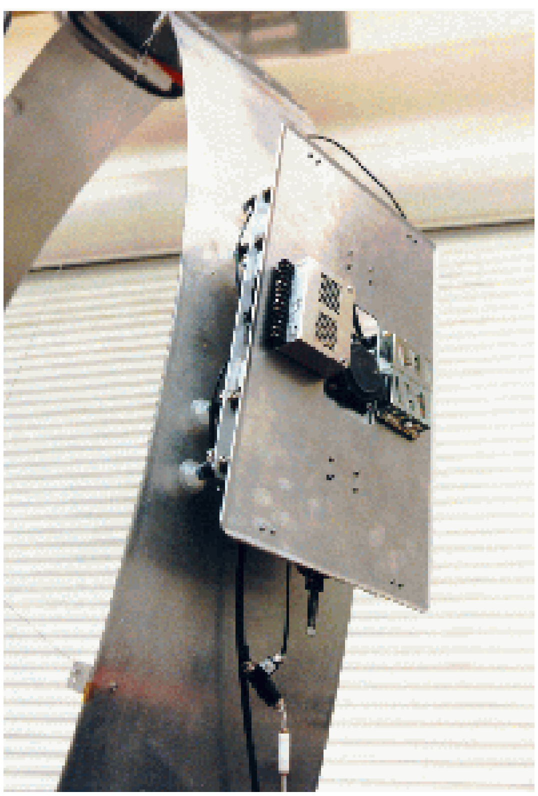

Fig. 4: MACS on a piece of sheet metal in the lab (left) and on a C5 airplane (above, at shoulder height, slightly to the left of the doorway).

highly trained technicians' unique hands-on skills in fabrication, electronics, and assembly (Barlow, Proniewicz), to developing this family of small, light weight, high carrying capacity ratio mobile platforms that use suction cups for attachment and ultrasonic motors for motion.

The MACS family walking paradigm of alternate attachment and detachment of half the suction cups[12] is essentially the same as ANDI's (Section 4.2). The group reports that in the future a descendant of the MACS I through III series with increased on-board intelligence, tetherless operation, operation over the internet, and integration of multiple sensor payloads might be able to carry NDI sensors, e.g., new miniature cameras, tap testers, eddy current sensors, ultrasonic sensors, etc., on an aircraft surface[11]. Fig. 4 shows MACS in the lab and on a C5 airplane. Inasmuch as Kelly Air Force Base is being shut down as part of the Base Realignment and Closing (BRAC) program, RACE's civilian leader Scott Petroski has taken a new assignment, and RACE is now slated for shutdown rather than relocation, the future of the MACS program seems uncertain.

4.5. CIMP: Carnegie Mellon University

CIMP, built in my laboratory (see Section 4.2) with support from the Ben Franklin Technology Center of Western Pennsylvania and my lab's spin-off company Aircraft Diagnostics Corporation, is an aircraft inspection robot that is explicitly *not* a "wall crawler." Chastised by the two lessons of ANDI (*if you spend all your time working on the robot's mobility you'll never get any inspection data* and *if you can't do visual inspection nobody will be interested in your robot*), we set out to demonstrate that a robot could generate data, first and foremost video data whose quality inspectors would gladly accept for routine visual inspection, and to deliver the data to an "inspector's workstation" off the airplane. To allow us to concentrate on inspection data and not inspection equipment transportation, we designed an interim robot whose mobility is limited to the fuselage crown: CIMP, the Crown Inspection Mobile Platform.

Fig. 5: CIMP on a 747 in a heavy maintenance bay at Northwest Airlines Minneapolis headquarters. The inspector, observed by a CMU staffer, is performing an eddy current check of a visual anomaly detected using the remote vision system shown in Fig. 7. Future models would incorporate remotely operated eddy current sensing.

Because CIMP works with gravity instead of against it, it does not need a tether. It was designed for the curvature of a DC-9, and for window-line to window-line on mobility on that aircraft type; however it turned out to be more convenient to test the prototype on a 747, on which it ran with no difficulty despite having the “wrong” curvature.

