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Mopping module design and experiments of a multifunction floor cleaning robot

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***Abstract* - The autonomous cleaning robot has entered the practical stage, and is getting more and more popular. Currently most researches of the cleaning robot focus on sensor technology, location and environment modeling theory. And these researches have made great progress, which proves the practicability of the cleaning robot further. In this paper, we firstly propose a novel method to mop the floor by using a sponge, and use this method to design a mopping module in the frame work of a multifunction floor cleaning robot. Then the parameters of the module are optimized by analyzing the amount of the pumping out and recycling water. Lastly, a real experiment is carried out to validate the method's effectiveness.**

***Index Terms* - Cleaning robot; Multifunction; Module; Vacuum cleaner; Mopping the floor technology**

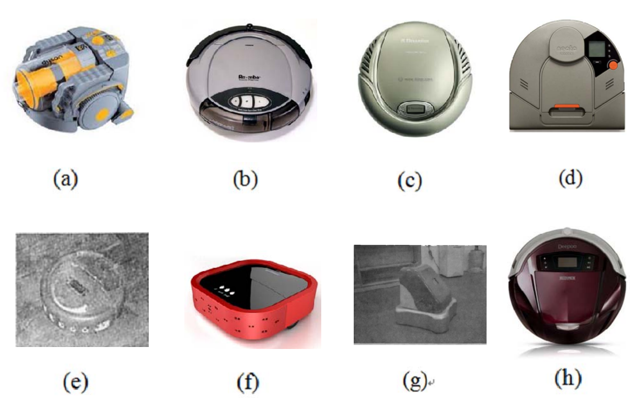
I. Introduction

The cleaning robot is a kind of special robot for the service of humanity. It can help us do the ground cleaning, and is the most likely service robot which can be used by the masses [1]. The Medium & Long Term Science and Technology Planning of China (2006~2020) clearly stated that the service robot will be the priority development of strategic hi-tech in the future. The Japanese robot industry association forecasts that the demand of service robot of Japan's market will be amount to $10 billion, and the world's market can be as high as $150 billion or more. By the year of 2016 the cleaning robot market will reach at $2 billion, it is indicated that the cleaning robot will be one of the main growth points. As a new technology in recent years, the cleaning robot gets the extensive research both at home and abroad. The cleaning robot technology has made breakthrough in nearly a decade and it has entered the stage of application.

At present, the cleaning robot can be divided into the vacuum cleaning robot, the mopping robot, and so on according to different functions. Among these robots, the vacuum cleaning robot was developed earlier. Dyson which is a British company developed an intelligent vacuum cleaner - DC06 in early 2001. As shown in Fig.1(a). The American professional robot company -- iRobot launched its own first intelligent automatic vacuum cleaner in September 2002, as shown in Fig.1(b). The famous home appliance manufacturer Electrolux of England also launched its own intelligent automatic vacuum cleaner which named Trilobite [2], as shown in Fig.1(c). Also the United States Neato Robotics company recently develops a vacuum cleaner robot named XV-14, as shown in Fig.1(d).

Machinery and Electronics Research Institute of Zhejiang University and Suzhou TEK Company cooperatively research and develop an intelligent automatic vacuum cleaner in 2001 [3], as shown in Fig.1(e). On January 16, 2006, an autonomous vacuuming robot was successfully developed by fluid transmission and control of state key laboratory of Zhejiang University [4], As shown in Fig.1(f). An autonomous vacuuming robot also successfully developed on June 8, 2007 in Harbin Institute of Technology [5], as shown in Fig.1(g). Ecovacs Company of Suzhou develops a vacuum cleaner robot named Deepoo 760, as shown in Fig.1(h). KV8 company develops KV8 510B, as shown in Fig.1(i). These two robots each have its own advantages and have good sales. Moreover, there are other scholars at home and abroad study in this field also achieved fruitful research results [6-9].

