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Research Article

Scalable Comprehensive Automatic Inspection, Cleaning, and Evaluation Mechanism for Large-Diameter Pipes

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Cleaning and inspection of pipelines and gun barrels are crucial for ensuring safety and integrity to extend their lifespan. Existing automatic inspection approaches lack high robustness, as well as portability, and have movement restrictions and complexity. This study presents the design and development of a scalable, comprehensive automated inspection, cleaning, and evaluation mechanism (CAICEM) for large-sized pipelines and barrels with diameters in the range of 105 mm–210 mm. The proposed system is divided into electrical and mechanical assemblies that are independently designed, tested, fabricated, integrated, and controlled with industrial grid controllers and processors. These actuators are suitably programmed to provide the desired actions through toggle switches on a simple housing subassembly. The stress analysis and material specifications are obtained using ANSYS to ensure robustness and practicability. Later, on-ground testing and optimization are performed before industrial prototyping. The inspection system of the proposed mechanism includes barrel-mounted and brush-mounted cameras with sensors utilized to keep track of the pipeline deposits and monitor user activity. The experimental results demonstrate that the proposed mechanism is cost-effective and achieves the desired objectives with minimum human efforts in the least possible time for both smooth and rifled large-diameter pipes and barrels.

Keywords: automatic inspection; gun barrel inspection system; in-pipe cleaning; intelligent systems; large-diameter pipe inspection; rifled pipe inspection

1. Introduction

The regular cleaning and inspection of pipelines and gun barrels are crucial to ensure their safety and integrity for an extended lifespan. However, the manual techniques for pipeline cleaning are inefficient in terms of time and cost. Such approaches require a significant workforce and pose severe threats to the lives of the workers. Therefore, automated inspection, cleaning, and quality evaluation are desirable to overcome the limitations of traditional approaches. Pipelines are an essential transportation medium in many industries, carrying raw materials including petroleum, gases, and waste over short to long distances [1]. Pipes are prone to damage because of corrosion, fractures, and mechanical damage, resulting in reduced productivity due to the deposited materials, erosion, and mechanical impurities. Traditionally, stainless steel is used to make industrial pipelines; hence, they are more prone to degradation over time, and it is common to have problems like loss of metal and corrosion, ultimately leading to pipe cracks, bursting, and deformations [2]. Pipelines used in the industrial sector vary in size, ranging from millimeters to meters, have complicated shapes and branches like T-shape and Y-shape, making cleaning more difficult. Therefore, using automated devices for inspection and cleaning operations is a better solution [1].

Cleaning and inspecting pipelines are regular activities to ensure the pipes' safety and integrity and prevent the problems associated with pipeline failure. Thus, damage can be minimized by comprehensive inspection, cleaning, and evaluation of the piping system. Pipeline inspection and cleaning are necessary to sustain its performance and extend its lifespan. Consequently, a pipeline that is properly designed and maintained can operate for a longer time [3]. Due to the large sizes and complex structures of pipelines, their inspection and cleaning are crucial but arduous and time-consuming [1]. Internal and external inspection is needed to ensure pipeline integrity to sustain its good condition and longevity. The tools used for inspection depend on the type of pipe. For example, in the case of large-diameter pipelines, visual inspection is the most cost-effective method, where a professional inspector checks it to identify pipeline degradation mechanisms. For metallic pipes, on the other hand, the gradual degradation results from corrosion and pitting, causing wall thinning, pinholes, and leaks [4, 5]. Automating cleaning eliminates the human aspect of labor-demanding or risky tasks and operates in an inaccessible environment. In addition, the simplified mechanism offers several advantages over manual inspection. It can maneuver easily, adjust to uneven surfaces inside pipes, move vertically, and remain stable without slipping. Automation is now widely used, extending beyond just heavy manufacturing. Cleaning and inspection tasks, which are often dirty and dangerous, are ideal for service robots to handle.

Automated technology works better and offers reduced downtime and lower costs, thereby leading to higher efficiency [6]. The manual cleaning procedure is tiresome, requiring several repetitions for in-depth cleaning that badly affects the workers' posture. Compared with manual cleaning, the automated procedures do not require multiple people and also eliminate the postural risks by reducing the physical workload [7]. In addition, automated cleaning provides higher recycling rates and produces lower sludge volume. These operations lead to higher occupational safety, reduced time needed for cleaning, and lower threat to human life in small and confined spaces [6]. An automatic cleaning apparatus for pipes usually includes a wheel and a brush rotating against the pipe's inner surface, which is applied with a cleaning solution and moved forward by wheel rotation [8]. Many automatic systems for pipeline cleaning have been developed, which offer operations from small- to large-sized pipes. The examination and cleaning of pipelines may be essential for enhancing security and efficiency with respect to industrial operations. Because specialized procedures like inspection, maintenance, and cleaning are costly, the use of automation and robots looks to be one of the most appealing options.

Advanced technologies and devices are needed to clean the inside of pipes to ensure the proper functionality of these pipes and their reliability. It is imperative to select the best from existing approaches, especially those that fulfill the operational requirements of the target industry. Despite several automated inspection methods in the existing literature, they are not general-purpose and suitable for large pipelines and gun barrels. For example, several mechanisms only offer spiral movement and have complex operational procedures. While others lack robustness and portability. Deployment of several of the mechanisms is complex when in-field cleaning is considered.

This study designs a new comprehensive automated cleaning mechanism to adapt to the piping system for inspecting and cleaning pipelines and barrels with a diameter ranging from 105 mm to 203 mm. This research aims to design an automated cleaning mechanism to complete the cleaning process with minimal manual intervention and reduce time compared to the traditional systems. The proposed CAICEM consists of a robust and rugged system powered by both alternating current (AC) and direct current (DC) power supply systems. The system has an improved brush design with separate hard and soft brushes for delicate cleaning. Furthermore, additional sensors are used to map the pipeline and localize the position of the system in the pipeline. The comprehensive mechanism can potentially inspect and clean the pipe during regular operations. The objective of the inspection system is to monitor pipe condition and detect damage to pipelines and barrels. It is important to track the damage over time, and appropriate repairs can be planned. The test case scenario for the current system is the inspection, cleaning, and evaluation of a gun barrel, but the proposed system can also be employed to pipeline architecture of varying diameters. In addition, the system possesses valuable qualities that make it different from traditional cleaning approaches. These include automation, time efficiency, cost-effectiveness, independence from the use of a particular cleaning solution, local development of the system, scalability, portability, and employability in multiple industries.

This study is further organized as follows. Section 2 gives a literature review of existing practices for cleaning in industries. Section 3 explains the conceptual design of the proposed in-pipe cleaning mechanism. Based on this conceptual design, the structural design of the proposed cleaning mechanism is described. Section 4 presents the latest cleaning and inspection results from tests, as well as stress, strain, and deformation analysis. Finally, conclusions are drawn in Section 5.

2. Related Work

This section describes the previous research work done in the civil and military sectors regarding in-pipe inspection and cleaning techniques.

2.1. In-Pipe Cleaning Robots. Pipelines allow the efficient transport of products such as crude oil, natural gas, water, and chemicals from extensive distribution networks to the targeted areas over long distances in less time. The diameter of pipelines varies depending on their type and the respective functionality. Inline inspecting and cleaning of pipelines are crucial to ensure stable working. Regular inspection of pipelines to detect defects and damages like corrosion, rusting, and cracks helps avoid catastrophic failures. However, manual inspection being time-consuming and error-prone poses severe threats to workers' health and safety because of exposure to various chemicals and substances that cause reduced levels of oxygen in the air.

To overcome these challenges, many researchers have proposed robot-based inspection and cleaning mechanisms that help remove human intervention and explore inaccessible areas. In-pipe inspection robots have been of great use for the maintenance of pipelines by inspecting and cleaning to ensure the safe operation of pipelines in industries. There are various types of in-pipe cleaning robots such as caterpillar wall-pressed, wheeled wall-pressed, and wheeled wall-pressing screws where the last type of robots are multiple locomotion type in-pipe inspection robots. They offer various advantages and help overcome the limitation of diameter adaptability of single locomotion type robots; hence, they have become a developing trend nowadays [9].

