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AUTOMATION FOR NONDESTRUCTIVE INSPECTION OF AIRCRAFT

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Abstract

We discuss the motivation and an architectural framework for using small mobile robots as automated aids to operators of nondestructive inspection (NDI) equipment. We review the need for aircraft skin inspection, and identify the constraints in commercial airlines operations that make small mobile robots the most attractive alternative for automated aids for NDI procedures. We describe the design and performance of the robot (ANDI) that we designed, built, and are testing for deployment of eddy current probes in prescribed commercial aircraft inspections. We discuss recent work aimed at also providing robotic aids for visual inspection.

I. Background

Our goal is to replicate and enhance the capability of aircraft skin inspectors who use hand-held instruments (and their own senses and intelligence) to detect and classify flaws in aging aircraft. Our underlying concept is to use mobile robots, automated control, and automated interpretation of sensors and instruments to make *difficult measurements in difficult environments.* Potential application area include not only airplane skins, the subject of this paper, but also problems such as bombs in luggage, contraband in cargo containers, verification of disarmament treaty compliance, characterizing environmentally contaminated sites, and a variety of manufacturing problems, e.g., measuring composition gradients in large process tanks, transportation problems, e.g., bridge inspection, and scientific research problems, e.g., checking the integrity, alignment, etc, of large instruments such as radio telescopes and particle accelerators. These few examples just begin to suggest the universe of potential application areas and specific applications. A general hierarchical paradigm for organizing the common issues of *measurement, manipulation, mobility,* and *monitoring* characteristic of all these problems is illustrated explicitly for the aging aircraft problem in Figure 1.

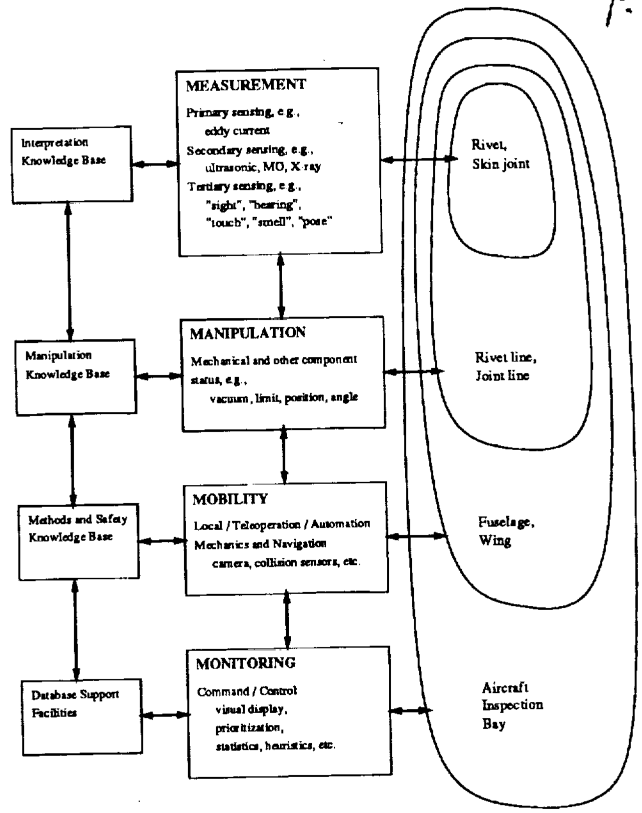

Figure 1: The 4M-s of automation for aircraft inspection.

II. Inspection of Aging Aircraft

Aircraft skins inflate and deflate with each cycle of pressurization and depressurization. The resulting stress causes several kinds of damage, primarily radial cracks around rivets, delamination of skin joints, and subsurface cracks in the structural members to which the skin is attached. Delamination is exacerbated by corrosion, which is particularly prevalent in warm moist climates. Cracks and corrosion, accelerated by island-hopping operation, resulted in April 1988 in a large section of skin tearing off the top of the fuselage of an Aloha Airlines Boeing 737. The resulting press coverage of the

*Senior Research Scientist, The Robotics Institute, School of Computer Science airplane's seemingly miraculous safe landing brought these problems prominently to the attention of the public, and resulted in an aggressive prevention, detection, and remediation program by aircraft operators in close cooperation with each other, the aircraft manufacturers, and the FAA[1,2,3]. Structural effects of aging in other areas, such as engines, fuel tanks, landing gear, etc, possibly will be the subjects of future automation research, but for the present our program is concentrating on skin and the immediate supporting substructures.

Through programs of periodic inspection of known problem areas on each aircraft type, skin cracks and corrosion are typically found well before they reach hazardous size. The problem areas are specified by "service bulletins" issued by aircraft manufacturers, and by "airworthiness directives" issued by the FAA. Compliance with airworthiness directives is mandatory. Compliance with service bulletins is at the airline operators discretion, but we are told that in practice they are treated as mandatory.

