Development of a Robotic System for Wind Turbine Tower Bolt Inspection and Maintenance

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Abstract: ***Manual inspection and tightening of tower section studs with nuts in wind turbines is a labour-intensive and high-risk task, often performed at significant heights under challenging environmental conditions. This process not only consumes considerable amounts of time but also exposes technicians to potential safety hazards. To address these challenges, a Robotic Tower Bolt Inspection and Tightening is proposed. This system is designed to autonomously navigate to the interface of tower sections, identify and assess the tightness of section bolts using integrated torque sensors and vision-based inspection modules, and perform corrective tightening where necessary. Equipped with advanced mobility mechanisms, the robot can operate in vertical and confined spaces, ensuring comprehensive coverage of all the bolt locations. Real-time data acquisition and wireless communication enable remote monitoring and control, reducing the need for human intervention. The system enhances operational safety, improves maintenance efficiency, and ensures consistent bolt tensioning, which is critical for the structural integrity and longevity of wind turbines. This paper presents the design, functionality, and advantages of the robotic system, maintenance practices in the wind energy sector through automation, and intelligent inspection.***

Keywords: Robotic inspection, Bolt tightening, Torque sensors, Vision-based inspection, Autonomous navigation, Real-time data acquisition, Wireless communication, Advanced mobility mechanisms, Vertical and confined space operation, Remote monitoring and control

1. Introduction

Wind energy has emerged as a leading source of renewable power, contributing significantly to global efforts to reduce carbon emissions and transition to sustainable energy systems. Wind turbines, the core components of wind farms, are complex structures composed of several critical parts, including the tower, nacelle, rotor, and blades[1]. Among these, the tower plays a vital role in supporting the entire turbine's structure and elevating the rotor to heights where wind speeds are optimal for energy generation. The tower is typically assembled in sections, joined together using bolts and nuts that must be securely tightened to ensure structural integrity and safe operation.

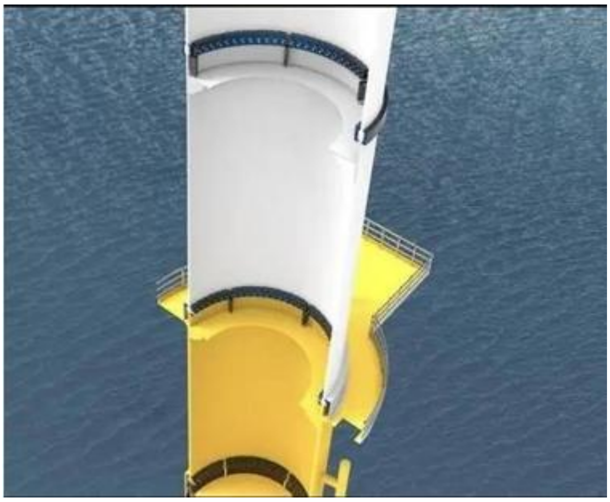


Figure 1

Figure 2

Manual inspection and tightening of these nuts is a labour-intensive and time-consuming process. Technicians must climb to considerable heights, often in challenging weather conditions, to perform these tasks. This not only slows down maintenance operations but also poses significant safety risks, including falls, fatigue, and exposure to high winds. As wind farms expand and turbine size increases, the need for safer, faster, and more reliable maintenance solutions becomes increasingly urgent.

Figure 3

To address these challenges, the development of a robotic system capable of performing automated inspection and tightening of tower section nuts presents a transformative solution. A robotic device would be designed to navigate the tower structure, identify loose or improperly torqued nuts, and apply the necessary force to secure them all without human intervention[2]. Equipped with sensors, cameras, and torque tools, the robot can ensure consistent and accurate maintenance, reducing human errors and improve overall turbine tower reliability[3].

The robotic system would also be capable of recording inspection data, enabling predictive maintenance and better asset management. By integrating with turbine monitoring systems, it can alert operators to potential issues before they become critical, minimizing downtime and repair costs[4]. Additionally, the robot can operate in harsh environments, extending maintenance capabilities to offshore wind farms and remote locations where manual inspection is even more difficult.

The development of robotic equipment for tower sections, nut inspections, and tightening not only enhances safety and efficiency but also supports the broader goals of sustainable energy production. It represents a significant step forward in automating wind turbine maintenance, ensuring that wind energy remains a reliable and cost-effective power source for the future[5].

2. The Importance of Bolt Integrity in Wind Turbines

Wind Turbine towers are typically constructed in multiple cylindrical sections that are bolted together during installation. These bolts must be tightened to precise torque specifications to ensure the structural integrity of the tower[6]. Over time, due to vibrations, thermal expansion, and environmental stressors, these bolts can loosen, leading to structural failures if not addressed properly [7].

