Support and Positioning Mechanism of a Detection Robot inside a Spherical Tank

Chunlei Tu1,2*, Shanshan Jin1, Kai Zheng2, Xingsong Wang1 and Sichong Sun3

Abstract
Large pressure equipment needs to be tested regularly to ensure safe operation; wall-climbing robots can carry the necessary tools to inspect spherical tanks, such as cameras and non-destructive testing equipment. However, a wall-climbing robot inside a spherical tank cannot be accurately positioned owing to the particularity of the spherical tank structure. This paper proposes a passive support and positioning mechanism fixed in a spherical tank to improve the adsorption capacity and positioning accuracy of the inspection robot. The main body of the mechanism was designed as a truss composed of carbon fiber telescopic rods and can work in spherical tanks with diameters of 4.6–15.7 m. The structural strength, stiffness, and stability of the mechanism are analyzed via force and deformation simulations. By constructing a mathematical model of the support and positioning mechanism, the influence of structural deformation on the supporting capacity is analyzed and calculated. The robot positioning method based on the support and positioning mechanism can effectively locate the robot inside a spherical tank. Experiments verified the support performance and robot positioning accuracy of the mechanism. This research proposes an auxiliary support and positioning mechanism for a detection robot inside a spherical tank, which can effectively improve the positioning accuracy of the robot and meet the robotic inspection requirements.

Keywords: Support mechanism, Inspection of the spherical tank, Ansys simulation, Robot positioning

1 Introduction
Spherical tanks are sealed containers for storing liquids or gases. To ensure their safety, regular maintenance is required. At present, regular maintenance usually utilizes the scaffolding method inside the spherical tank. Some research institutions have developed dedicated manned workbenches for the internal maintenance of spherical tanks. However, these methods require manual detection and maintenance, which are inefficient and safe. Therefore, the wall-climbing robot has become a research hotspot in the field of automatic inspection of spherical tanks.

The adsorption capacity is the basic ability of wall-climbing robots. At present, a variety of adsorption methods have been applied to wall-climbing robots, mainly including negative pressure adsorption [1–6], permanent magnet adsorption [7–15], thrust adsorption [16, 17], and bionic adsorption [18, 19].

Wall-climbing robots based on negative pressure adsorption are usually large and structurally complex, impeding adaptation to complex environments. Bionic wall-climbing robots imitate insects and reptiles to achieve wall-climbing but cannot currently meet the requirements of engineering applications. The adsorption capacity of the thrust adsorption robots is not affected by the conditions of the wall surface but the existing thrust adsorption robots usually use propellers or fans, which are large and consume significant energy. Magnetic adsorption robots use permanent magnets or magnetic wheels to climb on a metal wall; these have the advantages of strong adsorption, simple structure, and energy-efficiency.

The appropriate adsorption method should be selected according to the working environment. For the inspection of large metal equipment, such as spherical tanks,
the permanent magnet adsorption robots can adsorb sta-

bly but some influencing factors, such as rusts and welds,
affect the adsorption capacity and the inspection robot
for spherical tanks requires a more flexible and stable
structure.

There are many forms of permanent magnet wall-

climbing robots, such as magnetic-wheels climbing
robots [20–23], crawler climbing robots [24–27], and
omnidirectional-wheels climbing robots [28–31]. Wall-
climbing robots by permanent magnet adsorption can
be effectively used in bridges and ships for inspection
operations.

We have designed a variety of wall-climbing robots in

Refs. [32–35], which can effectively climb on the surface
of spherical tanks. Common positioning methods, such
as GPS, gyroscope, and machine vision, have poor posi-
tioning accuracy for the robot owing to the structural
particularity of the spherical tanks. This paper proposes
a spherical coordinate passive support mechanism fixed
to a spherical tank. The mechanism is connected to the
wall-climbing robot and provides thrust to the robot
via a pre-tightening force. It does not need to consume
electric energy and the thrust is not affected by rust or
weld height. Thus, the adsorption capacity of the robot
was enhanced. Furthermore, since the support mecha-
nism is driven by the robot, there is no need for com-

plicated control to ensure the mechanism follows the
robot’s movement. Moreover, the position of the robot
can be measured by detecting the attitude of the support
mechanism.

The remainder of this paper is organized as follows. In
Section 2, the structure of the support mechanism and
static analysis are presented. In Section 3, the mathemati-
cal models of the support mechanism are proposed, with
force analysis. In Section 4, the robot positioning scheme
based on the mechanism is presented. Experiments on
the support and positioning mechanism are presented in
Section 5. Finally, conclusions and future work are dis-
cussed in Section 6.