About 90% of skin inspection is visual, by inspectors trained for the task, most of the remainder is by eddy current probes, and a fraction of a percent is by other instrumentation of which the best known is probably ultrasonic. Our program is focused in its initial phases on automation as an aid to skin inspection using eddy current probes. Initially we will use machine vision to aid probe placement and robot navigation and to update the navigation database with descriptions of patches and other deviations from "as designed". We are beginning to investigate automated aids to visual inspection via a new program in which a small limited functionality robot will be used deploy 3D-stereoscopic cameras. Working with experienced visual inspectors, we will evaluate the acceptability of computer aided remote (teleoperated) visual inspection.

Eddy Current Inspection

The eddy current method[4] uses a transmitting coil and a receiving coil (they may physically be one coil) coupled electromagnetically through the metal under inspection. Eddy current probes vary in tip area from several square centimeters to about one square millimeter, obviously trading off decreasing areal coverage for increasing sensitivity to small flaws as the size decreases. Anomalies in the impedance that characterizes the coupling indicate cracks, corrosion thinning, and other flaws. Inspectors generally watch an x-y oscilloscope display whose x-axis represents the in-phase (resistive) part of the impedance and whose y-axis represents the quadrature-phase (inductive or capacitive) part of the impedance. Figure 2 illustrates a probe, and Figure 3 illustrates typical impedance plane signals. The inspectors compare patterns traced out on the screen when the probe is passed over a potential flaw with the pattern traced out when the same probe is passed over a calibration standard manufactured with a machined flaw in the simulated local structure. The probe geometry, operating frequency, scan path, etc, are chosen to optimize sensitivity to each anticipated flaw. High operating frequencies are attenuated in a short distance, and thus probe only the surface. Low operating frequencies penetrate deeper, and in some geometries can penetrate the skin entirely and probe for cracks in the supporting framework. Under typical operating conditions power levels are sufficiently low that the method is extremely linear, so it is possible to operate a probe with a composite multi-frequency transmitted waveform and to separate electronically the high-frequency surface-sensitive received signal components from the low-frequency substructure-sensitive components.

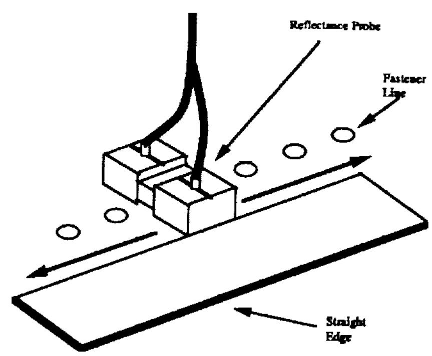

Figure 2: "Reflectance" or "pitch-catch" eddy current probe.

Modern eddy current systems can be set to alarm on traces that enter or fail to enter preset rectangular windows in complex impedance space. Initially we will rely on these alarms to alert the inspector to potential flaws indicated by anomalous signals. These areas will be marked for easy identification by the inspector, e.g., by daubing suspect rivet heads with a washable paint. Pattern recognition integrated with rule based systems is an accepted method for automating interpretation and classification of eddy current signals in other applications, e.g., inspection of heat exchanger tubes in nuclear power plants[5]. Neural network methods have been similarly successful in similar applications[6]. As the program progresses we will add additional software to implement promising approaches to automated and improved eddy current signal interpretation and classification.

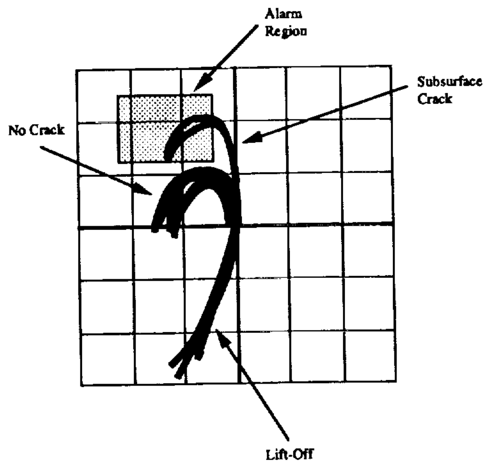

Figure 3: Eddy current signals in the complex impedance plane.

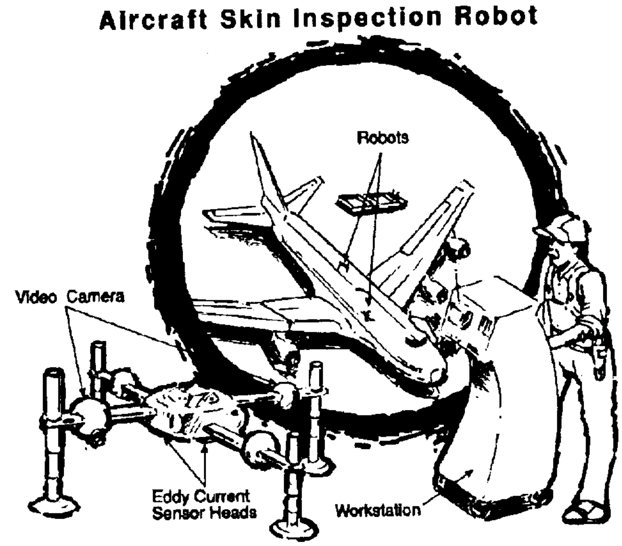

Figure 4: Concept sketch for ANDI.

