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Rubbot: Rubbing on Flexible Loose Surfaces

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Abstract— **This paper presents a newly-designed robot named ”Rubbot” dedicated to climbing on soft flexible clothes. Equipped with novel grippers which grip and rub on clothes, Rubbot is able to climb on flexible clothes and control how much fabric to grasp by feedback from infrared sensor. Rubbot also has a frame which has three passive folders which adjust the climbing posture of Rubbot. This not only makes Rubbot quite functional with clothes of different thicknesses and curved surfaces, but also makes Rubbot's motion more flexible. A theory of the deformation of cloth is then presented based on an analysis of creases created while Rubbot is climbing, this leads to a more reliable method to climb flexible surfaces. Finally experiments have verified that Rubbot is effective on flexible surfaces, as it can climb on 95% of the surfaces human clothes and still perform well on non-rigidly backed cloth.**

Fig. 1. Rubbot on clothes

I. INTRODUCTION

Climbing robots have many existing and potential applications. They are frequently sent to execute inspection and rescue missions. Their shape and size allow them to easily access caves and building ruins. Up to now, most research has focused on rigid-surface climbing. Much less work has been done on flexible-surface climbing. This paper introduces a novel climbing robot named Rubbot designed to climb soft cloth. The prototype of Rubbot is shown in Fig. 1. Rubbot has numerous potential applications. For example: it can perform inspection tasks with a remote inspector; By implementing a microphone on its frame, it immediately becomes an auto-answering device capable of helping people when both of their hands are occupied; And as a ”pet”, it can entertain people.

Currently, legged wall-climbing robots use tiny claws that highlight their bionic features [1] [2]. Wheeled robots demonstrate that wheels may be more appropriate for moving on flat stiff surfaces. Magnetized wheels are effective on magnetic walls and tanks [3] [4] [5]. There are also special wheeled robots that can adhere to walls by depending on an adhesive elastomer, fiber footpads, or suction cups [6] [7] [8]. ”Treebot” can climb on trees or similar surfaces because of its inchworm-like body [9]. Only very few studies have mentioned a flexible cloth-climbing robot. CLASH is first robot that can climb loose cloth and uses passive needle legs that are activated by a single motor [10]. Its mechanism of locomotion is comprised of six legs, only one actuator, and smooth engagement and disengagement of its passive needle feet. ”Clothbot”, another cloth climbing robot, consists of a gripper and a two DOFs tail, has succeeded climbing most parts of human cloth [11].

Since cloth is deformable and soft, a robot designed to climb on it should firstly be capable of maintaining its balance without regard to the ever-changing nature of cloth. Secondly, it should contain a mechanism to avoid negative cloth deformation, which might prevent a robot from moving smoothly.

Rubbot is composed of a pair of two-wheeld grippers and a foldable frame. Based on past results of using grippers [11] [12], Rubbot is designed with a pair of grippers. Different from Clothbot [11], Rubbot's two grippers are parallel so that they can grip cloth surfaces on their circumference. Because of this parallel feature, Rubbot is able to hold cloth firmly and remain in balance on its own. Moreover, Rubbot's foldable frame endows it with great flexibility to fit different shapes and thicknesses, and also decreases the number and degree of negative creases of cloth. Rubbot has performed better than previous cloth robots on rigidly-backed surfaces and succeeded to climb non-rigidly-backed surfaces at different angles. The newly-designed Rubbot's specifications are listed in Table I.

