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A Wheel-leg Hybrid Wall Climbing Robot with Multi-surface Locomotion Ability

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***Abstract*— A prototype of wheel-leg hybrid mobile robot that can move on both ground and wall surfaces is presented, which could be used for special tasks such as rescue, inspection, surveillance and reconnaissance. The wheel-leg hybrid locomotion mechanism enable the robot to achieve quick motion on wall surface, as well as obstacle- spanning on wall surfaces and smooth wall-to-wall transitions. And the wheel lifting mechanism enables the robot to move on both wall surfaces and ground. The robot is composed of a base body and a mechanical leg with 3 DOF. The base body is a big flat suction cup with three-wheeled locomotion mechanism inside, and there is a small flat sucker in the end of the mechanical leg. The new designed chamber seal has simple structure and has steady and reliable performance. A distributed embedded control system is also described which enable the robot operating manually and semi-autonomously in wheeled motion mode or legged motion mode. Kinematics model of the robot is established to analyze the robot's motion on the wall. And the locomotion gait of the robot is discussed. Experiments show that the robot can adhere on wall surface and realize the basic movements.**

I. Introduction

In resent years, mobile robots used for special tasks such as rescue, inspection, surveillance and reconnaissance have been studied hotly. For example, Urban robot from iRobot, Inc, US [1], Teodor from Telerob, Germany [2], Cyclops from AB Precision, UK [3], and so on. Not only mobile robots on ground, but also robots that can climb wall surfaces are developed for these missions. For example, NINJA developed by Tokyo Institute of Technology [4]. ROBUG II developed by Portsmouth Polytechnic [5]. Biped robot designed by Michigan State University [7]. And a single cup wall climbing robot developed by City College of New York [8]. These wall-climbing robots which can climb and move on vertical surfaces have wider working space than ground mobile robots. They can give people more help in vertical surfaces like outer wall surfaces of high structures to execute hazardous missions. So that, mobile robot with wall climbing ability receives high attention to be studied for these dangerous tasks in recent years.

Motion space is a key item for the robot's application. So, locomotion mechanics is one of the main problems for the developing of mobile robots. These dangerous tasks need robot have the ability to moving on as more surfaces as possible including ground surfaces, wall surfaces and other inclined surfaces, which can guarantee the robot able to carry out more missions. And mobility is also an important factor for robot's capability, high mobility and moving speed can enable robot to have high efficiency. Wheeled wall climbing robot has high moving speed, but it needs special equipment to carry it onto wall surfaces, which affect its agility. Legged wall climbing robots like biped robot, quadruped robot, etc, can transit between ground and wall surface and climb over obstacles on surfaces. These robots have more adjustability to working surface, but their moving speed is low. Therefore, mobile robot that has both the advantages of wheeled robot and legged robot is an ideal approach for the hazard missions, because it could have excellent surface adjustability and high moving speed.

Besides, wall climbing robots developed previously are always concerned for certain application in certain situation, such as maintaining nuclear facilities, inspection of stage tanks, cleaning high-rise building, painting, and they always have big body, high weight, and low agility [9-16]. Whereas, tasks as rescue, reconnaissance, etc, demand the robot have small size, low weight, high mobility and maneuverability. Technologies used in the previous wall-climb robots cannot meet the need of these new special tasks. So, new prototypes of self-contained wall-climbing robot need to be developed for these tasks [5-8].

In this paper, a new type of mobile robot with wheel-leg hybrid locomotion mechanism is proposed, which integrates the advantages of wheeled robots and legged robots. It can achieve quick motion as well as obstacle- spanning on wall surfaces, and even smooth wall-to-wall transition. And this robot adopts a lifting mechanism for the wheel mechanism to adjust the height of the robot's frame, which enable the robot to work on both ground and wall surfaces. Vacuum adhesion mechanism is used to be adaptive to versatile surfaces.

In section II, mechanical design of the robot is present. In section III, locomotion on ground and wall surfaces is analyzed, and kinematical model of the robot is discussed. In section IV, robot's control system is introduced. In section V, experiment of the robot is presented. And conclusions are

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made and future works are prospected in section VI.