III. Automated NonDestructive Inspector

We considered many approaches to automation-assisted eddy current probe deployment, with three primary variants: the gantry-based "car wash", the vehicle-based "cherry picker", and the self-contained "window washer". The pros and cons of these alternatives have been discussed in detail elsewhere[7, 8, 9, 10, 11, 12, 13, 14, 15]; in summary, the "window washer" design that we eventually chose for the system is dictated by the pragmatics of fitting NDI nondisruptively into the flow of passenger aircraft maintenance operations. These constraints suggest a small (under one meter maximum dimension) mobile platform that is able to walk or crawl over most if not all of the aircraft skin, whatever its orientation. This capability we achieve with active (vacuum assisted) suction cups. A concept sketch for the resulting robot (ANDI, the Automated NonDestructive Inspector) is shown in Figure 4. It is not the easiest approach, but it is the most acceptable, and incidentally it is the approach that requires the most interesting enabling research.

Cruciform Design

Because there is generally more fore-aft than circumferential inspection path, the robot is designed with a cruciform geometry that enables it to move along fore-aft paths most rapidly; this results in a design in which it moves on circumferential paths somewhat more slowly, and in skew directions adequately, but a bit awkwardly. The mechanical design is sketched in Figure 5 and shown close-up (with eddy current probe in the foreground and a graphical depiction of the probe output on the computer monitor screen in the background) in Figure 6. It has many features in common with the class of mobile robots known in the literature as "beam walkers"[16, 17]. However unlike most beam walkers our robot is able to side step almost as easily as it can walk forward or backward. The two cross members ("bridges") are normally locked at right angles to the main longitudinal member ("spine"), but they can be released to pivot freely by about 15° in either direction; this permits the robot to steer and thus to travel along paths that are neither strictly fore-aft nor strictly circumferential. Pneumatically actuated up-down degrees of freedom on the four suction cups at the ends of the bridges enable the walking motion, and another pneumatic actuator enables the raising and lowering of the eddy current probe. The sliding motions of the bridges along and perpendicular to the spine are actuated by electric motors.

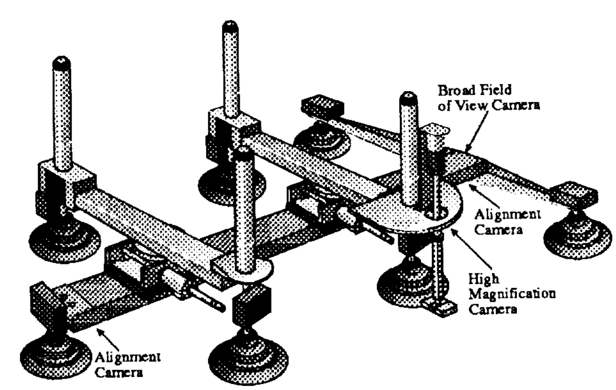

Figure 5: Mechanical features of ANDI, showing four camera mounting points.

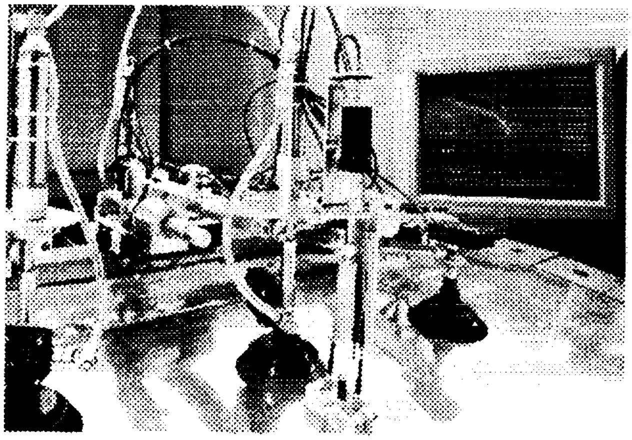

Figure 6: ANDI, showing eddy current probe and its signal on the computer monitor.

Alternative Designs

It is regrettably easy to confuse ANDI, particularly given its multiply anthropomorphic name**, with the much larger and more complex system of which it is essentially just the mechanical end effector. It is thus appropriate to emphasize explicitly that ANDI is just the first prototype mechanical end effector of a large and complex system (most of which is black boxes full of electronics and computers) that can accommodate many different end effectors. ANDI is designed to demonstrate the feasibility of using robots to assist inspectors of aging aircraft. But ANDI is not the last end effector that will ever be needed for this task. There are places on an airplane skin where ANDI cannot adhere, e.g., sharply curved regions around the nose, tail, and leading and trailing edges of the wings and horizontal and vertical stabilizers. There are places where ANDI can adhere but may turn out to be insufficiently agile to deploy the eddy current sensor in an effective pattern, e.g., perhaps around doors, windows, repair patches, etc. Our goal is to demonstrate what ANDI can do. We guess it can do something like 80% of the mandated and recommended eddy current inspections on DC-9 or Boeing 737 and larger aircraft. If ANDI proves its technical and economic worth in these applications, we are confident that we (and others!) will be able to design as many specialized mechanical end effectors as are needed to cover the applications ANDI cannot.

