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Path Planning for Clothes Climbing Robots on Deformable Clothes Surface

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***Abstract*— This paper proposes a novel path planning method for a robot to climb on the deformable clothes surface. Based on the deformable characteristic of the clothes, the tension force of clothes is analyzed and the model of tension degree is established. A clothes climbing robot called Clothbot is composed of a two-wheeled gripper and a 2 Degrees of Freedom (DOF) tail. Based on the locomotion of this robot, the weights of tension degree and the locomotion characteristic are added into the A^* algorithm. Combined with the two weights applied, the optimal path to the target for the Clothbot is obtained. The Clothbot has been developed to evaluate the algorithm. The simulation and the experiments have verified the feasibility of this method. In addition, The error state of the movement of the robot which is called side tumbling has been corrected by the motion of the 2-DOF tail.**

I. INTRODUCTION

Vertical climbing robots have numerous uses within service, cleaning, monitoring, and military applications. They can go deep into places that are dangerous or otherwise unreachable by humans. Current climbing robots can climb on vertical walls, glasses, or ceramic tiles. Climbing robots equipped with specialized grippers can climb on different rigid, vertical surface. Treebot uses elastic claws to grip the branches of trees firmly and moves by the extension of the omni-directional spine [1]. Chung proposes a movable gripper to move on trusses [2]. It consists of a rigid tail and a wheeled gripper which adjusts the inter-gripper distance. Waalbot [3] uses flat adhesive elastomer materials for attachment. It is composed of two rotation legs and a supporting tail. It performs well on the flat and rigid surfaces. CLASH [4] is regarded as the first cloth climbing robot. The robot, which has six legs connected to a movable spine, uses a simplified structure to achieve one-dimensional locomotion.

While the robot has the capability to climb on soft clothing, the motion planning on the deformable surface is the next problem to solve. In order to accomplish the task on the deformable surface, robot need the capability to arrive at the destination. There are existing motion planning works for climbing robots on the rigid surface such as glasses and walls [5], [6], [7], [8], [9], but these methods cannot be applied to the robot climbing on the deformable surface. Climbing on the vertical deformable surface is a new research topic. The main difference between the two types of surfaces is the dynamic deformation. The deformation, which is caused by the gripping, changes the shape of the surface nearby. Hence the obstacles appears unpredictably. As a result, robots not only need the capability to grip the vertical deformable surface but also are able to adapt to the deformation.

Different grippers determine the different strategies of the path planning. A robot called Clothbot has been developed in this work, which climbs on deformable clothes [10]. Clothbot has a two-wheeled gripper and a 2-DOF tail. The two-wheeled gripper clamps the clothes firmly and the tail adjusts the robot pose to navigate on the clothes surface. The prototype and the improved version of the Clothbot are shown in Fig. 1. The improved Clothbots have been equipped with 3-axis accelerometer and binary touch sensors.

Fig. 1. Prototype and the improved visions of Clothbot: the upper figures are the prototype of Clothbot and the lower robots are the improved Clothbots, which are equipped with protective shells.

This paper proposes a novel path planning algorithm to enable the robot to climb on the deformable clothes surface. To simplify the problem, we divide the overall path planning process into five stages: 1) establish the clothes

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model, 2) determine the tension of the deformable surface, by describing the degree of tightness gained from the analysis of the model, 3) transform the 3D model onto a 2D plane and remove the unreachable regions, 4) add the weights to the A^* algorithm to obtain the optimal path, 5) the robot performs the task of following the optimal path to reach the goal region. Because of the special mechanical structure of Clothbot, the algorithm is able to be optimized and the robot performs as expected.

The following parts are organized as follows. Section II is the brief introduction of Clothbot. The path planning is presented in section III. Section IV explains the system architecture of Clothbot. Experiments and results are shown in section V. Conclusions and the future works are presented in VI finally.

II. INTRODUCTION OF CLOTHBOT

Clothbot is a novel climbing robot which climbs on deformable clothes. It is composed of a two-wheeled gripper and a 2-DOF tail. The gripper clamps the clothes crease folded by the robot's gripper firmly and the tail adjusts its pose by the balance of the gravity. Fig. 2 shows the structure of Clothbot.

