Wall Climbing Delivery Robot with Biomimetic Remora Disk

Jiecun Wang, Yufan Wang, Xuan Yang

***Abstract*— This Paper showcases a study on a wall climbing delivery robot that aimed at contactless delivery and direct delivery. In this proposed concept, we used a remora-inspired suction cup (RSC) and a 6-DOF robot to design a compact but powerful wall climbing robot. We found out RSC can provide enough suction force to hold a robot to lift a 20kg load on a vertical rough surface, which gives as a baseline that we used to design a practical prototype. Preliminary simulation trials demonstrated that the proposed device was capable of delivering 20kg load.**

I. Introduction

As social distancing has been practiced during the pandemic, contactless delivery is not just a thing being temporarily implemented, but a great practice that can be kept after pandemic. However, for people living in high-rise buildings, it is always annoying to go downstairs to pick up the delivery, so we came up with the idea of building a climbing wall robot to deliver packages and food through the windows.

Currently, there are two methods to deliver through the window, one is utilizing drones and the other one is using 4-wheel climbing wall robots. Drone is efficient and powerful, but, being used in delivery, it is strictly limited to the weather condition, and can cause safety issues.[1] The other method used thrust generated by the fan to make the robot stick on to the wall and use the wheel to move and rotate; However, the thrust fan generated is not enough to hold the required load for delivery.[2] These two methods are shown in figure 1.

Our design is similar to a 4-wheel climbing wall robot, but ours can step over the obstacles and hold heavier load. We utilized 2 suction cups at the two ends of a 6 DOF robot arm. The suction cup adhered to the wall is considered as base, and the other end of the robot acts as end effector, when it finishes one step, the role of two ends switch over, and we iterate this process to make it move and avoid obstacles. We propose to use biomimetic remora disk (BRD) developed by Prof. Li and his team.[3] According to his paper, BRD can generates greater pull off stress(15.8 to 21.9 kPa on surface of roughness $R_a = 200\mu m$) and 1.4 to 1.7 times frictional force depending on the surface roughness. The size of the BRD prototype is 127mm in length and 72mm in width, with a mass of 129 g, which is a considerable compact size that can be installed on our robot arm. Besides the load target, we are aiming to have our robot step over an obstacle with maximum size 200mm in height and 150mm in width

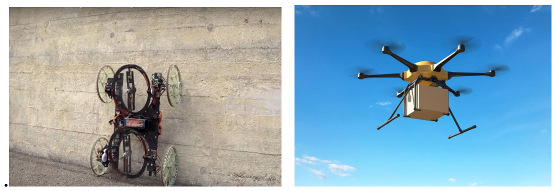

Figure 1. Vertigo(Left) and Drone delivery(Right)

II. Design Concept

A. Robot Structure

Our robot is designed to climb over obstacles. So The structure of the robot must be able to ensure its mobility and the ability to climb over obstacles. We designed a 6-DOF robot composed of a control center, 2 links, 2 suction cups and 6 motors.(figure) The two motors closest to the suction cups rotate about an axis perpendicular to the wall, which could allow the robot to change its climbing direction. Other four motors are parallel to the wall and are responsible for adjusting the climbing step length and obstacle climbing over posture.

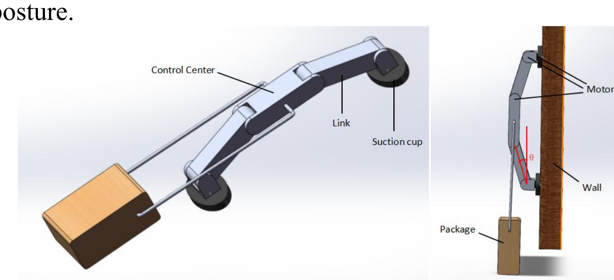

Figure 2. Robot Model

B. Parameter calculation

In order to climb over obstacles, the length of the robot should be determined according to the size of obstacles. On the exterior wall of a building, the most common obstacle is the waistline of the building. The common size of the waistline is 60mm × 120mm. Therefore, the structure parameters of the robot should be selected so that it can cross at least 60 mm high and 120 mm wide obstacles. We chose 200mm as the length of links and control center. θ is defined as the angle between the link and the wall. We calculated the width and height of the largest obstacle that can be crossed at different θ. we found that the requirement of 60mm × 120mm can be met.