Zholtayev et al. introduce a novel in-pipe inspection robot, named SIPIR in [10]. The robot's standout in-chassis motor actuation design protects the motors inside the chassis, enhancing traction, structural robustness, and autonomous navigation within pipes measuring roughly 350–450 âĂŕmm in diameter. SIPIR leverages a combined SLAM-based control system for stable motion, using PID algorithms and RC remote control for real-time adjustments. An AI-powered defect detection pipeline employing HSV masking, Gaussian blur, Canny edge detection, DBSCAN clustering, and deep learning (DL) via MobileNet identifies anomalies such as corrosion, welding flaws, deformations, cracks, and debris. Initial experiments achieved a mean average precision (mAP) of 93% in real-time defect detection.

Ma et al. provide a comprehensive state-of-the-art review of detection technologies for underground concrete sewage pipelines in [11]. The authors categorize nondestructive testing (NDT) methods such as CCTV visual inspection, ground-penetrating radar (GPR), laser 3D scanning, LiDAR, acoustic techniques, and fiber-optic sensing, evaluating their strengths, limitations, and applicability in assessing structural integrity, leaks, corrosion, and deformation. Emphasis is placed on robots equipped with stereo vision and laser scanning for quantitative diagnostics. The study discusses the potential integration of big data analytics and AI to enhance detection accuracy and operational efficiency. The authors conclude by emphasizing the potential and need for the development of hybrid inspection platforms and intelligent data processing frameworks, suggesting these innovations as key to future resilience and proactive maintenance in pipeline infrastructure.

The study [12] proposes a novel multisensor robotic system for sewer damage inspection, integrating a DL pipeline tailored to each sensor type (cameras and LiDAR). The design is based on limitations studied for existing 2D (image) and 3D (point cloud) inspection methods. The authors identified data quality and sensor limitations that undermine DL model performance. The design includes a front camera for capturing internal pipe surfaces, a high-resolution camera array for detailed defect visualization, and a LiDAR sensor for structural distortion detection. Damage types are strategically assigned to the most suitable sensor modality, enabling optimized DL models per data source. The multisensor, model-specific integration approach yields higher accuracy in defect detection than single-sensor setups.

The authors in [13] designed a capsule-type tool and did an experimental evaluation of an inspection robot specially engineered for ondol pipelines, the underfloor hydronic heating system unique to Korean homes. Given the difficulty of accessing embedded hot-water pipes for inspection and the high costs of identifying leaks or blockages post-installation, the researchers analyzed ondol pipe characteristics, diameter, curvature, and materials to derive specific system requirements. The authors designed a compact, capsule-shaped robot capable of navigating 12- to 25-mm-diameter pipes with multiple bends. Laboratory tests confirmed its curvature maneuverability and real-time image transmission quality, validating its field applicability. The system enables operators to view live video via a smartphone app and record inspection data. This tailored robotic platform addresses a critical maintenance gap in ondol infrastructure and offers a reliable and efficient solution.

Stüwe et al. [14] present two novel data evaluation methods for detecting the onset of scaling (mineral deposits) in pipelines using resonance testing. The authors compared a supervised ML approach using random forest and an unsupervised change detection method based on cross-correlation with baseline signal data. The ML model achieves over 90% accuracy across variations in sensor types and impactor diameters, while the cross-correlation technique sensitively detects scaling onset as thin as 0.5 mm. By demonstrating reliable submillimeter sensitivity with computationally efficient processing, this work advances scalable resonance-based monitoring. Table 1 shows the properties of different in-pipe inspection robots.

2.2. Commercial Products. Debnath et al. [22] propose a cost-effective inspection robot that consumes limited power and is stable as well as reusable. A parallelogram linkage mechanism is used, and the goal is to inspect the pipes with a 100 mm–250 mm diameter. The robot has three

Table 1: Properties of in-pipe inspection robots.

Inspection robot type	Properties
Wheeled-type robots	i. Simple, adaptable in diameter, and used in pipes with horizontal sections ii. Provide less support to the robot structure during motion inside the pipeline [15]
Caterpillar-type robots	i. Used for pipes with varying diameters ii. Provide a firm hold and support to the pipeline's interior [15]
Walking-in-type robots	i. It employs a mechanically complex structure and is rarely used in industries [16] ii. They are complex, costly, and low energy efficient but have greater mobility in natural surroundings [17]
Wall-pressed type robots	i. Useful for vertical pipes ii. The flexible links in the robot help avoid slippage and provide enough force to the robot for movement in vertical pipes [18]
Inchworm-type robots	i. Infrequently used for pipes with long distances [1] ii. It is suitable for use because of its simple structure and large traction capacity, but the limitation is its large size and discontinuous motion [19]
Pipe inspection gauge (PIG) type robots	i. Commonly used for inspecting pipes of larger diameters [20] ii. The robot is driven by force from the fluid differential pressure of liquid-filled pipes. Although it does not consume energy, the movement pattern is limited [21]

chained wheels, which are separated by 120° for unrestricted movement. The robot uses the global positioning system (GPS) to track its position. The robot can crawl inside the pipeline and adjust its diameter based on the pipe's diameter. In a pipeline with fewer bends, the robot works with wheels; in case of a more significant number of bends, a belt-driven system is used for the smooth movement of the robot. However, visual inspection is carried out using a Raspberry Pi 3 camera module. Night vision camera mode is enabled to study the corrosion rate of the pipe's inner surface, and crack detection is done using the ultrasonic method. Similarly, in [23], the authors investigate various design issues concerning the development of in-pipe inspection robots. A new inspection model is proposed to overcome critical design issues, and the kinematics and dynamics of the proposed model are discussed. The proposed robot follows a screw-type approach with an adaptable wheel for in-pipe inspection of pipes with a diameter of 127 mm–152 mm. It could move quickly through bends of pipelines and vertical and horizontal sections of pipes. An initial prototype is developed and subsequently tested in different situations to validate the model's behavior.

In the work by Gargade and Ohol [24], the mechanical construction and steering mechanism of the in-pipe inspection robot are discussed. Pertaining to the complex driving mechanism of the existing in-pipe inspection robots, a simple driving mechanism is developed. The developed robot comprises a body, foreleg, rear leg system, and springs. Each leg system consists of a DC motor, belt, pulley, wheel, and spring. A coiled spring is attached to each leg and the robot's body. These springs help the robot move freely inside the pipes with a diameter of 250 mm–500 mm. The robot can pass through straight pipelines, elbows, and reducers of various diameters. However, the robot is unable to pass through T-joints. In [25], an autonomous robotic system is proposed that can inspect the collectors at a power plant using thermographic images to detect and avoid leakages. Furthermore, thermal tracking is suggested for crack detection, and the addition of a robotic arm is advised to track the pipeline while performing the inspection. In another research [26], the design and implementation of a train-like waterproof inspection robot are discussed for inline inspection of ferromagnetic pipelines. The robot consists of omnidirectional wheels and magnets. Cameras are used for real-time inspection, and sensors are used to monitor the internal condition of the pipe, like temperature and humidity. The robot is designed to inspect pipes of 127 mm diameter or larger. The robot is tested under different conditions, and the designed robot can move in both upward and backward directions in straight and elbow-fitting pipes.

The invention of an underwater pipe inspection and cleaning robot is discussed by Landsberger et al. in [16]. The robot crawls to perform the underwater inspection and cleaning of the cable within the pipe. The robot is independent of pipe geometry, and it can inspect the pipes in the presence of high-water flow rates. It can clean the debris of the pipe without shutting down the facility provided by the pipe. In the recent work [27], a pipe inspection robot was designed using soft pneumatic actuators. The robot has a sliding mechanism, a holding mechanism, and a bending unit that makes possible the quick and efficient movement of the robot in pipes of varying sizes. In addition, an interface is designed for robot monitoring and control using LABVIEW. Experimental results demonstrate the successful implementation of the proposed mechanism. A new pipeline inspection robot model named "MasterPi" is proposed to inspect gas pipelines having a diameter of 20–24 inches [28]. The robot employs a two-wheel chain adaptive mechanism and operates in translational, helical, and 360° rotation modes. In addition, the robot possesses simultaneous driving and steering capability, making it distinct from other types of robots.

