A Brief Review on Robotic Floor-tiling

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***Abstract*—There are large quantities of tiles to be consumed every year all over the world. Developing construction robot to replace the worker to accomplish the floor-tiling task will play a key role in future construction automation. In this paper, a brief review on the research progress of the robotic floor-tiling is presented. Firstly, several kinds of manual floor-tiling methods are analyzed. Next, a survey on the tolerance requirements of tile installation is provided. Following that, the mechanisms of the floor-tiling robot technologies are highlighted. At last, the technical difficulties needed to be overcome is discussed and the future research work of the floor-tiling robot is prospected.**

Keywords—construction robot, robotic floor-tiling, automation, position measurement, motion control

I. Introduction

In recent years, robots are increasingly used in the construction applications. The floor-tiling robot is one type of construction robot, which is designed to assist workers to complete part of the tiling tasks or completely replace manual work by fully automatic tiling.

Fig. 1 shows the annual world consumption and production of ceramic tiles from 2012 to 2016. As can be seen, there is more than 10 billion square meters on consumption and production of ceramic tiles yearly. Moreover, there is an increasing trend every year, where the growth rate is at least 0.8% [1]. If we rely entirely on the workers to lay such large quantities of tiles, it will cost a lot of manpower and labor time. Therefore, some engineers have been developing floor-tiling robot to solve this problem so that the floor-tiling task can be completed in a more efficient way.

The main research impacts of floor-tiling robot are reflected in the following aspects:

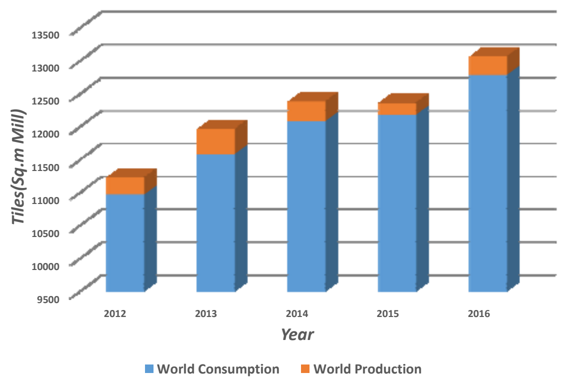


Fig. 1. World consumption and production of ceramic tiles from 2012 to 2016

- Improving the efficiency of floor tiling. Generally, one human worker would take about 24 to 48 seconds to install a tile among different floor-tiling methods [2], but the floor-tiling robot's work output is expected to be 2 to 5 times faster than that of the manual work [3,4].
- Achieving higher accuracy and ensuring better quality of floor-tiling in theory. Instead of observation by worker's eyes, floor-tiling robot can use cameras, laser sensors for the tile's positioning. Instead of placing the tile by the worker's hands and adjusting it by hammer, floor-tiling robot can use mechanical system to achieve better performance. The accuracy class could be in sub-millimeter theoretically [3].
- Guaranteeing the safety and the health of workers. In floor-tiling process, the environment is fully filled with mud, dust, noise, vibration and so on. And workers will

squat or kneel on the floor when laying the tile. By using the floor-tiling robot, the labour intensity can be lighten [5].

- Saving the cost. Jongeneel made a rough estimation of investments in [2] which shows that the cost of two floor-tiling robots is estimated to be €800,000, and about €114,000 can be saved by using floor-tiling robots instead of workers in three years.

II. ANALYSIS OF MANUAL FLOOR-TILING METHOD

There are generally three manual floor-tiling methods which are normally used in different applications.

A. *Thick-bed tiling*

Thick-bed tiling is also called mortar bed tiling, or thick-set tiling [6], which process is shown in Fig.2. This method can be described as the following steps.