II. Mechanical Design of Robot

Development of this mobile robot is to be used in ground and wall surfaces to carry out missions such as reconnaissance, surveillance. In order to be competent for the needs, aim of this new prototype of mobile robot is to construct a robot that can achieve quick motion to guarantee high efficiency and transition between ground and wall, as well as adjustability to complex terrain. To achieve the purpose, a combination locomotion mechanism of wheeled mechanism and legged mechanism is adopted. In this robot, wheeled mechanism is assigned as a mobile base, and legged mechanism added to it which can realize movement like other biped robots. Hence a wheel-leg hybrid locomotion mechanism is constructed

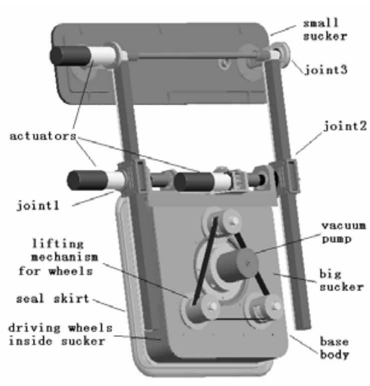


Fig. 1. Outlook of the novel wall climbing robot.

Configuration of the robot is shown in Fig. 1. The mobile base is composed of a big suction cup and a 3-wheel mechanism. The big suction cup forms a vacuum chamber by vacuum pump to generate adhesion force pressing the robot onto wall surface. The wheeled locomotion mechanism is fixed inside the big vacuum sucker. 3-wheel mechanism with two driving wheels and a castor wheel is used, because of its advantage in moving stability. In this way, the wheeled locomotion mechanism could work with the robot's sticking on surface.

There are always two suckers equipped in each foot for biped robot. In order to realize biped robot's moving forwards, backwards, and turning movements, they always have no less than four Degree of Freedom. Here, the wheeled locomotion mechanism has the ability to turn the orientation of the robot, so that the climbing mechanism only needs to have three DOF. Assignment of the wheeled locomotion mechanism is to drive robot to realize omni-orientation movement. On the other hand, assignment of the climbing mechanism is to transit between ground and wall surfaces and step over obstacles.

The biped configuration is realized by two rotational joints (joint 1 and joint 3) and a translational joint (joint 2). The translational joint is realized by rack and pinion mechanism driven by a DC motor. As shown in Fig. 1, there are two suction cups in the two ends, one is the big suction cup in the base body and the other one is at the tip of link3. The flat sucker is also a vacuum sucker equipping a small vacuum pump. The flat sucker and the big suction cup at the base body woke as the two pad of the biped configuration.

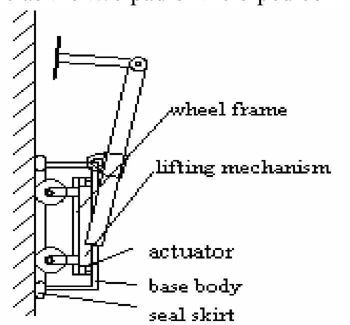


Fig. 2. Sketch of lifting mechanism for wheels.

Aim of the robot is to work on both wall surfaces and ground, so the robot should satisfy some needs of the robot's movement in the two conditions. The biped configuration let the robot could do transiting movement between ground and vertical surfaces. When the wheeled mechanism works to drive the robot moving on wall surfaces, the seal skirt needs to contact surface to seal the vacuum chamber inside the big suction cup, but when the robot work on ground, the seal skirt could not contact ground surface to keep from abrasion. So a lifting mechanism is introduced in to the design of the robot. As shown in Fig. 2, the lifting mechanism adds a DOF to the wheel mechanism. It can adjust the distance between the wheel frame and the robot's base body, which determines the distance between the seal skirt and surface. When robot works on wall surfaces, the lifting mechanism reduces the height of the base body to press the seal skirt against wall surface. And it can also give adjusting function for the sealing affect by adjust the distance. When robot works on ground, the wheel lifting mechanism raise the base body to separate seal skirt from contacting with surface.

The hybrid locomotion mechanism enables the robot to be able to move with high speed on smooth surfaces as well as step over obstacles such as protuberances, gaps on ground or wall surfaces.