Mopping robot has always been the research emphasis of cleaning robot industry [10-11]. As shown in Fig.1(j), the robot is named Scooba 390, and was developed by the iRobot company. Relied on rigorous work arrangements, the robot achieves the best effect of mopping the floor. As shown in Fig.1(k), the Mint 5200 also was produced by the iRobot company. Its outstanding navigation technology can realize full cover in theory. It is proved that the coverage can reach more than 90% in practical application, mopping effect is good.



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(i) (j) (k)

(a) DC06 (b) Roomba (c) Trilobites (d) Neato Robotics (e) HSR2000 (f)Zhejiang university cleaning robot (g) Harbin institute cleaning robot (h) Deepoo 760 (i) KV8 510B (j) Scooba 390 (k) Mint 5200

Fig.1 Cleaning robots

At present, the cleaning robot industry is in the period of high-speed development, there are varieties of cleaning robot products in the market. With the development of the cleaning robot industry, consumers put forward higher request to cleaning robot, functional diversification, more intelligent and lower price. Almost all existing cleaning robots are all overall structure. For example, the cleaner part of intelligent vacuum is fixed on the body, it is could not be separated from the body. The overall structure makes the intelligent cleaning robot can only complete its inherent vacuuming functions. If the floor needs to be washed, you have to buy an extra mopping robot. The way clean the floor by using several different cleaning robots is not a good choice because more robots means more space will be taken. Besides, this way also will increase manufacturing costs. It doesn't meet the trend of social development of low-carbon environmental protection. What's more, it is hard to find another mopping robot product besides the two series of Scooba and Mint. The residual water in mopping technology has been another biggest challenge which hinders the development of mopping robot industry. It is urgently find another high feasibility of mopping method to bring new vitality to the mopping robot technology.

This paper proposes a new mopping method to solve the residual water problem. And then a mopping module is presented in the frame work of a multifunction floor cleaning robot which is developed based on the idea of reconfiguration and function modular[12-13]. This robot can not only do vacuum cleaning work but also mop the floor. This method achieves the result that a robot could complete a variety of cleaning tasks. Moreover, this method avoids duplication of manufacturing robot platform, reduces the cleaning robot manufacturing costs. This meets the trend of social development of low-carbon environmental protection.

The rest of this paper is organized as follows. Section II introduces the design of the multi-function cleaning robot. We propose a new mopping method in Section III. Section IV optimizes the mopping module's geometric parameters and Section IV shows the results of the experiment about the mopping module. Finally conclusions are given in Section VI.

II. MULTIFUNCTION ROBOT CLEANER DESIGN

The device described in this paper is a kind of intelligent cleaning robot. In general, it is composed by drive part, sensor part, functional parts and control part, power supply part and so on. As showed in Fig 1, it shows some cleaning robots which were designed by others. It is obvious that the shapes of these cleaning robots are circle. The device's shape which was circle can avoid the robot being trapped. So the shape of the multifunction cleaning robot proposed in this paper is circle.

As shown in Fig.2, the functional part is independent from cleaning robot. So the cleaning robot can connect several functional modules, which makes a cleaning robot achieve many cleaning functions. (e.g., mop, dust collection, etc). That is to incorporate several cleaning robots into a robot. It can avoid the repetitive manufacturing platform and reduce the manufacturing cost. This method also meets with the social development trend of low carbon environmental protection.

