A Floor Tiling Robotic System

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Abstract

With the accelerated advancement of robot technology and sensor technology, construction challenges have become less difficult. The construction industry has been revolutionized by innovations in materials, equipment, and procedures, making it more efficient and safer. In recent years, however, an accelerated ageing society is compensating for the dearth of youthful and middle-aged workers. This paper proposes a Floor Tiling Robot robotic system that uses a vision-based solution to minimize labour-intensive, improve productivity, and increase the precision of the floor tiling process in order to reduce the material cost. The Floor Tiling Robot has implemented several systems, including a pneumatic vacuum suction system as a method for grasping floor tiles, a finite state machine as a method for robotic arm movement control algorithm and Canny Edge Detector algorithm as a method for floor tile positioning.

Keywords: Robotics, Automation, Computer Vision, IoT, Construction industry, Floor tiling robot

1. INTRODUCTION

The construction industry relies on floor tiling to provide functional and aesthetically appealing surfaces for a variety of spaces. Floor tiles contribute to the durability, sanitation, and overall atmosphere of residential and commercial buildings alike. Nevertheless, the manual process of floor tiling presents a number of obstacles and limitations.

Traditional methods of floor tiling rely largely on skilled labourers who lay each tile by hand. This procedure requires precise alignment, levelling, and uniform grout lines, which can be physically demanding and time-consuming. Moreover, manual tile installation is prone to human error, resulting in misalignments, irregular surfaces, and costly rework. There are a number of technologies and solutions able to implement robotic systems, however the author would like to choose the most suitable technology and solution to come out with the robotic systems for the user.

2. LITERATURE REVIEW

In 2014, Region-based Convolutional Neural Networks (R-CNN) models was published, which are used in computer vision and image processing. The R-CNN family recognizes the objects through their classification. The primary objective of R-CNN was to correctly locate the elements in the image [1]. Joseph Redmon and Ali Farhardi published YOLO v2, also known as YOLO 9000, in the same year as YOLO v1. This new YOLO model can detect over nine thousand object categories and can operate at 67 frames per second with 76.8% mAP on the Pascal VOC 2007 dataset [2]. Floor tile paving robot is a fully automated solution for paving large-format floor tiles at high speed and with consistently high quality. The compact, wireless system features all-wheel drive with an omni-directional mobile chassis. The visual measurement and positioning system with four cameras enable the tiles to be precisely aligned. To do this, the robot arm with vacuum grippers first vacuums the floor tile and rotates it 180 degrees. Then the robot moves back to apply the cement to the substrate. Finally, the tile is laid with millimetre precision on the fresh bed of adhesive [3]. This section discussed the technologies and solutions to implement the robotic system, Floor Tiling Robotic System. Fast R-CNN employs several innovations to improve training and testing speed while also increasing detection accuracy. Fast R-CNN trains the very deep VGG16 network 9x faster than R-CNN, is 213x faster at test-time, and achieves a higher mAP on PASCAL VOC 2012. Compared to SPPnet, Fast R-CNN trains VGG16 3x faster, tests 10x faster, and is more accurate [4].

Fast R-CNN employs several innovations to improve training and testing speed while also increasing detection accuracy. A computer interprets digital images as 2D or 3D matrices, where each value or pixel in the matrix represents the amplitude or "intensity" of the pixel. People are typically accustomed to interacting with 8-bit images, in which the amplitude value ranges from 0 to [5], [6]. Inverse kinematics can be accomplished, according to robot kinematics, when the rank of the system is less than the rank of the Jacobian matrix of each wheel of the robot, which reduces the degree of freedom of the robot's joints [7]. In this paper, the author has analysed several methods of manual floor tiling, overall [8], it has three manual floor tiling methods which are normally used in different applications. The manual floor tiling methods are thick-bed tiling (mortar bed tiling), thin set tilling (dry bond tiling), dry system. The authors have proposed a floor tiling robotic system called Floor Tiling Robot I System (FTR-I). Worldwide, over 10 billion m^2 of ceramics are consumed once a year. Gramazio Kohler Architects in partnership with ROB Technologies noticed that automatic tiling work can be of great value, they aimed to design a robot that can entirely replace human labour [9]. There are numerous varieties of industrial robots on the market, and each has its own benefits and drawbacks. Cartesian robots, SCARA robots, articulated robots, cylindrical robots, delta robots, polar robots, and collaborative robots are the most common forms of industrial robots [10], [11].

