Design and implementation of the floor tiling robot control system based on multi-motion unit structure and hierarchical control

Shun Wang¹, HuiXing Zhou²,³, ZhongYue Zhang², XiaoYu Zheng², YanNan Lv²

¹. School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China;
². School of Mechanical-electronic and Vehicle Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China.
³. Beijing Engineering Research Center of Monitoring for Construction Safety, Beijing 100044, China
1108140719001@stu.bucea.edu.cn

Abstract. The floor tiling is a hard work, and a high level of skill is also necessary for the operators. Therefore, the current global floor tiling construction costs continue to increase. The use of robots to replace manual operations is becoming more urgent. Robotic floor tiling can reduce the work intensity of workers while improving the efficiency and the quality. This paper proposes a control system scheme for a floor tiling robot. Based on the characteristics of the multi-motion unit structure of the robot and the design concept of hierarchical control, the control system was divided into the user layer, the system control layer, the intermediate drive layer and the hardware execution layer. The system had clear functions and strong reusability. The user layer played a role of human-computer interaction which received the user’s instructions. The system control layer was the brain of the robot, which was mainly responsible for the coordinated control of all the motion units during the floor tiling process. The middle driver layer provided the device controllers for all dedicated hardware devices, realized recognition of system control layer instructions and took the hardware execution layer devices to work. The hardware execution layer mainly executed the actions in the process of the floor tiling. The test results show that the control system can realize stable control for the floor tiling operation, and the system is stable and reliable. The research results on this study would provide a reference for the control system design of other construction robots or special equipment robots.

1. Introduction

In recent years, robotics and sensor technology have developed rapidly⁴,⁵, which has promoted the advancement of construction robot technology. Many construction robots for specific tasks are stationed on construction sites⁶. In the field of decoration, the use of ceramic tiles is very large, and the annual global ceramic tile installation exceeds 10 billion m². However, the ceramic tiles are mainly laid by manual methods, which is labor intensive and costly. Therefore, the floor tiling construction has the application prospect of using robotic tiling instead of manual tiling. Robotic floor tiling can improve the degree of automation, reduce labor intensity and avoid construction hazards, which also ensure the high efficiency and high quality. It is the development trend of floor tiling construction technology in modern construction industry.
In the decades, many researchers have focused on machine-automated floor tiling technology\cite{6-9}. However, the current research results only are carried out on a laboratory site and had not been applied on a construction site. The architectural environment has brought many challenges to the realization of robotic floor tiling, such as complex and changeable architectural scenes, many disturbances in the on-site environment, complex robot control systems, and high hardware development costs. The floor tiling robot is composed of multi-motion units. The robotic construction method requires a stable and reliable control system to drive each motion unit of the robot to achieve the final construction operation.

The studies on the control system of construction robots were always concerned by the researchers. Tang X et al. proposed a teleoperation construction robot control system based on virtual reality technology\cite{10}. Yoshinada et al. used teleoperation control to achieve dual-arm robot construction control\cite{11}. Lee Y S et al. proposed an integrated control system for curtain wall cleaning robots\cite{12}.

This paper proposes a robotic floor tiling tile control system based on a multi-motion unit structure and hierarchical control to realize floor tiling task.

2. The FTR-I robot hardware system

The control strategy mentioned in this paper is applied to the Floor Tiling Robot I system (FTR-I). The FTR-I consists of multiple functional units, which are the control panel unit, the main controller unit, the mobile platform unit, the collaborative robot arm, the end effector unit and the sensor unit. The FTR-I system is shown in figure 1.

2.1. Control panel

The control panel consists of a touch screen, a switch button and an emergency stop button. The control panel provides a human-computer interaction interface for the FTR-I, and the operator can perform operations such as program loading and parameter setting.

2.2. Main controller

The main controller choose the industrial computer PCX-9168, which receive the instructions from the control panel and performs the coordinated control of the units. It is the brain of FTR-I.

