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SURGICAL NONDESTRUCTIVE EVALUATION (SuNDE)

Gary Georgeson, Bill Motzer, and Paul Rutherford

The Boeing Company

**JULY 2011
Final Report**

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14. ABSTRACT This report summarizes the results of the Air Force program, Surgical NDE (SuNDE), and provides recommendations for the development and implementation of SuNDE to relevant limited access inspection applications. The motivation for SuNDE development is derived from the need to reduce costly disassembly and to extend inspection intervals by detecting smaller remote flaws. This report is an assessment of the needs and opportunities for cavity and obscured view inspections. The method chosen to bring the inspection challenges to light has been to develop and test a general SuNDE Tool on selected applications in an aircraft maintenance environment. That tool demonstrated the ability to perform eddy current cavity inspections from outside a wingbox with sensitivity to smaller size cracks around fasteners, which could enable extension of the current inspection interval over the present method. Special features of the tool included micro-video assistance for sensor placement and monitoring motions of the probe, self alignment of the sensor and automated rotation scanning. This report makes specific recommendations for continued development based upon the results of the tool evaluation and discussions with potential SuNDE users. In defining a future state for SuNDE, we also describe the opportunities for implementing autonomous NDE platforms, specifically, robotic snakes.						
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1.0 INTRODUCTION AND PROPOSAL CONCEPT, PHILOSOPHY, AND TEAM

1.1 Introduction

A key goal of the U.S. Air Force Research Laboratory NDE Branch is to reduce the Operation and Maintenance (O&M) costs associated with inspection. Nondestructive Evaluation (NDE) may require removal of systems and hardware to perform the inspection, and some platforms require structural disassembly to gain access for inspection. Inspection of these limited access areas of an aircraft is a significant issue for many aircraft, and results in significant down-time, labor, and potential damage costs. In order to meet the NDE challenges stated above, technology and methods are needed for the inspection of limited access areas on an aircraft without system or structure disassembly.

The increasing complexity of aerospace structures as aircraft designs have evolved has made NDE more difficult to apply successfully and cost-effectively implement. Often, a region of a particular structure that must be inspected is outside the application of traditional NDE methods. Alternatives to part removal or expensive re-designs in order to improve inspectability, are being sought within the aerospace industry. Common extenders and manipulation arms combined with existing NDE equipment have been used to aid probe placement on or near limited access areas of aircraft. However, these rudimentary tools are often not reliable or do not have the range of motion sufficient for adequate inspection coverage or effective detection of small flaws. Particular technical issues include sensor insertion around or through obscuring systems, sensor alignment relative to the structural area of interest, maintaining sensor contact with the structure and couplant minimization (with traditional ultrasound).

This report is a brief assessment of the needs and opportunities for limited access inspection within the aerospace industry, and a design concept to meet those needs which we have designated as the 'Surgical NDE (SuNDE)' tool. The approach chosen to bring the inspection challenges to light has been to develop and test a general SuNDE tool on selected applications in an aircraft maintenance environment. This report makes recommendations based upon the successful results of the tool evaluation by potential SuNDE users. In defining a future state for SuNDE concepts, we briefly explored potential opportunities for implementing autonomous NDE platforms, in particular, robotic snakes.

1.2 Concept and Technical Team

The SuNDE team included the Boeing Research & Technology (BR&T) organization, and subcontractors UniWest and Carnegie-Melon University (CMU). BR&T is an industry leader in NDE development and in limited access NDE processes and technology, and has access to technology transition focals associated with AF programs.

BR&T provided the project management, sensor design, SuNDE tool integration, and demonstrations aimed at assessing industry transition points for surgical NDE methods.

UniWest of Pasco, Washington is a leading manufacturer of nondestructive testing equipment with recognized expertise in the design, development and

commercialization of eddy current and ultrasonic instrumentation, and supporting equipment. UniWest previously designed, built and delivered a limited access eddy current inspection kit with a remote visual capability for the F-22 program, the US-1514 ExtendoProbe™. UniWest's contribution to the effort was to develop the SuNDE manipulator arm and rotating eddy current probe for crack inspection around fasteners.

CMU's Center for Biorobotics is a leader in the development of robots for search and rescue, medical surgery, bomb disarming, bridge inspection, and tank inspection. The CMU research group has constructed a variety of highly articulated snake robots, which can exploit their many internal degrees of freedom to thread through tightly packed volumes, accessing locations that people and conventional machinery otherwise cannot. CMU provided a demonstration of the potential of snake robots for use in limited access inspections, and made recommendations for future robotic development in support of SuNDE.

1.3 Key Program Elements

The long term goal of this program is to explore opportunities for the Air Force (and aerospace industry in general) toward future SuNDE technology development that will reduce costly disassembly during aircraft maintenance. It is our hope that this report serves as a foundational document for future SuNDE efforts.

A systematic approach to the problem of limited access inspection is needed in order to address the wide range of needs. The program approach was to [1] explore the issues of inspection in limited access areas and the potential contributions of alternative methods to assist inspectors in performing their tasks, [2] develop a general SuNDE Tool that could be tested and evaluated on a selected platform inspection configuration, [3] make use of the tool design development and test of the prototype solution, [4] define 'lessons learned' for future SuNDE developments and implementation, [5] develop and evaluate end effectors for modalities beyond eddy current, and [6] assess the potential and opportunities for advanced SuNDE approaches, with particular focus on robotic snakes.

[1] Limited Access Inspection -- There are a variety of issues and challenges related to providing effective inspection of structure that is not easily accessible to the inspector. A summary of the key processes and features that could be applied globally to SuNDE tools are listed in Section 2.0

[2] SuNDE Tool -- A general purpose surgical NDE tool was developed with a hand-held manipulator arm and a variety of end effectors. Details of the SuNDE Tool prototype are described in Section 3.4

[3] SuNDE Tool Design and Testing -- The design considerations, key elements, and design process for the prototype solution are described in Sections 3.1 and 3.3. The tool was tested and refined using a selected limited access aircraft inspection described in Section 3.2.

[4] Lessons Learned for SuNDE -- Industry feedback on the SuNDE Tool, discussions at selected NDE forums, and on-site visits to maintenance facilities were helpful in defining the challenges and opportunities related to present and future SuNDE applications. The details of the visits, with specific communication and feedback are given in Section 4.0

[5] End Effectors for SuNDE – NDE modalities for the SuNDE Tool beyond eddy current, specifically remote ultrasonic pulse echo, hybrid (non-contact/contact) through-transmission ultrasound, and remote digital radiography were developed and evaluated. They are described in Section 5.0.

[6] Advanced SuNDE – Various types of snake robots developed at the Carnegie Mellon University (CMU) Center for Biorobotics were demonstrated, discussions were conducted regarding obstructed inspection opportunities, and recommendations were made regarding future efforts to develop NDE snake robots for SuNDE applications. These recommendations are summarized in Section 6.0 and detailed in Appendix 3.

2.0 SUMMARY OF RESULTS

The objective of this program ‘Surgical NDE (SuNDE)’, has been to assess the challenges and opportunities for limited access inspection within the Air Force specifically, and the aerospace industry in general.

We found a variety of key processes and features of a SuNDE system that could be applied globally to future tools. These processes and features include:

- **CAD modeling of tool designs** and limited access inspection configuration; mock-ups and test hardware are also valuable for designing and testing out form, fit, balance, and other features for SuNDE tools.]
- **Maneuverable joints, with locking control knobs**, to aid in moving between inspection locations and proper positioning of the arm. Multiple axis joints (like the SuNDE Tool elbow joint) provide access to greater inspection volume and flexibility for maneuvering the tool.
- **Replaceable or expandable arm segment lengths**; SuNDE tool versatility is needed for the range of cavity inspection opportunities. Even if a single application is in mind, small configuration or access differences will require tool versatility (e.g. right hand side versus left hand side applications can have different access requirements).
- **Multiple cameras** mounted on the surgical arm aid in the delivery of the probe to the inspection site -one near the sensor, and one further back to provide situational awareness; a third remote camera, with motorized control would provide a side view that significantly improves the ease of sensor attachment for the operator, particularly for off-angle inspections (see Section 3.3).
- **For extended SuNDE arms, a mount for the tool at the access hole** provides needed balance, control and stability; a slider ball allows movement into and out of the cavity.
- **Enabling features for improved sensor coupling to the structure**; much of the SuNDE inspection time can be taken up by trying to orient the sensor end to ensure proper sensor coupling at the inspection site. Off-angle inspections requiring simultaneous movement of joints are a particular challenge for coupling. For eddy current inspection, proper coupling was enabled by gimbaling the eddy current probes and spring loading of the eddy current coils.
- **There is opportunity space for a small hand-held SuNDE tool (‘Mini-SuNDE’ tool)** that can improve the speed and POD of cavity inspections that are within reach of an NDE inspector but cannot be seen by him/her. Features could include a lighted micro-camera (attached to the handle or even a finger clip), replaceable/ adjustable extensions and joints, a heads-up display, and an end-effector to aid in attachment or orientation.
- **End effector approaches have the potential to broaden the applicability of SuNDE** to various types of structures and materials using various NDE modalities. Of particular SuNDE near-term benefits are the rotating micro-scanner for EC testing around fasteners, and the vacuum assistance attach/detach capability for UT inspection, where good orientation and coupling are essential. Lightweight capacitive machined ultrasonic

transducers (cMUTs), and magnetic coupling for control and alignment of TTU transducers also have potential.

- **Opportunity to provide Pre-Induction Inspection tools to prepare aircraft for depot maintenance.** There may also be a niche for SuNDE in pre-induction inspections, where visual or borescopic inspections are used, but are often not definitive enough to determine the damage state. For example, features are often mis-identified as cracks using a borescope are found to be paint lines or other surface phenomena once disassembly has taken place. A SuNDE tool could provide definitive information up front and reduce unnecessary work.

- **Autonomous Inspection.** In defining a future state for SuNDE, we see significant opportunities for implementing autonomous NDE using robotic snakes for obstructed inspections, where there is no direct line-of-site to the inspection area. ‘Surgical’ snakes that are attached to a base, and ‘Locomoting’ snakes that can crawl over distances are both ideal for this. Snake robots applied to SuNDE applications are discussed in Section 6.0, and recommendations for future development are provided in Section 7.2 and Appendix 3.

3.0 SURGICAL NDE (SUNDE) TOOL

3.1 Design Considerations

An analysis of limited access inspection areas for current aircraft revealed that there are two types of difficult-to-reach inspections. The first are ‘Cavity Inspections,’ where there is limited access to an open bay with somewhat limited physical obstructions, such as a wingbox. In these cases, the inspection areas are not within easy reach without some disassembly of the structure. Cavity inspections appear to require a broad range of extension, orientation and movement capabilities, often these inspection (if they can be accomplished by an inspector) are challenging due to requirements of access and the physical dexterity of the inspector to place the probe on the part. The other type of difficult-to-reach inspection is the ‘Obstructed Inspection,’ where plumbing, wiring, electronic systems, and other hardware obscure the location of the inspection. Obstructed inspections appear to be best addressed by a “follow-the-leader” insertion capability, where the sensor and arm can be moved to the inspection area along a contorted path that avoids obstructions or uses them for support or traction. Snake robots appear ideal for sensor placement for obstructed inspections (see Section 5.0 for more detail on obstructed inspection challenges).

The decision was made to focus program resources on a tool that primarily addresses open cavity inspection applications of SuNDE, while investigating potential candidate technologies for future development and implementation for obstructed inspection applications.

Aircraft cavity inspection challenges are significant. They include:

- Relatively small access portals
- Various sized cavities
- Distance from portal to inspection site that varies
- Limited operator situational awareness of inspection orientation or status
- Orientation of inspection site (relative to access) varies
- Internal or external obstructions are common
- Visibility is often low or non-existent
- NDI modality requirements vary (EC, UT, DR, etc.)
- Remote sensor orientation control
- Remote sensor coupling (for example, for UT)
- Remote sensor scanning (rotating eddy current)

An A-10 aircraft wing cavity crack inspection on the lower skin stringer runout fasteners was selected for demonstration that presented most of these challenges to exemplify the practical issues of open cavity inspection. This inspection is problematic with existing standard NDE tools. A key design consideration for the SuNDE Tool was that the probe placement envelope would work for the selected A-10 inspection, while maintaining

versatility for additional applications for other weapon systems. The arm articulation needed to provide the operator with sufficient manipulation control to get the sensor to the inspection location. The probe end and all joints along the tool needed to be small enough in cross-section to enter an access portal (which was 3.5 inch diameter). The tool needed to provide precise probe placement control at all times when inside the cavity. Visual situation awareness for the operator to effectively manipulate the probe in the cavity was a key requirement.

The elements of the SuNDE Tool development were as follows:

- Manipulator Arm – Develop a prototype hand-held manipulation arm, with video capture capability, and at least three pivot/rotation joints and 24 inches in length, which will receive interchangeable NDE probes.
- End Effectors – Design and demonstrate a variety of sensor end effectors to show the potential of remotely placed probes across a broad range of limited access inspection applications. The end effectors would specifically include a high frequency eddy current (EC) rotating probe, a vacuum-assisted mount to enable ultrasonic probe-to-structure coupling/decoupling, and a magnetically coupled attachment for limited access TTU (through-transmission ultrasound), and, finally, DR (digital radiography) inspections.
- SuNDE System Integration – Integrate manipulator arm and end effectors with appropriate eddy current, ultrasonic, digital radiography, and visual systems.
- Prototype Preliminary Evaluation – Evaluate the prototype system on an excised section of an A-10 aircraft wing with limited access inspection, to assess key functional characteristics.
- Prototype Demonstration and Feedback – Demonstrate the prototype SuNDE system on an A-10 wing eddy current inspection, and obtain feedback relevant to SuNDE advancement.
- Documentation and Feedback – Produce a video describing the SuNDE Tool and showing the use of end effectors for NDE sensors. Present the tool and program progress at selected NDE conferences (Aircraft Structural Integrity Program 2009, Aircraft Airworthiness & Sustainment 2010, Air Transport Association NDE 2010) and solicit relevant feedback.

3.2 Selected A-10 Limited Access Inspection

In order to understand limited access inspection issues, our approach was to develop a prototype SuNDE tool initiated from our knowledge of present limited access inspection challenges. While designed for a broad range of SuNDE applications, the resulting tool needed to be sufficiently demonstrated to support the required form, fit, and function of an inspection tool in a real life inspection situation. As stated above, an eddy current crack inspection on the fasteners on the lower wing skin stringers of the A10 aircraft was selected as the focus for a SuNDE ‘Cavity Inspection’ tool demonstration. The inspection is an ASIP (Airframe Structural Inspection Program) location that is currently performed with difficulty and with less than desirable sensitivity, through a limited access port. (An ASIP inspection location is a control point that is monitored at depot inspections or through routine maintenance inspection processes (Technical Orders).) The A-10 wing

structure cavity size and complexity is representative of the Air Force inspection need for limited access NDE methods. Figure 1 is a photograph of an A-10 aircraft in flight. The general location of the selected inspection is shown in the CAD views of Figure 2.



Figure 1. A-10 aircraft.

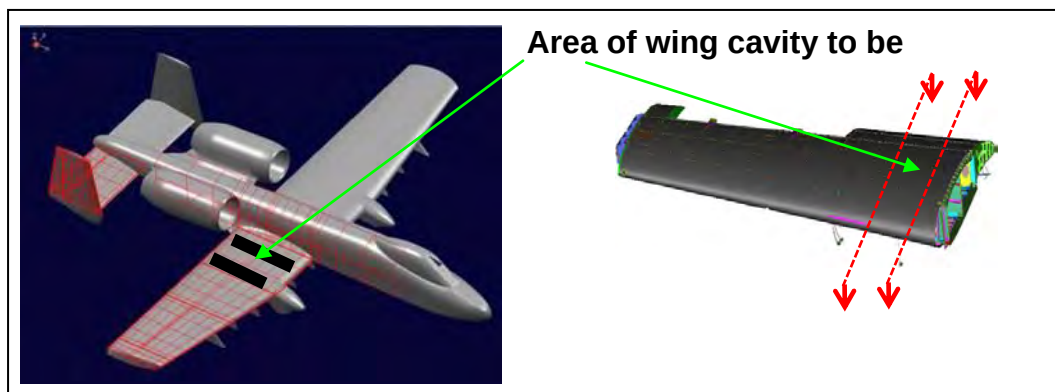


Figure 2. CAD view of an A-10 aircraft and wing showing the general location of the selected limited access inspection.

Figure 3 is a photograph of the primary selected inspection area for the on-aircraft demonstration. This region contains the attachment of the stringers to the external lower skin of the aircraft, and includes reinforcing straps on the stringers. The fastener at the end of the reinforcing strap on each stringer is the specific location of the inspection. A second inspection area was selected to ensure versatility in the tool design as this inspection is for the upper (top) portion of the A-10 wing cavity. This area is the spar-to-upper wing fastener row in the same section of the wing. This row of fasteners is above the access hole of the front wing spar (Figure 4). Although this location was used to help drive the SuNDE tool design, it was not selected for the final demonstration. The reason

for this is because it is an “off angle” inspection where the angle of insertion to place probe on part is neither parallel nor perpendicular to the tool insertion direction. The odd angle of insertion requires simultaneous multiple joint movements. Section 4.3 describes this inspection challenge, which made the inspection more tedious and time-consuming than the primary location.

