KT Journal of Mechanical Engineering

ISSN: 3048-9563 (Online)

Key Tech Services Publication, India

http://www.ktjme.com
https://doi.org/10.64188/3048956325010
Vol.: 2, No. 2, 2025, Pages: 01-11

SOLAR POWERED AUTONOMOUS LAWN MOWER USING GPS AND ULTRASONIC SENSORS

Humaid Saif Al Hatmi[1], Dinesh Keloth Kaithari[2], Abdulaziz Ali Al Mamari[3], Suhail Hamed Al Amarni[4]

[1,2,3,4]National University of Science and Technology, Muscat, Sultanate of Oman

Abstract

The research presents the design and implementation of a solar-powered autonomous lawn mower that integrates GPS navigation, compass-based heading alignment, and ultrasonic obstacle detection to operate without human intervention. Traditional lawn maintenance methods are labor-intensive, time-consuming, and often environmentally unsustainable due to the reliance on fuel-powered equipment. The present study addresses these challenges by introducing a low-cost, eco-friendly solution aimed at automating grass-cutting tasks using open-source components and renewable energy. The primary objective is to develop a robotic lawn mower that navigates using GPS coordinates, maintains directional accuracy through a digital compass (HMC5883L), and avoids obstacles using ultrasonic sensors. The entire system is managed through an Arduino Mega 2560 microcontroller, with motor control handled by L298N driver modules and a high-speed DC blade motor controlled via relay. The mower is powered by a rechargeable 12V battery that is charged by a solar panel, allowing for continuous outdoor operation. The methodology involved modular testing of individual components, followed by full integration and validation through field testing. The system was tested on a real lawn using pre-programmed coordinates and showed successful navigation, obstacle avoidance, and grass-cutting within the intended area. The study demonstrates the feasibility and importance of combining embedded systems with renewable energy for sustainable automation. Potential applications extend beyond household lawn care to include agriculture, landscape maintenance, and environmental robotics. This prototype serves as a foundation for future developments involving AI-based path planning, real-time mapping, and smart monitoring systems.

Received:20.06.2025 Revised: 15.07.2025 Accepted: 25.07.2025 Published Online: 31.07.2025

Keywords: Solar, Mower, Grass cutting, GPS, Agriculture

Corresponding author name and email: Dinesh Keloth Kaithari, dineshkeloth@nu.edu.om

How to cite this article: Humaid Saif Al Hatmi, Dinesh Keloth Kaithari, Abdulaziz Ali Al Mamari, Suhail Hamed Al Amarni, Solar-powered autonomous lawn mower using GPS and ultrasonic sensors, KT Journal of Mechanical Engineering, 2 (2), 2025, 1-11. https://doi.org/10.64188/3048956325010

1. Introduction

The design, development, and evaluation of a solar-powered autonomous lawn mower that utilizes GPS-based navigation, ultrasonic sensors, and compass direction correction to autonomously mow predefined outdoor areas without the need for perimeter wires were studied. The primary objective of the project was to create a low-cost, environmentally friendly robotic mowing solution using open-source platforms, renewable energy, and embedded systems. The prototype was built around the Arduino Mega 2560, integrated with four 12V DC drive motors and a high-speed 14,000 RPM cutting blade motor. Navigation relied on the Neo-6M GPS module for location tracking and the HMC5883L compass sensor for maintaining heading accuracy. Three ultrasonic sensors ensured real-time obstacle detection and rerouting capability, making the mower safe for use in semi-structured outdoor environments. A 20W solar panel was used to recharge a 12V LiPo battery, extending operation through hybrid energy management. The mower was tested on real lawns and demonstrated the ability to autonomously navigate, avoid obstacles, and effectively cut grass. GPS navigation maintained a location accuracy of ±2.5 meters, while ultrasonic detection achieved over 90% accuracy within a 20–150 cm range. The system's modular design allowed synchronized interaction between all hardware components, powered and coordinated by Arduino-based C programming. The project contributes to ongoing innovation in green automation, aligning with the United Nations Sustainable Development Goals (UNSDGs) by promoting clean energy and sustainable technology. Limitations such as GPS drift, solar recharge delays, and compass sensitivity were acknowledged, and recommendations such as RTK-GPS, IMU integration, and MPPT solar controllers were proposed for future development. The result successfully demonstrates the feasibility of constructing an affordable, solar-powered autonomous lawn mower using accessible technologies, positioning it as a foundation for further research, smart agriculture solutions, and scalable robotic lawn care systems. Traditional lawn mowing practices present several challenges. They require physical effort, repeated supervision, and significant time investment, especially for larger areas. Additionally, the frequent use of fuel-powered mowers contributes to air and noise pollution. There is an urgent need for a smarter, greener alternative that can automate this routine task while reducing environmental impact. Such a solution would be especially beneficial for elderly individuals, people with physical disabilities, and organizations managing large green spaces. By automating the process and leveraging solar energy, this project fulfills a modern need for sustainable automation. The use of open-source hardware also makes it accessible and reproducible for educational and commercial purposes. The main objectives of the project were:

i. To design and develop a solar-powered autonomous lawn mower system using open-source components.
ii. To implement GPS-based navigation for location tracking and compass-based heading alignment.
iii. To integrate an ultrasonic sensor system for obstacle detection and avoidance.
iv. To control mower movement and blade operation via an Arduino Mega and motor driver modules.

v. To validate the system's performance through real-world testing in open-field conditions.

2. Literature Review

They developed a high-precision autonomous lawnmower that could navigate large lawn areas using GPS combined with scanning laser technology. The project was initiated to overcome the limitations of boundary wire systems and to demonstrate accurate path following in open environments using real-time position correction and obstacle detection. It concluded that combining GPS with high-resolution LIDAR provides an effective solution for autonomous lawn mowing with high accuracy and safety. Their prototype demonstrated potential for scalable deployment in both residential and commercial settings. However, the use of LIDAR significantly increased the system cost and complexity. The researchers conducted a series of tests in both indoor and semi-structured outdoor environments. The robot's ability to avoid obstacles, respond to dynamic threats, and resume its original trajectory was measured quantitatively in terms of success rate and navigation efficiency [1]. The system demonstrated reliable avoidance of static and slow-moving obstacles, with the robot reacting in less than 1 second on average to new threats within its detection range. The VFH algorithm provided smooth and continuous path correction, minimizing jerky motion. However, sensor limitations were noted in certain conditions: soft surfaces could absorb sound waves, and the cone-shaped field of view occasionally created blind spots. The study concluded that ultrasonic sensors, despite their simplicity and affordability, are well-suited for real-time obstacle avoidance in mobile robots. The success of the VFH algorithm showed that computationally efficient methods could achieve adaptive navigation in uncertain environments without relying on costly sensors like LIDAR [2]. Testing was performed in controlled environments with varying obstacle types, including reflective (metal) and absorbent (foam) materials. The researchers also tested performance under different lighting and weather conditions to simulate real-world variability. The robot demonstrated consistent and accurate avoidance behavior in more than 90% of test scenarios. The ultrasonic sensors maintained reliable detection for objects within 20 to 300 cm. The system was also able to avoid most collisions, with response times under 200 milliseconds. However, reflectivity and surface texture affected sensor performance slightly, with false negatives occurring on soft objects. The authors concluded that ultrasonic sensors, when properly placed and tuned, provide reliable obstacle detection at a fraction of the cost of LIDAR or camera-based systems. The algorithm was lightweight enough to run on low-power microcontrollers and scalable for more complex robots [3]. However, they acknowledged the need for sensor redundancy and better filtering techniques to manage noisy data. Tests were conducted to evaluate the robot's response speed, multitasking capability under load, and control smoothness. The robot was also evaluated for system lag when all modules operated simultaneously. The Arduino Mega successfully handled three parallel tasks without notable performance degradation. Sensor readings were updated at a stable rate of approximately 10–15 Hz, and command latency over Bluetooth was under 250 milliseconds. Memory usage remained below 60%, and pin allocation was efficient, with room for additional modules. The robot operated reliably for extended periods when powered by a 12V 2200mAh battery. The study confirmed that Arduino Mega 2560 is a suitable controller for complex robotic systems that require multiple simultaneous sensor inputs and actuator outputs. Its large flash memory, higher I/O capacity, and multitasking capability made it ideal for moderately complex automation tasks, particularly in low-cost and educational projects [4]. The robot was tested over short paths (10 meters) and tasked with reaching multiple waypoints while maintaining orientation and avoiding unnecessary directional drift. The dual-sensor approach proved more reliable than GPS alone. The GPS module provided acceptable position updates (accuracy of 2.5 meters under open sky), while the compass improved real-time heading accuracy, especially during low-speed maneuvers. Heading correction reduced lateral deviation by approximately 35% compared to GPS-only navigation. However, fluctuations still occurred due to magnetometer noise and inconsistent GPS fixes. The study demonstrated that combining GPS with a digital compass sensor enhances directional stability for autonomous outdoor robots. The Arduino Mega's capacity to handle both modules simultaneously allowed for continuous feedback control and motor adjustment [5]. The approach was feasible