Because its power requirements are tiny compared to a robot that has to adhere to the fuselage in arbitrary orientations, CIMP does not need an umbilicus. It runs for several hours on its internal batteries; exactly how long depends on the variable demands of mobility, manipulation, illumination, etc. Control signals are transmitted to CIMP wirelessly using off-the-shelf model airplane transmitter technology. Video data are returned wirelessly using micropower radiofrequency channels; in the prototype these are off-the-shelf 2.4 GHz cable eliminators sold in the consumer market to connect a home VCR and TV set without dragging a wire under the rug. In a commercial version of CIMP somewhat more sophisticated (and costly) channel options would be appropriate to avoid signal degradation due to multipath effects.

Watching how visual inspectors work, we concluded that they use binocular disparity (the small differences between left and right eye perspectives) in several important ways. First, binocular disparity is the primary origin of stereopsis, the human perception of depth via the fusion of slightly different left and right eye images; depth perception is important for perceiving the difference between dents and lighting anomalies, bulges and depressions, etc. Second, aircraft inspectors routinely use dynamic lighting and grazing angles of observation to discern subtle textural anomalies even on essentially flat surfaces; these they apparently discriminate via the strong binocular disparity that originates in specular (vs. diffuse) reflection features. Thus we decided to provide CIMP with a 3D-stereoscopic video system that gives the inspectors remote *binocular* inspection capability.

Fig. 6: CIMP showing mobility (differentially driven wheels), sensor pod mounted off circumference-scanning carriage, and wide angle cameras for navigation and proprioception or “self-awareness” (upper right). The vertical stalk and the sensor pod rotate to change the camera viewing azimuth. Curvature was designed for window-line to window-line access on a DC9.

Fig. 5 shows a distant shot of CIMP on a 747 at Northwest Airlines heavy maintenance facility in Minneapolis MN. Fig. 6 shows a comprehensive view of CIMP, and Fig. 7 shows a close-up of the sensor pod, which contains the 3D-stereoscopic cameras and remotely controlled dynamic lighting, and potentially a variety of other sensors, e.g., eddy current probes. Fig. 8 shows a Northwest Airlines inspector at the workstation, operating the remote controller and observing the 3D-stereoscopic imagery.

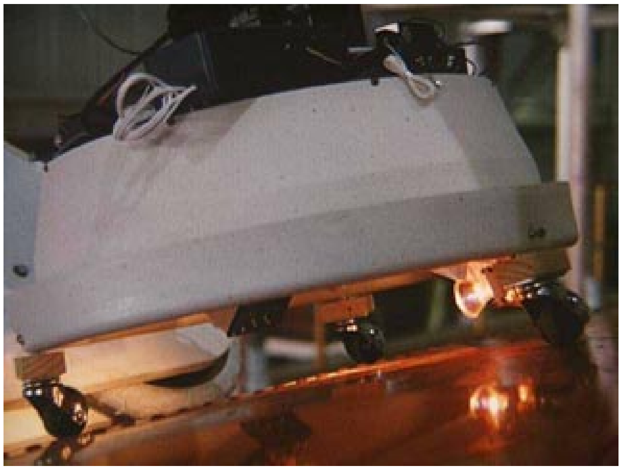

Fig. 7: Sensor pod, showing 3D-stereoscopic camera (white box with black endcap left of and below center) and remotely movable low angle illuminator. Inspector can remotely swing this illuminator in a 300 degree arc centered on the forward viewing direction of the camera, reproducing the way he typically uses his flashlight to pick up highlights. The flood illuminator is not visible in this view.

Fig. 9 shows several examples of the imagery returned by the inspection cameras; these pictures have been though several stages of subsampling prior to recording, 8mm taping, digitizing, and MPEG-type data compression, so their quality is not indicative of what the inspector sees live; the live view actually gives each eye an independent NTSC/VGA resolution signal stream with very high perceived quality.