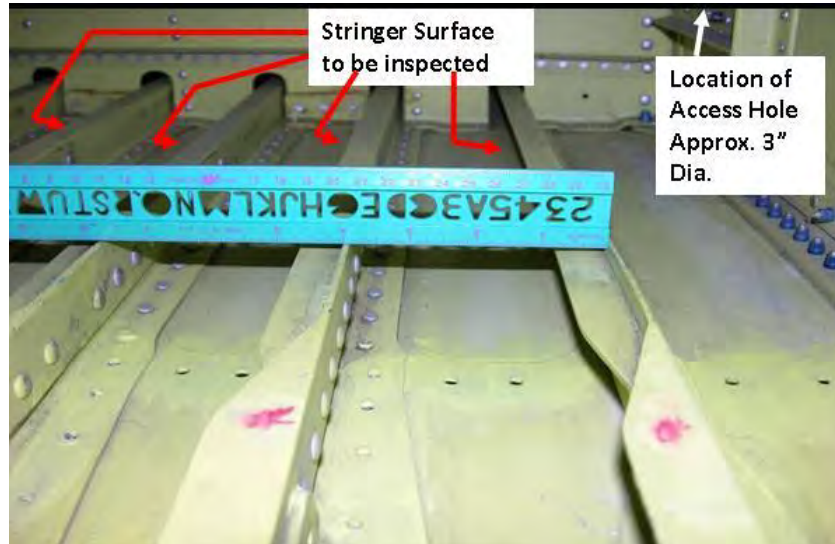


Figure 3. Primary selected A-10 wing inspection area, on the stringer runouts opposite the front spar access hole.

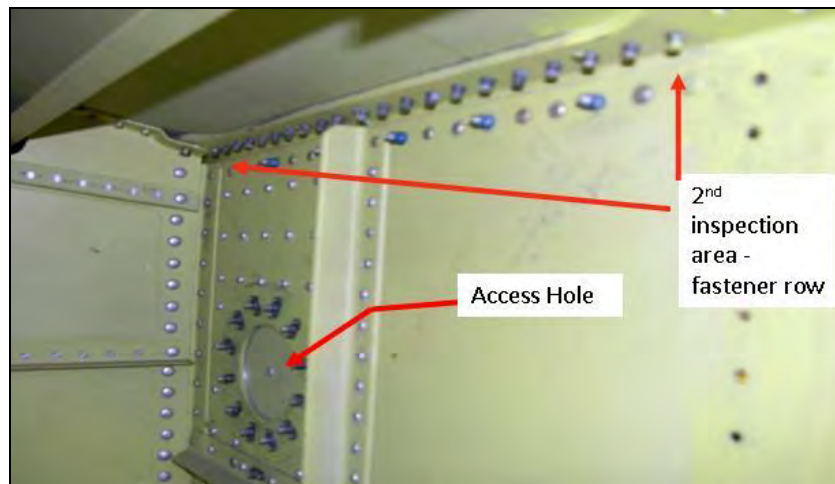


Figure 4. Alternate selected A-10 wing inspection area in the same cavity, but above the forward spar access hole.

The fasteners that required inspection are located at the stringer doubler (reinforcing strap) runout and are currently inspected with a boroscope method to look for a broken stringer, as shown in Figure 5. The stringer reinforcing strap (doubler) hides the crack from the access hole direction until it extends beyond the strap (Figure 6). To visually inspect for the smallest possible crack size, the inspection must be performed from the

opposite side on the stringer from the access hole, and under the stringer flange. This is an extremely difficult inspection with a borescope, and the method can't consistently detect cracks smaller than about 0.25 inches.

If a High Frequency Eddy Current (HFEC) method utilizing the SuNDE Tool can detect a 0.125 inch crack extending from the edge of the fastener hole in the stringer instead of a 0.25 inch crack or broken stringer, the location would require less frequent inspections (because cracks could confidently be identified smaller and earlier in their growth/propagation), thereby reducing maintenance time and labor costs. A successful SuNDE tool would provide the capability to go around the stringer flange and inspect with HFEC on the back side of the stringer.

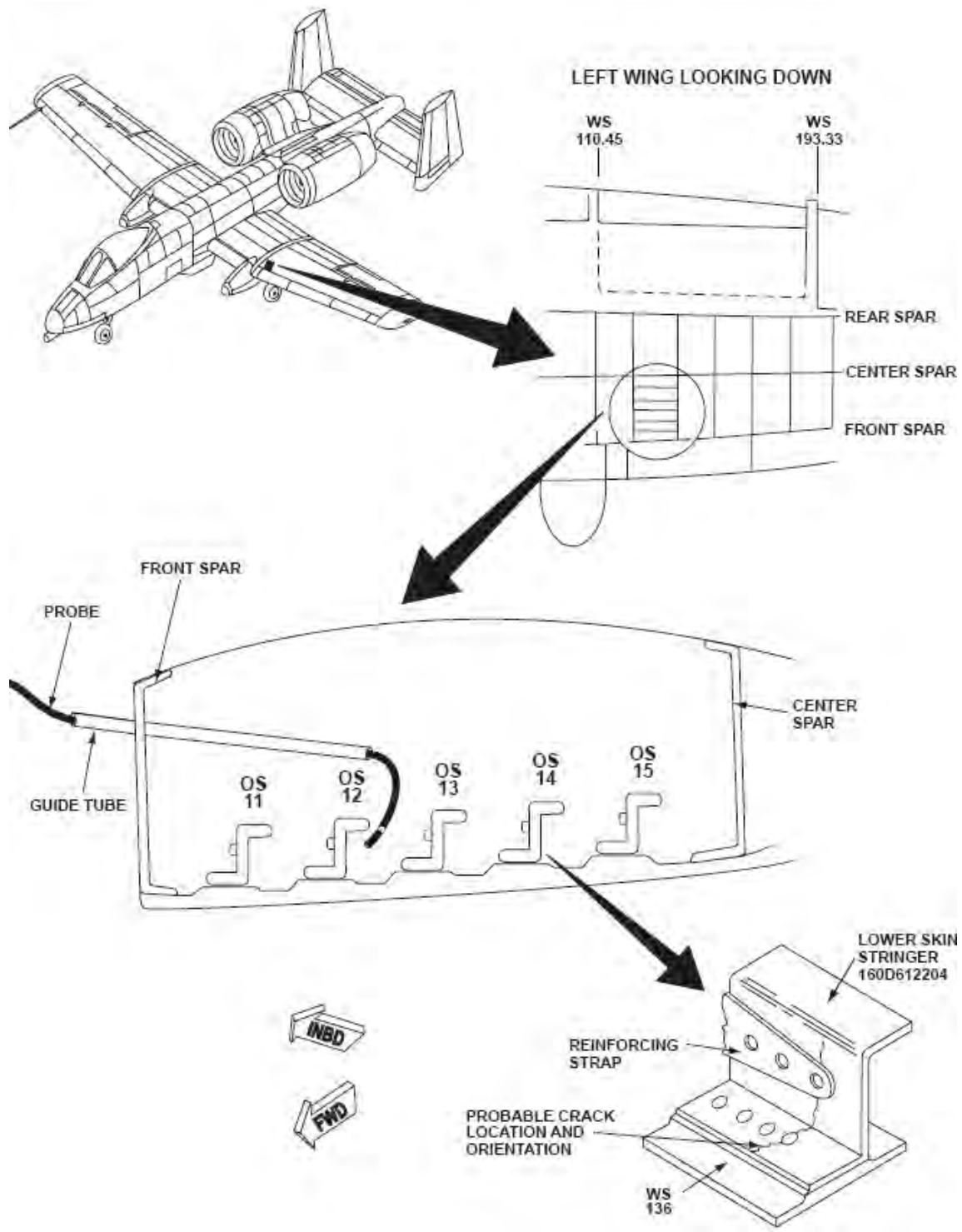


Figure 5. A-10 Boroscope Inspection at Stringer Doubler Runout.

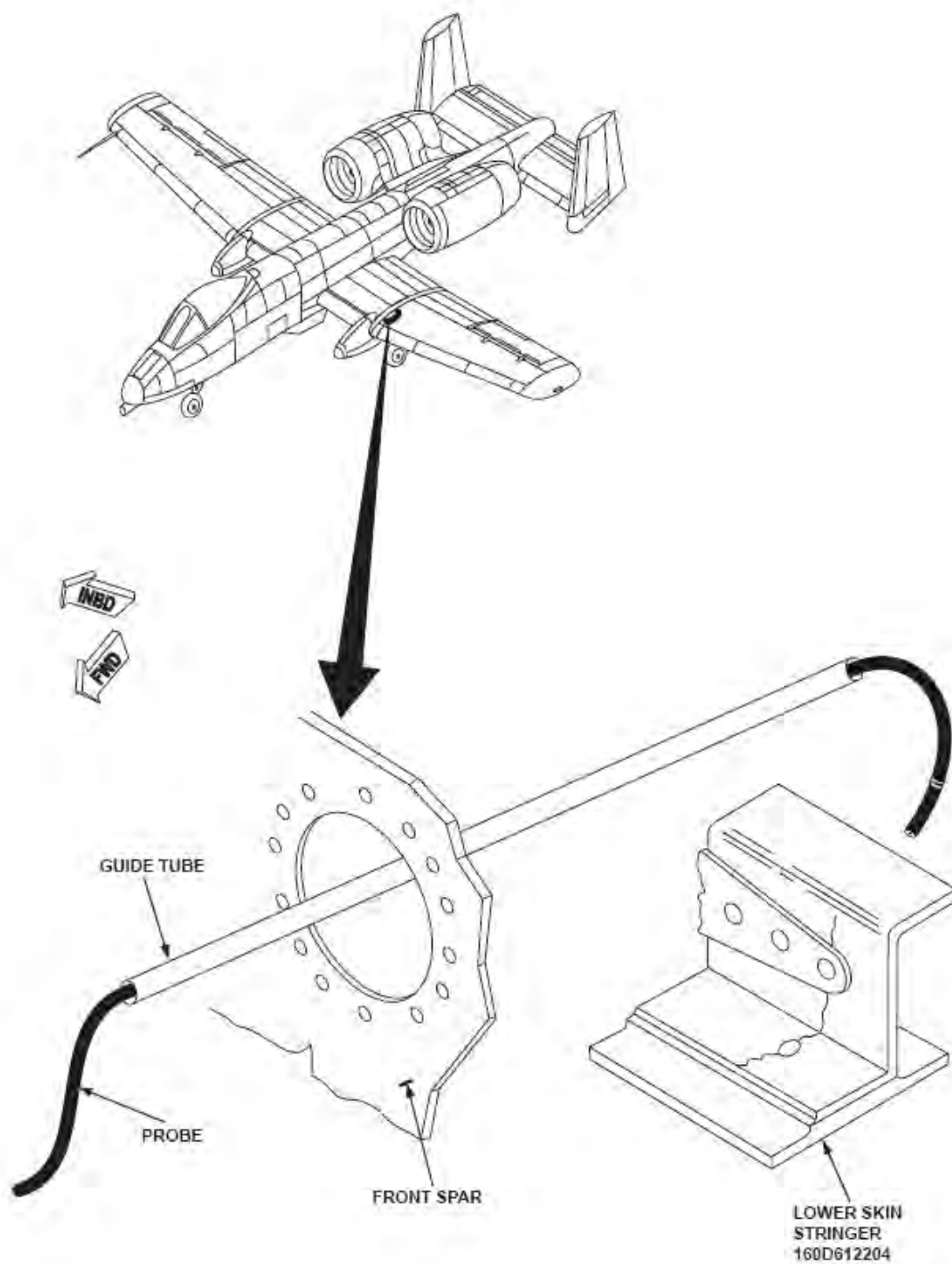


Figure 6. A-10 Inspection Required Under Stringer Flange.

3.3 SuNDE Tool Design Verification

Several developmental steps were conducted to ensure a successful design and demonstration of the SuNDE Tool on an A-10 wing inspection. An excised section of an A-10 wing from Hill AFB, containing the areas that currently require limited access inspection, was obtained. The SuNDE Tool was designed using CAD modeling. A CAD model of the A-10 inspection area (courtesy of the Boeing A-10 program) was used to verify the geometry and movement envelope of the tool, by modeling the inspection probe movement and placement scenarios. A physical mock-up of the surgical arm was fabricated to test out inspection scenarios in the wingbox and to verify the CAD model of the tool. The excised A-10 wing section was also used to test and refine the resulting prototype tool before the on-aircraft demonstration. It was also used to test the variety of end effectors designed under this program to verify broad applicability of the SuNDE tool.

3.3.1 Inspection Area Hardware

The excised A10 wing section (Figure 7), shows the access hole in the forward spar. Relevant features of interest (i.e. access, range of motion, ease of movement, and probe attachment to the fastener capabilities of the tool mock-up and prototype) were tested and verified using this section.

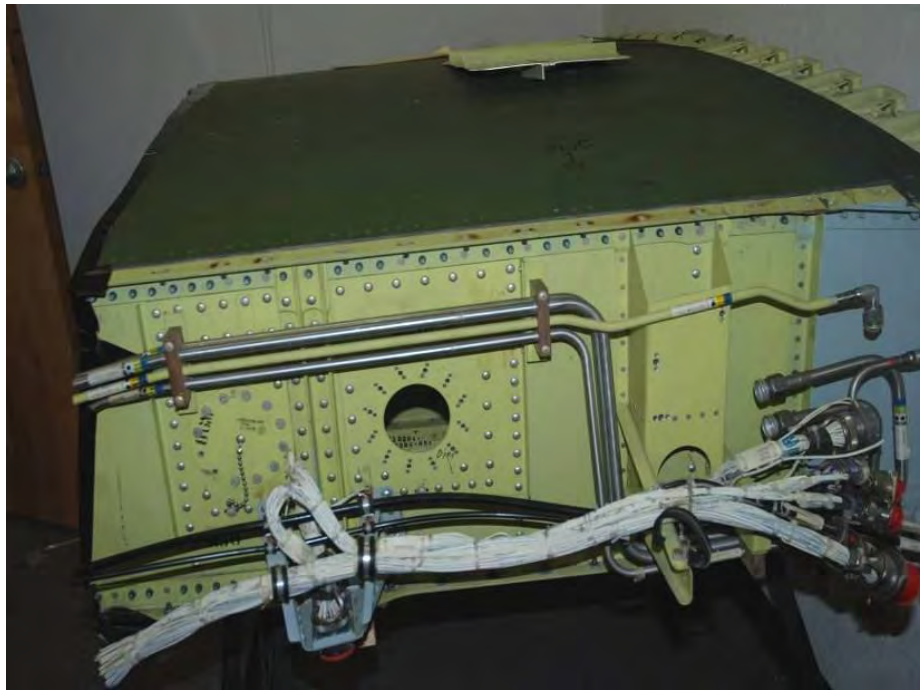


Figure 7. Excised A-10 wing section used for Surgical NDE Tool design. (forward looking aft)

3.3.2 CAD Model of Tool/Inspection Area

The CAD model of the A-10 cavity inspection volume (Figure 8), with the approximate dimensions of the structure, is indicated. The fastener locations on the lower wing skin stringer runouts are shown in the CAD model view (Figure 9). A CAD view of the A10 cavity (Figure 10) indicating the areas for the alternate inspection on the upper wing skin is also shown. Although these areas were not part of the official demonstration, the tool was successfully designed to be able to reach these fasteners as well as the primary inspection areas on the lower wing skin.

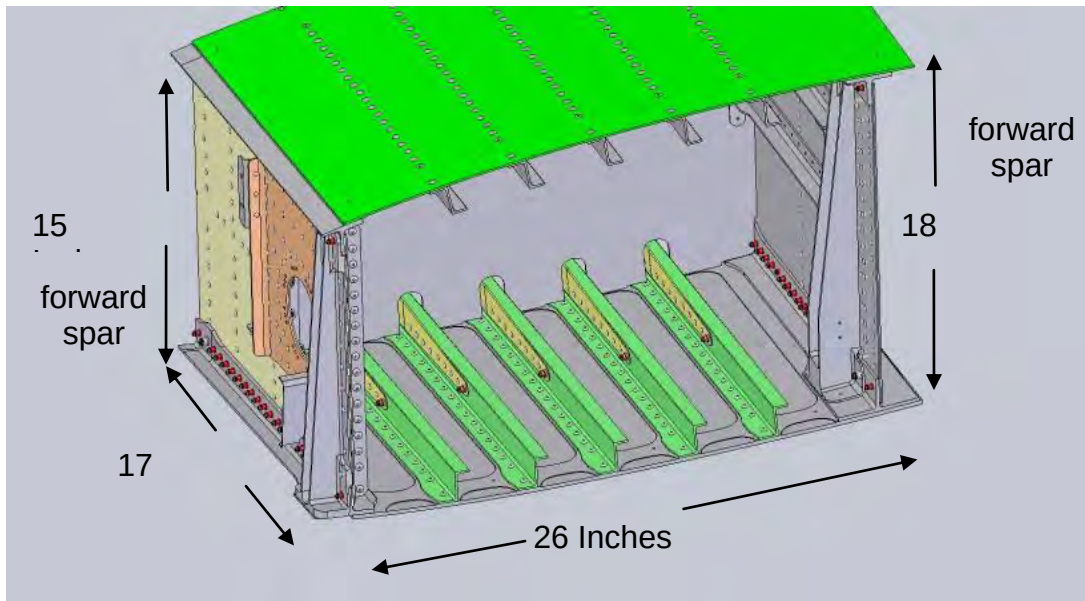


Figure 8. CAD model of the A10 cavity inspection volume.