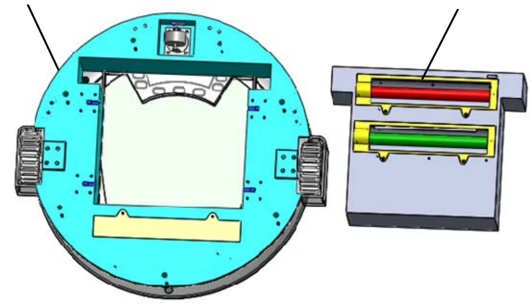

Fig.2 The diagram of the multi-function cleaning robot

A. *Multi-function robot cleaner design requirements*

The component of the multi-function robot cleaner in this paper includes: mobile platform, dust collection module, mopping module. Some function modules, such as monitoring module, air purification module will be designed to enrich the function of the multi-function cleaning robot in future work. Dust collection module or mopping modules can connect to the mobile platform by bolt. It is required that the connection must be reliable and electricity is stable, also the data transmission should be smooth. On the bases, the cleaning robot can realize the functions of vacuum and mop. About the motor selection, firstly, it is need to make sure the cleaning robot has enough driving force to make itself has the ability to cross a certain slope road; secondly, the cleaning robot has good ability to clean all sorts of material ground .

B. *The mechanism of the multi-function cleaner robot*

The middle of mobile platform is empty, where the function modules could be installed. There are a few advantages of it, from the aspects of stress analysis, such design insure that the force on the platform is symmetrical. So the mobile robot' motions will smooth and steady. As shown in Fig.3, the empty space is located in the middle of the platform, Function modules are connected to the mobile platform by bolts and the cover of the four bolts are fixed on the mobile platform by screws. So these bolts are placed between the bolt cover and the mobile platform can be free to move around in a certain trip. As shown in Fig.2, you need put the function module into the mobile platform from the bottom and move the four bolts to close position so the mobile platform connected with the functional module. Thus, this kind of connection mode is convenient for installation and removal.

The power source which is installed on the mobile platform supplies power to function module through the electric interface. The electric interfaces are docking exactly as long as the function module and mobile platform are connecting. The on and off of direct current are controlled by the main control panel which is installed on mobile platform. Moreover, the electric interfaces should implement the data transmission so that the cleaning robot achieves the purpose of controlling the functional modules. Several sensors are installed on mobile platform floor, facilitating the robot real time to monitor road conditions to prevent the cleaning robot falls off.

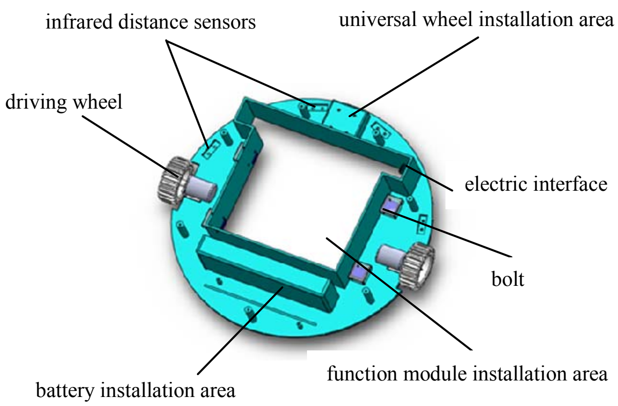

Fig.3 The mobile platform

C. *The working process of the multi-function cleaner robot*

When the floor needs to be cleaned, the mobile platform will be combined with a function module to form into a cleaning robot. Then the cleaning task will be accomplished by this robot. Which function module would be selected to combine with the mobile platform is depended on which task the cleaning robot will execute. For example, if the floor needs to be brushed, then the vacuum cleaning module will be combined with the mobile platform to form into a cleaning robot. As many other cleaning robots do, typical procedures of the cleaning work are listed below, as shown in Fig.4.

