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Design and Implementation of a LiDAR Scanner for Inspecting Aircraft's Internal Structures

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Abstract: In modern aviation, effective maintenance is crucial for ensuring aircraft safety and performance. Inspecting internal components within aircraft panels poses significant challenges, often requiring specialized tools like borescopes. This project aims to develop a LiDAR-based prototype scanner to generate high-resolution 3D images of internal structures, providing engineers with a comprehensive view for maintenance inspections. The system utilizes LiDAR (Light Detection and Ranging) technology to capture depth data, which is processed to create detailed 3D models that enable the identification of issues such as misalignment's, cracks, or missing components. A micro controller, such as an Arduino Uno, interfaces with the LiDAR sensor to collect data, which is then transmitted to a laptop for visualization and analysis. This non-invasive approach offers a quick and accurate alternative to traditional inspection methods, reducing reliance on manual borescopic techniques. While the current version serves as a proof of concept, future enhancements could include industrial-grade LiDAR sensors and automated inspection systems to meet stringent aviation safety standards. Ultimately, this project seeks to demonstrate the potential of LiDAR technology to improve the efficiency and accuracy of aircraft maintenance workflows.

Key Words: LiDAR, Aircraft Inspection, 3D Imaging, Maintenance, Non-Invasive Techniques

INTRODUCTION

Ensuring the safety and operational efficiency of an aircraft hinges on the integrity of its internal structure, which is why regular inspections are vital to identify and mitigate potential issues before they impair performance. To evaluate these components without inflicting damage, a diverse array of Non-Destructive Testing and Evaluation (NDT&E) methods is utilized. Among the simplest are visual and penetrant inspections, which rely on direct observation or dye application to expose surface defects, while tap-testing, a hands-on technique, detects subsurface irregularities by analyzing the sound from tapping the structure. Eddy current inspections harness electromagnetic induction to spot surface and near-surface flaws in conductive materials, and shearography and thermography reveal deeper defects through surface deformation and thermal patterns, respectively. Acoustic emission testing tracks energy releases from stressed materials to pinpoint active flaws, whereas radiographic and tomographic inspections use X-rays or gamma rays to visualize internal inconsistencies. Ultrasonic inspections, employing high-frequency sound waves, assess internal defects, thickness, and material properties.[1] Traditional non-destructive testing (NDT) methods, such as ultrasonic testing, X-ray inspection, and visual inspection, have been crucial in assessing the structural integrity of aircraft components. However, each technique has its limitations. Ultrasonic testing, which uses high-frequency sound waves to detect internal flaws, requires clean and smooth surfaces, can be challenging for complex geometries, and is heavily dependent on the technician's expertise.[2] X-ray inspection, which visualizes internal structures using X-rays or gamma rays, is restricted to smaller components that fit within the tomograph chamber and can be complicated by artifacts. Visual inspection, the simplest form of NDT, is subjective, limited to surface defects, and can be challenging for hard-to-reach areas. These limitations highlight the need for complementary NDT methods to ensure comprehensive assessment of aircraft components.[3] LiDAR (Light Detection and Ranging) is a remote sensing technology that uses laser light to measure distances to objects, enabling the creation of precise 3D representations of environments. By emitting laser pulses and analyzing the time it takes for reflections to return, LiDAR systems accurately determine distances to various surfaces, facilitating detailed mapping and object detection. The technology operates on three main sensing schemes: Pulsed Time-of-Flight (ToF), which measures the time interval between emission and reception of laser pulses; Amplitude-Modulated Continuous Wave (AMCW), which uses continuous laser beams with varying amplitudes to determine distance based on phase shifts; and Frequency-Modulated Continuous Wave (FMCW), which employs continuous laser beams with frequency modulation to measure distance and velocity simultaneously.[4] LiDAR (Light Detection and Ranging) technology offers significant advantages over traditional inspection techniques in aviation, enhancing safety, efficiency, and data accuracy.[5] LiDAR provides high-resolution, three-dimensional data for precise mapping and detection of structural anomalies, surpassing traditional methods. It enables rapid scanning of large areas, reducing inspection times and aircraft downtime. LiDAR also improves safety by allowing remote inspections, minimizing exposure to hazardous areas. Additionally, it facilitates comprehensive structural health monitoring by detecting surface abnormalities, mapping corrosion areas, and providing detailed point clouds. Furthermore, LiDAR can be integrated with Remotely Piloted Aircraft Systems (RPAS) to enhance inspection efficiency, accuracy, and safety.[6] LiDAR (Light Detection and Ranging) technology offers several advantages for aircraft internal inspections, making it a promising solution. LiDAR systems generate high-resolution 3D maps of aircraft interiors, enabling precise identification of structural anomalies, deformations, or foreign objects that may be difficult to detect using traditional methods. Additionally, LiDAR scanning allows for rapid data acquisition,

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significantly reducing aircraft downtime during inspections. Furthermore, LiDAR facilitates remote inspections, enhancing safety by minimizing the need for personnel to access confined or hazardous spaces, and reducing the risk of human error.[6]