CIMP has been sucessfully operated on a 747 at Northwest (as shown in the accompanying figures) and on a DC-9 at US Airlines. Working aircraft inspectors have been uniformly enthusiastic about the quality and utility of the imagery that the CIMP remote 3D-stereoscopic video system delivers. However many are skeptical about the economic benefits that might reasonably be expected from robotic deployment of inspection equipment. Some also question whether the introduction of robotic deployment equipment would enhance their job satisfaction; despite our best intentions to make the inspector's job easier, safer, etc., by "getting the man off the airplane," sometimes we find that the man likes his job because he likes being on the airplane.

Somewhat to our surprise, the inspectors have been enthusiastic about the idea of using computer image enhancement and automated image understanding for flaw detection. We have made significant progress in these areas, reported in [8], [9], and [10].

Fig. 8: Inspector at the prototype workstation. Small monitor at left shows one eye's view. Large monitor in front of inspector shows left and right eye views 3D-stereoscopically when viewed through the goggles seen. Inspector is driving robot, controlling lighting, cameras, etc, via the model radio controller joysticks, switches, and control knobs.

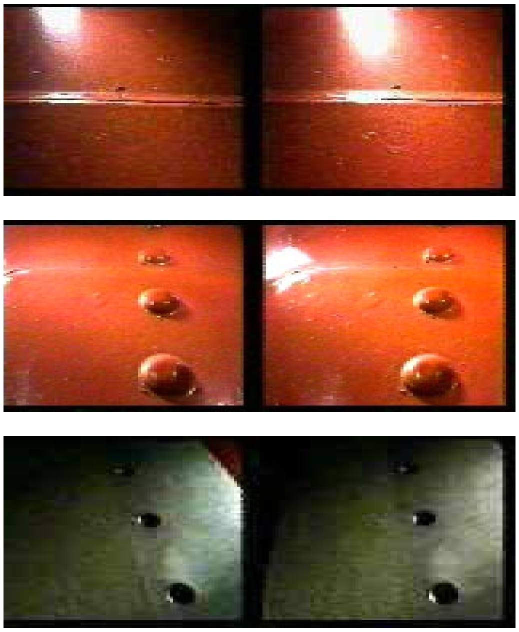

Fig. 9: Three left and right eye 3D-stereoscopic views from the 4.5x 3D-stereoscopic camera in the sensor pod. Top is a lap joint, middle is a row of buttonhead rivets, bottom is a sheet metal sample from a “defect library.” Note, in addition to the perspective differences between the two views (which stimulates depth perception), the distinct differences in specular reflections (which we believe stimulates texture recognition).

4.6. OTHER “WALL CLIMBING” ROBOTS

The Wichita State, Carnegie Mellon, Autocrawler, and JPL robots described above are all specifically targeted at aircraft skin inspection applications. Many other “wall climbing” systems developers mention aircraft inspection as possible applications for robots developed for other applications, or robots developed with an unfocused approach to wall climbing as a generic set of applications. Several of these, and a survey of them, are described briefly in this section.

4.6.1. ROBIN: VANDERBILT UNIVERSITY

Robert T. Pack et al in the Electrical Engineering Department at Vanderbilt University describe ROBIN, their ROBotic INspector[18]. It is essentially two rods connected by a hinge, with suction cups at the two free ends, and pneumatic actuators for walking, similar to earlier “walking-elbow” designs for space station maintenance robots[19], etc. Echoing the underlying theme of the present paper, the ROBIN’s inventors say “it is intended to carry cameras and other sensors onto man-made structures such as bridges, buildings, aircraft and ships for inspection ... cameras on its back and other contact sensors, like eddy current probes on its feet, but current development focuses on improving the climbing vehicle itself.”

4.6.2. TEXAS RESEARCH INSTITUTE / AUSTIN

Texas Research Institute / Austin, operator of the Nondestructive Testing Information Analysis Center (NTIAC), reports that among the products it has developed in sponsored R&D efforts for government and commercial applications there is a “rubber-to-metal debond robotic inspection system”[20] that sounds like it might be of interest in the aircraft skin inspection world. However at the time of this writing no further information was available.

