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# AVIWC

## Executive summary

The inspection of aerospace components coated with HVOF tungsten carbide is currently performed manually at Collins Aerospace. These cylindrical rods, used in landing gear and actuators, must be free of defects such as scratches, cracks, or porosity, since any flaw can compromise mechanical strength. However, manual inspection is slow, costly, operator-dependent, and lacks digital traceability, making it unsustainable as demand and certification requirements increase.

The AVIWC project, developed by Alta Scuola Politecnica with Collins Aerospace, explored automated alternatives. A dataset of 6,000 microscope images was used to train a Convolutional Neural Network (ResNet-18), achieving over 97% precision in detecting scratches and 99% accuracy on defect-free rods. Limited labeled data, however, prevented reliable detection of cracks and porosity. In addition, a site visit revealed that manual rod rotation is a key bottleneck.

The team therefore designed a low-cost mechatronic prototype ( $\approx\text{€}300$ ) using a stepper motor and Arduino, enabling smooth and repeatable rotation. This allows to reduce operator workload, standardize image capture, and create the basis for scalable AI inspection.

The project concludes that a hybrid approach—mechanical automation, AI, and human oversight—delivers significant benefits. It improves efficiency, reduces costs, ensures digital traceability, and aligns with aerospace certification standards, paving the way for sustainable industrial adoption.

## Key Words

Automated Visual Inspection; Tungsten Carbide Coatings; Artificial Intelligence; Mechanical Automation; Human-in-the-loop

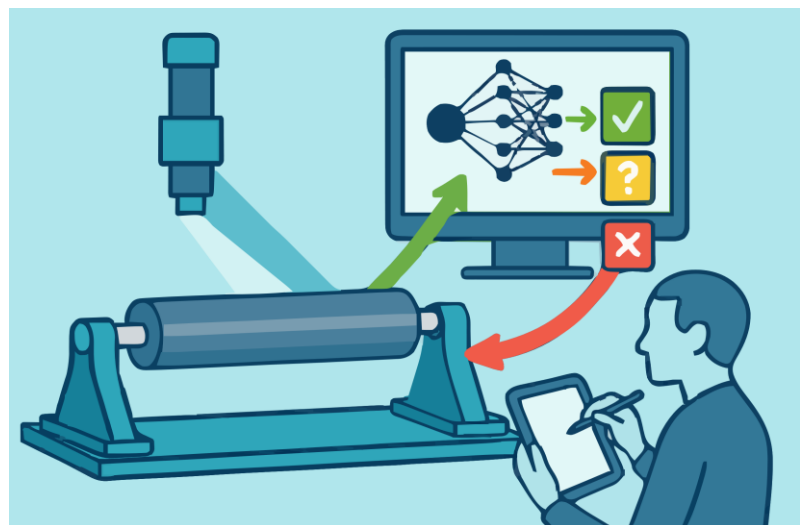
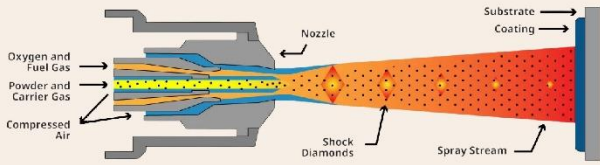
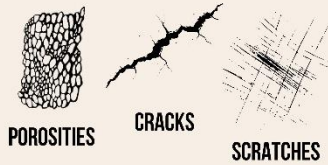


Figure 1: Human-in-the-loop automated visual inspection

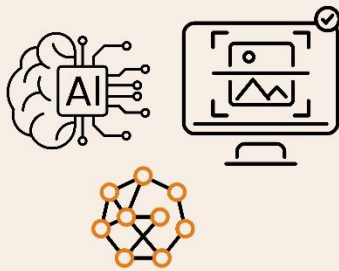


**HVOF technique  
generates surface defects**

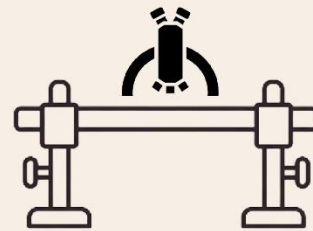
**Coatings are currently inspected  
manually by skilled operators  
through a microscope**



