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Design and Simulation Analysis of a Multi-Functional Public Restroom Cleaning Robot

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Abstract: The cleaning of urinals in public restrooms is primarily done manually, which is a complex process with low efficiency and high labor costs. Even after cleaning, a significant amount of bacteria remains on the surfaces, and in high-traffic public areas, the speed of manual cleaning cannot be guaranteed. Moreover, the built-in flushing systems of urinals are often inadequate for thoroughly cleaning residual stains, leading to persistent odors. This paper examines the shortcomings of existing urinal cleaning devices in China and, based on the requirements of the public restroom cleaning environment, proposes a solution utilizing a six-axis robotic arm, a robotic arm mobility device, and an electric brush to achieve multi-angle urinal cleaning. Finite element simulation software is used to simulate the cleaning trajectory of the robot to verify the feasibility of the cleaning operation, ensuring that it meets practical application needs.

1. Introduction

High-quality public restroom cleanliness is a crucial component of building a civilized city and directly reflects the level of urban public health. As China's economy continues to develop, local governments are placing greater emphasis on the construction of public service facilities, including the enhancement of public restroom environments. In this context, the traditional manual cleaning process for upright urinals is cumbersome, inefficient, and costly[1]. It takes a long time to clean, and a significant amount of bacteria remains on the urinal surfaces even after cleaning. Additionally, in high-traffic public areas, the speed and quality of manual cleaning are difficult to ensure. Therefore, automation of public restroom cleaning is necessary. At present, the research on urinal cleaning in China is still in its early stages. Most cleaning devices focus on either transforming the overall public restroom system or modifying the urinals to achieve automatic cleaning. These methods require high standards for the manufacturing process and design of the urinals, and the dimensions and costs of the modified urinals are uncontrollable and cannot guarantee suitable application scenarios. Additionally, some domestic urinal cleaning carts push the machine to a certain position, where the brush set inside the cavity performs the cleaning. However, the cleaning process is not visualized, making it difficult to guarantee effectiveness, possibly necessitating a second round of cleaning. Although domestically developed public restroom cleaning devices have achieved some success, there is still a need for continuous improvement in terms of cleaning efficiency, cost, and intelligence.

This paper, based on the cleaning tasks of public restrooms with high foot traffic and epidemic prevention requirements, designs a vertical urinal cleaning robot that integrates cleaning and disinfection functions. This cleaning robot not only has automatic identification and cleaning capabilities but also can automatically disinfect, effectively reducing the probability of bacteria and virus transmission in public restrooms. The cleaning robot utilizes a six-degree-of-freedom robotic arm structure[2], coupled with a robotic arm mobility device and an electric brush, enabling multi-angle cleaning of urinals. It has a large cleaning space, can clean urinals of various sizes, has broad application scope, and is suitable for various workplaces.

2. Overall Structural Design of the Cleaning Robot

The cleaning robot is mainly composed of a cleaning robot arm part, a cleaning robot arm moving device, an anti-sewage splash device, a visual recognition part, a disinfection part, and a robot drive part, and the overall structure is shown in Figure 1.

Figure 1: Overall structure diagram

2.1. A cleaning robot arm part

To ensure a wide range of motion and strong versatility for the designed cleaning robot, six degrees of freedom were chosen for the robot system[3]. These degrees of freedom include the base, swing, rear arm, front arm, rotation, pitch, and the end cleaning brush, all of which are rotary joints. The structure of the robotic arm is shown in Figure 2. The use of a six-axis robotic arm expands the cleaning range of the robot and the types of urinals it can clean. The six rotary joints allow the end cleaning brush to clean the urinal from multiple angles.

To simplify the kinematic model, the three intermediate rotary joints are set to rotate in the same direction. The parameters of the robotic arm are as follows: an arm span of 551 mm, a weight of 2.823 kg, and the primary materials used are aluminum alloy and polypropylene (PP) homopolymer.

