Proceedings of the ASME 2010 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2010
August 15-18, 2010, Montreal, Quebec, Canada

DETC2010-28687

EMPLOYING ASSUR TENSEGRITY STRUCTURES METHODS FOR SIMULATING A CATERPILLAR LOCOMOTION

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ABSTRACT

The paper presents an ongoing project aiming to build a robot, composed of Assur tensegrity structures, that mimics the caterpillar locomotion. Caterpillars are soft bodied animals capable of making complex movements with an astonishing fault-tolerance. In this model, a caterpillar segment is represented as a 2D tensegrity triad, consists of two cables and a linear actuator which are connected between two bars. The unique engineering properties of Assur tensegrity structures which were mathematically proved only this year, together with the suggested control algorithm share several analogies with the biological caterpillar. It provides each triad with an adjustable structural softness. Therefore, the proposed robot has a fault-tolerance and can adjust itself to the terrain roughness. This algorithm also reduces the control demands of the non-linear model of the triad by enabling simple motion control for the linear actuator and one of the cables, while the other cable is force controlled.

INTRODUCTION

Tensegrity structures are well known in the literature and were first patented by R. Buckminster Fuller in 1962 [1]. The analysis of a tensegrity system requires a different approach then that of a regular structure consisting of rods, for example [2, 3]. Tensegrity systems that can change their configuration were reported in the literature raising the problem of the difference between the theoretical model and the actual system, for example [4]. The mathematical foundation of this work relies on a different material- Assur trusses properties, that provides a different approach to the analysis of tensegrity structures and described in [5]. Therefore, a comprehensive literature review is not presented here.

The soft bodied caterpillar, as most living animals, does not have a stiff skeleton and uses a hydrostatic skeleton instead. A hydrostatic skeleton is defined as a fluid mechanism, which acts as a compressed element that provides the means by which the element under tension can antagonize. As a result, it follows that the contraction of one muscle affects all the rest, either by altering their lengths or by altering the tonus, which they are required to exert [6]. This characteristic resembles the fundamental property of Assur tensegrity trusses.

Several attempts were done to build robots that mimic or inspired by the caterpillar locomotion. A modular robot using three robotic modules of "Cube M" is presented in [7]. A computer simulation, in which each caterpillar segment is built of a Stewart platform, is reported in [8]. In both cases, the caterpillar segments are built of rigid elements, in contrast with a real caterpillar. A soft robot with continuously deformable body is reported in [9]. However, one of its major limitations is the coordination of the dynamics for very high degree-of-freedom systems. Furthermore, the inherent flexibility in soft systems means that actuators' placement is not obvious, nor is the motion that those actuators will create [10]. A Current work is being done to simulate a soft-bodied robot, using NVidia® PhysX; a hardware-accelerated physics engine, in order to evolve and optimize soft bodied gaits [11].

In this work, a different approach is presented. The structure that is being used in this work for modeling the caterpillar segment is a 2D triad. This model is not composed of soft elements, and yet, it demonstrates a structural softness.

Furthermore, the lack of soft elements allows a much easier simulation than the soft, very high DOF model described in [9].

The following sections are introduced in the paper: first the biological caterpillar's locomotion is presented. In the second section the theoretical background of Assur tensegrity trusses is introduced. We proceed to the third section and introduce the shape change algorithm of the control system. In the forth section the caterpillar model is discussed. In the fifth section, the results of the analysis are shown, and at last we discuss the further research.

THE BIOLOGICAL CATERPILLAR LOCOMOTION

Caterpillars are excellent soft-bodied climbers that have an astonishing fault-tolerant maneuverability and a powerful, stable, passive attachment [9]. The caterpillar is divided into three parts: the head, the thorax, which consists of three segments, each bearing a pair of true legs, and the abdomen. The abdomen of the tobacco hornworm, which constitutes over a three quarters of the total caterpillar's length, has eight segments: segments A1-A7 and the terminal segment (TS). The abdominal segments A3 to A6 and the terminal segment (TS) have a pair of fleshy protuberances called prolegs [12]. Fig. 1.

