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Wall-Climbing Robot with Mechanically Synchronized Gait

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***Abstract*— This paper presents a wall-climbing robot for inspection and glass cleaning of high rise building application. A novel quadruped mechanism is proposed, which is composed of a combination of a four-bar and slider crank mechanism with vacuum adhesion module. Adhesion feedback system with intelligent gripping ensures adhesion between vacuum cup and the graspable surface. The climbing motion is analyzed. A prototype of the wall-climbing robot with compact size and low power consumption has been developed and performance tests have been conducted. The experimental results demonstrate that the wall-climbing robot has characteristics such as excellent stability, good weight carrying capacity and no complex control logic.**

Keywords—Wall climbing robot, mechanically synchronized gait, vacuum adhesion with feedback mechanism, embedded system.

I. INTRODUCTION

The first wall climbing robot can be dated back to 60s last century, developed by Nishi [1]. This wall climbing robot has a large volume and is very heavy, using single vacuum sucking cup. Later, around 80s, the wall climbing robot has been developed rapidly. The last few years have witnessed a strong, renewed interest in climbing and walking robotic technologies for applications in three areas: Reliable non-destructive evaluation (NDE) and diagnosis in some hazardous environments [2]; welding and manipulation, especially of metallic structures in the construction industry [3]; and the cleaning and maintenance of high-rise buildings [4].

The development of walking and climbing offers a novel alternative solution to the above-mentioned areas. It is well-known that the wall-climbing robots should possess two basic but critical functions: locomotion and adhesion. Research on wall-climbing robot is mainly focused on these two aspects [5]-[7]. Currently, there are several different kinds of kinematics for motion on smooth vertical surfaces: Multiple legs, sliding frame, and wheeled and chain track vehicle [8], hybrid type [9]. There are also different principles of adhesion used by climbing robots: Vacuum grippers, negative pressure, propellers, and grasping grippers [10].

Many robots with multiple-legs kinematics are too complex due to many degrees of freedom. This kind of robot, which uses grasping grippers for attachment to the buildings, does not meet the requirements of miniaturization and low complexity. However if these legs are connected with each other, degree of freedom and so the complexity can be reduced.

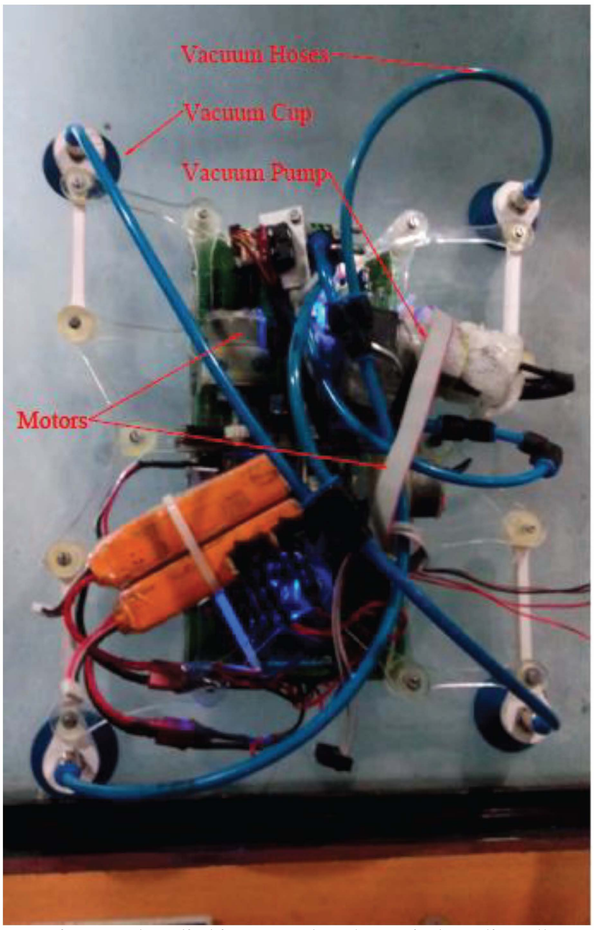

Fig. 1. Robot climbing upward on the vertical acrylic wall

Proposed robot reduces the need of complex control logic by using mechanically synchronized climbing gait. It uses only two actuators, still achieving motions in two independent directions which reduces cost without sacrificing mobility. Robot possesses excellent stability due to quadruped motion inspired by gecko climbing.