A block diagram of the currently envisioned complete system is shown in Figure 7.

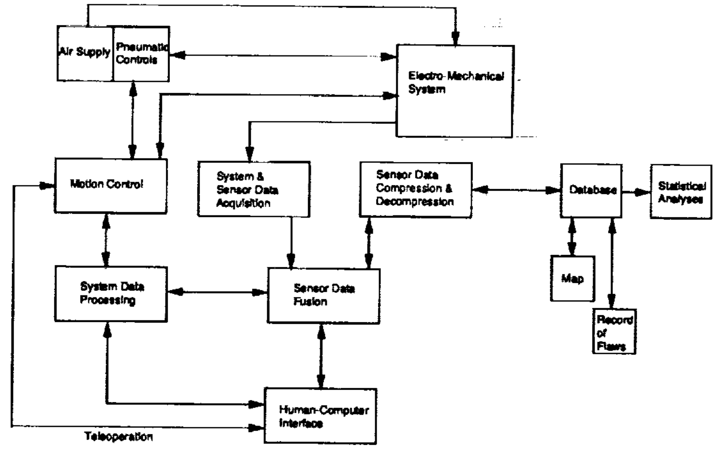

Figure 7: Block diagram of planned complete system.

Special Purpose Actuators

Our initial eddy current sensor deployment demonstration is targeted on part of a mandated inspection on the fuselage of a DC-9 that uses a "reflectance" or "pitch-catch" probe with mechanically independent but electrically coupled transmit and receive coils. This particular inspection has both a surface crack and a subsurface crack component which we address simultaneously by composite dual frequency operation. The reflectance probe geometry is sensitive to integrated conditions over a fairly large patch of skin (a few square millimeters), so it is forgiving of small errors in placement relative to the rivets under examination. Under these circumstances it is adequate to deploy the probe with a simple up-down lifter mechanism and let it self-align with the skin under the influence of a constant-force spring. Another part of the planned demonstration inspection uses a "pencil" probe with a single coil that has a much smaller sensitive area. It must thus be placed and scanned more accurately, e.g., along a path that is tangential to each rivet, which may require closed loop guidance. Another small but necessary part of the demonstration inspection requires moving a pencil probe completely around the circumference of several rivets. The more complex probe paths that this inspection component requires can in principle be achieved by coordinating the motions of bridge-along-spine and bridge-perpendicular-to-spine, but we anticipate that obtaining the necessary mechanical precision and simplicity of control may require adding some nominally

**Messrs Andrew Carnegie and Andrew Mellon both suggest ANDI.

redundant special purpose degrees of freedom, e.g., a rotary mechanism for precisely circumnavigating individual rivets.

Path Control

The path control system addresses mechanical positioning of the eddy current probe and the robot at four distance scales corresponding to the tasks of *alignment*, *guidance*, *navigation*, and *path planning*.

Alignment means the relative position of the eddy current or alternative probe and the rivet or other component under inspection. The inspection protocol is predicated on the assumption that the probe will be moved along a precise short path relative to the part geometry. Signal classification can be done meaningfully only if this path is followed.

Guidance means, for rivet inspection, moving the probe from one rivet to the next and arriving there in correct alignment. For other inspections, e.g., for corrosion somewhere along a skin joint, it means following the required inspection path. In this case it is differs from alignment only in distance scale.

Navigation means coordinating walking and probe guidance so that an inspection that spans multiple robot steps proceeds smoothly and certainly.

Path planning means being able to traverse as rapidly as possible, without inspecting, long distances between areas that require inspection. This is the scale at which collisions with undocumented parts of the airplane (e.g., a non-standard antenna), expected parts in an unexpected state (e.g., an access hatch left open during maintenance), and other maintenance equipment (e.g., a wrench left on a bolt head) are potentially serious problems.

We expect to achieve the necessary position accuracy by dead-reckoning using high mechanical precision motion over short distances between map database landmarks and using machine-vision-based correction at each landmark. The obvious landmarks are the rivets themselves, each of which is in principle individually identifiable in the aircraft design database. The eddy current signals themselves then provide an additional and perhaps finer level of correction: misalignment signatures are recognizable and quantifiable, although some sign ambiguities would have to be resolved by active sensing. Skin joints and skin joint intersections provide additional landmarks. They are particularly appropriate for navigation and path planning, in contrast with the rivets, which are particularly appropriate for alignment and guidance. Skin joints are farther apart than rivets, a disadvantage in terms of dead-reckoning error accumulation, but their existence is more consistent from airplane to airplane (of the same type) since their locations are less likely to be changed by modifications and repairs. The skin joints and skin joint intersections, referenced in terms of the underlying longeron (or stringer) and spar (or body station) identification numbers, are in fact the features in terms of which mandated and recommended inspections are defined.

In principle the map databases are all on-line at the factory for as-designed and as-built, and on-line at the hangar for as-modified and as-repaired. In practice the data are still on paper for all aircraft except the generation now in gestation, e.g., the Boeing 777, and we expect we will have to use ANDI to bootstrap populating its own map and exception database.

