Research, Design, and Development of a Sand Drawing Robot

Tri Cuong Do and Tri Dung Dang*

Institute of Intelligent and Interactive Technologies, University of Economics Ho Chi Minh City, Ho Chi Minh City, Vietnam

Email: cuongdt298@ueh.edu.vn (T.C.D); dungdt@ueh.edu.vn (T.D.D)

*Corresponding author

***Abstract*—This paper presents the research, design, and fabrication of a sand drawing robot capable of rendering detailed images on sandy surfaces. The robot integrates a robust mechanical system optimized for navigation and stability on deformable terrain, addressing challenges unique to sandy environments. Advanced control algorithms are developed for precise movement and drawing execution, ensuring consistent line quality and pattern accuracy. A user-friendly interface allows for custom image input, which is processed through sophisticated path-planning algorithms to generate executable instructions for the robot. Experimental results demonstrate the robot's ability to accurately reproduce complex designs, highlighting its potential applications in interactive art installations and educational settings. This work contributes to the field of robotics in Vietnam and worldwide by enhancing the precision and reliability of autonomous robots operating in dynamic and unstructured environments.**

***Keywords*—control algorithms, image processing, mechanical design, path planning, robotic art, sand drawing robot**

I. Introduction

The integration of robotics into the realm of art has paved the way for innovative applications that combine technological precision with creative expression [1–5]. Sand drawing robots epitomize this convergence, enabling the automated creation of intricate patterns and images on sand surfaces. These robots not only showcase advancements in robotic control systems and mechanical design but also contribute to interactive art installations and educational tools.

One prominent example in this field is the BeachBot developed by Disney Research Zurich, an autonomous robot designed to create large-scale sand art on beaches [6]. The BeachBot utilizes advanced path-planning algorithms and a unique mechanical structure to accurately reproduce complex designs on uneven sandy terrains. This project underscores the potential of robots to perform delicate artistic tasks in dynamic environments.

Another notable contribution is the "Sisyphus" kinetic art project by Bruce Shapiro, which employs robotic mechanisms to move a metal sphere through a bed of sand, creating continuously evolving patterns [7]. This installation illustrates the seamless blend of technology and art, showcasing how robotics can produce mesmerizing visual experiences.

Designing a sand drawing robot involves several challenges. Navigating and operating on a deformable surface like sand requires specialized locomotion and stability mechanisms [8]. Precise control systems are essential to manage the interaction between the drawing tool and the sand, ensuring consistent line quality and pattern accuracy [9]. Moreover, sophisticated image processing and path-generation algorithms are critical for translating digital designs into executable instructions for the robot [10].

Advancements in robotics have led to improvements in sensor technology and control algorithms, enabling robots to adapt to changes in the environment in real-time. Such developments are crucial for sand drawing robots, which must contend with variable surface conditions and obstacles. Region-based rendering techniques have also been explored to enhance the modularity and human-likeness of robotic painting, as demonstrated by Gülzow and Deussen [11] with their e-David system. Other robotic systems have leveraged contour-filling algorithms to reproduce watercolor effects using sponges, adding expressive texture to artistic outputs [12]. Mobile manipulators have enabled large-scale artistic expressions on nonplanar surfaces, showing that robotic systems can adapt to complex geometries while maintaining visual fidelity [13]. Preprocessing techniques such as aerial perspective and gamut compression have been applied in artistic robotic painting to achieve more human-like brushstroke rendering [14]. Genetic algorithms have proven effective in robotic pencil sketching, enabling fast and realistic approximations of visual inputs with machine creativity [15]. In the context of teleoperation, remote-controlled robot avatars have been developed for artistic portraiture, expanding the possibilities of human-robot creative collaboration [16]. Human–robot interaction has also been enhanced via eye-tracking interfaces, allowing users to control drawing robots

Manuscript received February 25, 2025; revised March 6, 2025; accepted April 23, 2025; published August 21, 2025.

doi: 10.18178/ijmerr.14.4.465-470

intuitively and with minimal physical input [17]. Performance evaluations of gaze-controlled drawing robots show their potential as assistive tools for individuals with movement impairments [18]. Collaborative robotic drawing projects highlight the importance of process-driven creativity, facilitated through transdisciplinary engagement between artists and engineers [19]. Recent work has introduced deep reinforcement learning in sketching tasks, enhancing adaptability and generating human-like results through cognitive robotic systems [20]. Advanced robotic painting platforms have been developed to reproduce authentic brushstroke colors through precise pigment mixing and pneumatic paint dispensing [21].