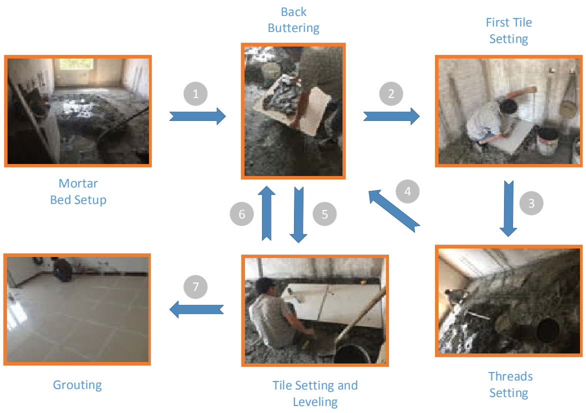


Fig. 2. Process chart for thick-bed tiling

(i) Measure and clean the room, make some marks on the wall or ground for tiling plan.

(ii) Mix cement and river sand (ratio 1:4 to 1:3) with some water to make the mortar, which is earth-dry, and then rough the ground and pack a mortar bed (usually 3 to 5 cm thick) over a surface of substrate.

(iii) Apply cement paste on a tile's back and set the first tile according to the marks made before.

(iv) Set threads according to the first tile's position as the datum for next tiles' setting.

(v) Repeat back buttering and tile setting, use rubber hammer and levelling instrument to fix tiles' position.

(vi) Normally after 48 hours, fill tile joints with grout and wipe off the excess of grout [7].

Thick-bed tiling has some advantages as shown below [2]:

- Level out unevenness in the substrate and create an ideal surface to which the tile can be bonded.
- Incorporate drainage slope in the tile layer if needed.
- Reinforce the substrate (e.g., wood framing applications).

B. *Thinset tiling*

Thinset tiling is also called dryset tiling, or drybond tiling [6]. Thinset mortar is a blend of cement, fine sand, and a unique blend of special additives [8]. Compared to thick-bed tiling, thinset tiling is not an appropriate method for laying tiles on a surface that is uneven, thinset mortar bed can only adjust the level or flatness of the laying tiles in very minor height (usually from 2.4 to 5 mm after the tiles have been properly embedded) [6,9], but thinset applications have the following advantages:

- Less expensive and typically faster to install than thick-bed tiling.
- The bonding strength of thinset material is 2-3 times stronger than the cement mortar.
- Reduce the volume of adhesive material and increase the building interior space.
- Easy operation, maintenance and high efficiency.

Fig.3 shows the thinset tiling process, in which the thinset mortar is applied to substrate surface. This method can be described as the following steps.

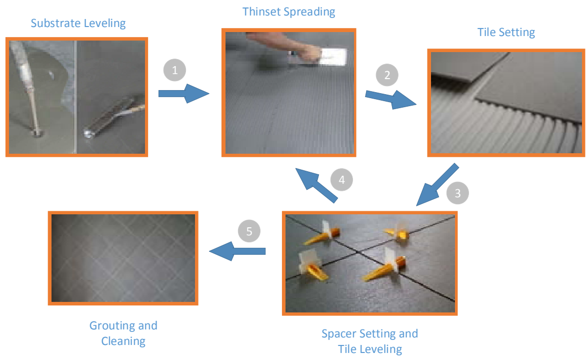


Fig. 3. Process chart for thinset tiling in which applying thinset mortar to substrate surface

(i) Level substrate by self-leveling epoxy or self-leveling cement.

(ii) Hold a notched trowel at a slight angle, push down and away to spread the thinset mortar directly to substrate surface, thinset mortar should be applied evenly and following the same direction [9].

(iii) Set tiles and spacers, plug wedge into spacer to leveling tiles.

(iv) Repeat thinset spreading, tile setting, spacer setting and tile leveling till all tiles be installed, then grout joints and clean the room.

Besides that, the thinset mortar can be also applied to tile's back. Comparing to applying thinset mortar to substrate surface, applying thinset mortar to tiles' back has the following advantages:

- Result in a flatter and cleaner tile floor.
- Beginners have more time to work at a slower pace for tile absorbing moisture from the thinset mortar slower

than substrate.

- Offer almost 100% coverage to reduce air pockets trapped under the tile.
- Provide a deeper, more secure base for joint grout.

