Surface Evaluation Network for Tethered Inspection and Nondestructive Evaluation (SENTINEL)

Michigan State University

Team Members:

Name	**Year**	**Major**
Abdulelah Mulla	Junior	Computer Science
Malhar Khisty	Sophomore	Computer Science
Tejas Agrawal	Freshman	Computer Science
Caleb Morrison	Junior	Electrical Engineering
Graison Lunden	Junior	Electrical Engineering
Matthew Atkinson	Junior	Electrical Engineering

Faculty Advisor:
Vaibhav Srivastava

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Project Summary:

- Aircraft Maintenance and Non Destructive Testing Focus.
- Address shortage of NDE technician laborers and greatly reduce aircraft inspection times by automating the subsurface scanning process while streamlining data collection for certified technicians.

A tethered unmanned aerial vehicle (TUAV) equipped with an eddy current sensor and a perching mechanism, enabling the TUAV to latch directly onto the surface of the aircraft to ensure stable NDT. A mobile ground control station (GCS) moves alongside the TUAV managing the tether and providing continuous power.

Project Image:

Team Composition/Roles:

Undergraduate Research Lab

Team:

- Abdulelah Mulla - Junior - Computer Science
- Malhar Khisty - Sophomore - Computer Science
- Tejas Agrawal - Freshman - Computer Science
- Caleb Morrison - Junior - Electrical Engineering
- Graison Lunder - Junior - Electrical Engineering
- Matthew Atkinson - Junior - Electrical Engineering

We are an undergraduate student research lab at Michigan State University who are 2x NASA USRC recipient, with experience in delivering quality projects that meet the stringent demands of the aerospace industry.

Proposed deployment timeline:

2026 – Project would kickoff in June, which includes rapid prototype development of the drone platform, eddy current tester, attachment mechanism, tether and moving ground control station, and LIO-SAM navigation systems.

2027 – Minimum Viable Product (MVP) is finalized and achieves completion, leading to the final engineering of the base product to achieve single instance usability.

2028-2030 – Regulatory and manufacturing phase. NAS 410 certification process and the supply chain setup for 3rd party components and the establishment of the assembly and shipping infrastructure.

2031 – System is ready for mass adoption, and is commercially available to tackle labor shortages in in the aerospace maintenance industry.

Abstract

Routine aircraft maintenance is mainly reliant on manual Non-Destructive Inspection (NDI) to detect subsurface damage on aircraft; one of the most common methods of NDI is Eddy Current Testing (ECT). As the aerospace industry is forecasted to face a critical labor shortage, with nearly 30% of certified NDT personnel nearing retirement, there is an emerging demand to increase inspection efficiency. The automation process of NDT currently struggles with a stability/mobility tradeoff, where robotic crawlers are stable but slow, and free flying drones lack the stability required for effective ECT. To address this challenge, we propose the Surface Evaluation Network for Tethered Inspection and Nondestructive Evaluation (SENTINEL); a Tethered Unmanned Aerial Vehicle (TUAV) that utilizes a perching mechanism to temporarily anchor the drone to the aircraft. SENTINEL operates as a human in the loop (HITL) tool, where certified inspectors use a digital interface to plan autonomous scan paths and review real time data. The TUAV navigates via SLAM and receives continuous power from a coordinated, mobile Ground Control Station (GCS) that prevents tether entanglement.

SENTINEL is designed to seamlessly integrate into current scheduled maintenance checks, by functioning as a tool that increases the efficiency of certified inspectors rather than replacing them. Leveraging established commercial components accelerates the development toward a 2031 mass deployment; however, the system must navigate complex technical and regulatory hurdles. SENTINEL tackles mobile base stability and tether entanglement through dynamic feedback control and coordinated path planning. The primary barrier for SENTINEL regulatorily is bureaucratic, where we need to ensure that the NDI data that is acquired by the TUAV complies with the rigorous NAS 410 certification standards. After overcoming these barriers, SENTINEL presents a great window of opportunity, by directly addressing the future labor bottleneck caused by an aging NDT workforce. The platform provides a high return on investment and enables the continued safety, efficiency, and economic competitiveness of aircraft maintenance.