Control panel unit, main controller unit, mobile platform unit, collaborative robotic arm, end effector unit, and sensor unit comprise the FTR-1's mechanical structure as shown in Fig. 1. The control panel unit is a robotic arm control panel that serves as the FTR-1's interface for human interaction.

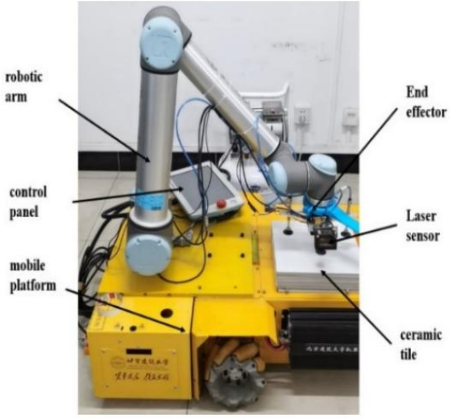


Fig. 1. FTR-I.

In this floor tiling robot, the authors have implemented a hierarchy robotic control system. As depicted in Fig. 2, the robotic system is composed of several layers: the user layer, the system control layer, the intermediate driving layer, and the hardware execution layer [12].

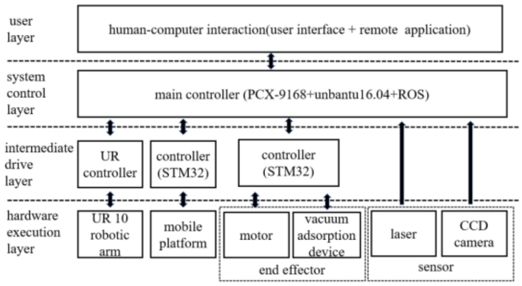


Fig. 2. Hierarchy Robotic System of FTR-I.

The RPN and the Fast R-CNN share convolutional computations, which drastically reduces the processing time [13]. In 2014, an improve edge detection Canny algorithm published. Particle swarm optimization (PSO) has been applied as a control algorithm for a number of selected mathematical models [14]. Apart from performing well basic functions like moving forward and backward, turning left and right, the robot is able to detect preceding obstacle, stop movement, and then identify suitable clear way for avoiding the obstacle [15].

3. RESEARCH METHODOLOGY

This section describes the design of a floor tiling robotic system that uses robotics to automate the floor tiling operation. The process of tiling a floor can require a lot of effort and time; this invention was created to increase the building industry's productivity. The author illustrated the potential of automation technologies in the construction industry in this part.

3.1 System Architecture of Floor Tiling Robotic System

The hardware design plays a critical role in laying the foundation for the robotic floor tiling system prototype. This segment demonstrated the considerations involved in selecting components and additionally furnished an in-depth examination of every facet of the hardware design procedure in order to guarantee accurate perception and precise motion of the robotic system.

The floor tiling robotic system's system architecture comprises various components, including a main controller, a microcontroller, sensors, and a pneumatic system. As illustrated in Fig. 3 below, the Raspberry Pi functions as the main controller of the entire system and the central processing unit responsible for monitoring and controlling critical operations such as image processing, communication, and decision-making. Raspberry Pi establishes communication connection with Arduino as a publisher. Arduino will operate as the microcontroller of the robotic system, facilitating control operations at a low level and enabling communication with sensors such as servo motors. Arduino facilitates synchronised operation of the pneumatic system, which includes a negative pressure vacuum pump, a solenoid valve, and a suction cup with spring actuator, in addition to the servo motors.

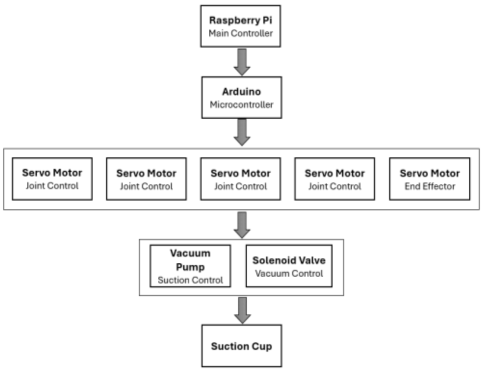


Fig. 3. System Architecture of Floor Tiling Robot.

3.2 Vacuum System and Camera Module

End effectors are affixed to the extremity of a robot's arm to facilitate its interaction with the immediate surroundings. Robotic systems rely on end effectors to effectively handle, manipulate, and sense objects. The robotic arm of the floor tiling system incorporates a pneumatic system as its end effector. This system comprises a negative pressure vacuum pump, a suction cup equipped with a spring plunger, and a solenoid valve.