TABLE I
THE SPECIFICATION OF RUBBOT

Weight	110g
Dimention	(82,40,30)mm
Radius of gripper's wheel	10mm
Thickness of gripper's wheel	8mm
Transversal folder rotation	(-10 +30) °
Longitudinal folder rotation	(0 +45) °

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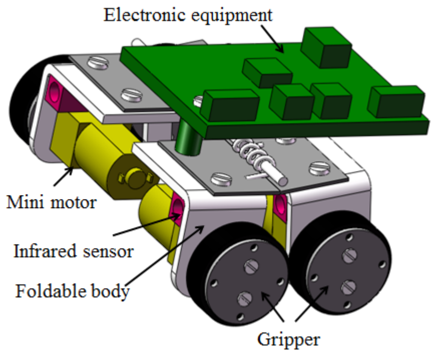

Fig. 2. CAD drawing of Rubbot

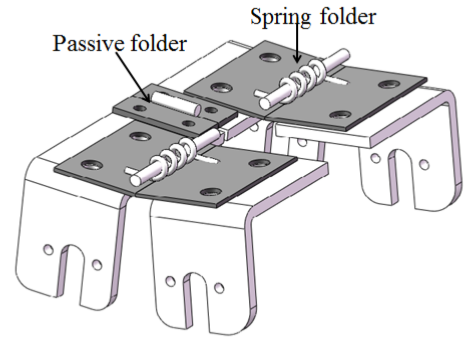

Fig. 4. Foldable frame

II. DESIGN

Rubbot consists of two grippers and a foldable frame (Fig. 2). The grippers grasp cloth firmly and rub it between its wheels to move and steer. The griping force is created by spring folders so that the thickness is adjustable. At the rear of the frame a passive folder links left and right parts. Infrared sensors are added to notify controller when the cloth is slipping out of the grippers.

A. Gripper

So far, climbing robots for rigid surfaces have provided many methods of climbing but few are suitable for climbing on soft surfaces. Soft surfaces are deformable, rough, and penetrable. Consequently, normal magnetic and air-pad sorption approaches are not applicable for penetrable or non-magnetized surface. Although climbing robots that employ a claw structure, such as "treebot" are able to grasp soft cloth, they can not maintain position when one of their claws loses the cloth, due the softness and uncertain shape of cloth. Although needle feet are applicable to soft surfaces, they are ineffective on impenetrable surfaces. Clothbot employs a movable gripper to climb stusses [11]; it uses a gripper consisting of two tangential wheels to climb clothes. The axis of the wheels is vertical to the surface of the cloth, and a tail is provided to control the amount of cloth that is grasped. However it still drops down from the cloth or turns over on it. Rubbot has similar grippers to Clothbot but use a wholly different grip approach and kinematic principle.

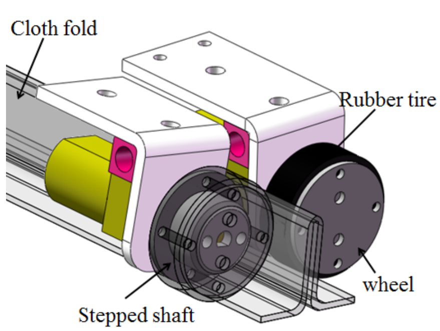

Fig. 3. Gripper

Fig. 3 presents the CAD schematic of Rubbot's gripper. A pair of grippers made up of two tangential wheels is fixed on the opposite flanks of frame. Each wheel is activated by a relative motor. To increase the friction between the cloth and the wheels, a rubber loop wraps around the circumferential surface of wheel.

B. Foldable frame

From a biological perspective, an animal trunk is not only used for storing internal organs and connecting branches, but also for adapting to circumstances by changing its shape and distribution of the arms and the legs of body. Until now, however, most climbing robots' bodies have only been used to connect branches and store objects, such as controllers and batteries. Treebot [9] is one exception, in that it changes its body's posture to move on trees and steer its direction. As the thickness and shape of clothes is unpredictable, we develop Rubbot with a foldable frame that can change the distance and angle of the axis between any two wheels.

The folder structure needs no activator or feedback control. Each joint is only linked by a folder. The CAD model of the foldable frame is shown in Fig. 4. The left and right parts are connected by a passive folder which can turn from -10°to 30°. It is designed to fit curved surfaces as it climbs. In the middle of each part, there is a passive spring folder designed to make the front and rear wheels continually tangent. This spring folder's rotation angle ranges from 0°to 45°to clip clothes of ever-changing thicknesses.