FUNDAMENTALS OF LiDAR TECHNOLOGY FOR STRUCTURAL INSPECTION

LiDAR (Light Detection and Ranging) is a remote sensing technology that measures distances by illuminating a target with laser light and analyzing the reflected signals to create precise, three-dimensional information about the target's shape and surface characteristics. The fundamental operating principle of LiDAR involves emitting laser pulses toward a target and recording the time it takes for each pulse to return after striking the target. By knowing the speed of light, the system calculates the distance to the target based on the time delay. This process allows LiDAR to generate accurate, high-resolution 3D representations of the scanned environment.[7] A lidar system transmits a light signal that interacts with targets in the air, then the back-scattered amount is received by the lidar receiver. The returned amount is corrected for attenuation/scattering conditions. Although they have some similarities with radars, their wavelength lies in the optical range from 0.350 to 10 micro m.[8] The power returned to a lidar is related to the particle surface area (D2) rather than the power of D6 for radar technology.The choice of the emission wavelength (k) depends on the application, being related to the atmospheric quantity to be measured, the availability of reliable and cost-effective laser sources, the optical atmospheric transmission, as well as eye safety issues. In lidar technology, a laser source emits pulses of light at pulse frequency of XL. Moving particles in the targeted volume back-scatter the light, which is assumed to follow Mie scattering theory. The frequency of the back-scattered light is shifted by the Doppler effect (fd = 2Vrk) of the moving particles in the volume. The Doppler shift (fd) is proportional to the radial speed of the particles (Vr), which is the projection of the wind vector along the line of sight of the laser. The back-scattered signal is then mixed with a reference beam light in an interferometer, providing heterodyne beat signal at the Doppler frequency fd from which the radial wind speed can be accurately derived.[8] LiDAR systems can be broadly categorized based on their sensing mechanisms. Three commonly used schemes are pulsed time of flight (TOF), amplitude-modulated continuous wave (AMCW) TOF, and frequency-modulated continuous wave (FMCW). Pulsed TOF measures the time interval between the emission of a laser pulse and the reception of its reflection, providing distance information. AMCW TOF involves modulating the amplitude of the continuous laser wave and analyzing the phase shift between the emitted and received signals to determine distance. FMCW LiDAR emits a frequency-modulated continuous wave and measures the frequency shift of the returned signal to calculate distance, offering advantages in velocity measurement and range resolution.The choice of LiDAR system—whether pulsed, AMCW, or FMCW—depends on factors such as the required range, resolution, and specific application needs. Each system has its advantages and limitations, making them suitable for different operational contexts. Advancements in LiDAR technology continue to enhance its capabilities, leading to more compact, efficient, and cost-effective solutions for various applications, including autonomous driving, environmental monitoring, and topographic mapping.[4] LiDAR systems can be categorized based on their platform: airborne, terrestrial, and mobile. Airborne LiDAR is typically mounted on aircraft and is used for large-scale topographic surveys, providing rapid data collection over extensive areas. Terrestrial LiDAR, on the other hand, is ground-based and is ideal for detailed inspections of smaller, specific areas, offering high-resolution data suitable for structural analysis. Mobile LiDAR systems are mounted on moving vehicles, facilitating efficient data collection along transportation corridors or other linear features.[7]

LiDAR TYPE	Method	Pros	Cons	Applications
ToF	Measures pulse return time	Simple, fast	Limited accuracy, light-sensitive	Robotics, self-driving, 3D mapping
AMCW	Measures phase shift of modulated light	Precise (short-range), less light-sensitive	Complex, limited range	Automation, gesture recognition, security
FMCW	Measures frequency shift	High accuracy, detects velocity	Expensive, complex	ADAS, environmental monitoring, industrial sensing

Table -1: A comparison of various LiDAR equipment based on their working principle.

A Lidar system consists of several key components. The laser source emits pulses, typically in the infrared spectrum (e.g., 905 nm or 1550 nm), with characteristics like pulse energy, repetition rate, and beam quality crucial for achieving accurate distance measurements. Optics and beam steering devices, such as collimating optics, beam expanders, and scanning mechanisms, help focus and direct the laser beam over the

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target area for 3D data acquisition. Detectors, like avalanche photo-diodes (APDs), capture the reflected light, converting it into electrical signals, which are amplified and filtered. Finally, data processing involves time-of-flight calculations, point cloud generation, and data filtering to extract meaningful insights, often using advanced algorithms and machine learning techniques for applications like object recognition or terrain mapping.[7] The data acquisition process involves emitting laser pulses towards a target and measuring the time it takes for the reflected signals to return. This method enables precise distance measurements, resulting in accurate 3D point clouds that represent the scanned environment. The processing of LiDAR data encompasses several critical steps to transform raw point clouds into usable information. Initially, data classification and noise cleaning are performed to differentiate between ground and non-ground points, removing any anomalies or irrelevant data. This step is vital for accurate terrain modeling and feature extraction. Following classification, ground filtering techniques are applied to extract the bare-earth surface by eliminating vegetation and other non-ground elements. This process is essential for applications requiring precise elevation models. Subsequently, surface generation involves interpolating the filtered point clouds to create digital terrain models (DTMs) or digital surface models (DSMs), which are foundational for various analyses, including geological assessments and infrastructure planning. Advanced processing may also include feature extraction, where specific elements such as buildings, vegetation, or other structures are identified and delineated from the point cloud data. This step supports applications in urban planning, forestry, and environmental monitoring. Furthermore, integrating LiDAR data with other sensor inputs, such as imagery from cameras, can enhance the richness of the dateset, providing both spatial and visual information for comprehensive analysis.[9]