for low-cost outdoor robots where precision navigation was desired without using RTK-GPS or vision systems. Software was developed using Arduino IDE, and serial output was used to track performance during testing. The motors were subjected to various load conditions to assess the system's adaptability and stability. The control loop operated continuously to maintain a target speed by comparing encoder feedback to the setpoint and adjusting PWM accordingly. The team measured how quickly the motors reached the target speed, how well they maintained it under changing load, and how much electrical noise or delay affected performance. The implementation of PID control led to significant improvements in speed, stability, and response time. Without PID, motors exhibited overshoot and hunting behavior, but with tuned PID values, they achieved smooth acceleration and minimal speed fluctuation (5% variance) under varying load conditions. The L298N module performed reliably within its current handling limits (2A per channel) but heated up under continuous high-speed operation, requiring passive heat sinks. The study concluded that PID control, when applied with an L298N driver and Arduino, offers a robust, cost-effective motor control strategy for differential drive robots. The integration of encoder feedback and real-time PID adjustments enabled precise control without needing expensive motor controllers or advanced processors [6-7]. The MFO-PSO algorithm achieved superior motor speed matching compared to PID, with synchronization error reduced to less than 2% between left and right motors. The robot maintained more accurate paths with smoother turning transitions and lower power spikes. The approach also reduced total energy consumption by up to 15% compared to fixed-gain PID control. However, the optimization process required higher processing power and memory, limiting real-time implementation on low-end microcontrollers [8-10]. Hossain and Haque concluded that hybrid metaheuristic algorithms like MFO-PSO offer notable improvements in motor coordination and energy efficiency in multi-motor mobile robots. While powerful, these algorithms are more suited to systems with onboard computers or high-capability controllers such as Raspberry Pi or industrial-grade microcontrollers. The hybrid model reduced weight by 20% while maintaining similar stiffness to aluminum-only frames. It also performed better in vibration damping. However, CFRP has increased cost and fabrication complexity, and is not easily repairable. They recommended aluminum and hybrid materials for mobile systems where lightweight and strength are both important. Their work supported modular robotic chassis development in controlled environments [11]. The results showed that stainless steel offered the best balance of durability and sharpness retention, maintaining performance even after 500 cutting cycles. HSS blades delivered slightly higher initial sharpness but wore out faster under load. HDPE blades were the lightest and least expensive but failed to sustain sharpness and strength, deforming after repeated use. In terms of power efficiency, stainless steel required slightly more torque than HDPE but delivered consistent performance over time. The study concluded that stainless steel is the most effective material for applications where both durability and cutting precision are required. It performs well under repeated mechanical stress and resists corrosion, a valuable trait for outdoor applications. Although heavier than HDPE, its long lifespan offsets the minor increase in energy use. Results showed that modular systems using GPS and ultrasonic sensors, powered by solar panels, can operate reliably across extended periods. Sensor fusion was found to reduce positional error and improve obstacle avoidance. Power systems managed through voltage regulators were able to maintain consistent operation in daylight conditions. The research confirms the viability of using affordable, off-the-shelf components to create autonomous outdoor machines. Findings stress the importance of accurate sensor calibration, modular electrical design, and efficient energy usage for long-term deployment [12]. The robots successfully demonstrated accurate turning and directional control using compass inputs. Integration of GPS and ultrasonic sensors significantly improved route stability and reduced collision risk. Energy-saving mechanisms such as blade deactivation during non-cutting states also proved to be effective. This literature confirms that sensor-driven control logic enhances robot autonomy and safety. Studies emphasize the efficiency of dual motor drivers, real-time rerouting, and modular construction in maintaining system adaptability during operation in unpredictable outdoor settings. The mower successfully detected obstacles within a 25–30 cm range and executed corrective maneuvers like pivoting or reversing. The blade relay switched ON and OFF as expected. The system completed boundary-constrained paths without manual control or major directional errors. The paper concludes that embedded systems using GPS and ultrasonic sensors are feasible for simple robotic tasks