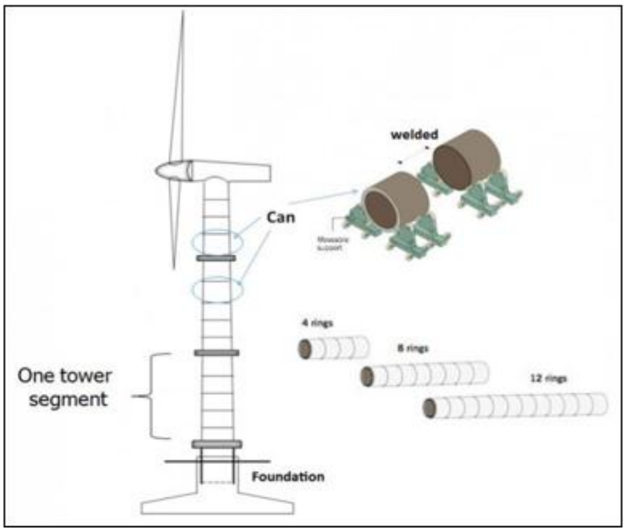


Figure 4

Loose bolts can cause misalignment between tower sections, increased wear and tear, and even catastrophic collapse in extreme cases. Therefore, regular inspection and maintenance of these bolts are critical to the safe and efficient operation of the wind turbines[8].

3. Manual Inspection: A Time-Consuming Process

Manual inspection of tower section bolts is a labour-intensive process that requires skilled technicians to climb the towers, often using ladders, lifts, or internal service elevators. Once at the inspection site, technicians must:

Visually inspect each bolt for signs of wear, corrosion, or damage. Use torque wrenches or other tools to check the tightness of each nut. Retightens any bolts to the specified torque values. This process can take several hours for the turbine, depending on the number of bolts and the accessibility of the joints. In large wind farms with dozens or even hundreds of turbines, the cumulative time and labour required for bolt inspection can be substantial.

Figure 5

Moreover, the repetitive nature of the task, combined with the physical strain of working in confined or awkward positions, can lead to the technician’s fatigue, increasing the likelihood of human errors[9]. Missed bolts, incorrect torque applications, or incomplete inspections can compromise the effectiveness of the maintenance process.

3.1 Safety Risks to Technicians

Perhaps the most pressing concern associated with manual inspection is the safety of the technicians performing the tasks. wind turbine towers exceed 100 meters in height, and technicians are often required to work at these heights for extended periods[10].

3.2 The risks include

Despite the use of safety harnesses, fall arrest systems, and other protective equipment, the risk of falling remains a serious hazard. A momentary lapse in attention, equipment malfunction, or sudden gust of wind can result in a fall with potentially fatal consequences.

Wind turbines are often situated in remote or offshore areas, where weather conditions can be unpredictable and harsh [11]. High winds, rain, snow, or extreme temperatures can make climbing and working on the tower dangerous. These conditions not only increase the risk of accidents but also limit the time windows during which maintenance can be safely performed [12].

Figure 6

The physical demands of climbing, carrying tools, and working in awkward positions can lead to musculoskeletal injuries and fatigue. overtime, this can reduce the efficiency and effectiveness of technicians and increase the risk of long-term health issues[13]. In the event of an accident or medical emergency, the remote location and height of the turbine can delay emergency response and complicate rescue operations. This adds another layer of risk to an already hazardous task[14].

3.3 System Overview

The robotic equipment is designed to autonomously inspect and tighten tower section nuts. It consists of several integrated components that work together to perform the required operations. The system is lifted to the tower section interface using designated lifting points on the main base frame. Once in position, the robot performs inspection and tightening tasks using a combination of mechanical movements, electrical drives, and vision-based guidance[2].

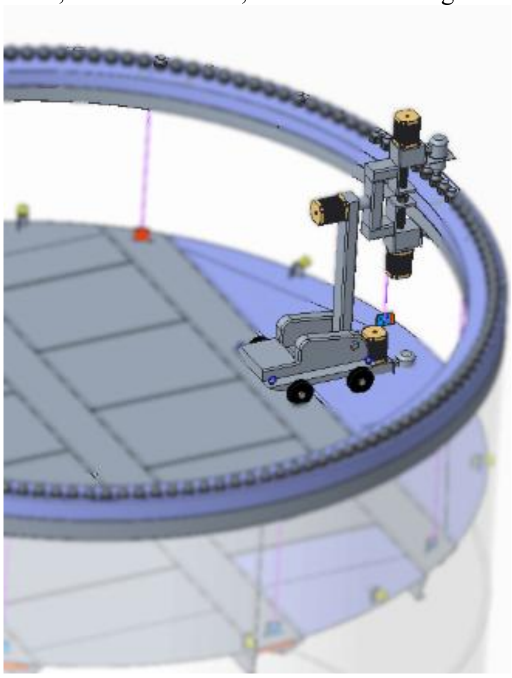


Figure 7

4. Mechanical Design and Components:

4.1 Base frame and Lifting Mechanism:

The base frame serves as a foundation of the robotic system. It is equipped with a system that allows the entire equipment to be hoisted to the tower section interface using cranes or hoists. The frame is designed to be lightweight and robust, capable of withstanding the mechanical stresses encountered during operation[15].

