Automation Tools for NonDestructive Inspection of Aircraft: Promise of Technology Transfer from the Civilian to the Military Sector

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Abstract

The FAA Aging Aircraft Research Program is supporting the development of a robotic mobile nondestructive inspection (NDI) instrument deployment tool at Carnegie Mellon University (CMU) with the active participation of USAir. The program has spawned several new relationships and entities: an alliance with an ARPA-funded research program at CMU having the capability to add 3D-stereoscopic enhanced visual inspection capability, a start-up company organized to commercialize the combined technologies, and State of Pennsylvania funding to foster this commercialization. As a result of these activities and connections the civilian sector appears to be ahead of the military sector in important aspects of automation for deployment of aircraft inspection equipment. A partnership between the university researchers, the airline operator, the start-up company, and the state government is thus emerging as the likely agent for transfer of the civilian-developed technology to the military sector.

1. Introduction

In the past three years significant progress has been made toward new systems that use small mobile robots to deploy remote electronic sensors and cameras for nondestructive inspection (NDI) of aircraft. Functionality has been demonstrated toward both automation-assisted (teleoperated) and future “autonomous” operation scenarios.

These advances have been made in the civilian sector primarily through FAA funding of the ANDI (Automated NonDestructive Inspector) mobile robot development program at Carnegie Mellon University (CMU). USAir has actively participated by providing CMU open access to their personnel and facilities, and by training CMU personnel in NDI methods and practices.

A start-up company, Aircraft Diagnostics Corporation (ADC), is working with CMU researchers and USAir, with assistance from the State of Pennsylvania’s Western Pennsylvania Advanced Technology Center - Ben Franklin Partnership (WPATC - BFP) to commercialize CMU's researchers’s progress in the civilian sector. Discussions with Air Force and military support organization personnel indicate that these successes put the civilian sector ahead of the military sector in important areas of automated NDI. ADC and CMU’s researchers have proposed a plan to

- study the military sector's needs,
- characterize the technology available to meet those needs,
- assess the overlap of needs and available solutions,
- develop a technology insertion plan for transferring suitable parts of the civilian sector technology into the military sector, and
- develop a research agenda for the military sector needs that cannot be satisfied by the civilian sector technology.

In the following sections we review the need for aircraft skin inspection, present an overview of the FAA’s ANDI program aimed at developing automation tools for deployment of NDI instrumentation, similarly overview the recent private sector effort to evaluate enhanced visual inspection technology that could be deployed by teleoperated robotic devices, discuss the relationships among the government and private sector entities, and examine how we foresee the parts coming together to achieve the desired technology insertion.

A summary of the technologies involved and the relationships among the participating entities is depicted graphically in Figure 1.