III. MECHANISM AND KINEMATICS

This section describes basic locomotion of Rubbot in terms of mechanism and kinematics.

A. Rubbing

Fig. 5 shows the position when Rubbot is moving on vertical cloth. Once the grippers grasp the cloth, the controller makes each two wheels on the same side have the same angular velocity. Detailed kinematics are described as follows: Grasp force F_N is provided by the spring folders. Since clothes are flexible, they are pulled by Rubbot's gravity, and the cloth deforms and tilts to an angle α. As soon as the motors employ torque on the wheels, friction appears come into being. In Fig. 5, f_A is friction between A and the

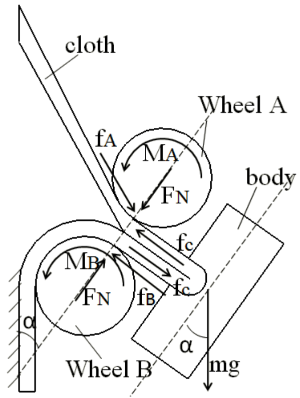

Fig. 5. Analysis of gripper's motion

cloth, f_B is between B and the cloth, and f_c is between the cloth and the cloth. They satisfy following equations.

$$\begin{cases} f_A \leq \mu_A F_N \\ f_B \leq \mu_B F_N \\ M_A = f_A r \\ M_B = f_B r \end{cases} \quad (1)$$

μ_A is the coefficient of friction between A and the cloth, μ_B is between B and the cloth. r is the radius of the wheel. The static friction f_c between cloth and cloth is:

$$f_c \leq \mu_c F_N \quad (2)$$

μ_c is the coefficient of friction in the cloth.

The friction coefficient between the cloth and rubber is much stronger than between the cloth and itself, as:

$$\mu_A = \mu_B > \mu_c \quad (3)$$

The vertical component force of f_A supports the mass of Rubbot. f_B must be greater than f_c so that wheel B will not slip on the cloth. If f_A and f_B satisfy the following conditions, Rubbot would succeed to climb vertically. Because there are four motors composed of two grippers on Rubbot and an incline angle α is generated by Rubbot's gravity, the equation is:

$$\begin{cases} 2 f_A \cos\alpha \geq mg \\ f_B \geq f_c \end{cases} \quad (4)$$

Then, the torques M_A and M_B should provide is:

$$\begin{cases} \mu_A F_N > \dfrac{M_A}{r} > \mu_c F_N \\ \mu_B F_N > \dfrac{M_B}{r} > f_C \end{cases} \quad (5)$$

Combine (1), (4) and (5), we get:

$$\begin{cases} \mu_A F_N > \dfrac{M_A}{r} > \dfrac{mg}{2\cos\alpha} \\ \mu_B F_N > \dfrac{M_B}{r} > f_c \end{cases} \quad (6)$$

The least torques M_A and M_B produced by each motor is:

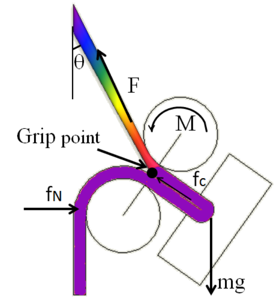

Fig. 6. Deformation of cloth from lateral view

$$\begin{cases} \mu_A F_N r > M_A > \dfrac{mgr}{4\cos\alpha} \\ \mu_A F_N r > M_A > f_c r \end{cases} \quad (7)$$

However, in attempts to achieve climbing straight upwards on flexible vertical cloth surface, cloth deformation cannot be ignored. Deformation of cloth influences function of grippers.