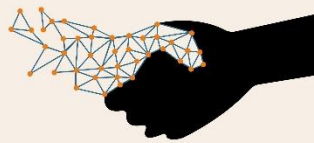
**SOLUTION**



**Convolutional Neural Network  
for  
Autonomous Visual Inspection**



**Motion System  
for  
Autonomous Rod Movimentation**



**Human-In-The-Loop system  
that automates inspection**



**Speed**



**Accuracy**



**Reliability**

**Project description  
written by the  
Principal Academic  
Tutor**

The Autonomous Visual Inspection of Tungsten-Based Coatings (AVIWC) project was developed through Alta Scuola Politecnica in partnership with Collins Aerospace to address quality control challenges for aerospace components using tungsten carbide coatings applied through High Velocity Oxygen Fuel processes. These coatings are essential for aerospace components such as actuator rods, shafts, and pistons that must endure extreme mechanical and thermal stress, making defect free surfaces critical for safety and performance.

Common defects include porosity, cracks and other surface irregularities that can compromise structural integrity and operational reliability. Currently, Collins Aerospace relies on skilled operators who manually inspect cylindrical surfaces under microscopes, rotating each component to detect and classify defects according to industrial specifications.

While effective, this manual approach is time consuming, with inspections taking several hours per component. In addition, it is physically and cognitively demanding, leading to operator fatigue and inconsistent evaluations, and lacks the repeatability and standardization required for aerospace certification processes. Additionally, comprehensive documentation and traceability are challenging to maintain with manual methods. Collins Aerospace established comprehensive requirements addressing technical, operational, and regulatory needs for the automated system.

The system must achieve high defect detection accuracy, minimize false negatives to prevent defective parts from passing inspection, while also reducing false positives to avoid unnecessary rework and associated costs. Finally, the system must provide faster inspection times compared to manual methods and integrate seamlessly with existing production workflows. From an operational perspective, the system requires a user-friendly interface, supporting a human in the loop approach that enables operator oversight for uncertain cases, while maintaining human expertise in the inspection process.

Regulatory compliance demands adherence to ISO-9001 and AS9100 standards, full traceability with auditable inspection records, secure data management, fail safe mechanisms, and repeatable objective inspection procedures. The solution must also be cost effective, demonstrating clear advantages over manual inspection through improved efficiency, sustainability, and scalability. The AVIWC project represents a comprehensive solution to a critical industrial challenge, combining automated inspection technology with human oversight, while meeting aerospace regulatory standards and production requirements.

**Team description by  
skill**

The AVIWC project was powered by a **multidisciplinary team** of students from Politecnico di Milano and Politecnico di Torino. Each member brought unique expertise that came together into one integrated solution. **Aerospace engineers** focused on industrial needs, certification rules, and validation strategies, ensuring the project met the strict requirements of the aerospace sector. **Computer engineers** built the digital backbone: they collected and prepared datasets, implemented a ResNet-18 CNN, and developed the AI pipeline to detect defects in coated rods. The **mechatronics engineer** designed and built the physical prototype, creating a precise and reliable system to rotate components and capture images systematically. By merging these skills, the team successfully connected the digital and physical worlds, enabling **automated inspection** that is **accurate, repeatable, and aligned** with certification standards.

## Goal

The goal of the AVIWC project is to automate the inspection of tungsten carbide-coated aerospace components by integrating artificial intelligence with mechanical automation. The main objectives of the system are:

- Reduce inspection time from five hours to less than one hour per part.
- Maintain human oversight in uncertain cases (human-in-the-loop approach).
- Ensure high classification accuracy (>95%) while minimizing false negatives.
- Offer a cost-effective and scalable solution for industrial deployment.
- Utilize hardware components that are modular and easily replaceable.
- Comply with general engineering standards and specific aerospace regulations.