II. MECHANICAL SYSTEM DESIGN

A. Mechanism Design

Basic design idea of the wall climbing robot is to locomote on the vertical surface with minimum number of actuators. For planar motion, the robot should possess at least two degrees of

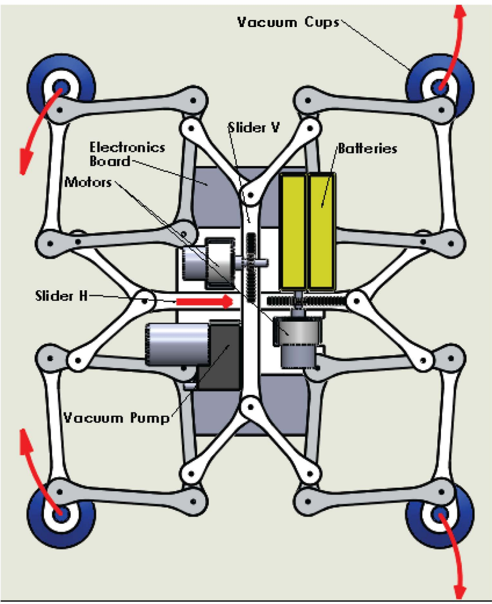

Fig. 2. Mechanism Overview with motion indication. Circled Area is detailed in the fig. 3

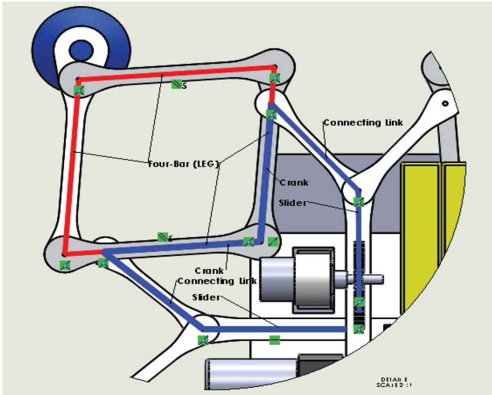

Fig. 3. Mechanism of Leg: Fourbar-Double Slider Crank

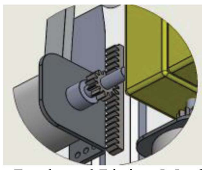

Fig. 4. Rack and Pinion Mechanism

freedom. Which implies that for quadruped, each leg should have two degrees of freedom. The mechanism proposed obtains two independent constrained motions of all legs of robot, where only one actuator is required per independent motion.

Each leg is a four-bar mechanism. If one joint is pivoted to the chassis then mechanism exhibit two degrees of freedom. These two degrees are controlled by two slider-crank mechanisms as shown in fig. 3.

A common slider is connected the four cranks through a connecting link as shown in fig. 2.Thus only two sliders control motion of four legs. As the slider slides to one of the side mutually opposite motions created for cranks on the opposite side. This makes legs reciprocate with a phase difference of 180 degrees, which is the motion of gecko be imitated.

These sliders are to be actuated with a linear actuator or rotary actuator via mechanism. Rack and pinion mechanism is provided for the linear motion as shown in fig. 4.

B. *Adhesion System*

The Robot has a vacuum adhesion system. It has a vacuum pump which continuously extracts air from vacuum cups. When cup is held against wall, due to atmospheric pressure outside, it gets pressed against wall and due to increased friction, vacuum cup is adhered to wall. Shear and Normal gripping force of the vacuum Cup depends upon internal structure of the cup and negative pressure developed.

For climbing, one pair of diagonally opposite cups should grip wall simultaneously and this should reverse for the next step. A directional control valve (DCV) is used to switch the flow of vacuum between the pair of the cups.

C. *Engagement and detachment considerations*

Vacuum Cup with 1.5 bellows retains contact with the wall surface when cup is not adhered to the wall.