1 Introduction

Aerospace is a vast industry, and the glamour of exciting new technologies such as hypersonic flight, commercial supersonic travel, and automated flight often overshadow the need for innovation in fundamental fields such as aircraft maintenance. A significant part of aircraft maintenance is routine inspection and checks. These inspections include visual and non-destructive inspection (NDI) methods, and are critical in assessing the state of the aircraft throughout its lifetime.

1.1 Assessment of current methods

Current methods of NDI are largely manual and are performed by a certified inspector. Most commonly, inspections for detecting sub-surface damage use eddy current or ultrasonic sensors. In the context of routine inspection and checks, Eddy Current Testing (ECT) is widely used due to its speed, quality, and ability to operate without a couplant. Using EDT, inspectors cover specific areas of the aircraft with small probes. Inspection times vary depending on several factors such as aircraft type, inspection area, and access complexity.

1.2 Industry demand and workforce outlook

With the transition into Industry 4.0 and the expected growth in the aerospace industry [1], there is an increasing need for growth in the maintenance, repair, and overhaul (MRO) of aircraft [2]. Specifically, the increase of data and the integration of cyber physical systems into routine inspection and checks is a critical goal [3-4]. As such, there exist future demands for increased efficiency of aircraft maintenance, which would have an economic impact on U.S. aerospace competitiveness.

1.3 Limitations of current automated NDI solutions

Robotic automation has been at the forefront of this evolution by dramatically increasing the leverage of skilled workers by allowing them to operate at a greater scale and consistency. Drones in particular have attracted the most attention due to their high mobility. Current state of the art (SOTA) solutions include visual inspection drones equipped with cameras used by Airlines such as Delta and Korea Air [5-6].

However, there is a continuing challenge with autonomous NDI platforms of balancing speed with stability and flexibility [7]. The main challenge of NDI in comparison to visual inspections is the need to be in contact or close proximity to the surface, which requires a highly stable sensor platform. In addition, the challenge of navigating the unique curvature of the aircraft increases the difficulty of finding the balance between speed, freedom of movement around the aircraft, and stability. Robotic crawlers [8] are an example of an automated platform that crawls along the surface of the aircraft carrying a NDI sensor. While highly stable, robotic crawlers generally have low speed and struggle to navigate complex geometries, for instance the wing roots, which are a regularly tested area. Other implementations such as the Boeing Giraffe [9] are arguably more flexible, but still rely on a limited range of motion provided by the robotic arm design, and are therefore only made for scanning the fuselage.

To increase speed and flexibility of the NDI platform, multiple solutions rely on the use of drones. In comparison to visual inspections, NDI requires stability of the sensor platform to achieve accurate readings. Unlike robotic crawlers and other ground based NDI platforms, drones face the challenge of maintaining precise positioning and contact force. Nonetheless, multiple solutions such as [10] and [11] implement the use of drones in NDI. These implementations were designed to fulfill the demand of a swift and stable NDI platform. However, all NDI drone platforms are mainly designed for industrial inspection uses, and additional changes to the system are needed to be considered for aircraft inspection.

While the discussed NDI platforms do offer some automation, it is clear that there are continuing areas of improvement in the area of automated NDI inspections for aircraft. Specifically, there is continuing and unfulfilled demand for increasing the speed and efficiency of automated NDI inspections.

2 Project Description

To overcome the current limitations of automated NDE platforms in aircraft routine inspection and checks, we propose updating NDE drone platform applications to satisfy the needs of aircraft maintenance. As opposed to existing NDE drone platforms [10–12], we focus our solution on ensuring the platform is able to scan the unique and varying surfaces of aircraft, maintain power throughout the inspection, and easily integratable into existing practices. By pairing NDI with a flexible drone platform, the "Surface Evaluation Network for Tethered Inspection and Nondestructive Evaluation" (SENTINEL) has the potential to vastly reduce inspection time for aircraft. In the event of an inspection, SENTINEL is autonomously deployed to the point of inspection outlined by certified inspectors. From there, the drone can latch on to the aircraft allowing for stable inspection and de-latch to maneuver around the aircraft. While in the air, SENTINEL utilizes an array of sensors including eddy current, LiDAR, and camera imaging. When the mission is complete, SENTINEL will autonomously land on the ground vehicle using precision landing.