In such a critical domain as the aerospace one, even small defects like pores, cracks, or delamination can compromise safety and lead to component rejection.

Currently, inspections are performed manually under microscopes, with operators rotating rods to scan their surfaces. This process is extremely time-consuming, physically demanding, and prone to inconsistency, especially in borderline cases.

With the rising demand for this kind of components and the stricter regulatory framework that the companies need to comply with, the current inspection approach is no longer sustainable, highlighting the urgent need for automation.

## Understanding the problem

Our project aims to address this problem by offering a reliable and high-performance solution that makes the operators work easier, improves the inspection chain efficiency, and brings economic advantages to the company.

The current inspection methodology relies on manual examination by skilled operators who use microscopes to visually assess the entire cylindrical surface of each component. While thorough, this approach presents several significant limitations. Each component requires up to five hours of continuous inspection time, making the process both labor-intensive and costly. The extended concentration periods required often result in operator fatigue, which can reduce detection accuracy and consistency. Moreover, the absence of standardized inspection protocols and digital documentation systems makes it challenging to ensure repeatability and provide objective evidence of compliance with stringent aerospace quality standards.

These operational challenges have become increasingly problematic as production volumes grow, and certification requirements become more demanding. The manual inspection approach introduces variability in results, escalates operational costs, and limits manufacturing scalability. These issues directly conflict with the industry's ongoing transition toward digital transformation and Industry 4.0 manufacturing principles.

The challenge therefore encompasses two critical objectives: achieving the highest possible defect detection accuracy while substantially reducing both inspection duration and human workload requirements. This necessitates a fundamental shift from traditional manual methods toward automated, digitally traceable, and highly repeatable inspection solutions. Such systems must maintain provisions for human oversight while enabling advanced data-driven analysis capabilities. Successfully addressing this challenge is essential for enhancing operational efficiency, ensuring compliance with aerospace regulatory standards, and establishing the groundwork for future AI-driven quality assurance systems.

## Exploring the opportunities

To overcome the limits of manual inspection, Automated Visual Inspection (AVI) has become a promising solution to improve reliability and efficiency. Early AVI relied on simple image-processing techniques such as edge detection or texture analysis, which worked only under controlled conditions and required constant manual tuning. Later, machine-learning methods like decision trees improved adaptability, but still depended on hand-crafted features and clean datasets.

The arrival of deep learning, and in particular Convolutional Neural Networks, represented a major turning point. CNNs are capable of automatically learning relevant features from raw images, which makes them highly effective even when conditions change, for instance when coatings vary in brightness, texture, or defect shape. They also scale well with large datasets and can highlight the location of defects through advanced visualization techniques. Nevertheless, their application to aerospace coatings is not without challenges: labeled datasets remain scarce, defects are often rare and highly variable, and the black-box nature of deep models raises certification concerns.

These limitations, however, open new opportunities. Active and semi-supervised learning approaches allow models to leverage large volumes of unlabeled data and request human annotations only for the most uncertain cases. At the same time, human-in-the-loop designs preserve operator involvement, enabling AI to provide speed and consistency while experts review ambiguous situations, ensuring accountability and trust. Equally important is mechanical automation: standardizing the rotation and positioning of rods ensures systematic image acquisition, reduces operator fatigue, and provides consistent data for AI algorithms.

Beyond the technical domain, the market itself offers strong incentives. The aerospace non-destructive testing sector is expanding at more than 7% annually, with forecasts exceeding 2.4 billion USD by 2033. This growth, reinforced by Industry 4.0 trends and stricter certification requirements, makes automated inspection not only feasible but strategically valuable.

## Generating a solution

The AVIWC project developed a hybrid solution integrating artificial intelligence and mechatronic automation.