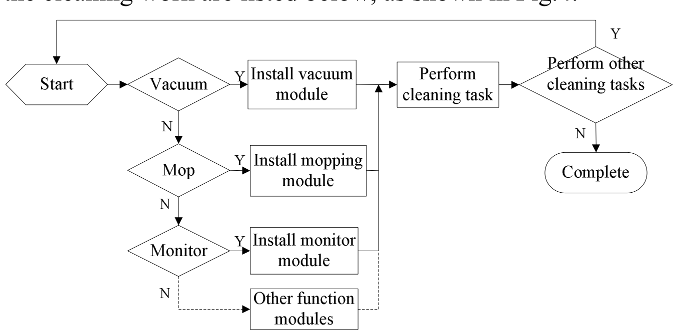

Fig.4 Flow diagram of the cleaning tasks

III. Mopping Module Design

How to mop the floor has been one of the most difficult problems needing to be solved in the cleaning robot industry. At present, there are only a few mop methods and they works inefficiently. One of these mopping methods can simply described as three steps: Firstly, the cleaning robot starts to move, at the same time spraying the cleaning fluid to the front of the cleaning robot; Secondly, brush will scrub the floor which has been sprinkled with cleaning fluid; Thirdly, the pump will extract the cleaning fluid from the ground. The robot in this method can clean up the ground. However a problem will not be solved: the cleaning fluid can't be completely pumped away from the ground. The remained cleaning fluid will cause damage to the ground (e.g., real wood, etc). This section solves the problem by using a sponge to extract the cleaning fluid, and designs a mopping module based on this method.

A. *The mechanism of the mopping module*

As shown in Fig.5, this mopping module mainly includes the module platform, motor, pump, brushes, water tank. There are two kinds of brushes: brush A and brush B, the brush A is installed in the front of module platform, the brush B which is a sponge brush is installed behind the brush, these two brushes are working together to finish the mopping task. Module platform is connected to the cleaning robot by bolts. In the front of the mopping module, there is a nozzle whose role is that letting the water pipe from the cleaning robot to the ground.

B. *The working process of the mopping module*

When the floor needs to be washed, the water should be filled up in the clean water storage area of water tank and connect the mopping module to the cleaning robot. In general, the working progress of mopping most has four steps.

Step 1: When the robot is powered on, pump A pumps a little clean water from water tank and sprays the water to the front of the cleaning robot.

Step 2: The motor drive brush A and brush B to roll respectively. Brush A first scrubbing of the floor which is spilled water.

Step 3: Brush B will blots sewage from the ground. A baffle is installed in the brush groove. The use of baffle is squeezing the sewage out of brush B.

Step 4: The sewage will be pumped to the sewage recycling area of water tank by pump B.

Due to the sponge's absorbent is very strongly, sponge can always absorb water from outside as long as keep the sponge water saturated state. When the robot mops the floor, mopping effect can be better guaranteed as long as control the speed of the robot clean and quickly clear the water from the sponge.

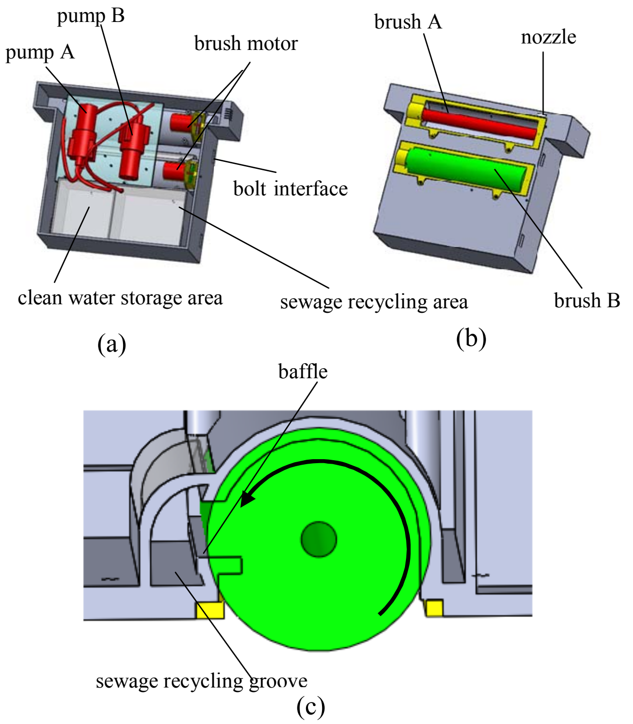

Fig.5 The mopping module observed form (a) top, (b) bottom, and (c) side, respectively.