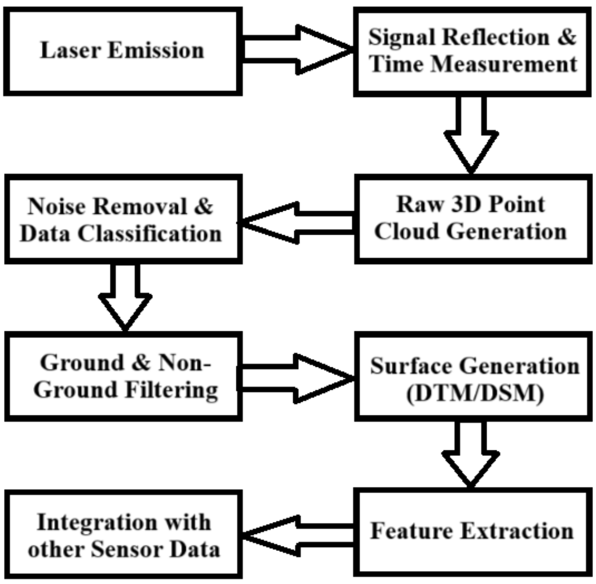

Fig -1: Block Diagram of LiDAR Data Processing Pipeline

LiDAR (Light Detection and Ranging) technology has become essential for collecting precise and dense topographic data across various applications. Processing LiDAR data effectively involves several critical steps, including data classification, ground filtering, surface modeling, and feature extraction. Data Classification and Ground Filtering: Raw LiDAR point clouds consist of numerous data points representing various surface features. Classifying these points into categories such as ground, vegetation, and structures is vital for accurate modeling. Ground filtering algorithms play a significant role in distinguishing ground points from non-ground points by analyzing the elevation differences and spatial distribution of the points. This step is crucial for generating accurate digital terrain models (DTMs). For instance, algorithms that identify predominant landform features can effectively classify ground and non-ground surfaces, facilitating the creation of precise surface models. Surface Modeling: Once the data is classified, creating a digital terrain model involves interpolating the ground points to form a continuous surface. This process transforms discrete LiDAR points into a 3D surface representation, which is essential for analyzing terrain features and conducting further spatial analyses. Various mathematical functions, such as point-based, triangular-based, and grid-based methods, are employed to construct these models, each offering unique advantages depending on the terrain's complexity and the desired resolution. Feature Extraction and Analysis: After constructing the surface model, extracting meaningful features like vegetation density, building structures, and other topographic elements is the next step. Advanced processing techniques, including the use of convolutional neural networks (CNNs) and visual analytics, have been integrated into LiDAR data processing to enhance feature extraction accuracy. These methods enable the identification and classification of various surface features with high precision, supporting applications ranging from urban planning to environmental monitoring.[10]

Types of LiDAR technologies relevant to inspection:

1. *Flash-Based LiDAR:*

Flash-based LiDAR systems operate by emitting a broad laser beam that illuminates the entire field of view in a single pulse. This approach allows for rapid capture of dynamic scenes, making it particularly suitable for applications requiring quick and comprehensive 3D imaging, such as autonomous vehicles, robotics, and augmented reality. The simultaneous illumination of the entire scene ensures that moving objects can be detected and mapped effectively, reducing the potential for motion-induced artifacts.[4]

2. *MEMS-Based LiDAR:*

Microelectromechanical Systems (MEMS)-based LiDAR utilize tiny mirrors that rapidly tilt to scan the environment. This scanning mechanism enables the system to capture

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detailed 3D information over a wide field of view. MEMS-based LiDAR systems are valued for their compact size, lightweight design, and ability to provide high-resolution imaging. They are particularly suitable for applications in autonomous driving, where real-time, detailed environmental mapping is crucial. However, it's important to note that MEMS mirrors are typically designed to operate in a single plane, and achieving two-dimensional scanning may require additional mechanisms, such as using two mirrors or employing multiple lasers.[4]

3. *OPA-Based LiDAR:*

Optical Phased Array (OPA)-based LiDAR systems leverage integrated photonics technology to electronically steer laser beams without moving parts. By adjusting the phase difference across an array of emitters, OPA allows for precise beam direction control. This electronic beam steering contributes to the durability and reliability of OPA-based LiDAR systems, as the absence of mechanical components reduces wear and potential points of failure. Additionally, OPA-based systems can achieve fast scanning speeds, compact form factors, and cost-effective manufacturing, especially when fabricated using complementary metal–oxide–semiconductor (CMOS) processes.[4]

Time of Flight Lidar Employing Dual-Modulation Frequencies Switching for Optimizing Unambiguous Range Extension and High Resolution. Time-of-Flight (ToF) LiDAR systems are widely utilized for precise distance measurements by calculating the time light takes to travel to a target and back. The fundamental principle involves emitting a light pulse towards a target and measuring the round-trip time; knowing the speed of light allows for accurate distance determination. However, challenges arise as increased modulation frequencies, used to enhance measurement resolution, can reduce the maximum unambiguous range. To address this issue, innovative approaches such as dual-modulation frequency switching have been developed, alternating between frequencies like 2 MHz and 10 MHz to extend range without compromising resolution. This method involves modulating the laser diode's intensity at these frequencies and using an avalanche photo detector to capture the reflected light, effectively balancing range extension with high-resolution measurements.[11]