The suction cup, vacuum suction pump, and 3-way 2-position solenoid valve work in concert to enable the suction-based manipulation of objects, including tiles, within a robotic system. The airflow is regulated by the solenoid valve, which transitions between phases in order to generate or discharge suction at the suction cup, as illustrated in Fig. 4 below. In the absence of activation of the solenoid valve, the airflow from the negative pressure vacuum compressor is redirected to the suction cup, thereby generating a vacuum, and ensuring the cup's secure attachment to the tile's surface. As the source of negative pressure, the vacuum suction compressor produces suction force that secures the object to the suction cup. By maintaining the necessary vacuum level, it guarantees a steady and dependable hold on the object during the entirety of the manipulation procedure.

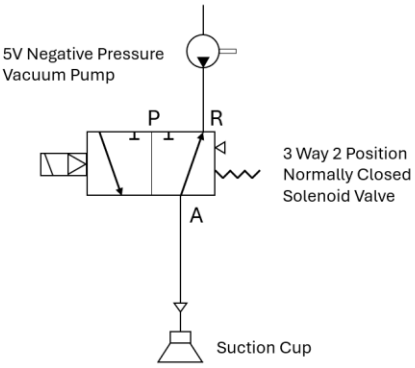


Fig. 4. Pneumatic Circuit Diagram of Vacuum System.

When used in conjunction with the suction system, the camera module serves as the visual monitor of the autonomous system, granting it perceptive abilities. By utilising the camera module's lens, the system acquires instantaneous visibility of its environment, which empowers it to precisely identify tile perimeters, corners, and possible impediments. The process of choosing an appropriate camera module is determined by factors including field of view, resolution, and compatibility with image processing algorithms. This guarantees a smooth integration of the module into the control architecture of the system. The IMX219 camera module will be designated as the visual sensor of the end effector.

3.3 Prototype and Wiring Diagram

The construction and connecting of physical parts necessary for the functioning of the robotic system constitute the hardware integration process. As shown in Fig. 5, the main parts of the system are the rigidly mounted robotic arm, servo motors, vacuum pump, solenoid valve, suction cup, and camera module.

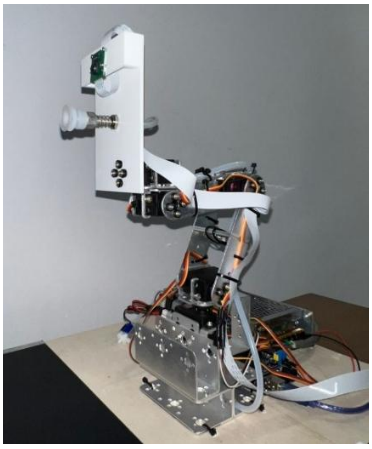


Fig. 5. Floor Tiling Robot Prototype.

The floor tiling robot's wiring diagram is depicted in Fig. 6. The Arduino Uno was affixed to the Arduino Sensor Shield, to which each MG996R servo motor was joined. Furthermore, a 5V 20A AC-DC power supply was linked to the Arduino. In the meantime, the IMX 219 camera module was connected to the Raspberry Pi, which maintained serial communication with the Arduino via a USB A-B cable.

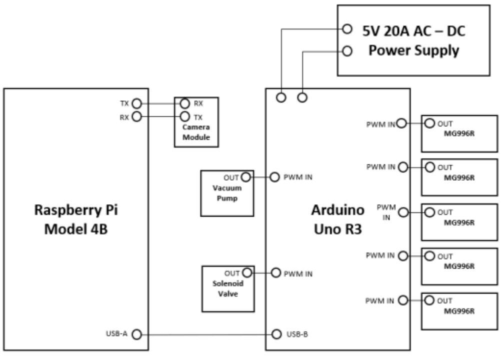


Fig. 6. Wiring Diagram of Floor Tiling Robot.

3.4 Floor Tiling Robot Control Algorithm Design

In conjunction with the control algorithm, a finite state machine (FSM) regulates the motion of the robotic arm. As illustrated in Fig. 7, the FSM establishes a number of states that correspond to different phases of the tile installation procedure, such as idle, initialization, tile collection, and tile placement. Transitions between states are initiated in response to user commands, while user commands will be determined based on the image processing result, thereby ensuring that the movements of the robotic arm are systematically controlled and coordinated. The FSM can be sectioned into several states:

I. Initialization State: The robotic arm enters an initialization state during system launch, during which it calibrates servo motors, initializes sensor readings, and makes operational preparations.

