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A MODEL OF CATERPILLAR LOCOMOTION BASED ON ASSUR TENSEGRITY STRUCTURES

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ABSTRACT

This paper presents an ongoing project aiming at building a robot composed of Assur tensegrity structures, which mimics caterpillar locomotion. Caterpillars are soft-bodied animals capable of making complex movements with astonishing fault-tolerance. In our model, each caterpillar segment is represented by a 2D tensegrity triad consisting of two bars connected by two cables and a strut. The cables represent the major longitudinal muscles of the caterpillar, while the strut represents hydrostatic pressure. The control scheme in this model is divided into localized low-level controllers and a high-level control unit. The unique engineering properties of Assur tensegrity structures, which were mathematically proved last year, together with the suggested control algorithm provide the model with robotic softness. Moreover, the degree of softness can be continuously changed during simulation, making this model suitable for simulation of soft-bodied caterpillars as well as other types of soft animals.

NOMENCLATURE

F	Force output
F_0	Initial force.
K	Stiffness coefficient.
L_0	Initial length
L	Real length
B	Damping coefficient
v	Real velocity

INTRODUCTION

Insect locomotion is a constant source of inspiration to engineers interested in the improvement of robot mobility, allowing complex yet smooth movements to fulfill various functions [1, 2]. Most bio-mechanical research on insects (as well as in general) tends to focus on legged locomotion [3]. Vast literature is dedicated to the control, coordination and integration of six-legged locomotion (see a recent example in [4]). There are many examples of six-legged robots that are based, to different degrees, on bio-mimicry (usually following the cockroach model [5]).

A particularly challenging model of insect locomotion is that of large moth and butterfly caterpillars. Though relatively slow, caterpillars exhibit an astonishingly efficient gait and excellent rough-terrain mobility. The primary mode of caterpillar locomotion is crawling. Locomotion is aided by three pairs of short, jointed thoracic legs (with a single claw at the tip) and three to five pairs of abdominal prolegs (fleshy protuberances ending in a series of hooks called crockets). A detailed description of the motor patterns and kinematics of caterpillar crawling was recently presented by Trimmer and colleagues [6]. In brief, crawling is based on a wave of muscular contractions that starts at the posterior end and progresses forward to the anterior. Anatomically, crawling is achieved by muscles attached to invaginations on the inside surface of a soft and flexible body wall.

The soft body wall does not constitute a suitable skeleton for the muscle to work against. Instead, the pressure of the

hemolymph within the body provides a hydrostatic skeleton. A hydrostatic skeleton is a fluid mechanism. It acts as a compressed element that provides the means by which the elements under tension can antagonize. As a result, the contraction of one muscle affects all the rest, either by altering their lengths or by altering the tonus [7].

One approach to simulating and building a robot that mimics the soft-bodied caterpillar is to use soft and deformable materials. However, this flexibility and deformability brings with it considerable complexity in control design. Soft-bodied robots can possess near-infinite degrees of freedom and have very complex dynamics [8]. In contrast, a robot built with rigid links, although much easier to control and simulate, lacks the ability to deform [9]. This paper presents a different approach. Using the properties of Assur tensegrity structures we simulate behavior which we call *structural softness*. The robot is not composed of soft elements, yet it deformed by external forces (Fig. 1).

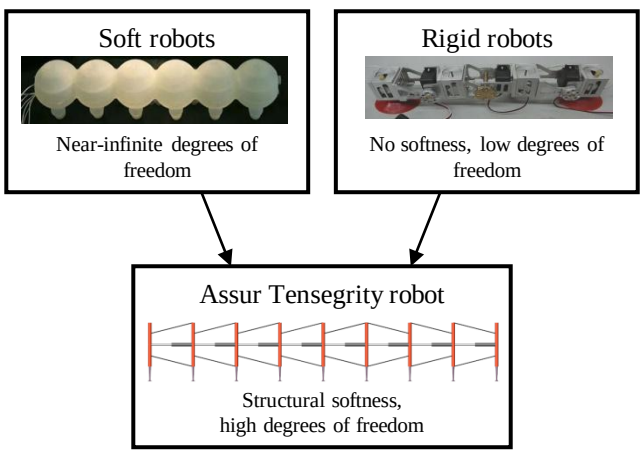


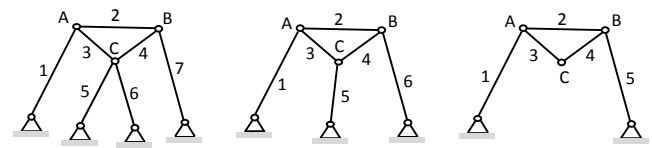
Figure 1. COMPARISON OF CATERPILLER MODELS[1]

PHYSICAL PRINCIPLES UNDERLYING THE MODEL

In this section, we will briefly introduce several unique engineering principles underlying our model.

