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Research on Model, Experiment and Application of Gravity Valve

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Abstract: In this paper, two kinds of gravity valves are designed: copper bead gravity valve and hose gravity valve. Firstly, the stress distribution on the substrate of the gravity valve is simulated when the copper bead and the substrate of the gravity valve is in the non-touched, half-touched or full-touched states respectively, and the fluid leakage laws are also analyzed in the different states, by ABAQUS 6.16. The flow rate control effects of the copper bead gravity valve with different cone angle are measured and analyzed experimentally, and the optimal cone angle is obtained. Secondly, the cross-section shapes of the hose are compared and analyzed by FEA (Finite Element Analysis) for several kinds of hose gravity valve. It is concluded that the shuttle hose has the best performance. Then the shuttle hose gravity valve is made and its flow characteristics are measured and analyzed with different length of the hose. Finally, the two kinds of gravity valve are compared and applied. The copper bead gravity valve is used in chemical reaction self-driven rolling robot. The hose gravity valve is used to control the end of bending brake stably for the angle sensor, and the hose gravity valve can also be used to establish mechanical feedback loop to facilitate the flow rate control by the angle.

Keywords: gravity valve; FEA; flow rate control; chemical reaction self-driven rolling robot; bending actuator

1 Introduction

Sensing, processing, execution, and feedback are the internal operation logic of the most automation equipment [1-3]. For some of the above functions, besides the way of circuit logic, feedback control can also be realized through mechanical structure and properties. The mechanical structure itself can sense the external environment and make response. Without circuit logic processor, the system can be simplified and then the response speed and robustness of the equipment can be improved [4]. Philipp Rothemund made a kind of flexible actuator based on the bi-stable valve. When the gas is injected into the flexible actuator, the cavity expands, which pushes the inner hose to undergo Eulerian buckling and blocks the gas to enter, thus driving the actuator to move back and forth. The core structure of the actuator is to use the distance between the diaphragms to control the flow in the hose [5]. Cagdas D. Onal designed a chemical reaction driven pump. It makes the diaphragm bend through the pressure generated by the reaction, and reduces the transition between catalyst and reaction liquid to realize self-dynamic regulation and form a mechanical feedback circuit [6]. P. S. sreetharan made a flying robot with flapping wing. It uses the differential structure to sense the current left and right angles and control the wing on the down side to speed up flapping [7].

In this paper, two kinds of gravity valves are designed, studied, and experimented, which can switch the open and close state of the gravity valve to control the flow by its own gravity. They can be used as a sensing and executing element for the self-sensing mechanical structures.

2 Modeling, simulation, and experiment of the copper bead gravity valve

2.1 Modeling and simulation analysis of the copper bead gravity valve

The copper bead gravity valve is composed of substrate, copper bead and upper cover. There is a channel with variable diameter inside the circular substrate. A copper bead is placed in the channel, and the upper cover is used to prevent the copper bead from falling, shown in figure 1. When the angle between the central axis of the copper bead gravity valve and the vertical line is different, the force acting on the copper bead is different, and the position of the copper bead will change. When the copper bead touches the substrate fully, the valve is closed; when the copper bead is separated from the substrate, the valve is opened. The main structural parameters of copper bead gravity valve are shown in Table 1.

(a) Structure diagram of gravity valve
The opening and closing status of the valve is controlled by the touch between copper bead and silica gel substrate. The angle $\theta_C$ of copper bead gravity valve is defined as the angle between outer wall and horizontal plane. When $\theta_C$ of copper bead gravity valve is different, there are three states between the copper bead and the substrate, namely, the non-touched, half-touched and full-touched states. The non-touched state is shown in figure 2(a). The copper bead is acted by supporting force $F_N$ which is perpendicular to the touched surface of the substrate, $F_S$ which is the supporting force of the upper cover, $G$ which is the gravity of the copper bead itself and $F_A$ which is the thrust of the fluid on the copper bead. The half-touched state is shown in figure 2(b). The copper bead touches the underside of the arc-surface of the silica gel substrate. Due to the super elasticity of silica gel substrate, under the action of $G$ and $F_A$, the substrate will deform downward. $F_C$ which is the pressure of the copper bead on the silica gel substrate is the resultant force of $G$ and $F_A$, which is the reaction force of $F_N$. At this time, the copper bead cannot touch the arc-surface of the silica gel substrate above the copper bead, so there is a gap. The full-touched state is shown in figure 2(c). The copper bead touched the arc-surface of the substrate fully, and the copper bead is subjected to the $F_A$, $F_N$, and $G$.