Fig. 6 shows how the cloth deforms as Rubbot is hanging on the cloth in the experiment. Fig. 7 reveals deformation from top and lateral views. Various colors represent the degree of deformation ranging from purple to red, the closer the color is to purple, the smaller is the deformation generated by cloth, and vice versa. It is obvious that under the effect of gravity, the Rubbot will drag the cloth at the gripping point. The cloth before the gripping point becomes longer because it supports the Rubbot, the cloth after the gripping-point will recover its original shape by elastic force. As a result, the distance that the two wheels in the gripper rotate is not the same. Assuming that the length of cloth below the wheel walks is L_1 and the margin of unit length coursed by deformation is Δ_L, the length the wheel above walks is:

$$L_2 = L_1 - \Delta_L \quad (8)$$

So keeping the angular velocity ratio of wheel A and down wheel B at:

$$\frac{n_A}{n_B} = \frac{L_1}{L_1 - \Delta_L} \quad (9)$$

n_A and n_B are the angular velocity of wheel A and B respectively. Only if n_A and n_B keep a certain ratio at (9), the volume of the cloth crease will be a constant.

In order to compensate for difference in distance, two sets of infrared radio sensors are implemented on both wings of

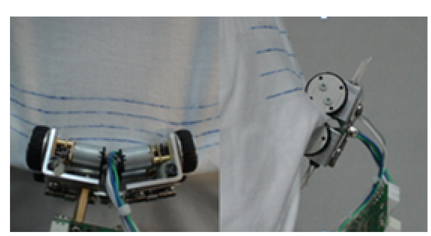

Fig. 7. Surface deformation of cloth

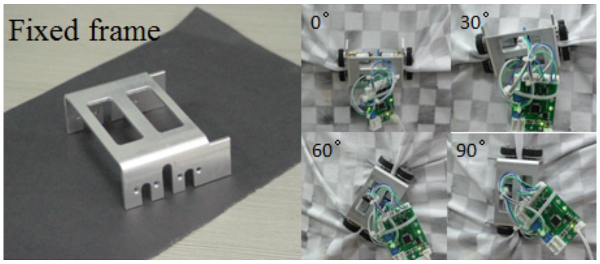

Fig. 8. Turning from 0°to 90°with fixed frame

the frame. As long as the top of crease is below infrared light, controller will command grippers to pull back cloth.

In order to discuss the kinematics of gripping, we need to identify how grippers work. In addition, the deformation of cloth exerts a negative effect on gripping. Sensors are needed to compensate for the distance caused by deformation.

B. Steering

Based on the gripper's locomotion proposed above, Rubbot will advance or retreat by keeping two grippers at the same pace and turning in the same direction. Aiming at finding the relation between the emergence of creases and the motion of Rubbot, we investigate kinematics and conduct experiments on two kinds of frames below.

1) Fixed frame: When the two grippers apply differential motion, Rubbot will turn (Fig. 8). Gripper has two dimensions of freedom when it cling to the cloth. Firstly, wheels have circumferential freedom that it can move vertical to the axle on the surface that it grasps. Additionally, wheels are allowed to turn on the surface. Nevertheless, flexible surfaces make an extraordinary difference when compared to their rigid counterparts. Because of the flexibility of cloth, both of the two freedoms are incomplete that friction and cloth deformation are coexisted. Fig. 9, it shows the motion of the wheels when Rubbot turns left.

The torque M_i (i=1,2,3,4) at the center O of Rubbot posed by each wheel is:

$$M_1 = M_2 = M_3 = M_4 = \frac{FL}{2} \tag{10}$$

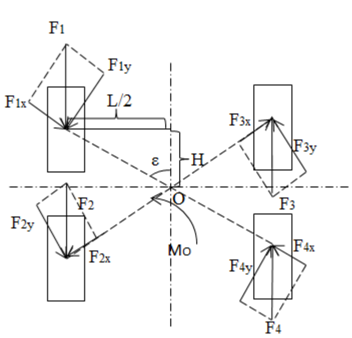

Fig. 9. Turning mechanics of parallel wheels, F_i is the friction wheel i applied on the cloth. F_ix and F_iy are the component force of F_i (i=1,2,3,4). $L/2$ is the distance from the center of the wheel to the vertical axle of the robot and H level axle.