Vision System

ANDI will have at least four cameras in the alignment, guidance, navigation, and path planning system. Cameras will also have roles in visual flaw detection, but not until a later phase of the program.

Macro Camera

The first camera will be mounted on the same platform as the eddy current probe, with a macro capability giving it a field-of-view of approximately one rivet. It will be used for fine alignment and for the inspector's visual observation of the appearance of the rivet and the adjacent skin at high magnification. In some inspections that require precision probe alignment the alignment control loop may incorporate the eddy current sensor signal as well. In later phases image understanding will be incorporated for visual flaw detection, and possibly as an adjunct to eddy current or other NDI probes. For example, a particular eddy current probe that has a radially symmetric field geometry may sensitively indicate the presence of a radial crack, but will obviously be blind to its orientation; it may then be useful to use the high magnification camera to find its orientation.

Alignment Cameras

The second and third cameras, each with medium magnification fields of view of about 10 cm x 15 cm, or a line of four to six rivets, will be mounted at the head and tail of the spine. These cameras will be used to locate line segments of rivets. A robust best-fit[18] to the head and tail line segments will guide the eddy current sensor along a scan line. This guidance functionality is required early, so these will be the first cameras installed on ANDI. Guidance is actually required before alignment, because the initial eddy current probe is of the "pitch-catch" or "reflectance" type, which is sufficiently tolerant of misalignment that little alignment (fine adjustment about the guidance line) is likely to be needed. The imagery from these cameras will also be made available to the inspector for opportunistic flaw detection of, for example, lightning holes and small dents. As in the case of the high magnification camera, automation of the flaw detection role for these cameras will come in a later project phase. However, we have already made substantial progress prototyping the computer vision based automation of the alignment function. Several rivet finding algorithms have been tried, including edge detection followed by region growing, gray level variance, and a trained neural network, yielding the general conclusion that even with uncontrolled lighting, low contrast, and interference from specular reflectances, any scale-sensitive operator that has the actual rivet size hard wired into it will succeed. A conventional robust line-fitting algorithm based on minimizing the mean absolute deviation almost always correctly draws the desired line through three, four, or five rivets even for the most ghastly poor images. Early results are discussed and illustrated in the following section.

Zoom Lens Camera

The fourth camera, with an ordinary zoom lens's range of focal lengths and working distances, will be mounted on a motorized pan-tilt head high above ANDI's tail end. In the initial experiments, before general purpose navigation and path planning algorithms are in place, ANDI will be teleoperated between inspection stations. Thus the fourth camera will initially be the inspector's eye on the robot's actual configuration, possible interferences or collisions, sensible paths between inspection stations, and gross visual flaws, e.g., pillowing due to extensive subsurface corrosion. As the program progresses machine vision algorithms will increasingly use this camera for proprioception (visually confirming that the actual robot pose corresponds to the control system's model of the pose), collision avoidance and footfall decisions (new radio antennas, skin patches, or raised head replacement rivets will have to be found, avoided, and entered into the database), long distance path planning between inspection stations, and opportunistic detection of large flaws.

Vision Based Alignment

While there are important exceptions that we will eventually have to address, most of the time rivets line up neatly in evenly spaced rows and columns. ANDI is designed to take maximum advantage of this design rule: what ANDI can do most effortlessly and precisely is to scan an eddy current sensor along a straight line segment parallel to and almost the full length of its spine. The essential alignment problem is thus to align the spine parallel to the line segment under inspection. The approach we are developing is to best-fit visually a short line segment near each end of the spine, best-fit the long line segment to the two short line segments, and scan along the long line segment open loop unless the eddy current data show features that suggest the rivet line wiggles enough that transverse corrections are needed.

On the assumption that if a computer vision algorithm works well with terrible looking images it will probably work better with better looking images, we developed our approach on a sequence of images that we collected with uncontrolled lighting, uncontrolled surroundings (which are obvious in specular reflection), poorly controlled camera standoff from the riveted surface (a test panel with a radius of curvature and other features comparable to a Boeing 737 or DC-9), and a consumer grade 8 mm camcorder camera that we scanned over the test panel by hand. We digitized to 8 bits x 3 colors about 80 frames grabbed from the tape at about 1.5 sec intervals. Each frame was digitized into 480 pixels x 512 lines x 3 colors, then averaged in 8 x 8 blocks into 60 pixel x 64 line x 3 color working images. At the lowered resolution the rivet line segment finding pipeline runs at approximately real-time (1.5 sec/frame) on a workstation. With the camera parameters and resolution we used, rivets are circular blobs that generally fit into a 7 x 7 block. A typical frame, with gray levels computed by averaging the RGB values, is shown in Figure 8.