This paper presents the research, design, and fabrication of a sand drawing robot capable of rendering detailed images on sand surfaces. The proposed system integrates a robust mechanical design optimized for sandy environments, advanced control algorithms for precise movement and drawing, and a user-friendly interface for custom image input. The objectives of this work are to enhance the precision and reliability of sand drawing robots and to explore their applications in artistic expression and education in Vietnam and worldwide.

II. Design of Sand Drawing Robot

A. Design Idea

Following an in-depth exploration of the BeachBot [6], key ideas were selected for the development of a new sand drawing robot. An initial basic design was established, as shown in Fig. 1, serving as the foundational concept for the project. Building upon this prototype, both the structural design and the aesthetic form of the robot were expanded and refined. The focus was on aspects ranging from the exterior appearance to the internal mechanisms to align with the project's objectives.

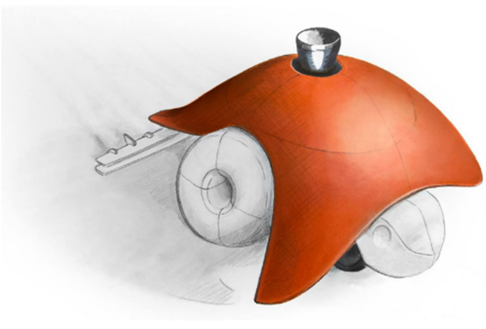

Fig. 1. Sand drawing robot.

The development process aimed to optimize the robot's functionality and ensure it met the goals of accurately rendering images on sand surfaces. Efforts concentrated on enhancing the mechanical str0ucture for better stability and mobility on sandy terrain, as well as integrating precise control systems for the drawing mechanism. This iterative design approach allowed for the creation of a robot that not only fulfills the technical requirements but also embodies an appealing and practical form factor suitable for the intended applications.

The sand drawing robot operates on sandy terrain by utilizing two primary drive wheels that generate traction when the motors are activated. Power is transmitted to these wheels through rigid couplings, ensuring efficient force transfer and stable movement on the deformable surface. The steering mechanism is comprised of a pivoting bracket that supports both drive motors and their respective wheels, enabling them to rotate about a vertical axis relative to the main chassis. A dedicated steering motor, coupled to this bracket through a gear or belt assembly, drives the pivot motion and precisely reorients the entire wheel–motor module for directional control. This approach ensures the two main drive wheels remain rigidly coupled to their motors for optimal power delivery, while the bracket's rotation provides smooth and responsive turning. By separating the steering function (pivoting the wheel–motor assembly) from the drive function (motors powering the wheels), the robot achieves both robust traction in sandy terrain and the precise maneuverability required for intricate sand drawing. This design results in a robot model that effectively combines traction and directional control, making it well-suited for navigating and drawing on sand surfaces, as shown in Fig. 2.

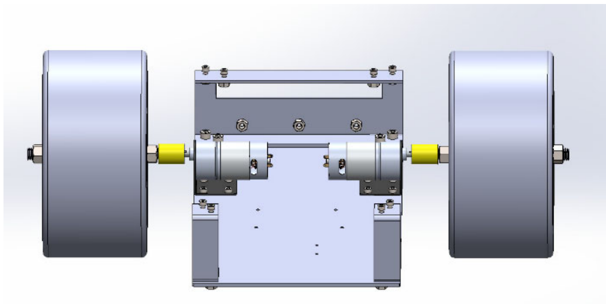

Fig. 2. Main 2-wheel drive schematic diagram.