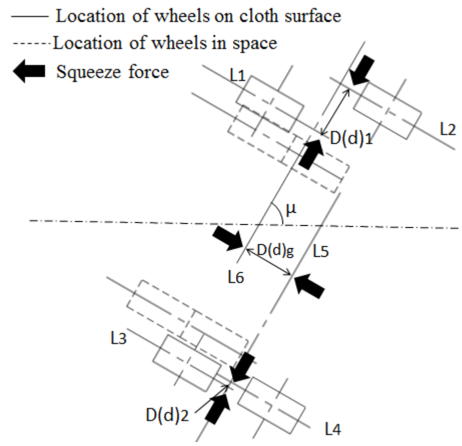

Fig. 10. Locations of wheels on cloth surface and in space. As the existence of F_{ix}, cloth is squeezed and creases come into being. Meanwhile, the route of wheels offset on cloth surface. L_1, L_2, L_3, L_4 are axial planes of wheels. L_5, L_6 are the centerline of grippers. $D(d)_1$, $D(d)_2$, $D(d)_3$ are the distance between L_1 and L_2, L_3 and L_4, L_5 and L_6. μ is the angle Rubbot turns.

And the total torque at O, torque M_o provides the turning force of rotating motion.

$$M_0 = M_1 + M_2 + M_3 + M_4 = 2FL \tag{11}$$

The cloth shape is in the charge of $F_{ix}(i = 1,2,3,4)$. Squeeze forces appear, as shown in Fig. 10 . This is where creases from.

$$F_{ix} = F_i \cos \varepsilon \tag{12}$$

As we hypothesized, the experimental results verified that the existence of creases is positively correlated with displacement. Fig. 11 presents the wheels' route using a frame with parallel wheels while Rubbot is turning 90°.

The existence of extra creases may have a negative impact on Rubbot's function. Above all, too many creases may overfill the gripper. In addition, it may also cause incomplete steering and uncontrolled turning angles.

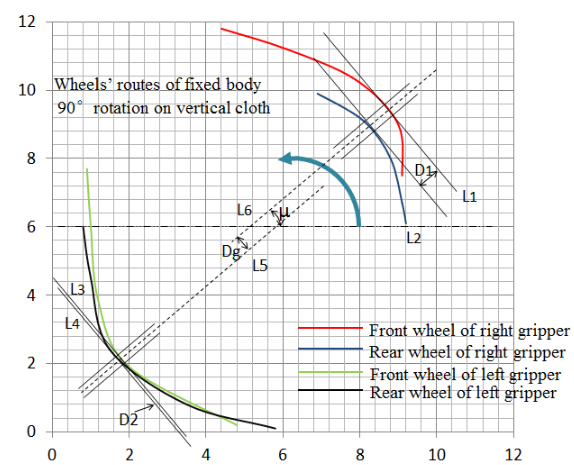

Fig. 11. Route of parallel wheels. The unit is *cm*. As the wheels are parallel to each other, the points on the routes with the same slope as the tangent are the locations of the wheels.

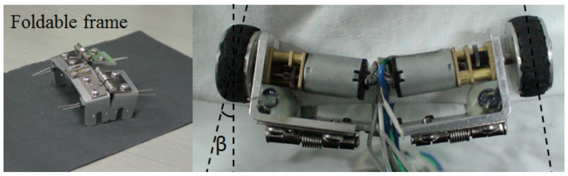

Fig. 12. Foldable frame

2) Foldable frame: In order to make Rubbot's turning smooth, a foldable frame has been implemented. Foldable frame has three folders. Owing to gravity, passive folder turns an angle β when it is hanging on cloth (Fig. 12). Fig. 13 shows the kinematics of the wheels of the foldable frame.