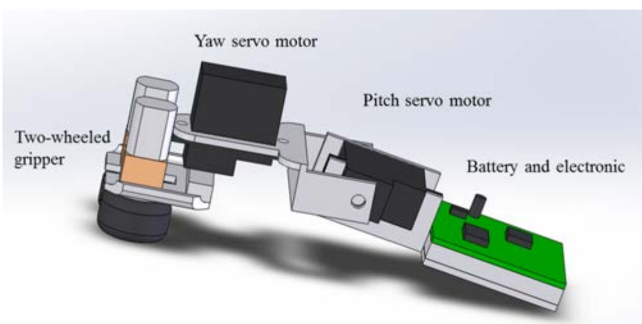

Fig. 2. Structure of Clothbot: Clothbot is composed of a two-wheeled gripper and a 2-DOF tail. The tail consists of the yaw and pitch servo motors. The battery and electronic are fixed at the end of the tail.

The Clothbot only grips a single point on the clothes by the two-wheeled gripper. The 2-DOF tail connects to the root of the gripper. So that the robot is hanged on the clothes. The two gripping wheels clamps the crease of the clothes and the rotation of the wheels drives the robot moving forward or backward following the crease. While the wheels rotate in the same direction, sliding is happened within the crease between the wheels. Hence the direction of the crease is changed. The 2-DOF tail controls the direction of the head of the Clothbot with the aid of gravity. Combined with this two motion, Clothbot maneuvers on the clothes surface flexibly. The diagram of motion control of the clothbot is shown in Fig. 3.

III. PATH PLANNING

There are numerous studies of path planning in normal environments [11],[12]. However, fewer studies have examined deformable surfaces. We propose a quasi-dynamic path planning method for climbing on deformable clothes. In

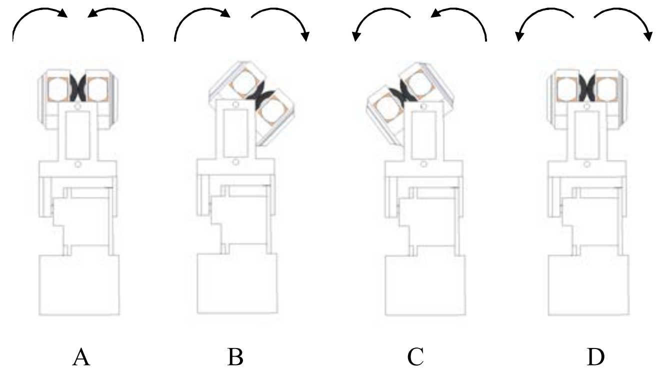

Fig. 3. Motion of Clothbot. A) While the two gripping wheels rotate inward, the robot moves upward. B) While the two gripping wheels both rotate clockwise, sliding is happened within the crease of the clothes between the wheels, then the direction of the crease is turn to right. With the anticlockwise swinging of the tail, the robot turns right. C) While the gripping wheels both rotate anticlockwise and the tail swings clockwise, the robot turns left. D) While the two gripping wheels rotate outward, the robot moves downward.

order to simplify the model of the body we assume that the human wearing the clothes is still. First we get the grid model, and then update the tension degree. We remove the unreachable region and then compute the optimal path. Finally the robot is guided to track the path with a unit length. After that, the tension degree is updated again. Fig. 4 shows the diagram of the path planning.

