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Design and Development of a Robotic System for Wind Turbine Tower Bolts

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Abstract: ***Ensuring structural integrity in utility-scale wind turbines requires consistent and reliable inspection of tower fastening systems. The proposed system is a fully automated mechatronic platform designed to perform intra-tower bolt inspection and retorquing without manual intervention. The device utilizes a multi-degree-of-freedom mechanical architecture mounted on a central rotary plate, enabling continuous 360° circumferential coverage within the confined tower passage. A cable-driven motor-pulley hoisting system provides precise vertical positioning, while a rack-and-pinion-based stabilization flange firmly braces the device against the tower wall, eliminating sway and ensuring a rigid operational environment during tightening. The articulated arm assembly consisting of primary, secondary, and tertiary arms-supports a torque-application end-effector capable of delivering controlled, repeatable tightening according to predefined torque setpoints. The ECU governs all subsystems under a deterministic, real-time control framework, sequencing hoisting, stabilization, rotation, arm deployment, bolt alignment, and torque application in a tightly coordinated manner. Mechanical compliance elements integrated into the device help absorb vibration during operation, preventing misalignment and ensuring consistent tool-to-bolt engagement. The system's modular three-plate structure allows individual plates, motors, and tools to be upgraded or serviced independently, improving long-term maintainability. By standardizing bolt-inspection and tightening procedures, the platform minimizes human involvement, shortens maintenance cycles, and ensures repeatable torque delivery across all tower segments. This automated architecture enhances operational continuity and ensures reliable, fleet-level bolt-maintenance quality with high repeatability and structural consistency.***

Keywords: Automated Bolt Inspection, Wind Turbine Maintenance, Mechatronic Platform, 360° Rotary Coverage, Cable-Driven Hoisting System, Rack-and-Pinion Stabilization, Articulated Robotic Arm, Torque-Controlled Tightening, Real-Time ECU Control, Modular Structural Design.

1. Introduction

The structural reliability of utility-scale wind turbines depends greatly on the health of the intra-tower bolted joints that connect each tower segment. These bolts are subjected to constantly changing aerodynamic, vibrational, and thermal loads during operation, making them vulnerable to preload loss, wear, and the gradual development of fatigue-related issues. Manual inspection methods often struggle to identify these early-stage problems due to restricted access, inconsistent measurement practices, and variations caused by human operators.

Inside the tower, the narrow geometry limits visibility and tool maneuverability, reducing the accuracy of standard torque checks and visual evaluations. Factors such as uneven lubrication, bolt-seating differences, and poor lighting create further uncertainty, while vibration and ambient operating noise contribute to inconsistent readings. As towers become taller and wider, manual inspections grow slower, riskier, and increasingly unreliable for achieving consistent results.0

These challenges highlight the need for a more dependable and repeatable way to evaluate bolt condition. An automated intra-tower inspection and torque-verification system address this requirement by providing stable anchoring, precise alignment, and controlled torque application for accurate assessment. With full 360-degree rotational coverage and coordinated motion control, the system ensures consistent, traceable evaluations that support proactive maintenance and enhance the long-term safety and performance of the turbine.

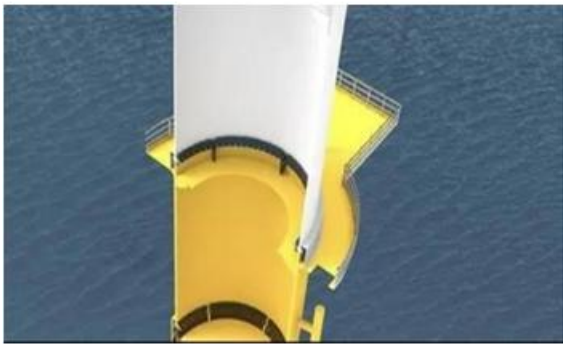

Figure 1

Figure 2

2. The Importance of Bolt Integrity in Wind Turbines

Bolted connections constitute the primary load-bearing interfaces within wind turbine assemblies, ensuring structural continuity between tower flanges, nacelle housings, and rotor hubs. Their mechanical performance underpins the turbine's ability to withstand multiaxial stress regimes, including axial compression, torsional shear, and dynamic bending moments induced by stochastic wind excitation. The preservation of bolt preload is critical, as it governs stress distribution across joint interfaces and mitigates localized stress risers that precipitate fatigue crack initiation. Inadequate bolt integrity compromises the global stiffness matrix of the tower structure, thereby amplifying modal vibrations and accelerating cumulative fatigue damage. Thus, bolt reliability is not merely a matter of mechanical fastening but a determinant of the turbine's structural resilience and operational longevity.[2]

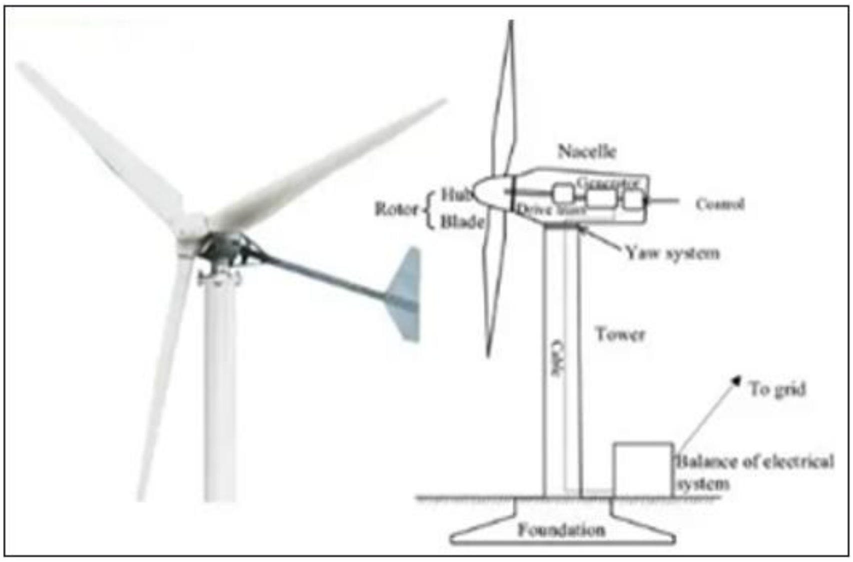

Figure 3

The ramifications of compromised bolt integrity extend beyond localized mechanical failure to encompass system-level reliability and safety hazards. Progressive loosening, corrosion-assisted degradation, or thread stripping can culminate in catastrophic joint separation, jeopardizing both asset performance and occupational safety. Offshore installations exacerbate these risks due to chloride-induced stress corrosion cracking and elevated cyclic loading from turbulent marine environments. International standards such as IEC 61400 and DNV-GL guidelines underscore the necessity of rigorous bolt inspection protocols, torque traceability, and compliance with confined-space safety regulations. In this context, bolt integrity emerges as a cornerstone of wind turbine reliability engineering, directly influencing lifecycle cost optimization, energy yield stability, and the broader sustainability of renewable energy infrastructure.[3]