2 Design of the Support Mechanism
2.1 Overall Structural Plan

Figure 1 describes how the support mechanism works
inside a spherical tank. The column of the support mecha-
nism is fixed at the spherical tank and the end of the
cantilever is elastically connected with the wall-climbing
robot and has a rotational degree of freedom.

The column and cantilever are connected via two rotat-
ing pairs and the intersection point of the axes of the
two rotating pairs is located at the center of the spherical
tank. The support mechanism is purely passive. The can-
tilever is driven by the wall-climbing robot and provides
continuous thrust to the robot.

The support mechanism designed in this study can pro-
vide 450 N thrust, the cantilever mass does not exceed
8 kg, and the total weight does not exceed 25 kg. It can
adapt to a spherical tank with a volume of 50–2000 m³
(corresponding to a diameter of 4.6–15.7 m).

2.2 Structural Design

The overall structural model of the support mechanism is
shown in Figure 2. It mainly comprises a cantilever, a col-
umn, an elastic pressing mechanism, a supporting base,
and a two-degree-of-freedom rotating platform.

The elastic pressing mechanism is at the end of the
cantilever and is connected to the climbing wall robot.
Its main body is a spring, which can adapt to the slight
deformation of the support mechanism during the work-
ing process. Simultaneously, adjusting the compression
of the spring can change the thrust value. It has a rotation
pair at the end so that the robot can adjust its attitude
arbitrarily, without the cantilever rotating.

The supporting base is composed of aluminum alloy
profiles. As shown in Figure 3, it is bolted to a series of
threaded holes in the manhole flange of the spherical
tank so that the entire mechanism is fixed to the spheri-
cal tank.

The two-degree-of-freedom rotating platform connects
the column and cantilever. As shown in Figure 4, it has
two rotating degrees of freedom. Two laser rangefinders
are installed on the platform to measure the length of the
cantilever and column and two angle sensors are used
to detect the rotation angles. According to the value of
these sensors, the support mechanism can be installed in
the correct position quickly and accurately. The sensors
also provide a basis for robot localization.
The cantilever and column of the support mechanism are retractable trusses. The main body is composed of carbon fiber telescopic rods and aluminum alloy cross-bars. The telescopic rods are connected by an expansion connection mechanism. Through relative rotation between the rods, the telescopic rods are locked and released. When folding, the mechanism can be transported into the tank through manholes. After expansion, the support mechanism can adapt to a spherical tank with a volume of $50\text{–}2000\ \text{m}^3$, according to the different expansion sizes.

### 2.3 Statics Simulation

The mechanical properties of the mechanism, such as rigidity, are required to be great. To perform a static analysis of the mechanism, a force analysis is first conducted. As shown in Figure 5, AB and BD represent the cantilever and column, respectively, and C and C$_3$ are their barycenters. $\alpha$ is the angle between the cantilever and the vertical direction. The force balance equation of the cantilever and column can be written as:

$$
\begin{align*}
F'_{AT} \cos \alpha + F'_{AN} \sin \alpha &= F_{BX}, \\
F'_{AT} \sin \alpha + F_{BY} &= G_2 + F'_{AN} \cos \alpha, \\
M_B &= G_2 L_{BC} \sin \alpha - F'_{AT} L_{AB} = 0,
\end{align*}
$$

(1)
where $G_2$ and $G_3$ are the gravity of the cantilever and column, respectively, and according to the design index, $G_2 \leq 80$N.

$M_D$ is the torque on the terminal position. $L_{BC}$, $L_{AB}$, and $L_{BD}$ indicate the length of the corresponding lines, and when working inside a spherical tank with a diameter of 15.7 m, $L_{AB} = L_{BD} = 7.85$ m.

According to the design index, the support mechanism needs to provide 450 N thrust; thus, $F'_{AN} = 450$ N, which can be substituted into Eq. (1) and Eq. (2). The calculation result indicates that the bending moments of the column and cantilever are largest when the cantilever is horizontal ($\alpha = 90^\circ$). This is the most dangerous situation and the force values are solved as: $F'_{AT} = 40$ N, $F_{BX} = 450$ N, $F_{BY} = 40$ N. Thus, the static simulation will be performed on the model when the cantilever is horizontal.