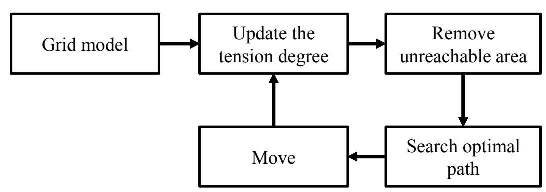

Fig. 4. Diagram of the path planning

A. Model of Deformable of Clothes

The most important stage of the path planning process is the parameterization of the climbing surface. Most path planning algorithms are based on the shape of its work space. In the present case, the conventional methods do not apply as the surface is deformable and unstable. Sachin Patil [13] has proposed a motion planning in highly deformable environments. He modeled the highly deformable environments by 2D grids. To describe the characteristics of clothing surface, tension degree is introduced into the modeling. Clothes can be easily folded and the tension on the material can differ at different places on the same item of clothing. For example, the bottom of a dress is loose while the area near the shoulder is tight. To represent the tension of the deformable surface, an equal cell size gird is superimposed on a T-shirt. The intersections of lines are nodes. While a body model wears this unique T-shirt, The gird on the surface of the clothes is nonuniform distribution because of the uneven surface of the body model. The uneven surface of the clothes is shown in Fig. 5.

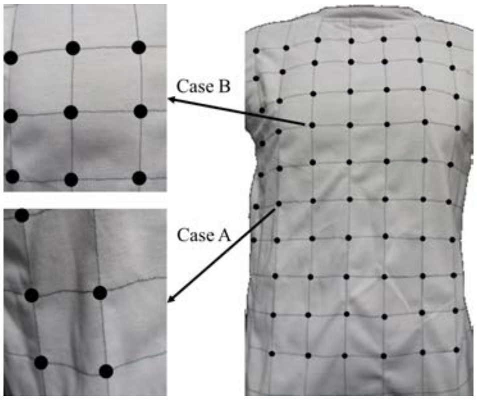

Fig. 5. Model of the clothes and the distance analyze of nodes: case A/case B is the loose/tight cloth and the distance between two adjacent nodes is less/large than the original distance.

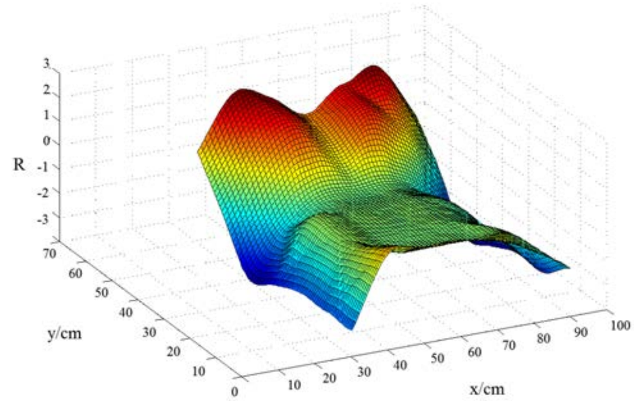

Fig. 6. The 3D model of tension degree: the x-y plane is the grid node index and the z axis is represented the tension degree between adjacent nodes.

B. Parameterization of Deformable Clothes

Clothing is characterized by deformability. The distances between adjacent nodes change when the clothes are worn on the body. The clothing can be compressed but has limited extension. The actual distance between the two adjacent nodes is represented by the following two cases. In case A, the actual distance is less than the original distance. In this case the clothes compresses and the crease is generated. In case B, the actual distance is larger than the original distance. Different types of cloth have different degrees of extension because of the different materials and weaving methods used. Most clothes are designed to extend to some degree for comfort reasons. Nonetheless in case B the distance of extension is not very large. Fig. 5 shows the girds shapes of the two cases.

We propose to use tension degree to describe the tightness of the clothes. We assume that the value of original distance between nodes is zero. If the clothing is tight, the value increases and vise versa. The value of the distance between adjacent nodes is obtained by a depth camera. Then the relative tension degree is estimated by the error between the original and the actual distance of the adjacent nodes.

Another significant characteristic of the model is that whether the support is under the clothes surface. The irregular body model leads to the gaps between the body model and the clothes surface. It is proved by the climbing experiments of Clothbot that the robot is easy to climb while there are supports under the cloth, because the range of adjusted angle driven by the pitch motor is large and the robot is stable. It is difficult to obtain the distribution of the supports under the clothing surface. Therefore we use prior knowledge of body shape and experiments to obtain the original distribution of tension degree. Tension degree is the incorporation of the original tension of the surface and the supports under the surface. While the original model of tension degree is acquired, the value obtained by the depth camera is used to adjust the original value. Finally the adjusted data of tension degree is obtained. The 3D model of tension degree is smoothed as shown in Fig. 6.