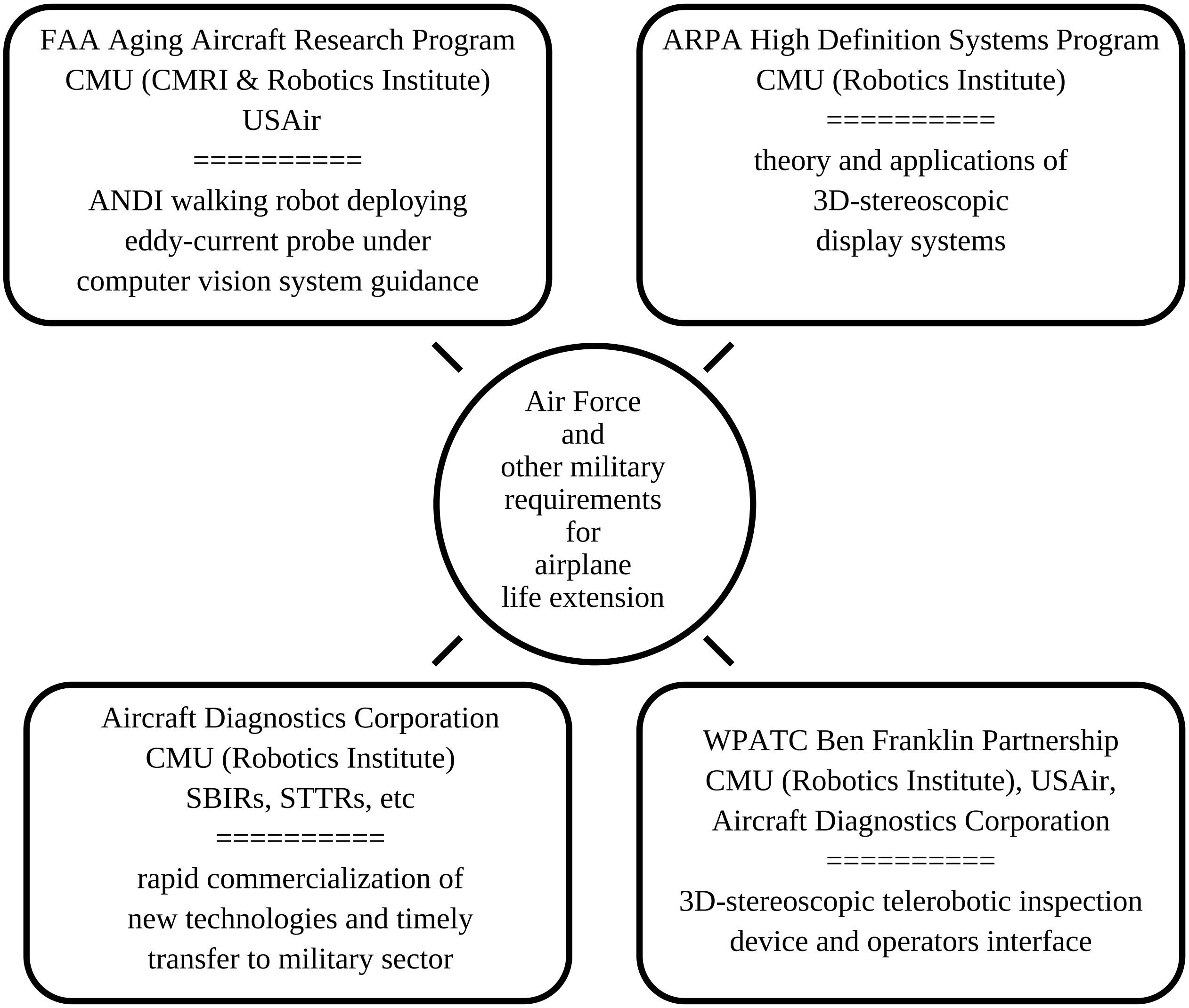

Figure 1: Civilian federal and state government, university, entrepreneurial, airline and military sector interactions fostering technology development, commercialization, and transfer.

2. Aircraft Skin Inspection

2.1 Background

Pressurized aircraft inflate and deflate with each take-off and landing ("cycle"). The resulting stresses send radial cracks out from the rivet holes; moisture- and salt-induced corrosion independently weakens adhesive-sealed lap joints. The combined effect of having both problems simultaneously became front page news in April 1988 when the forward section of the crown tore off of an Aloha Airlines airplane in flight. This incident stimulated initiation of the FAA Aging Aircraft Research Program by Congress and an extensive NDI and visual inspection program by commercial airline operators.

2.2 The Inspection Process

2.2.1 Focus

The inspection effort under this program focuses on the skin of the airplane where it is pressurized and least supported by a strong load-bearing understructure. The well-known photos of the Aloha incident provide graphic evidence for where this is: the fuselage, above the window line, between the cockpit and the rear pressure bulkhead. Experience, fatigue modelling calculations (supported by the aircraft manufacturers), and "terminating actions" (steps that the airline operators may take to reinforce vulnerable areas before they become a problem) allow further narrowing of the areas that require periodic inspection; thus contrary to the naive first impression that the entire skin is routinely inspected by NDI instrumentation, in fact only well defined and relatively small areas require this attention. On the other hand, the entire airplane is routinely inspected visually according to strict protocols. About 90% of the inspection effort is visual and about 10% is instrumented, mostly by eddy-current sensors, occasionally by ultrasonic sensors, and rarely by a variety of other sensors.