An extensive survey of beach sand surfaces was conducted to select raking mechanisms with appropriate curvature and thickness, ensuring compatibility with the desired line patterns when drawing on sand. Based on detailed calculations, the sand raking mechanism was designed to include eight optimally configured raking bars capable of automatically moving up and down to effectively manipulate the sand surface. In Fig. 3, four servo motors are mounted side by side along the rear portion of the robot's chassis, each aligned with a pair of these raking bars. A servo horn (or arm) on each motor connects through short linkages to its two respective bars, enabling them to pivot up or down in unison. By selectively activating each servo motor, the robot can independently raise or lower different pairs of raking bars, allowing precise control over which bars contact the sand at any given moment. This arrangement—where each motor operates two raking bars—balances mechanical simplicity with versatility, ensuring the system can accurately render intricate patterns according to programmed instructions.

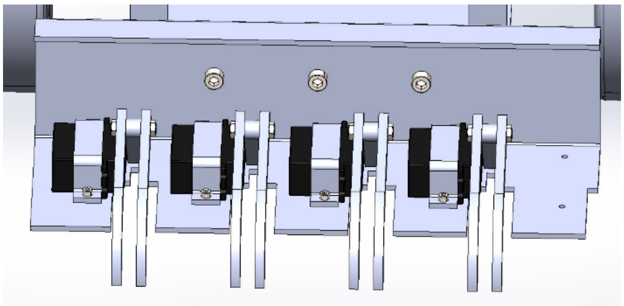

Fig. 3. Sand rake design.

B. System Dynamic

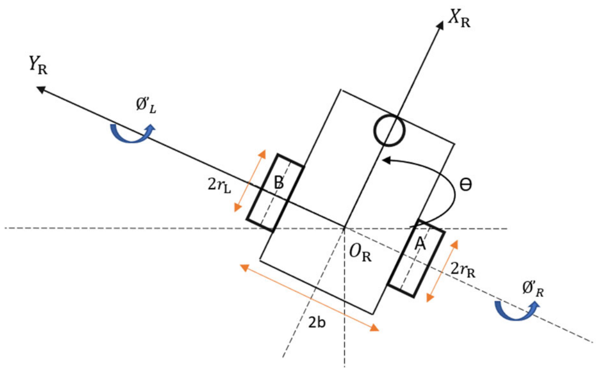

Fig. 4. Kinematic problem.

The motion of the sand drawing robot is analyzed using two coordinate systems: the global coordinate system Oxy, where the robot's initial position is defined, and the robot-fixed coordinate system O, attached to its frame as shown in Fig. 4. The robot's orientation relative to the global coordinate system is represented by the angle θ. The distance from the center to the left and right sides is *2b*. The angular velocities of the left and right wheels are denoted by $\dot{\varphi}_L$, and $\dot{\varphi}_R$ respectively, with corresponding wheel radius r_L and r_R. The robot's linear and angular velocities are V and ω, respectively.

The kinematic equations governing the robot's motion are shown as Eq. (1):

$$\dot{x} = V\cos(\theta),$$
$$\dot{y} = V\sin(\theta), \qquad (1)$$
$$\dot{\theta} = \omega.$$

These equations can be expressed in matrix form as Eq. (2):

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\cos(\theta) & \sin(\theta) & 0\\ -\sin(\theta) & \cos(\theta) & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}V\\ 0\\ \omega\end{bmatrix} \qquad (2)$$

Considering points *A* and *B* at the centers of the left and right wheels, respectively, the velocities of these wheels are calculated as Eq. (3):

$$V_A = r_R\dot{\varphi}_R, V_B = r_L\dot{\varphi}_L \qquad (3)$$

The robot's linear and angular velocities are related to the wheel velocities by Eqs. (4) and (5):

$$V = \frac{V_A+V_B}{2} = \frac{r_R\dot{\varphi}_R+r_L\dot{\varphi}_L}{2} \qquad (4)$$

$$\omega = \frac{V_R-V_L}{2b} = \frac{r_R\dot{\varphi}_R-r_L\dot{\varphi}_L}{2b} \qquad (5)$$

We expressed them in matrix form as Eq. (6):

$$\begin{bmatrix}V\\ \omega\end{bmatrix} = \begin{bmatrix}\frac{r_R}{2} & \frac{r_L}{2}\\ \frac{r_R}{2b} & -\frac{r_L}{2b}\end{bmatrix}\begin{bmatrix}\dot{\varphi}_R\\ \dot{\varphi}_L\end{bmatrix} \qquad (6)$$