Engineering systems can be generally categorized into three groups: over-constrained, well-constrained, and under-constrained. In CAD systems, for example, when too many dimensions are provided, the model is over-constrained because of redundancy. If insufficient measures are provided, the model cannot be produced and is under-constrained. Only when the minimum dimensions required to produce the model are provided do we have well-constrained data.

The same categorization can be similarly applied to mechanical systems, including structures, mechanisms, robots, etc. Suppose we have a 2D truss with number of joints j. If the number of rods is $2 \cdot j$ it is possible to calculate all the forces on all the rods using only force equilibrium around each joint. This is a well-constrained system, and it is known as a statically determinate truss. When the number of rods exceeds $2 \cdot j$, there is redundancy and the analysis is much more complicated. Furthermore, analysis requires consideration of additional parameters such as the material of the rods. This type of structure is known as a statically indeterminate truss. Finally, structures having fewer than $2 \cdot j$ rods would be under-constrained. These structures cannot sustain external force and are thus mobile. Examples of these three types of trusses appear in Fig. 2.



(a) Indeterminate truss (b) Determinate truss (c) Mechanism

Figure 2. CLASSIFICATION OF TRUSSES

Assur Tensegrity Structures

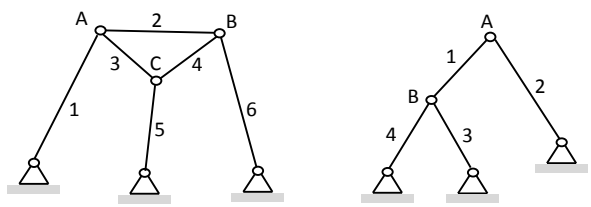
In order to achieve softness in our model, we chose to use tensegrity (a contraction of *tensile* and *integrity*) structures, a concept widely used both in engineering and biology [10]. Tensegrity structures consist of two types of elements: struts and cables. Each can sustain only one type of force–compression or tension respectively. One essential property of tensegrity structures is that stability is maintained by the existence of self-stressed equilibrium imposed by strut compression and cable tension. Note that there are several types of tensegrity systems. The original work of Fuller [11] involves continuous cables with struts being isolated from one another. In our model the cables are not continuous and struts are conjoined.

The main difference between our tensegrity model and others such as [12] is that our model consists of well-constrained, statically determinate tensegrity structures rather than indeterminate structures. Our work depends on one of the essential properties of determinate trusses. If one of the rods is removed, the structure becomes a mechanism. Once we reposition the rod we once again have a rigid structure. Therefore, changing the length of only one rod changes the shape of the entire structure. In contrast, indeterminate tensegrity structures present much greater complexity when trying to produce desired shape change.

Note that only indeterminate trusses can bear internal forces in almost any configuration. We chose to use determinate trusses to ease control and computational analysis, but in general, determinate structures cannot bear self-stress forces and therefore cannot be tensegrity structures. To overcome the latter problem, we chose a special type of determinate truss called an Assur Truss. Assur trusses originate from the work of Assur [13], who developed a method for decomposing any mechanism into primitive building blocks (called Assur

[1] Pictures are taken from [8] and [9]

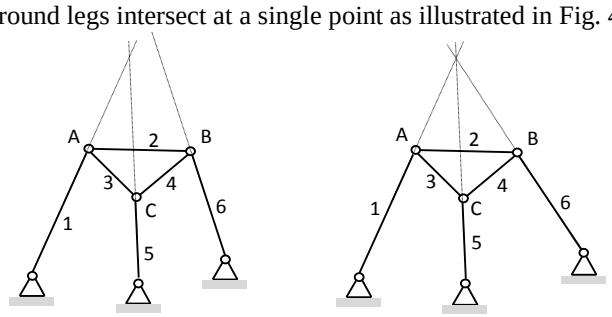
Groups) which are determinate trusses. It should be noted that there are an infinite number of Assur trusses, but all of them exhibit certain properties [14, 15]. One of the main properties is that removal of *any* link results in a mechanism composed of *all* other rods. In other words, changing the length of *any* rod will result in the motion of *all* remaining rods. For example, Fig. 3a depicts an Assur Truss (called a triad in this paper). Removing any link results in a mechanism. The truss in Fig. 3b is not an Assur Truss. Removing links 1 or 2 still leaves links 3 and 4 immobile.