C. Remove the Unreachable Region

The basic function of path planning is to reach the target while avoiding the obstacles [14]. The path planning for Clothbot has the following requirements.

1)Get the target place.
2)Find the closest path to the target.
3)Cannot drop from clothes.
4)Avoid obstacles.

Clothbot has good maneuverability on the clothing surface while the tension degree is within a certain range. There are two kinds of situation that the Clothbot is unable to reach the target destination: 1) the clothes is too tight to form a crease and the robot drop from the clothes and, 2) the clothes is too loose and has too many creases. In the second state Clothbot can hardly move because the crease around the robot produces too much resistance.

To ensure the robot can regularly climb on most clothing materials, nodes with high tension degree are treated as obstacles and are removed. Nodes with lower tension degree are also removed because of the high level of resistance. If connections between initial node and target node are available on the retaining lines, the path planning is feasible, and vice versa. The connecting lines that are retained constitute the feasible path to the target. The region is shown in fig. 7.

D. Analysis of the Direction of Clothbot

Clothbot uses gravity to adjust its pose. The robot head cannot face downward because the angle between the direction of gripper and the vertical line is plus or minus 90 degrees. Therefore, Clothbot has limited feasible pose. For example, if the robot wants to move in 5 o' clock direction, then it must turn to 11 o'clock and move backward, and vice versa. Due to the gravity, it is easier for Clothbot to move downward than upward. Therefore, Clothbot has different degrees of locomotion difficulty. A Locomotion Difficulty Index (LDI) is utilized to parameterize the locomotion difficulty.

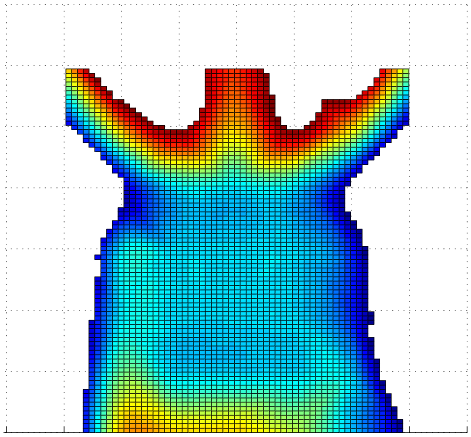

Fig. 7. Model of the retained reachable region

Moving along an upward slop has lower LDI than climbing straight up. Fig. 8 shows the four parts of the direction of robot movability.

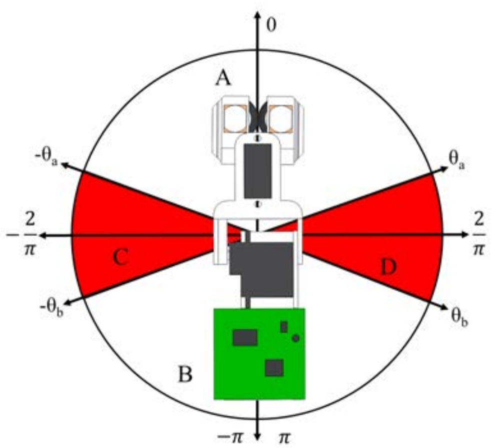

Fig. 8. Analysis of the direction of Clothbot: the white/red area indicates the feasible/infeasible direction of movement.

We model the LDI as a linear function of the angle between the turning direction and the vertical line. The value of LDI is 1 when the direction is straight downward. The corresponding function is as follows:

$$\begin{cases} R(\theta) = k_u|\theta| + 1 + t \quad (\theta \le |\theta_a|) \\ R(\theta) = \infty \quad (|\theta_a| < \theta \le |\theta_b|) \\ R(\theta) = k_d|\pi - \theta| + 1 \quad (|\theta_b| < \theta \le |\pi|), \end{cases} \tag{1}$$

where θ is the angle of the motion direction, $R(\theta)$ is the LDI related to θ, θ_a and θ_b are the thresholds of the angle of movement of the robot, t is the offset of the upward and the downward movement, and k_u and k_d are the coefficients of the LDI.