like lawn mowing. The project demonstrated functional automation and emphasized modular expansion and maintenance simplicity [13-14]. The research revealed that real-time decision-making using sensor fusion significantly improved mobility and reduced collision risks. Compass-assisted heading correction enhanced path straightness, while ultrasonic and infrared coordination improved rerouting behavior during obstacle encounters. The system also maintained operational stability across different lighting conditions. The literature concludes that using a distributed sensor network improves robotic responsiveness and environmental awareness. Modular hardware and software designs are emphasized for ease of debugging and expansion. Control logic relying on real-time feedback from multiple sensor types is shown to outperform single-sensor models. Results demonstrated that hybrid motion models combining compass-assisted navigation with obstacle detection produced smoother and more reliable trajectories. The integration of GPS with ultrasonic sensors allowed for accurate positional updates and effective path correction. Modular construction reduced failure rates and simplified troubleshooting. The literature emphasizes the effectiveness of intelligent motion planning and sensor fusion in autonomous robotic systems. It also highlights the importance of using modular architectures and low-cost components to enhance scalability and ease of implementation [15-16]. Findings showed that combining low-cost actuators with calibrated sensors produced efficient and cost-effective control systems. Actuators delivered stable performance with optimized PWM signals, and sensors achieved reliable detection up to 50 cm in varied lighting and weather conditions. Sensor mounting angle and shielding significantly influenced accuracy, particularly for ultrasonic modules. This literature confirms that real-time system efficiency in robotics depends heavily on precise sensor-actuator coordination. The use of calibrated, shielded sensors and controlled PWM-based actuation can significantly enhance both mobility and obstacle responsiveness. Modular component use is also emphasized for easy maintenance and system upgrades. The system was able to navigate a predefined rectangular boundary with minimal manual intervention. The ultrasonic sensors successfully detected obstacles within a safe threshold of 20 to 30 cm, triggering reversal and redirection actions. The blade motor activated reliably using a relay, and the GPS module provided adequate positional awareness in open-sky conditions. This literature supports the feasibility of building functional autonomous mowers using low-cost microcontrollers and sensors. The research confirms that integrating GPS with obstacle avoidance logic and blade actuation can result in a system capable of operating with minimal human interaction [17-20]. The training program resulted in participants being able to build and control fully functional Arduino-based projects such as automatic lights, object detection systems, and basic remote-controlled robots. Learners demonstrated improved ability to debug wiring errors, program microcontrollers, and integrate multiple hardware components in a logical sequence. The study concludes that Arduino is an ideal platform for rapid prototyping and embedded system education due to its open-source nature, community support, and compatibility with a wide range of sensors and modules. The hands-on approach used in the workshops effectively bridged the gap between theoretical knowledge and real-world hardware application. The performance evaluation revealed that the cutting efficiency of the solar-powered lawn mower ranged from 70.50% to 84.10%, while the cutting capacity varied between 0.05 ha/h and 0.27 ha/h. The uncut area percentage was found to range from 15.90% to 29.50%, depending on the blade configuration and thickness. These results indicate that the solar-powered mower is capable of effective lawn maintenance with varying performance based on blade design. The study concludes that solar-powered lawn mowers present a viable and environmentally friendly alternative to traditional fuel-powered mowers. By utilizing renewable solar energy, these mowers can reduce operational costs and minimize environmental pollution. The research highlights the importance of optimizing blade design to enhance cutting efficiency and overall performance [21]. Simulation results demonstrate that the proposed algorithms significantly outperform conventional harvest-then-cooperate approaches. Specifically, the optimized strategies achieve up to 88% reduction in schedule length across various network configurations, highlighting the effectiveness of joint optimization in enhancing network performance. The study concludes that integrating relay selection with scheduling and power control is crucial for optimizing the performance of wireless powered cooperative communication networks. The proposed algorithms provide a framework for achieving substantial improvements in energy efficiency and data transmission rates, which are essential for the sustainability of energy-harvesting networks [22-26].