This technique is most effective for the tiles that are larger than 200 mm × 200 mm in size and it is highly recommended for most vitrified porcelain tile installations due to the following three reasons:

- Small size tile is not convenient to spread thinset mortar onto it.
- Applying thinset mortar to every piece of tile's back will cost much time, so tile in big size is more suitable.
- Porcelain tile is with lower water absorption.

C. DRY SYSTEM

DRY SYSTEM is a reformative method to install ceramic tiles, which is highly recommended by some Spain and Italy ceramic tile factories in the last two years. DRY SYSTEM tile does not need any thinset or cement, it connects to each other only depends on the structure of itself as shown in Fig.4.

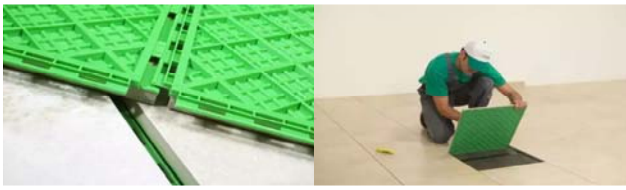


Fig. 4. Worker installing DRY SYSTEM tiles [10]

The manufacturers of the DRY SYSTEM announce that there are many remarkable advantages of this method:

- Decrease installing steps, and increase work efficiency.
- Price advantage. Although the DRY SYSTEM tile is slightly more expensive than the ordinary tile, it saves costs of other materials and installation, and the overall price is still highly competitive.
- Easy to operate and maintain. No worker is needed, you can change tiles like change clothes at any time.
- Seamless and no need to grout joints.
- Produce few dust and waste so that it looks so clean.

Although this new technique has so many advantages, there still need a period of time for its popularization. This is because the following reasons.

- There is a high requirement on the flatness of substrate.
- Most people think that it is not firm enough.
- There is no need to change tiles frequently.
- Significant technical difficulties and high production costs make few factories will put DRY SYSTEM tile into production.

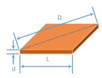
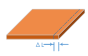
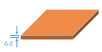
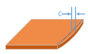
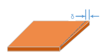
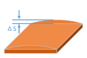
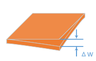
III. QUALITY INSPECTION STANDARD FOR FLOOR-TILING

Research on quality inspection standard is important and necessary because it can be used as a standard for verifying the quality of tile installing, and it can also be used as a rule of action for floor-tiling robot.

A. Deviation

Deviation includes two parts: dimensional quality of floor tile and tile placement tolerance. Both of them affect the accuracy of tile installation.

TABLE I. DIMENSIONAL QUALITY OF FLOOR TILE

	**Dimensional quality**	**Requirement**		**Example**		
		70≤N<150	**N≥150**	**100×100 tile**	**300×300 tile**	**600×600 tile**
	Length and width	|ΔL|<0.9mm	|ΔL/L|≤0.6% & |ΔL|≤2.0mm	|ΔL|<0.9mm	|ΔL|≤1.8mm	|ΔL|≤2.0mm
	Thickness	|Δd|<0.5mm	|Δd|≤0.5mm	|Δd|<0.5mm	|Δd|≤0.5mm	|Δd|≤0.5mm
	Straightness of sides, C/L	|C|<0.75mm	|C/L|≤0.5% & |C|≤1.5mm	|C|<0.75mm	|C|≤1.5mm	|C|≤1.5mm
	Rectangularity, δ/L	|δ|<0.75mm	|δ/L|≤0.5% & |δ|≤2.0mm	|δ|<0.75mm	|δ|≤1.5mm	|δ|≤2.0mm
	Center curvature, ΔC/D	|ΔC|<0.75mm	|ΔC/D|≤0.5% & |ΔC|≤2.0mm	|ΔC|<0.75mm	|ΔC|≤2.0mm	|ΔC|≤2.0mm
	Edge curvature, ΔS/L	|ΔS|<0.75mm	|ΔS/L|≤0.5% & |ΔS|≤2.0mm	|ΔS|<0.75mm	|ΔS|≤1.5mm	|ΔS|≤2.0mm
	Warpage, ΔW/D	|ΔW|<0.75mm	|ΔW/D|≤0.5% & |ΔW|≤2.0mm	|ΔW|<0.75mm	|ΔW|≤2.0mm	|ΔW|≤2.0mm

1) Dimensional quality of floor tile: While baking a tile, the fresh clay shrinks with respect to the shape in the mold. This is the reason why the dimensional quality of floor tile produced.