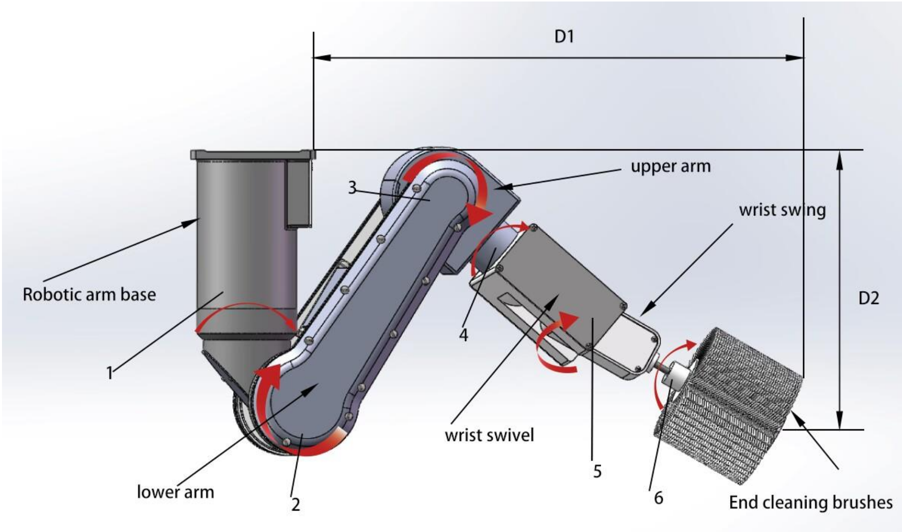
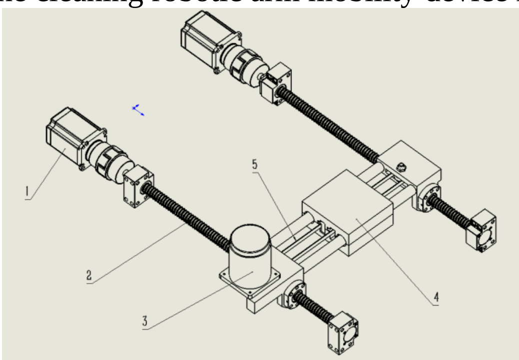


Figure 2: Mechanical arm structure diagram

2.2. A cleaning robot arm moving device

It consists of a stepper motor, ball screw, Panning motor, robotic arm fixing device, and belt. The ball screw, in conjunction with the stepper motor, drives the robotic arm fixing device to achieve forward and backward movement. The dual ball screw structure ensures the precision of motor movement.

On the two ball screws, a Panning motor is used in combination with belt transmission to drive the robotic arm fixing device, enabling left and right movements. By driving the robotic arm fixing device, the cleaning robotic arm can move on a plane, thereby maximizing the cleaning range of the robotic arm. The diagram of the cleaning robotic arm mobility device is shown in Figure 3.

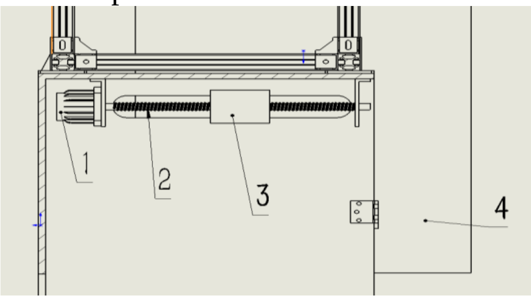


1. stepper motor 2. ball screw 3. Panning motor 4. robotic arm fixing device 5. belt

Figure 3: A cleaning robot arm moving device

2.3. Anti-sewage splash device

It consists of a stepper motor, a slider, a ball screw, and a transparent baffle, with the transparent baffle fixed onto the slider. During operation, the stepper motor drives the screw to move the slider. The movement freedom of the slider is constrained by a slot, allowing the slider to move along a predetermined trajectory, thereby achieving the effect of automatically extending and retracting the baffle. The transparent baffle can adhere to the wall, effectively preventing wastewater and debris from splashing out of the urinal cavity and contaminating the wall during cleaning. The transparent baffle allows for the observation of the cleaning process, reducing the likelihood of needing a second cleaning. The anti-splash transparent baffle device is shown in Figure 4.