2.1 Introducing the Solution

The integration of NDI systems into SOTA drones has proven beneficial in detecting structural defects and monitoring damage throughout varying structures, providing critical information to inspectors. Eddy Current sensors allow for structural readings of affected regions and assessment of damage and progression of damage. The ability of UAVs to fly around the aircraft and provide high-quality data has made them a beneficial tool in aircraft inspection. However, current SOTA drones still face limitations due the lack of an onboard NDI sensor capable of subsurface detection, which decreases inspection capabilities. To overcome this limitation, this proposal introduces the solution of incorporating an eddy current sensor for subsurface damage detection. To achieve safe, stable, and sustained inspection of the aircraft, the solution incorporates the use of a suction perching mechanism, sustained power through a tether, and a mobile ground control station for maneuverability. This outperforms current SOTA autonomous NDI platforms and provides improved maneuvering, significantly enhancing inspection capabilities.

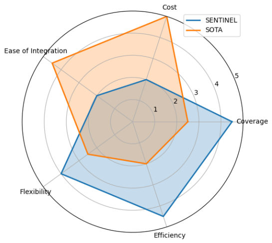


Figure 1: SENTINEL compared to SOTA solutions

2.2 Sensor Platform

However, one must note that the major challenge with the technical implementation of aerial nondestructive testing systems is providing the stability and required contact force for eddy current testing (ECT). The demand for precision and stability is much higher in ECT than, say, visual inspection; standoff tolerance in visual inspection is measured in centimeters, while ECT requires a lift-off distance of approximately 0.5 to 2 mm between the test instrument and the surface –

deviation from this threshold results in excessive signal drift. Commercially available drones are inherently incapable of meeting this criterion, as even the best commercially available unmanned aerial vehicles exhibit significant hover drift on the order of ±10 to ±50 mm even indoors. The SENTINEL system solves this problem through a novel perching mechanism that transforms the free flying drone into a temporary surface-attaching NDI platform, thus detaching the demand for stability from the flight control system.

2.3 Perching Mechanism Design

In order to obtain the necessary holding forces to achieve perching, the SENTINEL UAV makes use of a set of docking arms which will move to position the suction cup interface to provide a firm seal against the surface of the aircraft skin. In the process of perching, the UAV will fly over the selected inspection site and examine the surface using LiDAR sensors; then the docking arms will deploy the suction cups so as to achieve vacuum sealing, whereby all the mass of the UAV will be transferred to the suction cups and the propulsion forces will cease to provide any translation motion or vibration in order to achieve stable positioning on a stationary substrate.

The principle of vacuum cup-based perching used in SENTINEL is directly confirmed by experiment from the field of aerial robotics. According to the research carried out by Wopereis et al., a reliable reversible perching was demonstrated for a 1.8 kg quadrotor, where passive vacuum cups were successfully used to allow perching with 1.5 m/s and performing multiple perch-and-fly operations within a single flight [13]. Specifically, their experimental surface material used was aluminum and paint-treated, similar to aircraft skin material, while they observed a static friction coefficient between the rubber and aluminum of at least $\mu \geq 0.5$.

The assessment of sufficient holding forces can be made through the usual pneumatic calculation according to the model proposed in [13]. As stated there, the maximum normal load a passive vacuum cup can support is defined as follows: $F_{n,\max} = S \cdot A_v \cdot P_0$, where A_v is the cup area, P_0 is the atmospheric differential pressure, and S is the safety factor due to imperfection of vacuum or cup deformation. With two commercial suction cups having vacuum of 0.08 MPa and cup area of 0.5 cm^2 each, we obtain an estimated force of 80 N per cup, which is in total 160 N. Compared to drone mass in 5–8 kg (49–78 N), such a configuration will provide a safety margin of over 2 times. The shear capacity will be $F_v = \mu F_n$; using $\mu \geq 0.5$ for rubber-to-aluminum case, hence two cups provide at least 80 N of shear resistance, well over ECT requirements.