When air is extracted from the volume occupied by space between vacuum cups and wall together with air in vacuum hoses, negative pressure is developed. Some time is required to develop this sufficient pressure and so the adhesion, which is here termed as gripping time. Gripping time is inversely proportional to flow rate of the vacuum pump. This gripping time reduces the climbing speed of the robot. For successful attachment to the wall, all the circumference of the vacuum cup should be in the contact with wall. If some gap is created or remained, then it precludes vacuum from developing. Links of

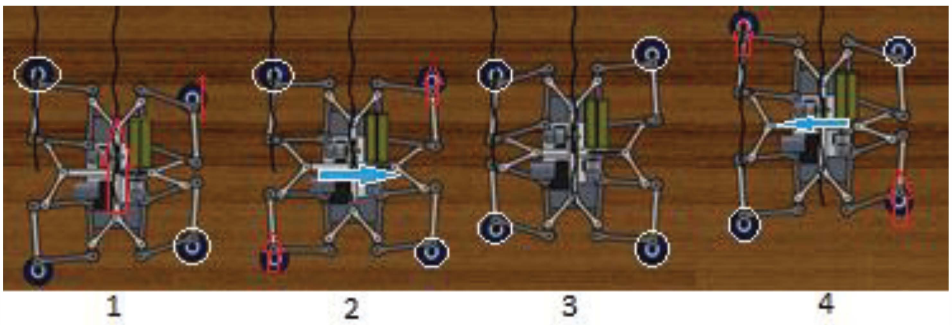

Fig. 5. Stages for climbing in upward direction

the robot should be sufficiently strong so that they don't bend much and hold the cups near to the wall.

One current sensor is provided to sense the current drawn by vacuum pump. When vacuum pump is attached to the wall, vacuum developed increases the current requirement of vacuum pump. This property is used as feedback in the control system. When robot is climbing, grasping feet may be exposed to some patch of wall contains holes or irregularities which prevents vacuum from developing and so the adhesion. Feedback detects such situations and algorithm changes the position of the feet, looking for a graspable patch of the wall in the vicinity.

III. Motion Analysis

A. *Climbing Analysis*

Fig. 5 describes different stages of climbing in upward direction.

Stage 1. Upper Left cup and its conjugate (diagonally opposite) is attached to the wall. As the slider moves towards right, robot and upper right leg move upwards. White circle in the diagrams indicate that vacuum cup is adhered to the wall. Red arrow indicates motion of cup.

Stage 2. Motion in the first step is continued. Blue arrow indicates motion of the slider.

Stage 3. Slider is moved till the maximum limit of stroke. All cups grip the wall at this stage. One step of climbing is now complete.

Stage 4. Next step for climbing in upward direction is shown in this stage.

B. *Velocity Analysis*

Velocity of the robot is obtained by multi-body simulation. Gripping delay is assumed as 1 sec.

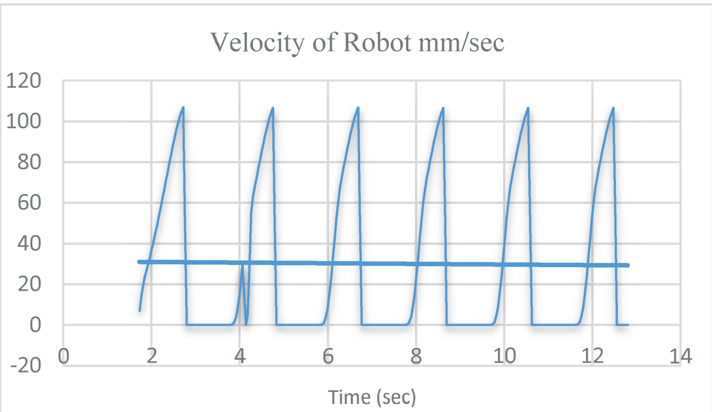

Fig. 6. Velocity of C.G. of Robot as it climbs vertically upwards

- Velocity of the robot is zero when cups are gripping the wall. (During gripping delay.)
- Average climbing speed of the robot is obtained as 30.02 mm/sec

C. *Angular Velocity of Motor*

The motor transmits motion to the Rack and consequently to the slider, which needs to be reciprocated for climbing in the same direction. Multi-body simulation is performed for vertical climbing. Angular velocity of the motor is plotted. Motor acceleration follows cycloidal path.