1. stepper motor 2.slider 3. ball screw 4. transparent baffle

Figure 4: Anti-sewage splash device

2.4. A visual recognition part

The visual recognition component is composed of a Raspberry Pi and a monocular camera. The monocular camera is connected to the Raspberry Pi via a USB data cable. The monocular camera captures real-time images and transmits them to the Raspberry Pi[4-5].

The target detection algorithm running on the Raspberry Pi identifies whether the image contains a urinal. If the image does not contain a urinal, a prompt is issued. If the image does contain a urinal, the monocular distance measurement algorithm is used to measure the distance between the urinal and the robot.

2.5. A disinfection part

A disinfection part consists of low-pressure atomising nozzle, plastic hose, disinfection water tank and water pump, one end of the plastic hose is connected to the low-pressure atomising nozzle and the other end is connected to the water pump. When disinfecting, the disinfectant water in the disinfectant tank is first extracted by the water pump, and then through the plastic hose, and finally sprayed out by the spray nozzle. The nozzle is fixed in front of the brush, the nozzle and the brush are driven by the motor, which can achieve the function of disinfection while cleaning and effectively improve the cleaning efficiency.

2.6. A robot drive part

The robot drive section consists of a 24V Li-ion battery power supply, an STM32 main control chip, a DC motor driver and a DC geared motor.

3. The Main Working Principle of the Cleaning Robot

Place the cleaning robot in front of the urinal that needs cleaning. First, the monocular camera captures real-time images and sends them to the Raspberry Pi via a USB data cable.

The target detection algorithm running on the Raspberry Pi identifies whether the captured image contains a urinal. If it does not, a prompt is issued. If the image contains a urinal, the monocular distance measurement algorithm measures the distance between the urinal and the cleaning robot. This distance information is then sent to the main control chip via serial communication[6].

The main control chip receives the distance information and inputs it into the PID algorithm. Based on the tuned PID algorithm, it calculates the corresponding PWM pulse signal for that distance and sends this PWM pulse signal to the DC motor driver. The DC motor driver then drives the motor to rotate, propelling the cleaning robot forward towards the urinal[7].

Once the cleaning robot reaches the predefined distance, the motor stops, and the cleaning robot halts. Subsequently, the stepper motor drives the slider to extend the baffle forward, ensuring that the baffle closely adheres to the wall, preventing wastewater and debris from splashing outwards.

After the baffle adheres to the wall, the cleaning robotic arm moving device moves the cleaning robot arm forward to a specified distance. When the cleaning robotic arm reaches the designated distance, it and the brush follow the pre-set cleaning trajectory to clean the urinal[8].

While the cleaning robotic arm is performing the cleaning operation, the water pump draws disinfectant from the disinfectant tank, which flows through a plastic hose, and is finally sprayed out by a low-pressure atomizing nozzle, thus performing the disinfection operation. Therefore, the cleaning robot can simultaneously carry out cleaning and disinfection tasks.

4. Performance Analysis

4.1. Parameter analysis of robotic arm D-H

From the literature, it is known that the kinematic analysis of the robotic arm requires a three-dimensional model of the six-degree-of-freedom robotic arm established to further establish the D-H coordinate system of the model. In this paper, the D-H method is used to establish the kinematic model of the robotic arm by linking the various joints of the arm and adding a coordinate system[9-10], as shown in Fig. 5, and connecting rod-related D-H parameters are shown in Table 1.

The D-H parameters of each connecting rod are shown in Table 1. Where α_{i-1} is the angle between z_i and z_{i-1} when viewed along the direction of x_{i-1}, a_{i-1} denotes the distance between z_i and z_{i-1} when viewed along the direction of x_{i-1} ($a_i > 0$), θ_i denotes the angle between x_i and x_{i-1} when viewed in the direction of z_i. d_i denotes the distance between x_i and x_{i-1} along the direction of z_i.

