An omni-directional mobile millimeter-sized microrobot with 3-mm electromagnetic micromotors for a micro-factory

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Abstract—This paper presents an omni-directional mobile microrobot for micro-assembly in a micro-factory. A novel structure is designed for omni-directional movement with three normal wheels. The millimeter-sized microrobot is actuated by four electromagnetic micromotors whose size is $3.1 \text{ mm} \times 3.1 \text{ mm} \times 1.4 \text{ mm}$. Three of the micromotors are for translation and the other one is for steering. The micromotor rotors are designed as the wheels to reduce the microrobot volume. A piezoelectric micro-gripper is fabricated for grasping micro-parts. The corresponding kinematics matrix is analyzed to prove the omni-directional mobility. A control system composed of two CCD cameras, a host computer and circuit board is designed. The macro camera is for a global view and the micro camera is for local supervision. Unique location methods are proposed for different scenarios. A microstep control approach for the micromotors is presented to satisfy the requirement of high positioning accuracy. The experiment demonstrates the mobility of the microrobot and the validity of the control system.

Keywords: Mobile microrobot; omni-directional; micromotor; micro-factory; kinematics.

1. INTRODUCTION

An omni-directional mobile microrobot has a small volume and good mobility. It can be used in a narrow space and special environment, such as a micro-factory, nuclear plant and some hazardous places.

Research on mobile microrobots has drawn much attention during the last decade. Various mobile microrobots were developed for different applications. Takeda [1] developed a chain-type micro-machine to inspect outer tube surfaces actuated by a

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Omni-directional robots or vehicles have been studied by several research groups. Generally, the research topics can be divided into two classes—special wheel structures and conventional wheel structures. West and Asada [9] developed a holonomic omni-directional vehicle with spherical wheels. Nagatani et al. [10] designed a robot driven by four Mecanum wheels for navigation research. Low and Leow [11] and William et al. [12] used universal wheels for omni-directional mobility. Ferrière et al. [13] designed an omni-mobile platform using a combination of spherical and universal wheels. These robots and vehicles with special wheels showed good mobility, but their structures are generally complex. Some researchers paid attention to designing omni-directional robots with conventional wheels, especially using dual-wheel structure. Park et al. [14] developed a mobile robot using three active casters. Yu et al. [15] designed an intelligent vehicle for old persons using two active split offset castors. Anglees et al. [16] developed an innovative dual-wheel structure with two motors which can achieve 3 d.o.f. on a plane. Ushimi et al. [17] also designed an omni-directional vehicle with a two-wheel caster-type odometer.

Research on mobile microrobots was done as well as on omni-directional mobile robots. However, few reports on omni-directional wheeled microrobots are available. It is difficult to realize millimeter-sized wheeled mobile microrobots with omni-directional structures because of their relatively complicated structure. In addition, an actuator with a higher output and several cubic millimeters volume for a microrobot is still not easy.

This paper describes an omni-directional mobile microrobot within 1 cm³ size, which is driven by 3 mm electromagnetic micromotors with a novel structure. The motivation for the research is to micro-assembly with a higher precision omni-directional wheeled microrobot in a micro-factory. The corresponding control system is also designed for application of the microrobot according to the microrobot characteristics.

The outline of this paper is as follows. Section 2 presents the design of the omni-directional microrobot. Section 3 analyzes the microrobot kinematics. The control system setup as well as the control principle are described in Section 4. Section 5 presents the experiment design and result, which is followed by conclusions.
2. MICROROBOT STRUCTURE

2.1. Omni-directional structure

The omni-directional microrobot consists of three normal wheels which are connected with each other through a set of micro-gears (a small micro-gear and three big micro-gears). The CAD model of the microrobot is shown in Fig. 1. The microrobot is driven by four electromagnetic micromotors whose diameter is 3 mm. Three micromotors are responsible for translational movement and their rotors are designed as the microrobot wheels directly. This design is very helpful to reduce the microrobot size. The fourth micromotor is for steering movement and is mounted in the middle part of the microrobot chassis.

The small micro-gear is connected with the axis of the steering micromotor. The large micro-gears, which are connected with the wheels through the shafts perpendicular to the chassis plane, are all joggled with the small micro-gear. The transmission ratio is 1:3.