2.4 Lift-Off Distance Control

With proper positioning achieved, the drone then activates its linear actuator to deploy the eddy current probe towards the inspection plane. In this configuration, the lift-off height of the probe is determined by the mechanical stiffness of the extended actuator, and not by feedback-based force control, thus simplifying the system architecture and avoiding potential stability issues posed by the latter type of control. The main design question is whether the bending due to the gravity-induced load on the probe will keep within the range of 0.5–2 mm lift-off. For a probe with mass of 50–100 g and actuator extension length of 100–150 mm, standard beam deflection calculations for steel or aluminum shaft show deflections measured in micrometers, below allowable error of 1.5 mmh.

2.5 Validation by Analogous Systems

The robustness of the SENTINEL perching platform is supported by converging experimental evidence provided by independent research teams. Wopereis et al. showed the repeatability of vacuum-cup based perching on flat substrates at higher-than-design impact speeds, enabling a 1.8

kg drone to perched and lift off repeatedly [13]. Following this precedent, further studies have added to the empirical evidence in support of vacuum-cups perching systems: the feasibility of such systems to achieve sufficient single-cup gripping force of up to 69.8 N at typical vacuum pressures when attaching drones to vertical aluminum surfaces has been proven experimentally [14], in agreement with the force margins found in the preceding analysis. Furthermore, autonomous vacuum-cup perching was experimentally verified to be correctly simulated in a Gazebo environment, demonstrating that the design approach adopted for SENTINEL is well-established as an efficient means of reducing risks in perching platform design prior to physical realization [15]. Overall, the above corpus of research shows that vacuum cup attachment can be achieved on smooth aluminum and painted substrates, passive vacuum technology can cope with drone class loads with ample safety margins, and perching is possible to perform autonomously. Compared to previous free-flying contact methods, the SENTINEL design approach is safer, since the perching maneuver entails full surface attachment and eliminates the need for force modulation during scanning, which is the most challenging part in previous NDT applications involving UAVs [26].

2.6 Power and Endurance

The first main advantage of the tethered-UAV system is its ability to provide non-stop power to the drone during the whole inspection mission period. As was mentioned above, using tethered power for UAV platforms allows operating a UAV indefinitely and avoiding limitations on flight endurance imposed by the onboard battery systems. In the context of the SENTINEL drone, it means that tethered power supply is especially important, since in addition to the drone's flight system, its onboard computer and eddy current probe would demand additional power for the whole duration of the inspection mission, which could last from one hour to 10 hours based on the complexity of the inspection check [16]. The use of battery replacement or additional battery charges would not solve the problem because it would be impossible to provide non-stop drone operation due to the necessity to stop and replace the battery or recharge the drone, which would significantly affect the performance gain provided by the new solution.

2.7 Regulatory Compliance

However, even beyond practical concerns like non-stop power delivery, another important advantage of the tethered system lies in the more relaxed regulatory requirements for such UAS compared to free-flying UAVs. Free-flying drones' operations at commercial aviation facilities are highly regulated by the FAA, and obtaining approval to conduct such inspections is a significant adoption challenge. However, due to different legal status of tethered drones, obtaining required approvals might be much easier in terms of regulatory compliance. This is mainly caused by the nature of a tethered UAS itself, when the drone's range of movement is limited and does not depend on software. Unlike free-flying drones whose range of operations can accidentally exceed geofenced areas, a tethered drone always has to operate in the predefined operational area since its range from the control point is defined by the tether itself, which makes a tethered UAS safer than a free-flying drone. Considering that the drone of the proposed design would be used indoors only, where it would be confined within the boundaries of an enclosed maintenance hangar, the tether would serve as an additional physical geofence. This feature makes the process of obtaining FAA certification (NAS 410 certification and facility approval) for SENTINEL significantly simpler.