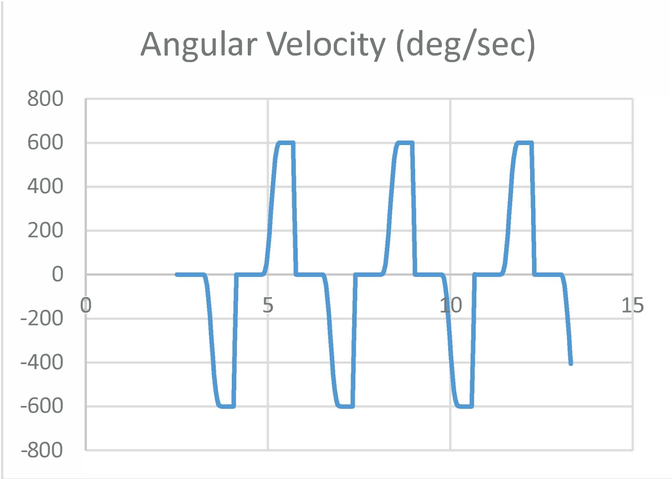

Fig. 7. Angular Velocity of Vertical Motor when robot climbs vertically upwards

Rack attached with slider oscillates with some pause at extreme positions. From the graph it is clear that with cycloidal acceleration, pinion attends its maximum angular velocity.

When the slider attends its extreme position, pinion stops. After the gripping delay, motion is repeated with the opposite directions.

D. *Torque Requirement of the motor*

When the robot is climbing the fig. 8 depicts forces acting on the mechanism.

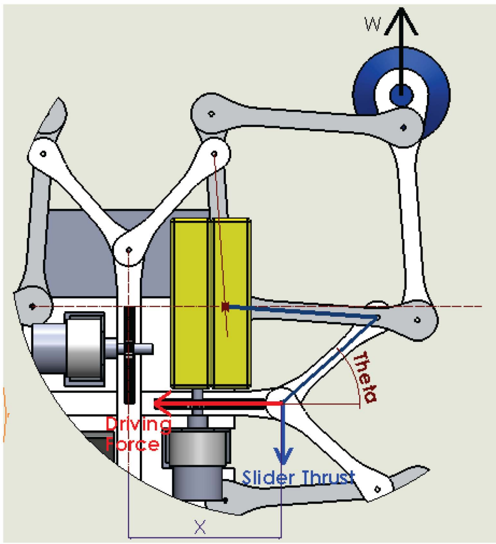

Fig. 8. Force Analysis of the upper right leg for the case of Robot climbing upwards

Driving Force is the tangential force exerted at the pitch diameter of the pinion. X represents the position of slider. W is the reaction force exerted by the wall against weight of the robot.

To perform this motion, the torque required by the motor is obtained from the multi-body analysis using ADAMS solver. Friction between the revolute and the prismatic joint is neglected for this analysis.

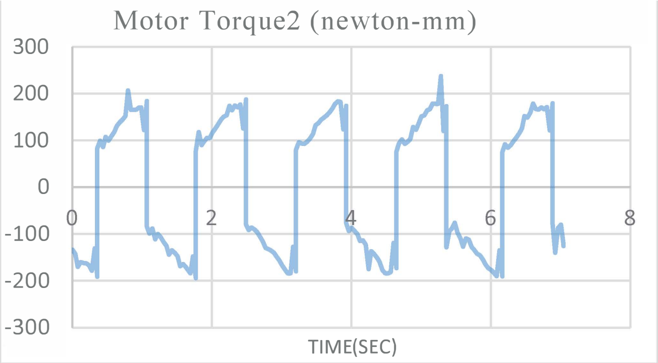

Fig. 9. Torque Requirements for the climbing with the average speed of 30mm/sec with 1 sec gripping delay

Torque fluctuates due to following reasons

1. Variation of the angle between slider and the connecting rod (Theta)
2. Acceleration of the robot.
3. Vibrations of the body parts.

Torque vs. Position of Slider

During climbing, the slider reciprocates. Position of the center of the slider oscillates with the amplitude of 20mm. Following plot gives the information about the torque with respect to the position of the slider.