3. Challenges in Conventional Inspection Practices

Conventional bolt inspection in wind turbine towers is predominantly manual, relying on technicians to climb into confined tower spaces and perform torque checks and visual assessments. This approach is inherently labor-intensive, time-consuming, and prone to human error. The confined geometry of towers, combined with the sheer number of bolts, makes comprehensive inspection difficult. Moreover, manual methods lack the diagnostic depth required to detect subsurface flaws, leading to latent defects that may remain undetected until catastrophic failure occurs. These limitations collectively compromise safety, reliability, and efficiency, underscoring the need for more advanced solutions.**Error! Reference source not found.**

Figure 4

Figure 5

3.1 Safety Risks in Confined Tower Environments

Technicians working inside turbine towers face restricted vertical enclosures with limited ventilation and narrow access routes. This environment introduces risks such as falls, entrapment, ergonomic strain, and occupational fatigue. Emergency response is inherently delayed in such confined spaces, magnifying the severity of accidents. The psychological stress of prolonged work in enclosed, high-risk environments further compromises inspection accuracy and worker well-being.

Figure 6

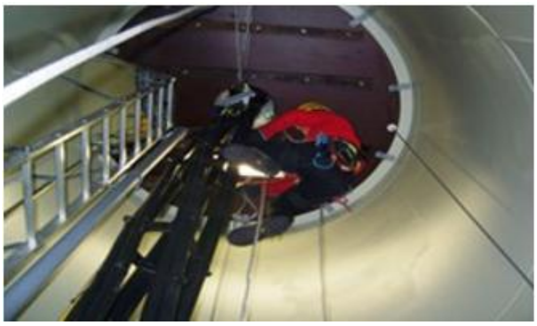

Figure 7

3.2 Limitations of Manual Torque and Visual Checks

Manual torque verification suffers from operator variability, tool calibration drift, and inconsistent preload restoration, resulting in non-uniform fastening quality. Visual inspections, while expedient, cannot detect subsurface anomalies such as fatigue micro-cracks, corrosion beneath bolt heads, or concealed thread wear. Coverage is often incomplete in geometrically complex or inaccessible regions, leaving defects undetected until failure manifests. These limitations undermine the repeatability, reliability, and diagnostic fidelity of conventional practices.

3.3 Need for Automation and Advanced Diagnostics

The shortcomings of manual inspection highlight the necessity for automation-enabled diagnostic platforms. Automated systems can deliver repeatable torque application, comprehensive coverage, and integration of non-destructive evaluation (NDE) techniques such as eddy-current and ultrasonic phased-array inspection. Real-time data logging and analytics enable predictive maintenance strategies, shifting the paradigm from reactive interventions to proactive asset management. Automation thus represents a transformative pathway toward safer, more efficient, and more reliable wind turbine maintenance practices.

4. System Architecture

4.1 Mechanical Layout and Modularity

The system uses a three-plate modular structure where each plate performs a specific mechanical and functional role, allowing compact transport and stable deployment. The foldable arms reduce the overall envelope size during movement through narrow lift passages while expanding into a rigid operational configuration. Each plate is independently detachable, enabling quick maintenance, upgrades, and easy replacement of motors, and arm components. This modular approach enhances serviceability, structural stability, and adaptability for future inspection or tooling requirements.

a) Top Plate Case: The top plate acts as the primary structural and actuation platform of the system, accommodating Motor-1 and the hoist-pulley assembly inside a dedicated protective enclosure designed to withstand dust, vibrations, heat, and environmental loads encountered inside lift passages. Its rigid geometry maintains stable alignment of rotating elements while ensuring consistent torque delivery for prolonged operation. The plate also supports the main upper load path, preventing deformation when the system experiences dynamic forces during movement or inspection cycles. With its modular attachment interface, the top plate allows quick removal and replacement of the motor unit without disturbing the rest of the structure, enabling efficient servicing and minimizing system downtime during field operation. [5]

b) Middle Plate Case: The middle plate contains a circular gear mechanism that provides a full 360-degree rotational capability, allowing the device to inspect bolts located around the tower circumference without repositioning the main assembly. This precision-machined gear train ensures smooth, backlash-free movement and maintains reliable angular alignment when torque forces are applied through extended arms. The plate evenly distributes rotational stress across its structure, preventing mechanical distortion during continuous rotational activity. By enabling uninterrupted circular motion, the middle plate significantly improves workflow efficiency, especially in environments with irregular bolt patterns or constrained access.[6]

c) Bottom Plate Case: The bottom plate serves as the foundation for system stability, holding auxiliary drive modules, the deployable stabilizing flange, and the rope-pivot assembly responsible for maintaining correct vertical alignment inside the shaft. It incorporates damping elements that absorb vibrations and shock loads, preventing them from reaching the sensitive components located above. The plate maintains a stable center of gravity even during heavy torque operations, ensuring the device remains balanced when arms are fully extended. Its reinforced construction also provides mounting points for arms, tools, and future attachments, functioning as the core structural base for the entire inspection unit.

d) Modular Architecture: The system's three-plate modular architecture allows each plate to be detached, upgraded, or serviced independently, reducing maintenance complexity and improving on-site operability. This modularity supports the integration of new motors, inspection mechanisms, or functional tools without requiring major changes to the overall structure. A uniform mechanical interface across all plates ensures proper alignment, secure bonding, and repeatable positioning during reassembly. This flexible modular arrangement future-proofs the device, enabling it to adapt to evolving operational requirements and advancements in automated bolt maintenance technology.