When the copper bead gravity valve is in the critical state of non-touched and half-touched state, the supporting force of the upper cover $F_S$ equals 0. The angle between the vertical support force $F_N$ and the gravity $G$ is $180^\circ-\delta$, shown in figure 3.

Where $\delta$ is:

$$\delta = \alpha \cdot (90^\circ + \theta_C) \quad (1)$$

At this time, the copper bead is in the force equilibrium,
so there are:

\[ F_A \cdot \sin(180^\circ - \alpha) = G \cdot \sin(\alpha - 90^\circ - \theta_C) \]  \hspace{1cm} (2)

Where, \( \alpha - 90^\circ > \theta_C \). For the no-touched state, it should meet the following condition:

\[ F_A \cdot \sin(180^\circ - \alpha) < G \cdot \sin(\alpha - 90^\circ - \theta_C) \]  \hspace{1cm} (3)

Therefore, when the angle \( \theta_C \) is fixed, the larger the angle \( \alpha \) of the cone is, the larger \( F_A \) required to reach the half-touched state is. In other words, when \( \theta_C \) is fixed, the smaller \( \alpha \) is, the easier the state changes from the no-touched state to the half-touched state.

In the half-touched state, the copper bead touches the arc-surface of the silica gel substrate, and the silica gel substrate deforms, while there is a gap on the upper side. At this time, the silica gel substrate is subjected to the pressure \( F_C \) of the copper bead. The pressure \( F_C \) is the resultant force of the gravity of the copper bead \( G \) and the thrust of the fluid on the copper bead \( F_A \), which is the reaction force of \( F_N \), shown in figure 4.

The end of the arc-surface on the silica gel substrate is point C. Since the copper bead is a homogeneous sphere, if the deformation of silica gel is small enough, the state of the copper bead depends on the acting point of \( F_C \). If point C is located on the right side of the direction of \( F_C \), it is in half-touched state. If point C is located on the left side, it is in full-touched state. There is a line \( L_C \) from point C to the mass center of copper bead shown in figure 4, and the angle \( \gamma_C \) between line \( L_C \) and the center line of gravity valve is as follows:

\[ \gamma_C = \arcsin \frac{m}{r_C} \]  \hspace{1cm} (4)

When \( m=1.4, r_C=2.5 \) (in Table 1), \( \gamma_C = 34^\circ \). Therefore, when the line \( L_C \) is perpendicular to the horizontal plane, \( \theta_C=90^\circ-\gamma_C = 56^\circ \), and the gravity valve changes from half-touched state to full-touched state.

Figure 4 Force analysis diagram of touch between copper bead and silica gel substrate

However, in practice, the silica gel is easy to deform, which will affect the angle from half-touched state to full-touched state. The FEA software ABAQUS 6.16 is used to analyze the state of the copper bead under different force direction. The material used for the substrate is Dragon Skin 0030 silica gel produced by Smooth-On Company, which has high hardness compared with the other same type of silicone material [8]. Dragon skin 0030 silica gel is super elastic, so the reduced order polynomial model is selected as the constitutive model, and the strain energy formula is as follows:

\[ U = \sum_{i=1}^{N} C_{10}(T_i - 3)^i \]  \hspace{1cm} (5)

Where \( U \) is the strain energy, and \( T_i \) is the first invariant of stress bias. The corresponding parameters of dragon skin 0030 silica gel are \( N=2 \), \( C_{10}=1190J \cdot m^{-3} \), \( C_{20}=23028J \cdot m^{-3} \). Because the hardness of copper bead is far different from that of silica gel, the copper bead is regarded as a rigid body. Since the pressure \( F_C \) is the resultant force of the gravity \( G \) of the copper bead and the thrust \( F_A \) of the fluid on the copper bead, when \( F_A \) is small, the gravity of the copper bead can be regarded as \( F_C \). The weight of 5 mm diameter copper ball is 6g, so \( F_C = 0.006N \). The angle between the horizontal plane and the force \( F_C \) is defined as \( \theta _1 \), shown in figure 5, and it’s easy to see angle \( \theta_1 \) and angle \( \theta_C \) are numerically equal. \( F_C \) with the angles \( \theta_1 \) of 30°, 45°, 60°, 75° and 56° is applied to the copper bead, which simulates the gravity on the copper bead. The results of FEA are shown in figure 5.

