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TREE CLIMBING ROBOT USING MECHATRONICS AND SOFTWARE CONTROL CONCEPT

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ABSTRACT

Through this paper, we propose an automatic tree climbing Strategies for a novel tree climbing robot that is named Tree-bot. The proposed concept aims to guide Tree-bot in climbing along an optimal path by the use of minimal sensing resources. Inspired by inchworms, the concept reconstructs the shape of a tree simply by the use of tactile sensors. It reveals how the realization of an environment can be achieved with limited tactile information. An efficient non-holonomic motion planning strategy is also proposed to make Tree-bot climb on an optimal path. This is accomplished by the prediction of the future shape of the tree.

Keywords: *Climbing robot, software control and sensor.*

INTRODUCTION

Now a day's climbing robots constitute a challenging research topic that has gained much attention from researchers. Most of the climbing robots that are reported in the literature are designed to work on man-made structures, such as vertical walls and glass windows (Shen *et al.,* 2005; Xu *et al.,* 2006; Kim *et al.,* 2008; Prahlad *et al.,* 2008; Aksak *et al.,* 2008 and Segal *et al.,* 2008). Few climbing robots have been designed to work on natural structures, such as trees. WOODY is one of the climbing robots that are designed to replace human workers in the removal of branches from trees (Kushihashi *et al.,* 2006). The robot fastens onto a tree by encircling an entire tree trunk and climbs up by extending and contracting its body. Kawasaki (2008) developed a climbing robot for tree pruning. It uses a gripping mechanism that was inspired by lumberjacks and uses a wheel-based driving system for vertical climbing. Aracil (2006) proposed a climbing robot, i.e., climbing parallel robot (CPR), which uses a Stewart–Gough platform to maneuver. RisE V2 is a wall climbing robot that imitates the movement of an insect, using six legs to maneuver. This robot has also been demonstrated to be able to climb trees vertically. For the aforementioned tree climbing robots, the workspaces are restricted to tree trunks only. Trees with branches and irregular shapes are not considered. Climbing on a tree with an irregular shape is a challenging task because the climbing motion and the adhesion method need to adapt to the complex and irregular surface. Tree-bot is the first robot that uses a continuum mechanism (McMahan *et al.,* 2006) for climbing. It opens a new field of applications for continuum mechanisms. Tree-bot is able to climb on irregularly shaped trees with a high degree of maneuverability. Tree-bot has the potential to be applied to various pursuits, such as harvesting, tree maintenance, and observation of tree dwelling animals. A certain level of autonomous climbing ability of Tree-bot helps reduce the complexity of manipulation required for operation by users. An autonomous climbing strategy for Tree-bot is, thus, proposed. To determine the motions to climb up autonomously in an unknown environment, a robot must be equipped with sensors that can explore the environment. There are many living creatures that do not rely on visual information but can navigate well in their natural environment. Inchworms, for example, navigate on trees by using only their sense of touch. Although the information that is obtained by tactile sensors is not rich, it is reliable. Furthermore, the processing of tactile information is much simpler than that of visual information. The remainder of this paper is organized as follows. In Section 2, we give an introduction to the mechanical design and sensing equipment of Tree-bot. In Section 3, the configuration of Tree-bot is presented. The workspace of Tree-bot on different shapes of trees is discussed in Section 4. In Section 5, we discuss the proposed autonomous climbing algorithm and present a tree-shape approximation method and motion planning strategy.