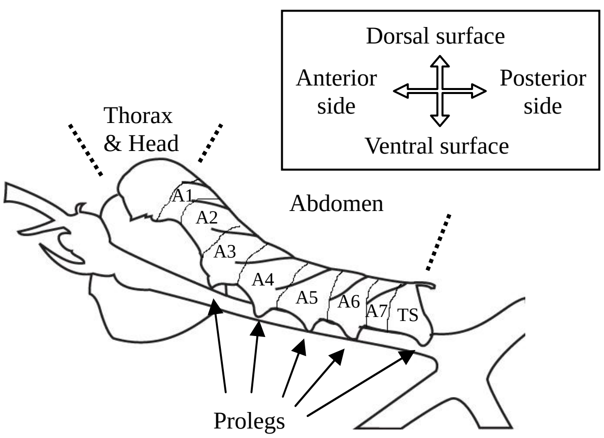


Figure 1. THE TOBACCO HORNWORM ANATOMY.

The caterpillars' locomotion is primarily done by crawling [13] and it may reflect the output of the central pattern generating network [14]. Caterpillars crawl via a wave of muscular contractions that start at the posterior and progress forward to the anterior. During this motion, at least three segments are in varying states of contraction at the same time. The two feet on both sides of each body segment move together. This phase motion of the lateral legs is very unusual, since in most other animals, the two legs of each lateral pair move exactly half a cycle out of phase from each other. The gaits of the prolegs of the four segments A3-A6 of the tent caterpillar are depicted in Fig. 2. Once a particular proleg pair has moved and has been "planted", there is no further movement by that proleg or body segment, until the next cycle. As speed increases, both stride frequencies and stride lengths increase significantly. The former is more correlated with the changes in velocity. Frequency varies by a factor of four over the speed range, whereas the stride length varies by about forty percent [8,15].

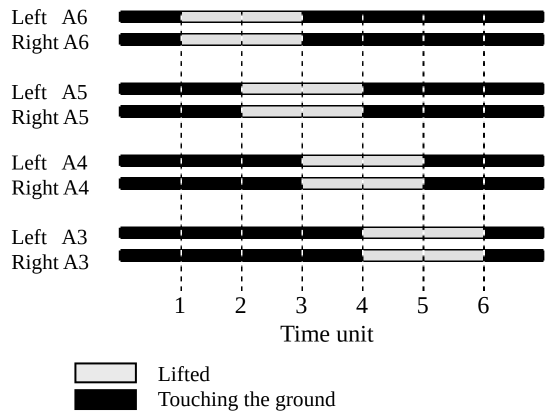


Figure 2. THE GAITS OF THE CATERPILLAR'S PROLEGS IN ABDOMINAL SEGMENTS A3-A6 DURING LOCOMOTION.

Muscles are attached to the inside surface of the body wall. The musculature is complex, with each abdominal body segment containing about seventy discrete muscles. Most muscles are contained entirely within the body segment. The major abdomen muscles are the ventral longitudinal muscle (VL1) and the dorsal longitudinal muscle (DL1) [12], Fig 3.

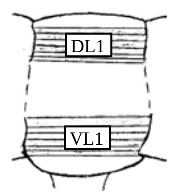


Figure 3. THE MAJOR ABDOMEN MUSCLES: VENTRAL LONGITUDINAL MUSCLE (VL1) AND DORSAL LONGITUDINAL MUSCLE (DL1).