(a) An Assur truss. (b) A truss that is not of Assur type

Figure 3. EXAMPLE OF TWO DIFFERENT TYPES OF DETERMINATE TRUSSES

We now move to the final physical property that underlies our model. As mentioned above, our decision to use tensegrity structures requires inner self-stress. To attain self-stress we employ a property unique to Assur trusses. In 2010 it was proved that every Assur Truss can assume a special configuration (called singularity) in which self-stress is present in all the elements [16]. For the triad used in our model, singularity is obtained when the continuations of the three ground legs intersect at a single point as illustrated in Fig. 4b.



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

Figure 4.TRIAD IN DIFFERENT CONFIGURATIONS

Based on the above, we now have our physical model. We employ an Assur Truss, in this case a triad. It is also a tensegrity structure with cable and strut elements, thus it is termed an Assur tensegrity truss, depicted in Fig 5.

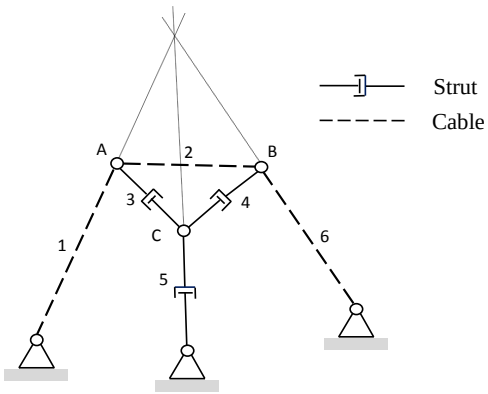


Figure 5. ASSUR TENSEGRITY TRIAD

THE CATERPILLAR MODEL

The biological caterpillar has a complex musculature. Each abdominal body segment includes around seventy discrete muscles, with most muscles contained entirely within the body segment. The major abdomenal muscles in each segment are the ventral longitudinal muscle (VL1) and the dorsal longitudinal muscle (DL1). Figure 6 demonstrates that the VL1 is not a single muscle that extends the entire length of the caterpillar body. Rather each segment has its own distinct VL1 muscle, which is controlled separately. The same is true for the DL1 muscle (and virtually all other caterpillar muscles). Each VL1 and DL1 muscle is attached to the sternal and tergal antecosta respectively (the antecostae are stiff ridges formed at the primary segmental line and provide a surface for the attachment of muscles) [17].

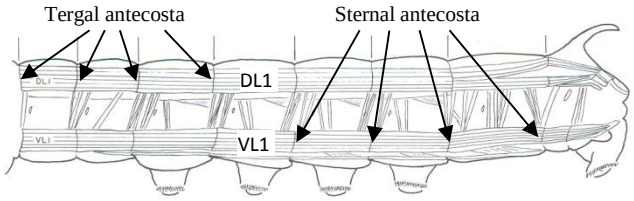


Figure 6. THE CATERPILLAR'S BODY AND ITS MAIN LONGITUDINAL MUSCLES[2]

Caterpillars have a relatively simple nervous system. Yet, 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 performed by the nervous system [18].

The caterpillar model presented here is a 2D model and therefore allows only planar locomotion. The structure of the model is inspired by the biological caterpillar. In this model,

[2] Picture is taken from [17]

each segment of the biological caterpillar is represented by a planar tensegrity triad. It consists of two cables and a strut which connect two bars. The cables connect the two ends of the bars and the strut connects the bars at the middle (Note that the top triangle shown in Fig. 5 is replaced with a rigid bar in the model triad). The whole caterpillar model consists of several segments connected in succession. The cables play the roles of the two major longitudinal muscles in the caterpillar segments. The upper cable represents the DL1 while the lower cable represents the VL1. The strut, which is always subjected to compression forces, represents the hydrostatic skeleton.

Legs are connected to the bottom of each bar. As in the biological caterpillar, the legs are not propulsive limbs. Rather, they are used for support and for generating controllable grip [19] (Fig. 7).