4.2 Kinematic Platform

a) Central Rotary Hub: The central rotary hub governs azimuth movement for the entire arm mechanism, enabling smooth and unrestricted circumferential rotation around the tower structure without the need to reposition the main chassis. Its rigid build withstands torsional loads generated when torque tools engage bolts, maintaining precise indexing even when the arms operate at maximum extension. The hub ensures consistent rotational behavior with reduced vibration transfer, contributing to accurate positioning and seamless transitions between inspection points. This improves efficiency within narrow tower environments where physical repositioning is difficult or time-consuming.

b) Primary Arm: The primary arm provides the main radial extension and serves as the most rigid element in the kinematic chain designed to deliver maximum stiffness when reaching bolts located farther from the central axis. Its robust structure minimizes bending or twisting under heavy torque loads, ensuring that the tightening or inspection process remains aligned and stable. The primary arm manages coarse positioning tasks, enabling the secondary and tertiary arms to operate only within their precision ranges. This structural stiffness maintains tool accuracy even when operating in dynamic shaft conditions where small disturbances are common.

c) Secondary Arm: The secondary arm delivers fine radial and axial positioning to reach bolts situated in recessed or obstructed zones where direct access is not possible. Its articulated joints enable controlled micro-adjustments that correct positional deviations caused by tower geometry, installation brackets, or uneven surface features. This arm compensates for angular or lateral misalignment during approach, ensuring the end-effector reaches the bolt with proper orientation. Its precise movement capability is essential in confined passageways where structural obstructions restrict free arm motion.

d) Tertiary arm: The tertiary arm supports the end-effectors such as torque tools and other functional modules, ensuring precise engagement with bolt heads. Its compact and highly controlled mechanism enables fine micro-alignments required for achieving proper torque loading and accurate positioning during operation. The tertiary arm maintains stable contact with the bolt, preventing slippage or misalignment even under vibration or reaction forces generated by the tightening tool. Its precision, repeatability, and small-range corrective capability make it ideal for operating in tight or restricted spaces where only minimal adjustments can be made without interfering with surrounding structures.

e) Hybrid Kinematic Chain: The integration of primary, secondary, and tertiary arms forms a hybrid kinematic arrangement that balances reach, stiffness, and precision, ensuring controlled and accurate performance throughout the inspection and tightening tasks. This distribution of motion reduces cumulative error typically encountered in long serial-link mechanisms while enabling full workspace coverage without shifting the base unit. The hybrid structure supports complex bolt layouts and allows efficient operation inside narrow lift shafts, making the device highly effective in structurally challenging inspection environments.

4.3 Actuation Overview

The actuation architecture comprises several specialized motion subsystems, each engineered to support a dedicated operational function. These subsystems work together to achieve precise motion control, stable operation inside the tower shaft, and reliable interaction with structural components during inspection and torque operations. The following sections provide an expanded description of each subsystem.

a) Vertical Motion: The device moves vertically using a motor-driven pulley hoist equipped with high-tensile steel ropes designed for durability and smooth travel inside the tower. The hoist motor provides controlled speed, allowing both fine positioning when approaching an inspection point and faster movement during transitions between tower segments. The ECU regulates hoist operation to prevent overload and ensure stable, balanced vertical motion throughout the entire inspection process. This controlled actuation enables reliable traversal of all tower levels while maintaining consistent system stability.

b) Stabilization: The stabilization system uses a radial rack-and-pinion-driven flange that extends outward to brace the device firmly against the tower wall. This mechanism provides the necessary structural support during scanning and torque operations by minimizing sway and vibration-induced movement. Once deployed, the flange ensures accurate positioning and maintains a secure anchoring force, preventing displacement or misalignment even during high-reaction torque events. Its controlled extension and rigid locking behavior make it suitable for maintaining stability within the confined lift passage of the tower.

c) Coverage: The central rotating plate enables full 360-degree operational coverage, allowing the device to reach bolts positioned all around the tower without needing to reposition the entire system. The rotation mechanism is engineered for smooth, backlash-free motion, ensuring consistent and controlled angular movement. High-load bearings support the rotating assembly, maintaining precise alignment during repeated inspection and tightening cycles. This design provides reliable rotational accuracy and ensures uninterrupted access to all bolt locations within each tower segment.

d) End-Effectors: The robotic arms are equipped with modular end-effectors designed to support torque-application tools and other functional modules required for bolt maintenance. The torque tool delivers controlled and consistent force, ensuring each bolt is tightened to the specified level regardless of bolt condition or orientation. The modular end-effector design allows quick replacement, customization, or upgrades without altering the arm structure. This flexibility enables the system to adapt to different operational requirements and simplifies maintenance during field deployment.

e) ECU-Based Control Coordination: All actuators operate under ECU supervision, which synchronizes motor commands, sensor inputs, and safety functions. The ECU manages smooth motion transitions, prevents collisions using sensor feedback, and adjusts torque based on bolt resistance. Integrated safety interlocks stop operations instantly during anomalies, ensuring accurate and reliable actuation control.

4.4 Design Consideration

a) Safety: The system ensures safety through controlled vertical movement and a stabilizing flange that firmly braces against the tower wall. This eliminates unintended shifts, sways, or collisions during torque operations. With stable positioning at all elevations, the device delivers predictable and repeatable performance.
b) Efficiency: It comes from a rotating plate and articulated arms that reach all bolt positions without moving the main body. This minimizes repositioning time, reduces energy use, and maintains continuous workflow across tower sections. The streamlined operation boosts overall inspection speed and consistency.
c) Scalability: The modular three-plate structure and standardized interfaces allow future upgrades without altering the core design. Additional mechanical tools or improved actuation modules can be integrated easily as requirements evolve. This adaptability ensures long-term usability and compatibility with new maintenance needs.
d) Precision: Precision is maintained through ECU-controlled motion that regulates torque delivery and synchronizes all actuation steps. The system ensures consistent tightening accuracy by maintaining stable positioning during tool engagement. Controlled motor output and rigid support mechanisms enable reliable performance under varying internal conditions.

5. Mechatronic Subsystems

5.1 Motor–Pulley Hoist Assembly

The vertical movement of the device is enabled by a top-mounted motor–pulley hoist system that suspends and lowers the unit through a steel-rope mechanism. The hoist motor, combined with a gearbox and pulley arrangement, provides sufficient lifting torque and controlled descent, ensuring smooth and safe traversal between tower sections. The rope selection, pulley diameter, and support frame are designed to handle static loads as well as dynamic effects during movement.

The top plate supports the hoist interface, while the middle plate offers 360° rotational access for bolt coverage. Rotation is driven by Motor-1, which engages the circular gear teeth integrated into the middle plate. Bearings and a cylindrical guide maintain alignment between the plates, ensuring smooth rotation without transferring excessive vibration.