Adhesion mechanisms used in the past mainly include magnetic devices, vacuum adhesion technique, propeller forces and even dry adhesion materials [9,18,19,20]. In order to enable the robot to adapt to versatile surfaces, negative air pressure adhesion technique is chosen, because this method can suit walls such as ceramic tile, glass, cement and brick walls [6,7,8,17].

When the robot moves on wall surface with wheeled motion mode, the adhesion fore generated by the big sucker should be keep in a certain degree. So, a flexible seal skirt is designed. The flexible sealing skirt could fill the gap between chamber and the wall surface to keep vacuum degree inside the sucker, so that the robot could receive a certain adhesion force to keep it on wall surface while wheeled mechanism is moving. On the other hand, smooth fabric outside the sealing skirt has small friction with surfaces, which could reduce energy consumption of the robot.

Specifications of the robot are shown in TABLE I.

TABLE I
SPECIFICATIONS OF THE ROBOT

Parameters	Value	Unit
Mass of robot	10	Kg
Size of base body (big sucker)	300X300X85	Mm^3
Size of small sucker	150X450X3	Mm^3
Speed of wheeled mechanism	10	m/min
Speed of legged mechanism (time to step over a ledge)	<12	s
Load capacity of big sucker	40	kg
Load capacity of small sucker	30	kg

III. LOCOMOTION AND KINEMATICS OF THE ROBOT

As the robot is designed for use on both ground terrain and wall surfaces, its locomotion can be discussed in three conditions, including motion on ground, motion on wall surface, and transition motion between ground and wall. Besides, the wheel-leg hybrid locomotion mechanism enables the robot to have two motion modes: wheeled motion mode and legged motion mode, which improves the robot's mobility evidently. The wheeled locomotion mechanism is used to realize high speed movement. And the legged mechanism is used to step over obstacles and transit between ground and wall surfaces.

A. Motion on ground terrain

When the robot works on ground terrain, it works like a normal wheeled mobile robot. The robot's lifting mechanism for the wheel mechanism raises the base body, and the seal skirt depart from touching with ground, as shown in Fig. 3. In Fig. 4, the model of robot's steering motion is illustrated. The differential driving wheels drive the robot to move. If the robot is operated to turn left or right, the two driving wheels (A and B) are controlled in different speed respectively by embedded motion controller. Wheel C is a caster, which is a used to form a triangle supporting area to keep the robot's moving stability.

Besides, in this condition the climbing mechanism could be used to carry out some missions by equipped some tools at the end of link3.

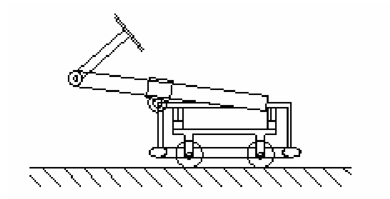


Fig. 3. Robot's movement on ground.

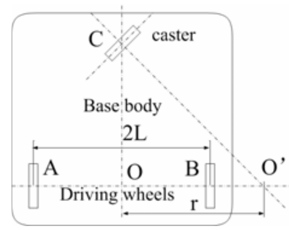


Fig. 4. Model of robot's motion on ground.

B. Transition Motion Between Ground and Wall

If the robot needs to climb a wall, the leg mechanism could be controlled to lift the robot onto wall surface.

As illustrated in Fig. 6, transition from floor to wall is realized by a sequence of movements. The sequence can also be divided into four periods:

*1)*The robot gets close to wall surface and keep a certain distance with it, as shown in Fig. 5.1);

*2)*operate the wheel lifting mechanism to lay down the base body, as shown in Fig. 5.2);

*3)*extend the mechanical leg to place the foot on wall surface , and let the flat sucker in the foot stick on surface, as shown in Fig. 5.2);

*4)*carry the base body onto wall surface, as shown in Fig.5.3);

*5)*land base body on vertical surface, and let it stick to surface, then release the climbing leg, as shown in Fig. 5.4).