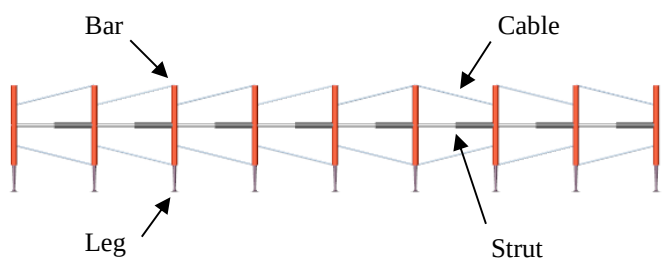


Figure 7. THE CATERPILLAR MODEL

THE CONTROL ALGORITHM

The control scheme of the caterpillar model is divided into two levels: high-level control and low-level control. Low-level control is composed of localized controllers for each of the strut or cable elements. Each low-level controller is independent of the others. That is, the controller output of an element is calculated using only that specific element's inputs. This independence is inspired by the mechanical characteristics of the caterpillar. The strut controllers simulate the internal pressure of the caterpillar's hydrostatic skeleton. The cable controllers simulate the elastic behavior of the muscles. Of course, the controllers are not intended to perfectly reproduce the behavior and characteristics of the caterpillar. Rather, they take inspiration from the general structural concept.

The role of the high-level control unit is to deliver commands to the low-level controllers in order to effect coordinated motion. In this way, the high-level unit simulates the function of the nervous system (Fig. 8).

Low-level Control

In general, robot degrees of freedom (DOFs) can be controlled by one of two control types: motion control or force control. Motion control is useful for many industrial applications. In motion control, the control variables are kinematic: position, velocity, and acceleration. Motion control is very accurate, each joint position being calculated and monitored at each point in time. This kind of control is not well

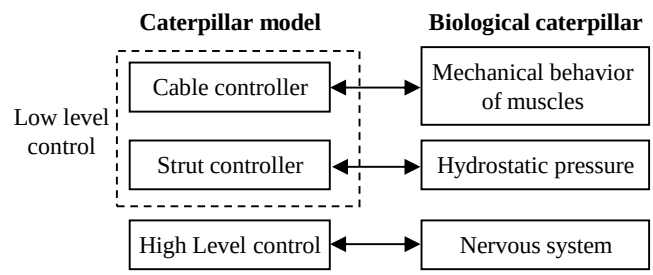


Figure 8. CONTROL SCHEME OF THE CATERPILLAR MODEL

fitted to the nature of soft robotics. Soft robots deform by external and internal forces. This makes it very difficult to control the exact motion parameters of the robot's DOFs at each point in time. The more suitable type of control for soft robots is force control.

In this model we employ a force control scheme based on impedance control [20]. The general control law for the low-level controllers is:

$$F = F_0 + K\left(L_0 - L\right) - Bv \tag{1}$$

The output force is a sum of three terms. F_0 is a constant and initial force which has the role of maintaining the self-stress forces inside the tensegrity segments. $K\left(L_0 - L\right)$ is the static (or elastic) relationship between output force and length, also known as stiffness. This term causes spring-like behavior: when the element length increases, the output force is also increased and vice versa. The degree of stiffness can be controlled by changing the stiffness coefficient (K). Finally, Bv is the relationship between output force and velocity. It functions as a damper in order to avoid fluctuations and to moderate element reaction time. It may also be thought of in terms of viscosity. This principal control law is implemented differently in struts and cables.

Struts. As mentioned, struts simulate the internal pressure of the caterpillar's hydrostatic skeleton. In the biological caterpillar the internal pressure is not isobarometric and the fluid pressure changes do not correlate well with movement [19]. For simplicity, our model assumes nearly constant pressure. The stiffness coefficient (K) is set to zero and the control law for struts is reduced to $F = F_0 - Bv$ with positive values of F_0 (compression force). The parameters of the strut controllers (F_0 and B) are constant during locomotion.

Cables. As mentioned, cables simulate the function of caterpillar muscles. The biological caterpillar muscles have a large, nonlinear, deformation range and display viscoelastic behavior [18]. Because muscle behavior is complex and very difficult to simulate, we model simplified behavior.