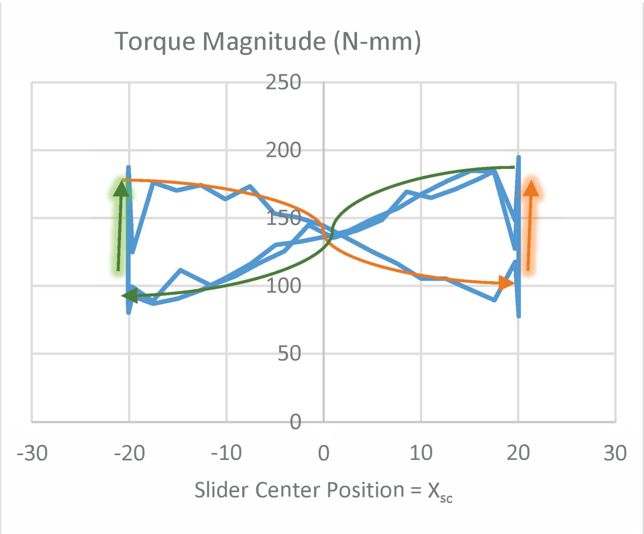

Fig. 10. Torque Variation with the slider motion. When the slider motion starts from -20 mm and end at 20 mm, the torque distribution is shown by the blue lines. While general trend-line is shown in the orange color.

From the plot it can be sensed that the torque is maximum (195N-mm) at the start of the motion. The torque gradually reduces as the slider propagates and attains minimum value at the end of the stroke, this repeats for the next cycle.

IV. Climbing Trajectory Planning

The robot can climb in any direction by changing the amplitude of the oscillation of motors. When only horizontal slider is oscillating, the robot climbs vertically upwards. (i.e. Φ = 90). Φ is the angle made by direction of movement of the robot with the lateral axis of the robot.

$$\tan(\Phi) = \frac{Amplitude\ of\ oscillation\ of\ the\ slider\ H}{Amplitude\ of\ oscillation\ of\ the\ slider\ V} \quad (1)$$

V. Electronic System

The electronics circuit board is mounted in the middle of the robot considering requirement of mechanical design of Robot. Power was supplied to robot using two LiPo batteries.

A. Embedded controller system

AVR Microcontroller, equipped with timers/counters, clock frequency, interrupts and flash memory is used for algorithm implementation. Controller was powered using buck regulator which converts 24V to 5V. Robot can be controlled manually through Bluetooth module when sequence of instructions are transmitted to robot. Also robot can execute sequence of steps in predetermined paths autonomously. Transition between these operation modes is possible.

B. Actuator and sensor system

DC motors were selected satisfying current, torque, and speed requirements. The speed of motor was controlled using PWM by controller. Motor driver is selected such that it satisfies the need of current. Drive circuit was designed for vacuum pump and directional control valve satisfying the need of current requirements. These drive circuits were interfaced with the controller using opto-coupler for isolation between controller and inductive load.

Closed loop system with PID control was used to control speed and position of robot which uses Rotary encoder for feedback. Rotary encoders with output of RS 422 standard were selected having differential output. This differential signal is applied to dual line receiver which helps in reducing distortion in signal.

Gripping of vacuum cups was governed by current sensor over vacuum pump. Change in current consumed by vacuum pump was sensed using current sensor. This change in current is converted in voltage using I-V converter. Instrumentation voltage amplifier with suitable gain was designed to convert output of I-V converter to achieve suitable range for ADC of controller. This ensures gripping of vacuum cups avoiding damage to robot because of falling of robot.

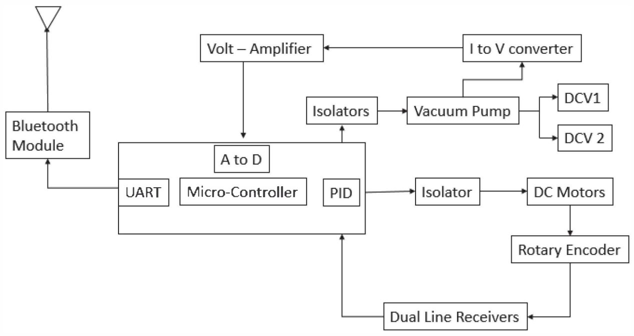

Fig. 11. Control Architecture

VI. EXPERIMENTAL RESULTS

The wall-climbing robot proposed in this paper has been successfully developed. In order to validate the effectiveness of the robot, laboratory and field experiments have been conducted. The contents of the experiments are conducted to test and investigate the actual trajectory and the velocity of the robot. The basic specifications are listed in Table I.