2.2.2 Process

Currently these inspections are carried out by highly trained aircraft maintenance personnel in a straightforward manual manner. An airplane is taken out of service, scaffolding and other means of access to all parts of the airplane's surface is arranged, safety harnesses and other safety gear are deployed, and a direct visual inspection is done. NDI materials characterization technology, such as eddy-current testing, is applied as required by FAA airworthiness directives and aircraft manufacturer service bulletins. Although there have been some recent trends toward using mobile computers to record the results, for the most part the data are recorded manually.

3. Automation for Inspection

3.1 NDI: The FAA’s ANDI Program

3.1.1 Background

As a small part of the FAA Aging Aircraft Research Program, research and demonstration of automation for deploying NDI instrumentation has been funded at CMU via a program in CMRI (Carnegie Mellon Research Institute, the university’s professionally staffed applied research unit) with the participation of faculty, staff, and students of the Robotics Institute (a basic research oriented academic unit in the School of Computer Science). Several commercial airline operators have provided advice and the benefit of their experience, particularly USAir, which has given exceedingly generously of its NDI personnel's time as well as invaluable access to its Pittsburgh maintenance and inspection facilities.

The first phase of the CMU/FAA effort was a study of the spectrum of aircraft inspection problems, a study of the spectrum of automation capabilities that might address these problems, and generation of a design concept for a prototype system defined by the overlap of needs and capabilities.

Based on this design concept the ANDI skin inspection robot has been prototyped in the second phase of the program. ANDI is now undergoing laboratory testing and control-computer program refinement in preparation for several demonstrations and field tests during mid-1994.

3.1.2 Equipment

Equipment used in the development effort includes the prototype robot, an airplane test panel that can be tilted to simulate a variety of positions on the fuselage, and an operator workstation that houses motor controllers, eddy-current sensor support electronics, and a computer for system control and the inspector's interface to the system.

The computer is a high performance 80486 PC running XWindows under Windows 3.1 under DOS. A single board computer on the robot maintains communication with the workstation and coordinates some basic functionalities.

3.1.3 Human-Computer Interface

The human-computer interface is being built using a hierarchical architecture that will give relatively unsophisticated computer users (e.g., most of the aircraft inspectors) access only to task-level functionality, whereas more sophisticated users (e.g., supervisors who need to develop new inspection protocols) will have access lower level control primitives. The menu-based interface includes a recording facility that allows non-programmers to build sophisticated event- and data-based motion sequences.

3.1.4 Sensors

ANDI deploys eddy-current sensors as the primary flaw detection modality, and uses a machine vision system for alignment, guidance, navigation and collision avoidance. Additional sensor modalities, including machine vision for inspection, are planned for later phases of the work.

3.1.5 Mechanical Features

The robot uses a cruciform “beam walker” design (see Figure 2) that affixes to the airplane skin with vacuum assisted suction cups. Electric power, air for the vacuum ejectors, pneumatic actuators, and air-bearings, and input and output signals are transported via an umbilical that will be attached to a safety-tether that will hang from the safety-rail above each airplane in the maintenance hangar.

3.1.6 Inspection sequence

At the start of an inspection, ANDI will be manually positioned near a manufacturing reference position with its main translation axis aligned approximately along the first line of rivets to be inspected. The primary sensors (eddy-current), secondary sensors (cameras) and system sensors (additional protection, alignment, guidance, and navigation aids) will then guide the robot alternately in scans over lines of rivets, lap joints, etc, and in walks to and alignments with subsequent sections.

