A flexible tree climbing robot: Treebot - Design and implementation

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A Flexible Tree Climbing Robot: Treebot – Design and Implementation

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Abstract— **This paper proposed a novel tree climbing robot "Treebot" that has high maneuverability on an irregular tree environment and surpasses the state of the art tree climbing robots. Treebot's body is a novel continuum maneuver structure that has high degrees of freedom and superior extension ability. Treebot also equips with a pair of omni-directional tree grippers that enable Treebot to adhere on a wide variety of trees with a wide range of gripping curvature. By combining these two novel designs, Treebot is able to reach many places on trees including branches. Treebot can maneuver on a complex tree environment, but only five actuators are used in the mechanism. As a result, Treebot can keep in compact size and lightweight. Although Treebot weighs only 600 grams, it has payload capability of 1.75 kg which is nearly three times of its own weight. On top of that, the special design of the gripper permits zero energy consumption in static gripping. Numerous experiments have been conducted on real trees. Experimental results reveal that Treebot has excellent climbing performance on a wide variety of trees.**

I. INTRODUCTION

Climbing robots have become a hot research topic in recent decades [1], [2], [3], [4], [5], [6], [7]. Most research in this area focuses on climbing manmade structures, such as vertical walls, glass windows, and structural frames. Little research has been conducted specifically on climbing natural structures such as trees. The nature of trees and manmade structures is very different. For example, trees have an irregular shape and their surface is not smooth. Some types of trees have soft bark that peels off easily. Hence, most of the methods applied in the development of wall-climbing robots are not applicable for tree climbing robots.

Preventing trees from failing is important to protect human life and property in urban areas. Most trees in urban areas require regular maintenance. To reach the upper parts of a tree to perform such maintenance, workers need to climb the tree. However, tree climbing is dangerous, and thus the development of a tree-climbing robot could assist or replace tree climbers in their work.

Several robots have been designed to climb trees. WOODY [8] is a climbing robot designed to replace human workers in removing branches from trees. The robot climbs by encircling the entire tree trunk. The size of the robot is thus proportional to the circumference of the trunk. WOODY avoids branches by turning its body and opening the gripper, but it requires an almost straight tree trunk. Kawasaki [9] also developed a climbing robot for tree pruning. It uses a gripping mechanism inspired by lumberjacks, and uses a wheel-based driving system for vertical climbing. It encircles the entire tree trunk for fastening on a tree. It cannot avoid branches as the fastening mechanism cannot be opened. Aracil [10] proposed a climbing robot, CPR, that uses a Gough-Stewart platform to maneuver. It consists of two rings that are joined by six linear actuators through universal and spherical joints at each end. Same as [9], the gripping mechanism cannot open and hence it can only climb on tree without existing of branch. However, it has greater maneuverability than the aforementioned two robots, and can climb a branchless tree trunk with a certain range of bending. RiSE V2 [11] is a wall-climbing robot that imitates the movement of an insect in using six legs to maneuver. This robot has also been demonstrated to be able to climb trees. As the gripping mechanism only occupies a portion of the surface to be climbed, the size of the robot is independent of the climbing target. As a result, it is relatively small. However, it did not claim whether it can perform other motions such as transition from a trunk to a branch. RiSE V3 [12] is another type of climbing robot designed to climb straight poles at high speed. It can be seen that these robots are limited to climbing straight tree trunks, and cannot climb trees that are curved or have branches. As branches and curvature are present in almost all trees, the application of these robots is strongly restricted.

Fig. 1. The tree climbing robot – Treebot.

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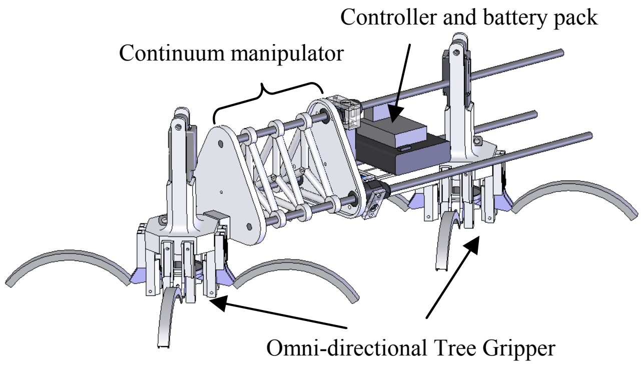


Fig. 2. Overall design of the proposed tree climbing robot.