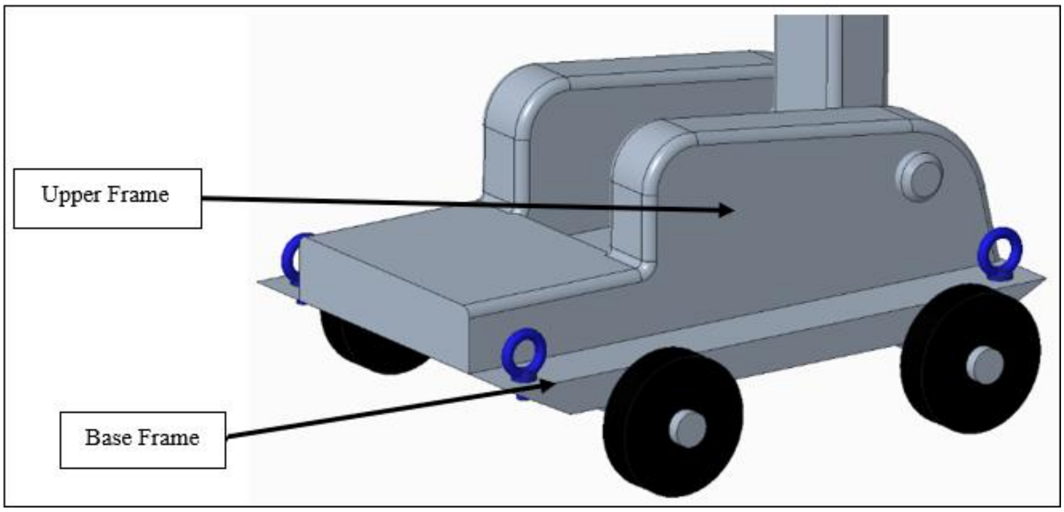


Figure 8

4.2 Upper Frame and Pivot Mechanism:

The upper frame is pivoted to the base frame and rotates about a vertical axis. This pivoting action allows the robot to align itself on the bolt interface on either side of the tower flange. The rotation is controlled by an electrical drive, enabling precise positioning of the tool frame for inspection and tightening.

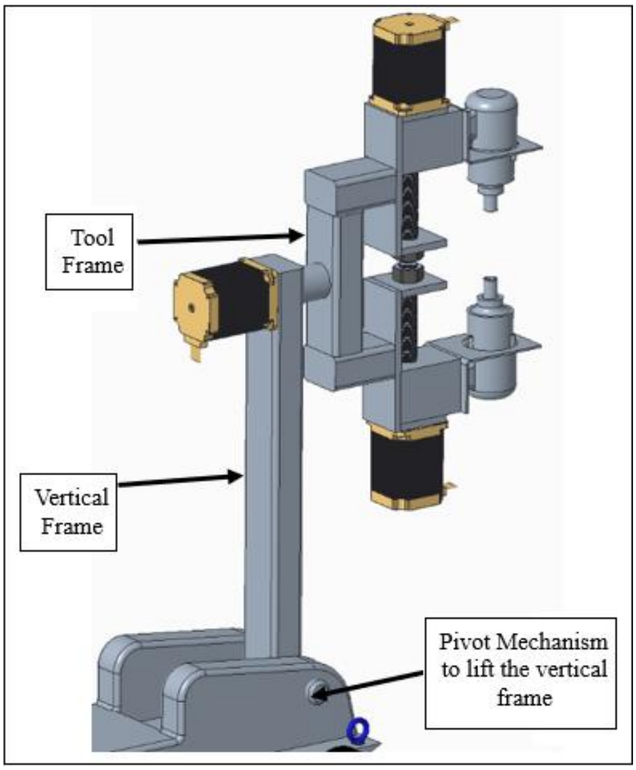


Figure 9

4.3 Vertical frame and tilting mechanism:

The vertical frame is linked to the upper frame and can tilt to reach the interference area. This tilting mechanism provides the necessary adjustment to access the bolts located at different positions around the flange[16]. The tilt is actuated by an electrical motor and controlled through feedback sensors to ensure accurate alignment[17].