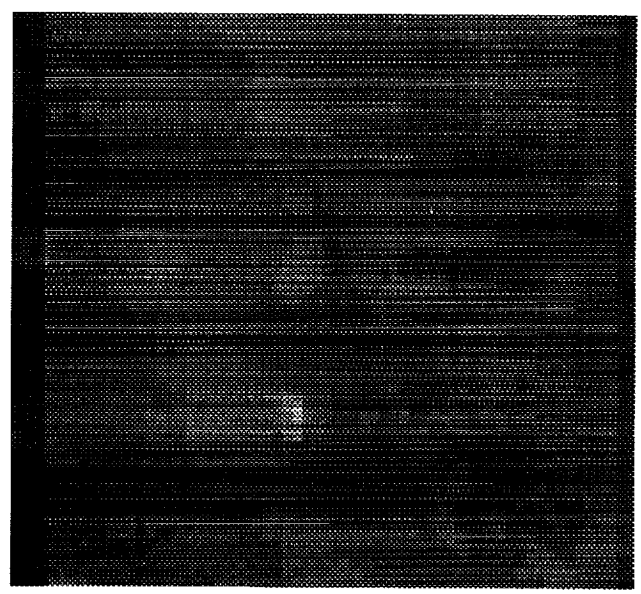

Figure 8: Raw image showing a line of rivets.

Conventional Algorithm

As mentioned in the previous section, finding rivets is easy even when the images are as ugly as this one: any sensible operator with a scale length matched to the rivet size works fine. Under these circumstances a useful strategy is to choose an operator that rarely misses a real rivet even at the price of occasionally finding a false rivet, provided that one or more downstream modules can be tailored to reliably reject false rivets. Finding all real rivets plus some non-rivets we can in fact do with a Canny edge detector[19]. Next we observe that specular reflections, the main potential source of false rivets, look different in each of the three color bands, whereas real breaks in the metal, e.g., rivet edges, have a generally neutral hue. Thus in the second image processing step we reject most of the non-rivets by fusing the three color bands, retaining only those pixels tagged by the edge detector separately in each band. The result is shown in Figure 9.

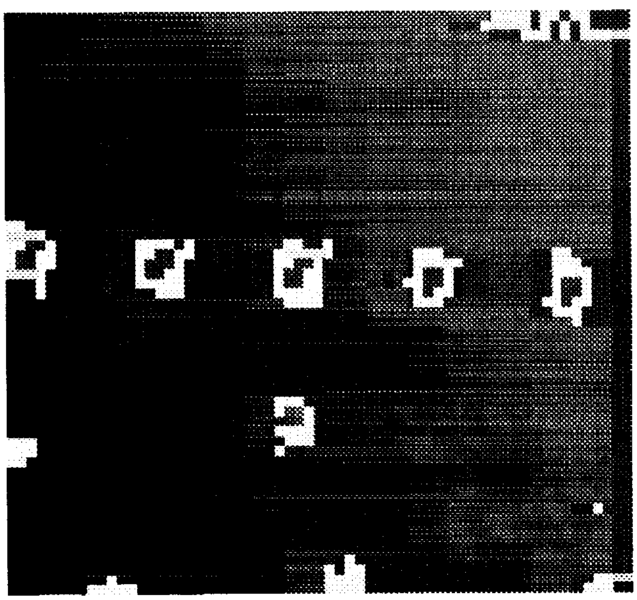

Figure 9: Rivet edge detection by the Canny operator.

Next a region-growing ("grass-fire"[20]) algorithm transforms the perimeters found by the edge detector into blobs filling the areas of the rivet heads. Blobs are rejected if they fail to meet simple geometrical criteria for rivets, e.g., area, aspect ratio, and fill factor within heuristic numerical bounds. The centroids of the surviving blobs are then used as input to a robust (insensitive to outlier) line fitting algorithm[18]. The result is shown in Figure 10.

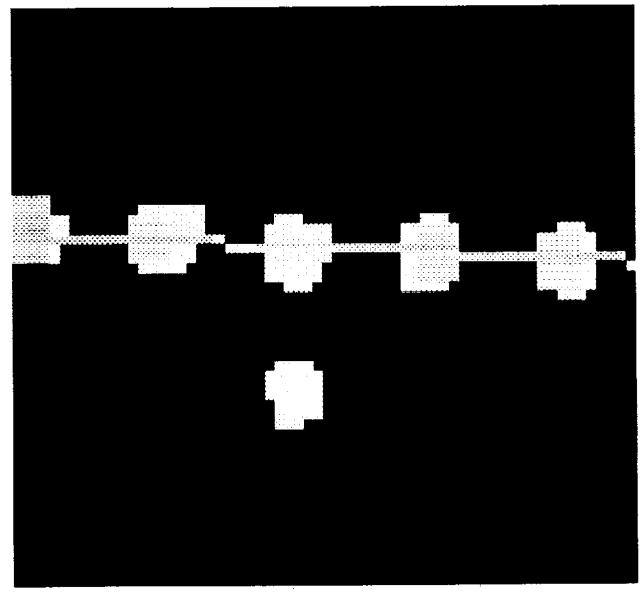

Figure 10: Line fit to the five rivets found.

Neural Network Algorithm

An alternative algorithm was built by training a neural network simulated in software. This method approaches the problem by saying that rather than discovering and finding suitable discrimination parameters and their ranges intuitively, relevant parameters and ranges can be found mechanically by systematically modifying the parameters of a generalized input-output network until it reliably behaves as a rivet/not-rivet classifier when applied to an operator-classified training set representative of the problem; if the training set is adequately representative of the problem domain then the trained network will also be able to classify rivets and not-rivets that were not in the training set.