Design of treebot: The design of Tree-bot is aimed to maximize the maneuverability and at the same time to minimize the weight as it is one of the critical concerns in a climbing robot. It is achieved by the minimization of the number of usage of actuators and adoption of the lightweight mechanism. Fig. 2 shows the structure of Tree-bot. Tree-bot is composed of three main elements: gripper, continuum body, and semi-passive joint. Two grippers are connected to the ends of the continuum body, respectively, and the semi-passive joint is installed between the body and the front gripper. The proposed gripper is designed to fasten onto a wide variety of trees with a wide range of sizes. The gripper is composed of four claws and tactile sensors. The gripper fastens onto a tree by means of claw penetration. The gripper should be appressed to the tree surface (the center of the gripper makes contact with the gripping surface and the centerline of the gripper is collinear with the surface) to generate maximal fastening force. Each gripper has one linear motor that actuates all four claws. The continuum body is a type of single-section continuum manipulator with a novel mechanism. It has high degrees of freedom (DOF) and a superior ability to extend that existing designs cannot achieve. The continuum body can extend more than ten times its contracted length. By comparison, OCTARM V has only 75% extension capability (Okamura and Curkosky, 2001). As the extension and contraction maneuvering mechanisms place the center of mass of Tree-bot close to the climbing surface, a smaller pitch-back moment is produced when climbing. The inherent passive compliance of the continuum body allows it to be sheared in 2 DOF along the *x*- and *y*-axes and be twisted about the *z*-axis by external force. To appress the gripper to a gripping surface, the gripper should have a certain turning ability about the *y*- and *z*-axes. However, the inherent compliance of the continuum body does not include rotational motion about the *y*-axis and only affords a limited twisting angle about the *z*-axis. As a result, a 2-DOF semi-passive revolute joint is installed between the front gripper and the continuum body. The joint can be locked and unlocked actively. To reduce the number of actuators, the lock/unlock action is controlled by a linear motor that controls the gripping motion of the front gripper. When the joint is unlocked, the joint can be rotated about the *y*- and *z*-axes. When the joint is locked, it actively returns to the initial orientation in which rotation about the *y*- and *z*-axes is zero. The locking mechanism is needed to fix the front gripper for exploring purpose, which will be discussed in Section 4. To realize the motions of Tree-bot and the environment, three types of sensors are installed: encoders, tactile sensors, and tilting sensors. Encoders are installed on each tendon of the driving motor to measure the posture of the continuum body. Four tactile sensors are installed on each gripper to detect the interaction between the gripper and the climbing surface. A three-axis tilting sensor is also attached to the front gripper to measure the direction of gravity. Consequently, only five actuators are used in Tree-bot, two for the motion of the grippers and three for the motion of the continuum body. The weight of Tree-bot including the battery is only 650 g, which is very light compared with other types of tree climbing robots. The climbing speed of Tree-bot is 73.3 cm/min with a maximum 1.75-kg payload, which is nearly three times its own weight.

Tilt sensor: Tilt sensors allow you to detect orientation or inclination. They are small, inexpensive, low-power and easy-to-use. If used properly, they will not wear out. Their simplicity makes them popular for toys, gadgets and appliances. Sometimes they are referred to as "mercury switches", "tilt switches" or "rolling ball sensors" for obvious reasons. They are usually made by a cavity of some sort (cylindrical is popular, although not always) and a conductive free mass inside, such as a blob of mercury or rolling ball. One end of the cavity has two conductive elements (poles). When the sensor is oriented so that that end is downwards, the mass rolls onto the poles and shorts them, acting as a switch throw. Tilt switches used to be made exclusively of mercury, but are rarer now since they are recognized as being extremely toxic.

Continuum mechanics: It is a branch of mechanics that deals with the analysis of the kinematics and the mechanical behavior of materials modelled as a continuous mass rather than as discrete particles. The French mathematician Augustin Louis Cauchy was the first to formulate such models in the 19th century, but research in the area continues today. Modelling an object as a continuum assumes that the substance of the object completely fills the space it occupies. Modelling objects in this way ignores the fact that matter is made of atoms, and so is not continuous; however, on length scales much greater than that of inter-atomic distances, such models are highly accurate (Fig.1).

Tactile Sensors: Tactile sensing is a field that is rapidly progressing and becoming more n useful. One major use of tactile sensing is minimally invasive surgery. This technology will allow surgeons to make smaller incisions and use sensors to virtually feel and look at the internal organs of a patient. A highly developed tactile sensor could even detect cancerous cells from healthy cells1. Tactile sensing can also be used in different interfaces with touch screens. For example, the iPhone uses touch technology and Microsoft has introduced Microsoft Surface2, a multi-touch interactive table-top that uses a combination of different technologies, including infra-red sensors, to detect touch. Similarly, hp's TouchSmart3 is using single-touch technology to change the way we use computers today. Eventually, touch technology could be used to develop prosthetics with touch feedback. The apple track pad also uses touch technology to understand the different ways of touching the mouse pad into different actions4. Today, there is a new boom in tactile sensing research. Historically, visual sensing has been the more widespread technology. Now, the potential of tactile technology is becoming more evident.