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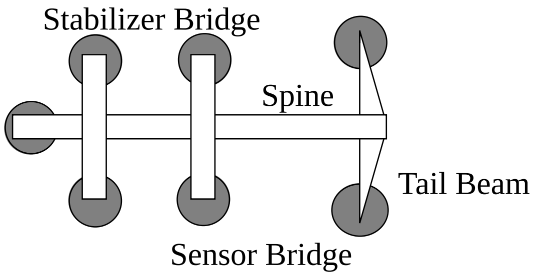

Figure 2: Major components of the ANDI cruciform “beam walker” robot.

Figure 3 shows a photograph of ANDI on an aircraft panel test section; in this close-up the eddy-current probe is visible in the foreground, the robot’s spine and suction-cup feet in the midground, and a computer monitor display of the complex impedance traced out by the probe as it is scanned over several good rivets, and one bad rivet is seen in the background.

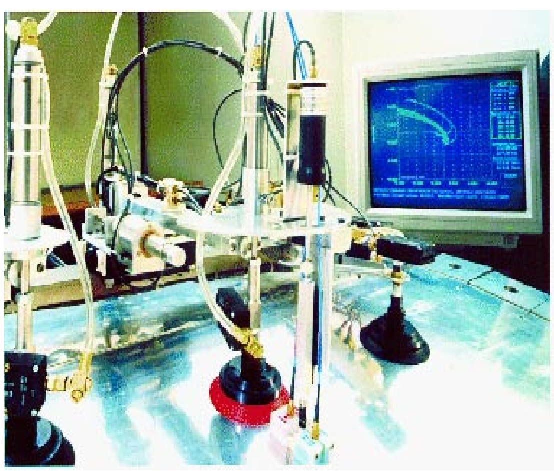

Figure 3: The ANDI robot. Eddy-current probe in foreground, eddy-current signal on monitor in background.

3.1.7 Vision System for Alignment

The output of a visual alignment algorithm that finds short rows of rivets and draws the imaginary line that joins them is shown in Figure 4. Short lines like this will be found at the robot’s head and tail; the spine will then be aligned with these two short lines, enabling the eddy-current sensor to scan precisely along the long line of rivets from the robot’s tail to its head. Several papers that describe ANDI’s system design, mechanics, and the background and operation of this algorithm in more detail are noted in the Bibliography.

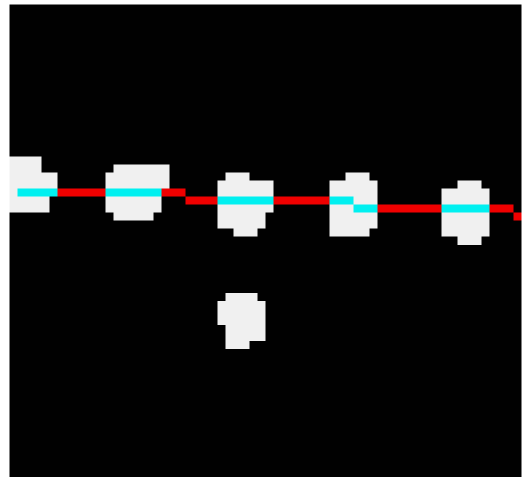

Figure 4: Output of an algorithm that finds rivets and lines of rivets.

3.1.8 Expected Technical Advantages

Speed and safety are expected to be improved when NDI inspectors have automated and teleoperated tools like ANDI routinely available to them. The improvement in data management, archiving, and accessibility that will follow on the heels of automating NDI instrument deployment is expected to convey improved signal detectability and interpretation, database access for retrospective and prospective analysis, and additional speed and safety advantages.

3.1.9 Expected Economic Advantages

These technical improvements are expected to be reflected in cost savings to the airline operators due to decreased setup time (the robot will be able to walk from ground-accessible locations to the airplane’s crown without erecting the scaffolding that a human inspector would need to get to the same place), decreased time for the inspection per se (because it seems likely that higher probe scanning speeds will become possible), and (once on-line data are integrated with flaw growth models) increased time between inspections.