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F. A. Jiecun Wang is with the Fu Foundation School of Engineering and Applied Science, Columbia University, NY 10027 USA (e-mail: jw4104@columbia.edu).

S. B. Yufan Wang is a student in Columbia University, New York, NY 10019 USA. (e-mail:yw3690@columbia.edu).

T. C. Xuan Yang is with the Mechanical Engineering Department, Columbia University, New York, NY 10027 USA. (e-mail: xy2472@columbia.edu).

Table Ⅰ The size of obstacles that can be crossed at different θ

The angle between link and wall(θ/°)	Obstacle height(mm)	Obstacle width(mm)
0	40.00	550
15	91.76	150
30	140.00	150
45	181.42	150
60	213.20	150

Next is the motor model. In order to climb over obstacles, the robot should do an action of rolling with a package hanging through its mass center. High torque motors are needed for lifting heavy packages. It is easy to know that in the process of climbing the wall, the motor providing the maximum torque is the wall-nearest one among motors whose shaft is parallel to the wall. The torque could be calculated by the formula:

$$T = F \times s \tag{1}$$

F is the gravity of robot and package. s is the maximum distance from F to the motor center. When the robot's body becomes a straight line perpendicular to the wall, s has the maximum value. At first, we assumed that the robot could lift a 20 kg package and we also assumed that the weight of the robot is 5 kg. The maximum s is 0.3 m. Using formula (1) we can found that the torque needed was 73.5 Nm. In this demand, we determined the motor model. When used with reduction gears, the motor can provide the torque of 141 Nm at the speed of 10rpm.

Table II Motor parameters

Model number	D(mm)	L(mm)	r(mm)
M3508	42	98	5
$T_m(N \cdot m)$	$n_m(rpm)$	m(g)	$U_n(V)$
3	469	400	24

Another parameter that limits the weight of the package is the friction at the suction cup. When the robot is climbing over obstacles, The gravity of the robot and the package should be less than the maximum static friction provided by the suction cup. With the following suction force formula:

$$W = \frac{P \times C}{101} \times 10.13 \tag{2}$$

suction force W could be calculated. P is the pressure produced on the suction cup and C is the area of suction cup. Finally we calculated a suction force of 472.4 N. Friction coefficient of silicone rubber is 0.9. So by the static friction formula:

$$f = \mu F \tag{3}$$

We can calculate the friction that one suction cup could offer. It's 425.2 N. And we introduce a safety factor S. Let S equal to 1.5 to ensure that the robot is absorbed on the wall during climbing process. So the maximum weight that the suction cup can carry could be calculated by the following formula:

$$F_m < f/S \tag{4}$$

It can be calculated that the maximum value of F_m cannot exceed 283.5N.

Using Solidworks, We can estimate the weight of the robot's aluminum shell, and suction cups. Then we added the weight of motors to estimate the overall weight of the robot. The estimated total weight is 5.72 kg. So the maximum weight of the package that the robot can carry is 23.2 kg.

III. Mathematical Modeling

A. DH Coordinate Frame

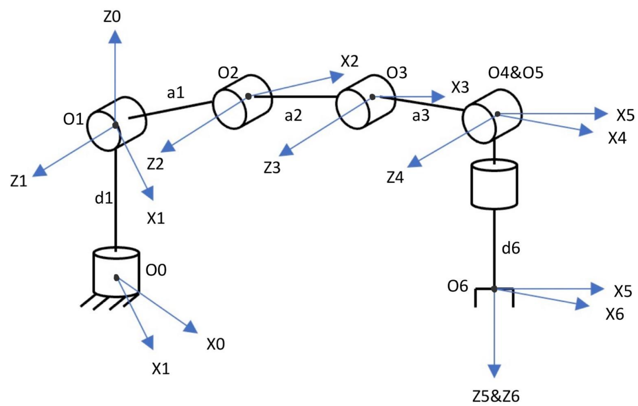


Figure 3. DH Coordinate Frame of Designed 6-DOF Robot

In order to define the movement of the robot, the DH coordinate frame for the whole manipulator needs to be defined based on the following rules:

- Choose z as the direction of each joint
- Choose x_i as $x_i = z_{i-1} \cdot z_i$ if z_{i-1} and z_i axes are not parallel
- Choose x_i pointing from proximal to distal if z_{i-1} and z_i axes are parallel

Therefore, DH coordinate frame for the designed 6-DOF wall climbing robot is given in Fig. 3.