Configuration of tree-bot: Fig. 2. shows the configuration of Tree-bot. In the notations, the superscript *r* and *f* denote the rear- and the front-gripper frame, respectively. *lf* and *lr* represent the distance from the end of the continuum body to the center of the front and the rear gripper, respectively. *hg* denotes the distance between the base of the gripper and the continuum body. The reference frames of the front and rear grippers are also illustrated in the figure. The direction of a gripper denotes the direction along the positive *z*-axis, where a normal direction denotes the direction toward the positive *x*-axis. McMahan *et al., (2006)* develops a kinematic model of a continuum-type manipulator. It is also applicable to the proposed continuum body. It formulates the relationship between the posture of virtual tendon and the length of each tendon. Fig. 4 shows the notation used to represent the parameters of each tendon and the posture of virtual tendon. S, κ, and φ denote the length, curvature, and the direction of bend of the virtual tendon, respectively. *si* denotes the length of each tendon, while *d* is the distance between tendons and virtual tendon. According to

McMahan *et al., (2006)*, the forward and inverse kinematics are defined as follows. To formulate the kinematics of Tree-bot, *lf* and *lr* must be considered. In addition, the mapping between the positions coordinates and the posture of Tree-bot should also be formulated in our application. As a result, the kinematics of Tree-bot is developed by extending (1) and (2). In view of the rear-gripper frame as shown in Fig. 3(a), the mapping between the end point of the robot (*xr f, yr f, zr f*) is formulated as

Workspace analysis:

To determine the motion of Tree-bot, the admissible climbing workspace on a tree surface must be identified. To ensure that the gripper can attach to a target position, the following conditions must be fulfilled.

1) The extension of the body does not exceed the limitation.

2) The bending curvature of the body does not exceed the limitation.

3) The curvature and texture of the target surface are within the operating range of the gripper.

4) The orientation of the gripper to appress to the target surface does not exceed the limitation.

5) No collision between the robot body and the tree.

Conditions 1)–4) are related to the mechanical limitation of Tree-bot, which are constant constrains, while Condition 5) can be checked by collision detection between the tree-shape model and the posture of Tree-bot.

Required Angle of Twist: By providing the shape of the tree and the position and orientation of the rear gripper, the angle of twist that is required to place the front gripper appressed to the target surface can be determined. It is assumed that the geometry of a segment of the tree can roughly be approximated as a straight or curved cylinder. The radius of the tree tree , length of the tree segment *S*tree , bending direction φtree , and bending curvature κ tree are used to represent the shape of the tree. *S*tree, φtree, and κtree represent the shapes of the centerline of the tree model, which is a concept similar to the description of a virtual tendon seem Fig. 4). The target position of the front gripper is defined by the angle of change θt and the length of centerline *St* for the target position that is illustrated in Fig. 6(a). The distance between the continuum body and the tree surface is defined as *hg*. The center of the rear gripper is located at the origin of the reference frame of the tree (*xT* – *yT* – *zT*). By using Shen *et al.,* (2005) and Spenko *et al.,* (2008), the coordinate *_Pt* and the normal vector *_nt* of the target position can be obtained.

Admissible Target Position: The admissible gripping positions can be determined by the consideration of all the necessary constraints. Fig. 7 illustrates the admissible gripping positions of the front gripper on a straight tree for different directions of the rear gripper. In the figure, the long arrow at the bottom denotes the direction of the rear gripper. The inner circle illustrates the circumference of the tree. The dots are the admissible positions of the front gripper with the small arrow that denotes the direction of the front, gripper. This information is useful to determine the motion of Treebot. It can be observed in the figure that when θrx increases, the admissible angle of change increases accordingly.

AUTOMATICM CLIMBING STRATEGY

Robots may topple sideways when climbing on an inclined tree. The optimal climbing position to avoid this tendency is above the centerline of the tree so that the gravitational force acts on the robot to direct it to the centerline of the tree (Okamura and Curkosky, 2001). In the following text, "upper apex" is used to describe this optimal position. The autonomous climbing algorithm aims to make Tree-bot climb a tree along the optimal path. The procedure for the autonomous climbing motion is shown in Fig. 8. It is assumed that Tree-bot is already attached to the tree by the rearm gripper, that the front gripper is detached, and that the continuum body is contracted to the minimum length. To complete the main loop of the procedure once is termed as a complete stride. By the repetition of the stride, Tree-bot can climb a tree along the optimal path. The following sections discuss this procedure in detail.