3.2 NDI and Visual Inspection: Contrasting Perspectives

3.2.1 The Airline Operator’s Perspective

Airline operators would rather increase the effectiveness and decrease the cost of visual inspection than of NDI: visual inspection is 90% of their effort and expense, NDI only 10%. The ANDI project, focusing (in its initial phases) on NDI inspection using eddy-current probes, is thus addressing the smaller part of the problem. Thus airline operators express skepticism about the viability of a robotic inspection tool that “gets the man off the airplane” for NDI, but still requires erecting scaffolding, donning a safety harness, etc, to complete the visual inspection.

3.2.2 The Scientist’s Perspective

The reason for learning to automate instrumented NDI first and visual inspection later is essentially a human factors issue. How to automate NDI signal interpretation is for the most part well understood, because NDI methods are artificial sensory modalities to which human inspectors have adapted. How to automate image interpretation precisely enough to satisfy the stringent requirements of aircraft inspection will require several years of research: visual inspection applies a quintessentially human sensory modality to which it is difficult to adapt machines. Thus to prove, as early as possible, the feasibility of automation tools for aircraft inspection in general, it is an entirely sensible scientific decision to address the easier NDI problem first, leaving the more difficult visual inspection problem for a later phase of the work.

3.2.3 The Entrepreneur’s Perspective

The entrepreneurs see this difference in perspective between the airline operator and the scientist as an open window of opportunity: they can, with a modest development effort, supply the airline operators with robotic devices that will lighten the burden of both the NDI and the visual inspection. The NDI devices can be deployed immediately with as high a level of underlying automation as is feasible and desirable; on the same robot, appropriate cameras, appropriately mounted and remotely controlled and monitored, can “get the man off the airplane” years before the scientist is ready to automate the image interpretation.

3.3 Summary and Scenario

Airplane skins need to be inspected to combat the aging effect of the pressurization-depressurization cycle. Inspection is now done manually. About 90% of the inspection is visual, 10% instrumented. Automation tools for inspection are expected to confer several advantages:

- improving performance by maintaining a high probability of detecting flaws
- improving repeatability by performing tests consistently
- reducing aircraft down time by significantly enhancing human inspectors’ productivity
- reducing inspection frequency by providing greater confidence in an airplane’s structural integrity
- improving safety by decreasing the need for the inspectors to be on the airplane

Although visual inspection is a larger burden than NDI inspection, initial work toward automation tools for inspection are focusing on NDI inspection; this is an appropriate tack because the automated signal interpretation is essentially solved for NDI instruments, but essentially open-ended for machine vision systems.

Given this situation, there is a window of opportunity in which the platform (the mobile robot) that deploys automated NDI equipment can also carry cameras whose imagery visual inspectors can interpret from the ground.

4. Remote Visual Inspection

4.1 Binocular Stereopsis

Visual inspection of aircraft appears to require (or at least to benefit significantly from) binocular stereopsis, the perception of depth that results from the slightly different (“disparate”) perspectives seen by right and left eyes viewing the same scene. The effect is illustrated in Figure 5, showing highly magnified left and right perspectives of a rivet hole surrounded by corrosion products; readers who are practiced at “free viewing” should have no difficulty fusing these images to perceived the result in (somewhat hyper-) stereo.

Binocular stereopsis is of course absent in normal photography and video, in which a single lens captures a single perspective. Thus it is reasonable to hypothesize that remote visual inspection, attempted via a camera that is piggy-backed on a mobile robot deployed primarily to do eddy-current inspection, might not provide acceptably detailed imagery for visual inspection. On the other hand, the hypothesis continues, two cameras displaced left-right relative to each other, like a pair of eyes, could be arranged to direct the appropriate perspective to the appropriate eye, producing binocular stereopsis remotely.