E. Improved A^* Algorithm

The improved A^* algorithm is employed in the path planning. A^* uses a best-first search and finds the least-cost path from the initial node to the target node [15]. The algorithm uses a heuristic function to determine the path in the tree. The function is as follows:

$$F(i) = G(i) + H(i), \tag{2}$$

where $F(i)$ is the expectation of the overall length of the path, $G(i)$ is the cost from the starting node to the current node, and $H(i)$ is an admissible heuristic estimate of the distance to the goal.

To apply A^* algorithm to the path planning of Clothbot, the weight of the different direction of movement and the tension degree are added in to the algorithm. Then $G(i)$ and $H(i)$ can be represented as follows:

$$\begin{aligned} G(i) = \sum_{n=0}^{i} ((k_t|R_t| + 1) \\ \times R(A(P(x_{n-1}, y_{n-1}) \to P(x_n, y_n))) \\ \times D(P(x_{n-1}, y_{n-1}) \to P(x_n, y_n))), \end{aligned} \tag{3}$$

where R_t is the tension degree of the current segment of the path, k_t is the coefficient of the tension degree, $D(P(x_{n-1}, y_{n-1}) \to P(x_n, y_n))$ is the geodesic distance between the current node and the next node, and $A(P(x_{n-1}, y_{n-1}) \to P(x_n, y_n))$ is the angle between the next direction of movement and the vertical axis.

$$\begin{aligned} H(i) = \min((k_t|R_t| + 1)) D(P(x_i, y_i) \to P(x_t, y_t)) \\ \times \min(R(A(P(x_i, y_i) \to P(x_t, y_t)))), \end{aligned} \tag{4}$$

where $D(P(x_i, y_i) \to P(x_t, y_t))$ is the distance between the target node and the current node, $A(P(x_i, y_i) \to P(x_t, y_t))$ is the angle between the target direction and vertical axis. The minimum of the tension degree is 0 and the minimum of the LDI is 1, so (4) can be simplified as follows:

$$H(i) = D(P(x_i, y_i) \to P(x_t, y_t)). \tag{5}$$

$H(i)$ is the minimum of the actual distance, therefore it must be less than the estimate value. Hence A^* algorithm can obtain the optimal path. Finally, we smooth the optimal path. Fig. 9 illustrates a path obtained by the improved A^* algorithm. In order to show the path clearly, the model of tension degree is light-colored in the figure. In the figure the red line (Path A) indicates the optimal path with the A^* algorithm while the green line (Path B) denotes the optimal path with improved A^* algorithm. It can be obtained that path B has lower curvature than path A. The original path obtained by the improved A^* algorithm has number of turning points. In order to make the robot track the optimal path easily we simplify the path by several line segment (Path C) which is suitable for robot to track. Fig. 9 shows the simplified path.

IV. SYSTEM ARCHITECTURE

A. Electronic Structure

The control of Clothbot is through Blue-tooth Transfer Module, which is equipped with most of handhold devices such as mobile phones and notebook computers. The Clothbot control system based on Java 2 Micro Edition (J2ME) platform is developed and installed on mobile phones with symbian system.

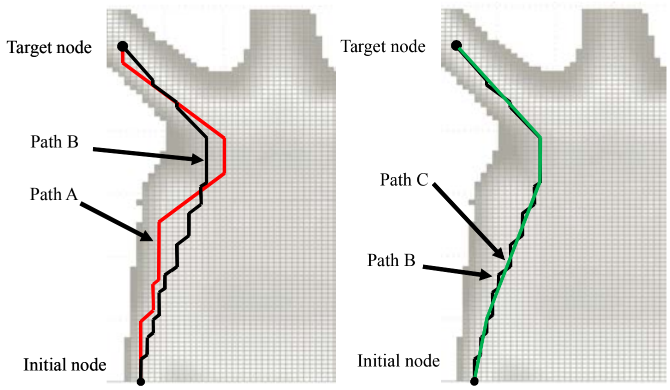

Fig. 9. The comparison between the path of A^* algorithm and the improved A^* algorithm: Path A is the path of the A^* algorithm while Path B is the path of the improved A^* algorithm with the weight of the locomotion, respectively. Path C is the smoothed path.