As a result, this paper proposes a novel tree climbing robot named Treebot (as shown in Fig. 1) that has high maneuverability on tree. Treebot equips with a pair of omni-directional tree grippers that able to grip on tree surface in a wide range of gripping curvature. It enables Treebot to grip tightly on large tree trunks and small branches. The applied continuum maneuver mechanism has large workspace and high degrees of freedom (DOF). It allows Treebot to perform various actions, such as moving between trunk and branches. Treebot is compact and lightweight, only five actuators are used. The special gripping mechanism allows zero energy consumption in static gripping. With the appropriate equipment, Treebot could assist workers to perform arboricultural tasks such as inspection and maintenance. It could also be used as a mobile surveillance system to observe the living behavior of tree living animals.

The paper is organized as follow. Section II describes the mechanical design and mechanism of Treebot. In Section III, the motion of Treebot is described. The prototype of Treebot is introduced in Section IV while the experimental results are summarized in Section V. Finally, conclusion is given in Section VI.

II. MECHANICAL DESIGN OF TREEBOT

The overall design of Treebot is shown in Fig. 2. The structure of Treebot is mainly composed of two parts: an omni-directional tree gripper and a continuum manipulator. Two grippers are connected to the ends of the continuum manipulator respectively. The grippers can adhere on a tree surface tightly while the continuum manipulator acts as maneuver mechanism to move another end of the gripper to a target position.

A. *Omni-directional Tree Gripper*

There are many innovative approaches to provide adhesive force such as vacuum suction [5], [13], [14], [15], magnetic attraction [6], [7], [16], [17], [18], elastomeric adhesive [4], [19], electroadhesive [2] and fibrillar adhesive [1], [3]. These methods work well on urban settings such as vertical walls and glass windows that are smooth and flat. However, they are not applicable on tree surface, as the nature of trees is totally different from urban settings. Claw climbing method

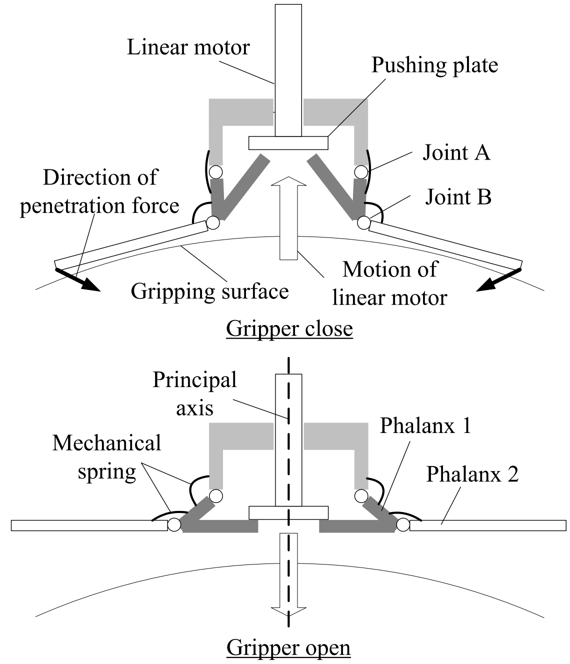


Fig. 3. Mechanism of the omni-directional tree gripper in cross-sectional view.

is widely used in tree living animals such as squirrels and birds. Through the observation of the tree living animals, the claw gripping is reliable on a tree surface. As a result, the claw gripping method is adopted to provide adhesive force. The design of the proposed gripper is aimed at providing adhesive force on a wide range of gripping curvature such that the gripper is able to adhere on tree trunks and branches. The gripper is designed to be omni-directional along its principal axis so that no additional orientation actuator and control is needed in x-axis (refer to the coordinate system in Fig. 6) and hence keeps Treebot in lightweight and simple.

The gripper is composed of four claws equally separated by 90 degrees. Fig. 3 illustrates the cross-sectional view of the gripper. Each claw is formed by two parts (Phalanx 1 and 2) and has surgical suture needles installed at the tip. The adhesive force of the gripper is generated by the spine penetration.

The claws adopt two bar linkages mechanism to generate optimal direction of acting force. Fig. 3 shows the gripping mechanism. All claws in a gripper are actuated by a linear motor. A pushing plate is mounted at the end of the linear motor. When the linear motor extends, the plate pushes all the phalanges 1 and hence makes the phalanges upward. The spring on joint A is further compressed and the spring on joint B is released at the same time. This motion pulls spines off from gripping substrate. When the linear motor contract, the compressed springs on joints generate a force to push claws back to the gripping substrate and at the same time the spring on joint B will further be compressed. Since the gripping force is generated by the preloaded springs only, the static gripping with zero energy consumption can be achieved. The constant force spring (a flat spiral spring) is adopted to ensure that the force is independent to the claw traveling angle. In addition, since the moving mechanism of each claw is independent, it allows the claws to travel in different angle. This ensures that all of the claws penetrate into the gripping substrate, even if it has an irregular shape, to generate the maximum force.