4.2 3D-Stereoscopy Research at CMU

4.2.1 Background

One of the members of the FAA’s ANDI team also has (at the CMU Robotics Institute) an ARPA High Definition Systems Program project aimed at getting an early start on exploiting the promise of large screen flat panel high definition displays for implementing 3D-stereoscopic display systems. Large screen high definition flat panel displays are

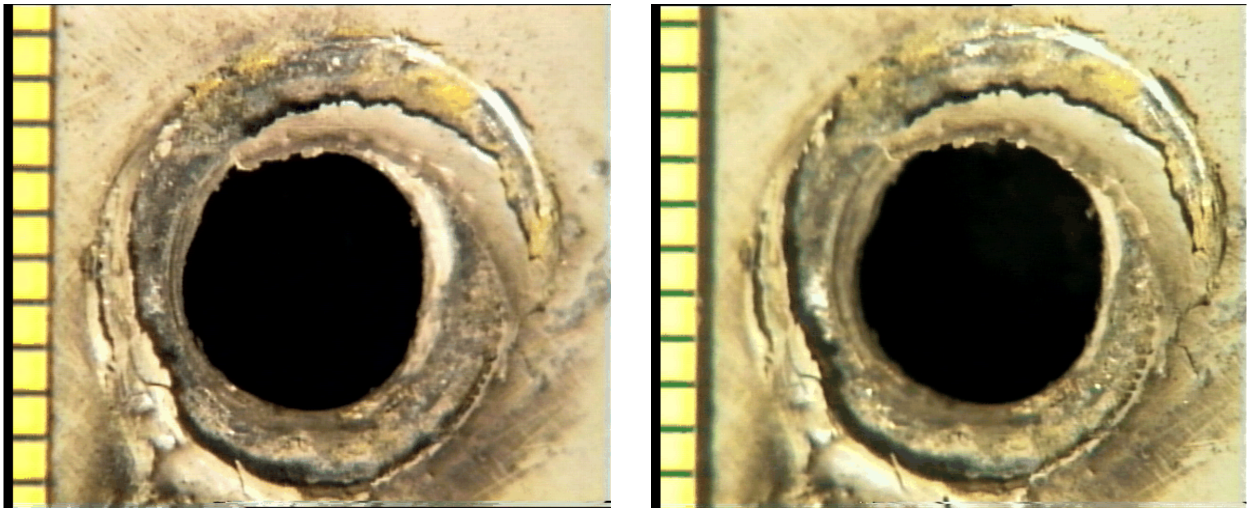

Figure 5: Left and right eye views of a rivet hole encrusted with corrosion. Scales at left in millimeters.

expected to be available and affordable within a few years. In the meantime this group is using existing high quality computer workstation displays as testbeds on which to learn how most effectively to implement 3D-stereoscopy for display of video and graphics. The graphics component of his research is stimulated by an Army Logistics application for displaying large and complex databases. The video component is stimulated by the perceived need to enhance the performance of remote visual inspection of aircraft.

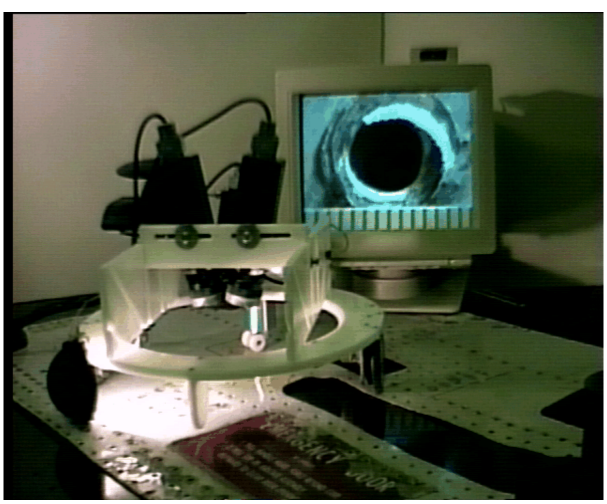

Figure 6: 3-D Stereoscopic camera-carrying robot for evaluating enhanced visual inspection. The monitor shows a frame similar to those shown in Figure 5.