2.3. Mobile platform

The mobile platform is controlled by STM 32 to realize the independent driving of the four wheels based on servo motors. The frame of the mobile platform system is shown in figure 2.

2.4. Collaborative robot arm

The robot arm of the FTR is the UR 10 robot manipulator arm, which has extremely high accuracy and safety, and it can realize man-machine collaboration.
2.5. **End effector**
The end effector mainly includes a connecting frame, a suction cup and a vibration motor, which are used to grab and place ceramic tiles when laying ceramic tiles.

2.6. **Sensor system**
The sensor system is composed of multiple sensors, including laser displacement sensors and CCD cameras, which are used to realize the environmental positioning and perception of the floor tiling process.

3. **The robot control system**
The robot control system is designed based on a hierarchical control and is divided into the user layer, the system control layer, the intermediate driving layer, and the hardware execution layer. The frame of the FTR-I control system is shown in figure 3.

![Diagram of the FTR-I control system](image)

**Figure 3. Frame of the FTR-I control system**

3.1. **User layer**
The user layer mainly includes the control panel and remote application, and its function is to realize human-computer interaction such as receive the control instructions from the operator.

3.2. **System control layer**
The system control layer is the core layer of the system, just like a human brain, which is mainly responsible for understanding the robot's instructions, real-time data processing, and motion control. The main controller is a high-performance industrial computer PCX-9168, with ubuntu16.04 and robot operating system (ROS) installed. The powerful ROS hardware compatibility package makes it easier for the control layer to communicate with the intermediate driver layer and hardware devices.

3.3. **Intermediate drive layer**
The UR10 robotic arm uses a UR controller for robotic arm motion control. The mobile platform uses STM32 monolithic for motion control. The vibration motor is used to sure tile glue dense in the floor tiling process, and the vacuum suction cup is used to grab and lay the tiles, which is controlled by STM32 monolithic.
3.4. Hardware execution layer
The robot uses a mecanum omnidirectional wheel mobile platform, and the robot have flexible steering capabilities. The robot arm uses a UR10 collaborative robot arm, which has high precision and safety. The vibration motor uses an eccentric vibration motor and is driven by a PWM signal. The ceramic tile grasping device use vacuum pneumatic and is equipped with a vacuum generator. The laser sensor and CCD camera communicate with the controller through the USB serial port, the laser sensor is used for vertical distance measurement, and the CCD camera is used for real-time measurement of the horizontal deviation between the current position of the tile and the target position.

4. Robotic floor tiling motion control

4.1. Kinematics analysis of mobile platform
It is assumed that the robot moves on a flat ground during the process of floor tiling task, the world coordinate system is defined as a rectangular coordinate system X-O-Y, and with the ground coordinate system as the world coordinate system. The robot coordinate system is defined as a rectangular coordinate system x-o-y, as shown in Figure 4.

![Figure 4. World coordinate system and robot coordinate system](image)

The speed of the mobile platform in the world coordinate system is \( v_w \), where the speed in the X-axis direction is \( W_Xv \), the speed in the Y-axis direction is \( W_Yv \), and the angular velocity is \( \Omega \). The speed of the mobile platform in the robot coordinate system is \( v_r \), where the speed in the x-axis direction is \( R_Xv \), the speed in the y-axis direction is \( R_Yv \), and the angular velocity is \( \Omega_R \). The angle between the robot coordinate system and the world coordinate system is \( \theta \), and the speed conversion relationship between the world coordinate system and the robot coordinate system is shown in formula 1.

\[
\begin{bmatrix}
W_Xv \\
W_Yv \\
\Omega
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
-\sin \theta & -\cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}^{-1}
\begin{bmatrix}
R_Xv \\
R_Yv \\
\Omega_R
\end{bmatrix} = T^{-1}
\begin{bmatrix}
V_X \\
V_Y \\
\Omega
\end{bmatrix} = T^{-1}v_r
\]

(1)

The free movement of the mobile platform is achieved through four independently driven mecanum wheels. The centers of the four wheels are at the same distance from the center of rotation of the mobile platform, which is masked k. In the robot coordinate system, the coordinates of the center points of the four wheels are \( (X_1,Y_1),(X_2,Y_2),(X_3,Y_3),(X_4,Y_4) \), and the speeds of each wheel is \( V_1, V_2, V_3 \) and \( V_4 \). Then, the inverse kinematics solution of the mobile platform is shown in formula (2).
4.2. Design of the vacuum suction system

The robot achieves grasping and laying the ceramic tile through the vacuum suction system. The robot pneumatic circuit and pneumatic hardware system diagrams are shown in figure 5 and figure 6.