Substituting into the kinematic equations, we obtain:

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\frac{r_R}{2}\cos(\theta) & \frac{r_L}{2}\cos(\theta)\\ \frac{r_R}{2}\sin(\theta) & \frac{r_L}{2}\sin(\theta)\\ \frac{r_R}{2b} & -\frac{r_L}{2b}\end{bmatrix}\begin{bmatrix}\dot{\varphi}_R\\ \dot{\varphi}_L\end{bmatrix} \qquad (7)$$

Eq. (7) provides the fundamental kinematic relationship connecting the wheel angular velocities to the robot's translational and rotational velocities, effectively mapping control inputs (wheel speeds) to the robot's motion outputs ($\dot{x}, \dot{y}, \dot{\theta}$). This direct link between input and output is crucial in designing and analyzing the control system, since it allows engineers to formulate appropriate control laws (e.g., for trajectory tracking or path following) and to predict how changes in each wheel's angular velocity will influence the robot's movement and orientation. Consequently, Eq. (7) serves as a cornerstone of the control system design, ensuring stable and precise robotic motion.

C. Electrical Control System Design

The block diagram of electrical control system is shown as Fig. 5. The robot's power system is designed to supply the necessary voltages to all components: 12 VDC for the microcontrollers and motors, and 5 VDC for the Raspberry Pi. This ensures that the microcontrollers, including the Arduino Mega2560 and Arduino Uno, as well as the Raspberry Pi and motors, receive stable and appropriate power for optimal performance.

When a user selects or uploads an image to be drawn via a web interface, the corresponding data is sent to the Raspberry Pi. The Raspberry Pi then communicates with the Arduino Mega 2560 via a UART connection, transmitting the drawing parameters. This communication allows for the seamless translation of digital designs into executable commands for the robot.

Once received, the Arduino Mega 2560 receives the drawing path parameters and sends the corresponding control signals to the MSD_H10 driver module. This driver is equipped with features for position, velocity, and acceleration control, as well as an integrated self-tuning Proportional Integral Derivative (PID) tool to aid in parameter identification and adjustment. This driver operates the two main drive wheel motors, ensuring they move precisely to create the intended patterns on the sand. When the robot is required to follow a curved trajectory, the H-bridge circuit module receives appropriate signals to control the steering motor, adjusting the robot's direction accordingly. This dynamic control system enables the robot to accurately navigate complex paths required for intricate sand drawings.

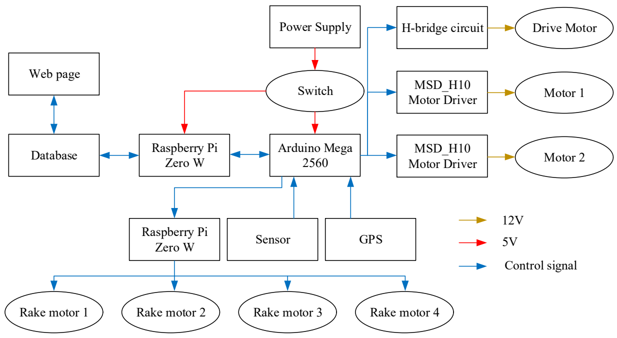

Fig. 5. Block diagram of electrical control system.

Sensors are integrated into the robot to enhance its autonomy and safety. When an obstacle is detected, the sensors send immediate feedback to the microcontroller, prompting the robot to temporarily pause its operation. This feature prevents potential collisions and allows the robot to either wait for the obstacle to be cleared or to recalibrate its path.

Upon reaching the designated drawing point, the Arduino Mega 2560 sends a digital trigger to the Arduino Uno, which activates (or deactivates) the rake motors responsible for etching lines in the sand. It is important to note that the rake motor, which is responsible for actuating the sand drawing mechanism, operates independently and is not involved in the trajectory control process. This coordinated communication between the microcontrollers ensures precise timing in the activation and deactivation of the drawing mechanism.

Additionally, a Global Positioning System (GPS) module is employed to determine the robot's current position on the sand surface. The GPS data allows the robot to navigate accurately and maintain alignment with the planned drawing coordinates. This geolocation capability is crucial for large-scale sand drawings, where precision in positioning directly affects the quality and accuracy of the rendered image.