The study [29] focused on designing a novel camera-based in-pipe inspection crawling robot that exploits soft elastic materials to become adaptable to pipes of varying diameters. The proposed system proves to be cost-effective and moves efficiently through straight and curved rigid pipes. In [30], the author presented an in-pipe inspection robot that offers enhanced stability and increased diameter adaptability compared to the existing screw-driven wall-pressed wheel-type in-pipe robots. The robotic system comprises a rigid body, two driving leg systems, two supporting leg systems, and an improved spring design. Experimental validation of the system showed that the robot smoothly traveled along vertical and horizontal pipelines with a diameter of 8–10 inches. The system is applicable for inspecting water, gas, and drain pipelines. The work presented by Vikram [31] focused on designing a miniature in-pipe inspection robot for narrow surface pipelines using a DC motor. Modeling of the robot was done in SolidWorks, and the simulations were performed to evaluate the performance of the robot.

Along the same lines, in [32], the author proposed a novel in-pipe robot inspection mechanism that helps the robot avoid obstacles. The robot has robust multivariable control in the presence of flow, and it is verified in a MATLAB simulation. Researchers proposed a modified version of a caterpillar-type robot that resembles an elephant's trunk. The modification aims to ease the locomotion of the robot in pipe bends and junctions [33]. The work of Alnaimi et al. highlighted an innovative approach to the design and development of pipeline inspection gauges (PIGs). The aim is to inspect and clean the pipes with a diameter of 6–14 inches. The PIG system comprises a DC motor, battery, DC controller, and radio transmitter. To inspect the pipeline with enhanced precision, Arduino software was used to generate simulated images of pipelines. The system was improved in terms of varying diameter adaptability, intense cleaning, and no fluid hammer effect; hence, it provides a fast and trouble-free solution for pigging operation [2]. A new pipe inspection robot design method based on the principle of pressing against the septum wheel was proposed by Moshayedi et al. The CATIA toolbox was used to design the robot. The robot structure can adapt itself to different pipe sizes [34].

2.3. Military Products. The barrels of guns are very important and need to be maintained properly. For normal operations and long life, barrels are cleaned after every use. A research study by Nam et al. [7] addressed the postural risks caused by the existing push and pull mechanism of gun barrel cleaning. The manual cleaning method is proven to be time-inefficient, unsafe, and tiring because of awkward postures, causing musculoskeletal disorders, and requires greater manpower as multiple soldiers perform the cleaning task. In comparison, the proposed ergonomic gun barrel cleaning method is time-efficient, does not involve pushing and pulling, requires only 1 soldier to operate the system, and has a greater safety index because of reduced postural disorder risks. The system only takes 20 min to perform the cleaning of the gun barrel and hence increases military power.

The proposal of An [8] focuses on an automated cleaning apparatus for a gun barrel to avoid the use of a conventional complicated driving system. The apparatus consists of wheels, a brush, and a planetary gear system. In the cleaning process, the outer surface of the wheel is in contact with the inner surface of the barrel, and the apparatus moves inside the gun barrel when the wheels rotate. By using a pump, a cleaning solution is applied, and the brush rotates against the barrel's inner surface by a planetary gear system. The objective of the automatic cleaning apparatus is to avoid component failure to operate the brush by avoiding excessive load on motors and to clean the gun barrel with a simple planetary gear system. Similarly, Blackburn et al. [35] proposed a tool for gun barrel cleaning. The cleaning tool consists of a handle, a lock member, and a barrel-shaped cleaning element. The tool is convenient and adaptable to barrels of varying diameters. By changing the outer diameter of the cleaning portion, the cleaning of gun barrels having different sizes can be done.

Carlton designed a tool to clean gun barrels efficiently. The cleaning device has a compression sleeve, a coupling member, and a retaining member. The device is adjustable to varying sizes and uses sponge-type cleaning swabs to remove the powder residues from the gun barrel [36]. Similarly, Bice performs gun barrel cleaning by using a device engaged with a conventional battery-powered reversible electric screwdriver. The device contains an elongated shaft, depending on the size of the gun barrel to be cleaned. The invention provides an advantageous power-driven cleaning tool [37]. Thomas Peterson discussed a gun barrel cleaning device that is based upon a quick-detachable coupling mechanism [38]. The invention of Hopkins is concerned with the devices for cleaning the gun's bores. The existing mechanism of gun barrel cleaning, such as brushes, swabs, and clothes, has the limitation of improper cleaning of rifled gun barrels. Hence, the present invention specifically focuses on helically rifled gun barrels. The objective is to compose an enhanced cleaning device suitable for small- and large-bore gun barrels, to carry out fast and in-depth cleaning. The aim is to use the wiping member in the device that can be removed and replaced easily whenever it becomes dirty. Another objective of the invention is a simple structure, effective operation, and minimum production cost [39].

Usually, the bore cleaning process includes a cleaning brush with a cleaning solution and takes about 1 h to bring a bore to wear-inspection standards. A new solventless bore cleaning technique was discussed by Bundy et al. [40] that employed silicon carbide grit impregnated on a nylon bristle brush. The proposed technique proved to be time-efficient, requires less manpower, is cost-effective, and does not cause any damage to chrome plating. In a research study [41], a precise system was developed using a diamond indenter and an optical system for measuring wear and predicting the service life of the gun barrel. The indentation apparatus consists of a pair of diamond indenters, while the optical system transmits the surface image for monitoring. An electron microscope is used in combination with a long-range profilometer to confirm the measurement accuracy. The system proved to be effective as it contributed to the precise detection of wear in minimal experimental time.

3. Proposed Design and Development Methodology

The design of an automated cleaning system is guided by the objective of efficient and low-cost cleaning of barrels. The primary problem is the cleaning of the pipeline, barrels, and sewage system. Pipeline cleaning is intricate and involves serious health and safety concerns. Pipelines of smaller diameters have regions that are inaccessible to humans to carry out manual cleaning. Furthermore, manual cleaning requires a larger group of people and is time-consuming. Therefore, the need for an automated, motorized cleaning system is inevitable. The cleaning machine should be portable, easy to use, and suitable for different diameter pipelines and barrels.

The initial step in the methodology focused on the objectives of the research is the selection of the appropriate and suitable components for the hardware design of the system so that the developed automated cleaning mechanism effectively meets the user requirements and overcomes the limitations of the previous studies. After system design, the next step is the ANSYS analysis of the system to conduct stress analysis tests. After obtaining satisfactory stress analysis, results for the materials used for the assembly design, fabrication, integration, and testing of the automated system on the ground are carried out. Figure 1 shows the workflow of the proposed methodology.

3.1. Design Requirements. The system design requirements are primarily based on the objectives of the automated cleaning mechanism. The proposed CAICEM primarily focuses on large-diameter pipes. In this study, "large diameter" refers to internal diameters ranging from 150 mm to 300 mm, which are common in defense and certain industrial applications. While we recognize that sewage and municipal pipelines can be significantly larger, the current CAICEM prototype is optimized for up to 300 mm. However, the underlying technology is inherently scalable, and the technical concept can be extended to accommodate larger diameters, making it adaptable for broader applications such as wastewater and municipal infrastructure in future iterations.

The aim is to design a system that is portable, cost-effective, and user-friendly and completes the task in the minimum time. Each component used in the system design is selected based on its effectiveness in fulfilling the objective of the research. Apart from electrical and mechanical design requirements, a hybrid brush design is also crucial to meet the user's cleaning requirements.

