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# Modeling of caterpillar crawl using novel tensegrity structures

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## Abstract

Caterpillars are soft-bodied animals. They have a relatively simple nervous system, and yet are capable of exhibiting complex movement. This paper presents a 2D caterpillar simulation which mimics caterpillar locomotion using Assur tensegrity structures. Tensegrity structures are structures composed of a set of elements always under compression and a set of elements always under tension. Assur tensegrities are a novel sub-group of tensegrity structures. In the model, each caterpillar segment is represented by a 2D Assur tensegrity structure called a triad. The mechanical structure and the control scheme of the model are inspired by the biological caterpillar. The unique engineering properties of Assur tensegrity structures, together with the suggested control scheme, provide the model with a controllable degree of softness—each segment can be either soft or rigid. The model exhibits several characteristics which are analogous to those of the biological caterpillar. One such characteristic is that the internal pressure of the caterpillar is not a function of its size. During growth, body mass is increased 10 000-fold, while internal pressure remains constant. In the same way, the model is able to maintain near constant internal forces regardless of size. The research also suggests that caterpillars do not invest considerably more energy while crawling than while resting.

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Insect locomotion is a constant source of inspiration to engineers interested in the improvement of robot mobility, allowing complex yet smooth movements [1, 2]. Most bio-mechanical research on insects (as well as in general) tends to focus on legged locomotion [3]. A particularly challenging model of insect locomotion is that of large moth and butterfly caterpillars. Although relatively slow, soft-bodied caterpillars exhibit an astonishingly efficient gait and excellent rough-terrain mobility.

Beyond the obvious challenges facing locomotion in all animals, including traveling across varied terrains, overcoming different environmental perturbations and more, soft-bodied animals must overcome further hurdles related to the generation and control of locomotion. The first relates to the absence of rigid articulation. Caterpillars, like many living

animals, do not have hard skeletons. Instead, they use a *hydrostatic skeleton* [4]: fluid and tissue pressure stiffens the body, allowing muscles to do useful work. As a result, the contraction of any one muscle affects all the rest, either by altering their length or their tension, which presents major challenges to the control system. A related need is maintaining and controlling the appropriate body rigidity throughout ontogeny, as the body size and mass increase [5]. But body rigidity must be carefully controlled, also at shorter timescales, through a changing environment and through changes in body proportions while locomoting.

The basic mode of caterpillar locomotion is crawling. 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. Crawling 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 crochets). The basic timing and patterning of the rhythmic motor pattern is assumed to be generated and controlled by a central pattern generating (CPG) network [7].

Several attempts have been made to build or simulate robots that mimic the caterpillar crawl. Wang *et al* [8] built a prototype robot which is assembled using two types of modules: joint actuation modules and adhesion modules. Another model was introduced by Stulce [9], who developed a computer simulation of a multibody robot with passive legs attached to it. The robot was assembled using a series of actuated Stewart-platforms (parallel manipulators with six linear actuators) connecting the bodies. In both cases, the caterpillar segments are built of rigid elements, in contrast to the soft-bodied real animal.

Trimmer *et al* [10] developed a caterpillar model using soft and deformable materials. However, the immense gain in flexibility and deformability brings with it considerable control complexity. Soft-bodied robots can possess near-infinite degrees of freedom (DOFs), and the dynamics of these systems call for the complex development of conventional control schemes. Nevertheless, the biological caterpillar can maneuver its soft body with a relatively simple nervous system [11].

Here, we present a caterpillar model that can control its degree of softness using a novel combination of a tensegrity structure in a special topology called an Assur graph and a variant of impedance control. Relying on these two foundations and using the biological caterpillar as a source of inspiration, we simulate the requisite softness while retaining simplicity.

### 1.1. Tensegrity robots

The word ‘*tensegrity*’ is a contraction of ‘tensional integrity’ and was coined by Richard Buckminster Fuller [12]. Tensegrity systems gain mechanical stability by maintaining a pre-equilibrated state using two types of elements: elements that are always tensioned (cables) and elements that are always compressed (struts). This pre-equilibrated state, in which the internal forces (compression and tension) stabilize the structure, is termed *pre-stress*.

The principles of tensegrity can be found at essentially every scale in nature. At the macroscopic level, the skeleton of vertebrates is compressed and stabilized by the pull of tensile muscles, tendons and ligaments. At the cellular level, the cytoskeleton provides a good example: contractile microfilaments provide tensile forces while microtubules provide the opposing compression. At the lower end of the scale, proteins and other key molecules in the body also stabilize themselves through the principles of tensegrity [13].

Although tensegrity structures are, by definition, static structures, they can be employed in robotic motion. Movement is achieved by changing the lengths of some of the tensegrity

elements, which in turn causes the shape of the robot to be altered. One of the major challenges in the design of such robots is the maintenance of pre-stress forces during motion, which is necessary to preserve structural stability. Many models of tensegrity robots can be found in the literature. Two representative examples are given below.

Rieffel *et al* [14] built a 15-strut tensegrity simulation with a high degree of dynamic coupling and complexity. In this model only the cables are actuated; the struts remain at the same length. The advantage of this strategy is that the stability of the robot is guaranteed since the actuators always *increase* the pre-stress forces. On the other hand, because strut length remains constant, the robot demonstrates only limited shape change.

A different strategy was introduced by Sultan and Skeleton [15]. They developed a shape change algorithm based on an equilibrium manifold: a pre-defined set of points corresponding to stable, pre-stressed, tensegrity configurations. The idea is to execute motion such that the motion path is close to the manifold. The advantage in doing so is that the successive configurations through which the structure passes are not much different from the equilibrium ones; hence, stability is maintained. Their paper demonstrates this method for a 6-bar tensegrity robot that moves only in a particular set of configurations called symmetrical configurations. In this type of motion, only three independent parameters are needed to describe the robot’s position. When asymmetrical shapes are considered, there are many independent parameters and the equilibrium manifold becomes too large.