II. Idle State: During periods of inactivity, the robotic arm awaits control system instructions before initiating the installation of tiles. It maintains a stationary state until a subsequent assignment is made.

III. Tile Pickup State: When a tile pickup command is given, the robotic arm enters the state designated for tile pickup. In this instance, the object performs accurate motions in order to approach the specified tile, activate the suction cup mechanism, and firmly grasp the tile.

IV. Tile Placement State: After a successful collection operation, the robotic arm enters the state of tile placement. The object precisely locates the desired location on the floor, aligns it with adjacent tiles, and then releases it with deliberate and controlled motions.

V. Error Handling State: Error handling states are integrated into the FSM in order to accommodate unforeseen issues, such as sensor failures and communication errors. These states facilitate the robotic arm in ceasing operations in a secure manner, informing the control system, and awaiting additional instructions.

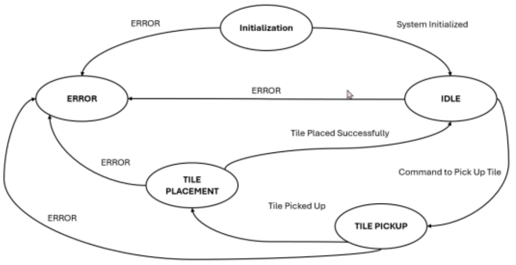


Fig. 7. Floor Tiling Robotic System Finite State Machine Diagram.

Although hardware limitations present certain difficulties, the control algorithm has been intentionally developed to be versatile and adjustable. To allow for the inclusion of uncertainties introduced during calibration and variations in tile positions, tolerance thresholds are incorporated. Furthermore, the implementation of adaptive strategies, including dynamic path planning and obstacle avoidance, serves to augment the system's capacity to adjust to environmental fluctuations and unanticipated impediments.

In summary, the control algorithm development for the robotic system for floor tiling recognises and resolves the hardware limitations that were imposed. By employing an open-loop control approach and a manual calibration procedure, the system adeptly manipulates and guides tiles to their assigned locations. Although functioning within these limitations, the control algorithm maintains its flexibility and adaptability, guaranteeing resilient performance in diverse circumstances.

3.5 Image Processing and Computer Vision

Within the framework of the floor tiling robotic system, the accurate perception and interpretation of the robot's surroundings are at the mercy of image processing and computer vision methodologies. This section provides further details regarding the robust image processing pipeline that has been developed to identify and evaluate the alignment of tiles within the robot's field of view.

The image pre-processing pipeline Fig. 8 commences by applying calibration parameters to undistorting raw images captured by the IMX219 camera module. After the image has been corrected for distortion, colour filtration is performed to distinguish white pixels that represent tiles. In this stage, the image is thresholder according to the colour of the tiles in order to preserve exclusively the white areas, thereby streamlining subsequent processing operations.

After filtration, the image undergoes a grayscale conversion in order to decrease computational complexity and improve the extraction of features. The grayscale image then undergoes a median blur operation in order to eliminate noise and level out irregularities, thereby enhancing the precision of subsequent feature extraction. By sharpening the blurred image, edges and details are accentuated, which facilitates the identification of tile boundaries and contours. In order to identify edges within the sharpened image, which highlights significant gradients and facilitates the localization of tile boundaries, canny edge detection is utilised. By defining and masking a region of interest (ROI) that corresponds to the floor area from the edge-detected image, subsequent processing is limited to pertinent areas that contain tiles.

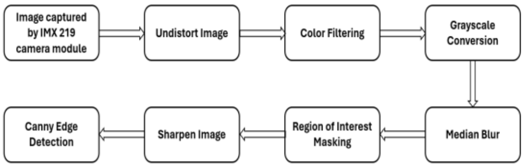


Fig. 8. Image Preprocessing Pipeline.

In order to identify and evaluate the alignment of floor tiles, tile detection and localization algorithms are implemented on the pre-processed image. The OpenCV ‘find Contours’ function is employed to identify contours that symbolise prospective tile boundaries, thereby delineating the precise locations of individual tiles within the ROI. Squares are selected from the detected contours according to their shape characteristics; contours are filtered by area, perimeter, and aspect ratio in order to identify square-shaped regions that correspond to tiles. The coordinates of the four vertices of each detected square are obtained, which symbolise the corners of specific tiles and function as benchmarks for further analysis.