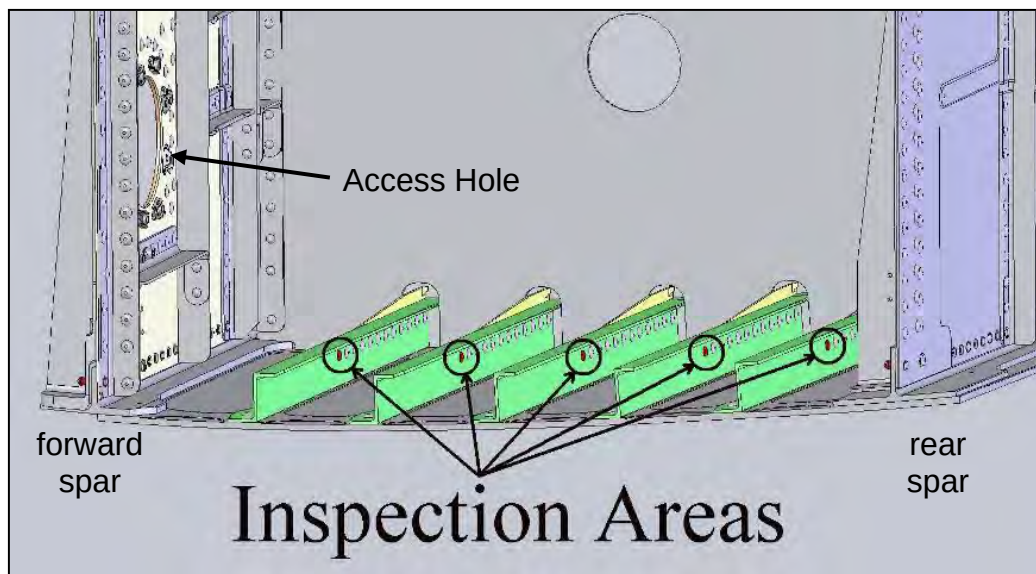


Figure 9. CAD view of the A10 cavity showing the inspection areas on the stringer runouts.

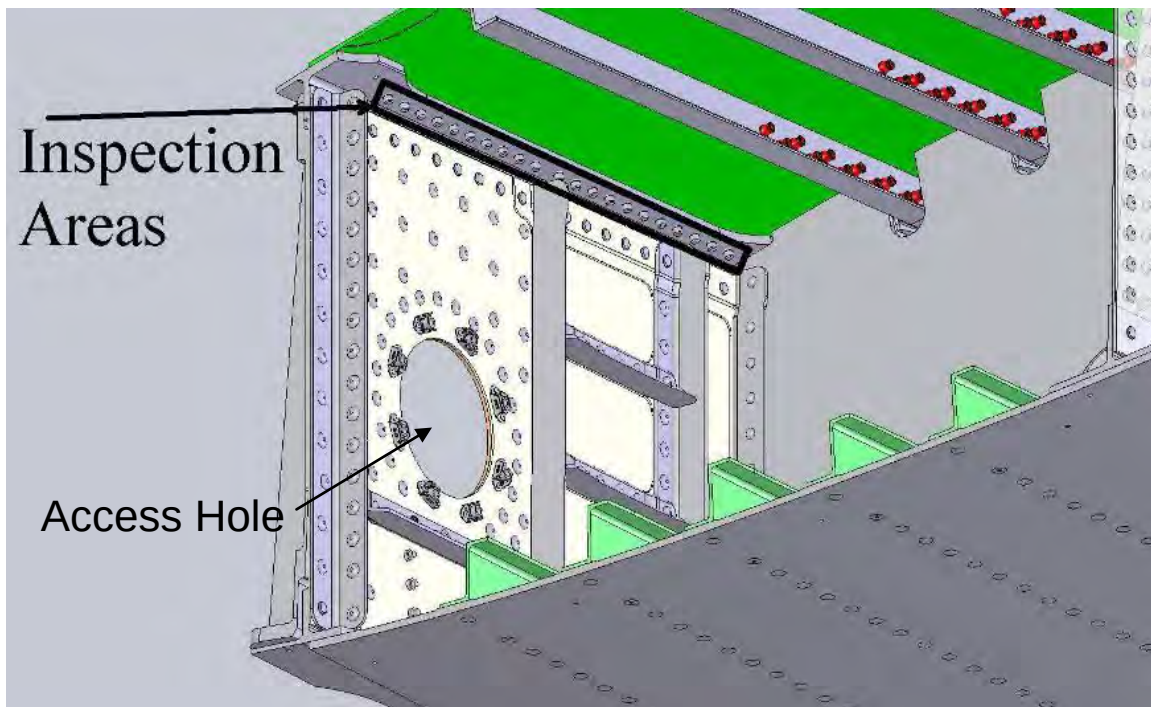


Figure 10. CAD view of the A10 cavity showing the inspection areas for the alternate inspection. The tool was successfully designed to be able to reach this area as well as the primary inspection area on the lower wing skin.

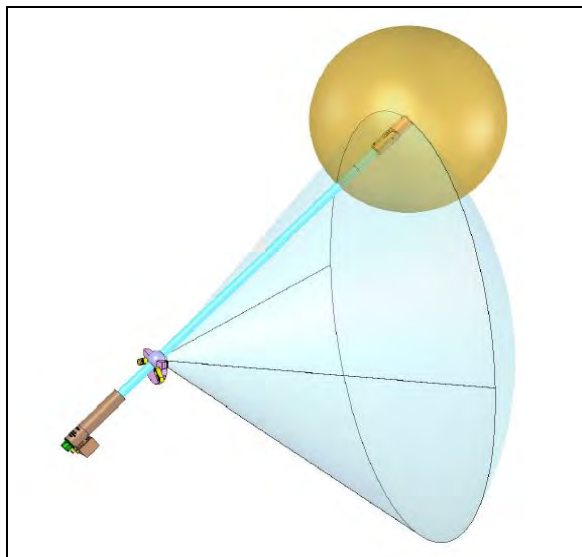


Figure 11. CAD view showing an example of the operating volume of the surgical NDE tool. The arm can cover a near 90° cone that can be rotated a full 360° around the insertion point, and the “wrist” joint allows complete directional freedom (represented by the sphere) of the forward arm segment.

For the SuNDE Tool manipulator arm, articulating joints were designed that allow a wide range of motion. A notional image of the CAD model of the tool demonstrating the large operating volume is shown in Figure 11. CAD views of inspection scenarios (Figure 12) modeling of the tool within the inspection volume for the two inspection areas are shown.

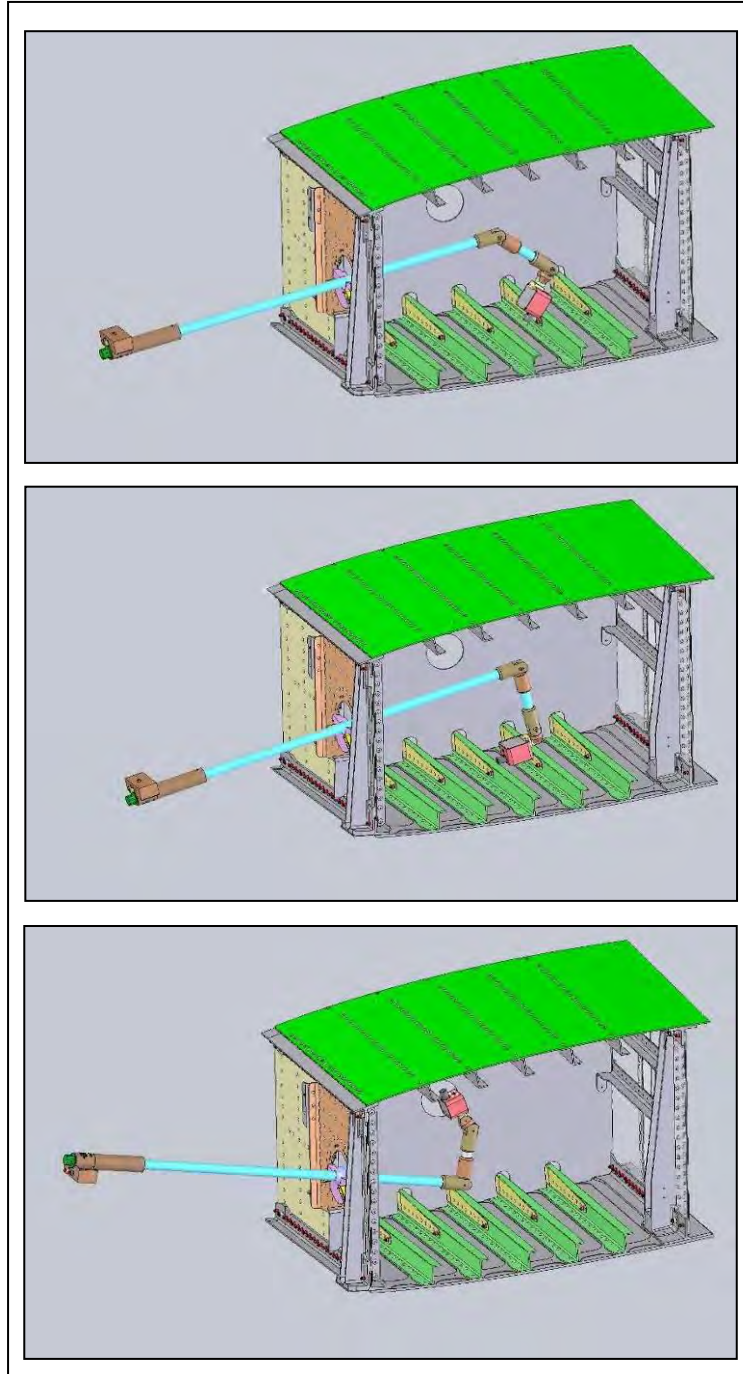


Figure 12. CAD views of inspection scenarios modeling the tool motions within the inspection volume for the lower (top 2 images) and upper (bottom image) inspection areas.

3.3.3 Mock-up of Surgical NDE Tool

A preliminary mock-up model was used to check the accuracy of the CAD designed SuNDE Tool. Figure 13 is a photograph of this tool. Articulation testing was done using the tool inside the A-10 wing section to determine if the SuNDE Tool would indeed reach the needed inspection areas. The mock-up also provided a general estimate of the SuNDE “feel” for the operator attempting the limited access inspections.

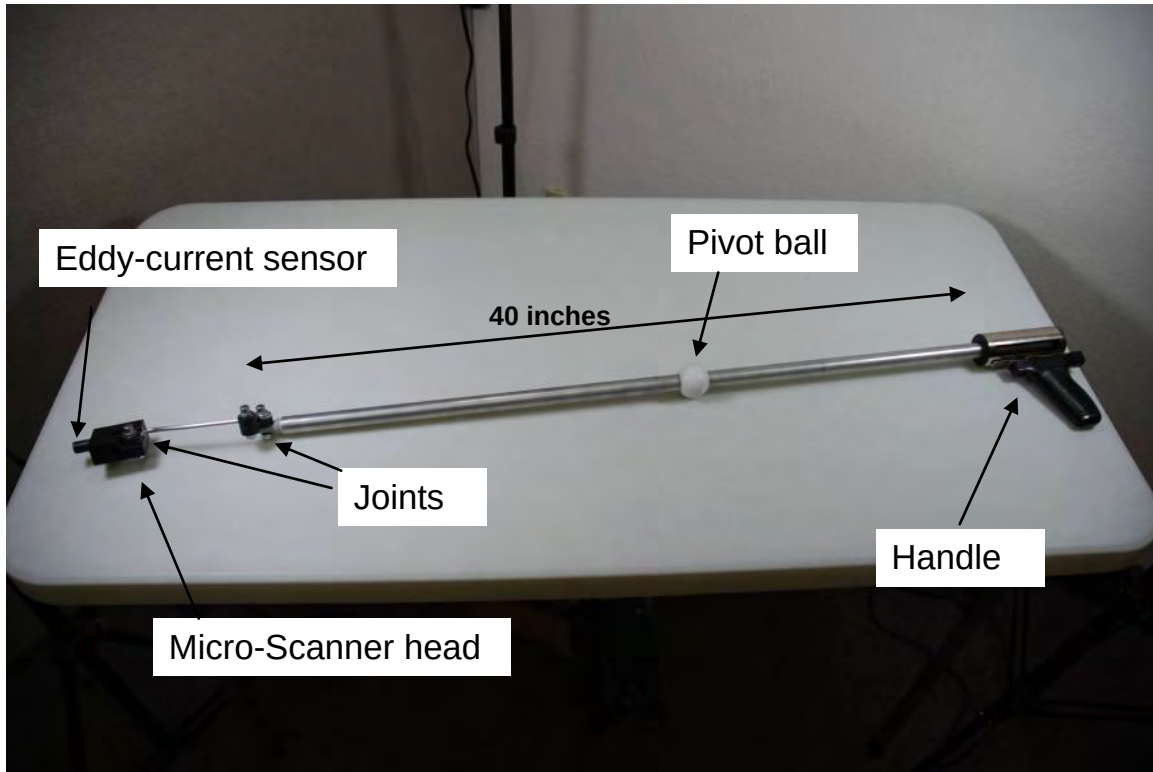


Figure 13. Photograph of the mock-up model used to verify the CAD model of the Surgical NDE Tool using inspection scenarios in the CAD A-10 wing section.

3.4 SuNDE Tool Design

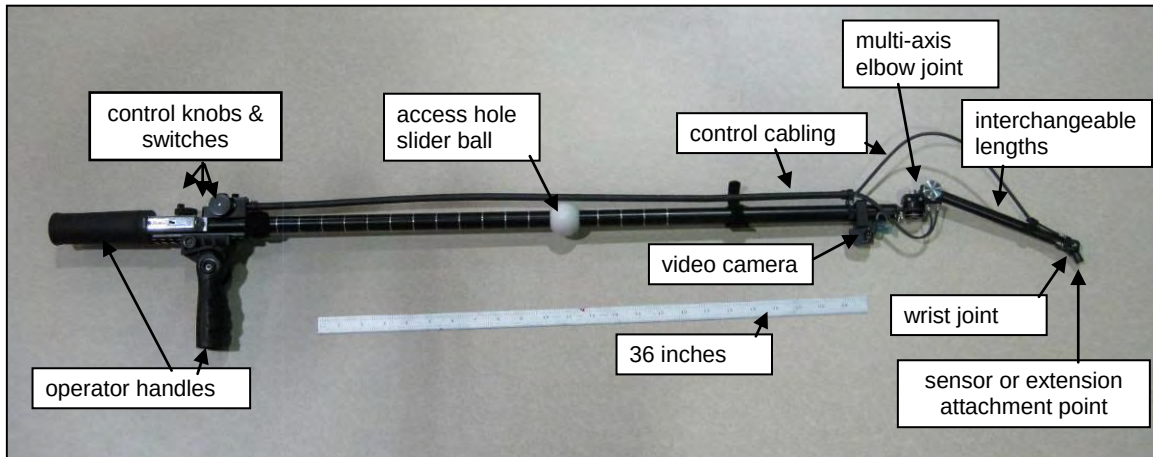


Figure 14. Surgical NDE (SuNDE) Tool.

The SuNDE Tool (Figure 14) was designed by UniWest, with direction and input from Boeing. It was designed for a broad range of cavity inspection applications, and not just the A-10 aircraft inspection areas previously mentioned. Other applications where this SuNDE tool could enable improved inspections are the AWACS trailing edge rudder panel, the KC-767 (International Tanker) strut, and the Boeing 787 center wing box. Some of the tool's important features are shown in the figure, and its size (relative to a yardstick) is indicated. The important features of the SuNDE Tool include: joints and arms for versatility and range, a manipulator control area for correct probe orientation, a rotating eddy current scanner for precise sensor positioning, video cameras for situational awareness, a slider ball for positioning and tool control, and quick-connectors for integrity of the tool's power and communication, as well as durability and rapid set-up. These important features are described below:

Joints and Arms for tool versatility and range: The tool is capable of precise operator manipulation of arm segments at the elbow and wrist joints identified in Figure 14. A close-up photo (Figure 15) illustrates the elbow and wrist joints on the tool. The elbow joint can rotate up or down ($+135^{\circ}$ through -90°) and left or right ($\pm 90^{\circ}$). The wrist joint can rotate up or down ($\pm 90^{\circ}$). The multi-axis elbow joint proved to be very effective for getting the sensor in the general inspection position and avoiding major obstacles as the tool is inserted to the cavity. The distance between the elbow and wrist can be adjusted from between 2 and 10 inches using interchangeable lengths (Figure 16) in various combinations. . This feature allows the SuNDE tool to be used in other applications where the inspection geometry is different.