FMCW LiDAR works by emitting a frequency-modulated optical signal and analyzing the reflected signal to obtain both distance and velocity information of a moving object. This is done through the beat signal between the original and reflected signals. Important parameters include the modulation period (T), chirp bandwidth (B), and the speed of light (c). The beat frequencies for upward and downward laser scans (fu and fd) include the Doppler frequency shift, and the starting frequency (fc) is the optical carrier frequency. The calculations assume a zero angle between the target's velocity vector and the LiDAR's line of sight, but if an angle θ is present, the equation needs to account for it by multiplying the denominator by cos(θ).Compared to the Time-of-Flight (TOF) method, FMCW has several advantages. Due to its coherent detection, it is less prone to interference from nearby LiDAR systems. In addition to distance, it can also measure velocity using the Doppler effect. FMCW provides higher depth accuracy and requires less optical peak power than the pulsed TOF method, which relies on strong optical pulses.[4]

EXPERIMENTAL OBSERVATIONS

We present experimental 3D LiDAR scans taken from an actual 3D LiDAR scanner. These scans provide a detailed visualization of the internal structure of the aft inspection panel of a Learjet 24D aircraft.

The LiDAR system integrated into recent iPhone models, beginning with the iPhone 13 Pro series, employs a direct Time-of-Flight (dToF) sensor based on vertical-cavity surface-emitting laser (VCSEL) technology. This compact solid-state LiDAR module emits near-infrared light (approximately 940 nm wavelength) and measures the time delay of the reflected signals to construct depth maps with high precision. Unlike traditional spinning or mechanical LiDAR systems, the iPhone's LiDAR uses a flash-based mechanism, illuminating an entire scene simultaneously, which enables rapid data acquisition suitable for handheld devices. The system offers depth sensing up to approximately 5 meters with minimal latency, optimized for augmented reality (AR) applications, 3D object scanning, and enhanced photography. Specially tuned for indoor and close-range performance, it balances low power consumption with spatial resolution appropriate for consumer-level 3D imaging. Its integration into a mobile device represents a significant engineering achievement, miniaturizing complex optical and computational processes into a thin handset form factor.[21]

The images below illustrate the results of the LiDAR scan, showcasing the detailed geometry and depth information of the inspection panel. Such scans are valuable in aviation maintenance and structural analysis, offering a non-invasive method to capture precise spatial data for inspection and documentation purposes.

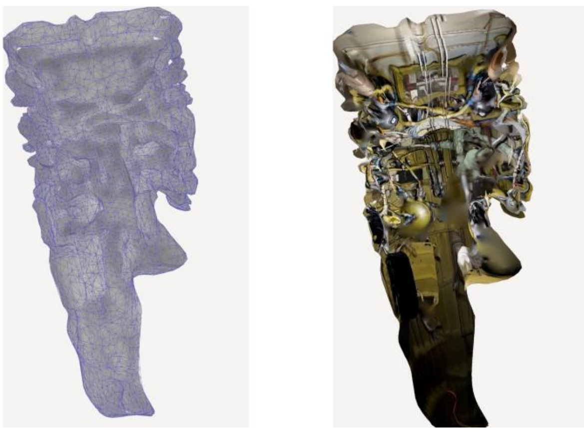

Fig -2: 3D LiDAR scan of the aft inspection panel of a Learjet 24D aircraft.

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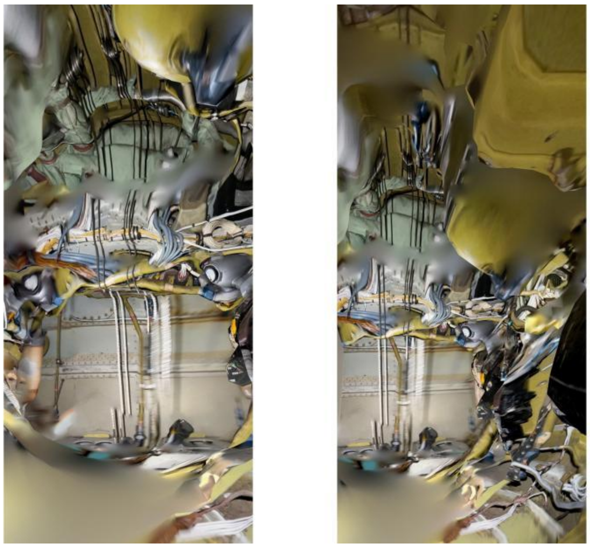

Fig -3: A 3D LiDAR scan of the aft inspection panel of a Learjet 24D aircraft from another angle.

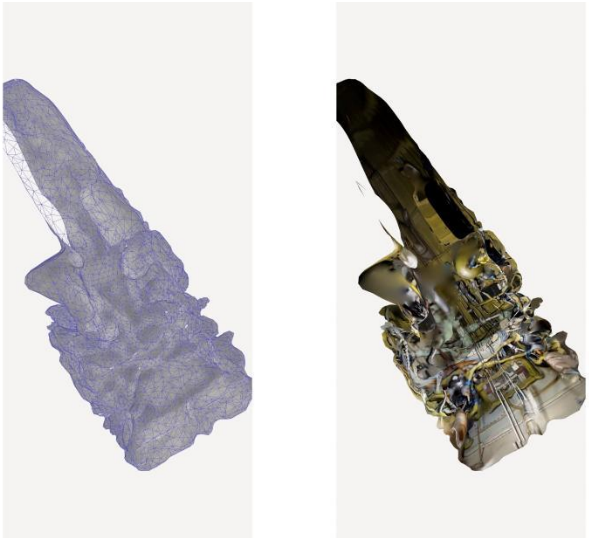

Fig -4: A 3D LiDAR scan of the aft inspection panel of a Learjet 24D aircraft from another angle.