The basic control law without the damping term represents a static, linear relationship between cable length and cable tension: $F = F_0 + K\left(L_0 - L\right)$ with negative values of F_0 (tension force). The implementation of the cable control law is more complex than that of the strut control law. The function which correlates cable length and cable tension is divided into three regions, each region having a different stiffness (different K value) (Fig 9). When cable length is within typical operating range, stiffness is set to a normal value. If the cable is stretched above 120% of resting length, stiffness is sharply increased. This behavior is modeled after a biological muscle (which has a physical limitation on the extent of stretching) and prevents extreme cable lengthening. If the cable is shortened and reaches critically low tension (about 15% of resting tension), cable tension remains at this minimum threshold value. This keeps the cable in constant tension and prevents cable looseness.

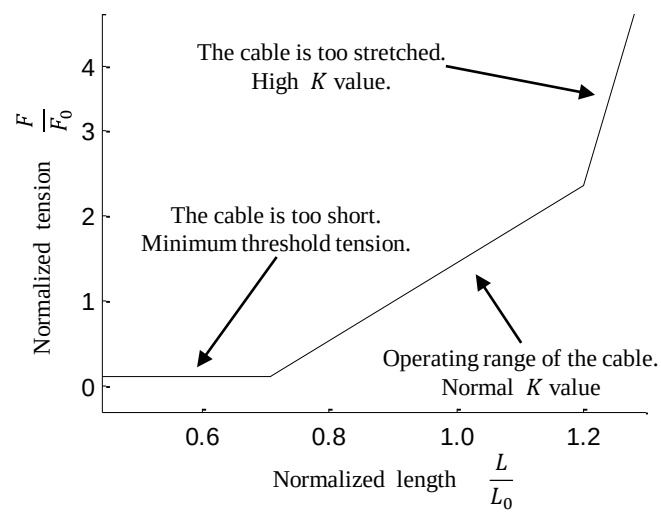


Figure 9. ELASTIC BEHAVIOR OF THE CABLE'S CONTROLLER

Of course, if the function described above remains constant, no locomotion is possible. In order to create motion, the cable controllers must be able to adjust behavior. For example, to make the cable stiffer and shorter, F_0 and K need higher values. Cable controller behavior is directed by a 'command' input. The 'command' input receives values between 0 and 1. A value of 0 indicates that the cable should be "relaxed" with low values of F_0 and K. A value of 1 indicates that the cable should be "shrunken" with high values of F_0 and K. Figure 10a shows a schematic diagram of the cable controller and Fig. 10b shows how the 'command' input affects controller behavior.

In addition to the static relationship between cable length and tension as described above, the control law also employs a damping term (Bv) which adds viscoelastic behavior to the cable and prevents unwanted fluctuations. The parameter B is constant during locomotion.

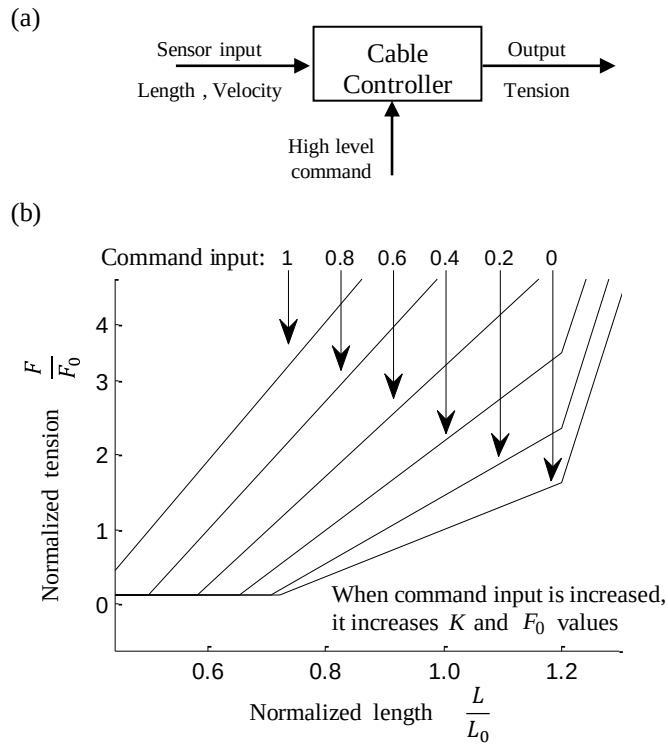


Figure 10. THE INPUT 'COMMAND' AND ITS EFFECT

Legs. Legs have only two positions: lifted or lowered. The transition between these positions is controlled by a simple motion controller which is not described here. Note that when a leg touches the ground it is "planted" and cannot be lifted regardless of the forces acting upon it. It can be released only when it is commanded to be lifted. This behavior is again modeled after the biological caterpillar [21].