B. Continuum Manipulator

There are many types of continuum manipulators, such as wire-driven [20], [21] and pneumatic-driven [22], [23], [24]. Most of them are able to bend in any direction and some are even able to extend to a certain extent. Most current research uses the continuum structure in robot arms, but few researchers have realized that it can also be applied to maneuvering. The continuum mechanism is a compliant structure, as it does not contain fixed joints [25]. Its inherent passive compliance is particular benefit for maneuvering in an arboreal environment, as it can often eliminates the need for complex force sensing and feedback control [26]. For climbing purposes, the manipulator must be compact and lightweight. There are many types of continuum manipulator, but none of them fulfills all of these requirements. Existing continuum manipulators need to connect to large external boxes that contain wire, drivers, motors, or air pumps. Although some pure wire-driven continuum manipulators [27], [28] have the potential to be more compact and lightweight, the manipulators are not extendable. Extendibility is important, as Walker [29] shows that the inclusion of extension ability for continuum manipulators extends the workspace considerably.

Due to these limitations, a novel design of continuum manipulator to maneuver with both bendable and extendable functionalities is proposed. The proposed continuum manipulator is a self-contained module that actuators are integrated and hence no external control box is required. It makes the proposed continuum manipulator compact and lightweight. In addition, the special driving mechanism allows superior extension ability that the existing designs cannot achieve.

Fig. 4 shows the CAD model of the proposed continuum manipulator. It is formed by three mechanical springs that are connected in parallel. The distance between the center of the continuum manipulator and springs are equal and the springs are equally separated by 120 degrees as shown in Fig. 9(a). One end of spring is fixed on a plate, while the other end does not have any fixed connection. The springs pass through a plate which contains three DC motors to control the length of springs between two plates independently. Through the control of the length of each spring, the continuum manipulator can perform bending and extension motions. Fig. 5 shows the prototype and illustrates the admissible motion of the continuum body. Commonly, the number of actuators required in each section of continuum manipulator is more than the number of admissible degrees of freedom. However, in the proposed structure, only three actuators are used but it can provide 3 DOF. This structure provides maximal DOF with minimal actuators. The actuation mechanism is similar to rack and pinion mechanism which allows unlimited extension of the continuum manipulator theoretically. In practice, it is limited by the length of the springs only. The spring can be treated as a bendable rack. The spring should only be allowed to bend in any direction but not able to compress or extend so as to keep a constant gap distance for pinion to drive. On top of that, keeping the springs in constant distance through the entire manipulator is important to keep a uniform shape. As a result, several passive spacers are installed at the middle of the manipulator to constrain the distance among springs. The maximal distance between constraint plates are constrained by wires.

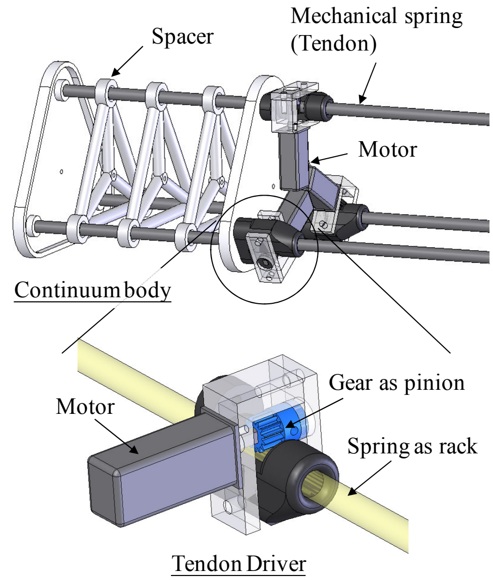


Fig. 4. Design of the proposed continuum manipulator.

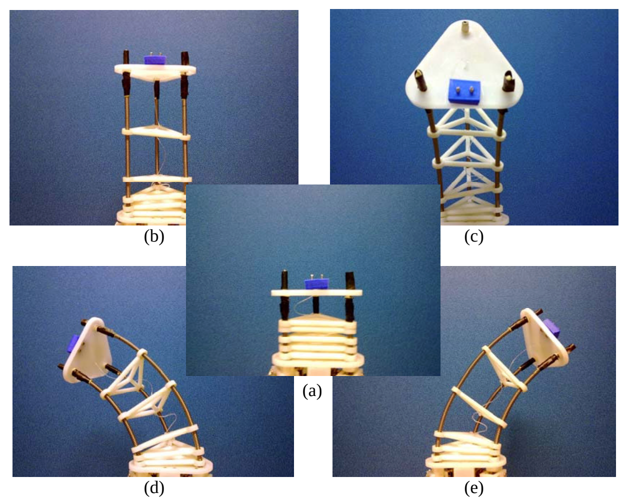


Fig. 5. Prototype of the continuum body and illustration of the degrees of freedom: (a) contraction; (b) extension; (c) forward bending; (d) right bending; (e) left bending.