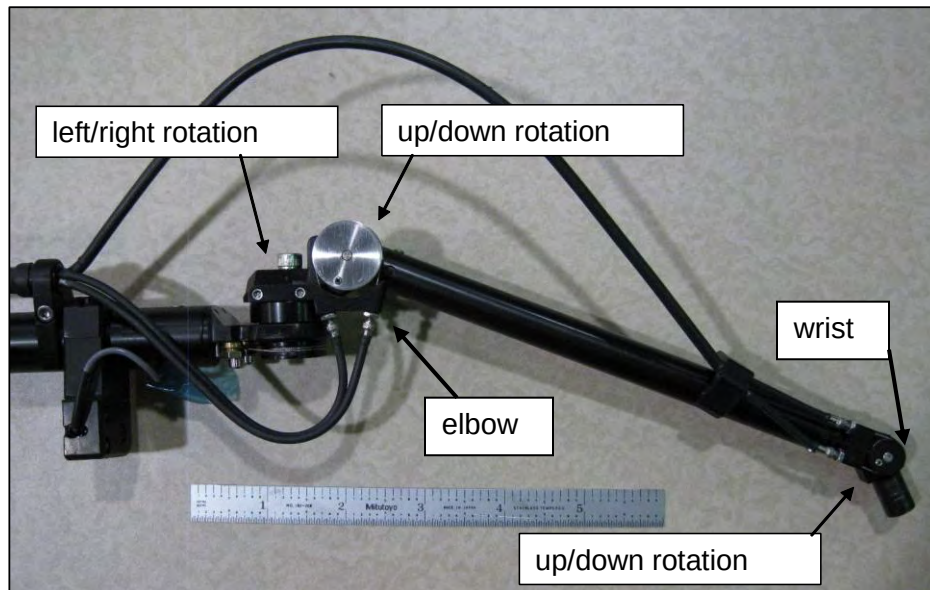


Figure 15. Elbow and wrist joints on the SuNDE Tool. The elbow joint can rotate up or down and left or right. The wrist joint can rotate up or down.



Figure 16. Various interchangeable lengths can be attached between the elbow and wrist as needed for the particular inspection scenario. A 90 degree fixture (shown at the bottom of the photo) can also be used if needed.



Figure 17. Three positions for the elbow joint showing the range of articulation.

Figure 17 shows three positions of the elbow that can be controlled by the up/down elbow control knob of Figure 18. The range of motion enables the SuNDE Tool to address a variety of inspection orientations.

Manipulator Control Area for correct probe orientation: The control area of the SuNDE tool is shown in Figure 18. The operator uses the control knobs to move the joints. Once in the correct position, they can be locked into place by the locking knobs.

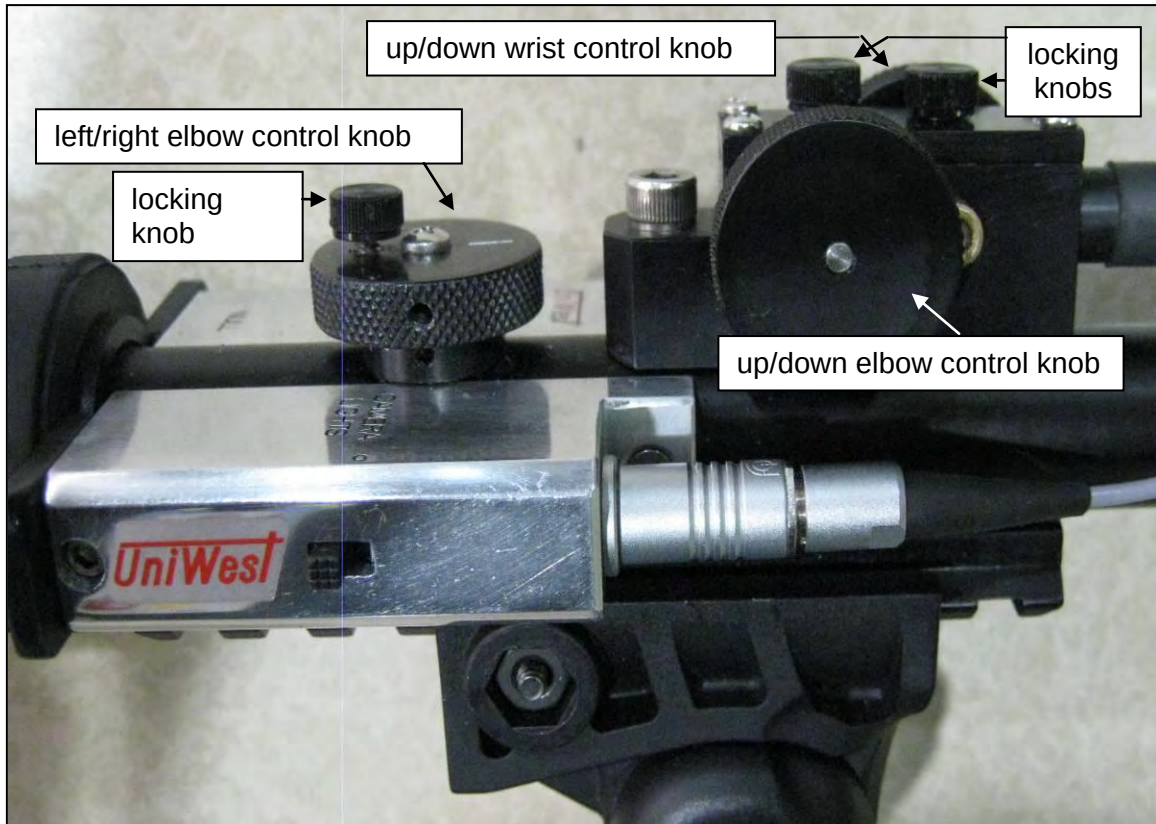


Figure 18. Control and locking knobs for SuNDE arm articulation.

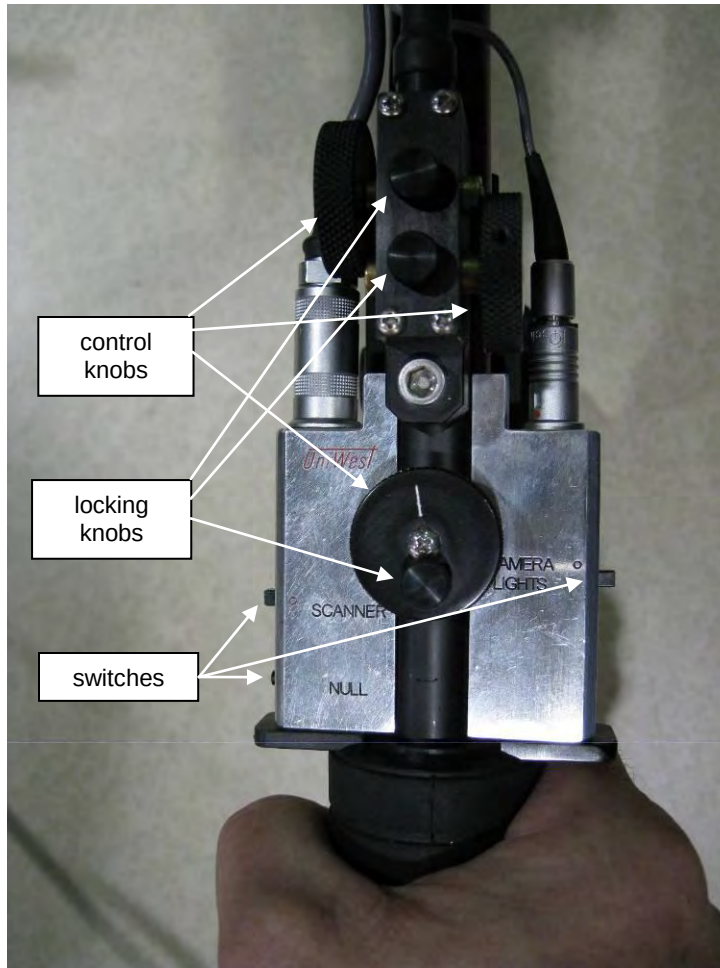


Figure 19. Top view of the manipulator control area.

Figure 19 is a top view of the same manipulator control area shown in Figure 18. Once in the correct position, the control knobs can be locked into place by the locking knobs. Switches on the sides of the control area are visible in Figure 19. They turn the rotating scanner and camera lights on and off, and allow the operator to null the eddy current probe and clear the impedance plane screen (to control the eddy current inspection parameters).

Eddy Current Rotating Scanner for precise sensor control: Many applications of SuNDE require crack inspections at remotely located fasteners. While eddy current is usually the modality of choice on aluminum structure, positioning and moving an eddy current coil around a remote fastener head is almost impossible to do via remote operator manipulation. To have a probe fixed to the end of the SuNDE tool, with the operator moving the probe by moving the tool would be extremely difficult to perform with the desired accuracy. The solution was to develop a new rotating eddy current micro scanner at the distal end of the arm. The probe uses the fastener itself for positioning and automatically rotates a coil around the fastener center.

The Micro Eddy Current Rotating Scanner (Figure 20) is mounted onto the end of the SuNDE Tool for HFEC crack inspection around raised fastener heads. A close-up photo is shown in the inset. The scanner rotates an eddy current sensor (Several prototype sensors are shown in Figure 21.) around the circumference of a fastener, and is connected to an eddy current tester, such as the UniWest US-454 EddyView™. The eddy current signal is observed on the tester display during the scan for indications of a crack. (See Appendix 1 for details on how a crack is detected.)

Video Cameras for situational awareness: A video camera located in the scanning head views the rotating probe and the area adjacent to it, providing sensor-to-structure positioning information to the operator. The LEDs in the scanner head provided the needed light for the camera.

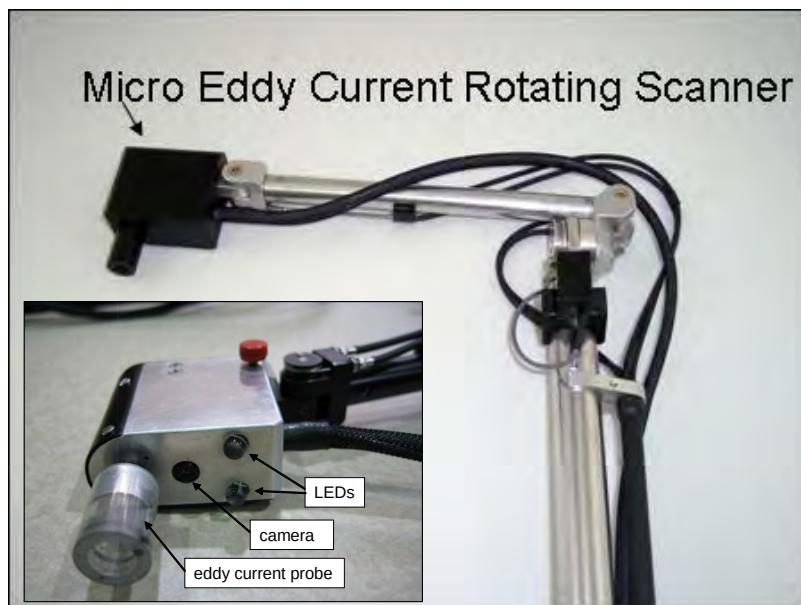


Figure 20. The micro eddy current rotating scanner on the end of the SuNDE Tool is designed to inspect for cracks around fasteners. The inset is a close-up view of the micro eddy current rotating scanner.



Figure 21. Top and side views of several prototype eddy current encircling probes. Two were made to inspect around two different size fastener heads on the A-10.

Direct visual observation is often not possible when placing an NDE sensor in the correct position in a cavity. If there is visual access, it is often difficult or partial and is often poorly lit. The solution chosen was an integrated remote visual approach. Miniature CCD cameras with video monitors provide an excellent remote visual capability. A camera mounted on the SuNDE arm (Figure 22) provides a macro „situational awareness“ view relative to the structure. The direction the camera is facing can be adjusted by the operator before tool insertion in order to get the best view for a particular inspection. A second camera is mounted near the NDE sensor to provide a close-up „sensor attachment aide“ view. This video camera is located in the HFEC scanning head (Figure 20). This camera views the rotating probe and the area adjacent to it, providing sensor-to-structure positioning information to the operator. LEDs are also mounted in the scanner to provide the necessary lighting for the camera. While a single video monitor with a camera switching capability can be used, multiple monitors (one for each camera) are preferred by most operators evaluating the SuNDE tool, because of the additional real time information they provide together.

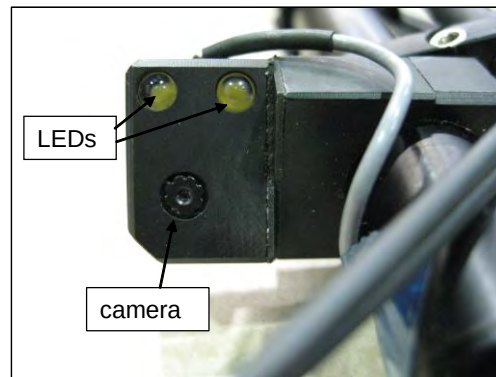


Figure 22. Lighted miniature video camera mounted on the SuNDE arm. (See also Figure 14.)

Slider Ball for positioning and tool control: The slider ball feature on the SuNDE Tool (Figures 23-25) provides the operator both translational and rotational control for improved manipulation. This feature is important for surgical NDE in general because extended reach tends to magnify any movements the operator makes while holding the handles. Circumferential detents on the tool arm allow for ball position stability and an indication of tool insertion depth for the operator. Figure 24 shows the tool holder that the slider ball (Figure 23) snaps into that goes into the access hole. The ball snaps into the center once the SuNDE Tool is inserted in the access hole. Fasteners on the two arms attach through holes for mounting the access panel. Figure 25 shows the SuNDE Tool holder mounted in an access hole. Once the holder is in place, the SuNDE Tool is inserted through the access hole and mounted using the sliding ball. The operator can then manipulate the tool with relative precision.

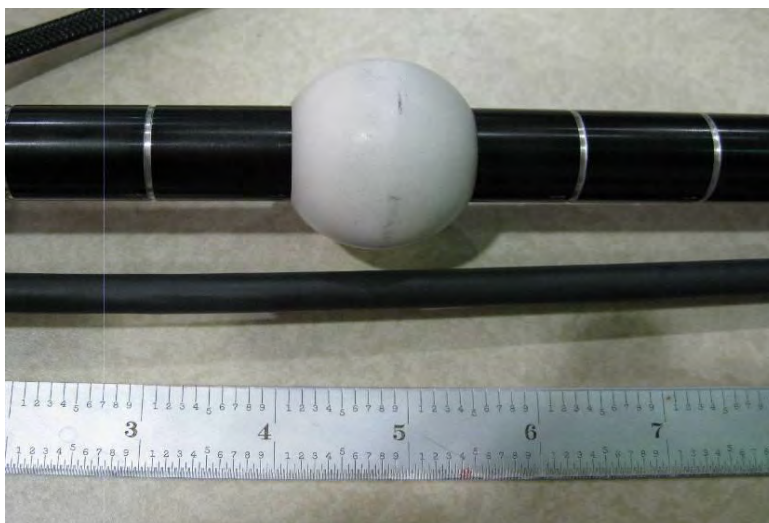


Figure 23. This slider ball provides tool stability for the operator by attaching to the holder mounted in the access port.



Figure 24. Access hole SuNDE Tool holder, front and back view.



Figure 25. Access hole SuNDE Tool holder, alone, mounted in an access hole.

Quick Connectors for system integrity, durability and rapid set-up: It is important that the SuNDE Tool can be rapidly assembled after transporting it to the inspection site, and disassembled rapidly after use. Quick connections (Figure 26) between the SuNDE Tool and power supply, and Tool and NDE instrument and video monitor(s) have been designed for this purpose. The quick connections ensure the integrity of the power and communication for the SuNDE Tool, and provide confidence that all parts are removed from the cavity when the inspection is complete. They also provide durability for depot maintenance use of the tool.



Figure 26. Close-up of quick-connections for the power source and communication with the eddy current tester and video monitor(s) for the micro scanner, eddy current probe, and cameras on SuNDE Tool.

The Integrated SuNDE Tool: The key features outlined above enable the SuNDE Tool to effectively address limited access cavity inspections for a range of applications. The tool and accompanying equipment are shown in Figure 27. The micro eddy current scanner is connected to the arm, as are the video monitors and eddy current tester, to make up an entire SuNDE system for HFEC applications. This is the specific set of equipment that was evaluated for demonstration of remote crack inspection on the A-10 wing. Figure 28 is a photograph of the SuNDE hardware being evaluated using the excised wing section. The side wall has been cut away to allow viewing of the tool during the evaluation. The scanner can be seen at an inspection location, providing eddy current data to the operator. Figure 29 is a close-up view of the scanner at that location. The SuNDE Tool was successfully designed to conduct this inspection.