High-level Control

The high-level control unit is analogous to the nervous system and is responsible for coordinating the motion of the model segments in a way that resembles a caterpillar crawl. As mentioned, internal pressure is assumed to be almost constant such that strut controller parameters do not need to be controlled by the high-level control unit. High-level control is left with controlling the cables and the legs. This is consistent with the fact that the nervous system controls the muscles but not hydrostatic pressure (at least not directly). Cables are controlled using the command inputs. Legs are controlled using the binary input which triggers lifting or lowering. For an eight segment caterpillar model, the high-level unit must control 16 continuous parameters (for 16 cables) and 9 binary parameters (for 9 legs).

RESULTS

Simulation of locomotion is similar to the locomotion of the biological caterpillar. A wave of stiffening and shortening passes through the segments from the posterior to the anterior.

After the wave passes, each segment becomes loose and relaxed until the next stride. The stages of one stride are illustrated in Fig. 11.

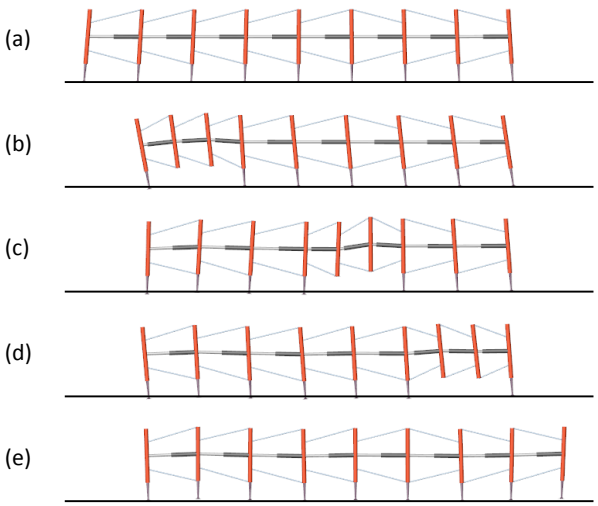


Figure 11. STAGES OF ONE STRIDE

The advantage of soft robotics is the model's ability to adjust its shape to the terrain (Fig. 12). Note that for both terrains, the flat one and the curved one, identical high-level algorithms and parameters were used. No adjustment was needed to account for different terrain. This example demonstrates one of the major advantages of this model. Low-level control takes on some of the control tasks otherwise performed by high-level control. Of course, this adaptability has limits. When facing large obstacles or very rough terrain, the model will be unable to correctly navigate. For these cases, other high-level strategies are required in addition to the basic crawling pattern.

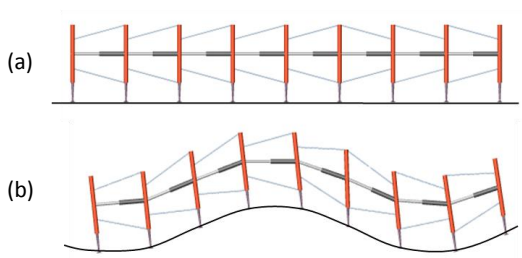


Figure 12. ADJUSTMENT TO THE TERRAIN

CONCLUSION AND FURTHER RESEARCH

This paper presents a model of a soft-bodied caterpillar and the results of crawling simulation. The model exhibits several key characteristics. First and foremost is the ability to allow deformation despite the use of rigid body dynamics (remember that the cable is under constant tension and is considered a rigid body in simulation). This is achieved with relatively low degrees of freedom in comparison with simulations which employ soft and deformable materials. Moreover, the degree of softness can be continuously changed.

Another characteristic of the model is derived from the fact that it employs Assur structures which are well-defined, determinate tensegrity structures (in contrast to over-defined, indeterminate tensegrity structures). The relationship between the external forces, the internal forces, and the shape of a segment (a single triad) is expressed by relatively simple equations which demand relatively low computational power. In addition, the relationship between these forces and segment shape is relatively intuitive.

Another characteristic, which correlates with the biological caterpillar, is that low-level control takes on some of the "burden" of control, resulting in relatively simple high-level control.

In the future, we intend to build a 2D mechanical model based on the results of this simulation, followed by developing a 3D caterpillar-like model.

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