III. Motion of Treebot

The configuration of the tree climbing robot is shown in Fig. 6. There is one active continuum manipulator driven by three actuators and a passive 1 DOF revolute joint with

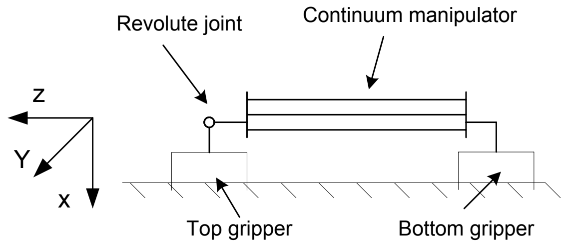


Fig. 6. Configuration of Treebot.

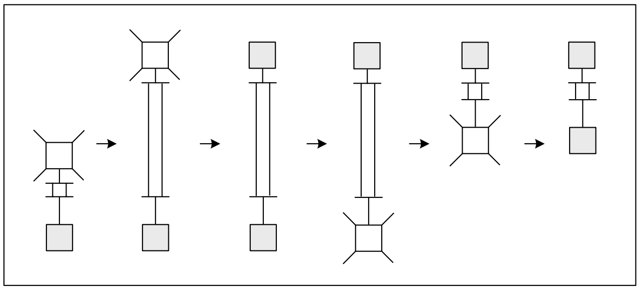


Fig. 7. A complete climbing gait of Treebot (moving forward).

mechanical spring. The continuum manipulator provides two DOF for bending and one DOF for extension. The inherent passive compliance also allows the continuum manipulator to be sheared in x- and y-axes and twisted in z-axis by external force. This passive compliance is resulted by the 2D bendable ability of the mechanical springs. The amount of compliance will increase when the continuum manipulator extends. This compliance is useful to place the gripper appressed to a gripping surface without using additional actuators and hence a lightweight mechanism can be achieved. Since the compliance does not include the revolute motion in y-axis which is also a key DOF to place the gripper in a proper way, a passive y-axis revolute joint with mechanical spring is installed between the top gripper and the continuum manipulator.

A. Locomotion of Treebot

The locomotion of Treebot is similar to inchworms which is a kind of biped locomotion. Fig. 7 shows a complete climbing gait of the locomotion. It is composed of six climbing steps. The square colored in grey represents the closed gripper that attached on the substrate while the square colored in white represents the opened gripper that detached on the substrate. The order of motion in the figure represents the locomotion of moving forward. The locomotion of moving backward is just in reverse order.

Treebot is able to change a moving direction in three-dimensional space by bending the continuum manipulator. It allows Treebot to climb along a curved shape of tree or avoid obstacles such as non-passing through branches. This ability makes Treebot has high maneuverability that surpass the existing tree climbing robots.

Fig. 8 shows part of climbing motions to avoid an obstacle on a tree. Treebot can first adjust the direction of the bottom gripper and then climb along this direction to avoid the obstacle. This method is also applicable for turning to another side on a branch or selecting a branch to climb.

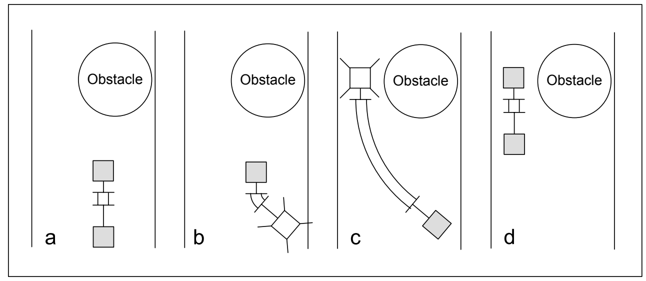
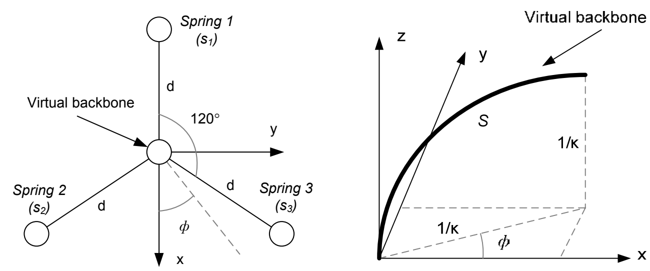


Fig. 8. Motions to avoid an obstacle.