Figure 5 Stress distribution map of substrate under \( F_C \) with different directions

It can be seen from figure 5 that when the angle \( \theta_1 \) increases, the stress on silica gel substrate changes from one side to two sides. When the angle between \( F_C \) and the horizontal direction is less than or equal to 45°, the copper bead touches one side of the substrate, and the other side is completely free of force, which is a half-touched state. When the angle \( \theta_1 \) increases more than 45°, the state between the
copper bead and the substrate changes from half-touched state to full-touched state. When the angle $\theta_1$ increases to 46°, the state between the copper bead and the substrate change from half-touched state to full-touched state. At this time, the copper bead touches the both sides of the substrate, and with the increase of the angle $\theta_1$, the force area of the left substrate increases. When the angle between $F_C$ and horizontal direction is 56°, the acting point of $F_C$ is just the point C. At this time, the left side of the substrate has touched the copper bead, causing the stress, so gravity valve has been in state of full contact.

According to the model analysis, $\theta_C = 56°$ is the transition angle between the half-touched state and the full-touched state. However, in FEA, when the angle $\theta_1$ between the force $F_C$ and the horizontal direction is 56°, in other words, when the angle $\theta_C$ is 56°, the force $F_C$ points to the point C. At this time, the left side of the substrate has touched with the copper bead, and stress has been produced on the touch surface. This is because the substrate is made of silica gel and deforms under the action of copper beads. It is in full touched when $\theta_C = 56°$. Therefore, the angle $\theta_C$ should be less than 56° when the half-touched state changes to the full-touched state. Finally, when the angle $\theta_C$ increases to 46°, the touch state between the copper bead and the substrate changes from half-touched state to full-touched state.

When the copper bead fully touches the substrate, ideally, the gravity valve will be closed and the flow rate is 0. However, in practice, because the arc-surface of silica gel substrate is cast by 3D printing mold, the surface is not smooth and the surface of copper bead is not a mirror. Therefore, the leakage of copper bead gravity valve is inevitable. The leakage in this case is simplified as a spherical slit flow and flow formula of spherical annular gap is as followed:

$$Q_c = \frac{\pi h_G^2}{\mu \Delta \theta_w} \Delta P$$ (6)

Where $Q_c$ is the leakage causing of the differential pressure, $h_G$ is the height of the gap, $\mu$ is the hydrodynamic viscosity, $\Delta \theta_w$ is the angle of the gap occupying the spherical surface, $\Delta P$ is the differential pressure between both ends of the gap. It can be seen that the leakage is related to $h_G$, $\Delta \theta_w$ and $\Delta P$.

In order to explore the influence of the cone angle $\alpha$ on the leakage in the full-touched state, the stress distribution of the arc-surface with different cone angle $\alpha$ is simulated and analyzed. The optimal cone angle $\alpha$ can be obtained by formula (6). In order to simplify the analysis, it is discussed when the copper bead gravity valve is placed vertically ($\theta_C = 90°$). $\alpha$ is set as 95°, 100°, 105° and 110° respectively. From the simulated results, the stress distribution at each point of the arc-surface can be obtained from $y_0$ to $y_1$ height. Where, $y_0$ is the height of point C ($y_0 = 2.0mm$) and $y_1$ is the highest point where the copper bead touches the arc-surface of the substrate. When $\alpha = 110°$, $y_1 = 3.4mm$, it is shown in figure 6.

![Figure 6 Stress distribution map of touch surface under different cone angle $\alpha$](image)

For the copper bead gravity valve, the gap height $h_G$ is negatively related to the contact stress between the copper bead and the substrate. It can be seen from figure 7 that the stress distribution of the touch surface at different heights has little difference for different cone inclination angles $\alpha$. Therefore, it can be approximately considered that the gap height $h_G$ is the same under different cone inclination angles $\alpha$. The smaller the cone angle $\alpha$ is, the larger the contact surface between the copper bead and the substrate is, which means the larger the angle $\Delta \theta_w$ of the gap in the sphere is. Because the pressure difference $\Delta P$ between both ends of the gap is equal, the smaller the angle of the cone $\alpha$ is, the smaller the leakage of the copper bead when it is in full contact with the substrate is. Combined with equation (6), because the pressure difference at both ends of the gap $\Delta P$ is equal, the smaller the cone angle $\alpha$ is, the smaller the leakage of copper bead in full contact with the substrate is.

