RE2 Robotics has developed a novel platform for autonomous and tele-operated nondestructive inspection (NDI) of aircraft coatings and components to increase productivity, reduce human error, and improve operational time and aircraft readiness. The platform, “Autonomous Non-Destructive Inspection of Aircraft (ARNDIA)”, fuses computer vision and machine learning algorithms with the lightweight and portable 7 Degree of Freedom (DOF) autonomous manipulator system that can be easily mounted onto aircraft surfaces. A variety of sensors and end effectors from third-party providers such as ultrasonic devices and time-domain terahertz sensors, can be easily integrated with ARNDIA through its Interface Control Document (ICD). After a sensor integration is completed, ARNDIA can autonomously scan aircraft components to detect areas of concern. In addition, because of its 7 DOF capability, ARNDIA can easily access difficult-to-reach components to perform NDI on them, which, if they were to inspected by a person, would otherwise require hours of labor removing other components just to access the ones of interest. ARNDIA utilizes path planning algorithms to plot the trajectories needed to perform NDI of the appropriate aircraft components. Through its use of computer vision, ARNDIA also ties the data it collects to geo-referenced locations on the component or airframe it is inspecting, and archives all data so that it can be exported for further analysis, if needed. RE2’s primary business area is the development and production of teleoperated and autonomous manipulation systems, and has extensive experience integrating its manipulators with a variety of third-party sensors and platforms. RE2 has sold over 650 robotic arms to the U.S. Department of Defense, and has worked extensively with DoD prime contractors.

Introduction

A key challenge across multiple agencies within the Department of Defense (DoD) is ensuring mission readiness of critical aviation assets. This challenge is increasingly exacerbated by the growing financial and time costs of carrying out key maintenance actions that are needed to ensure that aircraft are able to safely and effectively carry out their missions. The DoD is constantly seeking to optimize and improve upon maintenance practices for fixed wing aircraft and rotocraft. Non-destructive Inspection (NDI) tools are being increasingly utilized for reliable maintenance checks of aircraft coatings and structures without degrading performance of the tested structure. This saves significant cost and time in performing the maintenance action.

RE2 is an industry leader in the development and transition of unique robotic arms that have a wide range of applications, including optimizing and streamlining aircraft maintenance practices. The Autonomous Non-Destructive Inspection of Aircraft (ARNDIA) system is a robotic-arm-based solution for providing automated, non-destructive testing and inspection of aircraft composites while attached to the aircraft itself. Using ARNDIA to perform NDI on aircraft provides a wealth of opportunity for increased efficiency and robustness of test results, and reduced costs. Robotic arms are advantageous when paired with commonly used NDI sensor modalities, such as ultrasound. Increased interoperability and modularity are realized with a robotic arm solution, as multiple types of these sensors can be integrated as End of Arm Tooling (EOAT). This enables maintainers a more streamlined ability to switch between multiple testing systems using the same equipment.

As shown in Figure 1, ARNDIA is also a highly mobile robotic arm concept, and can be adapted or use while attached to the aircraft itself (as shown in Figure 1), as part of a ground vehicle, or a floor-mounted system, making this system highly mobile.
NDI Sensors for Composite Material Testing

Composite materials are rapidly becoming the material of choice across the DoD and aviation industries. These materials possess superior mechanical characteristics, such as high strength-to-weight ratios, and high stiffness-to-weight (density) ratios. Due to the nature of their physical characteristics, composite materials are subject to unique failure mechanisms, many of which are not readily discernable through visual inspection.

As composite materials are typically composed of multiple layers, damage and failure mechanisms can easily persist below the surface, out of the sight of a maintainer performing visual inspection. This is illustrated in the photograph of a composite sample shown in Figure 2, where composite bond line damage (right) is not detected at the surface (left).

Figure 2: Composite with bond line damage indicated by arrow at right. Damage is not detected with visual inspection (left)

Similarly, thermal damage is a persistent threat to aircraft composites due to the extreme conditions faced by aircraft composites under routine operation, and from unexpected fires and over-temperature events. Heat damage is often realized below the exterior surface of the aircraft, where it significantly less likely to be identified and analyzed properly by visual inspection. In early stages of heat stress, visual inspection may reveal discoloration but is incapable of determining the extent of underlying damage, residual strength and stiffness of thermally damaged material, or its overall remaining useful life. NDI sensors allow for this below-surface data to be taken, and this data can be used as input to model thermal degradation, the extent of thermal conduction, or other material lifetime projection models. Robotic arms allow this data to be taken more precisely and over a more complete area, further refining model results.