(a) (b)

Fig. 9. Notations of the kinematics of continuum manipulator.

B. Kinematics of the Continuum Manipulator

Jones [30] introduces a kinematic model for a general class of continuum robot. It is found that this model is also suitable to represent the properties of the proposed continuum manipulator. According to [30], the forward and backward kinematics in our notations and coordinate system can be formulated as:

Forward kinematics

$$\begin{bmatrix} S \\ \kappa \\ \phi \end{bmatrix} = \begin{bmatrix} \frac{s_1+s_2+s_3}{3} \\ 2\frac{\sqrt{{s_1}^2+{s_2}^2+{s_3}^2-s_1s_2-s_2s_3-s_1s_3}}{d(s_1+s_2+s_3)} \\ \cot^{-1}\left(-\frac{\sqrt{3}}{3}\frac{s_3+s_2-2s_1}{s_2-s_3}\right) \end{bmatrix} \quad (1)$$

Inverse kinematics

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = S \begin{bmatrix} 1+d\kappa\cos\phi \\ 1-\kappa d\sin(\pi/6-\phi) \\ 1-\kappa d\sin(\pi/6+\phi) \end{bmatrix} \quad (2)$$

where s_i is the length of spring i (i=1,2,3), d is the distance between spring and virtual backbone. S is the length of virtual backbone, κ is the curvature of virtual backbone and ϕ is the direction of curvature (Fig. 9(b)). The virtual backbone represents the entire continuum manipulator which located at the middle of the mechanical springs (Fig. 9(a)).

Assuming that one end is located at the origin, the Cartesian coordinates of another end point is:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{\kappa} \begin{bmatrix} [1-\cos(\kappa S)]\cos\phi \\ [1-\cos(\kappa S)]\sin\phi \\ \sin(\kappa S) \end{bmatrix} \quad (3)$$

In addition, the direction at the end point is:

$$\vec{v}' = Rot_z(\phi)\, Rot_y(\kappa S)\, Rot_z(-\phi)\, \vec{v} \tag{4}$$

where $Rot_z()$ and $Rot_y()$ are the 3D rotation matrix about z- and y-axis respectively. $\vec{v}'$ is the direction of the end point. $\vec{v}$ is the initial direction of the end point without bending.

C. Control of Treebot

In this state, Treebot is a remote control robot. The control input of the gripper is simply an on/off command to make grippers fully open or close. As for the control of the continuum manipulator, since it has three DOF, three channels of input are needed. One way is to directly input the length of each spring. However, it is not an intuitive way for human manipulation. Human being always has a perspective of the direction of motion when controlling something, i.e., the concept of left, right, front and back. As a result, to make an intuitive controller, we define three control inputs, i.e.,S_{input}, κ_{input}^{FB} and κ_{input}^{LR}. S_{input} controls the length of virtual backbone, κ_{input}^{FB} controls the magnitude of front and back bending while κ_{input}^{LR} controls the magnitude of left and right bending. The concept of front is defined as the direction of positive x-axis while the concept of left is defined as the direction of positive y-axis. The mapping from the control inputs to the posture of the continuum manipulator are:

$$\begin{bmatrix} S \\ \kappa \\ \phi \end{bmatrix} = \begin{bmatrix} S_{input} \\ \min\left(\sqrt{{\kappa_{input}^{FB}}^2 + {\kappa_{input}^{LR}}^2}, \kappa_{\max}\right) \\ \operatorname{atan2}\left(\kappa_{input}^{LR}, \kappa_{input}^{FB}\right) \end{bmatrix} \tag{5}$$

where $S_{input} \in [0, S_{\max}]$ and $\kappa_{input}^{FB}, \kappa_{input}^{LR} \in [-\kappa_{\max}, \kappa_{\max}]$.

Once the posture of the continuum manipulator is determined, the length of each spring can be found by (2).

D. Workspace Analysis

The workspace depends on the maximal bending curvature κ_{max}, maximal length S_{max} and the compliance of the mechanical springs. It is assumed that three mechanical springs have same maximal length and bendable curvature, i.e., $\kappa_{max} = 33.3m^{-1}$ and $S_{max} = 340mm$. By using the kinematic model introduced in Section III-B, the curves in Fig. 10 illustrates part of the reachable positions of the continuum manipulator. The green vectors in the figure represent the initial direction of the top gripper in maximal reachable positions. The reachable positions of the continuum manipulator do not equivalent to the workspace of the robot as the gripper work directionally. Since the compliance of the passive joint and continuum manipulator allow certain adjustment of the direction of gripper, the workspace at each reachable point of continuum manipulator is a spherical surface that illustrated in Fig. 11.