Advantages:
- Enables safe lifting and lowering of the device within the tower passage.
- Provides full circumferential access without shifting the main body.
- Reduces overall repositioning time and improves operational efficiency.
- Maintains mechanical isolation between rotating and fixed components.

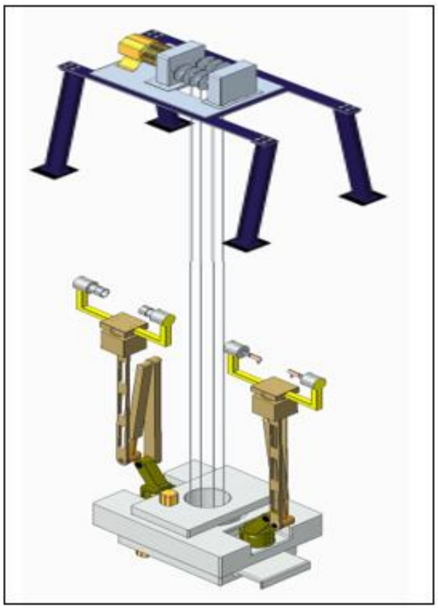

Figure 8

5.2 Rack-and-Pinion Stabilization Flange

Upon reaching the target elevation, stability is ensured by a flange mechanism extending from the bottom plate. Driven by a rack-and-pinion motorized system, the flange braces against the tower's inner wall, suppressing sway and vibrations. This creates a rigid work envelope, essential for precision tasks such as bolt inspection and torque application.

Key features include:
- Automatic deployment and retraction synchronized with ECU commands, ensuring smooth and precisely timed operation.
- Mechanically verified locking to confirm secure bracing before tool engagement, guaranteeing stability during tightening and inspection tasks.
- Compact housing design minimizes interference during vertical movement and transit, allowing unobstructed travel within the tower shaft.

5.3 Articulated Arms and Mechanisms

The device employs multi-tier articulated arms designed for confined geometry access. Each arm deploys from a docked position to reach bolts at varying offsets and depths.

Integrated tooling includes:
- Inspection heads (visual cameras, marking tools).
- Torque tooling for controlled fastening operations.
- Compact folding design enabling full retraction for safe transit.

The arms are engineered for high dexterity, allowing the device to adapt to diverse bolt configurations and structural geometries.

5.4 Torque-Controlled Tooling

5.4.1 Closed-Loop Torque Application

The torque-controlled tooling subsystem features a precision torque arm engineered to engage tower bolts with a stable, sensor-regulated torque output. Through tightening, the arm continuously communicates with the ECU, allowing real-time corrections that compensate for bolt surface wear, thread friction variability, or misalignment in the confined tower interior. This constant monitoring ensures each bolt experiences a smooth torque increase following an ideal torque-angle path, avoiding abrupt spikes that could damage joint components. The torque arm integrates seamlessly with the robot's rotating center plate and multi-axis arms-components visible in the system diagrams-ensuring that even bolts located in narrow, curved passages of the tower can be reached safely. By maintaining accuracy regardless of mechanical variations, the system eliminates the inaccuracies of manual tightening and provides stable joint integrity across every segment of the tower structure. In this way, the closed-loop design becomes a dependable interface between the robotic tool and critical flange connections, ending each tightening cycle with verified mechanical safety.

5.4.2 Real-Time Setpoint Tracking and Monitoring

During operation, the torque arm follows predefined torque setpoints programmed into the ECU according to wind-turbine manufacturer specifications, ensuring uniform load distribution across the tower's ring-flange bolts. As tightening begins, the ECU continuously evaluates the tool's torque progression and compares it against the expected torque-angle characteristics for that bolt type. Any irregular behavior-such as an unexpectedly rapid torque buildup (which may indicate thread interference) or unusually low resistance (which may suggest a loose or weakened bolt)-is detected through deviations in the torque-application pattern. Based on these variations, the ECU automatically regulates tool speed, motor current, or rotational rate to maintain controlled and steady advancement toward the final torque requirement. This closed-loop control ensures that every bolt is tightened with engineering precision, even when environmental factors such as dust, surface wear, or thread condition introduce variability. At the end of each tightening cycle, the system verifies that the final torque matches the programmed specification before proceeding to the next bolt, ensuring consistent structural reliability throughout the tower.

5.5 Integration and Safety Considerations

5.5.1 ECU-Coordinated Synchronization of Subsystems

The ECU functions as the supervisory controller responsible for coordinating all major subsystems, including the hoisting mechanism, stabilization flange, rotating plate assembly, inspection arms, torque arm, and bolt-handling modules. It manages the timing and sequence of each operation so that every subsystem activates only at the appropriate moment. For example, the stabilization flange must lock securely against the tower wall before the arms are allowed to extend, and the rotating plate must complete its angular positioning before the torque tool aligns with the next bolt row.

By controlling these dependencies, the ECU prevents mechanical interference between components and maintains safe operation within the narrow tower passage. This coordinated workflow ensures that each stage-lowering, stabilizing, rotating, aligning, tightening, and retracting-proceeds smoothly and in the correct order. Through this structured, step-by-step orchestration, the ECU enables predictable, controlled, and reliable operation across each tower segment, ensuring that every functional transition ends with verified alignment and positional stability.

5.5.2 Safety Interlocks, Inhibition Rules, and Operational Restrictions

To prevent unsafe interactions between moving components, the system incorporates multiple safety interlocks that restrict unauthorized or mechanically risky actions. The stabilization flange must be fully extended and securely locked before any arm-based operation is permitted, ensuring that the device remains firmly braced against the tower wall. Likewise, the hoisting mechanism is automatically inhibited during inspection and tightening activities, preventing accidental lifting or lowering that could destabilize the device or cause structural interference inside the tower shaft.

The ECU continuously evaluates operational parameters such as vibration levels, torque behavior, flange locking status, rotational alignment, and rope tension. If any abnormal condition is detected-such as excessive vibration, unexpected torque rise, rope slack, overheating, or misalignment-the system initiates an immediate emergency-stop sequence. These interlocks maintain strict mechanical boundaries, ensuring that each subsystem operates only under safe conditions. By enforcing these rules, the system concludes every operational cycle with a stable, controlled, and fully protected working environment.