The steering power can be amplified and transmitted to the wheels through the set of gears. Meanwhile, the steering accuracy of the microrobot is improved. The three wheels can steer synchronously and keep the same direction. The steering movement and the translational movement are independent of each other.

The photograph of the microrobot is shown in Fig. 2. Its size is 9 mm × 9 mm × 6 mm. Its total weight is about 2.8 g. The important parts of the microrobot, e.g., the micromotors, the micro-gears, etc., are fabricated by micro-fabrication technology. The wheels structures and set of joggled micro-gears can be observed from the Fig. 2b.

2.2. Electromagnetic micromotor

The electromagnetic micromotor is fabricated with non-silicon MEMS processes. Its structure is shown in Fig. 3. An axial flux is employed on the micromotor,
Figure 2. Microrobot photograph: (a) side view and (b) bottom view.

Figure 3. Structure of the micromotor: (a) model and (b) 3-mm micromotor photograph.

which can reduce the volume compared with the radius flux micromotor. The main characteristics of the electromagnetic micromotor are as follows:
- The rotor is mounted between two stators by a unique structure.
- The stator has multiple layers of slotless concentrated planar windings.
- The rotor has a multi-polar permanent magnet with high performance.
- The rotor is designed as the wheel directly to reduce the microrobot size.

The rotor mounted between two stators is made from a permanent magnetic alloy, which has eight magnetic poles. A stator winding consists of six layer coils, 42 turns and nine pairs. Its diameter is only 3 mm and the minimum line space is 1 µm, as shown in Fig. 4. The maximum operation current of coils is 300 mA and resistor is 62–70 Ω. The electromagnetic micromotor performance is shown in Table 1.
Figure 4. Photo of the six-coil stator.

Table 1.
Main performance indicators of the micromotor

<table>
<thead>
<tr>
<th>Size of micromotor (mm)</th>
<th>Maximum speed (rpm)</th>
<th>Weight (mg)</th>
<th>Maximum torque output (µN m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 × 3.1 × 1.4</td>
<td>20 000</td>
<td>115</td>
<td>8.3</td>
</tr>
</tbody>
</table>

2.3. Piezoelectric micro-gripper

On the top of the microrobot, a piezoelectric micro-gripper is connected with the steering shaft of the front wheel, which can be seen in Fig. 2a and in the side view of Fig. 1. It can turn together with the wheels, so its rotational accuracy is also improved through the set of micro-gears. Since its direction remains identical with the moving direction of the microrobot, the micro-gripper is used as the location sign of the microrobot. The micro-gripper can be removed conveniently for the magnetic connection mode.

The micro-gripper works based on the adverse piezoelectric effect. The piezoelectric micro-gripper arms generate distortion with about 107 V input. A plus voltage input makes the arms move away from each other, while a minus input makes them close, as shown in Fig. 5. The front part of each arm is mounted with two black gripper teeth which are made from SU8 glue, as shown in Fig. 6. SU8 glue can eliminate electrostatics and avoid damage during the micro-assembly process.

3. MICROROBOT KINEMATICS

3.1. Omni-directional characteristics

Since the microrobot moves on a plane, a planar coordinate system is defined, as shown in Fig. 7. XOY is the ground coordinate frame and XrOry is the microrobot coordinate frame attached to the microrobot chassis. The origin of XrOry is at the center point of one side of an equilateral triangle. The wheels are located at the
three vertexes of the equilateral triangle. Label 1 represents the front wheel, and 2 and 3 represent the two back wheels.

The microrobot position vector $\xi$ in the ground coordinate frame is defined as:

$$\xi = (x \, y \, \psi)^T \quad (1)$$

where $x$, $y$ are the coordinates of the point $O$, in the $XOY$ system and $\psi$ describes the orientation of the microrobot with respect to the $X$-axis.