In reality, the posture of the continuum manipulator may not exactly equal to the analytical result as shown in Fig. 10 due to the gravitational force. As mentioned in Section II, the continuum manipulator can be deformed by external force due to the inherent passive compliance. The magnitude of deformation is inversely proportional to the rigidity of the springs and proportional to the weight of Treebot.

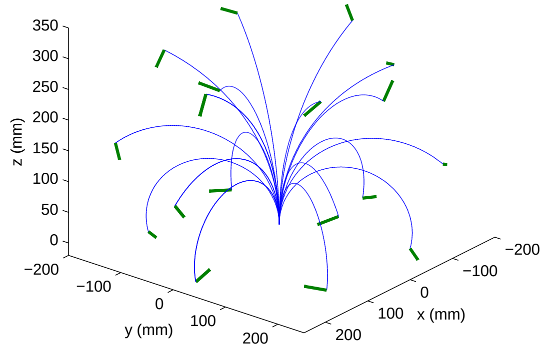


Fig. 10. Workspace of the continuum manipulator.

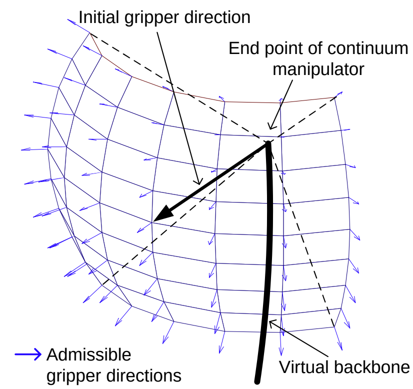


Fig. 11. Workspace of Treebot at each reachable position.

E. Limitation of Climbing Slope

As the additional revolute joint is a passive joint, the maximal climbing angle is determined by the location of the center of mass. Fig. 12(a) illustrates the relationship between the location of the center of mass and the limitation of the climbing slope. If the climbing angle exceeds the limit, the bottom gripper will be pulled out of the gripping substrate by the gravity as illustrated in Fig. 12(b). In this case, bending the body can make the bottom gripper contacts the surface but there is no method to place the bottom griper appressed to the tree surface as shown in Fig. 12(c). If the climbing angle does not exceed too much, the bottom gripper may still be able to grip the tree surface and provide enough gripping force as some tolerance of gripping direction is allowed. Treebot may still be able to climb up continuously if the top gripper can place appressed to the gripping surface by compliance.

IV. PROTOTYPE OF THE TREE CLIMBING ROBOT

Fig. 13 shows the prototype of Treebot. The mechanical parts are mainly made by polyoxymethylene plastic and aluminum alloy to keep Treebot in lightweight while the springs on continuum manipulator are made by steel. As a result, it only weight 600 grams. Treebot is able to extend 330 mm and the climbing speed is 22.4 cm/mins. It is able

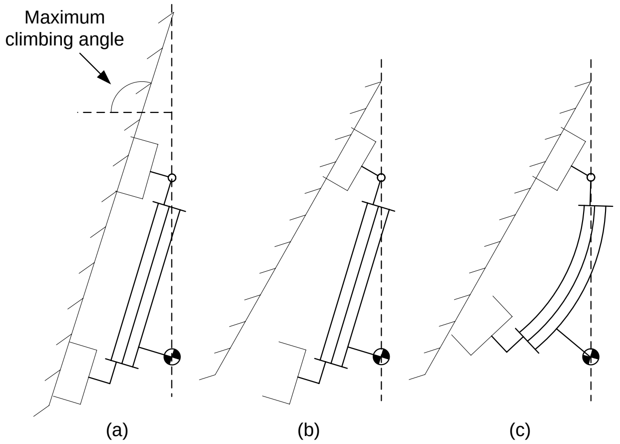


Fig. 12. Relationship between the location of center of mass and the limitation of climbing slope.

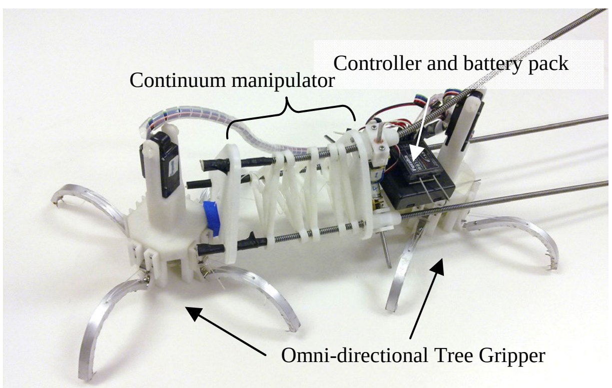


Fig. 13. Prototype of Treebot.