4.2.2 Application to Visual Inspection

A system to test the hypothesis that remote visual inspection is substantially more acceptable given 3D-stereoscopic vision than given only monocular vision is under construction. This new work is funded by the WPATC-BFP in support of ADC's plans to commercialize the union of the research reported by the FAA-sponsored ANDI team and the ARPA-sponsored 3D-stereoscopy team. USAir is also cooperating with this effort with advice, samples of airplane materials with various kinds of visibly detectable flaws, and feedback from experienced visual inspectors about the "look and feel" of the prototype system.

4.2.3 Equipment

Several kinds of display systems that achieve this "3D-TV" effect are in fact available commercially. The systems that currently deliver the highest number of pixels per frame and frames per second to each eye provides the equivalent of a full NTSC channel per eye. One of these systems has been purchased and mounted on a small mobile robot built to evaluate camera and lighting parameters for 3D-stereoscopy enhanced remote visual inspection. Figure 6 is a photograph of this equipment "inspecting" a scrap of airplane skin.

The two camera views are displayed on a VGA-resolution (640 pixel x 480 line x 60 frame/sec) computer monitor in an alternating left-eye / right-eye sequence. The inspector views this time-multiplexed image through special shuttering eye-wear that opens for the right eye when the right camera's view is on the monitor and for the left eye when the left camera's view is on the monitor. The alternation is sufficiently rapid that there is no perceptible flicker.

5. Studying the Military Sector

As a result of research initiated across the board by the FAA Aging Aircraft Research Program the cycle-related pressurization-depressurization problem and other stress-induced damage (including damage related more to flying hours than to number of takeoff-landing cycles) are becoming well understood in the commercial aviation sector. Similar problems presumably exist in the military sector. In addition, the military aviation sector presumably suffers additional problems related to factors such as their more extensive use of composites, their use of distributed fuel storage systems (we are told "where there is not electronics, there is fuel"), accelerated structural wear-and-tear due to high stress maneuvers, accelerated corrosion due to low altitude operation over water, and, of course, battle damage. However in contrast to the civilian aviation sector, to the best of our knowledge the military's problems have not been systematically studied from the perspective of evaluating technology prospects for automated inspection tools that could help foresee and forestall loss of aircraft and personnel.

There thus appears to be an opportunity for a program with three objectives that could build on the civilian capability in a "spin-on" effort directed at the goals military aviation might have for automated inspection tools:

- conduct a needs, capabilities, and opportunity characterization for the military sector analogous to the characterizations done for the civilian sector under FAA-sponsorship;
- facilitate insertion of the currently developed civilian sector technology capability into the military sector by illuminating areas of common need and suggesting routes for migration;
- establish a research agenda for the military sector needs that cannot be satisfied by the civilian sector technology.

These objectives are elaborated in turn in the following sections.

5.1 Needs Characterization

What are the military sector's needs for NDI of aircraft (or perhaps at first just aircraft skin and its supporting substructure)?

Answering this question will help us in the civilian sector to understand and explain the differences between the problems we know in the civilian sector and those we would address in the military sector.

What automation tools have we developed in the civilian sector that would be useful for deploying the NDI equipment that the military sector needs?

Automation tools for NDI deployment must fit the constraints of the operational problem and the culture into which the technology is inserted. In the civilian sector there at first appeared to be three distinct classes of approach: "car washes", "cherry pickers", and "window washers". "Car washes" are the class of approaches that envisage a large consolidated inspection station, e.g., a gantry employing several moving carriages to deploy a variety of specialized NDI sensor manipulators. "Cherry pickers" are the class of approaches that envisage boom-like structures affixed at the ground end to a truck-like vehicle, and at the airplane end carrying an end effector for NDI sensor manipulation. "Window washers" are the class of approaches that envisage small self-contained devices in communication with a ground station but with integrated on-board measurement, manipulation, and mobility capability, e.g., airplane skin crawlers like CMU's ANDI.