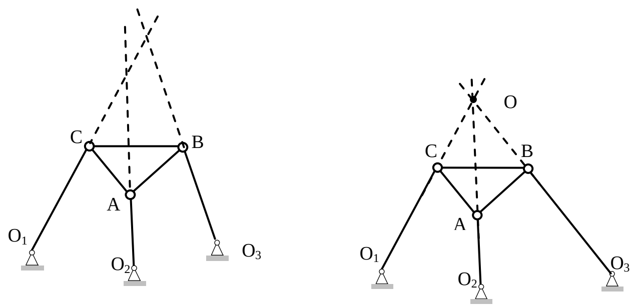
Caterpillars have a relatively simple nervous system, with each segment having a ganglion (a nerve complex) monitoring its movements. Despite their limited control resources, caterpillars are still able to coordinate hundreds of muscles in order to perform a variety of complex movements. It has been argued that the mechanical properties of the muscles are also responsible for some of the control tasks that would otherwise be attributed to the neural control. It is also assumed, that some muscles function primarily to maintain turgor, whereas others are primarily locomotory [16].

ASSUR TENSEGRITY TRUSSES

The theoretical foundation of the proposed robot relies on the properties of Assur trusses in general, and particularly on the singular configuration property, that guarantees the rigidity of the structure.

An Assur truss is defined as a determinate truss, in which applying an external force at any joint, results in forces in all the rods of the truss. The 2D triad appearing in Fig. 4a is an example of an Assur truss. A unique geometrical property of Assur trusses is that they have a configuration, in which there exists a self-stress in all the elements. An Assur truss in this configuration is said to be in a singular configuration.

The geometric characterization of the singular configuration of the 2D triad depends on the external forces that act upon it. When it is not subjected to external forces, the singularity is characterized by the intersections of the continuations of the three rods: (O_1C), (O_2A) and (O_3B) at the same point, denoted by O, Fig. 4b.



(a) Triad in general configuration. (b) Triad in singular configuration.

Figure 4. THE 2D TRIAD.

The scheme of the tensegrity deployable triad appears in Fig. 5. The triad consists of three linear actuators and three cables. In a singular configuration, the triad can sustain self-stress forces. The actuators are operated to sustain the compression forces while the cables sustain the tension forces. Thus, the triad is considered a tensegrity structure. Note that if the triad is not in singularity, the cables will lose their tension and the triad will collapse.

THE SHAPE CHANGE ALGORITHM

The principal shape change algorithm, used in this model, is based on the algorithm that is described and mathematically proven in [17]. The idea underlying this control algorithm is described as follows: In order to keep the triad in a singular configuration, it is sufficient to maintain the tension of only one cable. In Fig. 5, cable BO_3 is the force controlled cable.

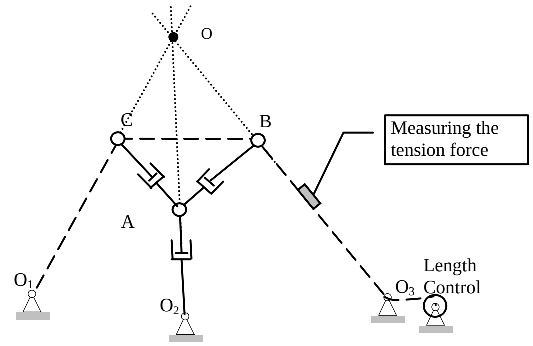


Figure 5. A TENSEGRITY TRIAD WHILE CABLE O_3B IS FORCE CONTROLLED.

In order to change the shape of the triad, the inverse kinematics of the new shape is calculated. Afterwards, a trajectory for the length change of each position controlled element (the actuators and the remaining two cables) is calculated independently. As explained above, the force controlled cable ensures that the triad will keep its singular state during its motion. If the cable becomes loose, its length will be shortened, which will bring back the triad to the singular configuration and vise versa, if the tension of the cable exceeds the determined value, it will become longer in order to enable the motion. The proposed shape change algorithm is simpler than those described in the literature, since the controlled elements are in fact decoupled, while still achieving the self- stress of the structure.

THE CATERPILLAR MODEL

In this model, the segment of the biological caterpillar is represented as a planar tensegrity triad. The triad in this model is a modification of the triad described above. It consists of two cables and a linear actuator connected between two bars. The cables are connected one at each side of the bars, and the linear actuator is connected in between, as shown in Fig 6. The cables can be thought of as representing the major longitudinal muscles of the caterpillar segments: The upper cable represents the ventral longitudinal muscle (VL1) and the lower cable represents the dorsal longitudinal muscle (DL1). The linear actuator, which is always subjected to compression forces, represents the hydrostatic skeleton.