IV. OPTIMIZATION OF THE MOPPING MODULE'S GEOMETRIC PARAMETERS

To ensure there is none water left on the floor after the robot cleaning the floor, it is necessary to optimize the mopping module's geometric parameters. In this section, the sponge's size, the length of the wiping bar and the power of the pumper are optimized in an ideal situation.

Define the sponge's volume ratio ρ as:

$$\rho = \frac{V_c}{V} \times 100\% \tag{1}$$

Where V is the sponge's volume in the natural situation, while V_c is the sponge's minimum volume when it has been compressed. Then in the ideal situation, one unit volume sponge can absorb water up to η unit volume:

$$\eta = 1 - \rho \tag{2}$$

If the sponge is compressed or expanded to be α times, then the new volume ration and the new absorption ration become to $\rho' = \rho/\alpha$ and $\eta' = 1 - \rho' = 1 - \rho/\alpha$, respectively.

For example, a piece of sponge whose volume is V can absorb ηV water in volume maximally. If it is compressed to be α times, then it can absorb $\eta' V = (1 - \rho/\alpha)V$ water in volume maximally.

To analyse the mopping module's capability of absorbing water, the geometric parameters is defined in Fig. 6. Suppose the sponge's volume ratio is ρ, and its shape is a torus from the side. The torus's inner diameter is r, while its outer diameter is R. The length of the sponge is L. The distance when the sponge is pressed on floor is h. The distance when the sponge is pressed by the baffle is d.

From Fig.6, a geometric constraint between R, r, d, and h is:

$$\begin{cases} R - r > d \\ R - r > h \end{cases} \tag{3}$$

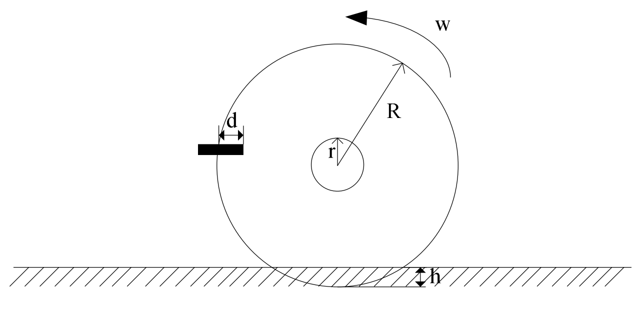

Fig.6 The diagram of sponge's working condition

When the cleaning robot works, the sponge rotates constantly with rotation speed ω. Then each part of the sponge will change periodically, as shown in Fig. 7. In state I, the sponge is pressed by the baffle with its outer diameter decreasing from R to $R - d$ while at the same time the sewage is squeezed from the sponge and collected in the recycling groove; In state II, the pressed part of the sponge rotates away from the baffle and gets back to its original status; In state III, the sponge is pressed by the ground with its outer diameter decreasing from R to $R - h$; From state III to state IV, the part of the sponge which is pressed in state III returns to its original state, also it absorb water from the floor. In state IV, the sponge absorbs the maximum water as it can.

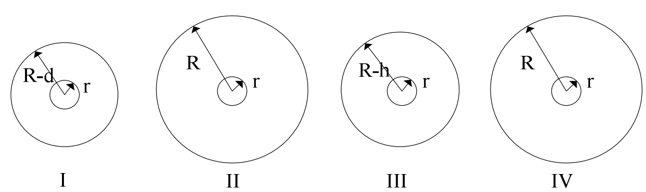

Fig.7 The four states of the sponge changes in a loop

In order to ensure the sponge do not leave water on the floor when it changes from states I to states III, it is required that the volume of the sponge in state I should less than the one in state II and III. This requires $R - h < R - d$, namely:

$$d > h \tag{4}$$

Under this condition, the water in sponge is not changing from state I to state III

$$W_1 = W_2 = W_3 \tag{5}$$

Where W_1, W_2 and W_3 denotes the amount of water stored in the sponge.