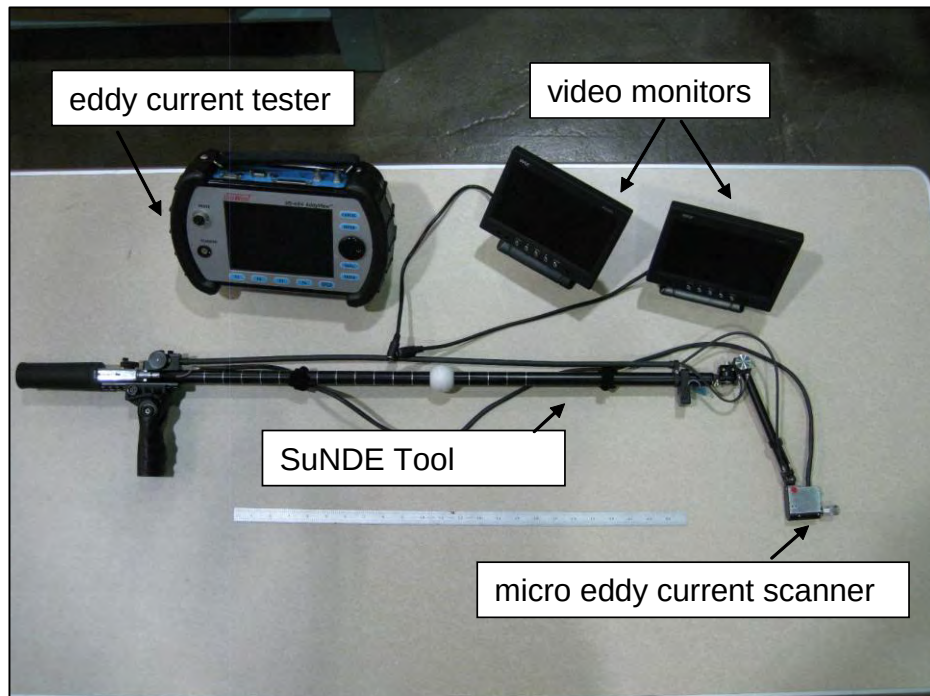


Figure 27. SuNDE Tool equipment for limited access HFEC inspection for cracks around fasteners.

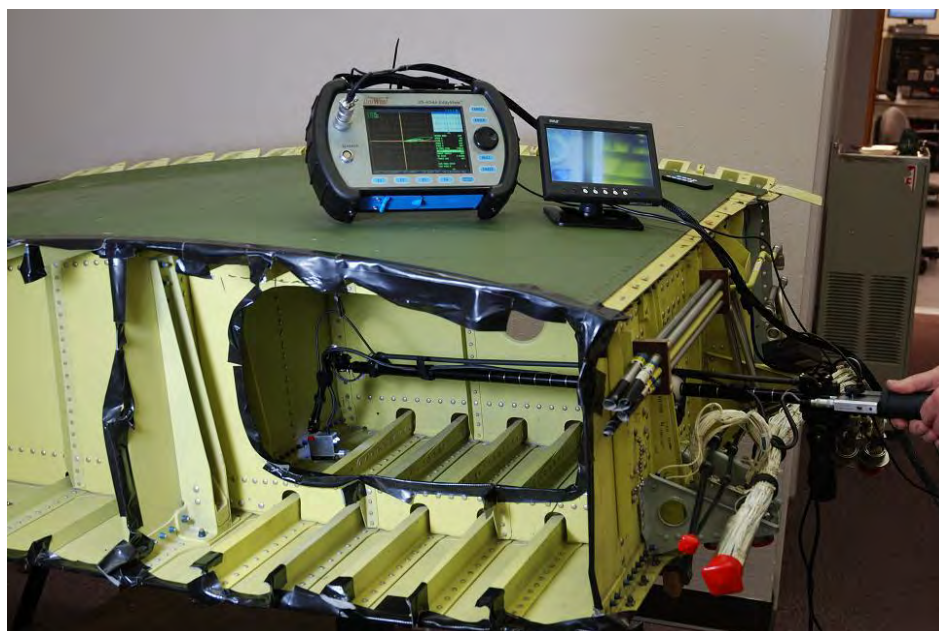


Figure 28. The SuNDE Tool is being evaluated for limited access HFEC inspection for cracks around fasteners in the A-10 wing section. (A single monitor with switchable cameras is being used here.)



Figure 29. The SuNDE Tool micro eddy current scanner is shown moving into position for the selected A-10 inspection.

3.5 Hill AFB Evaluation of the Surgical NDE Tool

The demonstration of the SuNDE tool was performed at Hill AFB, UT on an A-10 aircraft wing in depot maintenance in the selected primary inspection area of interest. The NDE performed was a High Frequency Eddy Current (HFEC) method utilizing the micro-eddy current rotating scanner to perform a 360° inspection around the stringer runout fasteners on the lower wing skin panel.

The tool was brought to the side of the wing, assembled, powered up, calibrated, checked for operation, and inserted into the access hole in the forward spar of the wing. Using the camera monitor to guide him, the operator was able adjust the orientation of the SuNDE tool segments and scanner in real time and attach to each fastener to be inspected. The eddy current inspection was developed to indicate when the probe was properly coupled onto the stringer. This was accomplished by having the eddy current probe “nulled” in air, instead of on the part. The specific set-up and procedure details for conducting this inspection are discussed in Appendix 1.

The inspection (Figure 30) at each runout fastener took about 5 minutes each, with most of that time coming from orienting the scanner to align it with the fastener and then place it onto the fastener itself so that a “good” inspection could be made.



Figure 30. A-10 Test Wing Box Surgical Demonstration at Hill AFB.

3.6 Inspection Results

The inspection of the selected areas of the A-10 wing was successful. The result showed the versatility of the SuNDE tool (the access port was in a different location than originally planned), as well as its effectiveness for this cavity inspection. The SuNDE tool gave the inspector the ability to reach around the stringer flanges, attach a probe to the structure, and inspect on the back side of the stringer with the HFEC method. The HFEC method utilizing the SuNDE tool, with a rotating eddy current probe and tester, is capable of detecting less than a 0.125-inch crack extending from the edge of the fastener hole in the stringer (as indicated from the eddy current impedance plane lift-off curve described in Appendix 1 and 2). This is approximately half the size of what can be consistently done with the present borescope method. The ability to detect a smaller crack than can presently be found means the ASIP (Airframe Structural Inspection Program) inspection location would require less frequent inspections (or permit longer inspection intervals) than are currently scheduled with the borescope method.

4.0 LESSONS LEARNED FOR SUNDE

The results of the SuNDE Tool development and assessment, as well as industry feedback regarding the tool, discussions at selected venues, and on-site visits to maintenance facilities provided important insights regarding SuNDE implementation challenges and opportunities.

4.1 Versatility

SuNDE tools that address only a narrow range of applications are obviously not going to be as valuable or useful as those that address a broad range of inspection problems. It would be impractical and too costly for users to have to have a specific tool for each and every application. On the other hand, what we found from our conversations with potential users, “one size” will not “fit all.” We expect a relatively small set of SuNDE tools, with attachments of a variety of NDE end effectors, could be implemented across the range of USAF (and aerospace) cavity and obstructed inspections. For example, inspectors maintaining fighter aircraft might require a small SuNDE tool for tight, obstructed spaces, while those inspectors maintaining cargo/tanker planes might use a larger multi-armed SuNDE tool similar to our prototype. Each tool should be as versatile as possible, able to incorporate various sensor types as needed, and having adjustments in form factor. Arms that extend or contract, interchangeable segments or joints, and replaceable end effectors are all expected to be very useful.

Our goal was to design a versatile SuNDE prototype tool that could be used in a range of inspection scenarios. The A-10 wing inspected at Hill AFB, UT had the access panels at a different location than the test wing box that was used to help design the SuNDE tool. Once this was realized, a different end extension length was quickly attached and real-time joint adjustments were made to maneuver the probe into position. The inspection was immediately successful with the slightly different access configuration because adjustments could be made “on the fly.” This rapid deployment on a slightly different configuration showed the versatility of the SuNDE tool to adapt to different cavity access situations, and points to a general use capability through interchangeable segment lengths. We learned that replaceable segments or adjustable lengths are at least a partial answer for a versatile SuNDE tool. This adjustability is important in a SuNDE tool that is utilized in applications where even minor configuration differences are expected, such as access port or left/right hand wing differences. Recommendations for general SuNDE tool types are provided in Section 2.0

4.2 Sensor Coupling

One of the difficult parts of the A-10 inspection was the required coupling of the eddy current probe to the part so that “lift-off” is not a problem when performing the inspection. Lift-off occurs when an eddy current sensor is not completely seated against the structure under inspection, and results in a reduced sensitivity to small cracks. A small amount of “gimbaling” was designed into the probe so it would couple with the part even if the probe end effector was at a slight angle from “normal” to the part. This gimbaling helped, but was not enough to guarantee easy self-coupling, and the inspection still required some time-consuming tool manipulation before coupling was accomplished.

Most of the 5 minutes per fastener required to conduct the A-10 inspection was taken up with this activity.

The SuNDE tool evaluation at Hill AFB led us to modify the probe for better coupling capability. The tool manipulation requirement has been significantly reduced with a spring loaded coil added to the probe (in addition to the gimbaling). The spring loaded eddy current coil allows enough pressure to couple the coil to the part so lift-off is not a problem at greater angles, and the inspection can be performed with very little tool manipulation. This probe modification and resulting benefit is an enabler for SuNDE eddy current inspection, and is described in detail in Appendix 2.

In general, any probe used for SuNDE should be designed to be relatively insensitive to attachment angle and pressure. Methods that will help the operator obtain good inspection data without having to sustain a perfect alignment or contact pressure will make the inspection easier, quicker and more accurate.

4.3 Off-Angle Inspections

The ability of the SuNDE tool to enable the inspection of the alternate A-10 wing area at the upper skin was evaluated. While the inspector could demonstrate inspections around these fasteners, it was very difficult placing the probe onto the fastener. The operator typically orients the probe for attachment by holding it just off the fastener using the on-probe camera, orienting the probe by making joint adjustments, and then moving it onto the fastener. This approach works fine when the fastener is largely perpendicular (as in the case of the primary inspection areas) or parallel to the main arm of the tool, because it can be rotated and slid into place using the sliding ball and no further joint movement.

However, for “off-angle inspections,” the situation is more complex. Off-angle inspections occur when the fasteners are neither perpendicular nor parallel to the main arm of a SuNDE tool inserted through an access hole. The fasteners create an odd angle of insertion for seating the probe on the structure. The direct path the SuNDE probe takes to get to the inspection site requires precise *simultaneous* rotation of the wrist and elbow joints as well as movement of the main arm. This was the case with the alternate A-10 inspection areas. The time and effort required to attach the probe to a single fastener was greater than the primary inspection area (One fastener took close to half an hour.). However, this approach would still be preferable to the time and cost of a teardown.

The spring loaded coil designed to improve probe coupling (described in Appendix 2) is a partial solution to the problem of off-angle attachment over fasteners. Alignment requirements can be relaxed and a good inspection can be done without precise simultaneous joint angle adjustments while moving onto the fastener. It also helps to align the probe while it is as close to the fastener as possible, so movement toward the fastener does not change their relative alignment too much.

Probe attachment to produce a good inspection is often a difficult task. Another solution to easier probe attachment is to add an additional camera that provides a side view of the probe and fastener. The side view provides the operator with important information about relative orientation of probe and fastener as they get closer together. The camera could be carefully positioned in the cavity at a location that provides a good side view. For the A-10 wing inspection demonstration, a small video camera with remote motorized

control and connected to a separate monitor was placed in the wing, showing that this approach would work. Alternatively, this additional camera could be placed on the SuNDE tool itself. However, this is a more complicated approach because its position must be off of the existing arms in order to get the needed side view. If the camera is mounted on an arm, that arm must be able to lay flat when the tool goes through the access hole, but rotate into a side position once it is inside. This can be done by adding cable control, but it further complicates a SuNDE tool.

4.4 Lessons Learned from Prototype Demonstration

During this program, several presentations and hands-on demonstrations of the SuNDE prototype tool were given at selected aerospace conferences. The purpose of these activities was to give potential users the opportunity to learn about the tool and learn from their expertise regarding application of the tool and incorporate viable changes into the prototype tool. A portable test stand made of two panels connected by four rods was fabricated in order to simulate a limited access inspection scenario for the demonstrations. The front panel has an access port through which the tool is inserted. A small stringer panel excised from an A-10 wing was placed inside the stand to represent fastener locations requiring inspections. The demonstration set-up (Figure 31), shows the stand, the panel, the SuNDE Tool with the rotating eddy current probe and test equipment.

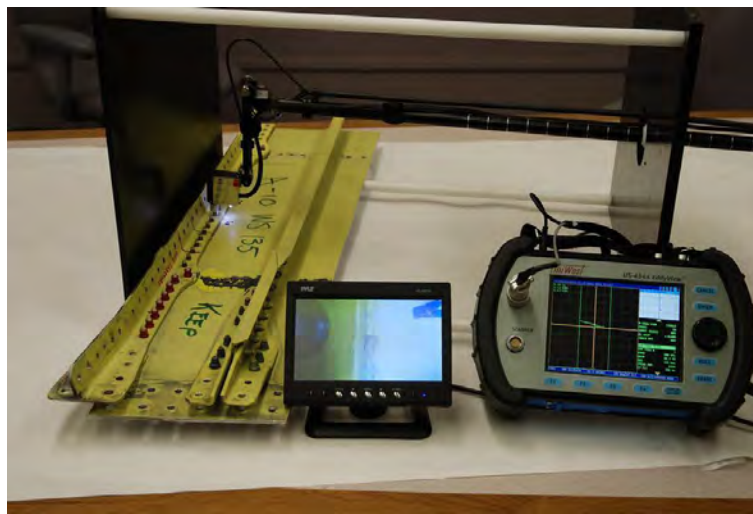


Figure 31. The SuNDE Tool was demonstrated at various industry conferences and technology expos. The limited access inspection scenario was created using a portable test box and stringer panel.

The following locations were visited during the program by SuNDE team members, with accompanying lessons learned:

ASIP (Aircraft Structural Integrity Program) Conference (Jacksonville, FL, Dec 2009); Demonstration of the SuNDE Tool to multiple USAF ASIP Managers.

With minimal training, attendees were able to successfully operate the tool. For any future SuNDE tool, simplicity of use will be important if it is going to be broadly used.

Aircraft Airworthiness & Sustainment (AA&S) Conference (Austin, TX, May 2010): Oral presentation ‘Surgical NDE Tool for Limited Access Inspection’ and tool demonstration.

The feedback obtained from this event was that a surgical NDE tool that made inspections easier in difficult-access-areas was certainly needed but the payoff over the current methods needed to be shown for each individual case.

ATA (Air Transportation Association) NDE Forum (Albuquerque, NM September 2010): The SuNDE Tool demonstration.

A smaller hand held version of the SuNDE tool was suggested, with camera and scanner on a shortened adjustable shaft for “arm length” fastener inspections with little or no visibility. Also discussed was the addition of a heads-up display to go with a SuNDE tool. Applications were suggested by inspectors from Northrop Grumman (C-130), and L3 Communications (P-3, C-130) in regards to inner wing cavity inspections. The use of the SuNDE tool for an interior inspection of commercial aircraft pylons (in particular 767) was suggested by an inspector at United Airlines.

Tinker AFB (November 2010): The goal was to discuss the tool’s application to inspection needs at those locations and to look for implementation potential. Hands-on SuNDE Tool demonstration, PowerPoint and video presentations were given.

An inspection was reviewed on an outboard wingtip area of an E-6 aircraft in depot maintenance. The inspection would benefit from the extended reach a SuNDE tool could provide, but the tool would need to be longer, as the required inspection area extended beyond its reach..

Warner Robins AFB (November 2010): Hands-on SuNDE Tool demonstration and presentation.

A C-5 strut ultrasonic shearwave inspection for cracks requires interior access, difficult handheld positioning and precise movement of a shearwave transducer, making the required corner crack size very difficult to reliably find. We were able to insert the SuNDE tool and show the potential usefulness for this application, but a tool with less joints and minor modifications would work better. The elbow and wrist joints are not needed, and it could be made shorter and lighter, and easier for an operator to handle for this application.

It was also discovered that pre-induction inspections on the C-130 aircraft might benefit from a SuNDE Tool. Visual or borescopic inspections are used, but are often not definitive enough, with features identified as cracks later found to be paint lines or other surface phenomena.

4.5 SuNDE Tool Development Methodology

The process for successful development of an effective SuNDE tool requires several important elements. Even if it is meant to be a general tool, there is no substitute for modeling the tool and the inspection of specific scenarios related to its expected use. A CAD model of the tool and corresponding inspection areas allows every inspection scenario to be checked for form and fit. We found the model very helpful early on in the design process. A physical mock-up of the tool was also valuable because it can show

you additional issues beyond the capabilities of the CAD model. For example, the weight distribution and ease of handling will be revealed with a mock-up. It also provided additional form and fit check.

Excised hardware of an actual A-10 wing structure was available for trial inspections for the course of this program. We found it valuable to test the tool before application of actual aircraft in a depot environment. A trial analysis on real hardware can point to needed design revisions, and prevent damage to the tool or structure before the tool is ready. Testing of a SuNDE tool on real structure in the expected configuration is important to elucidate any remaining issues and to help prepare the inspection procedure. If the tool is successfully manipulated to do the required inspection on the excised hardware, it is ready for the actual structure. If real hardware is not available for testing out the tool, a physical mock-up that closely resemble the inspection configuration and the inspection tool can be built and is used. While all of these design aids may not be available every time a SuNDE tool is developed, the use of as many as possible will streamline the effort, reduce re-design costs, and produce a more optimum tool.