Tree-Shape Approximation: The concept of tree-shape modeling is mentioned in Section IV. This section discusses the method used to approximate the values of the model parameters from information that is provided by the tactile sensors. Tree-bot explores the shape of a tree by tactile sensors that are attached to the front gripper and uses the exploration data to approximate the shape of the tree. The exploring motion of Tree-bot is based on the proposed exploring strategy. Approximation of the shape of the explored portion of the tree is useful to determine the location of the optimal climbing position and to predict the shape of the tree ahead for motion planning. There are many techniques for shape reconstruction by the usage of information from tactile sensors.

Exploring Strategy: The proposed exploring strategy aims to trace a growing path of a tree by the use of the front gripper, which is similar to the feature-tracing method presented in Jia and Tian (2010). The trajectory of the front gripper can then be used to reconstruct the shape of the tree. The top-left and top-right tactile sensors that are attached to the front gripper are used for exploring. The state and action pairs for the exploring motion are listed in Table I. A tactile sensor acts in a similar fashion to a mechanical switch. It is triggered when a force acts on the bottom part of the tactile sensor over a certain threshold. The forward and left directions are defined as the positive *xr* and *yr* directions, respectively. The top-left and top-right tactile sensors that are attached to the front gripper are used for exploring. The state and action pairs for the exploring motion are listed in Table I. A tactile sensor acts in a similar fashion to a mechanical switch It is triggered when a force acts on the bottom part of the tactile sensor over a certain threshold. The forward and left directions are defined as the positive *xr* and *yr* directions, respectively, in the exploring strategy, the front gripper and *yr* directions, respectively. In the exploring strategy, the front gripper approaches and leaves the tree surface repeatedly. When the front gripper leaves the growing path of a tree, only one side of the tactile sensor is triggered frequently. The front grippers, then, moves to eliminate this unbalanced triggering between tactile sensors to keep the front gripper follow the growing path of the tree. As only one tactile sensor is installed on each tactile sensor, there is no way to determine where force is exactly applied along the tactile sensors? As a result, to trigger a tactile sensor does not necessarily indicate that the center of the front gripper is placed on the tree surface. To obtain accurate data points, the selected points must include only those points at which both the left and right tactile sensors are triggered at the same time or where the average position of the points at which the left and right tactile sensors are triggered alternatively.

Motion Planning: The optimal solution to make Tree-bot follow the optimal path is to place the front gripper on and at the same time set the direction of the gripper parallel to the optimal path. it is impossible to achieve this solution in one stride. However, it can be achieved in two strides. In the first stride, the direction of the rear gripper is adjusted, and in the second stride, the front gripper is set on the optimal path with target direction (Fig. 5). Fig. 6 illustrates the concept to achieve the target position and direction in two strides. In the figure, the circle denotes the target position and the arrow represents the target direction. After (a) exploration, Tree-bot acquires the optimal position and direction for the front gripper. The continuum body then (b) contracts and (c) adjusts the direction of the rear gripper. Finally, the front gripper moves to the target position in (d) in the appropriate direction along the path. The forward motion is completed when (e) the continuum body contracts to pull up the rear gripper. It can be seen that it takes four motion steps to move forward, which quite time is consuming. In view of that, a more efficient motion planning strategy is, thus, proposed, as illustrated in Fig. 7. After (a) exploration, the front gripper moves directly to the target position by neglecting (b) the target direction. The continuum body then contracts and adjusts the direction of the rear gripper, such that the front gripper can move to the next target position and direction (marked as a dotted circle and arrow, respectively) in the next stride; see Fig. 7(c)–(e).The next target position and direction are approximated from the current information. This scheme also requires four motion steps to place the front gripper in the future target position and direction, but the robot moves forward twice in the process, allowing it to climb two times faster. However, the drawback of this method is that it may not go exactly to the target position and direction due to inaccurate estimation of the future target position and direction.

CONCLUSION

In this paper, the main contribution is proposed for development of an automatic tree climbing concept that enables Tree-bot to explore and climb autonomously on an irregularly shaped tree. This study includes the formulation of the kinematics of Tree-bot, an analysis of the workspace of Tree-bot on different shapes of trees, the tree-shape approximation method, and a motion planning strategy. The proposed motion planning strategy is also able to guide Tree-bot to climb on the optimal path of the tree.

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Table 1. Exploring strategy

State of the tactile sensors	Action of the continuum body
No tactile sensor is triggered	Bend forward with extension
Both tactile sensors are triggered	Bend backward with extension
Only left tactile sensor is triggered	Bend left and backward
Only right tactile sensor is triggered	Bend right and backward
Length of extension reaches a constant value	Finish exploration

Fig. 1. Simplified Structure of Tree-bot.