The equipment is an assemblage of two systems, i.e., a cleaning and inspection system. The main components and design considerations to develop the proposed automated cleaning, inspection, and evaluation mechanism, as well as the coordination mechanism of its various components, are as follows:

- Cleaning system: The cleaning system is an automated, controlled-driven system. An automated cleaning system needs a control system for its operation.
- Inspection system: The inspection system is composed of four cameras and sensors, and aids in monitoring the condition of the inner region of pipes and barrels.
- Control mechanism: The cleaning system is an automated, controlled-driven system. An automated cleaning system needs a control system for its operation.

3.2. System Design and Implementation. The design of the system comprises the cleaning system, inspection system, and control system, wherein electrical and mechanical design considerations play a pivotal role. The current focus of CAICEM is on the development and functional validation of the system, and its design aligns with general principles and best practices outlined in relevant inspection and maintenance guidelines, such as THE American Petroleum Institute (API) 1169 (API 1169 is a certification offered by the API for Pipeline Construction Inspectors) and ASME B31.8 for pipeline integrity and cleaning. Regional standards specific to defense applications and industrial safety protocols have also been considered during design and testing. As the system advances toward broader deployment, formal certification and compliance with national and international inspection standards will be pursued to ensure regulatory alignment and operational credibility.

3.2.1. Cleaning System. The cleaning system is an automated, controlled-driven system consisting of both electrical and mechanical parts and assemblies. The cleaning system is composed of three motors powered by both AC and DC, depending on the availability. The system is powered by a 12 V DC power supply through power connectors. The gearbox is attached to boost the torque of the DC motor. Two of the motors are placed on the rack of adapters, which helps in the linear motion of the brush inside the pipeline. One of the motors is used for the rotary motion of the brush inside the pipeline and barrel. On each side of the adopter, limiting switches are placed to switch the direction upon completion of one cycle and prevent the brush from sliding. The limiting switches work with a logic-based relay system. The H-bridge arrangement is used to flip the polarity of the motor, as well as to brake the motor by shorting the motor's terminals and allowing the motor to "free run" to a halt. When the brush touches the limiting switch, it goes from low to high, and the relay changes its state from NC to NO. This state change is fed to the H-bridge through a feedback IC, which thus changes the direction of the motor, i.e., from clockwise to anticlockwise and vice versa.

The mechanical assemblies are designed with the help of a computer-aided design (CAD) program. The assemblies include a front adaptor that is compatible with variable-diameter pipes and barrels. It is compatible with 105-mm–210-mm caliber gun barrels but can be adapted to any size and caliber. The front adopter of the system consists of a DC motor, a winch pulley system, a limiting switch, and power connectors. The adopter is installed on the front end of barrels and is shown in Figures 2(a) and 2(b). Bolts are used to insert and secure the adaptor. The rear adopter is

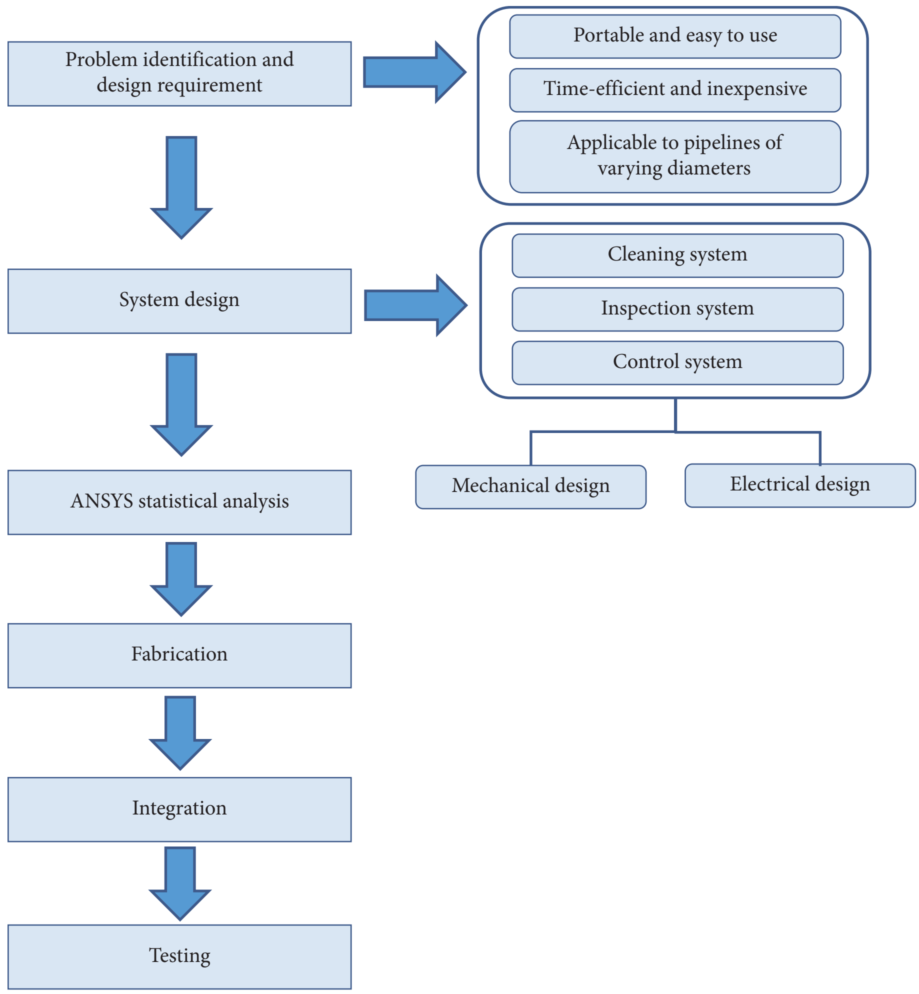


Figure 1: The overall workflow of the proposed methodology, comprising various tasks performed for CAICEM and their sequence. Starting with the problem identification, system design incorporates mechanical and electrical design, followed by statistical analysis of the CAICEM in ANSYS before fabrication and integration. In the end, testing is performed.

lightweight and compatible with variable-diameter pipes and barrels. The material selected for the fabrication is stainless steel, which is known for reliable sufficient strength. Aluminum is also a good choice in architectural applications since the alloying elements are magnesium and silicon. The fabrication of the metallic body is done after the CAD design in Solid Works. All the sections have been made using computer numerical control (CNC) machines and laser cutters. Holes are drilled once the model is built. The DC motor and winch are mounted on the front and rear adapters. The adapters are mounted on the holding rack and attached with the help of nuts and bolts.

3.2.2. Driving Mechanism. The driving mechanism of the cleaning system is a winch pulley–driven system. The winch pulley–driven system in CAICEM is designed to enable precise linear motion through the pipeline or barrel. Access to the start and end points is typically established through existing maintenance ports or customized entry points, depending on the application sector. For defense applications, access is straightforward via the gun barrel breech, while in industrial pipelines, entry is made through inspection hatches or flanged openings. The system is modular and portable, allowing easy setup at both ends, and includes guided insertion mechanisms to ensure safe and accurate deployment and retrieval.