Clothbot is equipped with two kinds of infrared sensors. Opposite type of infrared sensors are used in detection of the crease gripping by gripper. Reflection type infrared sensors are placed at both sides of the robot to detect the side tumbling. To keep balance, a three-axis accelerometer is equipped on the tail to obtain the pose of Clothbot.

B. Side Tumbling and Solution

Side tumbling of Clothbot is an unexpected state, which is encountered during the inclined climbing on clothes. The side of the robot is closed to the clothes surface. The cause of this state is the loosing of clothes. The unexpected climbing condition results in self-rotating about 90 degrees clockwise or anticlockwise at the roll direction. In this case, locomotion of Clothbot fails. Tail rotation is employed to address this problem. The tail has two DOFs, and it has the ability to complete a conical pendulum motion. Fig. 10 shows the sequence of motion to recovery from a side tumbling. When the side tumbling is clockwise, the tail actuates anticlockwise conical pendulum motion, and vice vera.

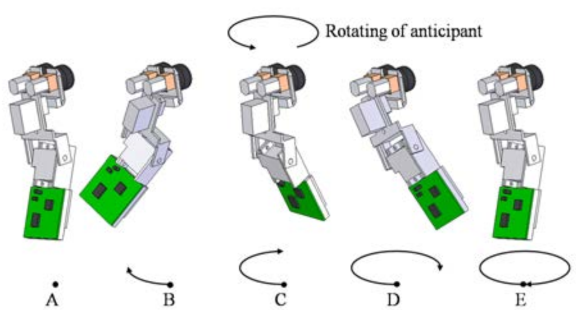

Fig. 10. Tail's motion to recover from a side tumbling

When the tail is moving at conical pendulum, the trajectory of the bottom of tail is an approximate circle and part of the trajectory contacts the clothes surface. The rotating force on clothes surface makes the Clothbot rotate in the opposite direction and recover from a side tumbling.

V. EXPERIMENTS

A. The Area of Reachable of Clothbot

In order to verify the area where Clothbot is able to climb, we kept the robot climbing on the clothes and recorded place where the robot cannot climb. Fig. 11 shows the comparison of the model established with tension degree and the actual area the robot cannot climb. It shows that the unreachable area is similar.

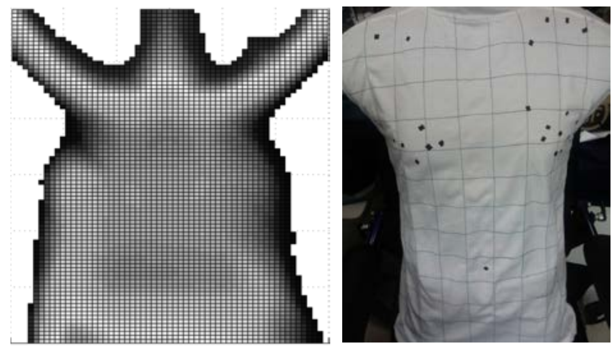

Fig. 11. Comparison between the model and the actual unreachable area: the black points on the clothes in the right figure are the recorded points where the robot cannot climb, while the white area in the left figure is the theoretical unreachable region. They have the similar shape on the clothes.

B. Path Planning

In order to evaluate the path planning method, a physical experiment have been conducted. The target region was set under right shoulder and the initial region was at the bottom of clothes. Fig. 12 shows the experiment of the path planning and Fig. 13 illustrates the planned path and the actual trajectory of Clothbot. The error between the two paths is caused by the manual operation of Clothbot. The robot can track the path acceptably and arrive at the target place successfully.