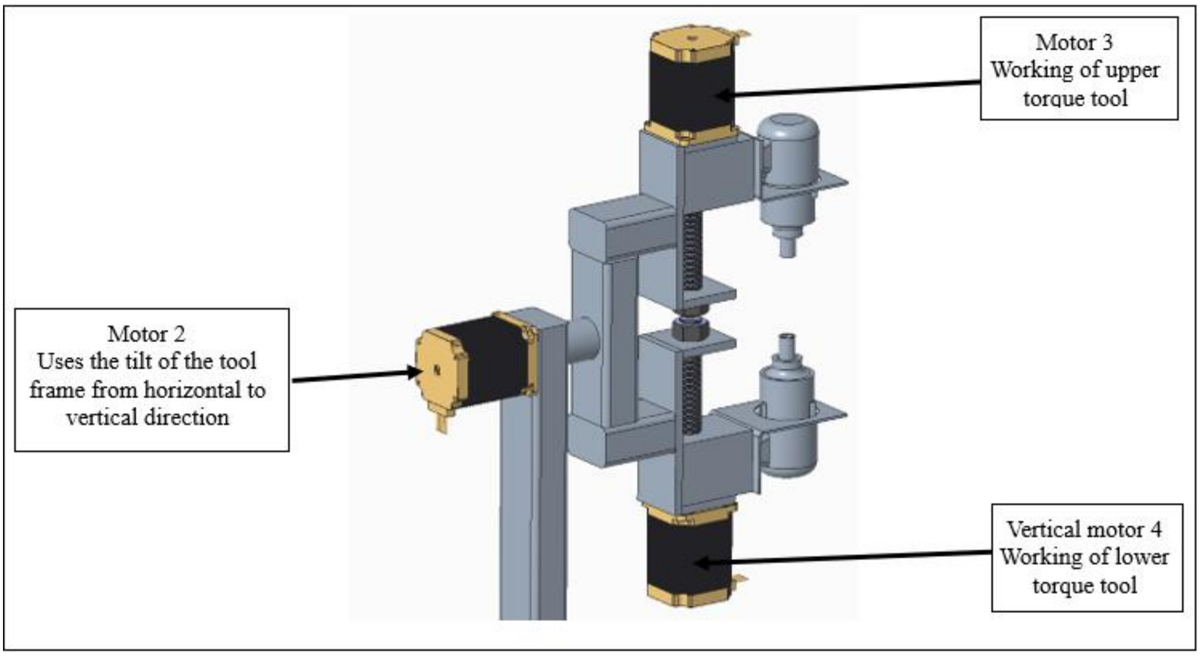


Figure 10

4.4 Tool Frame and screw mechanism:

The tool frame houses the inspection and tightening tools. It is mounted on a lead screw mechanism driven by an electrical motor. This mechanism allows vertical adjustment of the tool frame, enabling the robot to reach bolts at various heights along the flange[18]. The led screw provides precise linear motion and is equipped with limit switches to prevent overtravel.