The twisted stainless-steel wire has a 68-kg extensional strength and is 0.8 mm thick. The system has a modified brush design with separate hard and soft cleaning brushes for fine cleaning. The wire is attached to the brush and placed into the muzzle end of the barrel. The wire transfers the motion and force from one pulley to another. Before connecting the brush to the motors, the lock gears are released. The high-torque motors at each end help to drive the brush. As the brush moves through the barrel, the wire also moves smoothly inside the barrel from the entry point to the exit. When the control unit receives an encrypted signal to move ahead from the transmitter end, a pulse with modulation (PWM) pins connected to the H-bridge changes the logic to rotate the motor in the desired direction. The drive mechanism has the following modes of operation:

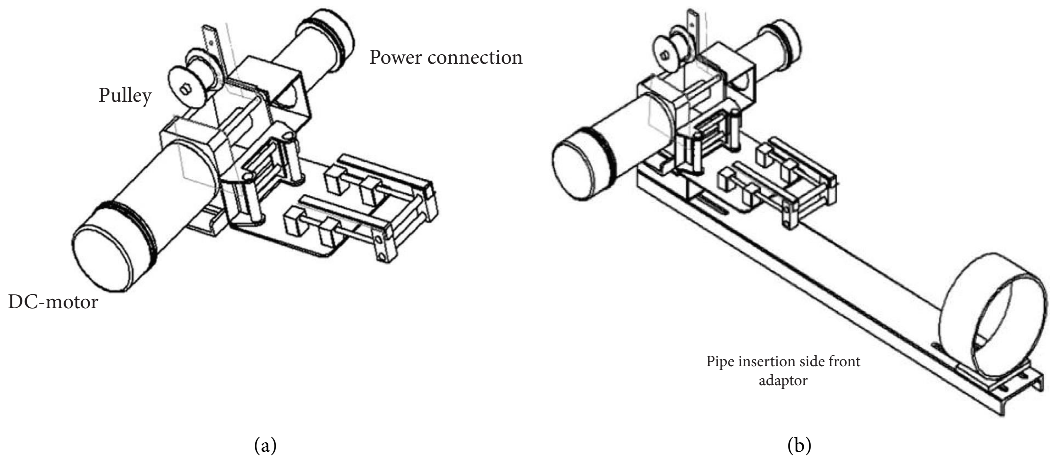


Figure 2: Schematic diagram of the front adaptor of the cleaning system. It contains a pulley, power connection, and DC motor to operate CAICEM.

i. Manual: The system is controlled manually by a toggle switch that moves the brush inside the barrel forward and backward.
ii. Auto: A self-locking momentary push-button switch controls the system in auto mode.
iii. Region-bound cleaning: The cleaning can also be carried out in a specific region by recording the boundary regions and setting a specific time.

3.2.3. Inspection Mechanism. The inspection system is required for monitoring the condition of the inner region of pipes and barrels. The semiautomatic inspection system consists of four cameras and sensors. Two of the cameras are fixed on the front and rear ends. The camera module is attached to the wire-connected brush and is made small enough to pass through the barrel easily. The camera helps to inspect the pipeline and detect deposits and blockages in the pipes. Another camera is attached to the system that records the activity of the worker who is operating the system. An ultrasonic sensor is attached to the brush to sense the obstruction inside the pipe and barrel. The inspection system comprises cameras and sensors, as well as the ability to record video and collect data. The system is controlled through a microcontroller present in the control unit. In the inspection module, the monitoring can be done from any remote location by connecting through Wi-Fi.

3.2.4. Control Mechanism. The control unit of the automated cleaning mechanism consists of an Arduino microcontroller, double-pole double-throw (DPDT) relays, a liquid crystal display (LCD), toggle switches, AC–DC converters, protection relays, and limit switches. An Arduino, along with some sensors, controls the operation of the automatic switching ON and OFF function. When the switch is pressed, the Arduino commands the DC motor to operate in the forward direction. When a cycle of cleaning is completed, it stops the DC motors. Arduino Mega controls the respective motors that carry out the cleaning operation. Arduino also takes input from the cameras and infrared (IR) sensors. It is programmed to take the command from the user, such as the selection of the mode (automatic and manual) or which operation to perform. The control system of the cleaning mechanism is housed in a portable trolley. The trolley is specially designed to keep the inspection mechanism, cleaning brushes, the control panel, and the power supply. The block diagram of the control unit is presented in Figure 3.

3.3. ANSYS Analysis. The FEM analysis of the designed automated cleaning system is done using ANSYS software. The model is analyzed under different loading conditions to check the stress concentration and deformation. Stress analysis is done to determine the reliability of the designed mechanism and the materials used. To analyze the strength of the stainless-steel material used within the designed system, the ANSYS tool is utilized.

4. Results and Discussion

The CAICEM system is designed for offline operation and requires temporary shutdown of the pipeline or gun barrel during deployment to ensure safety and optimal cleaning performance. This approach avoids potential risks associated with pressure fluctuations, fluid flow interference, and mechanical damage to both the system and the pipeline interior. However, for future iterations, design provisions are being explored to enable inline operation under controlled conditions. Risk mitigation strategies currently include predeployment pressure testing, isolation of pipeline sections, and integration of safety interlocks and remote monitoring to ensure operator and system safety throughout the operation.

4.1. Characteristics of CAICEM. The proposed system is more reliable, easier to troubleshoot, and less error-prone as there are no alignment and seepage issues due to the electrical design of the system. The system is also equipped with cameras and sensors, hence providing the advantage of

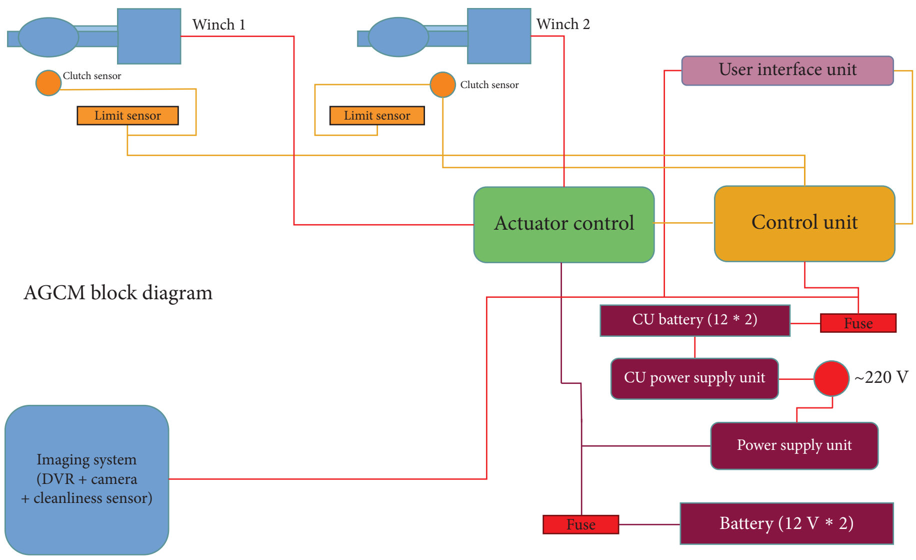


Figure 3: The control system for driving and the inspection system. Various components such as an imaging system (camera), a control unit, an actuator unit to control the brushes, batteries, winches, and a user interface unit to operate the CAICEM are included.

a video recording facility and data logging. There is an emergency stop option and storage compartments for batteries, accessories, and adapters. Stainless-steel material is preferred over aluminum because of its strength, high level of machinability, and ductility. Table 2 depicts a comparison between the properties of both steel and aluminum.

Table 2: Properties of stainless steel and aluminum.