Besides tile placement tolerance, dimensional quality of floor tile also influences the last tile installation effect.

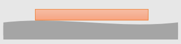
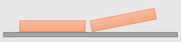
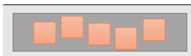
The standard BS EN ISO 10545-2-1997 [13] defines the dimensional characteristics (length, width, thickness, straightness of sides, rectangularity, surface flatness) and ISO 13006:2012 [14] establishes classifications, characteristics and marking requirements for ceramic tiles of the best commercial quality (first quality).

Table I gives an overview of tile tolerances of a dry pressed tile of class BIa/BIb/BIIa/BIIb. In general, the majority of tiles have a better quality than the one described in the standard.

2) Tile placement tolerance: There is a visual examination method of tiling that should be carried out from a distance of at least 1.5 m, and without acute angled lighting. As consumer satisfaction is rather subjective, a more quantitative quality description is needed [2]. The quality of floor tiling depends on regularity, which includes characteristics such as flatness, lipping, levelness. The standard PD ISO TR 17870-1 2015 [11] provides each reference limit value as the minimum acceptable level.

Table II gives the recommended tolerances about flatness, lipping, levelness from PD ISO TR 17870-1 2015 and permissible tolerances in joint width, divergence of a row of tiles from GB 50209 [12] as references quantifying what is visually regarded as a 'superbly' tiled floor for floor-tiling robot.

TABLE II. TILE PLACEMENT TOLERANCE

	Regularity characteristics	Recommended tolerance	Standard
	Flatness	≤ 3mm/2m	PD ISO TR 17870-1 2015
	Lipping	≤ 1mm for joints < 6mm ≤ 2mm for joints ≥ 6mm	
	Levelness	≤ L/600 L=measured length between fixed data	
	Joint width	≤ 2mm	GB 50209-2010
	Divergence of a row of tiles	≤ 3mm/5m	

B. Surface defects of floor tile

Surface defects of floor tile are defined in BS EN ISO 10545-2-1997 [13]. It includes cracks, crazing, dry spots, unevenness, pin hole, glaze devitrification, specks or spots, underglaze fault, decorating fault, chip, blister, rough edge and welt. There are many methods to find these surface defects, such as ultrasonic inspection, and computer vision, etc., where computer vision is the best choice for the defect detection in practice.

IV. DESIGN OF FLOOR-TILING ROBOT

Due to the advantages of using floor-tiling robot over human worker as mentioned in Section I, the floor-tiling robot becomes an important tool for such process. Therefore, more and more floor-tiling robots have been designed and developed, for example, Semi-automated Floor Tiling Robotic System [18], Tile Placement Robot [22], MRT (Mobile Robotic Tiling) [19], and so on.

During the development of the floor-tiling robot, its design should consider the following aspects: mechanical structure, positioning method, surface defects detection, and system design and integration.

A. Mechanical structure

According to the methods and the working steps of the manual floor tiling processes, floor-tiling robot needs at least 10 mechanical parts, including spreader, evener, comber, lifter, grasper, locater, placer, presser, leveler, and wiper, to complete the whole floor tiling process [15].

Moreover, the floor-tiling robot can be summarized into two categories: one is universal robot type, and the other is dedicated robot type. They have the same mechanical parts but different mechanical structure.

Developing floor-tiling robot of the universal robot type is usually based on the existing general robots which are available in the market like SCARA robot, Delta robot, six-axis robot and so on. In this case, it requires less development time on the mechanical structure design.