4. RESULTS AND DISCUSSION

4.1 Quantitative Metrics

To assess the Floor Tiling Robot's performance, an experiment was carried out. Every tile's paving time is recorded during the experiment, beginning when the Floor Tiling Robot is in the finite state machine's "IDLE" state. In order to assess if the Floor Tiling Robot had accurately positioned each tile, as shown in Fig. 9 and Fig. 10, six squares with a gap of 50 mm were marked on the floor so that they could be checked for alignment.

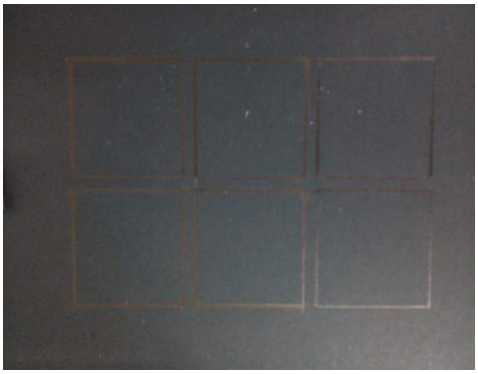


Fig. 9. Six Squares Marked on the Floor.

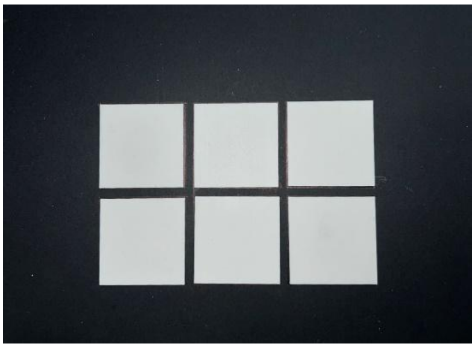


Fig. 10. Well Installed Floor Tiles.

The complete tiling process is shown in Fig. 11.The experiment was repeated 20 times, and the following quantitative results were obtained, as illustrated in Table 1 and Table 2:

- Total Installation Time: The total time for all tile installations across the 20 experiments was approximately 233.2 seconds.
- Average Installation Time per Tile: The average installation time per tile for tiles No. 1 to 6 was recorded as follows: 38.83 seconds, 38.75 seconds, 38.6 seconds, 39.1 seconds, 38.9 seconds, and 39 seconds, respectively. The total average installation time for all six tiles is approximately 38.87 seconds.
- Accuracy of Tile Placement: Overall, 70% of tiles were accurately placed in their correct position, with 84 tiles successfully positioned correctly. However, 36 tiles required adjustment or were inaccurately placed.
- Defect Angles: Tiles with imperfect angles were measured using an angle ruler ranging from 0° to 180°. Six tiles exhibited defective angles ranging from -5° to 7°.

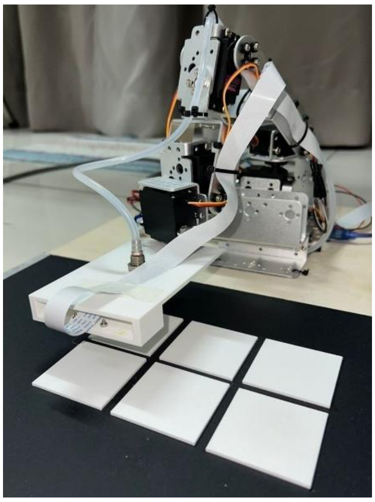
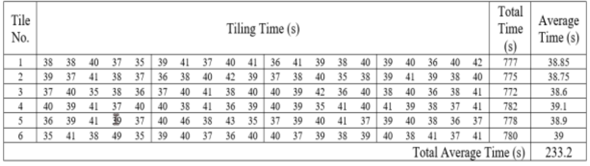


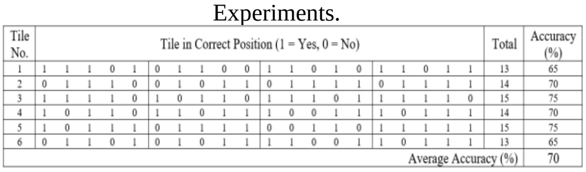
Fig. 11. Floor Tiling Robot's Tiling Process.

Table 1. Tiling Time Recorded During Experiments.