2.2 Experiment and analysis of copper bead gravity valve

The sealing effect of copper bead gravity valve is mainly
determined by tightly fitting between copper bead and silica gel substrate, which depends on the accuracy of manufacturing. In practice, there is thermal expansion and cold shrinkage when the silica gel is heated in the mold. In addition, there exists light internal stress when molding the silica gel, and there is small deformation when taking out silica gel from the mold. All these factors will make the radius $r_C$ of the arc-surface of silica gel substrate smaller than the design one, so it is necessary to increase the radius of the arc-surface in actual production. When $r_C = 2.8$mm copper bead can fit the substrate well. Different size gravity valve substrate with cone angle $\alpha$ from $95^\circ$ to $110^\circ$ are made, shown in figure 8.

![Figure 8 Substrate of copper bead gravity valve with different cone angle $\alpha$](image)

In air, the four copper bead gravity valves are applied by a pressure of $0.5\text{kPpa}$ to measure their corresponding flow rate with different angles $\theta_C$. The measure device used is shown in figure 9.

![Figure 9 Test device for copper bead gravity valve](image)

The test results are shown in figure 10. The results show that with the increase of angle $\theta_C$, when $\theta_C$ is near the $25^\circ$, the flow rate of copper bead gravity valve drops sharply. When $\theta_C > 25^\circ$, there exists an angle range, in which the flow is low and less than 2ml / s. In this range, the copper bead falls and touches the substrate. At this time, the copper bead fully touches the substrate, so the gravity valve is also in the closed state, and the flow rate through the gravity valve is lowest. That is, the leakage rate is lowest.

![Figure 10 Experimental results of copper bead gravity valve](image)

In this low flow range, the cone angle $\alpha$ is different, and the flow rate is also different. When the cone angle $\alpha$ is higher, the flow rate of gravity valve in closed state is larger, which is consistent with the conclusion of formula (6).

### 3 Modeling, simulation, and experiment of the hose gravity valve

#### 3.1 Simulation analysis of cross section shape of hose

The principle of hose gravity valve to use gravity to exert bending moment on the hose, leading to Eulerian buckling when the hose is bending and cutting off the flow, to control the flow in the pipeline. The square hose has enough space utilization when it is arranged intensively. Circular hose is the most common hose in practical application, with the advantage of small circumference of cylindrical hose under the same flow cross-section area and low-pressure loss at the bending part. The shuttle hoses can be easily collected. Since the shuttle shaped cross-section is deformed and compressed easily, which takes up less space. The shape and size of the cross-section of the hose play a decisive role in the bending moment when the buckling fracture phenomenon of the hose is used to control the flow rate of the valve. Therefore, three different cross-section shapes of hoses are designed, all of which have the same flow cross-section area without buckling. The hose sizes are shown in figure 11 and table 2. The wall thickness $w$ of the three kinds of hoses is 1mm, and the flow cross-section area without buckling cross-section area is $8.175\text{mm}^2$. 

| $\alpha$ (°) | Flow rate (ml/s) |
|-------------|------------------|
| 95          | 4.5              |
| 100         | 3.8              |
| 105         | 3.2              |
| 110         | 2.6              |

| $\theta_C$ (°) | Flow rate (ml/s) |
|---------------|------------------|
| 0             | 3                |
| 25            | 2.5              |
| 30            | 2                |
| 60            | 1.5              |

"Figure 11 and table 2. The wall thickness $w$ of the three kinds of hoses is 1mm, and the flow cross-section area without buckling cross-section area is $8.175\text{mm}^2"."
(a) Round hose

(b) Spindle hose

(c) Square hose

Figure 11 Schematic diagram of three kinds hoses

Figure 12 Stress distribution map of ABAQUS simulation results

Table 2 Hose sizes of three different cross-section shapes

|Dimension parameters| Value /mm |
|---------------------|-----------|
|l₁                   | 10.000    |
|w                    | 1.000     |
|aᵣ                   | 4.088     |
|bᵣ                   | 2.000     |
|rₑ                   | 1.613     |
|r₟                   | 5.000     |
|dᵣ                   | 4.000     |