3. Materials and Methods

3.1. System Development Approach

The development of the solar-powered autonomous lawn mower followed a sequential, test-driven approach to ensure functionality at each stage before integration. The entire system was divided into four primary modules:

1. Navigation Module – consisting of the GPS and compass sensors,
2. Obstacle Avoidance Module – based on ultrasonic sensors,
3. Motion Control Module – responsible for drive motor control and movement logic,
4. Cutting Module – involving a high-speed blade motor controlled via relay.

Each of these modules was tested individually to validate hardware connections and software logic, then integrated step-by-step. Initial testing was done on a breadboard setup before transferring the connections to a more permanent soldered platform mounted on the chassis.

3.2 Step-by-Step Procedure

The following is the complete implementation methodology:

Step 1: Component Integration on Chassis
The physical assembly began by cutting and welding stainless steel sheets to form the chassis frame. The plywood base plate was mounted onto the chassis to support the electronics. All motors, wheels, and the cutting blade were then securely attached. Next, the Arduino Mega, relay module, sensors, and power systems were mounted.

Step 2: Wiring and Power Configuration
The solar panel was connected to charge a 12V lithium-ion battery, which powered the entire circuit. Power rails were established to ensure voltage safety and current stability. The L298N motor driver was wired to control four 12V DC motors, while a separate relay module was connected to the blade motor.

Step 3: Programming and Code Upload
Using Arduino IDE, separate test codes were written for each module:

- GPS module code to extract and print coordinates.
- Compass test code to calculate heading and align North.
- Ultrasonic code to test object detection at various distances.
- Motor control logic code for direction (forward, turn, reverse, stop).
- Combined code for navigation, obstacle handling, and blade actuation.

Step 4: Logic Implementation and Testing

Once each component was validated, the full integration code was uploaded. The motion logic was implemented based on compass heading and GPS error calculation. Depending on sensor input and positional data, the mower made decisions to move straight, pivot, or stop.

Step 5: Relay Activation and Safety Control

The relay module was programmed to activate the 12V blade motor only when the mower was in motion and free from nearby obstacles. This safety feature ensured the blade would not operate when the mower was idle or blocked