Fig. 14. Tree climbing with 1.75 kg payload.

TABLE I
SPECIFICATIONS OF THE TREE CLIMBING ROBOT

Parameters	Values
Weight	600grams
Height	135mm
Width	175mm
Length (Minimum)	325mm
Length of extension	665mm
Maximal bending curvature	33.3m^{-1}
Power source	NiMh 4.8V 1000mAh
Continuous operating time	180 minutes
Maximal climb-up speed	22.4cm/min
Maximal climbing angle	105 degrees
Maximal payload	1.75kg

to lift up 1.75 kg extra weight which is nearly three times of its own weight (see Fig. 14). The detail specifications are summarized in Table I.

V. EXPERIMENTS AND RESULTS

Numerous experiments have been conducted to evaluate the performance of Treebot in different aspects, i.e., 1) Climbing on different species of trees; 2) Transition motion; 3) Turning motion; and 4) Slope climbing.

A. Climbing on different species of trees

The tree climbing tests have been implemented on thirteen species of trees. Fig. 15 shows some of the tested trees. Treebot is commanded to perform vertical climb up motion. The species of trees, diameters and the number of total trials and successful climbing gaits are summarized in Table II. Results show that Treebot performs well on a wide variety of trees. It can be noticed that the range of successful climbing diameter of tree is wide, from 64 mm to 452 mm. However, Treebot will fail on several species of trees, i.e., Melaleuca quinquenervia, Cinnamomum camphora and Bambusa vulgaris var. Striata. The reason of fail climbing on Bambusa vulgaris var. Striata is that the tree surface is very hard that the spine on gripper is difficult to penetrate. As for the Melaleuca quinquenervia and Cinnamomum camphora, their barks can be peeled off easily. Even the gripper can grip the tree, Treebot will fall with bark. By the experimental results, it can be concluded that Treebot performs well on the trees that the surfaces are not very hard and have less exfoliation.

B. Transition motion

In order to verify the maneuverability of Treebot, a transition motion from a trunk to a branch has been tested. An experiment has been implemented on a Bauhinia blakeana. The diameter of the initial gripping trunk is 280 mm and the slope is about 45 degrees while the diameter of the target gripping branch is 118 mm and the slope is about 90 degrees. Part of the transition motions are shown in Fig. 16. It shows that Treebot was succeeded to leave the trunk and completely climbed on the branch. This transition motion takes three climbing gaits within three minutes.

C. Turning motion

A turning motion has also been performed to evaluate the maneuverability of Treebot. The experiment was implemented on a trunk of a Bauhinia blakeana with diameter 207 mm. Fig. 17 shows part of the turning motions. It can be seen

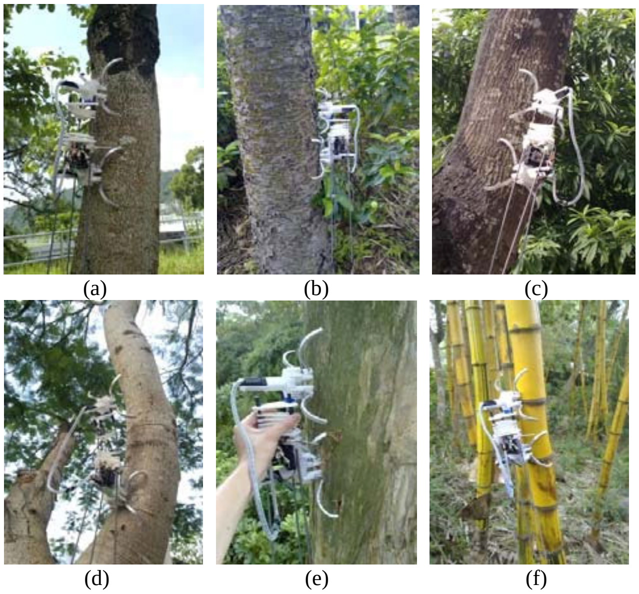


Fig. 15. Climbing test on different species of trees. (a) Bauhinia blakeana; (b) Araucaria heterophylla; (c) Acacia confuse; (d) Delonix regia; (e) Melaleuca quinquenervia; (f) Bambusa vulgaris var. Striata.