5.5.3 Diagnostics, Fault Detection, and Modular Safety Architecture

The device continuously runs diagnostic routines that check for early signs of subsystem degradation, including rising motor load, bearing friction, torque drift, flange slippage, encoder misalignment, and abnormal noise signatures. When potential faults are detected, the ECU isolates the affected subsystem and prevents its further use-allowing the remaining modules to retract safely without endangering the device or tower structure. This modular safety design ensures that no single failure cascades into a system-wide malfunction, which is particularly critical inside tall wind-turbine towers where access for manual recovery is limited.[7] The logged diagnostic data also supports predictive maintenance, enabling timely replacement of worn components. By combining fault isolation, predictive analytics, and modular redundancy, the system concludes each inspection or tightening sequence with a confirmed safe operational state, ensuring readiness for the next tower level.

6. Control Framework

6.1.1 ECU and Real-Time Control

The ECU functions as the central controller responsible for coordinating all mechanical and electronic elements of the device. It manages motor operations, motion control, rotational positioning, arm extension, tightening actions, and stabilizing mechanisms. By regulating trajectories, speeds, and operational sequences in real time, the ECU ensures smooth and predictable movement inside the tower. This centralized control enables stable performance during lowering, rotating, scanning, and tightening operations, even within confined tower spaces.

6.1.2 Real-Time Scheduling

The ECU follows a deterministic scheduling approach to execute all actions with precise timing. Each motor and mechanism operates in a predefined sequence that eliminates delays and prevents misalignment during lowering or stabilization. Accurate timing helps the device maintain correct positioning and ensures consistency throughout inspection and tightening operations across various tower sections.[8]

6.1.3 Hierarchical Control Layers

The system uses a hierarchical structure with low-level motor control, mid-level subsystem coordination, and high-level sequencing. This prevents conflicting commands and ensures that lowering, stabilizing, scanning, and tightening occur in the correct order. The layered approach enables efficient handling of complex tasks without overloading individual controllers.

6.2 Operational Sequencing

A supervisory state machine governs the entire operation, ensuring each step happens only under safe conditions. The device moves only when arms and the flange are retracted, then stabilizes before inspection begins. After validating bolt details, the tool applies the required torque and retracts all components before moving to the next section. Safety interlocks prevent any overlapping or unsafe action during the process.

6.3 Data Logging and Traceability

The ECU maintains a structured and comprehensive digital log of every bolt-related operation carried out by the robotic inspection device. This logging framework forms the backbone of system transparency, enabling precise tracking and verification of inspection and tightening activities throughout all tower segments.[9]

6.3.1 Bolt Identification and Inspection Tracking

The ECU logs every bolt's ID and position using encoder and sensor data. It records inspection results, including markings, length, and surface condition. These entries determine if a bolt meets standards or needs tightening. The stored information forms a long-term record for future maintenance analysis.

6.3.2 Torque Command and Execution Logging

For each tightening action, the ECU saves both the commanded torque and the actual applied torque. It records the torque-angle curve, tightening duration, and any detected anomalies. Time-stamped logs document the entire inspection and tightening sequence for full traceability. Time stamps are assigned to every stage of the operation-inspection, torque engagement, and tool retraction-forming a chronological record of system activity. This level of detail ensures that tightening events are fully documented and verifiable.

6.3.3 Maintenance Traceability and Predictive Insights

The All-logged data forms a complete maintenance record used for quality checks and compliance. Long-term trends reveal repeated deviations or degradation in specific bolt areas. These insights support predictive maintenance, helping prevent structural issues and improving overall system reliability.

7. Working Principle and Workflow

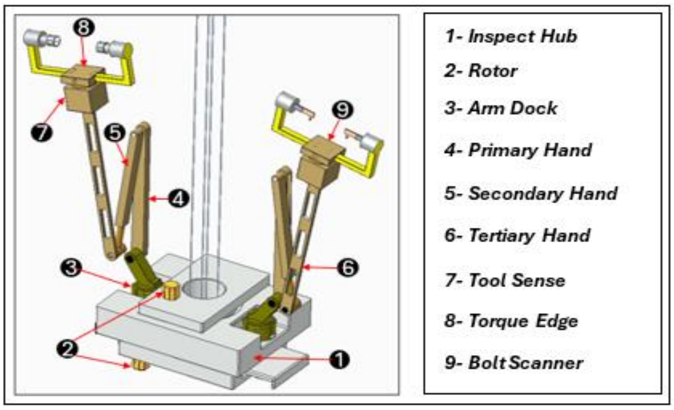

Figure 9

7.1 System Mounting and Vertical Deployment

The working process begins with the robotic inspection device being mounted at the top of the wind-turbine tower, where the compact folded-arm configuration ensures safe handling during installation. All articulated arms remain docked, preventing accidental contact with the lift passage walls as the system prepares for descent. The motor–pulley hoist assembly initiates vertical lowering under the ECU's real-time supervision, enabling smooth, vibration-free movement inside the narrow tower shaft. The ECU continuously monitors rope tension, motor load, and descent velocity to avoid sudden drops or imbalance, while clearance-checking logic ensures the device never drifts toward the walls.0 Integrated braking mechanisms activate automatically if tension anomalies are detected, providing another layer of safety for deployment in constrained environments. This carefully controlled descent sequence allows the system to reach the intended elevation with precision, forming the first critical step in the workflow where stability, accuracy and safety are ensured before any operational tasks begin.[11]

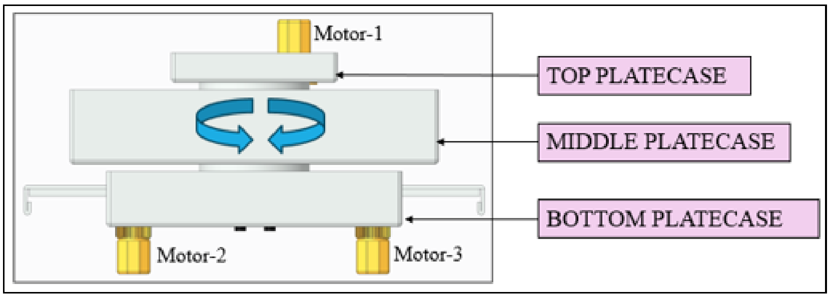

Figure 10

7.2 Stabilization at Target Elevation

Upon reaching the designated tower level, the stabilization phase begins with the rack-and-pinion-driven flange extending outward from the bottom plate casing. This flange presses firmly against the internal tower wall, eliminating sway, lateral drift, and oscillations that could affect inspection or tightening accuracy. The ECU evaluates the flange's mechanical engagement by monitoring extension position, locking status, and structural response during deployment. If the applied bracing force is insufficient or uneven, the ECU commands fine micro-adjustments to ensure complete and uniform stabilization across the contact surface.