B. DH parameters

Table III: DH parameters for designed 6-DOF robot

#Link	***a_i (mm)***	***d_i (mm)***	***α_i (degree)***	***θ_i (degree)***
1	0	d_1	π/2	θ_1
2	a_2	0	0	θ_2
3	a_3	0	0	θ_3
4	a_4	0	0	θ_4
5	0	0	0	θ_5
6	0	d_6	π/2	θ_6

The DH (Denavit-Hartenberg) parameters are the four parameters associated with a particular convention for attaching reference frames to the links. In order to define each parameter, the following rules need to be followed:

- a_i = distance along x_i from o_i to the intersection of the x_i and z_i axes
- d_i = distance along z_{i-1} from o_{i-1} to the intersection of the x_i and z_{i-1} axes, d_i is a variable if joint i is prismatic
- α_i= the angle between z_{i-1} and z_i measured about x_i
- θ_i = the angle between x_{i-1} and x_i measured about z_{i-1}, $_i$ is a variable if joint i is revolut

C. *Forward Kinematic Transformation*

Forward kinematic transformation is used to compute the position of the end-effector from specified values for the joint parameters. With DH parameters defined in Table 1, we can easily compute the homogeneous transformation matrices A by substituting the above parameters into (4)

$$A = \begin{vmatrix} c\theta & -s\theta * c\alpha & s\theta * s\alpha & a * c\theta \\ s\theta & c\theta * c\alpha & -c\theta * s\alpha & a * s\theta \\ 0 & s\alpha & c\alpha & d \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (4)$$

where cα = cosα, sα = sinα, cθ = cos θ, sθ = sin θ.

For the DH parameters for our designed 6-DOF robot:

$$A_1 = \begin{vmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad A_2 = \begin{vmatrix} c_2 & -s_2 & 0 & a_2c_2 \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$A_3 = \begin{vmatrix} c_3 & -s_3 & 0 & a_3c_3 \\ s_3 & c_3 & 0 & a_3s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad A_4 = \begin{vmatrix} c_4 & -s_4 & 0 & a_4c_4 \\ s_4 & c_4 & 0 & a_4s_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

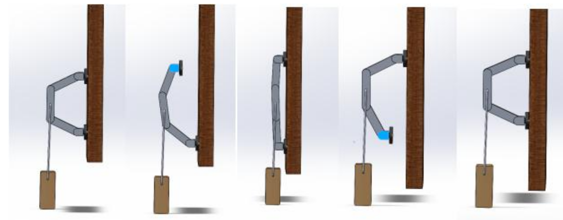
$$A_5 = \begin{vmatrix} c_5 & -s_5 & 0 & 0 \\ s_5 & c_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad A_6 = \begin{vmatrix} c_6 & 0 & s_6 & 0 \\ s_6 & 0 & -c_6 & 0 \\ 0 & 1 & 0 & d_6 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

From forward kinematic transformation matrix T, which can give us the position and orientation of the end-effector frame expressed in base frame, can be computed by (5)

$$T_0^6 = A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot A_6 \quad (5)$$

IV. SIMULATION RESULT

We use Solidworks to carry out preliminary motion simulation. In this motion simulation, we defined two methods of climbing. The first way is ordinary climbing. When there's no obstacles in the way climbing, the robot will use a creeping way to climb the wall(Figure 4. a). During this method, the robot will first hold the lower suction cup on the wall. Then the robot will stretch its body and let the upper suction cup hold the wall. Next the robot will move the lower suction cup up and return the posture at beginning. This method could help the robot move up with relative low torque, which could ensure the moving safety during wall-climbing process. The second method is obstacles climbing over method(Figure 4. b). When the robot is facing an obstacle, it will choose to roll and climb over the obstacle. In this method, the base and the end-effector are exchanged. At first, the robot will let the upper suction cup hold the wall. Then the robot will roll its body to climb over the obstacle. Next the new upper suction cup will hold the wall and the rolling process will be reproduced.