From state III to state IV, the sponge will absorb sewage from the floor. In the sponge is saturated in state I, then the water stored in the sponge during state I to state III will get the maximum. In this case, the sponge will absorb the least water from the floor when it changes form state III to state IV. Thus the largest water storage rate in state III can be calculated:

$$\begin{aligned}\eta_3 &= 1-\rho_3 = 1-\rho\Big/\left(\frac{\pi((R-h)^2-r^2)L}{\pi(R^2-r^2)L}\right) \\ &= 1-\frac{R^2-r^2}{(R-h)^2-r^2}\rho\end{aligned} \tag{6}$$

The amount of sewage stored in the sponge Q_3 during time interval Δt is:

$$\begin{aligned}W_3 &= V_3\cdot\eta_3 \\ &= \Delta t\cdot\omega L(((R-h)^2-r^2)-(R^2-r^2)\cdot\rho)\end{aligned} \tag{7}$$

Here, ω is the sponge's rotation speed.

To absorb sewage from the floor as much as possible, the sponge's water storage rate should get its maximum in state IV, namely:

$$\eta_4 = 1-\rho \tag{8}$$

The amount of sewage stored in the sponge Q_4 during time interval Δt is:

$$\begin{aligned}W_4 &= V_4\eta_4 = \omega\cdot\Delta t\cdot(R^2-r^2)\cdot L\cdot\eta_4 \\ &= \omega\cdot\Delta t\cdot L(R^2-r^2-(R^2-r^2)\rho)\end{aligned} \tag{9}$$

Then during the time interval Δt, the amount of the sewage that the sponge can absorb at least can be calculated as:

$$\begin{aligned}W &= W_4 - W_3 \\ &= \Delta t\cdot L(\omega+v/(R-h))(2Rh-h^2)\end{aligned} \tag{10}$$

If the power of the pumper is $Q(ml/\min)$, namely the pumper will Qml spray water each minute to the floor. Then during time interval Δt, the amount of the water sprayed to the floor is:

$$W' = Q\cdot\Delta t \tag{11}$$

In order to ensure the sponge can absorb the water which is sprayed by the pump, it is required:

$$W > W' \tag{12}$$

From eq. (9) - eq. (11), a constraint is achieved:

$$h > R-\sqrt{R^2-\frac{Q}{\omega L}} \tag{13}$$

According to eq. (3), eq. (4), and eq. (13), the constraints between the parameters are:

$$R-r > d > h > R-\sqrt{R^2-\frac{Q}{\omega L}} \tag{14}$$

V. Experiments

In this section, the mobile platform, the vacuum cleaning module, and the mopping module are produced. As shown in Fig.8. After the basic performance parameters (the max velocity, et. al.) are tested, two experiment are carried out to validate the effectiveness of the robot proposed in this paper: One is carried out with the robot which is assembled with the mobile platform and the vacuum cleaning module, the other is carried out with the robot which is assembled with the mobile platform and the mopping module.

Fig.8 The prototype of the mobile platform, the vacuum cleaning module and the mopping module

A. The test of basic performance parameters

To test the stability of the connection, the function module should be connected on the mobile platform by the bolts. The function module should be put the appropriate load, also the deformation of the bolt connection area should be validated. As shown in Fig.9, there is no obvious deformation happened in the bolts connection area. It can be considered that the connection is stable to combine the mobile platform and the function module.