4.6.3. SURVEY: MCGILL UNIVERSITY

A tabular "Survey of Climbing Robots," with annotated photos of some of the included robots, is available on the WWW at McGill University[21]. Note that many of these use magnets to attach to the surfaces of, e.g., steel liquid storage tanks, making them generally uninteresting for aircraft inspection.

5. LESSONS, CONCLUSIONS, AND THE FUTURE

After the Aloha "incident" of 1988 several research groups embarked confidently on paths toward mobile robotic platforms and computer-based automatic control systems for deployment of NDI and visual inspection equipment on aircraft surfaces. The ambitious plans included agile vehicles, sophisticated deployment of sophisticated sensors, a high level of intelligent, sensible autonomy in task and path planning, navigation, and inspection, elegant and functional human-computer interfaces, hierarchical data and information displays matched to the needs of inspectors, supervisors, and management, totally automated networked integration of inspection with maintenance, engineering, operations, and management databases, and the emergence of a safer and more economical inspection and maintenance system based on massive analysis of massive quantities of data that would permit just-in-time, but never earlier than necessary, predictive response to developing repair requirements. At the time of this writing, in mid-1997, there is still no working system that comes anywhere near these early expectations; there is not yet even a demonstration of a robot that is both agile (able to go 'anywhere' on the aircraft's skin) and functional (able to deliver data that inspectors want). Furthermore there is a sense of diminished confidence that there will be any such system any time soon.

On the positive side, in fact all four key modules needed by a useful robotic inspection system -- measurement, manipulation, mobility, and monitoring -- have been separately demonstrated. It has been hard to tie the modules together in a fully functional system in large part because the generic hard problems that must be faced in designing and building an aircraft skin mobility module -- adhering to arbitrarily curved and oriented surface regions, moving gracefully over lapjoints and buttonhead rivets, managing a safety tether and an energy-lifeline umbilicus -- have disproportionally diverted attention from the other three key modules.

However the diversion has actually paid off: we now have multiple examples of mobile platforms matched to various operational scenarios: ANDI for precision deployment of traditional point probe sensor types, AutoCrawler for manhandling large area surveying instruments, and MACS for the anticipated next generation of light weight sensors, among others.

In my lab we set out with CIMP to demonstrate a complete system via the expedient of temporarily sidestepping the general mobility problem: we built only a simple (though wireless!) platform whose mobility is restricted to the fuselage crown. Thus we were able to concentrate the extremely limited resources that were available to us for this project on demonstrating the single most important capability of a robotic inspection system: its ability to deliver useful inspection data to the ground. We succeeded in delivering inspection-quality visual data to an inspector who was remotely driving the robot from a rudimentary but acceptable workstation. The mobility and manipulation components were comprehensive enough that the inspector could scan along a useful path, stop at an possible flaw, and inspect more closely by varying the camera's viewing angle and the character of the illumination (flood or spot), and the direction of spot illumination.

In the lab, we have also made substantial progress toward useful image enhancement and automated image understanding algorithms for visually detectable flaws.

These successes are, at least to me, clear demonstrations that we are ready to respond to a well defined real-world application demand with a technically and economically justified system.

6. Acknowledgements

The cooperation of the commercial airline operators, especially US Airways and Northwest Airlines, has been essential to this work. The administrative support of Russell Jones and Roy Weatherbee of US Airways and Jeff Register of Northwest has been invaluable. The inspectors in both their organizations have been extremely hospitable and open, and remarkably tolerant of our incessant silly questions and wild ideas. The ANDI project was supported by the FAA Aging Aircraft Research program. The CIMP project was supported by the Ben Franklin Technology Center of Western Pennsylvania and Aircraft Diagnostics Corporation. The staff of the ANDI project at CMRI included Bill Kaufman, Chris Alberts, Chris Carroll, the late Court Wolfe, and many others; Alan Guisewite and graduate student Ian Davis helped on the Robotics Institute side. The staff of the CIMP project at the Robotics Institute included Gregg Podnar, Alan Guisewite, and graduate students Priyan Gunatilake and Huadong Wu.

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