(a) Ordinary Climbing

(b) Obstacles Climbing

Figure 4. Two methods of climbing

We also established our robot model with the MATLAB robotics toolbox and implemented cubic polynomial trajectory planning for each joint. To simplify the motion, we assumed the d1 and d6(Table Ⅲ) is negligible that will not affect the motion study of our robot. Initially, we obtained a relatively massive motion by simply type in the final position of our robot as shown in Figure 5.; However, this motion requires large motor torque and may theoretically tilt the suction cup and cause it detach from the surface. To optimize the trajectory, we tried to break the whole motion into 3 steps. The steps are shown in figure 6. With this optimization, we lower the center of mass of our robot so that when rotating the robot, it will not require motor torque as large as the original one.

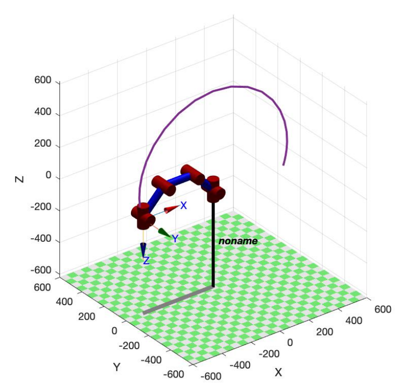


Figure 5. Trajectory Simulation

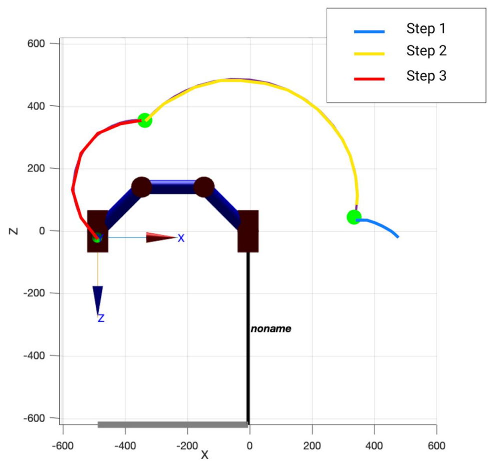


Figure 6. Example Trajectory Simulation within 3 Steps

V. Conclusion

Within this paper, the feasibility of the wall-climbing robot is verified. The maximum load of the robot is calculated. The 3D modeling of the robot is completed using SolidWorks. Review of solution methods to the forward kinematics problem is given. The motion trajectory of the robot is simulated using MATLAB. The further research direction is to develop the algorithm of path planning under environmental constraints, and to further improve the stability of the suction cup and the safety of the robot.

VI. Future Direction

In the future, we are going to build a prototype to conduct experimental evaluation and verification of robot and BRD performance. Also, we plan to study the roughness, texture and shape of New York high-rise buildings' walls so that we can future improve our robot design with that data. The current freedom of each joint is limited due to the mechanical structure of our robot, so we are going to optimize the joint connection to increase the workspace of our robot. Finally, we need to install a parachute to prevent accidents from robot falling.

References

[1]Rupprecht, Jonathan. "The Truth About Drone Delivery No One Is Talking About." *jrupprechtlaw*, jrupprechtlaw.com/drone-delivery/.

[2]"Disney Builds 4-Wheel Robot That Can Climb Walls." *wevolver*, ETH Zurich, 29 Dec. 2015, www.wevolver.com/wevolver.staff/vertigo.

[3]Li, Wen, et al. "A biorobotic adhesive disc for underwater hitchhiking inspired by the remora suckerfish." *Science Robotics*, vol. 2, no. 10, 20 Dec.2017,doi:10.1126/scirobotics.aan8072,www.wevolver.com/wevolver.staff/vertigo.