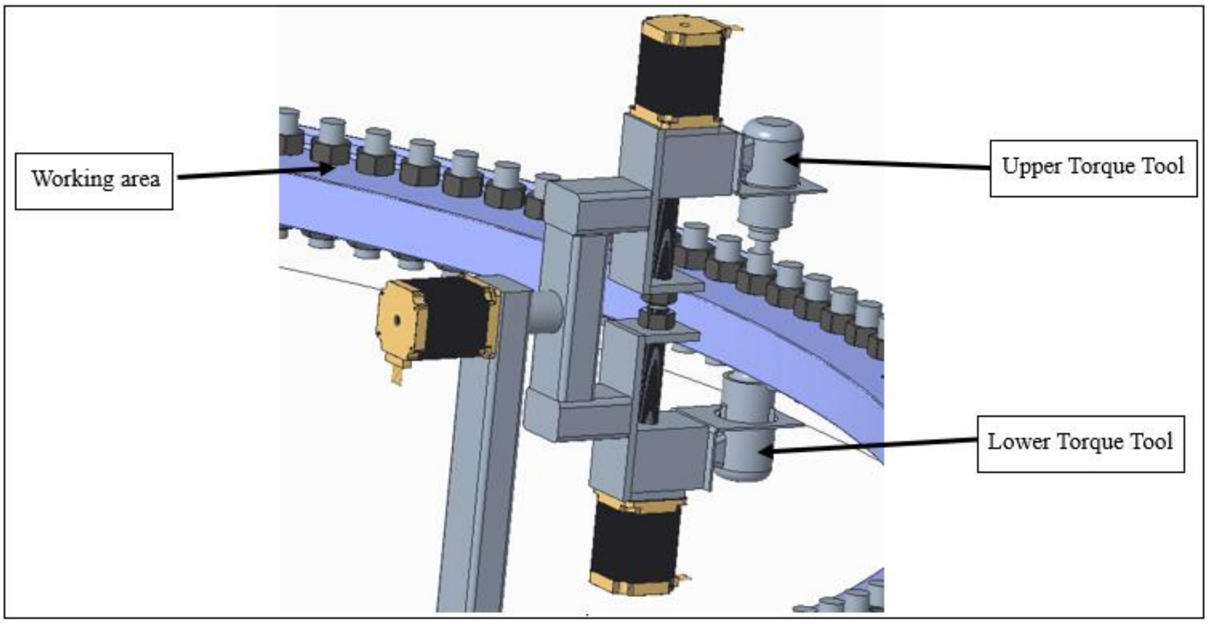


Figure 11

4.5 Inspection and tightening subsystem

The torque tool is mounted on the tool frame and is responsible for tightening the nuts to the specified torque values. It is electrically driven and equipped with a torque sensor that measures the applied force in real time. The tool is designed to accommodate different bolt sizes and can be programmed to apply varying torque levels based on the bolt specifications[19]. The robot is equipped with image-capturing cameras that serve multiple purposes. The camera helps in positioning the robot accurately relative to bolt interference. High-resolution images are captured to assess the condition of each bolt, including signs of wear, corrosion, or misalignment[20]. Images and videos are stored for maintenance records and future analysis. The vision system is integrated with an AI-based image processing algorithm to enhance detection accuracy and enable automated decision–making[21].

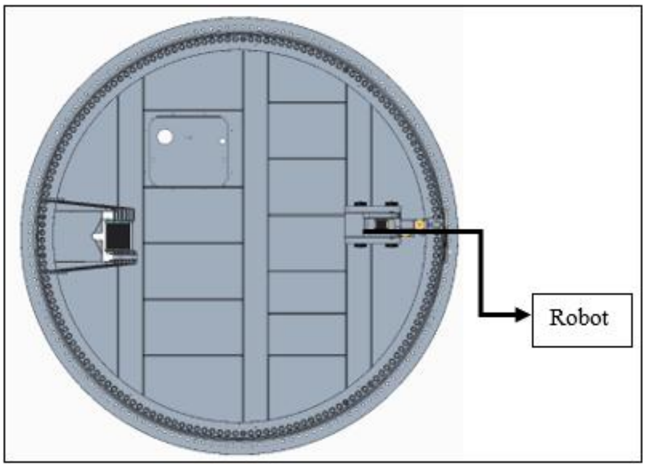
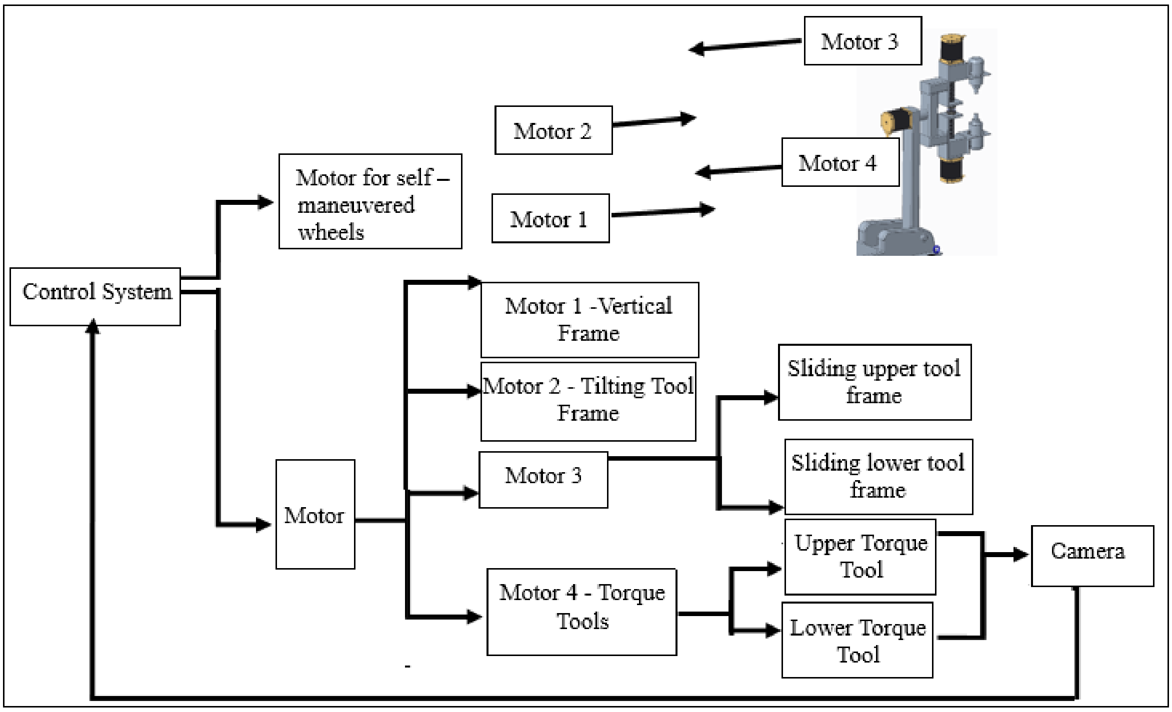


Figure 12: (Top View from the Nacelle section)

5. Control Systems and Operational Workflow

The robotic system is governed by an integrated control architecture that synchronizes all mechanical and electrical subsystems to ensure precise and safe operation. At its core is an embedded controller responsible for managing motor drives, interpreting sensor inputs, and handling communication protocols. A user interface enables remote monitoring and control, allowing technicians to supervise operations from a safe location[22]. Safety features such as emergency stop mechanisms, fault detection systems, and recovery protocols are embedded to ensure compliance with industrial safety standards[23].