Properties	Aluminum Al-6061-T6	Stainless steel 316
Tensile strength	310 MPa	445 MPa
Density	2.7 g/cm^3	8 g/cm^3
Elongation (%)	17%	30%
Young modulus	68.9 GPa	190 GPa

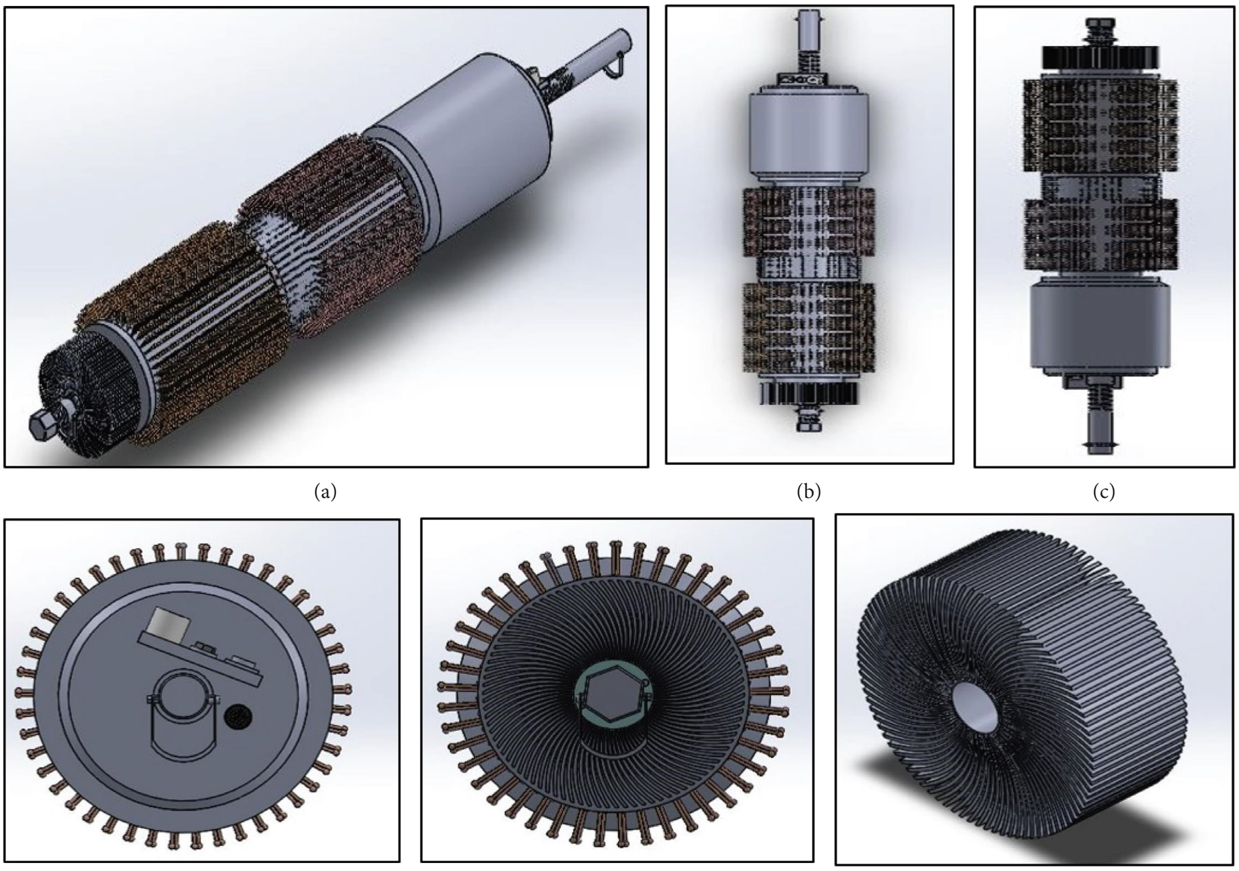
4.2. CAD Models. A novelty of the current system is the modified brush design that proves helpful in performing a multitude of in-depth cleaning tasks of the barrels and pipelines. CAD modeling is an important step in the design process because it helps to save resources and helps to design more accurate 3D models to analyze and modify them to update the designs to improve the quality. After the successful CAD modeling, ANSYS analysis is performed to carry out the stress and strain analysis on the components of the assemblies. The assembled isometric and side view of the brushes is depicted in Figures 4(a), 4(b), 4(c). Furthermore, the front and back view along with the isometric view of the spiral brush is shown in Figures 4(d), 4(e), 4(f). Figures 5(a), 5(b), 5(c) show the CAD of the proposed system.

4.3. ANSYS Stress Analysis. The following section describes the results of the ANSYS analysis and a comparison between the existing gun cleaning mechanism systems and the proposed automated gun cleaning mechanism. The designed system gave satisfactory results when the stress analysis was performed using ANSYS. The results are shown in Figures 6(a), 6(b), 6(c), 6(d), 6(e), 6(f), 6(g), 6(h), which depicts the total deformation which is resulted from applying stress to different parts of the system.

4.4. Fabrication and Integration. After the CAD modeling and permissible stress analysis results, the system components are fabricated and integrated so that the designed automated cleaning and mechanism system can be tested on the ground. The fabrication and integration system is shown in Figures 7(a), 7(b), 7(c), 7(d).

4.5. Testing and Performance Analysis. Our work has aimed to design a robust and adaptable pipe cleaning mechanism to overcome the cost associated with time and labor. The designed mechanism is tested, and it is found that the system successfully meets the criteria on which it was designed. Table 3 presents a detailed comparison between the newly designed automated gun cleaning mechanism and existing gun cleaning mechanisms. The proposed system outperforms all the existing cleaning systems in terms of cleaning time, labor required, and operating procedures. The system offers comprehensive cleaning due to the ideal brush contact area, its combined linear and rotatory movements, and suitable brush design. The local repair facility of the system makes it distinguishable from other cleaning mechanisms. Additionally, the feature of digital video recording has also been incorporated into the system. The cameras are mounted on two ends of pipes with suitable fixtures and with brush assist. It offers in-depth inspection and evaluation that is not found in other existing mechanisms.

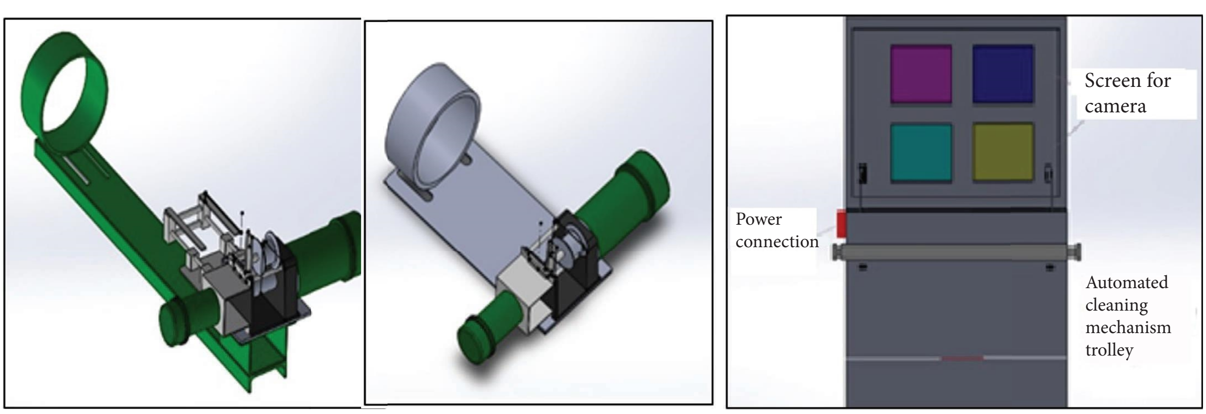
4.6. Use Cases for CAICEM. The proposed CAICEM is primarily designed for application in defense, particularly for artillery and armored barrel maintenance, oil and gas for cleaning and inspecting large-diameter pipelines, and water



(a) (b) (c)

(d) (e) (f)

FIGURE 4: Brush design: (a–c) are assembled isometric and side views of brush, (d) front view, (e) back view, and (f) spiral brush isometric view. The system is equipped with a modified brush design to perform fine cleaning. The custom design of the brush helps CAICEM adapt to different pipelines.