DESIGN AND IMPLEMENTATION OF A LOW-COST LIDAR SCANNER

Design of the LiDAR Scanner:

The architecture of the proposed LiDAR scanner is the result of a meticulous examination of existing low-cost rotational LiDAR modules, particularly those used in short-range 2D mapping applications. The system has been modularly divided into three physical and functional units: the Power Distribution Board, the Lower PCB, and the Upper Rotating PCB assembly. Each of these was designed with a distinct role, facilitating ease of maintenance, development scalability, and hardware isolation to reduce electromagnetic interference.

The Power Distribution Board is equipped with a CP2102 USB-to-UART bridge interface, chosen for its wide software support and reliable data transmission. This board is tasked with relaying both power and data via a USB Type-C interface. The use of USB Type-C was deliberate, considering its higher current handling capability and reversible connector design. The DP and DM lines from the USB port are directed to the CP2102, which handles serial communication with the host PC. The 5V supply line is branched out to feed the downstream circuitry on the Lower PCB.

The Lower PCB is designed to manage signal acquisition and wireless power transfer. It channels the 5V input into three major sub-circuits. The first is a low-dropout regulator (RT2515H), selected for its low quiescent current and excellent transient response, which powers an analog signal processing unit comprising an operational amplifier. This amplifier conditions the weak signals received from a photo-diode that detects modulated infrared pulses emitted from an LED on the upper rotating assembly. The signal conditioning chain includes amplification, offset adjustment, and noise filtering stages to improve signal integrity before passing it on to the distribution board.

The second path from the 5V input powers a wireless charging transmitter circuit that includes an XKT-412 controller IC. The controller drives a primary induction coil via an NCE3108A5 N-channel MOSFET, which acts as a switch to control current through the coil. The wireless power transmission is designed to be compact and to function reliably at short distances under a rotational context. The third 5V pathway energizes a discrete motor driver based on an NPN transistor configuration. This motor driver is used to rotate the Upper PCB assembly at a precise angular velocity.

The Upper PCB is wirelessly powered through a secondary coil aligned with the lower coil. The received voltage is passed through a rectifier circuit and subsequently regulated by an XL1583 buck converter. The buck converter reduces the voltage and improves efficiency, and its output is stabilized with an LC filter that includes a high-current inductor and a fast-switching diode. The 3.3V output from the buck converter powers the VDD_MCU rail, which in turn feeds the STM32 microcontroller and a TCST1103 optical interrupter. This optical sensor monitors the rotational position of the board and provides real-time angular feedback to the MCU.

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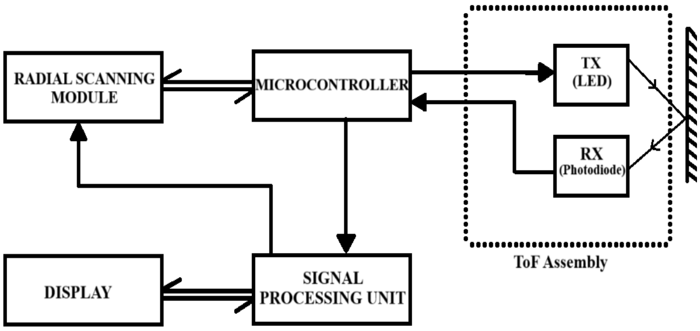

Fig -5: Block Diagram of LiDAR Data Processing Pipeline

Implementation Details:

The implementation phase involved iterative prototyping and testing of each subsystem. The CP2102 USB bridge was programmed to initiate serial communication with a host laptop using standard UART protocols. Concurrently, the board was configured to deliver a consistent 5V DC output to the Lower PCB, ensuring stable power delivery. The LDO regulator RT2515H was mounted with a decoupling capacitor network to reduce power supply ripple and electromagnetic noise.

The analog signal conditioning unit was designed with a dual-stage op-amp configuration to first amplify and then filter the signal received from the photo-diode. The signal was tested with various modulation frequencies to ensure robust decoding from the LED on the rotating assembly. Data was transmitted optically using UART modulation of the IR LED, and the resulting pulses were captured and demodulated on the Lower PCB.

To enable wireless power transfer, the XKT-412 and MOSFET circuit was tuned to resonate at the operating frequency of the secondary coil. This ensured maximum energy transfer efficiency. Heat dissipation in the MOSFET was managed by adding a heat sink, and waveform stability was monitored using an oscilloscope during testing. The rotating assembly's motor driver was fine-tuned to provide smooth, jitter-free rotation, essential for accurate spatial mapping.

On the Upper PCB, the secondary coil’s output was rectified and routed through a one-directional path to the XL1583 buck converter. This converter was programmed to output a regulated 3.3V suitable for powering the STM32 microcontroller and associated sensors. The LC filter design was calculated to attenuate high-frequency noise, with the inductor value chosen based on expected current draw and ripple specifications.