Figure 2: 6 inspection areas

2.8 Mobility and Tether Management

However, the main operational problem with the tether lies in the restriction it imposes upon the trajectory that the drone takes during flight. In an indoor environment, the entanglement with the various structures becomes highly probable due to the restricted flight path the drone must take during inspection, as outlined in [17–19]. Such entanglements pose a considerable threat of disrupting the inspection mission altogether and damaging either the drone or the inspected object, which cannot be allowed.

The reason why entanglement occurs in conventional TUAVs with tethers lies in the static nature of the end point of the tether: in order to prevent any possible wrapping of the cable around the structural elements, the drone must keep away from them when navigating near the aircraft. In this case, the SENTINEL solution provides for a mobile ground control station (GCS), making both ends of the tether variable. The GCS is a wheeled platform that moves alongside the inspected aircraft to reach specific inspection zones denoted as A, B, C, D, E, F in figure 2. At each point along the way, the GCS adjusts its position according to the geometry of the drone's current inspection zone in order to keep the tether clear of the aircraft's body. Zone A covers the nose and crown, Zone B and F cover the part of the fuselage that extends from the nose to the wing, Zone C and E extend from the wing to the tail, and Zone D covers the tail region. To make sure that the tether will remain untangled throughout the mission, the algorithm ensures that the GCS always stays on the side opposite to the current inspection zone.

The winch controlling the length of the cable and maintaining the correct level of tension is mounted onto the moving GCS. Proper cable tension is crucial to provide stable control over the drone because a lack thereof causes unpredictable dynamics once the cable becomes taught. On the other hand, overly high cable tension may hinder drone movements, thus making the process inefficient. Therefore, the winch controls the cable's length according to the drone position data gathered by the SLAM algorithm. As a result, the tether maintains stable tension in two operation modes: the first is the stationary inspection mode, during which the GCS remains motionless, and the winch only performs slight movements to allow the drone switch between perching positions in the current zone. When changing inspection zone, the GCS moves to the next zone and changes the tether length so that the drone will remain stationary during the changeover, thus preserving its inspection position.

2.9 Control and Stability

The stability of a TUAV system with a mobile ground station is non-trivial and requires advanced control. Although there is extensive research on TUAV control, as mentioned in [20–24], a mobile ground station introduces additional challenges, as it intermittently moves to different inspection waypoints (A–F, as depicted in Figure 1).

The operational concept has two phases: (1) Stationary inspection, where the GCS holds a stationary position at a waypoint while the drone conducts the inspection of the aircraft with only the cable length changing through the actuated winch, and (2) Transition, where both the GCS and drone coordinate to move to the next stationary waypoint.

Tognon et al. in their research article [25] demonstrated the exponential stability of a UAV tethered to an actuated winch mounted on a moving platform using observer-based dynamic feedback linearization. The model takes into account a platform that is meant to "translate and rotate in 3D, independently from the aerial robot" and "can represent, e.g., a ground vehicle" [25], which directly matches with our system architecture.

Importantly, their stability proof is valid for arbitrary trajectories of the platform, including the stationary case, where the velocity is zero, during our inspection phase. For our implementation, we will utilize their observer-based controller, as described by Equations 16–18 in their work [25].

2.10 Expected Impact

In summary, this solution is designed to bridge the existing gap between speed, flexibility, and stability of automated NDI platforms. Given there is an existing demand for such a platform, as demonstrated by various industry adaptations [5–12], the proposed solution can fulfill such demands. Due to the ease of integration into existing processes and improvements on SOTA solutions, adaptation of the SENTINEL platform would increase overall efficiency of aircraft inspections.

3 Concept of Operations

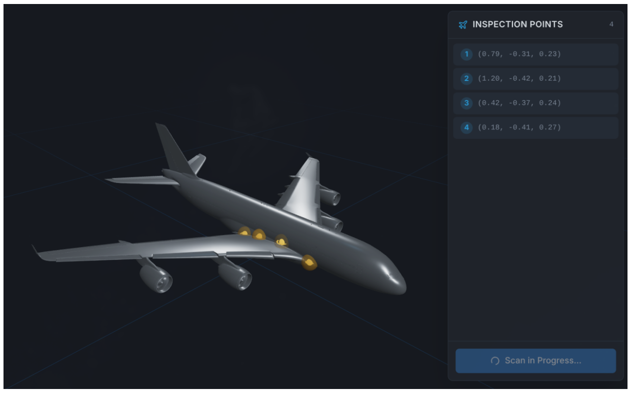
With the use of the proposed solution, a certified inspector would plan, conduct, and examine inspection through the use of an application connected to the system. The first step in the inspection process would be planning the mission by selecting inspection areas using a 3D model of the aircraft. Using the uploaded mission, the system selects the most appropriate path and determines the appropriate inspection areas to navigate. After the inspector's approval, the drone takes off and begins the inspection. Data of the Eddy Current sensor is displayed to the inspector as the inspection is taking place, and can be stored for future evaluation.