5.0 END EFFECTORS FOR SUNDE TOOLS

Several end effectors were designed under this program to enable a broad range of applications for this flexible tool. Most SuNDE approaches will require enabling technology to locate and hold NDE probes in the needed position and orientation for proper inspections. The SuNDE Tool was successfully demonstrated with a unique scanner (rotating eddy current probe and integrated camera), as the initially demonstrated end effector. This scanner is described in Section 3.4, SuNDE Tool Design.

NDE modalities beyond eddy current, specifically remote ultrasonic pulse echo, hybrid (non-contact/contact) through-transmission ultrasound, and remote digital radiography were developed and demonstrated under a separate program task. Special probes and shoes were designed, fabricated, and attached to the SuNDE arm and connected to NDE instruments for testing and evaluation with these various modalities. The technologies were specifically: vacuum assist attach/detach for ultrasonic pulse echo coupling assist, capacitive machined ultrasonic transducers (cMUTs), and magnetic coupling for control and alignment of TTU transducers. These technologies were attached to the SuNDE manipulation arm as end effectors to demonstrate a broader range of applications. They are described below.

5.1 Vacuum Assist End Effector

A novel vacuum assist attachment was developed for the SuNDE Tool that would enable rapid transducer attachment/detachment to and from the structure when conducting ultrasonic pulse echo inspection. The Vacuum Assist End Effector draws vacuum through several small rubber cups adjacent to the transducer face, using a forced air venturi pump (A CAD drawing of the Vacuum Assist End Effector (Figure 32) and photos (Figure 33) are shown.) When the inspector positions the transducer near the surface and location to be inspected, he/she pushes a button on the manipulator arm that lets the air flow in the feed line and creates the vacuum at the cups at the probe end. Once the cups touch the surface of the structure, this vacuum pulls the transducer against it. The pressure of the transducer against the structure is controlled and consistent. The ultrasonic signal at that location can be observed and analyzed by the operator. To re-position the transducer, the operator releases the vacuum button momentarily, moves the probe tip to the desired location, and again pushes the vacuum button to enable the vacuum and pull the transducer into contact with the surface. Water from a dribbler line, ultrasonic gel, or a soft rubber is used for the couplant, the choice of which will depend upon the application.

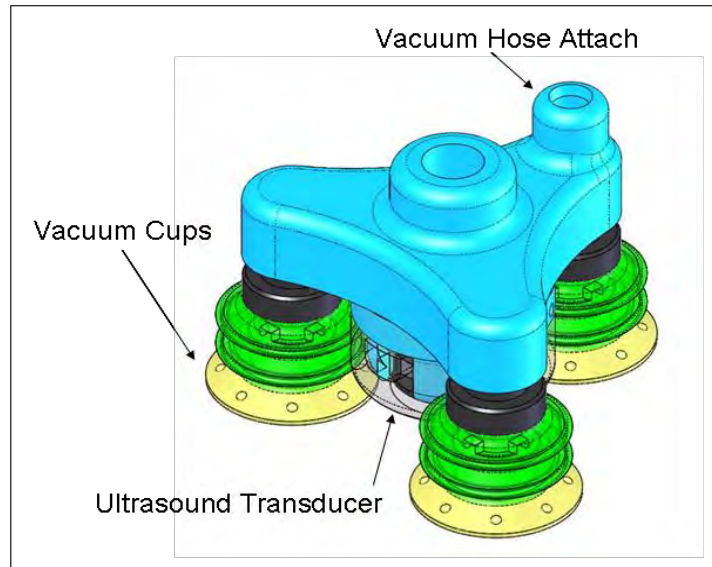


Figure 32. CAD drawing of 'Vacuum Assist End Effector' for enabling good coupling of an ultrasonic sensor to the structure.

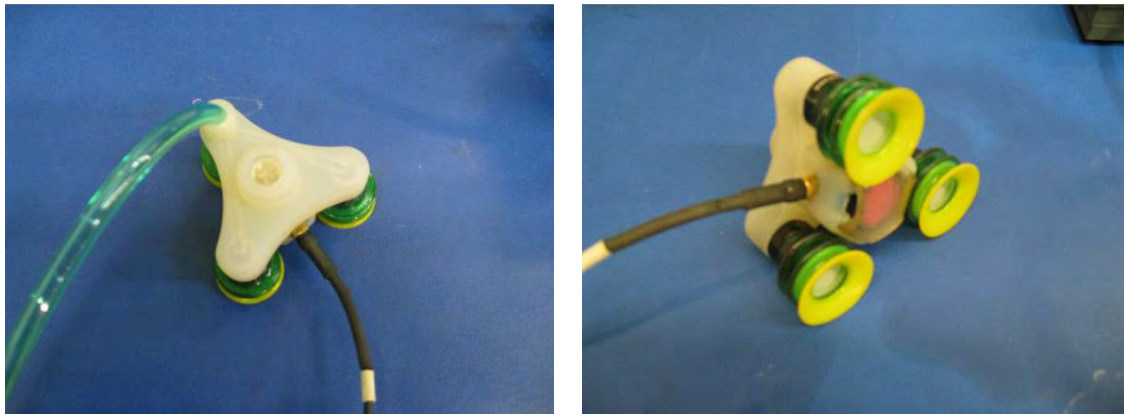


Figure 33. Vacuum Assist End Effector.

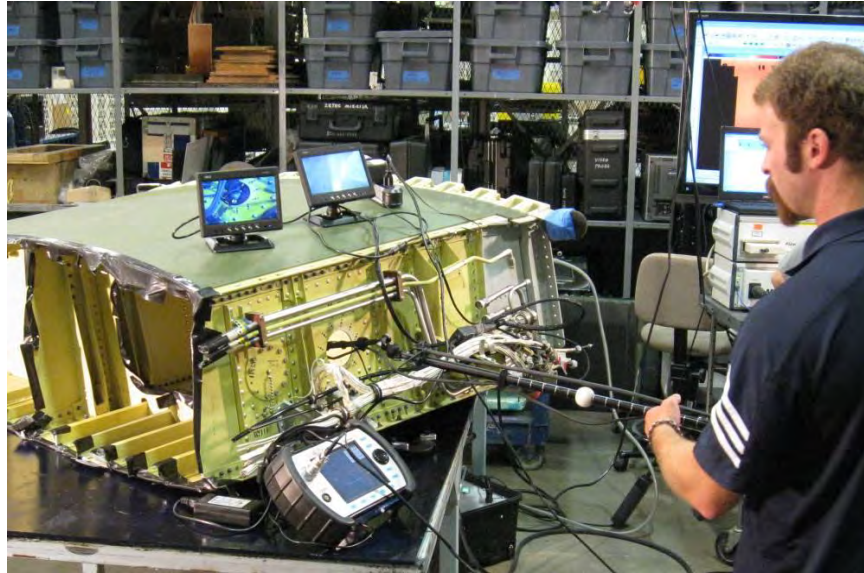


Figure 34. The SuNDE Tool was successfully tested with the Vacuum Assist End Effector. A composite panel inside the A-10 wing section was used for the pulse echo ultrasound inspection scenario.

The SuNDE Tool was successfully lab-tested with the Vacuum Assist End Effector attachment. A composite panel inside the excised A-10 wing section was used for the pulse echo ultrasound inspection scenario (Figure 34). The interior of the wingbox is shown in Figure 35. The Vacuum Assist End Effector was successfully self-coupled to the composite panel under inspection. Delamination damage in the panel could be located and identified by the SuNDE Tool operator. The successful coupling results could be generalized to other ultrasound testing, such as angle beam shearwave ultrasound for crack inspection.

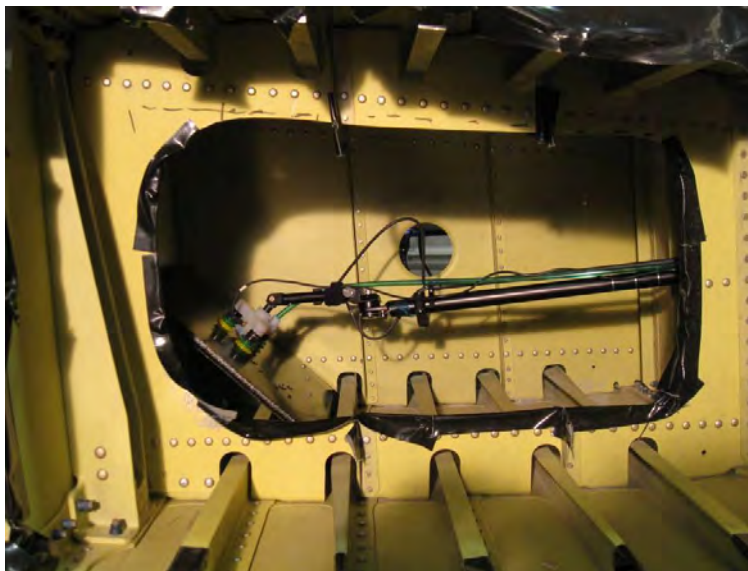


Figure 35. Remote Pulse Echo inspection using the Vacuum Assist End Effector on the Surgical NDE Tool.

5.2 TTU End Effector

Many aircraft control surfaces, such as leading and trailing edges, are made of sandwich structure, such as honeycomb. Through transmission ultrasound (TTU) may be used, but often requires removal of the structure. While bondtesters and low frequency ultrasonic methods are often used for in-service inspection for impact damage, there are situations where there is damage to the interior and these methods are insufficient. For example, the spar or web of a wingbox can be made of sandwich structure. Surgical TTU is an option for on-aircraft inspection of these structures. The SuNDE tool can enable the inspector to use limited access TTU.

In some limited access inspection locations, the use of water or gel couplant for TTU testing could create problems with nearby hardware or electronics. Removing couplant after an inspection can also be very difficult. The couplant issue is overcome by using a capacitive machined ultrasonic transducer (cMUT) as an air coupled transmitter internally. Studies at Boeing and General Electric* have shown that cMUT transducers can be made very light as well as efficient for air coupling of ultrasound up to 1 MHz. A standard piezoelectric receiving transducer can be used for the exterior. The piezoelectric receiver provides high sensitivity to the TTU for the air coupled transmitter. Figure 36 shows an example of a cMUT transducer made by General Electric Global Research for Boeing. The alignment and tracking of the two transducers (between the outside to the inside) for SuNDE would normally be a challenge. A novel approach developed previously by Boeing is to control and align the TTU system by magnetically coupling the transducers. Magnets attached to the transducers on each side of the structure automatically align to each other when placed near enough to magnetically couple.

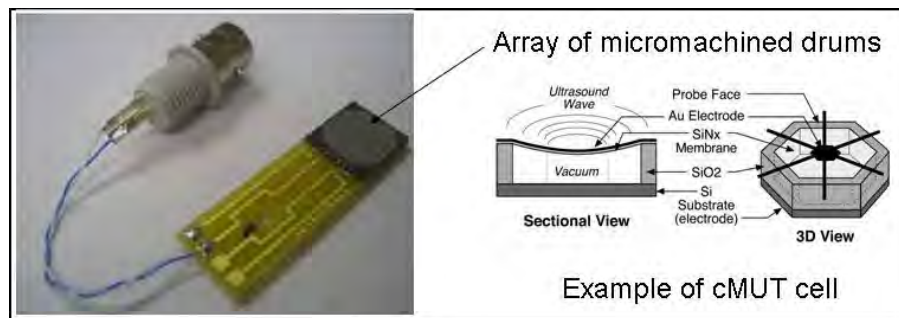


Figure 36. Light weight cMUT configuration.

With the combination of the cMUT and a piezoelectric dribbler system, a remote surgical NDE TTU method was developed under this program. Photographs of the magnetically coupled hybrid TTU end effector are shown in Figure 37. The left photo shows the cMUT mounted in a fixture at the end of the SuNDE Tool. Magnets hold this sensor to the structure and directly across from the external piezoelectric ultrasonic transducer in the right photo. Once the transducers are magnetically connected to each other, the

* "Development of Air-Coupled Ultrasound Transducers for Nondestructive Evaluation" Xuefeng Wang, Ying Fan, Wei-Cheng Tian, Hyon-Jin Kwon², Stacey Kennerly, Glenn Claydon, and Andrew May, IEEE CMUT 2008, Tucson, AZ, USA, January 13-17, 2008

operator can move the external fixture around, and the transducers remain aligned. A test of this magnetically coupled hybrid TTU approach was conducted. A sample of the results is shown in Figure 38. The graphic display of ultrasonic signal from magnetically coupled hybrid TTU, shows the ultrasonic signal through “good” composite material (left), and delaminated material (right). The operator could easily find the delaminated areas of a composite panel, with the SuNDE providing backside access.

The SuNDE Tool may or may not be disconnected during a TTU inspection. The cMUT based internal transmitter is small and lightweight, so it easily follows the motion of the external fixture with dribbler transducer. This approach would work well for the inspection of composite laminate and honeycomb structure as well as metal honeycomb and metal bonded structure where only one side is easily accessed. The addition of a tracking system for the outside transducer would allow imaging to be performed. An alternative is to use a Surgical NDE Tool to move the internal cMUT transducer in confined areas and allow the external dribbler to follow, thereby obtaining TTU inspection in limited access areas.



Figure 37. Magnetically coupled hybrid TTU end effector for SuNDE, with an internal cMUT and external piezoelectric transducer.



Figure 38. Graphic display of ultrasonic signal from magnetically coupled hybrid TTU, showing signal through “good” composite material (left), and delaminated material (right). No signal is able to pass through the delamination.

5.3 Remote Access Digital Radiography

Portable radiography systems have recently become available that use CMOS digital X-ray detectors controlled by software that runs on a tablet PC. These systems are being used in the dental industry to replace X-ray film. The detectors are small enough (0.75 to 1.0 inches on a side) to be easily placed into a patient's mouth. Figure 39 is a photograph of the system, showing the tablet PC and one of the detectors. When combined with a portable X-ray source, this system can provide digital radiography (DR) capabilities for SuNDE applications.

A housing was designed and fabricated to hold a CMOS X-ray detector on the end of the SuNDE Tool (Figure 40). The housing also holds magnets that couple across a structure to an exterior fixture with corresponding magnets that locate the detector. This set-up allows inspector control of the detector positioning from the outside of the structure. A successful test of the SuNDE Tool with remote DR was conducted using the excised A-10 wing section as the demonstration structure (Figure 41). An example of a DR image taken from the honeycomb panel is shown in Figure 42. A damaged cell wall is indicated.

The result demonstrated that SuNDE can be expanded to include digital radiography in remote access regions.

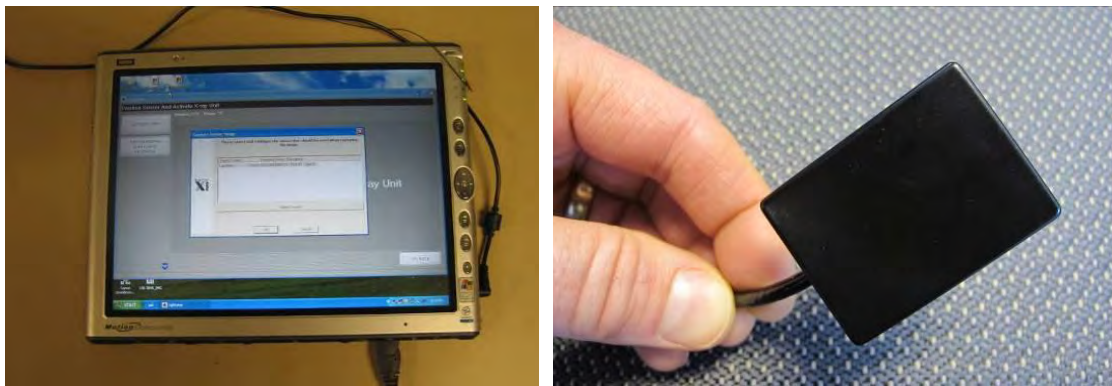


Figure 39. Portable digital radiography system and small CMOS X-ray detector.

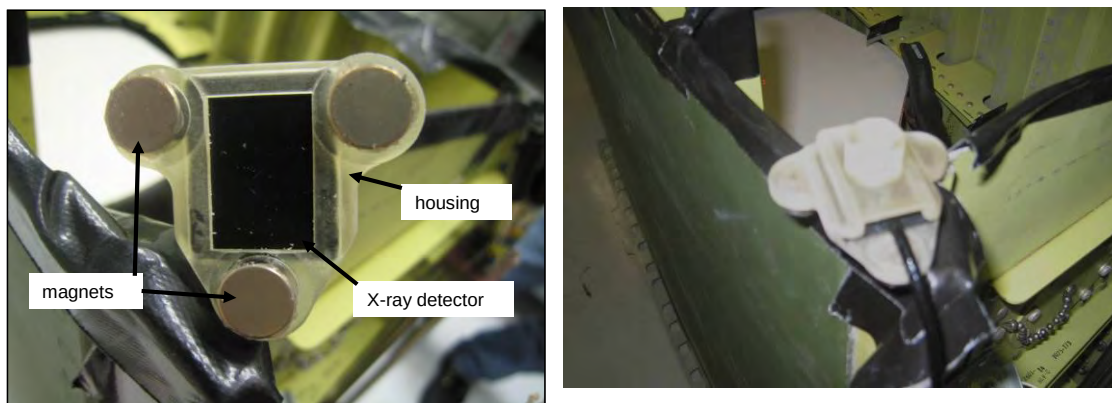


Figure 40. Front and back sides of the Remote X-ray End Effector for the SuNDE Tool.