Schematic Diagram of the Wind Turbine Bolt Inspection and Maintenance Robot

The operational workflow begins with the deployment in the tower section interface using designated lifting points on the base frame. Once positioned, the upper frame pivots to align with the bolt interference, followed by tilting of the vertical frame to access the flange area. The lead screw mechanism then adjusts the vertical position of the tool frame to match the bolt height. Cameras guide the inspection process, capturing high-resolution images for analysis. The torque tool subsequently applies the required torque to each nut. All inspection and tightening data are logged and transmitted for review and maintenance planning [24].

6. Design Consideration

The design of the robotic equipment was guided by several critical engineering principles. Structural integrity was prioritized to ensure the system could withstand operational loads and environmental stresses encountered at turbine heights[25]. Precision in the positioning of torque application was essential for effective bolt maintenance. Modularity was incorporated to facilitate easy replacement of components and adaptability across different turbine models. durability was ensured through the selection of corrosion-resistant materials and vibration-tolerant components[26]. finally, the system was developed in accordance with electrical and mechanical safety standards to guarantee reliable and secure operation in field conditions.

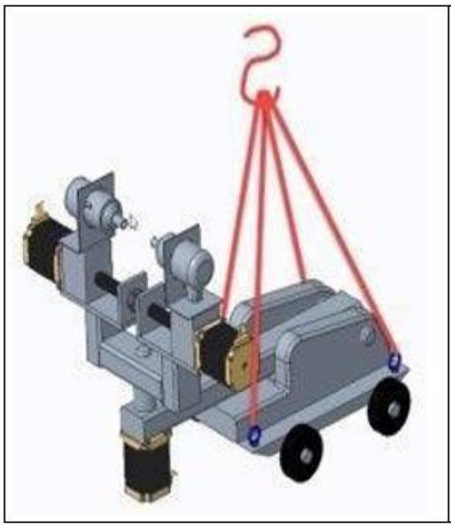


Figure 13

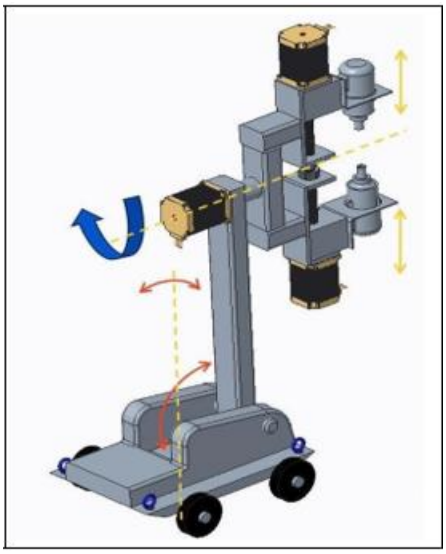


Figure 14

The development of this robotic system offers transformative benefits over conventional manual methods. safety is significantly enhanced by minimizing technician exposure to hazardous environments. operational efficiency is improved through faster inspection and tightening cycles, reducing turbine downtime. the system ensures consistent quality by applying uniform torque and conducting assessments. Real-time data acquisition supports predictive maintenance strategies, enabling proactive fault management. Collectively, these advantages contribute to substantial cost savings in labour, maintenance, and energy production losses[27].

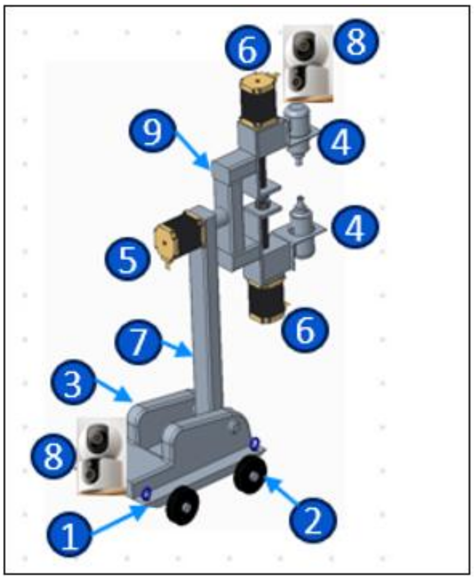


Figure 15

Main Components:
1) Main Chassis / Base Frame
2) Self Maneuvered wheels
3) Upper Frame pivoted to the base frame
4) Torquing Tool
5) Electrical Drive for tilting Tool frame
6) Electrical Drive for tool
7) Vertical Frame
8) Image Capturing & Guiding Camera
9) Tool frame

Although primarily designed for wind turbine tower maintenance, the robotic system's architecture is versatile and can be adapted for other vertical infrastructure applications. These include transmission tower inspections, industrial chimney maintenance, and servicing of offshore platform bolts[28]. Future enhancements include the integration of multi-functional tools for cleaning and lubrication. AI-driven fault classification for autonomous decision making, cloud-based analytics for fleet-wide optimization, and autonomous deployment systems for remote and offshore operations. These developments will further expand the system's capabilities and its role in intelligent infrastructure maintenance[29].