The column and cantilever models were established in ANSYS with maximum expansion size and analyzed to solve the deformation condition. Figures 6 and 7 show the deformation curves. The simulation results are listed in Table 1.

| Component | Maximum axial deformation (mm) | Maximum tangential deformation (mm) | Maximum axial stress (MPa) | Maximum shear stress (MPa) |
|-----------|-------------------------------|-------------------------------------|--------------------------|---------------------------|
| Column    | 0.0503                        | 24.59                               | 41.17                    | 26.75                     |
| Cantilever| 0.0752                        | 2.908                               | 4.05                     | 3.48                      |

\[
\begin{align*}
\sum F_X &= F'_{BX} - F_{DX} = 0, \\
\sum F_Y &= F_{DY} - F'_{BY} - G_3 = 0, \\
\sum M &= M_D - F_{BX}L_{BD} = 0,
\end{align*}
\]  

\[(2)\]

where $G_2$ and $G_3$ are the gravity of the cantilever and column, respectively, and according to the design index, $G_2 \leq 80$N.

According to the results, the maximum stresses are much smaller than the allowable stress so the column and cantilever meet the strength requirement. For further analysis, eigenvalue buckling analysis is performed to confirm whether the column and cantilever are unstable under the working condition. The simulation results show that the critical loads of the first-order eigenvalue buckling of the column and the cantilever are 895.48 N and 8778.6 N, respectively, which are greater than the working load (450 N). Therefore, the structure satisfies the stability requirements.

### 3 Analysis of Support Performance

The thrust of the robot is provided by the preload generated when the support mechanism is installed. However, when the robot is in different positions, the force of the mechanism is different, resulting in different deformation of the support mechanism. This deformation will affect the spring compression amount and result in the change in thrust. Therefore, it is necessary to establish a mathematical model to analyze the impact of the deformation of the support mechanism on the thrust.

First, the thrust that maintains a 20 kg robot without slipping and overturning is calculated. Figure 8 shows the force of the robot when the adsorption force results from the thrust of the support mechanism. The simulation results show that the critical loads of the first-order eigenvalue buckling of the column and the cantilever are 895.48 N and 8778.6 N, respectively, which are greater than the working load (450 N). Therefore, the structure satisfies the stability requirements.

When the robot does not slip, the forces satisfy:

\[
\begin{align*}
F_{AN} &= F_{N1} + F_{N2} + G_r \cos \alpha, \\
F_{AT} + G_r \sin \alpha &\leq F_{f1} + F_{f2}, \\
F_{f1} &= \mu F_{N1}; F_{f2} = \mu F_{N2}.
\end{align*}
\]  

\[(3)\]
The following equation can be obtained according to Figure 5:

\[ F_{AT} = F'_{AT} = G_2 \sin \alpha \frac{L_{BC}}{L_{AB}}. \]  

(4)

Substituting Eq. (4) into Eq. (3) yields:

\[ F_{AN} \geq \frac{1}{\mu} \left( G_2 \frac{L_{BC}}{L_{AB}} + G_r \right) \sin \alpha + G_r \cos \alpha. \]  

(5)

Therefore, the thrust that maintains the robot without slipping at various positions satisfies the following equation:

\[ F_{AN} \geq \left( \frac{1}{\mu} \left( G_2 \frac{L_{BC}}{L_{AB}} + G_r \right) \sin \alpha + G_r \cos \alpha \right)_{\text{max}} \]

\[ = \sqrt{\left( \frac{1}{\mu} \left( G_2 \frac{L_{BC}}{L_{AB}} + G_r \right) \right)^2 + G_r^2}. \]  

(6)

The result is 447.12 N after the relevant value substitutions.

When the robot does not rotate around the contact point (A2) between its rear wheel and the wall, the torque about A2 satisfies:

\[ M_{A2} = \frac{L}{2} F_{AN} - L F_{N1} - \frac{L}{2} G_r \cos \alpha - h G_r \sin \alpha - H F_{AT} \geq 0. \]  

(7)

According to the above analysis, if the support mechanism can provide a supporting force of over 450 N, a robot with a mass of less than 20 kg will not slide or capsize in any position inside the spherical tank.