Figure 41. *Remote X-ray End Effector on the SuNDE Tool is used to inspect a limited access nomex honeycomb panel (identified in the photograph by its white facsheet) mounted inside the A-10 wing section.*

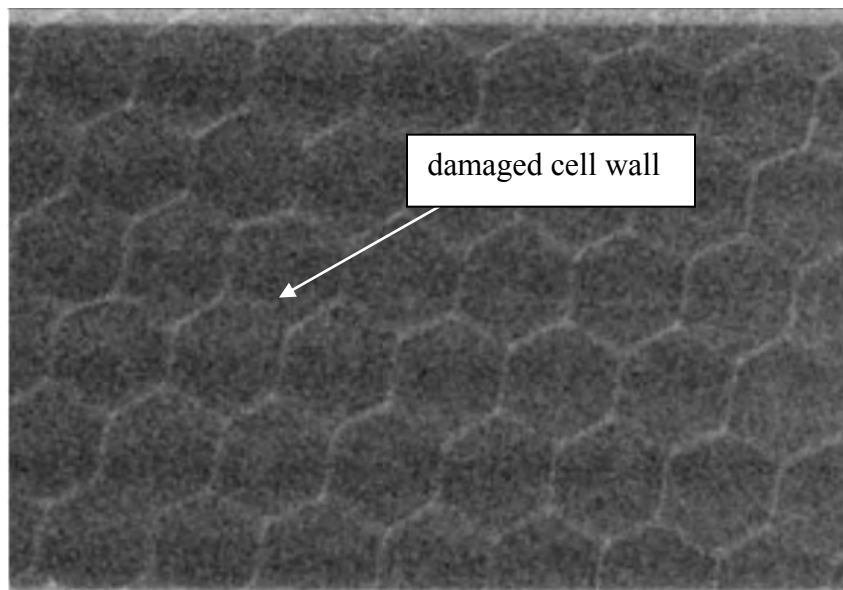


Figure 42. *DR image of the nomex honeycomb panel taken using the SuNDE Tool with the Remote X-ray End Effector. The cell walls of the panel are visible in the image, including one damaged wall.*

5.4 SuNDE Video

A video showing each technology and documenting the demonstrations was produced. This short video points to the broad range of the SuNDE Tool's applicability to various structures and defect types and serves to introduce the tool and its capabilities to potential customers. The video also demonstrates various inspection modalities including surgical eddy current, through transmission and pulse echo ultrasound, and digital radiography. These modalities are enabled using new end effector technology developments. Vacuum assisted attachment, magnetically coupled NDE, cMUT transducers, and CMOS X-ray sensors were all demonstrated on the SuNDE Tool. An excised section of an A-10 wing

was used as a generic limited access structure, with composite laminate and sandwich structure added for specific inspections. Digital copies of the SuNDE video are available from the Program Manager, Charles Buynak, of the AFRL NDE Branch, (AFRL/RXLP).

5.5 Lessons Learned from the End Effector Development

Each of the end effectors was generally successful in helping the SuNDE Tool operator obtain good NDE data from the particular modality. They were easy to attach to the SuNDE arm, and could be used by any inspector familiar with that modality. We learned that ‘vacuum assist’ is an effective way of coupling an ultrasonic transducer to a structure. Magnetic coupling also worked well with a SuNDE tool. We did learn, however, that these end effectors may, at times, be too large for the space they are expected to be used in. Corners, adjacent stiffeners, fasteners, and other structure can get in the way of applying the larger devices to the structure under inspection. In particular, miniaturization of the vacuum assist and magnetic coupling end effectors is needed for broader use.

6.0 ADVANCED SURGICAL NDE WITH ROBOTIC SNAKES

The SuNDE Tool designed and tested under this program was aimed at possible solutions to limited access NDE issues related to cavity inspection on aircraft. The other set of limited access inspections, are obstructed inspections, where plumbing, wiring, electronic systems, and other hardware obscure the location of the inspection.

6.1 Obstructed Inspection challenges

Aircraft obstructed inspection challenges are significant. They include the same challenges as cavity inspections (listed in Section 3.1) but have additional ones:

- Obstructing structure or systems between inspector and inspection area.
- No direct line-of-sight to the inspection area.
- No direct lighting.
- Sealants and aircraft lubricating materials may impede probe path.
- Potentially, tight or very crowded space containing multiple subsystems.
- Typical movements required for NDE scanning may not be possible.
- Obstructing hardware may represent a ‘snagging’ element (hazard) to a SuNDE probe (sensor, apparatus, cables, etc)
- Obstructing hardware may be delicate (wiring, electrical components, etc.).
- Removal of obstructions may be impossible, time-consuming and potentially damaging.
- Removal of obstructing hardware may not be cost-effective or feasible.

6.2 Snake Robots for Obstructed Inspection

Obstructed inspections are best addressed by a “follow-the-leader” insertion capability, where the sensor can be translated to the inspection area along a path that avoids the obstructions. Robotic snakes appear ideal for this, and one that apply to SuNDE can be divided into two distinct categories: ‘Surgical’ snakes and ‘Locomoting’ snakes.

‘Surgical’ Snake robots are the most common type of snake robot, and are operated from a base or platform that is stationary or translatable. Surgical snake robots, developed to assist in medical procedures on the human heart, are beginning to be applied outside the medical field. They can often be operated using a computer and a directional controller or joystick. The head of a snake robot can enter through a single point and be directed until it reaches the inspection location.

‘Locomoting’ or free crawling snake robots are capable of moving separate from a base location and can be guided remotely, though typically with a tethering cable, that is included primarily for power. (Note: While Surgical snake and other types of robots can be placed on a translating base that rolls or walks, when used in reference to snake robots, ‘Locomoting’ refers to those with free crawling ability similar to an actual snake.) Locomoting snake robots have distinct benefits over other types of moving robots in that

they can be inserted into small holes, can crawl across a variety of terrains, and can climb over, under, and around structure. They can be designed to have various types of gaits, or crawling actions, depending upon what they are traversing over or crawling through.

Both Surgical and Locomoting snakes can have ‘follow-the-leader’ motional control, where the body follows the direction of the head. This prevents the body of the snake from bumping into sensitive structure, and allows it to move through small openings.

Both types of snake robots have the potential to provide advanced SuNDE capability and must be considered when defining the opportunity space for future SuNDE. ‘Surgical’ snake robots will, of course, be more effective when the inspection location is relatively near the access port, while ‘Locomoting’ snakes robots can potentially travel deep into a structure, even with many obstructions.

As part of the program, robotic snakes were evaluated for aircraft obstructed inspection capabilities. The SuNDE program team worked with the Carnegie Mellon University (CMU) Center for Biorobotics and its director, Dr. Howie Choset, to establish the SuNDE-specific development needs for robotic snakes. At CMU, surgical and locomotive robotic snakes are being developed for a variety of medical, military, and commercial applications. Robotic snakes on pedestals or wheels are being developed. For those unfamiliar with robotic snakes, a good website to get familiar with them is <http://www.cs.cmu.edu/~biorobotics/serpentine/serpentine.html>.

CMU presented their assessment of the state of the art of snake robots and evaluation of their potential for accomplishing obstructed inspection (Figure 43). A variety of robots were demonstrated and discussed, including urban search, crawling, pedestal, and surgical robots (Figures 44). The visit to CMU generated a host of valuable discussions regarding the development needs for addressing the specific obstructed inspection challenges listed above. Path planning, motion, localization, and mechanical design issues related to robotic snake were discussed.

Robots can be programmed to follow repeatable paths around obstructions to do an inspection, which can enable SuNDE. They can be programmed to sense and verify both their location and shape, so that knowledge can be used for situational awareness. Once in position, the robot can potentially attach or wedge itself within a structure and conduct local scanning that is programmed or joystick-driven. The mechanical design of robotic snakes can be oriented toward SuNDE, making them capable of carrying various sensors, and making needed scanning motions to collect NDE data.

Recommendations regarding the development needs of locomotive and surgical snakes for advanced SuNDE were contributed by Dr. Choset. He recommended that the robotic snakes be modified and improved for inspection in aircraft environments. His recommendations for SuNDE snake robot development address issues related to obstructed inspection, and have been summarized in Section 7.0. Appendix 3 contains Dr. Choset’s entire report.



Figure 43. AFRL Program manager Charles Buynak is holding a free crawling snake robot during the program visit to CMU. Observing are Dr. Eric Lindgren of AFRL (center) and Preston Morgan from Boeing Research & Technology.

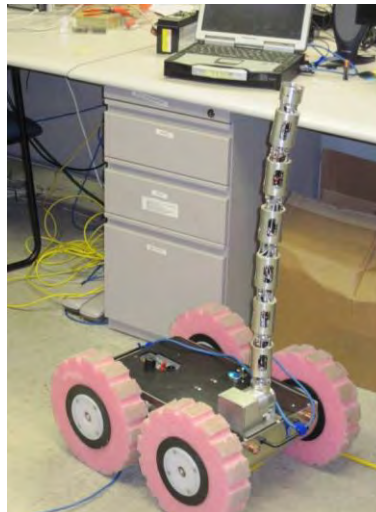


Figure 44. Examples of robotic snakes demonstrated during the program visit to CMU. The locomoting or free crawling snake (on the left) is observed climbing a pole. The surgical type snake on a moveable pedestal (on the right) can be directed to a location of interest.

7.0 RECOMMENDATIONS

7.1 Implementation of SuNDE Tools

There is opportunity space for near term implementation of SuNDE tools at the aircraft maintenance level. Guided by the results of this program, optimized SuNDE tools can be inserted into the ALCs as programs identify improvement opportunities and funding resources for SuNDE insertion.

With the groundwork laid for understanding SuNDE issues and important features, cavity inspections can be addressed almost immediately. The approach should be to show clear benefit through inspection time savings, disassembly reduction, smaller crack detection, improved reliability, or ergonomic benefits.

Economies of scale can reduce SuNDE Tool costs if the Air Force focuses on a small number of SuNDE tools that can be applied as broadly as possible, with optional features and detachable/extendable segments and joints. Implementation costs can be kept lower if these SuNDE tools can be made to utilize currently approved NDE testers. We envision **three basic hand-held SuNDE tools** for cavity inspections:

1. The first recommended tool is a **controllable multi-jointed SuNDE tool** with the basic enabling features of the present prototype (listed in Section 2.0 'Summary of Results'). There is a need for a tool like this for inspectors at an access portal inspecting locations in a cavity beyond his/her reach. It could be offered with specific program needs in view, with shorter or longer arms, and more or less degrees of freedom. From our survey of the ALC applications, it is clear that program "pull" for the technology, as well as good communication regarding the specific opportunity is important. This can be generated by follow-on site visits to program maintenance focals and more in-depth discussions where specific applications showed potential.

The first application of this tool may be **pre-induction inspections**, where visual or borescopic inspections are planned or used, but are often not definitive enough to determine the damage state. A SuNDE tool could provide definitive information up front and reduce unnecessary work. We recommend a visit be made to Warner Robins AFB to assess this potential opportunity for SuNDE implementation on C-130 pre induction inspections.

2. Development efforts are also recommended to develop a **"skinny" SuNDE tool** that can fit into the size of access holes typically utilized by borescopes. The size of the access holes will limit the implementation of SuNDE tools that are the general size of the current test tool. Some pre-induction inspections of the C-130 may fall into this category. This will likely require a new approach to SuNDE tool manipulation, such as internal control cabling, joint micro-motors, or MEMS. As part of this program, we would recommend a review of current borescope inspection applications to determine where there are opportunities to replace a 'visual only' with the 'visual plus sensor' SuNDE approach within the Air Force.

3. We also recommend the development of a **Mini-SuNDE tool** for inspections out of the inspector's line of sight but within reach. In this case, the human arm is the 'manipulator arm' that gets the sensor to the needed inspection location. This tool would address an expressed need by inspectors for situational awareness and assistance in probe placement.

Optional features could include a lighted micro-camera (attached to the handle or even a finger clip), replaceable/ adjustable extensions and joints, a heads-up display, and end-effector to aid in attachment or orientation, depending on the customer preference and inspection need. For example, a concept for a scanning shearwave ultrasound end effector with a camera that drops over each fastener was conceived for cavity inspection for small buried corner cracks in steels adjacent to fasteners (a C-5 strut application). The Mini-SuNDE tool would help the inspector to ‘view’ the inspection site even if reaching through a small access port or around substructure, and more easily and repeatably, conduct the inspection. Along with saving inspection time, and improving ergonomics, this new tool may also extend the inspection intervals in some cavity inspection cases if smaller defects can be more reliably found.

In the case of the C-5, this compact SuNDE tool would require that he/she crawl inside the structure. However, there are many occasions where an inspection area can be reached from the exterior of the aircraft, but it is simply not seen by the inspector. The ability to precisely control the position and motion of the transducer would make the inspection much easier and quicker, and provide a higher probability of detection (POD). The ability to find smaller cracks would allow the increase in inspection intervals, thereby lowering inspection costs for this structure.)

7.2 Robotic Snake Development for Advanced SuNDE

There are opportunities for implementing advanced SuNDE using robotic snakes for obstructed inspections. However before that can happen, research and development in robotic snakes are needed in four categories: Mechanism Development, Electronics, Software, and Support Hardware. While Appendix 3 has his complete report written by Dr. Howie Choset, director of CMU’s Center for Biorobotics, we summarize the recommendations here:

• Mechanism Development

For locomotive or free-crawling snakes, the means are needed to enable it to carry one or more sensors into a confined space, “wedge” itself into place, and go through a guided or pre-programmed inspection. Either a lighter tether or on-board power would allow deeper or more complex movements, but there must always be a means for getting a snake out if it stops working properly. A sheath or special “snake skin” will be needed for applications where it could get snagged or if the environment is hostile to the snake (ie. in a fuel cell or adjacent to high electrical power).

For surgical, non-locomotive snakes, advances are required to make them longer than is currently available in order to get a sensor to the needed aircraft limited access inspection locations. Many inspection areas are several feet or more away from an access port. Lengthening these snakes will require developing novel ways of providing sufficient strength and radius of curvature while making them longer.

• Electronics

The integration of non-contact sensors for navigation, environment mapping, feature detection, and situational awareness is needed for both types of snake robots.

Force or contact sensors must be implemented into robotic snakes, based either upon current sensing of torques, voltage measurement of spring sensors, whiskers, or joint torque sensors.

For extended, or untethered travel of locomoting snakes, researchers will need to improve the efficiency of existing electronics, in order to extend battery life and reduce dissipated heat.

- **Software**

‘Gaits’ are the cyclic motions that propel the snake in a desired direction. New gaits have to be developed that enable robotic snakes to crawl around aircraft environments and handle the host of challenges they will face. ‘Irregular’ or non-cyclical gaits may be necessary or to get around obstructions typical in an aircraft.

Better ‘Estimation’ for locomotive navigation and positioning is needed for robotic snakes. These include estimators to infer the current configuration of the snake, how far it has moved, and the geometry of its immediate surroundings, and its physical location within the structure – so we know exactly where all parts of the snake are at all time.

‘Mapping’ development, for inspection results as well as tracking, is needed that involves creating three-dimensional maps of the volume the snake robot is encountering, to allow reporting to an inspector the possible location of faults and allow the robot to return to such locations for further inspection.

Simplified ‘User interfaces’ are needed for guidance, control and display of the snake configuration and its environment.

- **Support Hardware**

Realistic mock-ups of relevant aircraft obstructed inspection scenarios are needed for snake robot SuNDE testing and development purposes.

We recommend the Air Force consider establishing multi-year programs for both the surgical and locomotive robotic snakes that can be done in stages. These are detailed in Appendix 3 but are summarized below:

- **Surgical Snake**

Stage 1: Develop surgical snake robot with detachable sensors

Stage 2: Develop module sensor support for the distal portion of the probe, integrating a digital camera, and develop estimation techniques for the configuration of the snake robot.

Stage 3: Increase the length of the snake and decrease its radius of curvature.

- **Locomoting (Free Crawling) Snake**

Stage 1: Develop a crawling snake borescope, a smaller and lighter tether, sensors to measure the force the robot exerts on the environment, and new gaits for specific tasks and stages.

Stage 2: Develop a modular unit for multiple sensors, add a camera to the tail of the robot, add user interface, investigate the voltage and whisker force sensor, improve the

power electronics for longer robot running time, develop effective gaits and future mapping technologies, and develop estimation technologies for determining robot configuration.

Stage 3: Develop a robot 'parking brake' add on-board power to mitigate the need for a larger/heavier tether, develop new gaits for specific tasks (at this, and all stages) and, develop mapping technologies to store detailed information of the inspection and repair tasks.