Tile No.	Tiling Time (s)																				Total Time (s)	Average Time (s)
1	38	38	40	37	35	39	41	37	40	41	36	41	39	38	40	39	40	36	40	42	777	38.85
2	39	37	41	38	37	36	38	40	42	39	37	38	40	35	38	39	41	39	38	40	775	38.75
3	37	40	35	38	36	37	40	41	38	40	40	39	42	36	40	38	40	36	38	41	772	38.6
4	40	39	41	37	40	40	38	41	36	39	40	39	35	41	40	41	39	38	37	41	782	39.1
5	36	39	41	39	37	40	46	38	43	35	37	39	40	41	37	39	40	38	36	37	778	38.9
6	35	41	38	49	35	39	40	37	36	40	40	37	39	38	39	40	38	41	37	41	780	39
																					Total Average Time (s)	233.2

Table 2. Accuracy of Tile Installation Recorded during Experiments.



Tile No.	Tile in Correct Position (1 = Yes, 0 = No)																				Total	Accuracy (%)
1	1	1	1	0	1	0	1	1	0	0	1	1	0	1	0	1	1	0	1	1	13	65
2	0	1	1	1	0	0	1	0	1	1	0	1	1	1	1	0	1	1	1	1	14	70
3	1	1	1	1	0	1	0	1	1	0	1	1	1	0	1	1	1	1	1	0	15	75
4	1	0	1	1	0	1	1	0	1	1	1	0	0	1	1	1	0	1	1	1	14	70
5	1	0	1	1	1	0	1	1	1	1	0	0	1	1	0	1	1	1	1	1	15	75
6	0	1	1	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1	13	65
																					Average Accuracy (%)	70

4.2 *Qualitative Analysis on System Reliability*

Based on the inaccurate results obtained from the experiment, it can be observed that servo motors may not always reach the exact same position despite receiving the same input signals. MG996R is typically used in small robotics applications. On the other hand, standard MG996R servo motors do not have any feedback mechanisms like potentiometers or encoders. There is no direct method for the servo motor to determine its current position if there is no feedback mechanism in place. As a result, compared to servo motors with feedback systems, the motor's position precision may be limited, and it is more difficult to adopt advanced control techniques like hysteresis.

Furthermore, the MG996R servo motor's datasheet states that its dead band width is 5 microseconds. The range of input signals that the servo motor does not react to or move inside is referred to as the dead band width. Because the servo motor might not react to slight changes in the input signal until the signal exceeds the dead band range, dead band width might cause differences in placement. Because of this, the motor might not change its position if the input signal is within the dead band range, which could result in tiny positioning errors, particularly if the input signal varies near the dead band's edge.

On the other hand, the threshold values utilized by the Canny algorithm for edge detection have a substantial effect on the final results, as shown in Fig. 12, the red colour region still contains noise. These thresholds determine which edges are deemed strong and which are deemed weak, and they play a crucial role in determining the sensitivity and precision of edge detection.

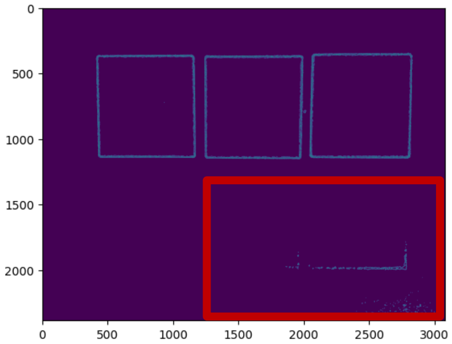


Fig. 12. The image noise increased due to light condition.

The qualitative analysis concludes by highlighting how crucial it is to solve issues and improve the functionality of crucial parts, like servo motors and image processing algorithms, in order to increase the floor tiling robotic system's dependability and longevity. To reduce positioning mistakes, strategies for enhancing servo motor precision should be investigated. These may include the use of feedback systems or the improvement of control approaches. Similar to this, threshold settings in image processing algorithms can be carefully adjusted to provide consistent performance in a variety of environmental situations and increase the accuracy of edge identification. Through the implementation of these principles, the system can become more dependability and robust in practical tiling applications, hence augmenting its overall efficacy and user contentment.

5. CONCLUSION

The aim of this study was to conduct a thorough assessment of the floor tiling robotic system to ascertain its efficiency, reliability, and ease of use for the automation of floor tiling process. Combining objective evaluation, quantitative data, and qualitative analysis led to several important findings. These results provided useful details regarding the advantages and disadvantages of the system. Although the system demonstrated potential for automating floor tiling process, further development and optimisation are needed to address identified issues and enhance general usability and dependability.

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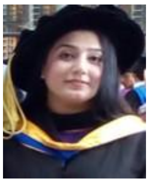

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