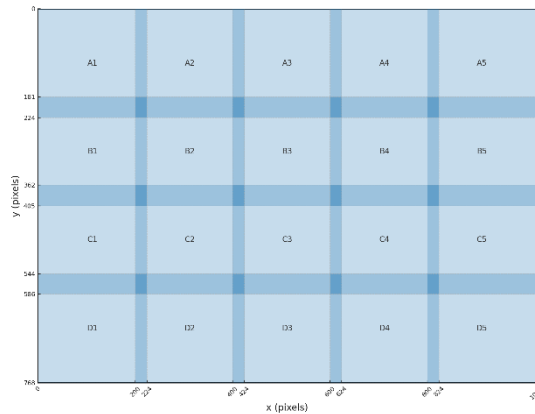


Figure 2: Tiles partitioning

### Phase 1 — AI Development:

A ResNet-18 was trained on microscope images to classify surfaces as “OK” or “Faulty,” based on the presence of scratches. Each image was segmented into 20 tiles according to the scheme in Figure 2 to enlarge the dataset and to make the model focus on the identification of the single scratches rather than the overall appearance of the texture. The tiles were then manually labelled. The classification of all the tiles composing an image are then aggregated to make inference on the whole image. Precisely, if at least one tile is classified as ‘faulty’, then the entire image is considered ‘faulty’.

The complete classification report on the validation set can be found in Figure 3. The key result is the 100% recall at image-level for the faulty class, meaning that no ‘faulty’ image was classified as ‘ok’, at the cost of some false negatives. Another key result is the low inference time of 7ms, due to the efficient size of the model.

While this method has proven to be effective for the recognition of scratches, it was not possible to train it to classify other types of defects, because only 3 samples of them were available.

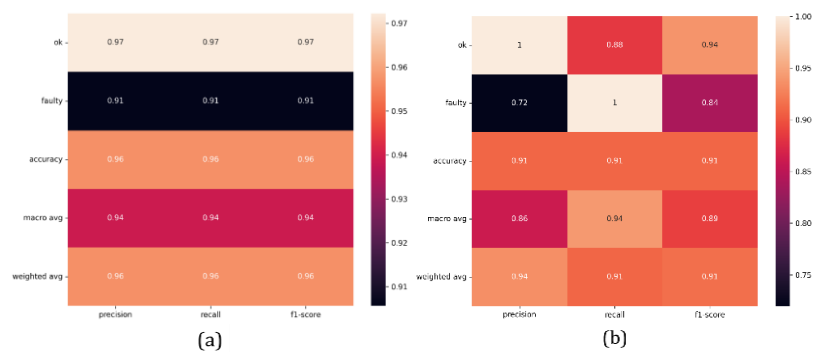


Figure 3. Classification reports: (a) at tile-level, (b) at full-image level

### Phase 2 — Mechanical Automation:

Observations of the manual inspection process highlighted rod rotation as the main bottleneck.

The team designed a prototype system with the following features:

- Motorized Actuation: a stepper motor was coupled to the rod via a flexible joint, ensuring smooth torque transmission and minimizing vibrations. If higher torque is needed, the design can be upgraded with a gear reduction. This choice guarantees precise angular positioning with excellent repeatability.
- Shaft Support and Alignment: the rod is stabilized through a system of fixed and floating bearings, which maintain alignment while allowing small axial displacements. Adjustable supports ensure correct positioning under the microscope, improving inspection accuracy.
- Control and Interface: an Arduino-based controller drives the motor using dedicated drivers. Operators can define rotation steps through a simple serial interface. Even with open-loop control, the system achieved sufficient accuracy and repeatability for inspection purposes.

Key Benefits

- Consistent and repeatable rod rotation.
- Elimination of the need for manual handling.
- Improved accuracy and traceability because of stable positioning supports systematic image capture.
- Low cost solution, built from commercial off-the-shelf components (stepper, Arduino, modular supports), with straightforward upgrade paths for industrial deployment.

The prototype successfully demonstrated the technical feasibility of an affordable and modular system capable of rotating coated rods smoothly and accurately. It lays the groundwork for systematic image acquisition and future integration with AI-based inspection.

## Main bibliographic references

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