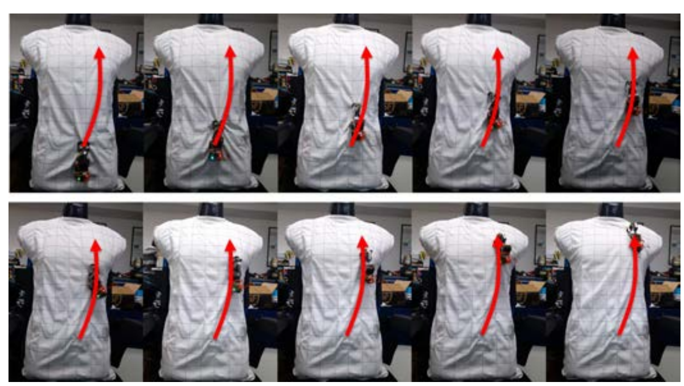

Fig. 12. Path planning test

C. Side Tumbling

This experiment evaluates the method to solve side tumbling. Fig. 14 shows the five states of side tumbling correction corresponding to Fig. 10. The left figure in Fig. 14 is the side tumbling state of Clothbot. Table I shows that the

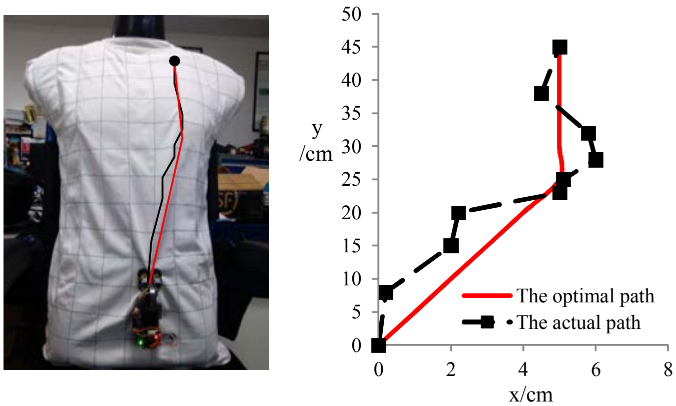

Fig. 13. Comparison between the optimal and the actual path in the test

TABLE I
SOLVING OF THE SIDE TUMBLING

Side tumbling	Successful solved	Total tests
Left tumbling	40	50
Right tumbling	42	50

total number of tests and the number of successful trial. It is separated into left tumbling and right tumbling. The rate of success is 82 percent.

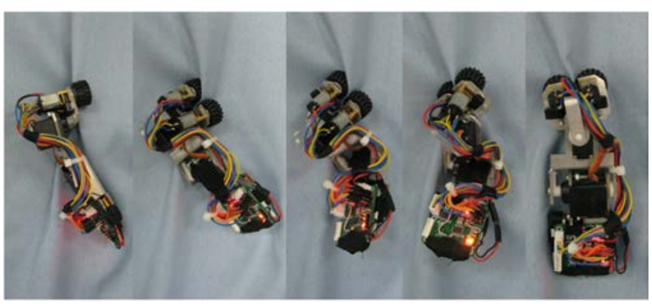

Fig. 14. The performance on recovery from the side tumbling

VI. CONCLUSION AND FUTURE WORKS

This paper proposed a novel path planning method for a robot to climb on deformable clothes. Based on the tension force of the clothes surface we parameterized the surface by tension degree. Combined the LDI of the robot and the tension degree of the clothes, the improved A^* algorithm is applied and the planned path is represented. The theoretical analysis and the experiments show that the path planning method has a satisfying performance. This path planning method not only can be utilized on the clothes climbing, but also could be applied on other deformable surface path planning. Finally the problem of side tumbling has been solved successfully.

The method of path planning on deformable surface is achieved, however, there are several topics to research. The value of the tension degree is low accuracy and the method to obtain the value contain the prior knowledge. We will explore other effective methods to obtain the dynamic tension degree. The control of the robot is manual and the next work is to achieve the automatic tracking of the planned path to improve the accuracy of the tracking.

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