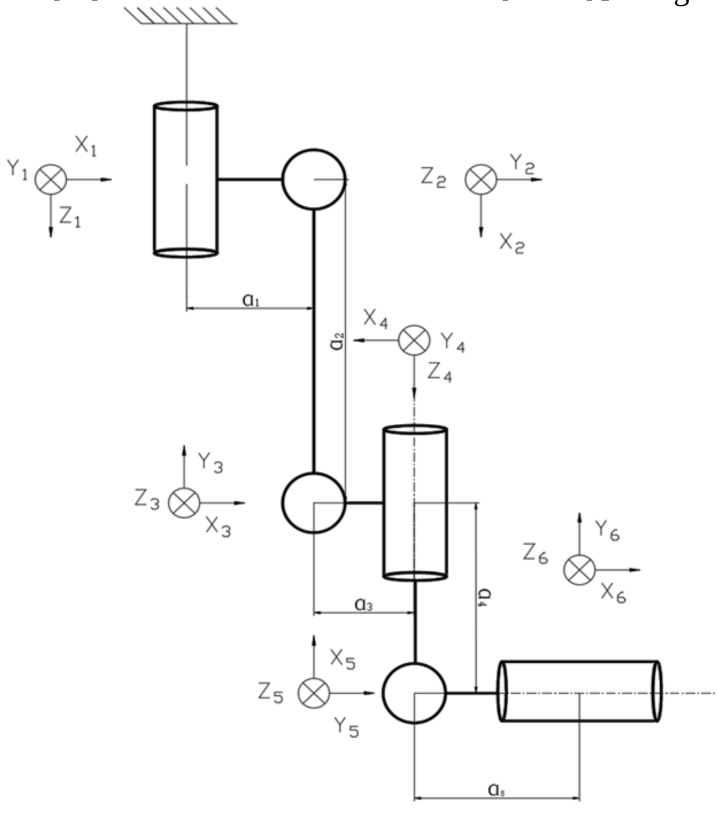


Figure 5: Coordinate system of connecting rods

Table 1: Connecting rod parameter table

Joint name	a_{i-1}(mm)	α_{i-1}(°)	θ_i (°)	Range of joints /(°)	d_i/mm
1	0	0	0	-180~180°	0
2	55	-90	-90	-45~90°	54.07
3	200	0	0	-90~120°	0
4	50	90	-90	-90~150°	63.64
5	100	0	0	-90~45°	50
6	67	-90	-90	-180~180°	63.81

4.2. Kinetic modelling

The designed robotic arm has a complex structure and a high number of degrees of freedom, making it difficult to build the model. In SolidWorks, the models can be saved as STEP format files based on whether there will be relative motion between them. After importing these into WorkBench software, the necessary rotary pairs, planar pairs, and material properties can be added. To simplify the model, the materials for the robotic arm are defined as aluminum alloy and PP homopolymer, with an overall mass of 2.823 kg.

In WorkBench, the trajectory of the robotic arm is planned by confirming the positions of the starting and ending points and the motion path. The movement of the robotic arm is achieved by adding displacement distances to the planar joints at different time steps, as shown in Table 2. The initial position of the midpoint of the brush is at a horizontal height D_1=370 mm from the base, with a horizontal length D_2=220 mm. The simulation time is set to 155 seconds, and the end cleaning brush of the robotic arm moves at a speed of 10 mm/s and rotates at an angular speed of 500 r/min. The trajectory of the brush's movement is shown in Figure 6, where the cleaning brush of the robotic arm performs six continuous movements.

Table 2: Brush movement direction and length

	1	2	3	4	5	6
direction	+y	-x	-y	+x	+y	-x
length	150mm	180mm	300mm	400mm	300mm	220mm

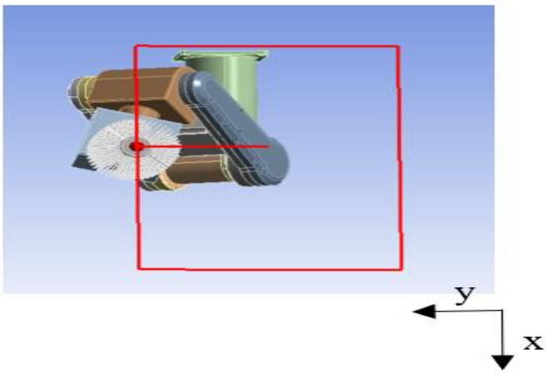


Figure 6: End cleaning brush trajectory diagram

By defining the speed and the material of the arm, the force or moment required to drive the joints can be obtained after simulation.