To implement this method we constructed and trained (using the back-propagation algorithm[21]) a three layer neural net with an input layer consisting of 147 units (a 7 x 7 retina in each of three color bands), five hidden units, and one output unit whose binarized output we interpret as "rivet" and "not-rivet". The network was trained on 40 frames and tested on 40 different frames. Figure 11 shows the output of the trained neural network operator: bright areas are "rivet-like", dark areas are "not-rivet-like". Figure 12 shows the result of thresholding and extracting connected regions of this image, and also the performance of the robust line fitting algorithm on the result.

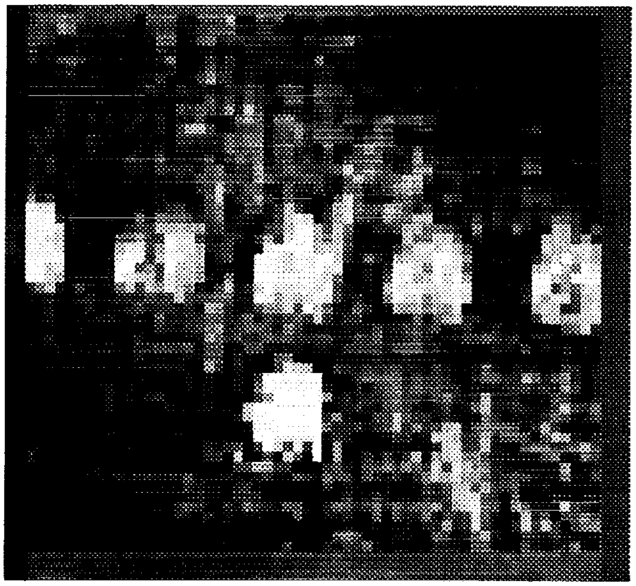

Figure 11: Rivet image found by the neural network.

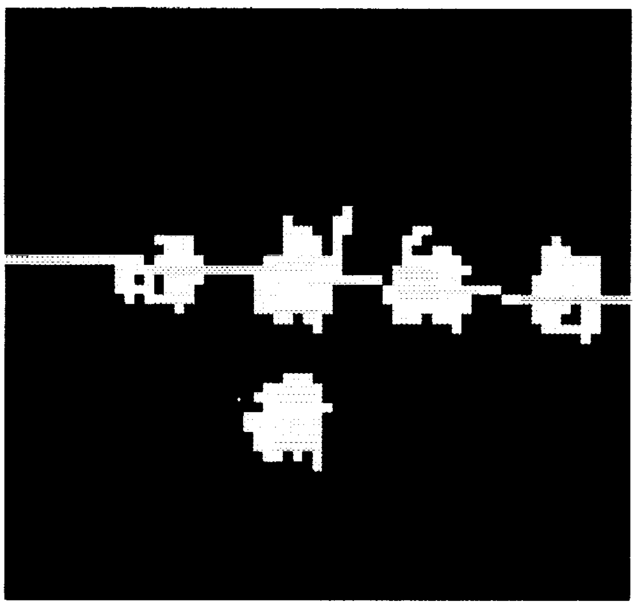

Figure 12: Line fit to the rivets found in the neural network image.

Inspector's Workstation

Figure 4 depicts an inspector's workstation adapted to the environment and culture of aircraft maintenance and inspection. During ANDI's laboratory research and development phases the interim implementation of this workstation is based on two 80486-based PCs. One supports the inspector's mouse-and-menu-based interface, serial communications with the motor controllers, and a general purpose data acquisition and control system with multiple analog-to-digital inputs, digital-to-analog outputs, and digital input and output lines for interacting with various sensors (e.g., suction cup vacuum) and actuators (e.g., solenoid valves controlling pneumatic cylinders). The second PC supports the eddy current probe system and its display. The interim vision system is on an independent proprietary computing platform. It now supports alignment of the robot spine with rivet lines. Its permanent successor will support the additional vision system requirements outlined above.

As development continues the multiple platforms and displays will be rationalized. Our aim is to distribute processing power (which will include providing ANDI with on-board computing power for pose and gait control, etc), and to coalesce the multiple displays by using a powerful windowing system to give the inspector access to controls, signals, images, and data on a single screen. A rudimentary interim database is in place for this function during laboratory tests of vision based alignment, eddy current sensor scanning, and navigation during walking between scanned locations.