Figure 9 illustrates the deformation model of the support mechanism where point A is the connection point between the support mechanism and the robot. BD represents the initial state of the column and point B is at the center of the tank. B'D represents the column with deformation and BB' describes the deformation quantity. BB' is assumed to be horizontal as the deformation mainly occurs in the horizontal direction. Then, each length can be written as:

\[ l_{AB} = R - h_r, \]  

(8)

\[ l_{AB'} = l_k - d{l}_k + l_x - d{l}_x, \]  

(9)

\[ l_{BB'} = d{l}_s, \]  

(10)

where \( d{l}_k \) is the compressed length of the spring. \( d{l}_x \) is the axial deformation of the cantilever under the working pressure. \( d{l}_s \) represents the horizontal deformation of the column. These are calculated as follows:

\[ d{l}_k = \frac{F_{AN}}{k}, \]  

(11)

\[ d{l}_x = \frac{F_{AN}}{k_x}, \]  

(12)

\[ d{l}_s = \frac{F_{BN}}{k_s}, \]  

(13)

and, from \( \triangle ABB' \), the following is satisfied:

\[ l_{AB}^2 = l_{AB'}^2 + l_{BB'}^2 - 2 \times l_{AB'} \times l_{BB'} \times \cos(90 - \alpha). \]  

(14)

The meanings and values of these symbols are listed in Table 3.
According to Eq. (2), the horizontal force on the column $F_{BX}$ can be expressed as:

$$F_{BX} = G \frac{L_{BC}}{L_{AB}} \sin \alpha \cos \alpha + F_{AN} \sin \alpha. \quad (15)$$

Substituting the values mentioned above into Eq. (14), the following can be derived:

$$R - h_r = l_k - \frac{F_{AN}}{k} + l_x - \frac{F_{AN}}{k_x} \left\{ \left( G \frac{L_{BC}}{L_{AB}} \sin \alpha \cos \alpha + \frac{F_{AN}}{k} \sin \alpha \right) \frac{l_k}{k} + l_x - \frac{F_{AN}}{k_x} \right\} - 2 \times \left( l_k - \frac{F_{AN}}{k} + l_x - \frac{F_{AN}}{k_x} \right) \times (G \frac{L_{BC}}{L_{AB}} \sin \alpha \cos \alpha + \frac{F_{AN}}{k} \sin \alpha) \times \sin \alpha \quad (16)$$

Eq. (16) describes how the thrust provided by the support mechanism varies with angle $\alpha$ as the support mechanism deforms. This value is related to $l_x$, the initial length of the cantilever.

The mechanism should be able to pass smoothly through all points of the tank; the initial condition is set such that when the cantilever is vertical the mechanism has no deformation in the horizontal direction; i.e., $dl_x = 0$ when $\alpha = 0^\circ$. According to Eq. (16), the following can be deduced:

$$R - h_r = l_k - \frac{F_{AN}}{k} + l_x - \frac{F_{AN}}{k_x}. \quad (17)$$

Given the initial axial force $F_{AN} = 700$ N, the initial length of the cantilever is solved as $l_x = 7534.5$ mm.

Substituting the value of $l_x$ into Eq. (16), the curve of the thrust $F_{AN}$ with the cantilever angle $2\alpha$ is solved, as shown in Figure 10. Thus, considering the deformation, the thrust provided by the support mechanism is still over 450 N, which satisfies the design objective. Additionally, Figure 11 shows the curve of the horizontal forces on column $F_{BX}$ with a cantilever angle $2\alpha$. It can be observed that the maximum horizontal force on the column is still around 450 N, which is smaller than the critical load (895.48 N). Hence, the deformation of the column must be within the linear range and no structural instability will occur.

From this analysis, it can be seen that, although the deformation of the support mechanism is inevitable, by adjusting the initial length of the cantilever and changing the compression amount of the spring, the mechanism can still provide sufficient force to ensure stable adsorption for the robot with certain geometric deformation.

4 Robot Positioning Method

The support mechanism is a spherical coordinate-type mechanism. The length of the mechanism is fixed and the points reached by the end of the cantilever constitute a spherical surface. Therefore, the positioning problem of the robot is converted into the position solution at the end of the support mechanism. The mathematical model is shown in Figure 12, where Point A represents the position of the robot and lines AB and BD represent the cantilever and the column.

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**Table 3 Equation parameters**

| Parameter                              | Value     |
|----------------------------------------|-----------|
| Radius of the working spherical tank R | 7850 mm   |
| Height of the robot $h_r$             | 180 mm    |
| Initial length of the spring $l_k$    | 270 mm    |
| Initial length of the cantilever $l_x$| –         |
| Axial stiffness of the cantilever $k_x$| 5984.04 N/mm |
| Horizontal stiffness of the column $k_x$| 18.3 N/mm  |
| Spring stiffness $k$                  | 10 N/mm   |

---

**Figure 10** Thrust $F_{AN}$ under mechanism deformation

**Figure 11** The horizontal forces on the column $F_{BX}$ under mechanism deformation
respectively. Thus, the three-dimensional position coordinates of the robot can be expressed as follows:

\[
\begin{align*}
    x &= R \times \sin \alpha \times \cos \theta, \\
    y &= R \times \sin \alpha \times \sin \theta, \\
    z &= R \times \cos \alpha. 
\end{align*}
\]  

By detecting the value of \((R, \alpha, \theta)\), the robot at the end of the cantilever can be directly positioned and its absolute coordinate position inside the spherical tank can be calculated.