On the other hand, developing floor-tiling robot of the dedicated robot type is usually take more time in the mechanical structure design but it can save cost.

For example, a six-axis robot can be employed as both the lifter and locater in floor-tiling robot [4, 16, 17], but dedicated floor-tiling robot need a conveyor to transport ceramic tiles [3, 18].

Fig. 5 is a comparison between the floor-tiling robots of the universal robot type and the dedicated robot type. Thick-bed tiling usually requires the robot to be the dedicated robot type, and the universal robot type is suitable for thinset tiling, for the reasons that thick-bed tiling requires high-strength mechanical structures to finish thick-bed applying and tile leveling, but thinset tiling is relatively flexible and light-force.

Fig. 5. Floor-tiling robots of the dedicated robot type (left) [2] and the universal robot type (right) [19]

B. Positioning method

For the positioning method, it mainly has three types: point laser, computer vision, and strip laser plus computer vision.

1) Point laser: This method is using point laser sensor to get the information about edges of some pre-installed reference tiles (edge thickness, edge curvature, edge length), and then calculate the position of tiles to be installed.

Gramazio Kohler Architects in partnership with ROB Technologies have developed a floor-tiling robot fixed four point laser sensors on terminal actuator [19]. Fig. 6 shows the working principle of the robot using the point laser sensors, the robot translates the terminal actuator to get relative position between the laser sensors and the edges of the adjacent reference tiles, and adjusts the posture of the terminal actuator to lay the tile based on these sensing information.

However, using this method needs to ensure that the relative position of the terminal actuator and the tile to be laid is certain. And this method does not guarantee good levelness.

2) Computer vision: Computer vision is a universal method to solve various problems, which is also suitable for tile positioning.

In [3], the researchers proposed a tile positioning method base on computer vision. The Canny operator is used to detect the edges in the tile images while the Hough transform is used to model the strongest lines in the edge images. Edge images after processing are used to determine the position of the tile to be installed.

Comparing to the point laser method, computer vision can get the information of more than one tile's edge at the same time without multi-stage movement of the terminal actuator or end effector. It can have higher efficiency in positioning, but it may get bad results for highly reflective and patterned tiles.

3) Strip laser plus computer vision: This method combines the laser method and the computer vision method, which overcomes the disadvantages of those two methods [2,16].

Fig. 6 shows the working principle of this method. As can be seen in Fig. 6, five laser lines are used to position a tile with respect to three adjacent tiles. A is measured for joint width, B is measured for tile lift, A and B decide the tile position to be placed.

The identification of the laser line in this method is not affected by the texture or the color of the background. Furthermore, the linear accuracy can reach 0.2 mm and the angular accuracy can reach 0.1° by using this method.

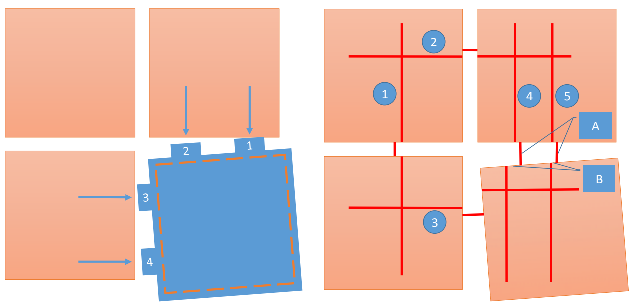


Fig. 6. Four point laser sensors (left) and five laser lines (right) used to position a tile with respect to three adjacent tiles

C. *Surface defects detection*

The function of surface defects detection can help floor-tiling robot to pick out the defective tiles instead of installing them. As mentioned previously, the computer vision is the most efficient way in the surface defects detection.

Generally, computer vision detection of tile surface defects involves image preprocessing algorithms, image segmentation algorithms, image feature extraction and selection algorithms, image recognition algorithms, etc.

There are many computer vision methods developed for the surface defects detection.

In Navon's research, the tile's area and its moments of inertia obtained by edge-based segmentation method were used to identify defective tiles [4]. However, the broken tiles in which broken parts are not too far apart and the tiles have small defects on surface would still have almost the same calculated area as the good tiles.