As calculated above, total torque m_o and the lateral force posed by each wheel f_{ix} is:

$$m_1 = m_2 = m_3 = m_4 = \frac{FL}{2}\frac{\sin(\varepsilon+\beta)}{\sin(\varepsilon)} \tag{13}$$

$$m_0 = m_1 + m_2 + m_3 + m_4 = 2FL\frac{\sin(\varepsilon+\beta)}{\sin(\varepsilon)} \tag{14}$$

$$f_{ix} = f_i \cos(\varepsilon+\beta)(i = 1,2,3,4) \tag{15}$$

Combining (10), (11), (12), (13), (14) and (15), for 90°> β >0°, so:

$$\begin{cases} M_O < m_o \\ F_{ix} > f_{ix} \end{cases} \tag{16}$$

The experiment proves the above inference. Fig. 14 shows the wheels' route using a foldable frame. And Fig. 15 compares the displacement of fixed and foldable frames, confirming that foldable frames are more advantageous. As we expected, the displacement of the wheels of a foldable frame is always less than that of a fixed one.

$$\begin{cases} d_1 < D_1 \\ d_2 < D_2 \\ d_3 < D_3 \end{cases} \tag{17}$$

In short, we have compared two kinds of frames. Firstly, kinematic analysis is conducted to prove foldable frame's advantages theoretically. Then, the outcomes of the experiments have verified our inferences. Foldable frames smooth the turning of Rubbot by decreasing the number and the degree of creases. Although negative creases are relatively

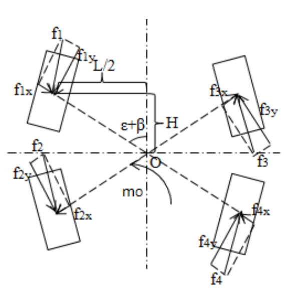

Fig. 13. Turning mechanics of foldable frame

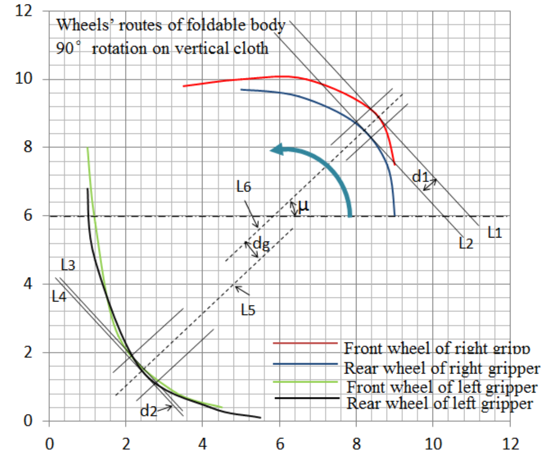

Fig. 14. Route of wheels on foldable frame, the unit is *cm*.

decreased, grippers may still grip into excessive cloth. Spring folders above grippers will unfold to avoid cloth jam and maintain Rubbot's functionality, even when more than one crease is in the gripper.

IV. EXPERIMENTS

Various experiments have been done on Rubbot to prove its functionality and advantages: a) comprehensive comparison with present cloth robot, b) moving on clothes of different angles, c) climbing on different fabrics.

A. Comprehensive comparison with present cloth-climbing robots

TABLE II
COMPARISON WITH OTHER CLOTH CLIMBING ROBOTS

	Rubbot	Clothbot	CLASH
size(mm)	(82,40,30)	(135,44,57)	(10,5,10)
mass(g)	110	140	15
vertical speed(mm/s)	25	20	15
degrees of freedom	2	2	1
steering angle(°)	(-180,+180)	(-85,+85)	(-0,+0)
numbers of actuators	4	4	1