3.1 Support Systems Needs and TRL

The technologies involved in the SENTINEL platform vary in range from mature to lab tested. In this solution, we take use of mature technologies such as SLAM and eddy current NDI which have a TRL of 8 indicating validation through test and demonstration. Novel components of our system, such as autonomous mission planning, mobile GCS with tether coordination, and perching mechanism have been validated in lab environments and are considered to have a TRL of 4.

3.2 Minimal Barriers to Adoption

SENTINEL is designed as a force-multiplying tool for the already available personnel in the NDT domain and not a replacement; thus, only minor organizational changes will be required to adapt to



1	(0.79, -0.31, 0.23)
2	(1.20, -0.42, 0.21)
3	(0.42, -0.37, 0.24)
4	(0.18, -0.41, 0.27)

Figure 3: User interface for the digital twin and inspection data visualization.

this technology. SENTINEL functions under the supervision of NAS 410 certified inspectors who are currently tasked with performing eddy current tests. According to the NDT standards, NAS 410 certification allows one to perform configuration, calibration of NDT tools, and conducting the tests themselves. In addition, NAS 410 Level II certified inspector has the authority to perform the tests and interpret their results in the context of the relevant industry standard. On the other hand, level 3 certificate holder possesses additional supervisory authority over the entire process. Thus, the main thing that is changing for the current system is the means through which the scan is being performed: instead of moving a probe around, the inspection task will be delegated to an autonomous platform.

It can be argued that there will be little new training involved in this situation. As mentioned before, the inspector now needs to oversee the mission rather than execute it. Therefore, the main task will be to learn how to use SENTINEL software for the mission planning process, including learning about possible edge case scenarios and what measures should be taken, e.g., if the perching fails or there is a tether-tension warning. One can expect that this training will take no more than a few hours, which means that the skills gained by inspectors within current framework can be fully transferred to SENTINEL system.

The system would come with its own software, however we would use the available APIs in MRO softwares to integrate inspection tracking into the overall system.

Finally, with respect to platform certification, it can be noted that the FAA and relevant standards committee may require SENTINEL to be certified as the data-collecting device used in airworthiness inspections. The main question here will be the possibility of using SENTINEL data within the context of NAS 410 regulations, which currently do not consider the concept of autonomous data collection. It will be required to submit the proof of data equivalency (that is, prove that the collected data are equal or better in quality) to NASC. Such a procedure has been previously done for automated C-scan devices and phased array ultrasonics systems.

3.3 Connectivity Constraints

One major challenge for this task is the precise navigation of the drone. This application is unique because it requires the drone to fly around an airframe, inside a hangar. Consequently, improper flight planning is very likely to cause hazardous collisions.

Keeping this in mind, we have decided to use SLAM as the drone's primary navigation system for a few reasons. Since this use case requires precise navigation, trying to achieve that accuracy with GPS systems would require a RTK-GPS setup, costing thousands of dollars for highly accurate setups. Even then, GPS has much worse performance on the z-axis, which for this use case is equally important. Additionally, GPS signals are often unreliable or completely unavailable within hangar environments due to limited sky visibility and signal obstruction. Addressing this would require further infrastructure, such as GPS repeaters. In contrast, SLAM leverages onboard sensors to achieve comparable or superior accuracy across all three axes without dependence on external infrastructure. For instance, SOTA SLAM methods like LIO-SAM [29] have proven to accumulate less than 20 cm of error over routes hundreds of meters long using LIDAR and IMU data. The route around a plane would be much smaller. For reference, a 747 is approximately 70 meters from nose to tail. So we expect much less error, but an exact estimate would require experimentation.