In [20], Hocenski developed a method to detect color and surface defects on ceramic tiles images by the improved Canny edge detector. Actually, the Canny edge detector can smooth the image, find its gradient, do non-maximum suppression and define threshold to eliminate insignificant edges. In this way, the edges with the defect on images could be found. For thresholds defining, the histogram subtraction method was used to divide the background area from the image area in histogram. Using the improved Canny edge detector, the system can obtain good results on detecting defect like cracks, scratches, spots and blobs, but not for glaze faults.

In [21], Hanzaei developed an automatic image processing system for detection and classification of ceramic tile surface defects. In this system, the statistical methods: Rotation Invariant Measure of Local Variance (RIMLV) and the structural methods: Close morphological operator are combined for defect detection. Moreover, eight optimized features (area, perimeter, length of major axis, length of minor axis, elongation, thinness ratio, eccentricity and extent) can be extracted from defect by taking advantage of geometrical features.

D. *System design*

Floor-tiling robot's system is a complex system which includes many subsystems [22, 23, 24]. It basically consists of the following subsystems.

- HMI (Human Machine Interface, also known as user interface), which is the medium for information interaction and exchange between the system and the operator/user.
- The main controller, which is responsible for coordinating and managing the slave controllers of the various subsystems, decomposing the tile laying process into various sub-tasks and delivering to the subsystems.
- Unlike the industrial robots working on the production line, construction robots are often required to have the ability to move and work on the construction site, so the

mobile platform system is a very important part of the construction robot. In the floor-tiling robot, the mobile platform system is often used only as a coarse positioning system.

- For the grabbing and placing of tiles, vacuum suction cups are commonly used in the actuator system.
- The sensor system enables precise positioning of tiles by using the robot system.

Fig. 7 shows a general floor-tiling robot's frame diagram. During the operation, the operator/user send control instructions to the main controller via HMI, and then the main controller outputs the control signals to each related subsystem, including mobile platform system, actuator system, and robot system. Meanwhile, the sensor subsystem feedbacks the measured information to the main controller to form the closed-loop control system.

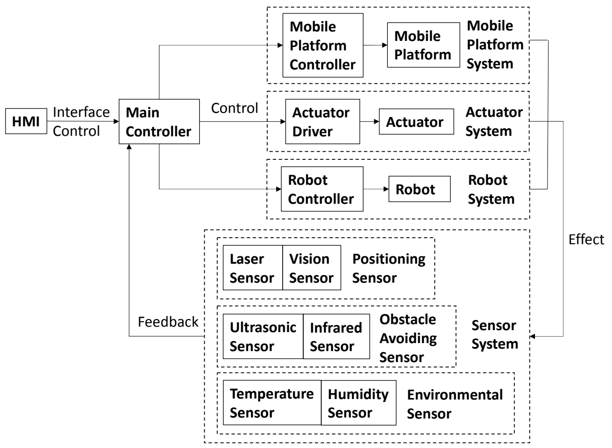


Fig. 7. General floor-tiling robot's frame diagram

V. Conclusions and Challenges

Developing floor-tiling robot is meaningful in improving efficiency, achieving higher accuracy and ensuring better quality in floor-tiling, as well as guaranteeing the safety and health of workers and saving the cost in the future.

When installing a tile, the placement tolerance, dimensional quality and surface defects of floor tile should be taken into consideration. There are three main positioning method: point laser, computer vision and strip laser plus computer vision. Furthermore, the computer vision method is widely used in detecting surface defects.

Floor-tiling robot's system is a complex system which includes many subsystems. Therefore, it is important to realize communication between various subsystems and ensure real-time performance.

There are still some problems with the floor-tiling robot, such as heavy weight, large volume, high cost and so on. In the future, floor-tiling robot should be designed not only for large area, but also for the small room. In addition, it should become more intelligent in autonomous path planning and adaptive paving operations based on different room/working conditions.

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