III. RESULTS

The sand drawing robot has been constructed with an optimized design to operate effectively on beach sand surfaces as shown in Figs. 6 and 7.

The sand drawing robot was tested in a real-world beach environment to evaluate its performance in rendering basic geometric shapes on the sand surface. The shapes selected for this assessment were a circle, a rectangle, and a star, each presenting unique challenges in terms of navigation and drawing precision.

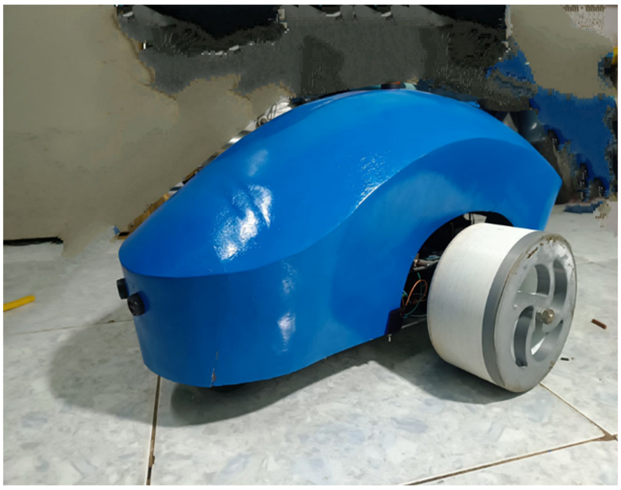

Fig. 6. Sand drawing robot.

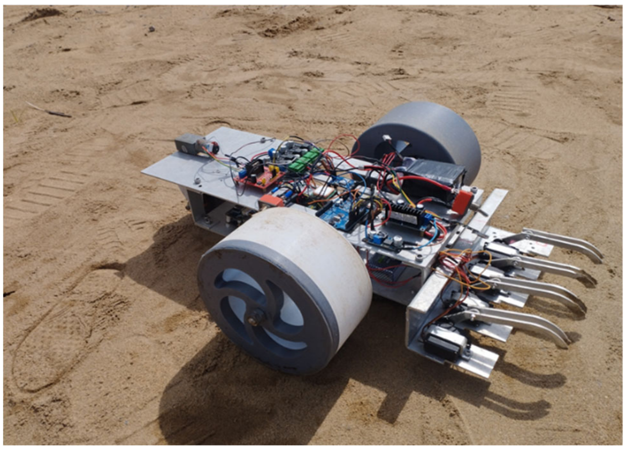

Fig. 7. Detail system.

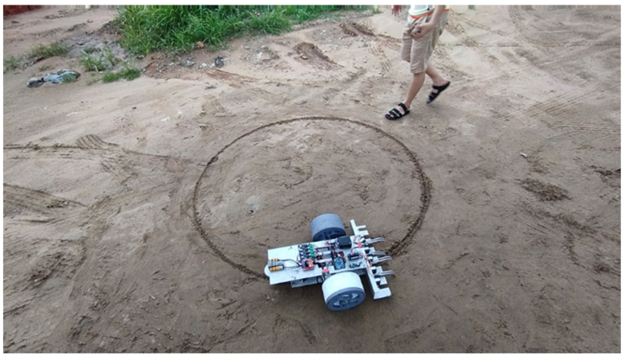

Fig. 8. Circle drawing test.

For the circle drawing test, the robot was programmed to create a circle with a predefined radius as shown in Fig. 8. The robot executed a smooth circular path by maintaining a constant angular velocity and adjusting its wheel speeds accordingly. The resulting circle etched into the sand was continuous and exhibited a uniform curvature. Measurements indicated that the circle's diameter closely matched the intended dimensions, with a deviation of less than 2%. This demonstrated the robot's capability to perform precise curved movements and maintain consistent positioning despite the uneven nature of the sandy terrain.