For this gravity valve, the resistance of the valve is negatively related to the cross-section area, and the flow rate is positively related to the cross-section area. Therefore, in order to research the relationship between the flow cross-section area of the valve and the bending angle, and analyze the advantages and disadvantages of the three kinds of hoses, the bending of the three kinds of hoses is simulated and analyzed. The hose material is Ecoflex-0030 silica gel produced by Smooth-On Company. This silica gel belongs to super elastic material. So, one of the phenomenological models, the Yeoh model is used to describe the hyper elasticity of silica gel and the formula of strain energy is as follows:

$$ U = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \quad (7) $$

Where $U$ is the strain energy, and $I_1$ is the stress invariant. For this silica gel, the coefficient is $C_{10}$=1.27×10⁻² MPa, $C_{20}$=4.23×10⁻⁴ MPa, $C_{30}$=-1.45×10⁻⁶ MPa [9]. The above three different cross-section hoses are modeled. In the process of hose bending, the flow cross-section area is different, and the flow rate mainly depends on the minimum flow cross-section area. Therefore, the minimum flow cross-section area of the hose is defined as $S_m$. To facilitate the finite element analysis, a rigid rectangular support is embedded at both ends of the hose, and the inside of the rigid rectangular support is empty, shown in figure 12.

The change of the minimum $S_m$ with the bending angle $\theta_m$ is shown in figure 13. It can be seen from figure 12 and figure 13 that after buckling and then bending, the minimum flow cross-section area $S_m$ of three shapes of hoses changes greatly with the change of bending angle $\theta_m$. Among them, when the bending angle $\theta_m$ is less than 90 °, the shuttle hose $S_m$ drops fastest, and the square hose is the second. When the bending angle $\theta$ is greater than 90 °, $S_m$ of circular hose and shuttle hose decreases and is close to 0, while $S_m$ of square hose decreases slowly. For square hose, when the bending angle $\theta_m$ is in the range of 40°~90° and or 90°~180°, the minimum flow cross-section area $S_m$ of square hose has a good linear correlation with the bending angle $\theta_m$. So, the bending phenomenon of square hose can be used to control the flow cross-section area of microchannel.
However, it is not enough to only consider the minimum flow cross-section area under different bending angles \( \theta_m \). In some cases, the gravity valve is expected to be light in weight and small in size. Since the gravity valve relies on the gravity of the weight to produce the bending moment, the greater the bending angle \( \theta_m \) is, the better it is. The changes of bending angle \( \theta_m \) with the bending moment applied by the hose of three kinds of hose are shown in figure 12. Under a certain bending moment, the bending moments of circular hose and square hose are almost the same when they are bent to a certain angle. Under the same bending moment, the bending angle of the shuttle hose is 1.3 times larger than the others. So, the shuttle hose is more suitable for making gravity valve.

In practical application, it is complicated to obtain a constant bending moment for bending structure. In order to simplify the design, the hose gravity valve directly uses gravity to drive the hose to bend. The hose gravity valve is composed of substrate, hose, weight base and weight, shown in figure 15. The substrate is used to fix the valve, and the substrate can rotate vertically relative to the ground. The shuttle hose is connected between substrate and weight. The sizes of the shuttle hose are shown in table 2.

According to the size of the shuttle hose, the hose mold is made by the way of stereolithography 3D printing and use Ecoflex-0030 silica gel produced by Smooth-On Company. And 3D printing is also used to make the substrate and weight base. Among them, a hose is installed between the substrate and the weight base, and the length of the shuttle hose between the substrate and the weight base is 4mm, 5mm, 6mm, 7mm and 8mm, respectively. Then the metal weight is installed on the weight base. The weight of both the weight base and the metal weight is 8g. The experimental result chart of hose gravity valve is shown in Figure 16.

The experimental results show that with the increase of the angle \( \theta_c \), the flow rate of all the bends decreases. Except for 4mm length, under the same bending angle, the shorter the hose length is, the lower the flow rate is. The reason is gravity cannot provide enough torque to bend the gravity valve when the length of the hose is 4mm, which is too short. When the angle of gravity valve is less than 75°, with the decrease of bending angle, the gap of the flow rate for these hose gravity valves decreases, because the effect of hose bending on flow rate is reduced, while the effect of hose length on resistance is increased. Among them, when the bending angle of the gravity valve with 5mm length hose is greater than or equal to 75°, the flow through the valve is always close to 0. It shows that the gravity valve with 5 mm hose length has better flow rate control performance.