The orthogonal rotation matrix is described as:

$$R(\psi) = \begin{pmatrix}
\cos \psi & \sin \psi & 0 \\
-\sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{pmatrix}. \quad (2)$$
A general position description of a wheel in the microrobot coordinate frame is shown in Fig. 8. When the wheel rolls on a plane without slipping, the relative velocity between the wheel and the ground at the contact point equals zero. Therefore, two kinematic constraints in and out of the wheel plane should be satisfied [18], which are described as follows.

\[
\begin{align*}
- \sin(\alpha_i + \beta_i) \cos(\alpha_i + \beta_i) l_i \cos \beta_i \cdot R(\psi) \cdot \dot{\xi} + r \cdot \dot{\phi} &= 0 \quad (i = 1, 2, 3) \\
\cos(\alpha_i + \beta_i) \sin(\alpha_i + \beta_i) l_i \sin \beta_i \cdot R(\psi) \cdot \dot{\xi} &= 0 \quad (i = 1, 2, 3),
\end{align*}
\]

where \( l_i \) is the distance between the \( i \)th wheel center point \( O_i \) and the microrobot coordinate origin \( O_r \), \( \alpha_i \) is the angle of \( O_r O_i \) with respect to the \( X_r \) axis of the microrobot coordinate frame, \( \beta_i \) is the orientation of the \( i \)th wheel plane with respect to \( O_r O_i \), \( r \) is the wheel radius and \( \dot{\phi} \) is the wheel rotational velocity.

When the wheel rotational vector \( \dot{\phi} \) equals a suitable value, (3) will not constrain the movement of the microrobot along the wheel plane. Equation (4) will always constrain the microrobot movement orthogonal to the wheel plane. Considering each of the three wheels generates a constraint as (4), the whole kinematic constraint can be expressed as a general matrix as

\[
J(\beta_c) \cdot R(\psi) \cdot \dot{\xi} = 0,
\]

Figure 7. Coordinate frame for the microrobot.

Figure 8. A general position description for a wheel.
where:
\[
J(\beta_c) = \\
\begin{pmatrix}
\cos(\alpha_1 + \beta_1) & \sin(\alpha_1 + \beta_1) & l_1 \sin \beta_1 \\
\cos(\alpha_2 + \beta_2) & \sin(\alpha_2 + \beta_2) & l_2 \sin \beta_2 \\
\cos(\alpha_3 + \beta_3) & \sin(\alpha_3 + \beta_3) & l_3 \sin \beta_3
\end{pmatrix}
\]

The distance \( l_i \) and angle \( \alpha_i \) are constants relevant to the microrobot structure, and the angle \( \beta_i \) is the unique variant in the matrix \( J(\beta_c) \). When the microrobot steers, the three wheels turn together and their relative steering angles are equal. Assuming that the initial orientation of the wheels is along the negative direction of the \( Y_r \)-axis and they steer anti-clockwise to an angle of \( \beta_c \), the detailed position description and steering angle of the wheels are shown in Fig. 9 and summarized in Table 2 respectively. Substituting the values in Table 2 for the parameters in \( J(\beta_c) \) and transforming this matrix, the determinant of the \( J(\beta_c) \) can be calculated as:

\[
K(\beta_c) = \\
\begin{pmatrix}
-\cos \beta_c & -\sin \beta_c & -\sqrt{3}a \cos \beta_c \\
0 & 0 & a(\sin \beta_c - \sqrt{3} \cos \beta_c) \\
0 & 0 & 0
\end{pmatrix}
\]

According to Ref. [18], the microrobot freedom of steering \( \delta_s \) equals \( \text{Rank} J(\beta_c) \) and the freedom of mobility \( \delta_m \) equals \( 3 - \text{Rank} J(\beta_c) \). Since the rank of the matrix \( J(\beta_c) \) equals \( K(\beta_c) \), the microrobot has one freedom of mobility, which means that the microrobot can achieve one kind of motion without reorientation of the wheels. For the three wheels to keep parallel all the time, the transient center of rotation of them can be taken to be located at an infinite position. Therefore, the only movement mode of the microrobot is the translational movement. However, the maneuverability freedom of the microrobot is defined as \( \delta_M = \delta_m + \delta_s \), whose value equals 3. It means that the microrobot can achieve omni-directional movement by reorientation of the wheels.
Table 2.
Wheel posture parameters