This stabilization mechanism is essential for creating a rigid and vibration-free operating environment. Even minor movement can alter arm alignment, affect rotational positioning, or influence torque-application precision. Only after the flange's secure engagement is confirmed does the ECU permit arm extension and tool activation, ensuring that all subsequent operations take place under stable, repeatable, and structurally reliable conditions.

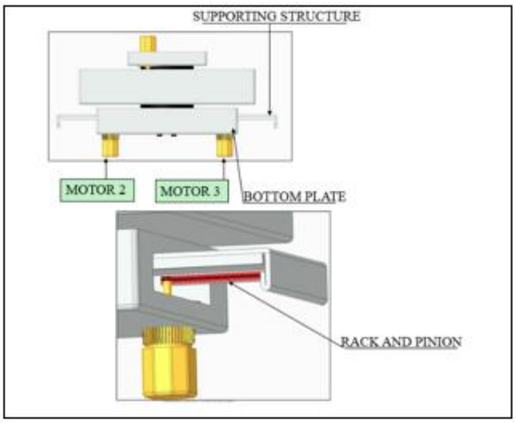

Figure 11

7.3 360° Coverage and Arm Deployment

Once stabilized, the central rotating plate assembly becomes active, enabling complete 360° circumferential coverage of all bolts present in that tower segment. This rotation capability removes the need for repositioning the device body, improving efficiency and reducing mechanical wear. After rotation aligns the system with a bolt group, the articulated arms extend with controlled precision to reach bolts positioned at various depths, angles, or offsets along the tower wall. Each arm includes inspection modules capable of verifying bolt markings, measuring bolt length, and assessing surface conditions to detect corrosion or wear. These inspections allow the system to confirm bolt identity and determine whether tightening is required based on structural conditions. The combination of rotational indexing and multi-axis arm articulation ensures that every bolt can be accessed regardless of tower geometry, guaranteeing comprehensive inspection without human intervention in hazardous vertical environments.

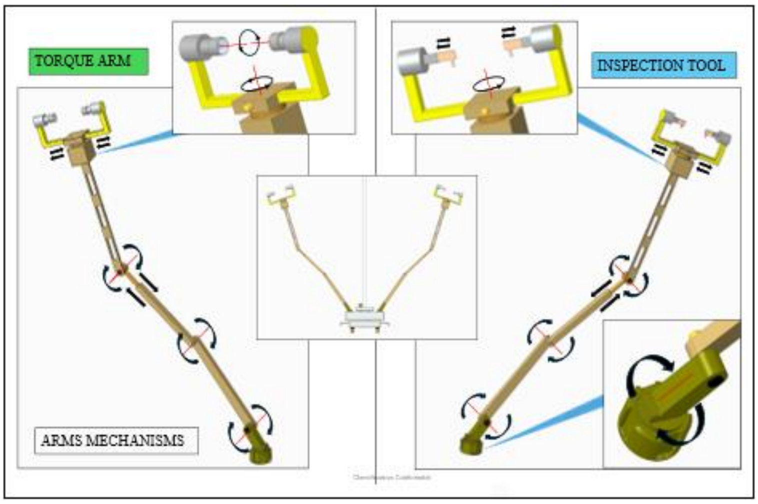

Figure 12

7.4 Torque Application and Verification

When inspection data indicates that a bolt requires tightening, the torque-controlled tooling engages to apply the exact torque specified by engineering guidelines. The torque arm operates in closed-loop mode, continuously measuring torque and angle to maintain precise adherence to the setpoint while avoiding over-torquing or thread damage. The ECU monitors this process in real time, comparing live torque values with predetermined requirements and halting the operation if abnormal patterns such as torque spikes or sudden resistance are detected. During every torque cycle, the ECU logs both commanded and achieved torque values, creating a complete trace of the tightening event linked to the bolt's specific ID and location. This ensures high repeatability, allows maintenance verification at any future time, and contributes to long-term structural reliability of the tower. Through this process, the device ensures that torque application is not only accurate but also fully auditable and compliant with safety standards.

7.5 Retraction and Section-Wise Progression

After finishing inspection and torque-adjustment for all bolts at the current elevation, the device transitions into its retraction phase to prepare for movement to the next tower segment. The articulated arms fold smoothly back into their docking bays, preventing any obstruction during vertical movement. Simultaneously, the stabilization flange retracts into the bottom plate casing, returning the system to its compact transit state. The ECU performs safety checks to ensure that all components are fully retracted before authorizing the hoist to resume downward movement. Once verified, the motor–pulley assembly lowers the device to the next inspection section, repeating the cycle of stabilization, inspection, torque application, and retraction. This structured, section-wise progression guarantees full coverage of all bolts from top to bottom, reducing the need for human entry into the hazardous tower interior while maximizing accuracy and operational efficiency.

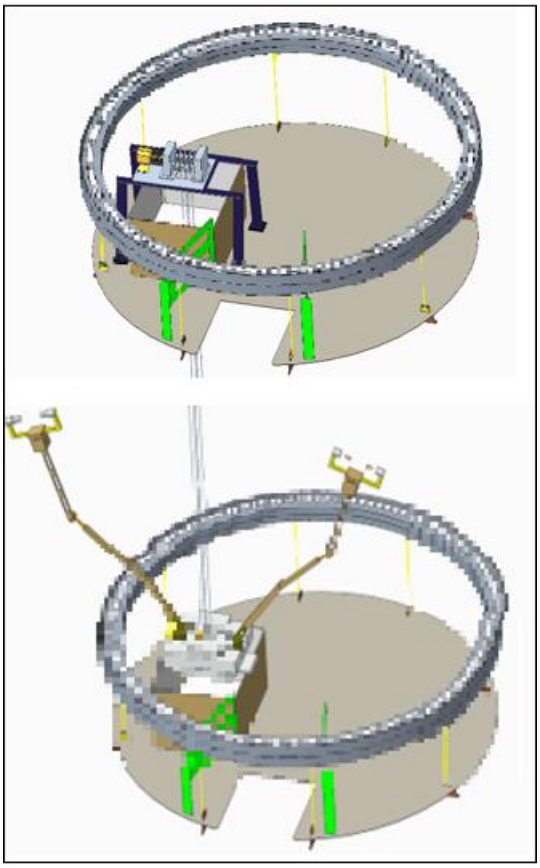

Figure 13

7.6 Summary of Workflow Benefits

The overall workflow delivers multiple operational advantages by integrating a safety-oriented design, automated sequencing, and precisely coordinated subsystem control. Safety is ensured through built-in interlocks that prevent incorrect or unsafe actions, such as extending the arms before stabilization or applying torque before proper alignment. Automation greatly improves operational efficiency by enabling continuous, section-by-section progression without manual repositioning, thereby minimizing downtime between tasks.