(a) (b) (c)

FIGURE 5: The computer-aided design model of various components of CAICEM, (a) front-end adopter, (b) rear-end adopter, and (c) automated cleaning mechanism trolley.

utility sectors such as municipal water mains and waste systems. In addition, it has the following use cases:

i. Manufacturing and Industrial Plants: CAICEM can be used to inspect machinery and production lines to check pipes for dirt, grease, or similar objects causing line blockage. Such inspection helps enhance line longevity and product quality, thereby reducing downtime.

ii. Inspection of Laboratories: Inspection of laboratories, particularly those involving the use of various

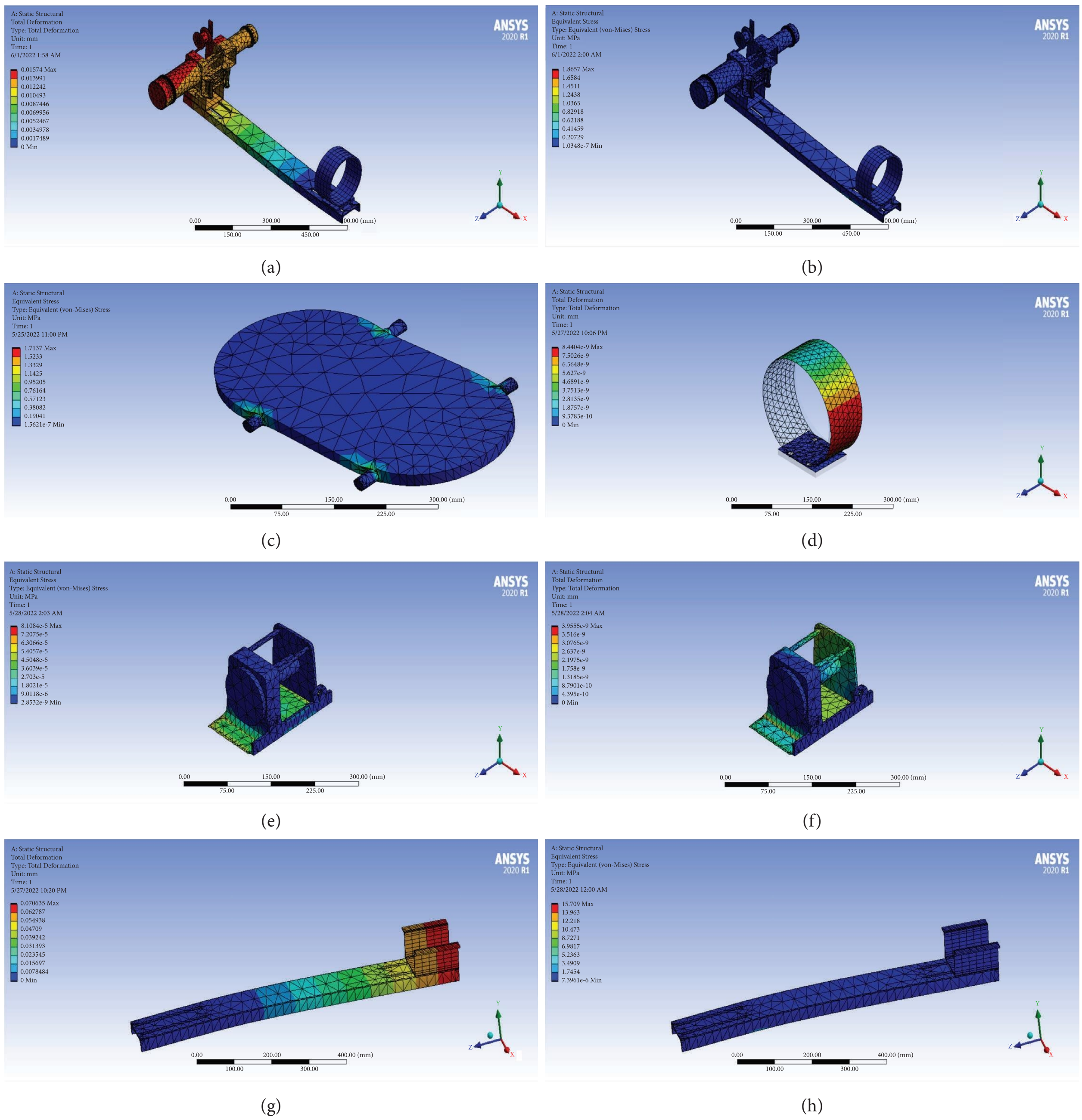
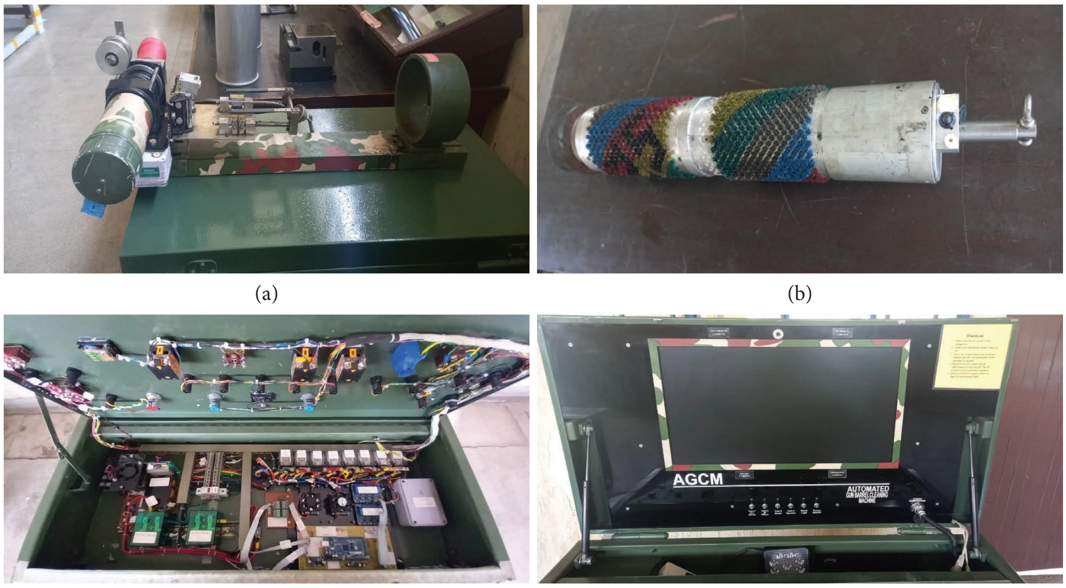


Figure 6: ANSYS stress analysis results. Various types of stress analysis are performed, such as total deformation measured in mm and equivalent (von-Mises) stress measured in MPA.

chemicals that can lead to the disposition of vax, dust, chemical reaction outcomes, etc., in the exhaust lines, is very important for equipment and human safety. The proposed CAICEM can be adopted for this purpose as well. It can help ensure compliance with stringent ISO standards concerning laboratories and other equipment.

iii. Food Processing Plants: Automated inspection of units involving food production is critical for hygiene. Continuous steam from cooking units can cause deposition of different substances in exhaust lines, leading the unhygienic outcomes. In addition, food production units have disposal of waste via different lines, which can lead to blockage if not monitored and inspected periodically. The proposed CAICEM system can help check such pipes efficiently and clean them automatically.

iv. Oil and Gas Industry: Automatic inspection of cleaning of pipelines for crude oil and gas is very important to clean wax, scale, and similar other deposits. Cleaning prevents blockage, reduces the risk of corrosion and blocked flow, and minimizes system downtime.



(a) (b) (c) (d)

Figure 7: After ANSYS analysis, fabrication of components and their integration is carried out. The figure shows AGCM fabrication and integration of CAICEM. It shows an operational unit, an integrated cleaning brush, an electrical control unit, and a user interface to operate CAICEM.

v. Water Treatment and Supply: Water distribution pipes can become narrow due to corrosion, sediments, and rust. Periodic inspection and cleaning are necessary to eliminate biofilms, sediments, etc., to ensure safe and clean water delivery for public health. CAICEM can help achieve this objective.

vi. Beverage Industry: For beverage clean-in-place systems, CAICEM can be used for internal inspection and cleaning of lines carrying milk, syrups, beverages, etc., to maintain hygiene without dismantling equipment. Such cleaning helps reduce contamination risk and helps comply with health standards.

vii. Mining and Slurry Transport: Inspection and cleaning of pipelines involving mining-related content, such as minerals or mineral-containing fluid, is very important. Similarly, cleaning pipes transporting abrasive slurry helps minimize wear, prevents clogging, and extends pipe lifespan. CAICEM is a potential system to inspect and clean such pipelines.

viii. Nuclear and Power Plants: Another important use case of the proposed CAICEM is the cleaning of cooling system pipes and heat exchangers used in nuclear and power plants. It enhances their thermal efficiency and prevents deposition of scale and radioactive contamination.