TABLE I ROBOT SPECIFICATION

Specification	Measurement
Size	350×350×70
No. of arms	4
No. of motors/actuators used	2 DC Motors, 100 RPM
Weight (kg)	2.02 kg
Weight Carrying Capacity	2 kg
Climbing speed (cm/sec)	2.6 cm/sec
Possible directions for movement	Vertical and Lateral
Batteries	LiPo 2200mAh
Vacuum Cups (four)	Schmalz PGA 43 1.5 Bellow
Controller IC used	Atmega 128
Vacuum Pump	12 V, 12W , pressure range 0-32psi, free flow range 12-15lpm

A. *Trajectory of the robot*

For the verification of theoretical and computational predictions, a prototype is manufactured. Marker is put on the body of Robot. Video is shot for vertical climbing of the robot and video is processed and the trajectory is plotted.

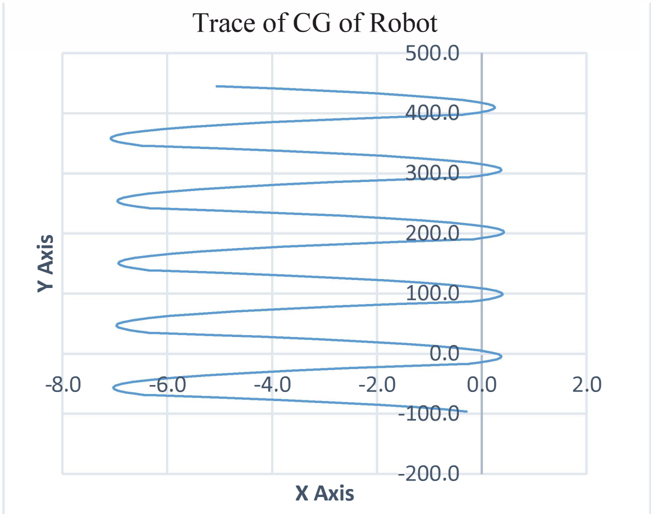

Fig. 12. Trace of marker. is plotted by processing the captured video. This plot explains lateral swings of the robot when it climbs vertically.

Output suggests that the robot travels almost vertically with slight horizontal swings. Magnitude of those swings is very less (1/100 times) the vertical leaps. These swings however introduce some vibrations in the system.

B. *Velocity of the robot.*

Actual velocity is slightly less than velocity obtained from simulation because friction between revolute joints offer an additional resistance to motion initiated by the motor, due to which robot climbs with slightly less acceleration.

However velocity of the robot while climbing down is more because weight of the robot helps motor to perform motion and acts against the friction, increases acceleration.

While moving laterally motor does not have to work against weight of the robot. Motor has to acts only against dynamic effects of robot. This leads to very less torque requirement of the robot.

TABLE II

Direction	Velocity (mm/sec)
Upwards	26
Downwards	35
Lateral	30

VII. CONCLUSION

Design is inspired by climbing motion of gecko. Innovative mechanism that generates synchronized leg movement suitable for wall climbing was developed. This reduces the complexities that are faced when control strategies for independent legs are implemented. Enablers of the design were (1) ability to coordinate a cyclic motion of grasping feet through mechanical design and (2) intelligent gripping by adhesion feedback. Basic constraint on velocity is gripping time of vacuum cups. The proposed robot can be used for surveillance purposes by using camera and wireless video streaming. It can be used for window cleaning of high rise buildings.

In future research, the adhesion mechanism will be optimized to reduce gripping time and to reduce noise, which makes the robot adaptive to the anti-hijacking tasks. The leg linkages will be developed which will enable it to climb the walls with multi levels. This will enable robot to overcome the obstacles such as window grills. Furthermore, the sensor system will be upgraded to enhance the autonomous control ability of the robot.

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