Database and Archiving

Aircraft skin inspections are now pass/fail. There is no requirement to record anomalies the reporting threshold. In practice, we are told, airline operators repair all detected flaws, even those below the mandatory and recommended thresholds. Even if this were not the case, pass/fail recording would not necessarily be risky: the thresholds have substantial safety margins, and there are good growth models[22] for predicting how far in the future will repair be necessary. These encouraging practices and circumstances notwithstanding, we nevertheless expect that the predictive capabilities that will follow database archiving and statistical analysis of quantitative inspection results will facilitate maintenance scheduling and potentially increase safety. Thus an on-line distributed database, with an architecture open to access from multiple potential inspection and maintenance locations and tools for trend analysis, improved statistical predictions, and pattern discovery is an integral part of our program. We envision a hierarchical architecture with aircraft type at the top, followed by production series, customer configuration, fleet-wide modifications, and, on an airplane-by-airplane basis, records of individual modifications and repairs. These include individual functional modifications, repair patches, plated regions, regions with oversize replacement rivets, etc. These structural features need to be documented for robot navigation as well as for maintenance.

IV. Visual Inspection

As mentioned earlier, close to 90% of aircraft inspection is visual; our choice of eddy current inspection for the first demonstration of automation to aid aircraft inspectors was driven by the relative simplicity of automating deployment of eddy current probes (and NDI probes in general) in comparison with visual inspection. Unlike NDI, where the goal is usually to detect a flaw whose location and nature is known in advance (from previous experience or from computer modelling), visual inspection has a substantial opportunistic component. The visual inspector's goal is to find not only the anticipated failures, but "everything else" as well: dents, lightning strikes, and other kinds of damage of an unpredictable nature in unpredicatable locations. The open-ended quality of this task makes it an unlikely candidate for a level of automation approaching the level we are planning for NDI.

However discussions with airline management and NDI inspection personnel suggest that an integral visual inspection capability may be perceived as an indispensable component of any economically viable system of automated aids to NDI.

In response to this perception, a mobile end-effector like ANDI does suggest itself as a teleoperable platform from which ground-based visual inspection might efficiently be conducted. If this could be accomplished, it would be valuable for many of the same reasons that ground-based NDI is valuable: reduced set-up time, human-factors issues of inspector performance in a difficult environment, inspector safety, database access, data archiving, etc. The question is whether remote cameras can provide sufficiently high quality (presumably meaning primarily high resolution) imagery to satisfy the notoriously fussy (we are comforted to say) visual inspectors. We recently began a program whose goal is to answer this question. This program combines elements of the FAA-sponsored ANDI project with salient elements of an ARPA-sponsored project in 3D-Stereoscopy Technologies for image and graphics visualization.

One of the costs of human inspection is attributable to the difficulty of safely getting the inspector to the right place on the airplane: it involves erecting scaffolding, providing safety harnesses, etc, all of which can take more time than the inspection per se. ANDI can be placed on an airplane fuselage at human chest level, and directed to move to any area requiring inspection without erecting scaffolding and without endangering the human inspector. Thus even a teleoperated capability, with only the most rudimentary elements of automation (e.g., computer coordination of gait), could permit the inspector rapidly and safely to perform the necessary visual inspections. With appropriately selected cameras and actuators thus could clearly be done at the required variety of points-of-view, magnifications, lighting conditions, etc.

3D-Stereoscopic Vision

We are particularly interested in the prospect of providing the visual inspector with binocular 3D-stereoscopic vision. Stereoscopic perception appears to be important to the visual inspectors who we have observed on the job. We speculate that this may be because of its importance both in perceiving and in rejecting the effects of specular reflection off the mirror-like aircraft skin. Specular reflection appears to be important to inspectors looking for the presence or absence of specific flaws: they often move their heads and lights as the look for an expected tell-tale glint. Specular reflection is particularly apparent in binocular 3D-stereoscopic imagery because the sharply directed reflection appears much brighter in one or the other image, in contrast to the diffuse reflections, whose intensities are evenly balanced in the two images. [For this reason waterfalls and fast running streams, which are notoriously difficult to photograph (and paint) well, look spectacularly realistic in 3D-stereoscopic imagery.] Furthermore, the depth perception provided by 3D-stereoscopic imagery also makes it easy to reject artifacts of the environment that are reflected by the aircraft skin. Without depth perception it is impossible to know (except by high-level knowledge of the context) whether features of the imagery are in the skin or in the environment and seen in reflection. With depth perception, image features that are not in the plane of the skin can be rejected straightforwardly, even automatically.

The components required in a 3D-stereoscopic system are (1) a matched pair of cameras (analogous to the human's two eyes), (2) suitable and suitably controllable lighting, and (3) a display that is capable of directing the image corresponding to the right camera to the operator's right eye and the image corresponding to the left camera to the operator's left eye. There is no ideal way to accomplish (3). Special video taping equipment is also needed if the imagery is to be recorded. A variety of commercially available solutions have pros and cons that we are evaluating in context of the visual inspection application. Available solutions include frame, field, and subfield sequential methods with active shuttering eyewear, field and sequential methods with interline-polarization and passive eyewear, and "virtual reality" approaches using head-mounted displays. We have one subfield sequential and one interline-polarization system operational, so will conduct our initial experiments with these systems.

We are building for these experiments a simple mobile manipulator that will move over an airplane panel test surface according to the inspector's instructions mediated by a computer that will support a suitably high-level interface. A simple mobile manipulator (in contrast to ANDI) will suffice because (unlike ANDI) it will have to operate, for these evaluation experiments, only on a more-or-less horizontal surface.

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