The positioning method can be realized using two laser range finders and two angular displacement sensors. Angle sensor 1 directly measures the rotation angle of the pitch axis. Owing to size limitations, the rotation range is \((-50^\circ\sim 90^\circ)\), corresponding to \(\alpha\) from \(140^\circ\) to \(0^\circ\). Angle sensor 2 indirectly detects the rotation angle of the rotating axis through a pair of gears with a gear ratio of 50/100 and the rotation ranges from 0 to 360°, corresponding to \(\theta\) from 0 to 360°.

Therefore, through the two sets of sensors, the absolute coordinate position of the robot can be obtained and the measurement space satisfies the following constraints:

\[
\begin{align*}
    \theta &\in [0, 360^\circ), \\
    \alpha &\in [0, 140^\circ], \\
    R &\in [2.3, 7.85].
\end{align*}
\]

As shown in Figure 13, the space between the two hemispherical surfaces is the actual measurement space of the support mechanism.

5 Experiments

As shown in Figure 14, the prototype of the support mechanism was developed.
5.1 Support Capability Testing
To detect the pressure exerted by the support mechanism on the wall surface, a pressure sensor is connected at the end of the cantilever, as shown in Figure 15. By adding the initial compression of the spring and the initial length of the cantilever, different pressures can be detected. The maximum pressure value measured in the experiment was approximately 280 N. To prevent the support mechanism from capsizing or moving, the pressure value will not continue to increase. At this time, there is no obvious deformation of the support mechanism. The experimental results show that the support mechanism can bear a certain supporting force and the supporting force is adjustable within a certain range. The test results demonstrate that the mechanism can satisfy the requirements of stability and safety.

5.2 Positioning Accuracy Testing
The support mechanism is designed for a spherical tank; however, when the length of the cantilever is variable, the arbitrary position in the reachable space of the cantilever can be solved. As shown in Figure 16, when the columns of the support mechanism are located on the centerline of the cylinder, the coordinates of any point on cylinder $A(x, y, z)$ can be expressed as:

$$
\begin{align*}
  x &= l_{AB} \times \sin \alpha \times \cos \theta, \\
  y &= l_{AB} \times \sin \alpha \times \sin \theta, \\
  z &= l_{BD} + l_{AB} \times \cos \alpha.
\end{align*}
$$

(20)

The coordinates can also be determined by its height $h$ and circumference $l$. The relation is satisfied as:

$$
\begin{align*}
  h &= l_{BD} + l_{AB} \times \cos \alpha, \\
  l &= R \times (\theta - \theta_0),
\end{align*}
$$

(21)

where $\theta_0$ is the initial rotation angle.

To test the positioning accuracy of the support mechanism, 20 points on the surface of the cylindrical tank were measured by the support mechanism. The result is shown in Figure 17.

The average errors of the height and circumference are 3.34 cm and 1.23 cm, respectively, and the average errors of the two rotation angles are 0.995° and 0.329°. The two angle sensors are the same; however, because angle sensor 2 transmits from the rotation shaft by gear, the measurement precision of rotation angle 2 is improved. As a result, the height of the points in the system for the cylindrical tank has a much greater error than the perimeter.

5.3 Comprehensive Testing
As shown in Figure 18, the support mechanism is connected to a magnetic adsorption robot. The robot moves along the circumference and the support mechanism calculates the trajectory of the robot, as shown in Figure 19. The results indicate that the support mechanism can locate the position of the robot in real-time.
6 Conclusions

(1) In response to the positioning requirements of the spherical tank wall-climbing robot, we proposed a telescopic passive support and positioning mechanism and simulated and analyzed the mechanism deformation.

(2) The force analysis of the supporting and positioning mechanism indicates that the mechanism can provide sufficient force to ensure stable adsorption of the wall-climbing robot.

(3) The mechanism can effectively locate the climbing robot on the inner surface of the spherical tank.

(4) Experiments indicate that the support and positioning mechanism for the wall-climbing robot has sufficient support capability and the positioning accuracy can meet the operational requirements.

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Authors’ contributions
CT was in charge of the whole trial; SJ and XW wrote the manuscript; KZ and SS assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

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Competing Interests
The authors declare no competing financial interests.

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