The ECU's detailed logging of operational steps provides complete traceability for inspection and tightening activities, supporting adherence to engineering requirements and enabling long-term structural evaluation. Additionally, the modular design of the system allows it to adapt to towers with varying diameters, flange geometries, and bolt arrangements, offering a flexible and scalable solution for different turbine configurations. This structured and repeatable workflow ensures that every bolt is properly accessed, evaluated, tightened when necessary, and fully documented resulting in a reliable, safe, and systematic maintenance process.

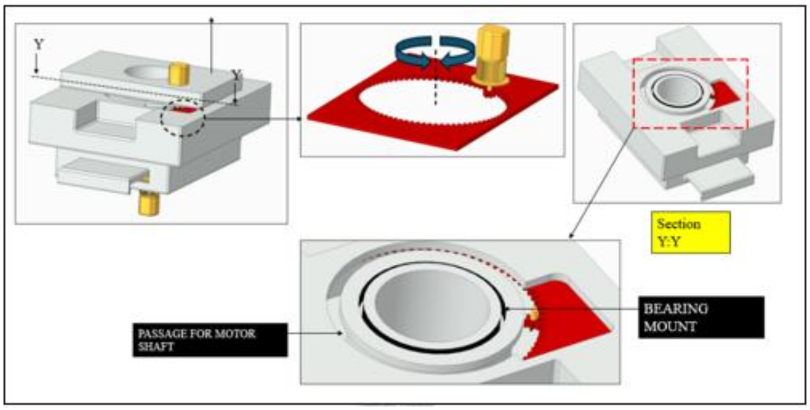

Figure 14

8. Performance and Reliability Assessment

8.1 Coverage and Accessibility

The rotating plate integrated with articulated inspection arms provides complete circumferential reach around the tower interior, enabling the system to access every bolt located within a given elevation without requiring manual repositioning. This significantly reduces the operational burden compared to traditional maintenance approaches where workers must relocate platforms or climb between levels to inspect individual bolt clusters. The foldable design of the arms allows the device to pass safely through the narrow lift passages when moving between sections, preventing accidental impact with the tower walls or internal structures. Once deployed, the arms can extend across varied offsets and angles, ensuring accessibility to bolts positioned in geometrically constrained regions where manual access would be severely limited. By eliminating blind spots and improving reachability, the architecture ensures that no fastener is overlooked during inspection, thereby enhancing structural reliability and minimizing maintenance gaps across the tower height.

8.2 Stability and Anti-Sway Effectiveness

Inspection and torque operations require high structural stability to guarantee repeatability, and the rack-and-pinion anchoring system provides a robust mechanism for suppressing sway and unwanted motion while the device is suspended inside the tower. As the flange extends outward, it braces firmly against the tower wall, creating a rigid support frame that counteracts motion caused by rope dynamics, wind loading transmitted through the structure, or residual vibrations generated during arm movement. This secure anchoring is particularly crucial for torque application, since even minor lateral sway can distort torque delivery and compromise preload accuracy. It also supports consistent imaging during visual or sensor-based inspections, allowing defect-detection systems to capture high-quality, reproducible data.[12] By mechanically coupling the robotic platform to the tower surface, the system creates a stable operating envelope that ensures repeatable performance across multiple operational cycles and tower segments.

8.3 Torque Precision and Repeatability

The torque-controlled tooling, supervised by the ECU, ensures that every bolt receives a consistent and accurate preload, minimizing dependence on operator skill and reducing variability between maintenance cycles. During torque application, real-time monitoring measures the applied torque and rotational angle, allowing the ECU to detect deviations from the specified setpoint and correct them instantly. This ensures precise compliance with engineering torque specifications and reduces the risk of under-torquing or over-torquing, both of which can compromise structural integrity. The ECU also captures and logs detailed torque data for quality assurance, enabling engineers to verify the integrity of the tightened joints and review performance trends over time. Post-maintenance analytics can then be used to detect early signs of bolt fatigue, repeated torque anomalies, or degraded joint behavior, supporting predictive maintenance strategies. Together, these capabilities ensure long-term reliability, especially in high-load environments such as wind-turbine towers and industrial flange systems.

8.4 Operational Efficiency

8.4.1 Improved Inspection Throughput Through Segment-Wise Automation

Segment-wise automation significantly enhances inspection throughput by enabling the system to move from one tower segment to another without requiring manual repositioning or operator intervention. The rotating plate and multi-axis arm mechanisms allow complete bolt-cluster coverage within each elevation, eliminating the need for technicians to physically move inside the tower or reposition equipment. Because the robot can autonomously manage bolt identification, inspection, and torque application, overall maintenance duration is reduced substantially compared to manual workflows. This reduction in manual handling time translates into shorter outage windows for the wind turbine, improving asset availability and power generation continuity. Automation also ensures repeatable performance across segments, reducing variability between inspection cycles and making the entire process more predictable and efficient.[13]

8.4.2 Enhanced Safety Through Reduced Human Exposure

Operational efficiency is closely tied to safety, as the automated workflow minimizes worker exposure to confined spaces, ladder climbs, and elevated maintenance environments typically encountered inside wind-turbine towers. With the robotic system taking over inspection and torquing responsibilities, personnel no longer need to perform physically demanding or high-risk activities such as reaching around narrow passageways or balancing on internal platforms. This reduction in human presence significantly lowers the likelihood of accidents, falls, or fatigue-related errors during extended maintenance sessions. The system's ability to independently stabilize itself, reach bolts at multiple depths, and apply controlled torque ensures that every operation is carried out under consistently safe mechanical conditions. As a result, both safety compliance and operational reliability are improved while reducing the number of technicians required onsite.