4.7. Adaptability of Proposed CAICEM for Use Cases. The proposed system is designed to perform automatic inspection and cleaning for pipelines and is equipped with various sensors. For driving, it uses a winch pulley–driven system. With a modified brush design, the system can adapt to fine cleaning easily. The high-torque motors in the CAICEM system help drive the brush easily for various diameters of pipes. The CAICEM has four cameras and sensors that help inspect and detect deposits in pipelines. The ultrasonic sensor helps sense obstructions inside the pipeline. Primarily designed for defense and the oil and gas sector, the system can be adapted to different uses.

For defense applications, it handles high-precision cleaning of rifled barrels to ensure firing accuracy and safety. In the oil and gas sector, CAICEM adapts to long-distance, variable-terrain pipelines with features like adjustable propulsion, corrosion-resistant materials, and explosion-proof components. For water and chemical pipelines, it supports noninvasive cleaning with modular brushes and fluid-safe enclosures. The system's modularity and sensor suite allow real-time environmental adaptation, making it suitable for varied deployment conditions such as temperature extremes, confined spaces, or hazardous atmospheres.

4.8. Operational and Environmental Constraints. The deployment of CAICEM across diverse industrial and defense applications necessitates careful consideration with respect to operational and environmental constraints. The proposed CAICEM is currently optimized to perform offline inspection and cleaning. It means that it requires temporary isolation of the pipeline during cleaning and inspection operations. This approach ensures personnel safety and equipment protection, particularly in high-pressure or hazardous fluid environments such as oil and gas pipelines.

Temperature and humidity variations are accounted for through adaptive control of mechanical and sensor subsystems. This enables operation in environments ranging from arid field conditions to damp, confined water pipelines.

Table 3: Comparison between the proposed CAICEM and existing cleaning systems.

Property	Manual cleaning	CAICEM	In-pipe inspection [26]	Vappro ABC [42]	Nam et al. [7]
Crew	6–8	1-2	—	2 (66% reduced manpower)	1
Pipelines applicable	All	Gun artillery (105-mm, 122-mm, 130-mm, 150-mm rifled bore) Armor guns (125-mm smooth bore) Single machine for both rifled and smooth bore	Applicable to 5-inch (127 mm) diameter to flat plates	Barrels ranging from 75 mm to 240 mm diameter	(Artillery and battle tanks) applicable to gun barrels of diameter 76 mm, 105 mm, 120 mm, 125 mm, 127 mm, and 155 mm
Cleaning time	60 min	20 min	—	75% more-gun barrels cleaned	20 min
Cleaning quality	Very low	High (both linear and rotary motion and lengthy metal brush)	—	High	High
Type of motors	NA	Three motors (2 for linear and 1 for rotary motion) -1.5 KW permanent magnet DC motors			
AC/DC aval	NA	DC—24 V AC—220 V	—	DC—12 V	
Weight	NA	100 kg (less than 10 kg fittings)	3 kg	Light weight	8.7–13.5 kg
Ease of use in battlefield	NA	Easy	—	Easy	Excellent
Robustness	NA	Highly robust	—	Robust	Robust
Local repair facility and reliability	NA	High due to indigenous dev and aval of parts locally			
Cost	NA	0.95 Mn			
Complexity of fitting and cleaning setup	NA	Very easy, screw less snap fit	—	Quick and easy	Easy to setup
Effort	Cumbersome and jerky process	Automated, quick, easy, smooth process	—	Less effort required, no muscle injuries	Reduces postural risks associated with manual cleaning
Cleaning movement	Linear only	Both linear and rotatory	Longitudinal and traverse motions	Forward and backward	Spiral
Machine portability	NA	Portable	—	Portable	Fair
Brush type	Brush size depends on gun type	Separate hard brush for tough and soft brush for fine cleaning (10–20 inch large)	NA	Bore bush	Wire brushes and cotton brushes (brush size is specific to the diameter of the gun)
Inspection and recording (cameras and sensors used)	Manual	Brush-mounted and barrel-mounted cameras with DVR facility up to 20 GB. Three levels of cleaning sensors are provided	Cameras and sensor to monitor pipe's internal condition. Three humidity sensors, 4 temperature sensors	Endoscope was used for inspection	NA
Cleaning oil/spray	Manual	Oil spraying mechanism with 4x spray nozzles with std cleaning oil reservoir, brush with spraying option available	NA	Vappro 818 bore cleaning solution is used	Cleaning oil is applied
Emergency switch	N/A	Emergency stop option available	NA	NA	NA

CAICEM's modular architecture allows for customization to align with the sector-specific constraints. For example, it has a compact design for space-limited defense applications. It can extend cable lengths and reinforce chassis for remote and rugged terrain in pipeline networks, which is important for adaptable systems. Emergency safety features such as fail-safe shutdown, obstacle detection, and remote override are also incorporated for unexpected operational scenarios.

Future improvements are envisioned to expand inline operation capabilities by introducing real-time data relay, live-flow adaptability, and wireless control. Such extensions will enhance the system's capabilities to reduce system downtime and expand applicability. Overall, CAICEM's design prioritizes flexibility, robustness, and safety under a wide range of operational and environmental conditions.

4.9. Limitations. While the current development of CAICEM demonstrates promising capabilities in automated cleaning and inspection of large-diameter pipelines and gun barrels, several limitations remain. The system is presently designed for offline operation, requiring temporary shutdowns, which may limit deployment in critical infrastructure with continuous operational demands. Additionally, while initial testing provides comparative performance indicators, extensive quantitative analysis, including long-term durability, statistical repeatability, and failure-mode evaluation, is pending and forms part of ongoing work.

Another limitation lies in the current adaptability to highly variable internal geometries or real-time navigation in complex pipeline networks, which may require enhanced sensing and AI-driven path planning. Environmental constraints such as extreme temperature operation and chemical exposure tolerance also require further validation in field conditions.

4.10. Future Work. In view of the discussed limitations and potential use of the proposed CAICEM, the following extensions are foreseen:

i. Inline Operations: Future work will focus on enabling inline operation through robust sealing and flow-compatible control mechanisms, integration of wireless telemetry for real-time data acquisition.
ii. Sector-specific Adaptations: Detailed sector-specific adaptations, such as explosion-proof configurations for petrochemical pipelines and compact variants for armored vehicle maintenance, will be explored.
iii. Diverse Environmental Scenarios: Scaling up testing under diverse environmental scenarios and formal reliability assessments will further enhance CAICEM's readiness for industrial and military deployment.
iv. AI-Based Assessment: The current version of CAICEM supports both remote control and automatic operation, allowing operators to manage and monitor the system from a safe distance with minimal manual intervention. However, it does not yet incorporate AI-based assessment or decision-making. Integration of AI for advanced fault detection, adaptive navigation, and data-driven inspection analysis is part of the planned future enhancements to further improve autonomy and operational intelligence.

5. Conclusions

This study proposes a novel cleaning, inspection, and assessment method that operates smoothly even in the most challenging circumstances. The mechanism is successfully designed and tested. Every module has been reasoned out and placed carefully, thus contributing to the best working of the unit. The design and working of the system are simple to facilitate the layman's and workers' usage on the ground. The system is portable, carried out in a trolley, and can be operated easily by two people. The system is robust, user-friendly, cost-effective, and time-efficient. It uses both AC and DC power, which significantly improves the initial design. The designed automated gun cleaning mechanism system makes the cleaning procedures of gun barrels much easier and quicker, ultimately enhancing the life span of the pipelines. In addition, the postural risks associated with the manual gun cleaning tasks have also been eliminated. The system's portability feature is also helpful in wartime situations. The improvement in automated cleaning systems is sufficiently advanced to ensure safe and reliable operation and meets the user's expectation of effective cleaning.

Data Availability Statement

The dataset used in this study is available from the corresponding author upon request.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

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