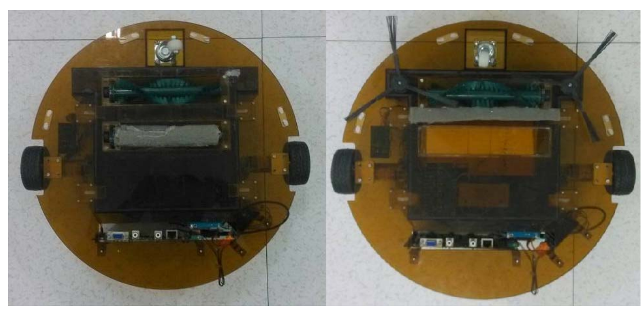

Fig.9 The mopping robot(left) and the vacuum cleaning robot(right)

In the actual test, the maximum speed is 0.51 meters per second. Because the floor of the house is not always flat and there may be carpets in the room, the cleaning robot needs to have ability to climb up the floor with a certain slope. In the test, the robot's climbing angles is up to 8.9 degrees. It is proved that the results of experiments are in conformity with the results of theoretical calculation. The test results also show that cleaning robot can realizes 70 ~ 80 minutes of continuously sweeping or mopping the floor. After a charge, the robot can clean a house whose area is 120 square meters or below.

TABLE I
PARAMETERS OF THE MOPPING MODULE

R (mm)	18	r (mm)	9
d (mm)	3	h (mm)	2

L (mm)	140	Q (ml/min)	60
ω (r/min)	399		

The geometric parameters of the real mopping module are designed as Table I. They satisfied the constraints described in eq. (14).

B. The performance experiment of mopping module

The mainly work in this part is testing the performance of mopping module. The laboratory was selected to be the experiment site. The floor of the laboratory is made of rubber. In this experiment, some related works need to be done in advance: Firstly, sticking the ink to the clean ground; Secondly, installing the mop module on the robot to make the cleaning robot has the mop function; Thirdly, making the cleaning robot washes the ground which was dirty. There are two indicators: one is checking the clean degree after the robot cleaned the ground; the other is testing whether remained fluid is under control or not. After several times' experiments, it is confirmed that the robot cleaner's mopping function is effective. As shown in Fig.8, this group of pictures show us the process of cleaning robot cleans a period of the ground, through image contrast, the stain on the ground is cleaned out and there is no obvious water on the ground, on this basis, the working performance of mop module can be thought meets the design requirements.

If the parameters of the mopping module are not comply with the requirements of Table I. Whether the cleaning robot could performance well or not, according to the several times' experiments, it is concluded that if the parameters of the mopping module is changed, the cleaning robot cannot clean up the floor.

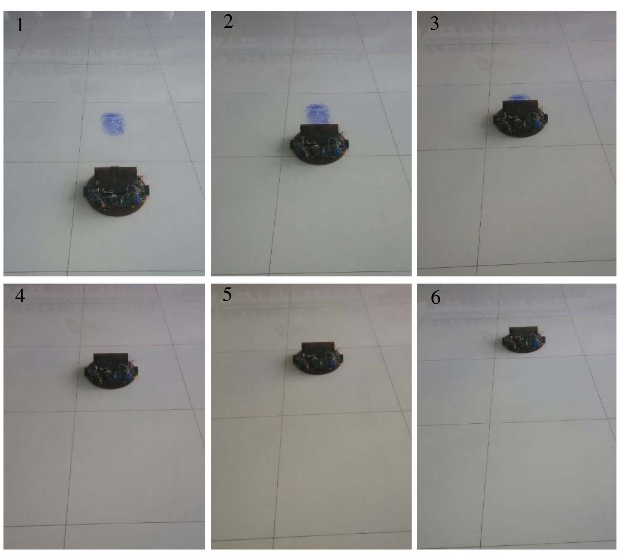

Fig.8 The diagram of mopping process

VI. CONCLUSION

In this paper, a multifunction cleaner robot together with the mobile platform, the vacuum cleaning module, and the mopping module are proposed firstly. Then the mechanism design and the working process of the mopping robot are described. Finally, two experiments are carried out to validate the effectiveness of this cleaning robot. Currently, the prototype's basic cleaning functions, namely vacuum cleaning and mopping the floor, perform well. In future, we will research on the robot's control system and the intelligence theory to make it do cleaning tasks autonomously.

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