The STM32 microcontroller was clocked using an external 8 MHz crystal oscillator for time-sensitive operations. It handled ToF sensor data acquisition, optical communication to the lower board, and interpretation of the TCST1103’s output to determine angular position. All collected data was timestamped and packetized for transmission. Each subsystem was tested independently for performance benchmarks before being integrated into the final prototype.

ADVANTAGES & CHALLENGES OF LiDAR FOR AIRCRAFT INTERNAL INSPECTION

1.Benefits of LiDAR-Based Inspection

LiDAR devices offer a significant advantage over traditional non-contact sensors in that they do not require physical installation on or direct access to the structures being assessed. This results in considerable time and labor savings, while also enhancing workplace safety. Additionally, LiDAR technology operates independently of natural light, making it an ideal tool for field measurements in various lighting conditions. Laser-based scanning of concrete structures provides engineers with detailed insights into the extent of any damage. The 3D point clouds generated by these scans deliver precise, quantifiable data on the severity of cracks and surface deterioration, a level of detail that is more difficult to obtain using conventional optical devices like cameras or traditional surveying methods. [6]

LiDAR (Light Detection and Ranging) differs from traditional systems like cameras or radar because it provides precise distance measurements and creates high-resolution 3D representations of objects. This ability allows LiDAR to accurately detect and distinguish small, fast-moving objects, such as drones, by analyzing both their size and movement patterns. LiDAR has proven to be highly effective in detecting, localizing, and tracking objects within close and mid-range distances, even in challenging environmental conditions. Its strength lies in its capacity to generate detailed 3D spatial data with high accuracy, making it particularly valuable in applications that demand precision and reliability. Due to its durability, accuracy, and ability to capture fine details. LiDAR has become the preferred sensor technology in fields like airspace security, surveillance, and autonomous navigation. As UAV (Unmanned Aerial Vehicle) technology continues to evolve, LiDAR's performance advantages keep it at the forefront of UAV detection and tracking systems. [12]

2. Higher accuracy and resolution than traditional methods.

Traditionally, visual inspection has been the most common method for identifying issues like tears, distortion, deterioration, dents, corrosion, and other surface defects. In this process, qualified personnel manually inspect the surfaces. However, the challenge lies in the lack of contrast and reflectivity in many surfaces, which makes it hard to spot these defects. To aid in detection, inspectors often need special equipment such as flashlights and mirrors. Additionally, the effectiveness of visual inspections relies heavily on the inspector’s eyesight, with visual acuity being a critical factor. Maintenance personnel must pass visual acuity tests, and age can significantly affect an inspector’s ability to detect defects, as the capacity to spot issues tends to decrease with age.With advancements in technology, LiDAR sensors and photogrammetry cameras have become increasingly popular for aerial 3D mapping. These tools are relatively affordable, lightweight, and capable of providing high-resolution 3D reconstructions. This article will explore the possibility of applying these technologies to aerospace maintenance using low-cost devices, such as the Sony Alpha 6000 mirrorless camera combined with photogrammetry software, the ZED stereoscopic camera, and the Microsoft Kinect One LiDAR sensor. [13]

3.AI-driven real-time defect detection.

Combining Artificial Intelligence (AI) with LiDAR helps analyze data in real time, making it possible to quickly find and classify defects. This fast detection speeds up decisions for maintenance and repairs, improving the overall efficiency of the process. One study used a deep learning method with convolutional neural networks (CNNs) to detect defects in aircraft manufacturing, which led to a 52.88% reduction in delays and a 34.32% drop in rework costs. [14]

4.Integration with IoT and digital twin technology

In modern production environments, a digital twin serves as a vital tool for the recording, storage, and processing of data. Typically, two types of digital twins are distinguished: one that represents the entire production system and another that is specific to individual components within the system. In manufacturing contexts, data derived from measurements and the production process is primarily leveraged for quality monitoring and the identification of deviations from expected behavior. This real-time monitoring ensures that products meet the required standards and that any anomalies are promptly addressed. A comprehensive overview of the various applications of digital twins in industrial settings reveals their broad utility in process optimization and predictive maintenance. Similarly, the range of definitions and applications of the digital twin concept, particularly within the context of cyber-physical systems (CPS), which are systems that integrate physical processes with computational elements for enhanced performance and automation. In these scenarios, semantic models for data representation have proven to be particularly effective, as they allow for the efficient integration and access to diverse manufacturing datasets. These models enable a more coherent understanding of complex production processes, facilitating the extraction of actionable insights from disparate data sources.

Furthermore, the use of ontologies—structured frameworks for representing knowledge—has been shown to be a powerful tool for managing sensor data and controlling sensor networks. In specialized sectors like aircraft manufacturing, the demand for digital twins is especially pronounced, as the complexity of aircraft components and the precision required in their production necessitate sophisticated monitoring and control systems. Airbus's vision for leveraging digital twins to enhance the production process, aligning with the broader industry trend toward increasing the role of digital technologies in optimizing manufacturing workflows.