### 3.2 The experiment and analysis of hose gravity valve
4 Comparison and application of the two gravity valves

4.1 Comparison of the two gravity valves

According to the conclusions above, the flow rate of copper bead gravity valve changes suddenly when it is opened and closed, and the opening and closing angles are basically symmetrical. So, the copper bead gravity valve is suitable for the fluid conveying system which needs to switch off the flow. In addition, the installation of copper bead gravity valve has no direction limitation, which can work in any direction of rotation.

When the shuttle hose gravity valve is from opened to closed, the flow rate changes slowly relatively, so it is suitable for the applications that the flow rate needs to be controlled smoothly according to the angle. And the bending direction of the shuttle hose gravity valve should be the same as its side. In practical application, one end of the hose is not fixed, so the collision should be prevented.

4.2 Application of the copper bead gravity valve

The chemical reaction self-driving rolling robot is a kind of robot that changes its center of gravity to roll. The structure and motion principle of chemical reaction self-driving rolling robot are shown in figure 17. The rolling robot is divided into six reaction chambers A ~ F. Six chambers are evenly distributed in the circumferential direction. Catalyst is placed in each chamber. The two adjacent chambers are connected through a check valve. Three non-adjacent chambers are selected to install copper bead gravity valve. When the rolling robot is placed on the horizontal plane and the angle between the fluid outlet direction of copper bead gravity valve and the plumb line is within a certain range, this valve is closed and the other valves are opened. When the reaction liquid is injected into chamber F of the rolling robot, because the one-way valve will block the flow of the reaction liquid to chamber E. At this time, the reaction liquid will flow to chamber A and then gradually fill chamber A and chamber B. After a certain amount of reaction liquid is injected, place the rolling robot on the horizontal plane. Because the center of the roller is symmetrical, the chamber filled with reaction liquid will be at the bottom under of the rolling robot, and the front liquid level and the rear liquid level are on a horizontal line, shown in figure 17.

Figure 17 Schematic diagram of chemical reaction self-driving rolling robot

After the reaction liquid is injected, when the reaction liquid touches the catalyst, the reaction will produce gas, which will separate from the liquid phase and accumulate above the liquid surface. In chamber F, because the check valve is connected between chamber F and chamber E, the fluid cannot flow from chamber F to chamber E. Therefore, a high-pressure area will be formed above the liquid level of chamber F. In chamber A, a gas phase isolation area will be formed between the catalyst and the liquid level to prevent further reaction. As a result, sustained responses only occur in chamber F. Because the gravity valve is closed in this angle range, the high-pressure area will push the reaction liquid of chamber F to flow into chamber a and then to chamber B. The front liquid level will lower and the back liquid level will rise, and the overall center of gravity of the rolling robot will shift and roll. The reaction liquid used in this experiment is hydrogen peroxide (30% by mass) and the catalyst is manganese dioxide particles. The reaction equation is:

\[
\text{H}_2\text{O}_2 \xrightarrow{\text{MnO}_2} \text{H}_2\text{O} + \text{O}_2 \uparrow
\]  

(8)

The main components of self-driving rolling robot include roller body, catalyst, check valve, pressing plate, gravity valve and cover film. The roller body is the structural foundation of the whole rolling robot, which is made by 3D printing method, shown in figure 18. Use duckbill valve as check valve. The size of duckbill valve is \(\varnothing 7.45 \text{mm} \times \varnothing 4.2 \text{mm} \times 6.86 \text{mm}\). The one-way valve is
installed in the hole between the chamber and the chamber. The one-way valve pressing plate is used to press the one-way valve for fastening and sealing. Manganese dioxide catalyst is placed in one corner of the chamber. The cover film is made of transparent TPU material, which is attached to one side of the roller body. On the one hand, the transparent cover film prevents the outflow of internal reaction liquid and gas. On the other hand, the transparent cover film is conducive to observing the internal chemical reaction of the rolling robot and the position information of the liquid surface.

Note: the arrow direction is the installation direction

Figure 18 The parts of the rolling robot

The rolling robot with the reaction liquid is placed on the platform or on the ground, and the rolling robot starts to roll. The actual motion process of rolling robot is shown in Figure 19. In 105 seconds, the rolling speed increases firstly and then decreases. The maximum rolling speed is 2°/s.