TABLE II

CLIMBING PERFORMANCE ON DIFFERENT SPECIES OF TREES

Tree	Diameter (mm)	No. of steps (Success / Total)
Bombax malabaricum	452	20/20
Callistemon viminalis	315	20/20
Delonix regia	309	20/20
Bauhinia blakeana	80,207	20/20
Bauhinia variegate	258	20/20
Roystonea regia	325	20/20
Acacia confuse	229	20/20
Grevillea robusta	159	20/20
Bambusa ventricosa	64,95	20/20
Araucaria heterophylla	277	20/20
Cinnamomum camphora	210,293	13/20
Bambusa vulgaris var. Striata	99	1/5
Melaleuca quinquenervia	446	0/5

that Treebot moved from the front side to the back side. This motion takes five climbing gaits around five minutes. The compliance succeeded to make the gripper normal to the tree surface (Fig. 17(b), (c) and (d)) so that Treebot can perform the turning motion successfully.

D. Slope climbing

As mentioned in Section III-E, the climbing slope of the robot is limited in 105 degrees. This experiment examined the maximal climbing slope of Treebot. It has been implemented on a Bauhinia blakeana with diameter 172 mm. The climbing angle is about 103 degrees. Part of the climbing motions can be found in Fig. 18. It can be seen that Treebot climbed up the tree successfully. There is no over slope climbing effect appeared in the experiment.

Treebot also tried to climb up a tree with a slope larger than its climbing limit. As shown in Fig. 19, Treebot tried

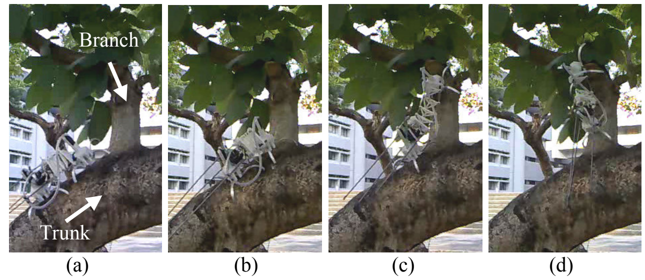


Fig. 16. Branch transition on a Bauhinia blakeana.

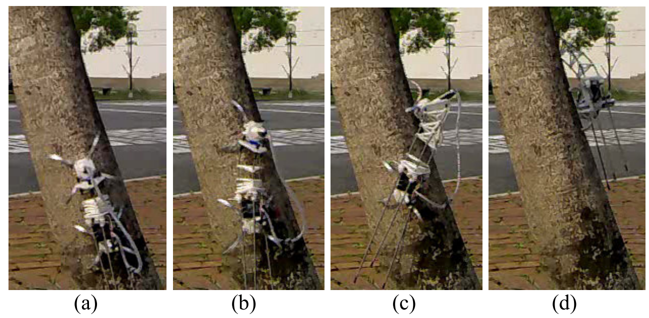


Fig. 17. Turning Motion on a Bauhinia blakeana.

to climb up on a Bauhinia blakeana with diameter 207 mm. The climbing angle is about 110 degrees. It can be noticed in Fig. 19(b) and (d) that the over slope climbing effect occurred. This position cannot be adjusted as the compliance of Treebot is not enough to compensate the outward angle. As a result, Treebot cannot climb up further.

VI. CONCLUSION

In this paper, a novel tree climbing robot "Treebot" is presented that the maneuverability surpasses the state of the art tree climbing robots. It is composed of a pair of omni-directional tree grippers for holding the robot on a tree surface and a novel 3 DOF continuum manipulator for maneuvering. The locomotion and workspace of Treebot are also discussed. Numerous experiments have been conducted. Experimental results reveal that Treebot has excellent climbing performance on a wide range of trees. It is found that it works well on trees that surfaces are not very hard and have less exfoliation. Results also show that the Treebot has high maneuverability on tree environment.

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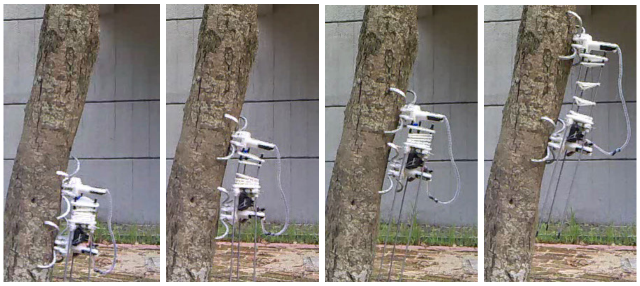

(a) (b) (c) (d)

Fig. 18. 103 degrees slope climbing.

(a) (b) (c) (d)

Fig. 19. 110 degrees slope climbing.

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