At its core, a digital twin is a uniquely identifiable, digital representation of a physical or logical object, which can be utilized for various purposes. This object may exist in the present, be planned for the future, or even no longer exist. The primary function of a digital twin is to link and integrate various forms of information, typically stored in a digital thread, to reflect the object's characteristics, state, and behavior from multiple perspectives. The digital twin is also capable of interacting with a range of application layers, allowing it to work seamlessly with models, simulations, and predictive tools, thus enabling a more accurate description and prediction of the object's behavior over time. Additionally, digital twins can be hierarchically structured, with several smaller digital twins working together to form a larger, more comprehensive system. These interconnected digital twins can reference one another, creating a network of virtual representations that dynamically mirror their physical counterparts. As long as the physical object remains in existence, the digital twin is continuously updated, ensuring it remains synchronized with the real-world object, thereby maintaining its relevance and accuracy. [15]

5.Advancements in miniaturized LiDAR sensors

A silicon-based optical phased array Lidar is a compact device that combines a laser, beam splitter, phase modulator, and other electronics onto a tiny platform just a few square millimeters in size. This makes the device much smaller. Because the photoelectric integrated circuit used in this Lidar is compatible with existing CMOS technology (a widely used process in electronics), it helps lower the cost of production.

Unlike traditional mechanical or MEMS (Micro-Electro-Mechanical Systems) Lidar, which move parts to scan, the optical phased array Lidar uses a phase modulator to control the direction of the laser beam. The phase modulator adjusts each individual laser beam, causing constructive interference (where the beams strengthen each other) in the desired direction, and destructive interference (where they cancel out) in other directions. This makes the laser beam more powerful in the chosen direction and almost nonexistent in others, effectively controlling where the laser scans. By making the array of lasers larger or optimizing the way the components are arranged on the chip, this technology can achieve longer ranges and higher resolution for measuring distances. [16]

6.LiDAR performance in high-light or reflective environments.

Each type of sensor comes with its own set of advantages and limitations, making them suitable for different applications. Ultrasonic sensors, which work by emitting sound waves, are effective at detecting objects over short distances, making them ideal for use in systems like parking assistance. Cameras, on the other hand, can capture visual information from the surrounding environment but struggle in low-light conditions, such as at night, or in poor weather conditions. Additionally, cameras cannot measure the velocity or distances of objects directly, which limits their usefulness in certain situations. Radar sensors, which use radio waves, can detect objects over long distances and perform well in challenging environmental conditions like darkness or fog, but they offer lower resolution compared to other sensor types. LiDAR systems, which rely on near-infrared light, are capable of accurately measuring distances and generating 3D point cloud maps with high speed and precision, making them excellent for applications requiring detailed environmental mapping and object detection.

A specific implementation of LiDAR involves using a single-beam LiDAR system equipped with a SPAD (Single-Photon Avalanche Diode) sensor, which is highly sensitive and can be easily integrated into CMOS (Complementary Metal-Oxide-Semiconductor) circuits. To reduce production costs, the system utilizes ADCs (Analog-to-Digital Converters) that operate at a digitizing rate of 125 million samples per second. This system has been successfully tested in both high light intensity conditions indoors and outdoors, with measurement ranges spanning from 10 meters to 90 meters. Various methods, such as Peak, CC, and CCP techniques, are applied to estimate Time of Flight (ToF) and distances, with an emphasis on minimizing the impact of background light noise. These methods help enhance the system's accuracy, precision, and the success rate of measurements.

When the LiDAR system is designed for long-distance measurements, it features a small Field of View (FOV), which effectively reduces interference from external light sources. However, when measuring at shorter ranges, particularly below 5 meters, the laser beam becomes nearly parallel to the focusing lens. This reduces the system's ability to detect the reflected signal with a narrow FOV. One potential solution to this issue is to reduce the focal length, which would increase the FOV and allow the system to detect objects at shorter distances. However, this would compromise the system's ability to measure at long distances. Another option is to use SPADs with a larger active area, which would expand the FOV, but this would increase both the cost and design complexity of the system. Ultimately, the choice of sensor depends on the specific goals of the research or application, as well as the trade-offs between performance, cost, and complexity. Moreover, using high-resolution ADCs, which can improve measurement accuracy, adds to the overall expense of the system. [17]

7..Non-Contact and Non-Destructive.

Non-contact methods offer a way to avoid the problems associated with contact-based sensors. Among these, wireless embedded sensors seem to be one of the most practical solutions. Additionally, hybrid sensing, which combines multiple sensor types, can provide more accurate damage detection. However, it comes with the drawback of higher costs and the generation of large amounts of data. Despite these challenges, there is still room for improvement in all non-contact methods.

In summary, non-contact techniques are becoming widely used to detect various types of damage—like cracks, delamination, or peeling—in materials such as metal, concrete, and composites. However, it's important to carefully choose the right technique, as detecting damage early is crucial.For example, three different non-contact sensing methods were tested to monitor the health of a cable-stayed bridge. These methods included laser scanning, a robotic total station, and digital leveling. These techniques were used to gather data on displacement at four specific points on the bridge. While the data from all three methods was consistent and useful for identifying changes in the bridge's structure, damage localization (finding exactly where the damage is) and characterization (understanding the type of damage) could only be done by taking measurements at multiple points. This multi-sensor approach confirmed that tracking the changes in displacement between undamaged and damaged states is a reliable way to detect damage, although more sensors and measurement points are needed to pinpoint the exact problem. [18]

8. 360° Coverage and Accessibility.

LiDAR sensors, with their rotating heads, can scan a full 360° around them, making them great for exploring hard-to-reach or cramped spaces, like inside aircraft. The LiDAR 360 sensors use 3D point cloud data to cover everything around them in all directions. On the other hand, the Livox Avia sensor captures more focused 3D data at specific times, often representing the position of the drone. To make sure the data from both sensors match up, their timestamps are synchronized.