Figure 19 Motion process of the chemical reaction self-driving rolling robot

4.3 Application of the shuttle hose gravity valve

Flexible gripper is a kind of flexible pneumatic actuator driven by air pressure, which is generally used to grab irregular objects or fragile products [10]. Nowadays, the flexible bending actuator on the manipulator controls the air pressure to adjust the angle of the actuator end. To precisely control the angle of the end, a sensor should be installed at the end as feedback. If the flexible bending actuator is expected to change the angle at the head, and the angle at the end can be kept stable to achieve the effect of "pan tilt" [11], the hose gravity valve at the end of the flexible bending actuator can be installed and its principle is shown in figure 20. As the flexible actuator, the larger the bending angle is, the larger the pressure is. A gravity valve is installed at the end of the bending actuator. When gas is poured into the head of the bent actuator at the constant pressure, the bent actuator will bend. Meanwhile the angle of the head of the bending actuator is δ1, and the angle of the end is γ1 and the shuttle hose gravity valve at the end is at θm = 180° – γ1, which is state 1. When the head end angle δ1 decreases to δ2, if the flow through the gravity valve does not change, the end angle γ1 will also increase to γ2, and the bending actuator is in state 2. However, the increase of the end angle will reduce θm. At this time, the flow rate through the gravity valve will decrease, the pressure inside the bending actuator will increase, and the bending angle of the bending actuator will increase. At this time, the end angle γ2 will decrease to γ3. Therefore, when the shuttle hose gravity valve is installed at the end of the bending actuator, the end angle γ can be kept relatively constant.

Figure 20 The change of the end angle for the bending actuator

Note1: Assumed gravity valve don’t become deformed and the flow rate isn’t changed
Note2: As the flow rate of gravity valve decreases, the pressure inside the actuator increases and the bending angle of actuator increases

To verify this phenomenon, two identical bending actuators are fabricated using silica gel. The shuttle hose gravity valve is installed at the end of the flexible bending actuator A. The outlet of the bending actuator A is connected to the outlet of the shuttle hose gravity valve. The same gravity valve is installed at the end of the bending actuator B. However, the outlet of the bending actuator B is connected to the atmosphere, shown in Figure 21.
The heads of the two bending actuators are installed on an iron stand. The air pressure of 40 kPa is applied to the inlet of the two flexible bending actuators. When the head angle $\delta$ changed, the change of the end angle $\gamma$ can be observed, shown in figure 22. When the head angle $\delta$ changes in the range of 20° to 65°, the end angle $\gamma$ of the flexible actuator A changes about 5° and the end angle $\gamma$ of the flexible actuator B changes about 25°.

**Figure 21** The bending actuator with the shuttle hose gravity valve

**Figure 22** Experimental results of the flexible bending actuators

5 Conclusions

(1) According to the characteristics that the flow rate of gravity valve changes with its angle, two kinds of gravity valves are designed, which are copper bead gravity valve and hose gravity valve. The mathematical model of the copper bead gravity valve is established, and the stress distribution on the touched surface between the copper bead and the substrate is analyzed by FEA. Through the experiment of copper bead gravity valve with different cone angle, the optimized cone angle 95° is obtained.

(2) Based on FEA of circular, shuttle and square hose, it is concluded that the bending moment of shuttle hose is minimum and the flow rate is easy to control. The shuttle hose gravity valves with 4 mm-8 mm are made, and the flow rate through the valve at different angles $\theta_c$ is measured and analyzed.

(3) A chemical reaction self-driving rolling robot is designed. The copper bead gravity valve is used as the flow rate control part of each chamber in the rolling robot, and the rolling speed of the robot is 2°/s in the experiments.

(4) The shuttle hose gravity valve is applied to stabilize the end of the bending actuator. Compared with the bending actuator without usage of the hose gravity valve, the end angle of the bending actuator with the hose gravity valve can be kept relatively constantly. As an integral part of sensing and control, both of above gravity values realize the mechanical feedback loop, which simplifies the system design and is suitable for the application of controlling the flow rate using its angle.

6 Declaration

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Availability of data and materials
The datasets supporting the conclusions of this article are included within the article.

Authors’ contributions
The author’s contributions: Writing-original draft, Writing-review & editing, Yuan Yu, Huaisong Wu, Youzhi Liu; Investigation, Yuan Yu and Youzhi Liu; Methodology, Yuan Yu, Weiming Yang and Zhiwei Jiao; Validation, Huaisong Wu; Formal analysis, Yuan Yu, Huaisong Wu and Zhiwei Jiao. All authors have read and agreed to the published version of the manuscript.

Competing interests
The authors declare no competing financial interests.

Consent for publication
Not applicable

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Not applicable

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