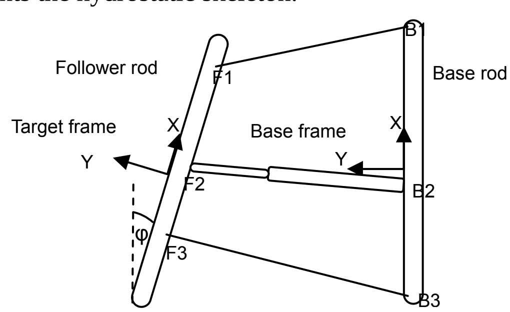


Figure 6. THE 2D TENSEGRITY TRIAD MODEL USED AS A SEGMENT OF THE CATERPILLAR.

Following the shape change algorithm described above, the linear actuator and one of the cables are position controlled while the remaining cable is force controlled. As described above, the singular configuration of the triad depends on the external forces that act upon it. The singularity constraint reduces one degree of freedom.

When there are no external forces, the singularity is characterized by the intersection of the continuations of the cables and the linear actuator at the same point (similar to the standard triad). Using this information, an inverse kinematics can be calculated as follows: The coordinates of the target frame relative to the base frame are given. The coordinates of the base connection points (B1-B3) are easily calculated. The coordinates of the connection points of the follower (F1-F3) can be described as a function of the target frame coordinates and the unknown angle φ (remember that the triad has only two DOF and therefore the angle is dependant). Afterwards, the three line equations of the two cables and the linear actuator are calculated. The algebraic formulation of three lines that intersect at one point is that the determinant of their coefficients is zero. Each line in Eqn. (1) has the coefficients of one line equation (The nomenclature used in this equation is taken from Fig. 6).

$$\begin{vmatrix} B1_y - F1_y & F1_x - B1_x & B1_y \cdot F1_x - B1_x \cdot F1_y \\ B2_y - F2_y & F2_x - B2_x & B2_y \cdot F2_x - B2_x \cdot F2_y \\ B3_y - F3_y & F3_x - B3_x & B3_y \cdot F3_x - B3_x \cdot F3_y \end{vmatrix} = 0 \qquad (1)$$

Solving this equation gives the angle φ. Having φ, the calculation of the cables and the actuator lengths is simple.

The geometric characterization of the singular configuration, when the follower is subjected to an external force on its C.M. (for example the gravity), was also developed and the inverse kinematics equation was calculated (not shown here). However, the triad in this model can be subjected to other external forces such as the ground contact and the forces applied at each triad by its neighboring triads. The calculation of the exact inverse kinematics in all of these cases is very complicated and impractical.

This seemingly disadvantage makes this model suitable for simulating the caterpillar's soft body. The triad responses to external forces and demonstrates a behavior that is referred to as a structural softness.

Moreover, the degree of "softness" of each triad can be controlled during the simulation. This property is accomplished by altering the tension in the force controlled cable, which as a result affects the self-stress forces. As the self-stress forces are decreased, the triad becomes softer, and vise versa. This property makes the robot, like the biological caterpillar, fault-tolerant.

Motion Control

The basic shape control algorithm described above can have many variants. The guiding principle that must be kept is that at least one cable is maintained in tension. For example, the force control can be applied to both cables, instead of one. Another alternative is to apply a combination of force control and position control to a single cable. An interesting option is to provide the cables with the mechanical properties of the biological caterpillar muscles, under both passive and stimulated conditions as described in [18].

The higher control level can be inspired by the biological caterpillar, consists of local control unit for each triad and global control unit for the entire caterpillar.

RESULTS

The Caterpillar model was built using MATLAB® Simulink & SimMechanics, such that all the six connection points of the cables and the linear actuator to the rods can be easily modified. It is important to examine different configurations for future optimization. The results of several simulations, demonstrating the properties that were discussed in the previous section, are shown.