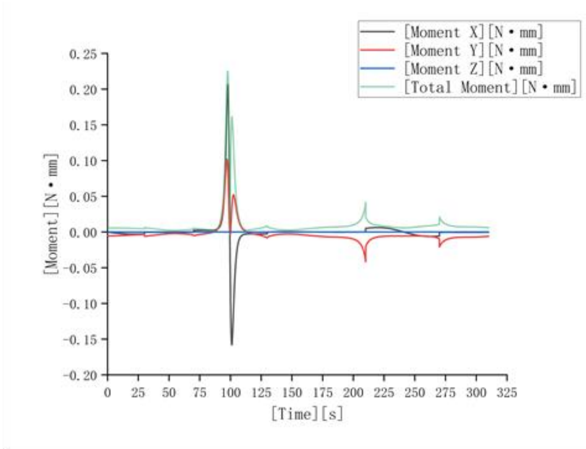


Figure 7: Joint 1 torque versus time

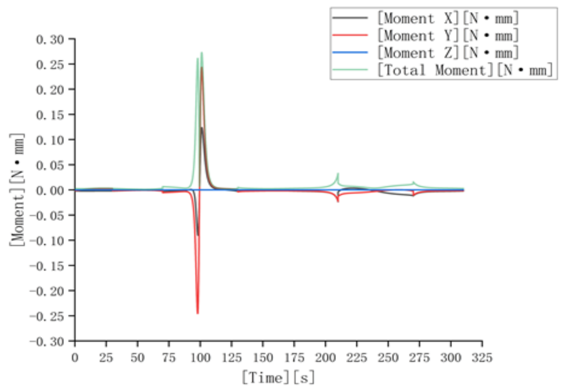


Figure 8: Joint 2 torque versus time

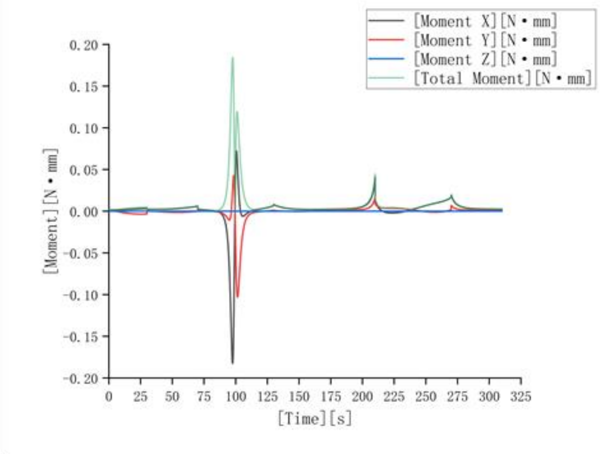


Figure 9: Joint 3 torque versus time

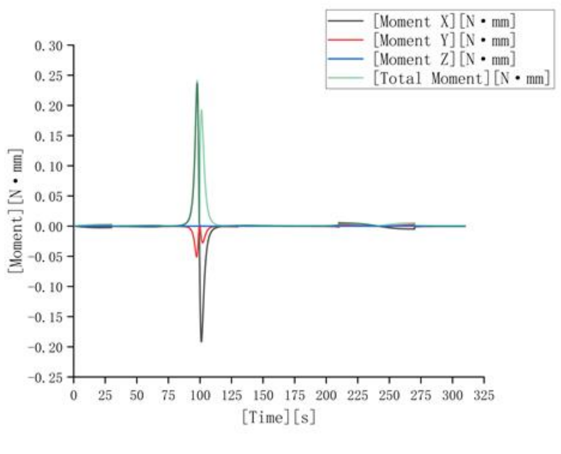


Figure 10: Joint 4 torque versus time

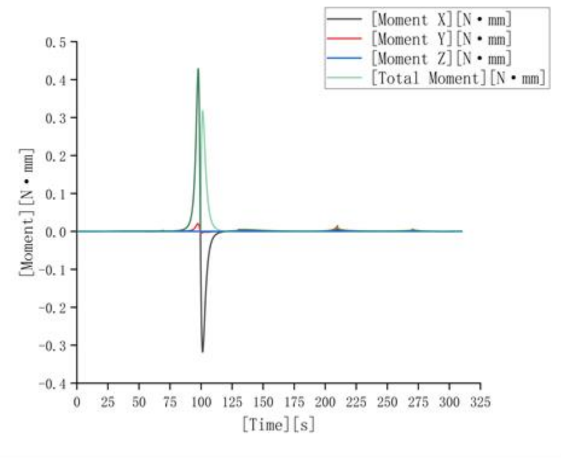


Figure 11: Joint 5 torque versus time

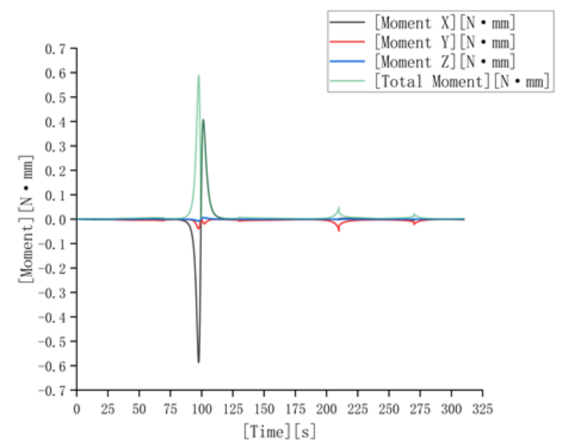


Figure 12: Joint 6 torque versus time

The moments of the joints in the XYZ direction and the magnitude of their combined moments are shown in Figs. 7-12, from which it can be seen that the moments of the joints in the XYZ direction change smoothly, with no sudden fluctuations, and the moments in each direction tend to level off at the end of the joint movement, which indicates that the robotic arm operates smoothly in the simulation process. The only sudden change occurs in the 102-103s, at the end of the fourth paragraph, the arm cleaning brush is in the limit position at this time.

By looking at Figures 8 and 10, it can be seen that joints 2 and 4 also use other mutation points in addition to having characteristics in common with the rest of the joints in 102-103s, and by analysing them, we can understand that all these mutation points are due to a change in the direction of motion and a sudden start-up, and therefore the moments of these will suddenly become larger.

4.3. Joint 6 Motor Selection

Table 3: Motor for Joint 6

Motor Model	rated voltage(V)	Rated power(W)	No-load RPM(rpm)	Rated torque(N.mm)	External Dimension(mm)	Eccentric shaft diameter(mm)
37GB520-B	12	5	600	19	32	6

After comparison, a suitable motor can be selected, and the mechanism chooses the 37GB520-B model motor of Shenzhen Guangwan Electronics Co., Ltd, which belongs to the miniature DC geared motor, specific parameters is shown in Table 3. The output torque and the maximum speed can realise the movement of the parts of the mechanism, and the motor is equipped with a speed reducer, which can achieve the effect of reducing the output speed and increasing the torque at the same time.

5. Conclusion

With the continuous development of China's urbanisation, the hygiene and cleaning tasks in public places are becoming more and more burdensome, and the traditional manual cleaning time and difficulty increases, cleaning efficiency decreases, and labour costs are further increased. This urinal cleaning device can achieve automated cleaning and disinfection through a mechanical arm, which can improve work efficiency, reduce the investment in labour costs, and reduce the risk of spreading bacteria and viruses. At present, there are very few products of the same type on the market, the product has a great market prospect, wide space for development, and has high scientific and technological value and application value.

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