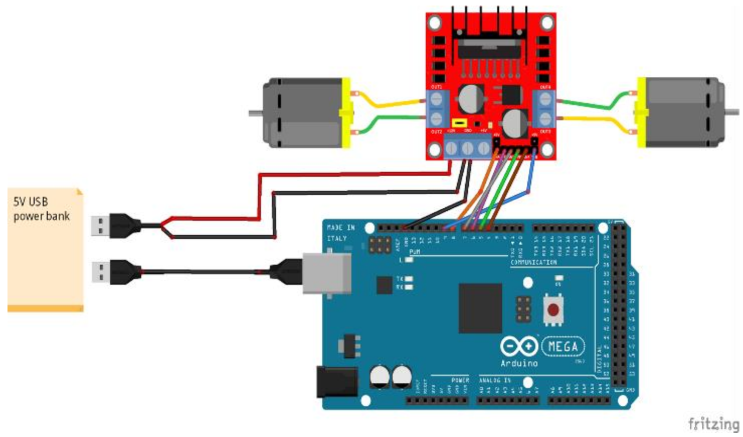

Figure 1: Motor Driver with Arduino

3.5.2 Software Tools

The lawn mower's brain relies heavily on software for both programming and logic implementation. Below are the major software tools and libraries used in this project:

Table 1: Software Tools

Software / Library	Function
Arduino IDE	Development environment for writing, compiling, and uploading code
TinyGPS++ Library	Parses GPS data and converts NMEA strings into readable coordinates
Wire.h	Enables I2C communication (used by compass module HMC5883L)

Software Serial. h	Allows serial communication on other digital pins (for GPS module)
Proteus / Fritzing	Used for circuit simulation and visual schematic design
Serial Monitor (IDE)	Real-time data logging from sensors and debugging

Conclusions

The solar-powered autonomous lawn mower successfully demonstrated the viability of creating a wire-free, GPS-guided robotic system capable of performing grass cutting operations with minimal human intervention. The results fulfilled the main objectives, including designing, building, and testing a cost-effective, eco-friendly autonomous mower that integrates sensor-based obstacle avoidance, GPS-based path following, and solar recharging for improved sustainability. The integration of the Neo-6M GPS module and the HMC5883L compass enabled effective navigation and directional correction across open spaces. Ultrasonic sensors provided reliable obstacle detection, and the relay-controlled blade motor operated only under safe motion conditions, contributing to both energy efficiency and safety. The system architecture, developed using the Arduino Mega platform, proved to be modular, flexible, and responsive under real-world testing scenarios. Furthermore, the hybrid power system combining a 12V LiPo battery with solar panel recharging validated the project's alignment with sustainable development practices. While certain limitations, such as GPS drift, compass interference, and limited solar recharging efficiency, were noted, these challenges are typical in early-stage embedded robotics and do not detract from the system's overall success. The project demonstrated that an affordable and environmentally sustainable autonomous mowing system can be built using off-the-shelf components and open-source platforms. The results aligned with the research goals and support its broader contribution to smart automation and green technology.

References

1. Abbas, A., Pirah Peerzada and Wasi hyder larik, DC Motor Speed Control Through Arduino and L298N Motor Driver Using PID Controller, 2025, 20211204
2. Abdulrahman, M. and Khan, A., Autonomous mobile robots: sensor fusion and navigation, *Robotics & Automation Systems,* 2020, 12(3) 122–130
3. Babatunde Soyoye, Development and performance evaluation of a solar-powered lawn mower, Turkish Journal of Agricultural Engineering Research, 2021, 2(2), 348-362
4. Banzi, M. and Shiloh, M., Getting Started with Arduino. 2014, 3rd edition, Sebastopol, CA: Maker Media
5. Bates, D. and Graas, van, GPS-guided autonomous lawnmower with scanning laser obstacle Detection, 2025, 3082–3088

6. Beddoes, J. and Parr, J. G., Manufacturing and applications of stainless steels, *Metals,* 2020 10(3) 1-10

7. Bhuiyan, M.Z.H. and Sabina, S.A. Multipurpose surveillance robot using Arduino Mega 2560 and Bluetooth module HC-05, 2024,202439304001

8. Daniyan, I., Balogun, V., Adeodu, A., Oladapo, B., Peter, J. K. and Mpofu, K., Development and performance evaluation of a robot for lawn mowing, *Procedia Manufacturing,* 2020, 4, 42-48. https://doi.org/10.1016/j.promfg.2020.06.009