Figure 7 demonstrates the "softness" of the tensegrity triad while subjected to several external forces. In these simulations, the right rod is fixed while the left rod is subjected to three different forces. The length of the upper rod and the actuator is constant. The lower cable is force controlled. For the sake of clarity, geometric, mass and force values are not indicated, thus the results are shown in qualitative manner.

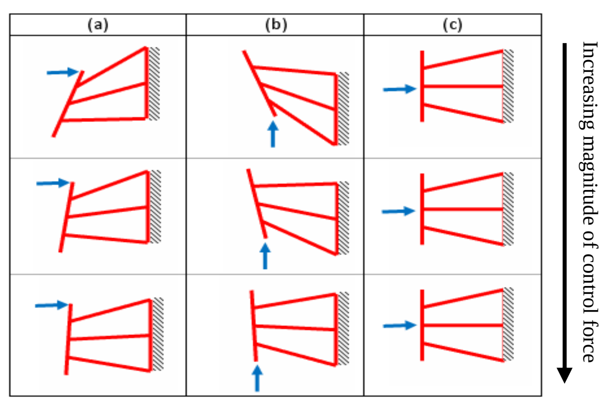


Figure 7. DEMONSTRATION OF THE STRUCTURAL SOFTNESS OF THE TENSEGRITY TRIAD.

The intersection of the continuations of the upper cable and the linear actuator (which have a constant length) is the instant center of the rod. The forces in (a) and (b) change the position of the rod. Nevertheless, as the tension in the force controlled cable (the lower cable) increases, the effect of the external force decreases. The force in (c) does not apply any moment to the instant center of the rod, and therefore does not affect the triad.

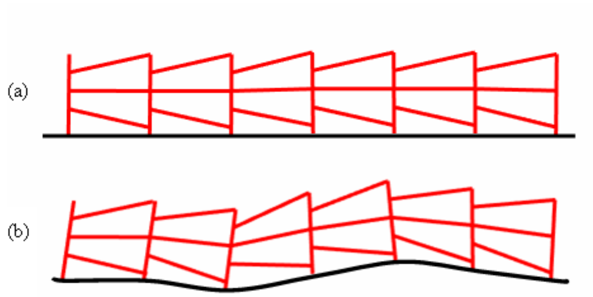


Figure 8. THE SIMULATION OF THE CHAIN DEMONSTRATING THE TERRAIN ADJUSTABILITY.

Figure 8 shows the fault tolerance of the robot, i.e., its ability to adjust itself to the terrain without any high level control. In this simulation both cables in each triad were independently force controlled, although the force magnitude was not constant. The force in each cable was controlled with spring-like properties. When the cable stretches and becomes longer, the tension force increases and vice versa. Note that although the tension magnitude decreases as the length of the cable is shorter, it is constantly remains in tension.

DISCUSSION AND FURTHER RESEARCH

In the paper we introduced an ongoing project, aiming to build a robot that mimics the soft-bodied caterpillar locomotion. The main property of the caterpillar, from our point of view, is its capability of being soft, and therefore has high maneuverability. The model achieves this property by using tensegrity structure principles in general, and in particular the 2D triad and its main property of the singular state and the new shape change algorithm, which was found to be very efficient. One outcome of this model is the terrain-compatibility behavior.

The research is now focusing on the higher level control. The idea is to design a control unit that is inspired by the neural system of the biological caterpillar: a local control unit for each triad and a higher level control unit that is responsible for the motion planning of the complete caterpillar's locomotion. This aim will be achieved by developing optimal gaits for the simulation that might resemble the biological caterpillar gaits. It is believed that another outcome of this model will be its ability to control the caterpillar movements with a relatively simple control unit, as in the biological caterpillar.

In the future, we intend to build a 2D mechanical model based on the results of this project. Afterwards, we plan to develop a 3D caterpillar-like model.

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