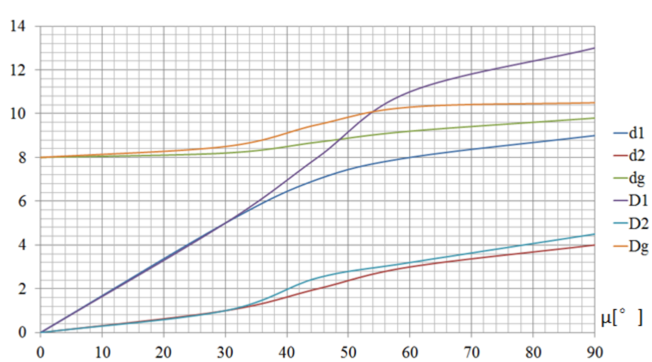

Fig. 15. Displacement range from 0°to 90°. The unit of D_g and d_g is cm, and $D1, D2, d1, d2$ is mm.

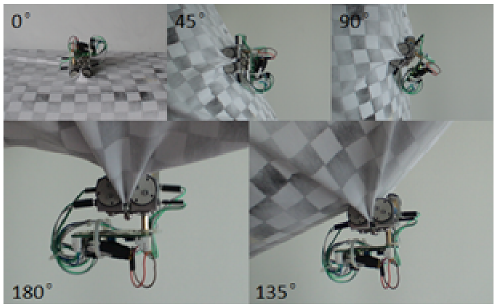

Fig. 16. The exhibition of climbing different angles, 0°, 45°, 90°are rigidly backed. 135°, 180°are vacant backed. The cloth climbed contains 5% spandex and 95% cotton.

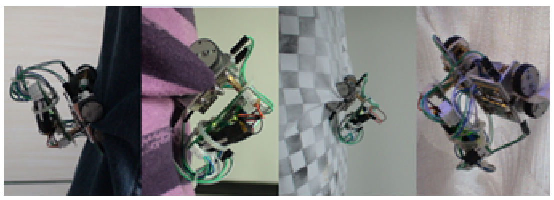

Fig. 17. Rubbot on denim, woolen, cotton and silk

Detailed information on the three main cloth-climbing robots is presented in Table II. Rubbot has a relatively smaller size and lower mass. Rubbot also has faster vertical velocity. Additionally, Rubbot enjoys several unparalleled advantages. It can climb on the shoulders and arms of humans, even though the shape of cloth on these body is irregular and non-rigidly backed.

B. Moving

This experiment is aimed at proving that the Rubbot can adapt itself to both inclined and non-inclined surfaces by assuming different postures. Fig. 16 shows the posture of Rubbot hanging on curtains of different angles.

Rubbot could move flexibly on the cloth of the entire angle, even if when it is non-rigidly backed (Table III).

Currently, most climbing robots are only applied on specific surfaces possessing certain features, such as penetrable, rigidly-backed, or magnetic. The data above reveal Rubbot's excellent applicability for diverse environments. Rubbot is able to conduct inspections while relying less on circumstance.

C. Climbing on different fabrics

The function of grippers partly depends on the fabric's coefficient of friction. Moving experiments have been conducted on various different fabrics. Rubbot is shown to still succeed to climb cloth made of denim, woolen, cotton and silk (Fig. 17).

TABLE III

MOVING CAPABILITY OF DIFFERENT ANGLE

angle(°)	Straight moving	Turning
0	√	√
45	√	√
90	√	√
135	√	√
180	√	√

V. CONCLUSION AND FUTURE WORK

Rubbot is designed to climb flexible surfaces. Experiments confirmed that gripper structure offers significant advantages for cloth climbing. Moreover with its foldable frame structure, moving on cloth becomes more smooth. Additionally, though kinematic analysis of Rubbot's rotation and force calculation of cloth, we find a theory of how creases are generated on cloth. Finally, a series of experiments have verified Rubbot's unprecedented performance when climbing flexible loose cloth.

Research on flexible surface climbing still has many questions that need to be solved. The theory of cloth deformation needs to be completed. In addition, a future task is to make use of positive creases and eliminate negative ones. In conclusion, continued research is needed to discover better and better ways to climb flexible cloth.

ACKNOWLEDGMENT

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