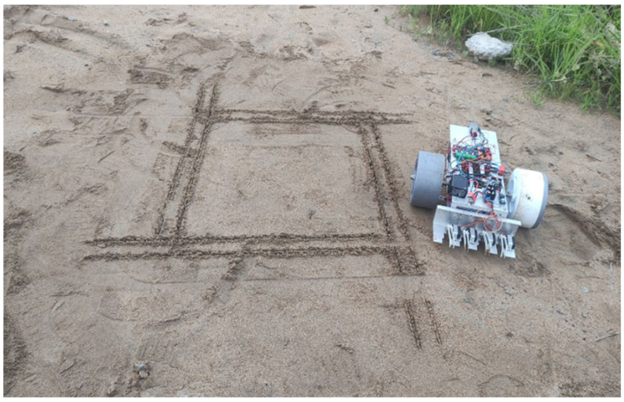

Fig. 9. Rectangle drawing test.

In the rectangle drawing test, the robot was instructed to draw a rectangle with specified length and width as shown in Fig. 9. This required the robot to execute straight-line motions and make sharp 90-degree turns at each corner. The robot successfully navigated the path, and the rectangle drawn on the sand had straight edges and well-defined angles. The dimensional accuracy was within a 3% margin of error compared to the planned measurements. This test confirmed the robot's ability to control linear movements and accurately change direction, essential for rendering polygonal shapes.

Fig. 10. Star drawing test.

The star shape presented a more complex challenge due to its intricate design involving intersecting lines and acute angles as shown in Fig. 10. The robot's control system was tasked with following a path that required precise coordination between linear and rotational movements. The robot managed to draw the star shape on the sand, with all five points clearly identifiable. While the overall shape was recognizable, minor discrepancies were observed at the intersection points where lines overlapped. These imperfections were attributed to slight delays in the robot's response time when executing rapid directional changes. Nonetheless, the successful completion of the star shape demonstrated the robot's proficiency in handling complex patterns.

The results from these tests indicate that the sand drawing robot effectively translates programmed geometric patterns into physical drawings on a sandy surface. The robot maintained high accuracy levels in both simple and complex shapes, showcasing the robustness of its mechanical design and control algorithms. Minor deviations in the drawings highlight areas for potential improvement, such as enhancing the responsiveness of the steering mechanism and refining the path-planning algorithms to better handle abrupt changes in direction. At present, we are only implementing open-loop control based on the pre-calculated trajectory, and no additional closed-loop feedback control is applied to compensate for the differences in wheel resistance due to variable surface deformations. We acknowledge that incorporating a closed-loop control strategy could further enhance the system's performance under conditions of asymmetric load or terrain variations. As such, future work will focus on integrating closed-loop control, possibly by exploiting the full capability of the MSD_H10's self-tuning PID tools, to dynamically adjust and compensate for discrepancies in wheel speeds. Overall, the successful execution of these shapes validates the robot's capabilities and its potential for applications in artistic expression and educational demonstrations.

IV. Conclusion

This paper presented the comprehensive design and construction of a sand drawing robot capable of rendering detailed images on sandy surfaces, effectively combining robotic technology with artistic expression. The robot's optimized mechanical structure—including two primary drive wheels and an eight-bar sand raking mechanism controlled by four servo motors—allowed for precise movement and drawing on deformable terrain. Integrated control systems using an Arduino Mega2560 microcontroller and a Raspberry Pi facilitated seamless communication between user inputs and robotic actions, while sensors and GPS enhanced adaptability and safety. Experimental results, including successful drawings of a circle, rectangle, and star, demonstrated the robot's proficiency in executing both simple and complex patterns with high accuracy. This project contributes to the field of robotics by addressing challenges associated with operating in dynamic environments, holding potential for applications in interactive art installations and educational settings. Future work will focus on expanding capabilities, improving adaptability to varying sand conditions, and collecting the necessary evidence data to rigorously evaluate the system's accuracy and reliability.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

TCD and TDD conceptualization and methodology; TCD wrote the manuscript; TDD writing, review and editing; and TDD supervised; TDD project administration; all authors had approved the final version.

FUNDING

This research is funded by University of Economics Ho Chi Minh City–UEH University, Vietnam.

ACKNOWLEDGMENT

The authors would like to thank the University of Economics Ho Chi Minh City–UEH University in Vietnam for providing financial support and study facilities.