<table>
<thead>
<tr>
<th>Wheel</th>
<th>$\alpha_i$</th>
<th>$\beta_i$</th>
<th>$l_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-\pi/2$</td>
<td>$-(\frac{\pi}{2} - \beta_c)$</td>
<td>$\sqrt{3}a$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$\beta_c$</td>
<td>$a$</td>
</tr>
<tr>
<td>3</td>
<td>$\pi$</td>
<td>$\beta_c$</td>
<td>$a$</td>
</tr>
</tbody>
</table>

3.2. Kinematic equation

According to (5), the vector $R(\psi) \cdot \dot{\xi}$ belongs to $N[J(\beta_c)]$, which is the null space of the matrix $J(\beta_c)$. The microrobot velocity $\dot{\xi}$ can be expressed as:

$$\dot{\xi} = R^T(\psi) \cdot \Sigma(\beta_c) \cdot \sigma,$$

where $\Sigma(\beta_c) = (-\sin \beta_c \cos \beta_c, 0)^T$ represents a base of $N[J(\beta_c)]$ and $\sigma$ represents the input of control for the translational movement.

The wheel steering velocity is defined as:

$$\dot{\beta}_c = \tau,$$

where $\tau$ is the input of control for steering movement.

The kinematics model of the microrobot is expressed as:

$$\dot{k} = M(k) \cdot p,$$

where $\dot{k} = (\dot{x}, \dot{y}, \dot{\psi}, \dot{\beta}_c)^T$, $M(k) = (R^T(\psi) \cdot \Sigma(\beta_c), 0)$ and $p = (\sigma, \tau)^T$.

Introducing the relative parameters to (9), we have:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \\ \dot{\beta}_c \end{pmatrix} = \begin{pmatrix} -C_\psi \cdot S_\beta - S_\psi \cdot C_\beta & 0 \\ -S_\psi \cdot S_\beta + C_\psi \cdot C_\beta & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \sigma \\ \tau \end{pmatrix},$$

where $C_\psi$ and $S_\psi$ represent $\cos \psi$ and $\sin \psi$, respectively, and $C_\beta$ and $S_\beta$ represent $\cos \beta_c$ and $\sin \beta_c$, respectively. The relation between the microrobot movement situation and the input can be determined through this equation.

When the microrobot steers, just the wheels change their orientation, i.e., the microrobot chassis does not move. Since the microrobot coordinate frame is attached to the chassis, the orientation angle $\psi$ does not change. This characteristic is also demonstrated by (10) in which the angle velocity $\dot{\psi}$ always equals zero.

Figure 10 shows the movement situation with a given input. The input of control is selected as a half-period sinusoidal signal to simulate a smooth acceleration and deceleration motion, as shown in Fig. 10a. Its frequency equals 0.1 Hz and the amplitude is 1.0. The angles $\psi$ and $\beta$ are determined as $\pi/4$ and $\pi/18$, respectively. The velocity and the position simulation results have negative values along the X-axis in the ground coordinate frame, as shown in Fig. 10b and 10c. The situation
Figure 10. Kinematic simulation of the microrobot: (a) input signal for simulation, (b) velocity along the $x$- and $y$-axis, and (c) position with respect to the $x$- and $y$-axis.

along the $Y$-axis is the opposite. Furthermore, the absolute values of the velocity and the position along the $X$-axis are larger than those along the $Y$-axis.
4. MICROROBOT CONTROL

Based on the microrobot characteristics and application purpose of micro-assembly, a control system composed of two work platforms, two cameras for image capture, a host computer and a control board is designed, as shown in Fig. 11. The cameras capture the microrobot images which are sent to and processed by the host computer. Based on the location of the microrobot, the host computer determines the action of the microrobot, such as the movement modes (forward, backward and steering) and step numbers (single-step and multi-step). The objective is to move to the micro-work platform quickly and complete the micro-assembly task.
4.1. Vision system and microrobot location

CCD camera systems are very common in soccer robot systems and micro-operation microrobot systems. The soccer microrobot system usually uses one macro-CCD camera (global vision) to supervise the whole scenario [19]. Some micro-position platforms utilize only one micro-CCD camera to realize local location with high precision [20, 21]. In an European Union project, a double CCD system is used for a micro-assembly station [22]—one is for the global view and the other is for the location view. In these micro-position platforms and micro-assembly systems, the mobile microrobots all have a leged structure and are driven by piezoelectric principle.