![Figure 5: Pneumatic circuit diagram of vacuum suction handling system](image)

![Figure 6: Schematic diagram of the tile edges as a position reference](image)

The vacuum suction system can monitor the air pressure in real time and control the air pressure by switch, then grab a ceramic tile through four rubber suction cups. The air source of the system adopts an air compressor, and a filter pressure reducing valve is installed at the outlet to prevent dust from clogging the vacuum generator.

4.3. Ceramic tile position measurement and laying control

During the construction process, the spatial positioning of the tile will directly affect the quality of the final floor tiling. This study uses a measurement method based on vision sensor and laser sensor to achieve spatial positioning of the tile being laid. The tile to be laid calculates the desired position based on the position of the tile that has been laid. The vision sensor is used to measure the plane size, which is shown in figure 7. The laser sensor measures the distance of the tile to lay in the vertical direction. The position deviation matrix is calculated through formula (3).

\[
V_x = V_{Rx} + V_{Ry} + k \cdot \omega_R \\
V_y = V_{Rx} - V_{Ry} + k \cdot \omega_R \\
V_z = V_{Rx} + V_{Ry} - k \cdot \omega_R \\
V_{z'} = V_{Rx} - V_{Ry} - k \cdot \omega_R
\]

(2)

\[
\begin{bmatrix}
V_x \\
V_y \\
V_z \\
\end{bmatrix} = \begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta z \\
\end{bmatrix} = \begin{bmatrix}
-cos \alpha & -sin \alpha & 0 & 0 \\
\sin \alpha & cos \alpha & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

(3)

The control flow of robotic floor tiling is shown in figure 8. First, the robot controls the UR10 robotic arm and the end effector to grab a tile. Then, the tile is moved to the target position. After that, CCD camera takes a picture of the tile and detects the edge of the tile, and the laser sensor obtains the height of the tile to the target position. The system control layer calculates the deviation between the current position and the target position. If the deviation exceeds the tiling accuracy requirement, the manipulator...
move the tile to the accuracy position, and the above process is repeated until the accuracy meets the tiling accuracy requirement.

**Figure 8.** Flow chart of robotic floor tiling operation control

**Figure 9.** Experimental verification for robotic floor tiling control system

### 4.4. Experiment verification

The design of this control system is to coordinate the control of multi-motion units to complete the robotic floor tiling operation. Therefore, we have carried out experimental verification on the floor tiling control system in this section.

**Table 1.** Tile position deviation in experimental verification.

| Tile number | x direction deviation (mm) | y direction deviation (mm) | z direction deviation (mm) | α angle deviation (°) |
|-------------|----------------------------|----------------------------|---------------------------|-----------------------|
| 1           | 0.432                      | 0.316                      | 0.125                     | 0.113                 |
| 2           | 0.416                      | 0.248                      | 0.168                     | 0.125                 |
| 3           | 0.358                      | 0.192                      | 0.175                     | 0.144                 |
| 4           | 0.232                      | 0.420                      | 0.195                     | 0.137                 |
| 5           | 0.312                      | 0.326                      | 0.186                     | 0.146                 |
| 6           | 0.204                      | 0.284                      | 0.215                     | 0.192                 |
| 7           | 0.172                      | 0.371                      | 0.163                     | 0.156                 |
| 8           | 0.504                      | 0.186                      | 0.108                     | 0.162                 |
| 9           | 0.328                      | 0.239                      | 0.146                     | 0.147                 |

The system verification experiment is shown in figure 9. The mobile platform will re-adjust the position for itself when every three tile have been laid. A total of nine ceramic tiles are laid. Table 1 shows the comparison between the actual positions of 10 tiles and the theoretical standard positions. It shows that the average position deviation of the ceramic tiles is 0.26mm, the maximum deviation is 0.504mm, the average angle deviation is 0.15°, and the maximum deviation is 0.192°.