8.4.3 Shortened Inspection Cycles and Higher Asset Availability

The automated workflow compresses inspection cycle times by removing repetitive manual steps, such as relocating ladders, manually rotating positions, or individually accessing bolts in difficult-to-reach areas. Once deployed at a segment, the device performs stabilization, inspection, and torque actions in a continuous flow, thereby reducing downtime per segment and speeding up the overall tower-wide maintenance process. Faster cycle completion translates directly into higher turbine availability, as the system returns to power production sooner. This efficiency makes the robotic solution ideal for large-scale wind farms where multiple turbines require regular bolt maintenance, allowing operators to manage larger fleets with reduced maintenance overhead. In high-volume environments, the time saved on each turbine adds up to substantial operational gains.

9. Conclusion

The proposed robotic inspection and torque-maintenance architecture demonstrate strong potential for achieving high bolt-coverage efficiency, structural stability, torque accuracy, and overall operational effectiveness within wind-turbine towers. By integrating mechanical innovations such as the rotating plate assembly, multi-axis articulated arms, and the rack-and-pinion stabilization flange with an ECU-supervised control framework, the system delivers a high degree of automation, repeatability, and robustness. These components work cohesively to minimize human exposure to hazardous tower environments while ensuring consistent inspection and tightening quality across all tower segments. The ECU-driven workflows, combined with a comprehensive data-logging framework and tightly regulated torque-application process, enhance the reliability and traceability of maintenance operations. Although the design-level analysis indicates significant advantages over traditional manual practices, quantitative prototype testing will be essential to validate performance with respect to bolt-coverage rate, torque precision, cycle-time efficiency, and stabilization effectiveness. The results of these evaluations will guide further optimization and support the system's progression toward real-world deployment in wind-energy maintenance environments.

References

[1] Moreau, Louis. (2024). Optical and Structural Developments in Air Traffic Control Tower Glazing. Challenging Glass Conference Proceedings. 9. 10.47982/cgc.9.624. https://www.researchgate.net/publication/381475228_Optical_and_Structural_Developments_in_Air_Traffic_Control_Tower_Glazing

[2] Zhang, J.; Luo, W.; Chen, T.; Yan, X.; Zhang, J.; Zhu, M.; Zhang, H. Analysis and Experimental Study of Contact Stress in Bolted Connections of Pitch Bearings. Lubricants 2025, 13, 129. **https://doi.org/10.3390/lubricants13030129**

[3] J. Liu et al., Experimental and numerical studies of bolted joints subjected to axial excitation, Wear (2016) [2] X. Jiang et al., Investigation into the loosening mechanism of bolt in curvic coupling subjected to transverse loading, Eng. Fail. Anal., (2013) [3] N.G. Pai et al., Three-dimensional finite element analysis of threaded fastener loosening due to dynamic shear load, Eng. Fail. Anal., (2002) [4] N.G. Pai et al., Experimental study of loosening of threaded fasteners due to dynamic shear loads, J. Sound Vib. (2002) [5] X.J. Jiang et al., Investigation into the loosening mechanism of bolt in curvic coupling subjected to transverse loading, Eng. Fail. Anal., (2013) [6] N. Liu et al. A simplified continuum damage mechanics based modeling strategy for cumulative fatigue damage assessment of metallic bolted joints, Int. J. Fatigue, (2020) [7] J. Wang et al., Fatigue behavior of stainless steel bolts in tension and shear under constant-amplitude loading Int. J. Fatigue, (2020) [8] S.M. Hosseini et al., Behavior of blind bolt shear connectors subjected to static and fatigue loading, Eng. Struct., (2020) [9] Y.Y. Jiang et al., An experimental study of self-loosening of bolted joints, J. Mech. Des., (2004) **https://doi.org/10.22214/ijraset.2025.66977**

[4] Sun, H.; Dong, J.; Liu, H.; Shi, W.; Feng, Q.; Yao, K.; Huang, S.; Peng, L.; Cai, Z. Review of Non-Destructive Testing for Wind Turbine Bolts. Sensors 2025, 25, 5726. https://doi.org/10.3390/s25185726

[5] Ahmed, Ali. (2024). HOIST MECHANISM DESIGN. 10.13140/RG.2.2.16435.64809. https://www.researchgate.net/publication/378863038_HOIST_MECHANISM_DESIGN

[6] Luan, X.; Yu, H.; Ding, C.; Zhang, Y.; He, M.; Zhou, J.; Liu, Y. A Review of Research on Precision Rotary Motion Systems and Driving Methods. Appl. Sci. 2025, 15, 6745. https://doi.org/10.3390/app15126745

[7] Hassan, I.U.; Panduru, K.; Walsh, J. An In-Depth Study of Vibration Sensors for Condition Monitoring. Sensors 2024, 24, 740. https://doi.org/10.3390/s24030740

[8] K.Suganyadevi. (2022). A Multicore ECU-Based Automotive Software Domain Combining Runnable Sequencing and Task Scheduling. https://www.researchgate.net/publication/374700271_A_Multicore_ECU-Based_Automotive_Software_Domain_Combining_Runnable_Sequencing_and_Task_Scheduling

[9] Alam, Md Swawibe Ul. (2018). Securing Vehicle Electronic Control Unit (ECU) Communications and Stored Data. https://www.researchgate.net/publication/327828954_Securing_Vehicle_Electronic_Control_Unit_ECU_Communications_and_Stored_Data

[10] J.; Du, S.; Kallweit, S.; Duelberg, E.; Engemann, H. Design of a Multi-Robot System for Wind Turbine

Maintenance. Energies 2020, 13, 2552. https://doi.org/10.3390/en13102552

[11] Jianyu, Duan & Wang, Zhen & Jing, Xiaopu & Nan, Jiangfeng. (2025). Integrated brake system functions safety analysis, design and validation. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 240. 10.1177/09544070251318177. https://www.researchgate.net/publication/389160927_Integrated_brake_system_functional_safety_analysis_design_and_validation

[12] Tarte, Shrinivas. (2020). Different methods of torque auditing for inspection of torque on tightened bolts. https://www.researchgate.net/publication/346627524_Different_methods_of_torque_auditing_for_inspection_of_torque_on_tightened_bolts

[13] Ajiga, Daniel & Okeleke, Patrick & Folorunsho, Samuel & Ezeigweneme, Chinedu. (2024). The role of software automation in improving industrial operations and efficiency. 10.53430/ijeru.2024.7.1.0031. https://www.researchgate.net/publication/383410390_The_role_of_software_automation_in_improving_industrial_operations_and_efficiency