3.4 Data Pipeline

For our data pipeline, we will be using a wireless implementation. The first step is data acquisition; for this we will have an onboard microcontroller to digitize the analog signals from the eddy current sensor. Prior to the digitization of the analog signals, they will pass through a bandpass filter to mitigate electromagnetic interference (EMI) noise. This data would be packaged with the sensor readings with timestamps to ensure synchronization with the NDE data and the position that is provided from the LIO-SAM navigation system.

To ensure data loss is prevented throughout the inspection, the drone will perpetually log all data to an onboard drive. The transmitted signals will then be captured in real time by a ROS network that is hosted by a digital twin PC inside our Ground Control Station (GCS) via a high bandwidth Wi-Fi connection. This enables our digital twin to concurrently display a high fidelity model of the aircraft, with mesh points that link to the published NDE data captured. Furthermore, the data is logged and saved to enable monitoring of changes over time.

3.5 Challenges Posed by Adverse Environmental Conditions

Operations of this system are limited to a hangar environment for safety. Due to the close proximity of the drone to the aircraft, stability of the system needs to be guaranteed. Wind and other environmental conditions can cause the system to be momentarily unstable. Thus, inspections are limited to hangar environments to ensure safety. This limitation, however, should not be seen as a substantial limitation as most eddy current inspections are performed in a closed environment.

4 Pathway to Deployment

From the ground up, this system is designed for a rapid development cycle, all the way up to deployment. Most choices have been made to ensure optimal accuracy while using generic, and thus easy to maintain, core technology. For instance, our core method of inspection, the eddy current tester, is a well-established tool. Drones have demonstrated the ability to implement precise control in many instances. As for the auxiliary technologies we propose to use in this project, such as the tethering system, SLAM navigation, and the data pipeline, they are all components that have proven capabilities in other use cases. Our project is to combine these technologies into a usable platform. Deep research takes time and involves uncertainty. Although it certainly has much to offer, since this challenge specifically demands near-guaranteed deployability, this platform is meant to be a primarily engineering challenge. However, it does leave scope for research at the frontier of NDI. By offering a platform mechanically and positionally capable of automation, ML methods for NDI analysis can be tested faster, and have massive economic leverage when deployed [30].

As for the pathway to deployment, assuming work starts by June 2026, we dedicate until the end of 2027 for the MVP. We aim to develop the prototype within the first few weeks, but the MVP would be the bare minimum usable version. Dedicating a whole 1.5 years is reasonable as we want the base product to be truly well engineered. However, it would still be usable only in a single instance. The main challenge after that is pushing it to the market. A massive hurdle for that is bureaucracy. Currently, NDI testers have to be certified according to NAS 410. Analysis of the data gathered by these systems is still done by technicians, so this system is ideally okay to use. However, we acknowledge that concerns regarding the accuracy of data produced by the drone-based scanning system may be under doubt. Since this is a niche, new, bureaucratic front, it is hard to guess the estimated time required. However, much of the work can be done in parallel with that. This would include transitioning from using consumer parts to assemble the drone to setting up a supply chain of the most cost-effective and reliable parts needed for the assembly. Of course, in addition, infrastructure would need to be set up to assemble the system and ship it out. We do not expect this to take more than 3–4 years, based on estimates in the report from IMARC Group [28]. We are confident that setting up manufacturing would not take much longer simply due to the fact that all the core, hard to manufacture components, such as the eddy current sensor, motor, PCBs, etc., will be bought through 3rd-party suppliers. Overall, given that we expect to be done with the MVP by 2027, and it would take 3–4 years for the supply chain to be set up, in parallel with bureaucratic approvals, we think the system can be ready for mass adoption by 2031. Of course, unforeseen circumstances may arise, such as bureaucratic delays or slow funding. However, it is reasonable to think the 4-year margin of error would likely accommodate this.