The experimental results show that the accuracy of the system meets the actual construction requirements of floor tiling, and the control process is stable.

### 5. Conclusion and future work

A control system of the robotic floor tiling based on a multi-motion unit structure is proposed in this study. Based on the design concept of hierarchical control, the robot control system is divided into the user layer, the system control layer, the intermediate drive layer and the hardware execution layer. The user layer mainly realizes the human-computer interaction function and the robot operating parameter setting. The system control layer is the core of the control system. It receives instructions from the user layer and performs coordinated control of all the multi-motion units of the system according to the
instructions to achieve the floor tiling construction tasks. The driver layer realizes reliable real-time communication between the system control layer and the hardware execution layer. The hardware execution layer realizes the execution tasks of each device.

The system has clear functions at all levels, and it is low coupling, high stability, and strong reusability. The effectiveness of the system is verified through experiments, and it provides a reference for the system control design of other construction robots.

In the future research, we will standardize the hierarchical structure of the system to realize the versatility of the control system, and extend the system to other mobile construction robots, such as spray robots, inspection robots.

Acknowledgments
This study is supported by Key Science and Technology Projects of China under grant NO.KZ202110016024. It is also support by the BUCEA Doctor Graduate Scientific Research Ability Improvement Project

References
[1] Wu Q, Liu Y and Wu C 2018 An overview of current situations of robot industry development EDP Sciences (ITM Web of Conf.) D 17 03019.
[2] Bayram B, İnce G 2018 Advances in Robotics in the Era of Industry 4.0 Industry 4.0: Managing The Digital Transformation (Cham) (Springer) pp 187-200.
[3] Madsen A J 2019 The SAM100: Analyzing Labor Productivity J.
[4] Gifithaler M, Sandy T, Drfler K, Brooks I and Buchli J 2017 Mobile robotic fabrication at 1: 1 scale: the in situ fabricator J. Construction Robotics vol 1(1-4) pp3-14.
[5] Dakhli Z and Lafhaj Z 2017 Robotic mechanical design for brick-laying automation J. Cogent Engineering vol 4(1) D 1361600.
[6] Apostolopoulos, Dimitrios, Hagen Schempf, and Jay West 1996 Mobile robot for automatic installation of floor tiles Proc. of IEEE Int. Conf. on Robotics and Automation vol 4 (IEEE) pp 3652-57.
[7] Jongeneel J P R 2010 Robotic tiling of rough floors: A design study J.
[8] Khan A, Saharuddin K, Industri U, Kampus S and Ridzuan P D 2011 A semi-automated floor tiling robotic system 2011 IEEE Conf. on Sustainable Utilization and Development in Engineering and Technology (IEEE) .
[9] Li X, Sun C, Cheng W, Jiang X and Liu Y H 2019 Adaptive Vision-Based Control for Robotic Tiling with Uncalibrated Cameras and Limited FOV 2019 IEEE 15th Int. Conf. on Control and Automation (IEEE) .
[10] Tang X and Yamada H 2011 Tele-operation construction robot control system with virtual reality technology J. Procedia Engineering vol 15 pp 1071-76.
[11] Yoshinada H, Kurashiki K, Kondo D, Nagatani K and Tadokoro S 2019 Dual-Arm Construction Robot with Remote-Control Function: Results from the ImPACT Tough Robotics Challenge Disaster Robotics (Cham) (Springer) pp195-264.
[12] Lee Y S, Kim S H, Gil M S, et al 2018 The study on the integrated control system for curtain wall building facade cleaning robot Automation in Construction vol 94 pp 39-46.