APPENDIX 1: A-10 HFEC INSPECTION SET-UP

The HFEC impedance plane setup for the A-10 eddy current inspection was developed to aid the inspector in knowing when the probe was coupled onto the stringer so the inspection could be performed properly. This was accomplished by having the eddy current probe “nulled” in air, instead of on the part (as is often done), and then, as the probe is brought down over the fastener, the eddy current display “dot” comes down to the position where it is coupled with the stringer. Examples of the dot motion on the display and the different anomaly indications from different “lift off” amounts (Figures A1 and A2) are illustrated below. With this method, the operator can see that the probe is coupled when the dot is in the lower right region of the curve (as indicated in Figure A2).

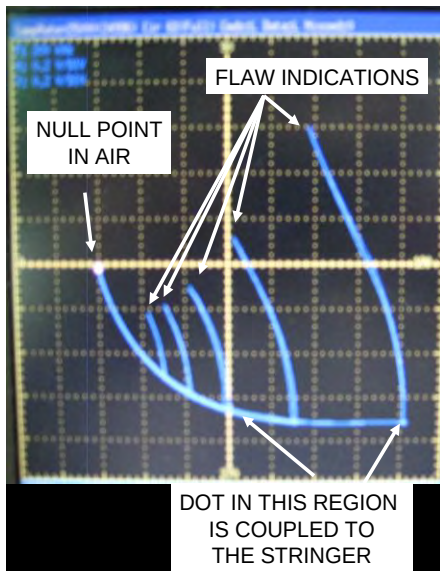


Figure A1: High Frequency Eddy Current (HFEC) Impedance Plane Display.

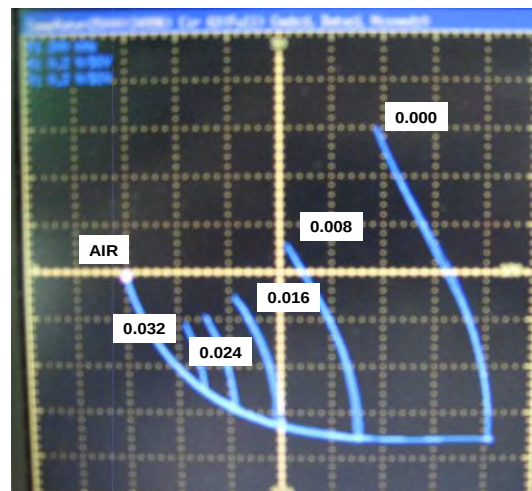


Figure A2: High Frequency Eddy Current (HFEC) Impedance Plane Display. (Lift-off amounts are shown in inches.)

In these figures (A1 and A2), there are multiple flaw indications shown. These are not for different flaw sizes, but instead they are for the same flaw (0.050 inch deep EDM notch) with different amounts of “lift-off”, or distance the probe is uncoupled from the part. Figure A2 identifies the indications with the amount of distance the probe is off (or uncoupled from) the part. To obtain a 3:1 signal-to-noise (S/N), the probe cannot be “lifted-off” the part more than 0.016 inches. If the “lift-off” is greater than this, the flaw indication is detectable, but the S/N is less than desirable. Seating the eddy current scanner over the fastener so that the sensor lies as flat as possible on the structure is paramount to conducting a proper inspection.

APPENDIX 2: SPRING-LOADED EDDY CURRENT COIL ON MICRO-SCANNER FOR SUNDE APPLICATIONS

One of the SuNDE challenges identified during the A-10 wing inspection demonstration was the difficulty the operator faced trying to obtain adequate probe coupling. While the demonstration was successful, it was felt that it took longer than it needed to take. Much of the time for the inspection was related to getting the probe seated around the fasteners with minimal lift-off. With the rotating eddy current scanner, the maximum horizontal lift-off that could be tolerated and still give a good signal-to-noise was 0.008 - 0.016 in. (Figure A2.). Above that value, the signal begins to be too close to the lift-off curve, and becomes difficult to separate a crack from lift-off.

For this reason, an eddy current coil with an axial spring-loading mount was incorporated into the probe. The coil was designed to have a 0.008 inch range in movement. The eddy current probe design is shown in Figure A3. The spring loading increases the probe compliance to the surface of the structure under inspection.

Testing with the new probe was done on the A-10 wing section used for SuNDE tool development. The gimbaling on the old probe and the new probe is about 10° for both (Figure A4). This gimbaling allows an inspection to be performed at angle up to 10° (Figure A5) which aids in the inspection. However, as discussed previously, proper orientation required for inspection is still difficult. Even with the gimbaling, the eddy current “dot” on the impedance plane display moves around during a complete rotation, (Figure A6). This indicates that the coil itself experiences a small amount of lift-off from the structure.

When the new probe with a spring loaded coil was tested, another 5° (15° total) of angle from normal (Figure A7) could be added, while the probe still provided a quality inspection. . The test inspection showed this new probe was also better because lift-off is reduced even at the larger angle. Also, the “dot” on the impedance plane moved around much less during the coil rotation around the fastener (see Figure A8).

The improvement of the eddy current probe is important for SuNDE inspections, because it reduced the orientation requirement for an inspection and makes it easier and quicker to accomplish for the inspector. In a SuNDE test run using the A-10 wing section stringer runout inspection, a reduction of at least 50% in inspection time was realized.



Figure A3: Design of the probe with a spring loaded coil. The .008 inch range is indicated.(Note that this entire probe is also gimbaled to allow for good seating during off-angle approaches.)

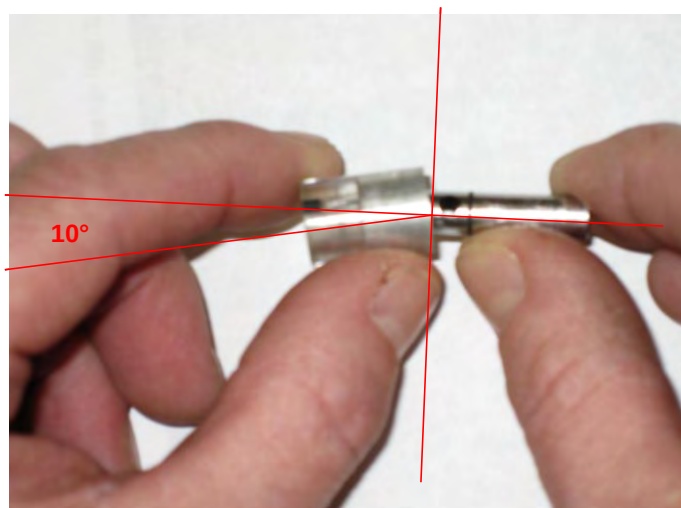


Figure A4: Probe gimbaling allows for seating during off-angle approaches.

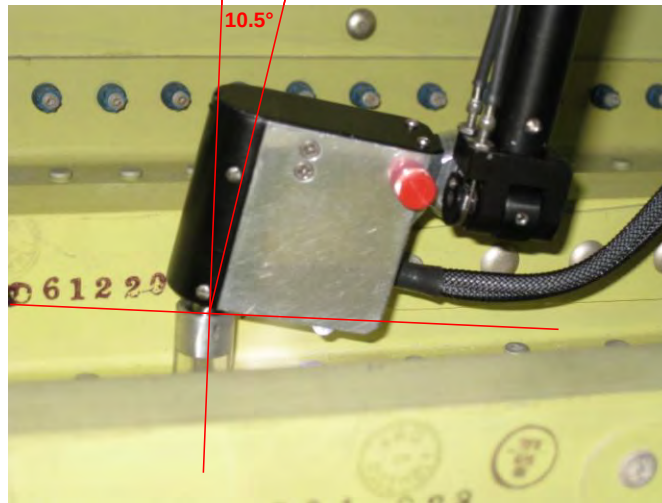


Figure A5: *Approximate maximum scanner-to-probe gimbaling angle during an inspection.*

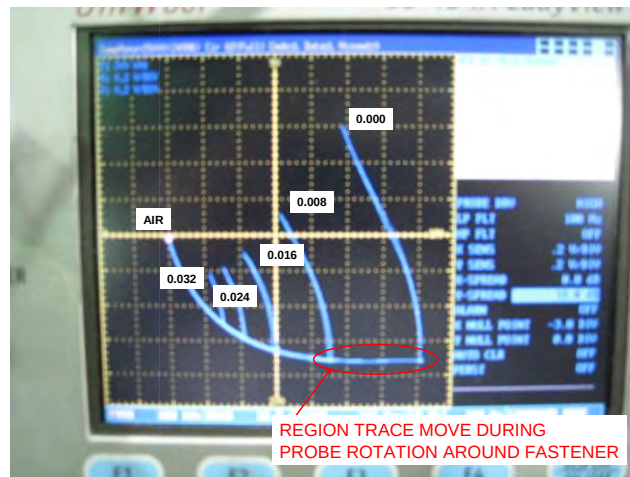


Figure A6: *Eddy current impedance plane display showing region of movement of the “dot” with the original probe during the coil rotation around the fastener.*

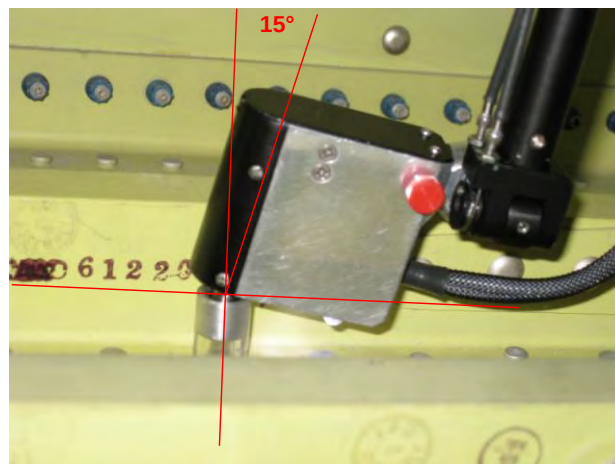


Figure A7: *Approximate maximum scanner-to-probe gimbaling angle using new spring loaded coil during an inspection.*



REGION TRACE MOVE DURING PROBE ROTATION AROUND FASTENER

APPENDIX 3: RECOMMENDATIONS FOR SNAKE ROBOT WORK FOR INSPECTION

The following is the write-up of the recommendations by Dr. Howie Choset of CMU to the program team regarding the development of robotic snakes for SuNDE applications. These recommendations are summarized in Section 7.2.

Howie Choset

June 30, 2009

Carnegie Mellon University

Snake robots are highly articulated mechanisms that can thread through tightly packed volumes accessing locations that people and machinery otherwise cannot access. The benefit to aircraft inspection can be profound when inspections can take significantly less time, at a reduced cost, and with a higher fidelity of accuracy. On June 23rd, personnel from Boeing and the Air Force visited the Carnegie Mellon Biorobotics Lab to assess the state of the art, first hand, of Choset's snake robots and their potential for inspection.

The purpose of this report is to provide informal suggestions for future development of snake robots for inspection tasks. Omitted from this report is a detail account of the state of the art, but I believe my research group's robots represent an excellent example of the state of the art in terms of snake robots. I welcome any questions about other snake robot technologies if questions arise.

As impressive the demonstration on June 23rd was, there is plenty of room for development. I would separate the list of suggested advances into four categories: mechanism development, electronics, software, and support hardware. No one category is necessarily more important than the other, but certainly we can start development doing a little bit from each and building upon results from each.

I. Mechanism Development

A. Free-crawling Mechanism

1. Ability for snake robot to "wedge" itself so as to apply force for another tool
2. Mounts for sensors and support electronics
3. Means by which the snake robot can carry a conventional borescope
4. A lighter/smaller tether
5. On-board power, if desired
6. A sheath to protect the snake, if entering an extremely dirty environment.

B. Surgical Snake Mechanism

1. elongate it
2. tighter radius of curvature
3. Mounts for sensors

II. Electronics

A. Non contact Sensors

1. Navigation sensors, such as accelerometers, placed on board so as to gage progress
2. Mapping sensors, which aid in creating a map of the environment so as to report structural problems, but also be used for navigation
3. Environmental sensors, to specifically detect features in the environment
4. Additional cameras, at least one at the tail.

B. Force/Contact Sensors (in degrees of difficulty)

1. current sensor: this is the low-cost quick and dirty approach to measure the current of the motor. Through use of simple kinematics, we can convert torque to force and viola we are done. Unfortunately, current sensing may be prone to noise and hence not sufficient. However, given its low cost, justifies examination
2. voltage measuring spring between sensor and surface; this is how force sensors are normally built. This option may be more accurate but also more expensive, in terms of cost and volume occupied on the robot, which may be limited.
3. whisker – create a whisker or antenna and measure the reaction forces on the base where the antenna meets the robot using strain gages.
4. joint torque sensors – speaks for itself.

C. Power electronics. We need to improve the efficiency of our existing electronics, so as to extend battery life if we go untethered and reduce dissipated heat.

III. Software

- A. Gaits - cyclic motions that propel the snake in a desired direction. Clearly, the inside of a air craft represents new structures that we have not encountered and therefore, new gaits have to be developed. I am not concerned with our ability to develop a new gait for any new challenge, but we need to do better. In other words, we need to develop a means by which a generic set of gaits are defined and therefore can handle a host of challenges, beyond those anticipated by the designer
- B. Estimation – we need to use the internal sensors for navigation to better locomote as well as navigate in the confined spaces. Already, there is work on behavior estimation for mobile robots, but such robots are single rigid bodies – snakes are multi-bodied. Drawing from our work on localization, we will develop better snake estimators to infer the current configuration of the snake, how far it has moved, and the geometry of its immediate surroundings (i.e., the diameter of a pipe, the angle it makes with the ground, etc.).

- C. Mapping – Borrowing techniques from mobile robot mapping, and combining them with results in estimation, we can create a three-dimensional map of the volume the snake robot has explored. Moreover, we can spatially annotate the environmental sensor readings, so as to more easily report to a user the possible location of faults and allow the robot to return to such locations for further surveying.
- D. User interface – we need to make the robot controlled by someone who does not have a PhD in Robotics. This is the goal of current work whose support ends in October. Also, we need a means by which we will display a map, and the environmental sensors.

IV. Support Hardware

- A. Better control case that integrates desired environmental sensors and is more portable
- B. An obstacle course in my lab for testing purposes

Development Suggestions: The following is a list of suggestions, grouped in stages, starting from the simplest to the more complex.

Surgical Snake

Stage 1: Overall near-term recommendation is to build a duplicate surgical snake robot which is either identical to the current one or 15 mm in diameter, but still of the same length. We will place an available sensor on board for testing.

Stage 2: Naturally, future applications will require different sensors and therefore a module sensor support for the distal portion of the probe would be the next development milestone. This stage should also include integrating digital camera information so as to store maps of the inspection sites. This would include developing estimation techniques for the configuration of the snake robot.

Stage 3: Increasing the length of the probe and then decreasing its radius of curvature. This will also require updating the feeding mechanism to handle a larger snake.

Finally, if the Air Force can tolerate a larger diameter robot, say one of 35mm in diameter, then we have an alternative design that may allow the robot to be more elongated.

Free crawling snake

Stage 1: The first stage should include development tasks that leverage as much as possible the existing designs. Developing a means by which the current snake can “drag” a borescope is the best first step because it may in “one shot” solve all inspection problems. However, I do not believe we will be able to carry a borescope to all desired locations of an engine. This stage also includes the development of a smaller and lighter tether; the idea here is that the lighter the tether, the greater the distance the robot can climb. This stage includes the use of current sensors to measure the force the robot exerts on the environment. Finally, development of new gaits (i.e. controllers) for specific tasks must occur at this, and all stages; these will be task dependent.

Stage 2 Develop a modular unit at the distal portion of the free crawling snake robot that can allow for multiple sensors to be installed so as to make the robot “agnostic” to choice of sensors. Also, add a camera to the tail of the robot. This will naturally include developing the electronics that allows the user to select among sensors and the user interface to display information coming from the sensors. This stage will investigate the voltage and whisker sensor, described above, to measure force. We will also improve the power electronics in this stage so as to allow for longer

robot running time. Finally, development of new gaits (i.e. controllers) for specific tasks must occur at this, and all stages; these will be task dependent. At this stage, however, in order to develop effective gaits (and future mapping technologies), we need to develop estimation technologies so as to fully understand the configuration of the robot as it progresses through its environment. Continue working on user interface.

Stage 3: For all diagnostic and repair tasks, the robot must be able to wedge itself into a fixed location. This feature cannot be underscored enough. Already, we have considered designs of a parking brake, so that the robot can climb to a location and turn itself off. This effort takes this concept one step further: climb to a location and with no power, immobilize itself to the point where it can resist reaction forces. Leveraging the improved power electronics, this stage will also include adding on-board power to the snake robot; even if the mechanism still requires a tether, on-board power mitigates the need for a larger/heavier tether thereby allowing the robot to crawl further. Finally, development of new gaits (i.e. controllers) for specific tasks must occur at this, and all stages; these will be task dependent and will exploit the new braking mechanism. We will build upon the estimation techniques from the previous stage to developing mapping technologies to store detailed information of the inspection and repair tasks.