In this paper, two CCD cameras are used to supervise a wheeled mobile millimeter-sized microrobot in different scenarios. The microrobot is designed to perform micro-assembly operations on a micro-platform, so a high-resolution CCD camera is set above the micro-platform and supervises the assembly process. The micro-CCD camera has 4 µm pixel precision and can supervise a 2 mm × 2 mm area. On the macro-platform, the moving distance of the microrobot is much larger and the requirement for the location precision is not so high. Therefore, a macro-CCD camera set on the platform ceiling can satisfy the location requirement. Its supervised area is about 15 cm × 15 cm.

The function of the CCD cameras is to locate the microrobot. Different location methods are designed according to different scenarios. On the macro-platform, the microrobot is located by the macro-CCD camera. Two actual situations are considered. First, the micro-gripper direction represents the microrobot direction. Second, the micro-gripper will be shaded by the micro-camera when the microrobot moves near the micro-platform.

In Ref. [19], three LEDs are mounted on the top of the microrobot to form an isosceles triangle for location; however, the method is not suitable for the present microrobot, because the microrobot chassis always keeps position when the wheels steer. Moreover, some extra control wires are needed to light the LEDs, which will be influenced by the mobility.
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Figure 13. Locating the microrobot in macro-scenery.

As shown in Fig. 12, a round white ‘cap’ is pasted on the top of the micro-gripper, which represents the microrobot body in the macro-scenery. Furthermore, a white ‘tail’ is also pasted to judge the microrobot direction. The image of the ‘cap’ and ‘tail’ captured by the macro-CCD camera is shown in Fig. 13. The angle $\theta_R$ represents the microrobot direction angle, which equals the angle between the $Y$ axis and the extension line in reverse direction of the tail. The locating precision of the macro-CCD system is about 0.9 mm (X-axis), 0.7 mm (Y-axis) and 0.25° (angle).

When the microrobot moves near the micro-platform and the micro-camera can capture the micro-gripper, the microrobot will be located by the micro-camera. The microrobot position is determined by the center of the micro-gripper, as shown in Fig. 14. The coordinate origin is the target point. The grasped micro-part will be released until the micro-gripper center is adjusted to locate at the origin. The location precision of the micro-CCD camera is about 0.012 mm (X-axis) and 0.008 mm (Y-axis).

4.2. Control principle

The diagram of the vision-feedback control system is shown in Fig. 15. The cameras capture the static images when the microrobot stops. After obtaining the robot position, the motion planning controller will send commands to the control circuit board through a RS-232 port. After the microrobot finishes executing the commands, it will remain immobile and wait to be re-captured. On the control board, a pulse width modulation (PWM) controller is used to realize a novel microstep control method for high positional accuracy of the microrobot.

4.2.1. Motion planning. Since the micromotors employ open-loop control and the microrobot movement may be influenced by some uncertain factors, e.g., assembly error and platform smoothness, it is difficult to realize ideal translational movement. The longer the microrobot moves, the larger the movement error is.
Figure 14. Locating the microrobot in micro-scenery (P is the micro-gripper and the micro-part center, i.e., the cross-point of the four black gripper teeth).

Figure 15. Diagram of the vision feedback control system.

However, a shorter movement distance will increase the adjustment times and whole time cost. Therefore, a motion planning method is necessary.

As shown in Fig. 16, ‘A’ represents the macro-platform, while ‘B’ represents the micro-platform, i.e., the target position. The macro-platform is divided into four areas, i.e., I, II, III and IV. Two principles are taken into account in the motion planning. First, movement error has a direct relation with the movement distance. Second, if the microrobot moves the same distances in areas I and IV and generates the same movement error, the adjusted angle in area IV will be larger than in area I. Therefore, according to the distances between the four areas and target position, the designing movement distances are decreasing from area I to IV. That is to say that the microrobot can move longer in areas I and II, while shorter in areas III and IV.
Moreover, the feedback control is employed in areas III and IV to ensure the angle error within a permitted scope after adjustment every time.