A multi-sensor platform uses two 360° LiDAR scanners along with cameras that can move in different directions. These cameras capture both regular and thermal infrared images. In this system, the LiDAR first detects and tracks flying objects in 3D space. Once an object is found, both the infrared and visible cameras automatically focus on it to take 2D pictures. The combination of these sensors makes the detection more reliable. Radar is used for long-range detection, LiDAR provides detailed 3D spatial data, and cameras give both optical and infrared images. The 3D position of an object is calculated using the depth data from LiDAR and the center point of the camera image. By combining all this data, the system improves the accuracy and speed of detecting objects, while also reducing false alarms. [12]

9. Challenge and limitations:

Lidar datasets often come with information about how accurate they are, usually showing the expected range of error in horizontal and vertical measurements. The vertical accuracy (height) is often stated as a root mean square error (RMSE), which typically ranges from 10 cm to 20 cm. The horizontal accuracy (location) usually ranges from 20 cm to 1 meter, at a 95% confidence level. This information tells you how accurate the lidar system is when it was calibrated, but it doesn't explain which types of terrain the accuracy applies to. Additionally, it doesn't account for errors that might happen when creating Digital Elevation Models (DEMs) or during the processing of lidar data to remove things like trees and buildings to show the bare ground, which can be a big challenge for getting precise ground elevation measurements. [19]

10. Data Processing and Challenges:

LiDAR (Light Detection and Ranging) point cloud data is used to create detailed 3D models of the environment. The process of working with LiDAR data involves several key steps. First, the data is acquired using LiDAR sensors, which scan the surroundings and collect a vast amount of 3D points that represent the surface of objects. Next, the data needs to be registered, meaning multiple LiDAR scans are aligned into a common coordinate system to create a unified model. After registration, filtering is performed to remove noise or irrelevant data points that don't contribute to the analysis. The data is then segmented, which means dividing it into smaller, meaningful parts based on specific characteristics, such as separating trees, buildings, and roads. Following segmentation, the point cloud is classified, where each point is assigned a label (for example, "ground," "vegetation," or "building"). Finally, the data might be converted into other formats, such as meshes or grids, to make it more suitable for different applications like mapping, urban planning, or forestry.

A major challenge in working with LiDAR point clouds is storing and managing the massive datasets they generate. These datasets can be extremely large, often too big to fit into a computer's main memory, which makes storage and retrieval a critical concern. One common approach to solving this problem is to organize the 3D data using spatial data structures that subdivide the space into smaller sections, making it easier to manage. The most widely used of these structures is the octree, which divides the space into eight smaller cubic sections at each level. Other alternatives include Kd-trees, R-trees, and sparse voxel grids. These structures not only help organize the data for efficient processing but also allow for faster spatial queries, which is essential for real-time applications. Additionally, subdividing the data into smaller chunks can significantly reduce the amount of data that needs to be transferred over a network, making the system more efficient.

Since LiDAR datasets are often too large to fit into a computer's primary memory, they are typically stored in secondary memory, such as hard drives or SSDs. In some cases, they are stored in distributed systems, which might involve clusters of servers or cloud storage. This ensures that the data can be accessed and processed in pieces as needed. For easier storage and transmission, the data is often compressed. LiDAR datasets are usually stored in specific file formats, such as LAS (LiDAR Data Exchange Format) and its compressed version LAZ, but other formats like PCD, SPD, and HDF5 are also used. These formats are designed to store not just the 3D point data but also additional metadata or attributes, such as point intensity, classification, and GPS data. Formats like OBJ or PLY are more general 3D formats that can also store LiDAR data, though they are less specialized.

Given the size and complexity of LiDAR datasets, one of the main challenges today is ensuring that this data can be processed and made available for use across various applications. With the rise of more powerful computing systems and faster communication networks, solutions for storing, indexing, and retrieving this large volume of data have become more important than ever. Efficient storage and data compression are essential to ensuring that LiDAR data can be shared and analyzed effectively, especially in remote sensing, urban planning, and environmental monitoring, where such datasets are crucial for making decisions. [20]

CONCLUSION

In conclusion, the implementation of 3D LiDAR scanning technology in aircraft inspection and maintenance offers a significant advancement in precision, efficiency, and reliability. By utilizing LiDAR-based scanning, intricate structural details of the aft inspection panel of a Learjet 24D aircraft were successfully captured, demonstrating the potential of this technology in aviation applications. The ability to generate high-resolution 3D models allows for thorough assessments, early defect detection, and improved maintenance planning, ultimately enhancing aircraft safety and operational efficiency.This study highlights the benefits of integrating LiDAR scanning into routine maintenance procedures, reducing manual inspection time, minimizing human error, and improving overall workflow. As technology continues to evolve, further advancements such as AI-driven defect detection and real-time data analysis could further optimize this approach. The adoption of LiDAR in aviation maintenance represents a step toward modernizing traditional inspection methods, ensuring greater accuracy while streamlining processes.

The successful application of 3D LiDAR scanning in this project reinforces its potential for widespread adoption in the aviation industry. Future research and development can expand its capabilities, integrating it with other non-destructive testing methods to create a more comprehensive inspection framework. Embracing such innovative solutions will contribute to safer, more efficient, and technologically advanced aircraft maintenance practices in the years to come.

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