REFERENCES

[1] C. Bian and S. Lu, "Personalized recommendation of entertainment robots in fine arts education based on human–computer interaction and data mining," *Entertain. Comput.*, vol. 51, 100740, 2024.
[2] J. Chao and Z. Yingren, "Entertainment type robots based on machine learning and game teaching mode applied in dance action planning of art teaching," *Entertain. Comput.*, vol. 52, 100851, 2025.
[3] Z. Zhenhua and G. Feng, "Application of social entertainment robots based on machine learning algorithms and the Internet of Things in collaborative art performances," *Entertain. Comput.*, vol. 52, 100784, 2025.
[4] X. Liao and P. Cao, "Digital media entertainment technology based on artificial intelligence robot in art teaching simulation," *Entertain. Comput.*, vol. 52, 100792, 2025.
[5] S. Maeyama and S. Yuta, "Mobile robots in art museum for remote appreciation via internet," presented at the *IEEE/RSJ IROS 2002 Workshop on Robots in Exhibitions*, Lausanne, Switzerland, Sept. 2002.
[6] E. Ackerman. (Jan 2015). Beachbot turns an ordinary beach into an artist's canvas. *IEEE Spectrum*. [Online]. Available: https://spectrum.ieee.org/disney-research-beachbot
[7] B. Shapiro. Sisyphus: The kinetic sand drawing machine. *Sisyphus Industries*. [Online]. Available: https://www.sisyphus-industries.com/
[8] M. W. Spong, S. Hutchinson, and M. Vidyasagar, *Robot Modeling and Control*, 1st ed., Hoboken, NJ, USA: Wiley, 2006.
[9] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to Autonomous Mobile Robots*, 2nd ed. Cambridge, MA, USA: MIT Press, 2011.
[10] R. C. Gonzalez and R. E. Woods, *Digital Image Processing*, 4th ed. Hoboken, NJ, USA: Pearson, 2018.
[11] J. M. Gülzow and O. Deussen, "Region-based approaches in robotic painting," *Arts*, vol. 11, no. 4, 77, 2022.
[12] L. Scalera, G. Canever, S. Seriani, A. Gasparetto, and P. Gallina, "Robotic sponge and watercolor painting based on image-processing and contour-filling algorithms," *Actuators*, vol. 11, no. 2, 62, 2022.
[13] D. Song, J. Park, and Y. J. Kim, "SSK: Robotic pen-art system for large, nonplanar canvas," *IEEE Trans. Robot.*, vol. 39, no. 4, pp. 3106–3119, 2023.
[14] A. Karimov, E. Kopets, G. Kolev, S. Leonov, L. Scalera, and D. Butusov, "Image preprocessing for artistic robotic painting," *Inventions*, vol. 6, no. 1, 19, 2021.
[15] M. Adamik, J. Goga, J. Pavlovicova, A. Babinec, and I. Sekaj, "Fast robotic pencil drawing based on image evolution by means of genetic algorithm," *Robot. Auton. Syst.*, vol. 148, 103912, 2022.
[16] L. Chen, A. Swikir, and S. Haddadin, "Drawing Elon Musk: A robot avatar for remote manipulation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Prague, 2021, pp. 4244–4251.
[17] L. Scalera, S. Seriani, P. Gallina, M. Lentini, and A. Gasparetto, "Human–robot interaction through eye tracking for artistic drawing," *Robotics*, vol. 10, no. 2, 54, 2021.
[18] L. Scalera, E. Maset, S. Seriani, A. Gasparetto, and P. Gallina, "Performance evaluation of a robotic architecture for drawing with eyes," *Int. J. Mech. Control*, vol. 22, no. 2, pp. 53–60, 2021.
[19] C. G. Cubero, M. Pekarik, V. Rizzo, and E. Jochum, "The robot is present: Creative approaches for artistic expression with robots," *Front. Robot. AI*, vol. 8, 662249, 2021.
[20] R. Fernandez-Fernandez, J. G. Victores, and C. Balaguer, "Deep robot sketching: An application of deep Q-learning networks for human-like sketching," *Cogn. Syst. Res.*, vol. 81, pp. 57–63, 2023.
[21] A. Karimov, E. Kopets, S. Leonov, L. Scalera, and D. Butusov, "A robot for artistic painting in authentic colors," *J. Intell. Robot. Syst.*, vol. 107, no. 3, 34, 2023.