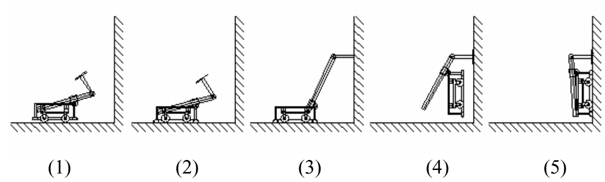


Fig. 5. Robot's movement to transit from ground to vertical surface.

C. Motion on Wall Surface

Robot's movements on wall surfaces mainly include: moving upwards, moving downwards, turning, transition to the other surface, spanning obstacles, and so on.

Among these movements, moving upwards and down wards can be realized by wheeled mechanism or climbing mechanism; turning movement is conducted by wheeled mechanism, by controlling the two driving wheels in differential way; and transition movement between surfaces and obstacle-spanning movements is realized by climbing mechanism.

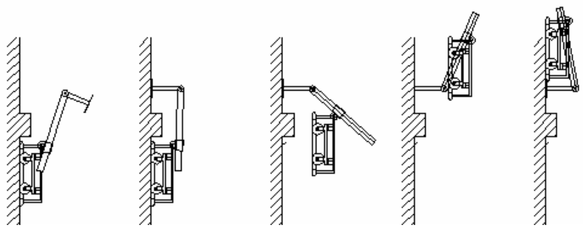
Obstacle-spanning movement of the robot can be divided into two conditions, 1) span protrude 2) span gap. As shown in Fig. 6, the movement sequence to span a ledge can be divided into four periods:

*1)*The robot gets close to the ledge, as Fig. 6.1);

*2)*extend the mechanical leg to drive it over the ledge, and let the flat sucker in the foot stick on surface, as shown in Fig. 6.2);

*3)*the three DOF mechanical leg lifts the base body over the ledge, as shown in Fig.6.3,4);

*4)*base body lands on surface, release and retract the climbing leg, as Fig. 6.5).



(1) (2) (3) (4) (5)

Fig. 6. Robot's movement to span a ledge.

Obstacles like Protrudes on wall surface always take on different shapes in section, but they could be predigested into a unique shape-rectangle. So the obstacle-spanning ability of the climbing mechanism could be expressed by the width and height of biggest rectangular obstacles that it can step over. Width and height of the obstacle can be calculated by (1),

$$w_{obstacle} = \sqrt{{d_{2\max}}^2 - (a_3 - H_1)^2} - \frac{L_{sucker}}{2} - W_1$$

$$h_{obstacle} = H_1 + W_1 \frac{a_3 - h_1}{\sqrt{{d_{2\max}}^2 - (a_3 - H_1)^2}} \tag{1}$$

Where, w_{obstacle} represents width of ledge; $h_{\text{obastacle}}$ represents height of ledge; H_1 is the height of joint 1; W_1 is the distance from axis of joint 1 to front of base body; and L_{sucker} is the length of the small sucker. Here, the width of the obstacle is the main item.

Considering that the wheel mechanism can move in 2D terrain with the movements-move forwards, move backwards, turn left, turn right, and turn with zero radius, the position and orientation of the robot's body is determined by the 3-wheel mechanism. The 3-wheel mechanism has two joint variables-rotational angles of the two driving wheels. As shown in Fig.7, coordinate of the robot's base body is established in the center of the two driving wheels' axis. r is the driving wheels' radios, and distance between the two wheels is $2L$. Position/orientation of the robot's base body can be expressed by $(x,y,\theta)^{\mathrm{T}}$, which is shown as (2).

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{r}{2} J_1(\theta, L) \begin{bmatrix} \dot{\phi}_1 \\ \dot{\phi}_2 \end{bmatrix} \tag{2}$$

$$J_1(\theta, L) = \begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ -1/L & 1/L \end{bmatrix}$$

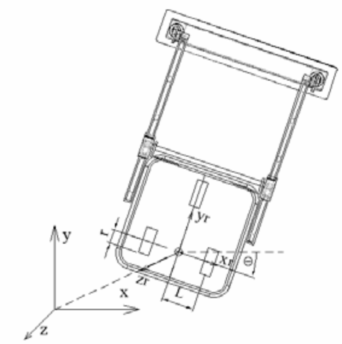


Fig. 7. Coordinates frames of the base body

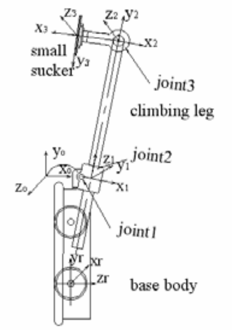


Fig. 8. Coordinates frames of the mechanical leg.