4.2.2. Micromotor control. As depicted in the CAD model in Fig. 1, three micromotors are used for translational driving. Since the micromotors are assembled manually, it is difficult to make their performance equal. The actual experiment demonstrated that the microrobot shook when driven by three micromotors. Thus, the micromotor on the front wheel is taken off. Then the microrobot can move more stably than before, although some driving ability may be affected.

The two micromotors for translational movement are controlled as a whole by inputting the same control signal. The micromotor can be controlled as a DC motor or as a step motor according to different applications. Therefore, the microrobot can move quickly with a speed of 0–5 cm/s or step-by-step.

The positional accuracy is a key factor for a micro-assembly microrobot, which shows how many steps per revolution the micromotor can achieve. With the two to three phases approach conducted, the micromotor needs to change 12 steps rotating in an electrical cycle (Fig. 17), while 48 steps in a mechanical cycle. Since the micromotor has four pairs of magnetic poles and the wheel diameter is 3.3 mm, the gear ratio is 1:3, the microrobot has positional accuracy of 0.22 mm (\(\pi \cdot 3.3/48\)) for translational movement and 2.5° (360°/48/3) for steering movement. Such accuracy is not high enough to satisfy the micro-assembly requirement.

Fabricating more poles and coils on the micromotor can increase the step numbers. However, it is very difficult to do this on a 3-mm substrate constrained by the microfabrication technology. Through such control the direction and value of current in the phase can realize the high positional accuracy, but the phases employ start connecting. When the current in one phase is changed, the other two are changed together.

A novel microstep control method is designed for the micromotor to improve the positional accuracy. According to the miss-step phenomenon of the motor, when

![Figure 16. The divisions for motion planning.](image)
the motor commutates a state between two adjacent states (e.g., $S_1$ and $S_2$) and the commutation frequency is much higher than the start frequency of the motor, the motor rotor will stop at neither $S_1$ nor $S_2$, but a middle position. Therefore, a new step can be added into the step sequence.

An example is shown in Fig. 18. ‘−AC’ and ‘−A–BC’ represent two adjacent states at $30^\circ$ by electrical angle. The minus sign represents the current output from the corresponding phase. $\vec{T}_2$ and $\vec{T}_3$ are torque vectors of the two states. Assuming the commutation frequency is $1/t_1$, and the conducted time of ‘−AC’ is $t_2$ and ‘−A–BC’ is $t_3$, the duty cycles of the two states are described as $\alpha = t_2/t_1$ and $\beta = t_3/t_1$. The vector magnitudes can be presented as $|\vec{T}_2| = \alpha \cdot T$ and $|\vec{T}_3| = \beta \cdot (2\sqrt{3}T/3)$, where $T$ and $2\sqrt{3}T/3$ represent the maximum vector magnitudes of the two sates when their duty cycle equals one, respectively. (The ratio $2\sqrt{3}/3$ can be obtained by analyzing the current value in the phases.)

The vector $\vec{T}_m$ is the synthetical vector of $\vec{T}_2$ and $\vec{T}_3$, which is the middle state where the micromotor rotor will stop. The magnitude of $\vec{T}_m$ equals $T$. The angle $\theta$ between $\vec{T}_m$ and $\vec{T}_2$ represents the direction of $\vec{T}_m$. Based on the vector relation in Fig. 18, the expressions of the duty cycle can be obtained as:

$$\alpha = \sin(\pi/6 - \theta)/\sin(5\pi/6) = 2\sin(\pi/6 - \theta)$$

### Figure 17
Two to three phases conducted of the micromotor: (a) 12-step sequence and (b) vectors.

### Figure 18
Vector relation between $\vec{T}_m$, $\vec{T}_2$ and $\vec{T}_3$ (arrow represents vector direction, while its length represents the vector magnitude).
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Figure 19. Photo of the microrobot grasping a jewel bearing (1, 0.6 mm bearing; 2, micro-gripper arms; 3, cap; 4, tail).

\[ \beta = \sqrt{3} \sin \theta / 2 \sin(\pi/6) = \sqrt{3} \sin \theta. \]  \hspace{1cm} (12)

It is obviously that \( \theta \) can be determined by the duty cycles \( \alpha \) and \( \beta \). Theoretically, a middle state with any angle could be obtained through controlling \( \alpha \) and \( \beta \). To ensure the micromotor steps evenly and stably, two middle states \( \theta = 10^\circ \) and \( \theta = 20^\circ \) are inserted according to the actual experiment. Therefore, the micromotor can achieve 36 steps in 360° by electrical angle, while 144 steps in 360° by mechanical angle. The positional accuracy of the microrobot is presently 0.07 mm in translational movement and 0.83° in steering movement, which can satisfy the application requirements.