After the infrastructure is set up, all that is left is adoption by customers. We think that by the 2030s, the demand for these systems would be immense, and promises a high return on investment. Currently, the NDI workforce is facing a critical shortage that poses both an industry and public safety concern [27]. According to *Quality Magazine*, a 2023 report from the American Society for Nondestructive Testing (ASNT) found that nearly 30% of certified NDI personnel are over the age of 55, with retirements accelerating and fewer new professionals entering the field [27]. Given the average age of retirement is under 65 in the US, up to 30% of the workforce is going to be depleted within the next 10 years. Meanwhile, the rate of incoming professionals is lower. This clearly opens a massive window of opportunity for an automation system to provide exceptional return on investment, while not hurting the job market by “taking” jobs. The aerospace industry demands more and more NDI, the lack of an automation system like this to remedy the labor shortage would bottleneck progress, and significantly slow economic growth in this field.

4.1 Time-Motion Analysis

In order to estimate the improvement in efficiency due to the implementation of SENTINEL technology, an estimate for the time motion analysis for manually conducting eddy current testing inspection for fuselage lap joints in narrow-body aircraft belonging to the B737 class—the one most common in scheduled maintenance—was produced. This estimate has been triangulated by using published probe parameters, MRO baseline data, and FAA regulations on set-up and documentation requirements as opposed to being taken from only one source, because no published per component breakdown was available in literature.

Manual ECT Inspection Process Manual ECT inspection process includes four steps. Access and Setup—where a workstand is positioned, access to the inspection point is provided, and the equipment is calibrated using a reference standard—takes about 15-25 minutes per zone. This corresponds with FAA AC 25-29 that states the need for intensive calibration and access to reference standard in case of ECT with the material of a part, and is confirmed by CMU ANDI research proving that the time taken for access may exceed inspection time [9, 33]. Active inspection using a single-coil pencil probe at a rate of about 25–40 mm/s with a distance of about 3–5 mm will take a typical 0.5 m^2 lap-joint zone approximately 60-90 minutes, which corresponds with Olympus ECA 9 hours for 12 m^2 of A330 fuselage skin [35].

The system SENTINEL minimizes or even eliminates all three out of four elements. Autonomous navigation results in reducing overhead access time to 5-10 minutes. Scan speed is constant since it depends on physical properties of the ECT probe. Repositioning overhead is reduced to 5-8%, while documentation process is completely automated. All this leads to the conservative 31% increase in direct time spent per zone. Most importantly, autonomy allows an inspector to monitor up to 2-3 zones simultaneously and to achieve throughput improvements of 60-75%, which cannot be physically achieved manually. This statement correlates with the findings of Barbaric et al. [31] for drones used for inspections.

4.2 Key Developments Since Initial proposal

Since the initial conception of the system, the SENTINEL concept has been improved in several ways. First, there is now independent experimental evidence for the feasibility of the perching process using the vacuum-cup perching approach: the work of Wopereis et al. [13], Ang et al. [14], and Chen et al. [15] together proves that perching through vacuum cups is feasible at drone-like loadings with suitable safety margins while being able to prove it in simulation before actual physical implementation. Second, the lift-off problem has been solved: beam deflection analysis of the linear actuator due to probe loading reveals deflections in micrometer units, hence the elimination of the necessity for closed-loop control of lifting force. Third, the control approach used by SENTINEL has now been justified mathematically based on the proof of exponential stability by Tognon et al. [25], who use an observer-based dynamic feedback linearization strategy.

4.3 Conclusion

Sentinel addresses the existing and growing need for automating aircraft NDT through an integration of a suction perching mechanism, power tether, mobile GCS for tether management, and SLAM-based navigation. Each design feature was selected to resolve the limitations of current methods, namely the need for stability fulfilled by the ECT solution, power endurance provided by the tether, and avoidance of the entanglement hazard associated with free-flight. Designed on commercially available technology and supported by the validated control algorithm presented in a peer-reviewed study, Sentinel represents a deployable solution, not a concept. Its mass adoption is projected for 2031 due to the expected massive reduction in numbers of certified NDT workers. The purpose of Sentinel is not to replace but to support the certified inspector when he/she is needed most.

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