Where, Φ_1 and Φ_2 denote the two driving motors' rotational angle respectively.

Because the movement of climbing mechanism is to realize climbing movement in 2D terrain, so that kinematics of the climbing mechanism only needs to analysis the relationship between the foot of climbing leg and the base body. And the relationship could be expressed by the position/orientation of the foot to the base body, which is expressed by $(x_{03},y_{03},\varphi_{03})^T$, as in (4). Assignment of coordinate frames is illustrated in Fig. 8. The link parameters are shown in TABLE II. θ_1, d_2, and θ_3 are joint variables, and a_1 represents length of link 1, a_3 represent length of link 3.

Here, the value of the lifting mechanism for wheels is denoted by d_{lift}. As in (4), z_{r0} in ${}^{r}T_0$ is calculated by,

$$z_{r0} = z_{r0}^{'} + d_{lift} \tag{3}$$

Where, z_{r0}' is a constant value.

TABLE II

LINK COORDINATE PARAMETERS OF THE MECHANICALLEG

joint	θ_i /°	d_i /mm	a_i /mm	α_i /°	Range of joint variable
Joint1	θ_1	0	a_1=20	-90	θ_1=0~360°
Joint2	0	d_2	0	90	d_2=72~467 *mm*
Joint3	θ_3	0	a_3=95	0	θ_3=-57°~237°

$${}^{r}T_0 = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & y_{ro} \\ 1 & 0 & 0 & z_{ro} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{0}T_1 = \begin{bmatrix} C\theta_1 & 0 & -S\theta_1 & a_1 C\theta_1 \\ S\theta_1 & 0 & C\theta_1 & a_1 S\theta_1 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$
{}^{1}T_{2}=\begin{bmatrix}1&0&0&0\\0&0&-1&0\\0&1&0&d_2\\0&0&0&1\end{bmatrix},\quad {}^{2}T_{3}=\begin{bmatrix}C\theta_3&-S\theta_3&0&a_3C\theta_3\\S\theta_3&C\theta_3&0&a_3S\theta_3\\0&0&1&0\\0&0&0&1\end{bmatrix}
$$

$$
\begin{aligned}
{}^{r}T_{3}&={}^{r}T_{0}\,{}^{0}T_{1}\,{}^{1}T_{2}\,{}^{2}T_{3}\\
&=\begin{bmatrix}0&0&-1&0\\S\theta_{13}&C\theta_{13}&0&a_3S\theta_{13}+a_1S\theta_1+d_2C\theta_1+y_{r0}\\C\theta_{13}&-S\theta_{13}&0&a_3C\theta_{13}+a_1C\theta_1-d_2S\theta_1+z_{r0}\\0&0&0&1\end{bmatrix}
\end{aligned}\tag{4}
$$

IV. CONTROL SYSTEM

Control of the robot's movement is operated by operator using wireless control system. Control system of the robot is composed of controllers on the robot and remote control station on the ground, as shown in Fig. 9. Wireless communication modules are used to communicate between them. In order to be convenient for design, maintenance, and expanding of the control system, controllers on the robot is designed as a distributed control system, which includes: center controller, wheel controller, leg controller, sensors suit, and battery module. Modular design of the control system is convenient for the respective control of wheel mechanism and leg mechanism.