5. MICROROBOT EXPERIMENT

5.1. Experiment design

To demonstrate the performance of the whole microrobot system and explore the application, a bearing/axis micro-assembly experiment is designed. The microrobot taking a jewel bearing (Fig. 19) will move from the macro-platform to the micro-assembly platform on which an axis is set. The bearing will be released and dropped onto the axis by the microrobot. The whole process will be done automatically.

The user can configure the control parameters and supervise the assembly process through the designed interface on a computer, as shown in Fig. 20. The user programs on the host computer are developed using Visual C++ 6.0 software.

5.2. Experiment results

The microrobot system completes the bearing/axis micro-assembly automatically. The bearing diameter is 0.6 mm, while the axis is 0.35 mm. Some photos of the micro-assembly process extracted from a video which records the experiment process are shown in Fig. 21.

A schematic drawing of the movement trajectory is shown Fig. 22. The trajectory is divided into ‘\( n + 1 \)’ sectors by the ‘\( n \)’ location points. More sectors can reduce the nonlinearity of the trajectory, but can also increase the whole time cost. The
movement distances gradually decrease from the start point to the final target point. The steering angles have larger values at points S₃ and S₅ because more movement errors are accumulated after long distance movement. The microrobot does not adjust its direction on some points, such as S₁, S₂, S₄ and S₆, etc., as the movement error does not exceed the limit value.

The adjustment points are very dense near the goal (from Sᵢ to Sᵣ), because the movement distance and the permitted movement error are reduced in the system. Otherwise, the microrobot usually adjusts more than once on these points, as visual feedback control is employed near the target area. When the microrobot adjusts its direction on these points, the visual system can detect the angle error. If the error is not within a permitted scope, the adjustment continues until the requirement is satisfied.

The experimental process and result show the mobility and positional accuracy of the microrobot, the validity of the whole control system, and demonstrate the feasibility of some novel methods, such as the motion planning, location, microstep control, etc.

6. CONCLUSIONS

A millimeter-sized mobile microrobot for micro-assembly in a micro-factory is described. The microrobot has omni-directional movement characteristics. It is driven by electromagnetic motors which can achieve step movement with satisfying precision. A micro-gripper is mounted on the microrobot as the operating tool. The corresponding kinematics models are derived to illustrate the kinematics characteristics.

An experimented platform is built to perform the relative research on the microrobot, such as the microrobot performance, control methods, visual system, appli-
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Figure 21. Photos of the experiment by the microrobot (1, micro-camera; 2, micro-assembly platform; 3, axis; 4, the bearing is already on the axis). (a) Move quickly on the macro-platform (larger movement distance and less direction adjustment times). (b) Move close to the micro-assembly platform (movement distance decreases and direction adjustment times increase).

cations, etc. A bearing/axis micro-assembly experiment is introduced to show the performance of the microrobot and the validity of the control system. Through the experiment, we also explore the application of the microrobot system and established a foundation for later application research.

During the experiment, the step distance of the microrobot is sometimes uneven. As shown in Fig. 23, inputting the same control signal, the second step is larger than the first step. According to the supervised results on the PC screen, the wheel
Figure 21. (Continued.) (c) Gripper moves above the axis (location by micro-camera, more adjustment step-by-step). (d) Adjust the gripper center to aim at the axis and release the bearing.

slip of the microrobot needs further improvement. Wheel slip is a complicated and important problem which will influence the positional precision and increase the adjustment times of the microrobot. Therefore, our next work will focus on this phenomenon and try to find a method to solve the problem.

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Figure 22. Schematic of the microrobot trajectory. (S, the start point; G, goal; Si−n, location points).

Figure 23. Position adjustment of the micro-gripper supervised through a PC screen: (a) start position (take the right side of the black frame as reference), (b) first step (move about one bearing width) and (c) Second step (move about two bearing widths).
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