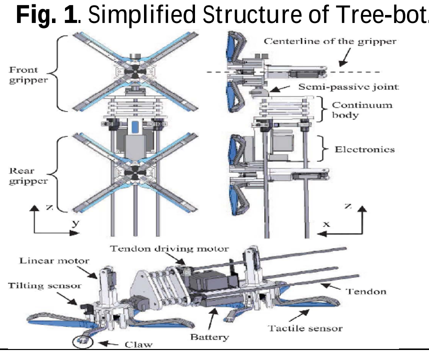


Fig. 2. Configuration of Tree-bot.

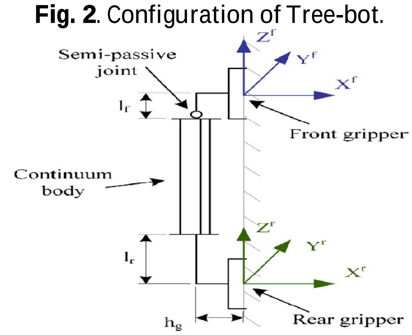


Fig. 3. notations to define the centerline of the tree model or the posture of the continuum body.

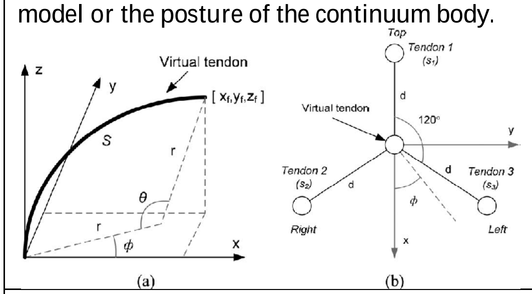


Fig. 4. Notations to define the kinematics of Treebot

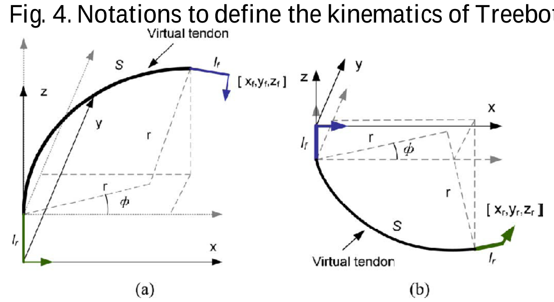


Fig. 5. Flow chart of the autonomous climbing strategy.

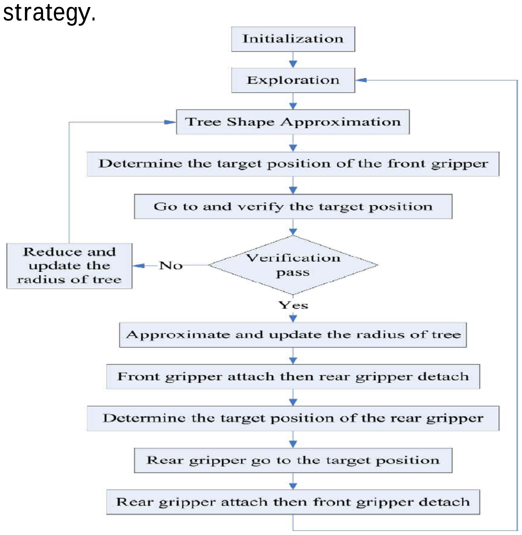


Fig. 6. Series of motion required to place the front gripper to the target position and direction.

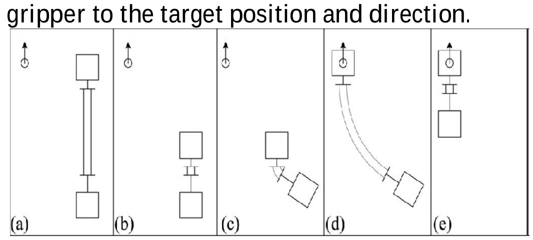
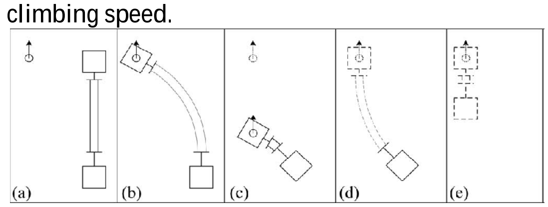


Fig. 7. More efficient strategy to increase the climbing speed.



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