References

[1] Qusay Hassan, Sameer Algburi, Aws Zuhair Sameen, Hayder M. Salman, Marek Jaszczur, A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications, Results in Engineering, Volume 20, 2023, 101621, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2023.101621.

[2] Mohammed Eesa Asif, Alireza Rastegarpanah, Rustam Stolkin, Robotic disassembly for end-of-life products focusing on task and motion planning: A comprehensive survey, Journal of Manufacturing Systems, Volume 77, 2024, Pages 483-524, ISSN 0278-6125, https://doi.org/10.1016/j.jmsy.2024.09.010.

[3] Mohd Javaid, Abid Haleem, Ravi Pratap Singh, Rajiv Suman, Substantial capabilities of robotics in enhancing industry 4.0 implementation, Cognitive Robotics, Volume 1, 2021, Pages 58-75, ISSN 2667-2413, https://doi.org/10.1016/j.cogr.2021.06.001.

[4] Mohsen Soori, Behrooz Arezoo, Roza Dastres, Artificial intelligence, machine learning and deep learning in advanced robotics, a review, Cognitive Robotics, Volume 3, 2023, Pages 54-70, ISSN 2667-2413, https://doi.org/10.1016/j.cogr.2023.04.001.

[5] Khalid, Omer & Hao, Guangbo & Desmond, Cian & Macdonald, Hamish & Devoy McAuliffe, Fiona & Dooly, Gerard & Hu, Weifei. (2022). Applications of robotics in floating offshore wind farm operations and maintenance: Literature review and trends. Wind Energy. 25. https://doi.org/10.1002/we.2773.

[6] Wout Weijtjens, Andre Stang, Christof Devriendt, Peter Schaumann, Bolted ring flanges in offshore-wind support structures - in-situ validation of load-transfer behaviour, Journal of Constructional Steel Research, Volume 176, 2021, 106361, ISSN 0143-974X, https://doi.org/10.1016/j.jcsr.2020.106361.

[7] Bohai Tan, Tao Wang, Qian Fang, Dan Yang, Hu Wang, Guangtao Lu, Bolt looseness monitoring using dynamic mode decomposition with piezoelectric active sensing, Measurement, Volume 238, 2024, 115204, ISSN 0263-2241, https://doi.org/10.1016/j.measurement.2024.115204.

[8] Valdez, Rhandall & Palacios, Edwin & Tutivén Gálvez, Christian & Segui, Yolanda. (2024). Bolt-loosening detection in offshore wind turbines' jacket-type supports. Structural Health Monitoring. https://doi.org/10.1177/14759217241268522

[9] Yeow, Jian & Ng, Poh Kiat & Tan, Khong & Chin, Tee & Lim, Wei. (2014). Effects of Stress, Repetition, Fatigue and Work Environment on Human Error in Manufacturing Industries. Journal of Applied Sciences. 14. 3464-3471. https://doi.org/10.3923/jas.2014.3464.3471

[10] Milligan, Gemma & O Halloran, Joseph & Tipton, Mike. (2019). A Job Task Analysis for Technicians in the Offshore Wind Industry. Work. 63. 1-9. https://doi.org/10.3233/WOR-192961

[11] Bosubabu Sambana, P. Appala Naidu, Ranga Jarabala, V.N.S.L. Narayana, Performance validation of wind turbines using machine learning methodologies, Materials Today: Proceedings, Volume 80, Part 3, 2023, Pages 2845-2849, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.07.049.