Ultrasonic sensing is a widely used NDI technique for evaluating aircraft composite materials, both at and below the surface, for thermal degradation, bond line damage or any other structural failures incurred by the material. As an ultrasonic wave travels through the composite, it interacts with various layers of a composite material or with artifacts on the surface or sub-surface. The ultrasonic technique most effectively employed by ARNDIA is a pulse-echo configuration. This configuration uses the same transducer to send and receive acoustic waves, and can be configured in such a way that submersing the tested material in water is not necessary. The reflected waves are captured and converted back into an electrical signal that is analyzed to reveal structural information about the scanned composite material. Information garnered from an ultrasonic measurement can be used to determine multiple parameters about a composite, such as heat conduction, thermoset matrix pyrolysis, oxidation of carbon fibers, thermal expansion and diffusion of decomposition gases on the temperature distribution.

NDI Sensor Integration with Robotic Arms

Robotic arms provide several key advantages as NDI solutions. Robotic arms can be integrated anywhere on the flightline, and pairing a robotic arm for sensor-based testing provides robust test results no matter where it is implemented, including areas that are difficult or dangerous for human maintainers to access. ARNDIA can achieve more accurate and repeatable sensor placement than is achievable with human maintainers with greater and more precise sensor coverage. ARNDIA autonomously provides geo-referenced data from the integrated sensor, at a high level of precision. This geo-referencing can be used to provide precise location information for specific damage that is discovered during data acquisition and analysis. Automating this process provides significant time, and by extension cost, savings.

Another advantage for employing ARNDIA, is the ability to customize the arm to reach into
spaces within the aircraft or rotorcraft that are not easily accessible by human maintainers. ARNDIA robotic arm possesses seven (7) degrees of freedom, which lends itself to greater physical flexibility, greater agility in path planning and computer vision algorithm implementation and execution. This is illustrated in Figure 4 on a rotorcraft hull, showing a few of the many locations within a helicopter that have highly constrained access to areas inside the craft where inspection must be performed. This includes composite materials and also can include checking the torque of the craft’s bolt joints. In these instances, in the absence of robotic arm technologies, the outer hull of the craft may need to be removed. Introducing a host of complications to the maintenance processes, including:

- Unintended failures from improper component replacement
- Additional time to replace components
- Additional flight worthiness checks, and added cost and time for when these check fail

Such an advantage lessens the physical burden of an aging DoD maintenance force, and indirectly reduces the overall cost of aircraft maintenance.

**RE2 Capabilities**

RE2’s core area of expertise is intelligent mobile manipulation, and the company has advanced the state of the art of manipulator capabilities in numerous areas of aviation, including NDI, in support of ARNDIA. RE2 is currently involved in several commercial projects aimed at advancing autonomous and tele-operated capabilities both for robotic arms and fully integrated systems. Some examples of RE2’s previous work in automation and tele-operation capabilities in aviation-related areas include the following:

- Tel-operated airfield repair, an effort in which RE2 is developing a fully integrated system whereby equipment for clearing a damaged airfield and Explosive Ordinance Disposal (EOD) was made remotely operable utilizing a robotic manipulator and applique
- Robotic aircraft refueling, wherein RE2 is integrating a system for autonomously refueling rotorcraft in remote, unmanned locations
- Automating active runway operations, wherein RE2 is working with a major airport to develop a system for automated aircraft refueling, baggage handling, and grey water disposal using robotic arms on Unmanned Ground Vehicles (UGVs)
- An automated system for coating the inlet of military aircraft, leveraging the ability to maneuver robotic arms into tight spaces.

Each of these efforts has advanced RE2’s capability in bringing automated and tele-operated solutions to bear for aviation applications. Each iteration of technology development has strengthened RE2’s ability to provide overall cost reduction, ease the physical burden on the maintenance community, and provide more robust and efficient results. ARNDIA is an extension of this capability, providing an automated solution for more streamlined and effective NDI, thereby significantly advancing aviation maintenance practices.

**Summary**

ARDNIA is a novel platform for performing NDI of aircraft composites, providing multiple advantages over purely human-based inspection techniques. ARNDIA can easily be mounted onto aircraft surfaces and provides geo-referenced data over a wide area of the aircraft, including areas that are difficult to reach by maintainers. This solution enables significant reduction of burden on the aging DoD labor force, and will be instrumental in providing efficient and cost effective next-generation NDI capability. ARNDIA is supported by RE2’s portfolio of tele-operated and autonomous robotic solutions that have supported DoD missions for nearly two decades.

**References**

2. “Indestructible Achieves New Approval from Leading Helicopter Engine Manufacturer”, Business News, January 10, 2019,