It became clear early in the civilian sector study that the "cherry picker" approach sends shivers down the spines of airline operators: they already have enough problems with their airplanes getting bumped by service vehicles, e.g., booms carrying de-icing nozzles. Furthermore maneuvering a service vehicle in a maintenance hanger is disruptive of other operations that proceed in parallel with inspection. Any "cherry picker" design will thus have to invest heavily in addressing these concerns. However it is not obvious that the constraints and culture of military sector operations make it so difficult to implement this technically so attractive approach.

It similarly became clear early in the civilian sector study that the "car wash", which implies centralized inspection locations, would be too disruptive to scheduled operations to be acceptable. However in at least some parts of the military sector it may turn out that this is the most effective and economical approach. On the other hand, it is unlikely that this would be true everywhere; for example, if airplanes need to be inspected on aircraft carriers an ANDI-like design may be the only practical alternative, as it was in (at least the early stages of) the civilian sector effort.

What is the opportunity for automation tools to meet all or part of the military sector's need for NDI of aircraft?

Opportunity is the overlap of need and capability weighted by the urgency of the need. In the civilian sector this assessment led to the decision that ANDI would initially deploy eddy-current sensors, which account for about 10% of the inspection burden, rather than vision sensors, which account for about 90% of the inspection burden, because automating deployment of eddy-current sensing is primarily a matter of designing a suitable platform for achieving the required mobility and manipulation capabilities, whereas automating deployment of vision sensors would require solution of more difficult problems in automated image acquisition, image processing, and image understanding.

The answer to this question would be an approximately ordered list of inspection tasks that could be automated, the order reflecting more-or-less the products of urgencies and visibilities.

5.2 Identify Commonalities

How can the progress that has been made in the civilian sector be applied in the military sector?

To the extent that the military sector has NDI automation needs that are similar to those that have already been addressed and solved in the civilian sector, the civilian sector solutions may be inexpensively and rapidly adapted to the military sector's needs. It may also be useful to identify functionally related military needs, not necessarily for inspection or only for inspection, that can be satisfied by technology similar to that which has been developed for automated inspection in the civilian sector. For example, a military sector requirement for frequent removal and replacement of a sealant bead might be effectively automated by an ANDI-like robot.

5.3 Establish Research Agenda

What urgent military sector needs cannot be addressed by incremental adaptations of known automation technologies?

For example, in the civilian sector automating inspection inside wheel wells appears to be a formidable problem because of the three-dimensional complexity of wiring and plumbing in wheel wells. In the military sector it may turn out that there is a pressing need to inspect fuel systems for leaks, but existing sensor, manipulator, or mobility components are too big or too clumsy to fit where they need to go to do the inspection. These kinds of problems should be organized in a research agenda structured to facilitate early achievement of useful results, and an ongoing chain of achievements from incremental progress.

5.4 Potential Spin-Offs

Several technology areas known to be of interest in the miliary sector also relate to the automation tools for NDI effort. Several of these are mentioned briefly in the following paragraphs. This list is intended to be exemplary rather than exhaustive. In addition, the Bibliography refers to several articles describing other applications that may be amenable to similar approaches, e.g., explosives detection, contraband detection, and inspecting and cleaning ships.

5.4.1 Massively Distributed Databases

Massively distributed databases are critical to functional deployment of automated tools for NDI systems. In total maintenance systems employing these tools, inspection data and robot navigation data will have to be continually accessed and updated, rapidly and securely, on a worldwide geographical scale.

5.4.2 Vehicle Technology

Technologies needed by and that might be developed for navigation and communication on the microcosmic globe of an airplane's exterior differ primarily in scale from those relating to navigation and communication on land, sea, and air. An integrated airplane inspection and maintenance system thus potentially provides a testbed for larger scale systems.

5.4.3 Environment Technology

It is only a sequence of small steps from finding cracks in an airplane's skin by using automation tools that deploy NDI instruments to using the same deployment platform for automated detection of leaks of environmentally hazardous aviation fluids, then to adapting the technology to environmental sensor deployment in non-aviation related applications.

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