[12] Dinakaran, M. & V, Manoj. (2025). Innovative Safety Measures for Chimney Construction in Thermal Power Plants. International Research Journal on Advanced Engineering Hub (IRJAEH). 3. 990-1003. https://doi.org/10.47392/IRJAEH.2025.0142.
[13] Odebiyi, Daniel & Okafor, Udoka. (2023). Musculoskeletal Disorders, Workplace Ergonomics and Injury Prevention. 10.5772/intechopen.106031. https://doi.org/10.5772/intechopen.106031.
[14] Soren Pedersen, Dewan Ahsan, Emergency preparedness and response: Insights from the emerging offshore wind industry, Safety Science, Volume 121, 2020, Pages 516-528, ISSN 0925-7535, https://doi.org/10.1016/j.ssci.2019.09.022.
[15] Masashi Kotobuki, Binggong Yan, Li Lu, Recent progress on cathode materials for rechargeable magnesium batteries, Energy Storage Materials, Volume 54, 2023, Pages 227-253, ISSN 2405-8297, https://doi.org/10.1016/j.ensm.2022.10.034.
[16] Chao Li, Nan Pang, Kai Xu, Qingling Geng, Xiangyu Wang, Feihong Yun and Lei Gao, Open Access Article, Application of Multi-Cylinder Synchronous Control for Telescopic Mechanism of Marine Steel Pile Cleaning Equipment, https://doi.org/10.3390/jmse11051010
[17] Redekar, Abhijeet & Deb, Dipankar & Ozana, Stepan. (2022). Functionality Analysis of Electric Actuators in Renewable Energy Systems—A Review. Sensors. 22. 4273. https://doi.org/10.3390/s22114273.
[18] Roy A. Parisher, Robert A. Rhea, Chapter 5 - Valves, Editor(s): Roy A. Parisher, Robert A. Rhea, Pipe Drafting and Design (Fourth Edition), Gulf Professional Publishing, 2022, Pages 87-117, ISBN 9780128220474, https://doi.org/10.1016/B978-0-12-822047-4.00007-8.
[19] Heeyeon Jeong, Kyungjun Choi, Seong Jun Park, Cheol Hoon Park, Hyouk Ryeol Choi and Uikyum Kim, Rugged and Compact Three-Axis Force/Torque Sensor for Wearable Robots. https://doi.org/10.3390/s21082770
[20] Alan Bole, Alan Wall, Andy Norris, Chapter 1 - Basic Radar Principles, Editor(s): Alan Bole, Alan Wall, Andy Norris, Radar and ARPA Manual (Third Edition), Butterworth-Heinemann, 2014, Pages 1-28, ISBN 9780080977522, https://doi.org/10.1016/B978-0-08-097752-2.00001-5.
[21] Leila Farahzadi, Ibrahim Odeh, Mahdi Kioumarsi, Behrouz Shafei, Automated image-based condition assessment of the built environment: A state-of-the-art investigation of damage characteristics and detection requirements, Results in Engineering, Volume 26, 2025, 104978, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2025.104978.
[22] Ronit Shah, Arockia Selvakumar Arockia Doss, Natrayan Lakshmaiya, Advancements in AI-enhanced collaborative robotics: towards safer, smarter, and human-centric industrial automation, Results in Engineering, Volume 27, 2025, 105704, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2025.105704.
[23] Abid Haleem, Mohd Javaid, Ravi Pratap Singh, Encouraging Safety 4.0 to enhance industrial culture: An extensive study of its technologies, roles, and challenges, Green Technologies and Sustainability, Volume 3, Issue 3, 2025, 100158, ISSN 2949-7361, https://doi.org/10.1016/j.rineng.2025.105704.
[24] Dario Croccolo, Massimiliano De Agostinis, Stefano Fini, Muhammad Yasir Khan, Mattia Mele And Giorgio Olmi, Optimization of Bolted Joints: A Literature Review https://doi.org/10.3390/met13101708.
[25] Esmaeil Zavvar, Paulo Rosa-Santos, Francisco Taveira-Pinto, Elyas Ghafoori, Lifetime extension of offshore support structures of wind turbines: A review, Renewable and Sustainable Energy Reviews, Volume 217, 2025, 115788, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2025.115788.
[26] Xuecheng Luan, Hanwen Yu, Chunxiao Ding, Ying Zhang, Mingxuan He, Jinglei Zhou, Yandong Liu, A Review of Research on Precision Rotary Motion Systems and Driving Methods, Volume 15, Issue 12, https://doi.org/10.3390/app15126745
[27] Rana, Sohel. (2025). AI-DRIVEN FAULT DETECTION AND PREDICTIVE MAINTENANCE IN ELECTRICAL POWER SYSTEMS: A SYSTEMATIC REVIEW OF DATA- DRIVEN APPROACHES, DIGITAL TWINS, AND SELF-HEALING GRIDS. American Journal of Advanced Technology and Engineering Solutions. 01. 258-289. https://doi.org/10.63125/4p25x993
[28] Omara, Ahmed & Nasser, Adel & Alsayed, Ahmad & Nabawy, Mostafa. (2025). Towards Multimodal Robot Design for Wind Turbine Inspections. https://doi.org/10.2514/6.2025-0843
[29] Hussain, Md & Rahman, Md & Ramasamy, Devarajan. (2024). Artificial Intelligence-Driven Vehicle Fault Diagnosis to Revolutionize Automotive Maintenance: A Review. Computer Modeling in Engineering & Sciences. 141. 951-996 https://doi.org/10.32604/cmes.2024.056022