9. Koren, Y. and Borenstein, J., Obstacle avoidance with ultrasonic sensors, IEEE Journal of Robotics and Automation, 1991

10. Kumar, R. and Poonia, R.C., Smart robotic systems using sensors and embedded controllers, *Journal of Intelligent Automation*, 2021, 8(4) 45–58

11. Liu, C. and Zhang, X., Design of solar-powered smart lawn mowers using MPPT controller, *Renewable Energy Engineering,* 2018, 13(2) 110–117

12. Ma, J., Obstacle detection and avoidance using ultrasonic sensors in autonomous robots, *Highlights in Science, Engineering, and Technology*, 2023, 71, 68-78. https://doi.org/10.54097/hset.v71i.12378

13. Marín-Marín, J.A., García-Tudela, P.A. and Duo-Terrón, P., Computational thinking and programming with Arduino in education, *Heliyon,* 2023, 9(4) 1-10

14. Mitra, S., Roy, D., and Banerjee, T., GPS-based navigation and mapping techniques in autonomous outdoor robots, *International Journal of Advanced Robotics,* 2020, 15(1) 67–75

15. Onalan, Aysun Gurur, Salik, E.D. and Coleri, S., Relay selection, scheduling, and power control in wireless powered cooperative communication networks, 2020

16. Ong, C.G., Fermano, J.C., and Daniot II, A.C.P., An impact study on the Arduino programming training for beginners, *International Association for Development of the Information Society,* 2022

17. Park, J.M., Kim, H. J., and Lee, S., A new class of lightweight, stainless steels with ultra-high strength and high ductility, *Scientific Reports,* 2020, 10, 1-10

18. Patel, A. and Mehta, R., Real-time kinematic GPS implementation for precision navigation. *International Journal of Electronics and Communication Engineering,* 2021, 11(2), 65–70

19. Rashid, H. Microcontroller-based mobile robotics: control and performance evaluation. *International Journal of Robotics Research,* 2021, 9(2) 33–41

20. Reda, M., Onsy, A., Haikal, A.Y. and Ghanbari, A., Motor speed control of four-wheel differential drive robots using a new hybrid moth-flame particle swarm optimization (MFPSO) Algorithm, *Journal of Intelligent and Robotic Systems*, 2025. https://doi.org/10.1007/s10846-025-02228-1

21. Singh, P. and Verma, K., Renewable energy solutions for autonomous systems, Energy and

Automation, 2019, 5(1) 88–96

22. Wang, R., Lu, Z., Wang, Y. and Li, Z., Design and analysis of a lightweight robotic arm based on a load-adaptive hoisting mechanism, *Actuators,* 2025, 14(2) 71-79. https://doi.org/10.3390/act14020071

23. Yin, H., Liu, J., and Yang, F., Hybrid structure design of lightweight robotic arms based on carbon fiber reinforced plastic and aluminum alloy, IEEE, 2019, 7, 64932–64945. https://doi.org/10.1109/ACCESS.2019.2915363

24. Zhou, J., Tang, C., Zhu, M., Chen, W., Yang, H., Wei, D., and He, G., Numerical simulation, and experimental research on cutting force of milling deicing robot milling cutter, *Processes,* 2025, 13(1) 140-152. https://doi.org/10.3390/pr13010140

25. Bhatkar V. W., Design of vertical fire tube boiler using IBR code and FEA analysis, Int Journal of Nanotechnology, IJNT, V18, N11/12, pp. 1041-1050, 2021, Inder Science Publication https://doi.org/10.1504/IJNT.2021.119226

26. Bhatkar V.W., A. Sur, An experimental analysis of liquid air jet pump, Frontiers in Heat and Mass Transfer, Vol. 17, No.12, Sept. 2021, pp. 1-5. https://doi.org/10.5098/hmt.17.12