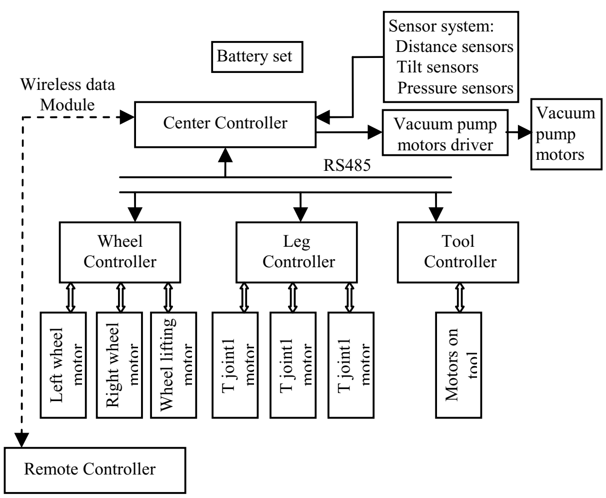


Fig. 9. Control system block diagram

High performance MCU-ATmega128 from ATMEL which have high speed performance, large volume on-board program and data memories, is very suitable for embedded control system. So it is selected as the core of every controller module.

Center controller with ATmega128 as core is assumed to control the other modules on the robot to realize robot's movements. Center controller can exchange data via RS485 protocol with the child controllers including control commands and state information of robot. And it exchanges data including commands and information with the remote control station on ground via wireless data module STR30.

Based on modular design principle, a driving control module for multi DC motors is designed, which is used for both wheel mechanism and leg mechanism. ATmega128 controls the three motors in proper way according trajectory of wheels or climbing leg to realize the needed trajectory.

Locomotion of the robot needs to obtain condition information of the robot and environments around it, so there are some sensors equipped on the robot. A 2-axis inclination sensor is used, in order to obtain real-time orientation of the robot when it moves on wall surface, which can realize angle measurement in the range of 360°. Two air pressure sensors are used to detect the pressure inside the two vacuum suckers. And infrared sensors are used to detected obstacles in the environments.

The robot can be operated both manually by telecontrol and semi-autonomously. According the command received from remote controller, the robot can be controlled in wheeled motion mode or legged motion mode.

As shown in Fig. 9, the remote control station on the ground which is a PC, gives commands to the center controller on the robot, for example move forwards, turn right, step over a ledge, step over a gap and so on. The center controller interprets these commands, and reads data from sensor system to obtain status messages of its self and information about environment. Then task level planner in center controller generates task commands that robot should conducted. Based on the task commands, trajectory planner in center controller generates a set of desired joint values for the robot's locomotion mechanism. These joint data is transferred to wheel controller or leg controller via RS485 protocol according to control commands, to drive the motors to realize robot's movements.

The assignment that wheeled mechanism and legged mechanism are controlled by two control module respectively is helpful for the realization of wheeled motion mode and legged motion mode, and enhances reliability of the two motion mode.

V. EXPERIMENTS

Fig. 10 shows the experiment of the robot working on vertical glass surface. The experiment shows that the adhesion of the small suction cup can bear the gravity of the robot's body, and the climbing mechanism can realize robot's legged motion on wall surface under the embedded controller designed for the robot.

In the experiments, the vacuum degree inside the two suckers is tested by vacuum sensor. They are listed in TABLE III. The load capacity of the small sucker could guarantee robot's inchworm-like movement and transition movement between ground and wall.

TABLE III
LOAD CAPACITY OF SUCKERS

Parameters	Big sucker	Small sucker
Vacuum degree	-2000 Pa	-20 KPa
Load capacity	40 Kg	30 Kg

Fig. 10. Experiment on glass surface.

VI. CONCLUSION

The new prototype of mobile robot presented in the paper have the ability to work on both ground and wall surfaces. With the wheel-leg hybrid locomotion mechanism, the robot has two motion mode-wheeled locomotion mode and legged-climbing locomotion mode, which evidently improves the mobility of the robot. So the robot has both high moving speed and excellent obstacle-spanning capability. And the wheel lifting mechanism facilitates robot's switching between motion on ground and motion on wall surfaces. The new locomotion mechanism overcomes the limitations of previous wall-climbing robots in term of capability, mobility, and adaptability. Distributed embedded control system designed for the robot is compatible for the control of the locomotion mechanism, and it is convenient for the maintaining and expanding of the robot system. In the further, efforts will be made to improve the mechanism design and complete the sensor system to realize robot's sensing to the environments, and design control algorithm for the robot's movement in unknown terrains.

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