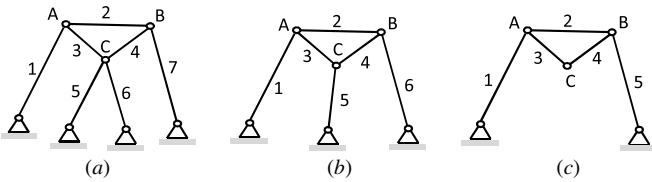
This paper presents a different approach for controlling the shape change of tensegrity robots, which is described in the following section.

## 2. Underlying mechanical principles

Engineering systems can be generally categorized into three groups: over-constrained, well-constrained and under-constrained. In computer-aided design (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 we provide the minimum dimensions required to produce the model do we have well-constrained data [16].

The same categorization can be similarly applied to mechanical systems, including structures, mechanisms, robots, etc. Suppose we have a two-dimensional structure<sup>4</sup> with a number of joints  $j$ . If the number of rods is  $2j$  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 called a *statically determinate structure*. When the number of rods exceeds  $2j$ , there is redundancy, and the analysis is much more complicated. Furthermore, analysis

<sup>4</sup> We have used the word ‘structure’ throughout this section to avoid unnecessary technical terminology. The particular type of structure we refer to is known in mechanical engineering as a truss. A truss is a structure composed of rods which are connected only at their ends.



**Figure 1.** Classification of structures: (a) a statically indeterminate structure, (b) a statically determinate structure and (c) a mechanism.

requires consideration of additional parameters such as the material of the rods. This type of structure is called a *statically indeterminate structure*. Finally, structures having fewer than  $2j$  rods are under-constrained. These structures cannot sustain external force and are thus mobile [17]. Examples of these three types of structures appear in figure 1.

The main novelty proposed by our tensegrity model in relation to others is that our model consists of well-constrained, statically determinate, tensegrity structures rather than indeterminate structures (as in [14]). Our work is based on one of the essential properties of determinate structures: changing the length of a single rod changes the shape of the structure (although this does not imply that *all* the rods in the structure are necessarily affected). Indeterminate tensegrity structures present much greater complexity when trying to produce desired shape change. On the other hand, only indeterminate structures can bear pre-stress forces in almost any configuration (which are essential in tensegrity structures). The use of determinate structures eases control and computational analysis, but, in general, determinate structures cannot bear pre-stress forces and therefore cannot be tensegrity structures.

To overcome the latter problem, a special type of determinate structure called an *Assur structure* was chosen. Assur structures originate from the work of Assur [18], who developed a method for decomposing any mechanism into primitive building blocks (called Assur groups), which are determinate structures. It should be noted that there are an

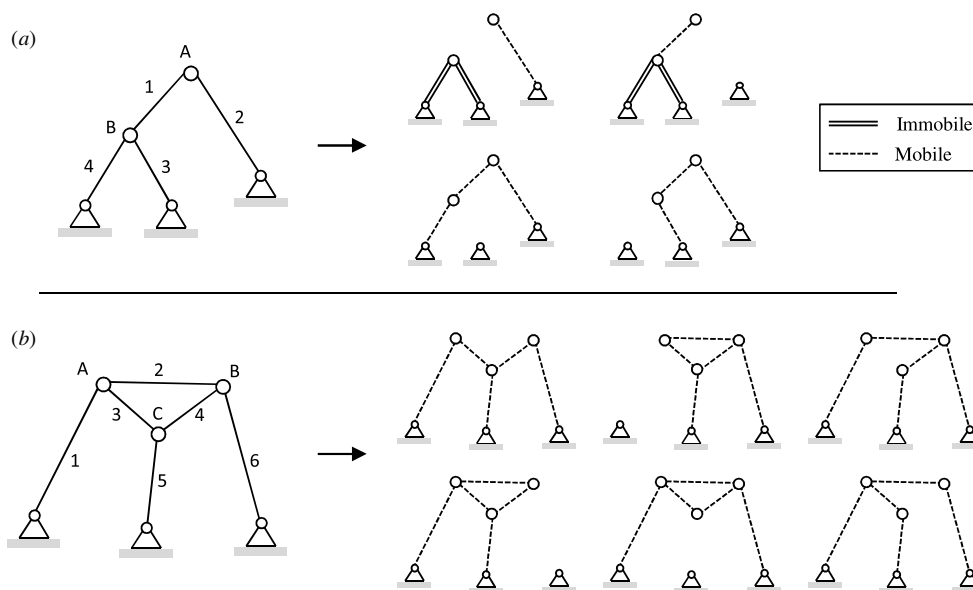
infinite number of Assur structures, but all of them exhibit certain similar properties [19, 20]. One of the main properties of an Assur structure is that removal of *any* rod results in a mechanism composed of *all* other rods. In other words, changing the length of *any* rod will result in the motion of *all* remaining rods. For example, the structure in figure 2(a) is not an Assur Structure. Removing rods 1 or 2 still leaves rods 3 and 4 immobile. On the other hand, figure 2(b) depicts an Assur structure (called a triad in this paper). Removing *any* rod results in a mechanism of *all* five remaining rods.

We now move to the final physical property that underlies our model. As mentioned above, our decision to use tensegrity structures requires inner pre-stress. To attain pre-stress, a property unique to Assur structures is employed. In 2010, it was proved that every Assur structure can assume a special configuration (called singularity) in which pre-stress is present in *all* the elements [21]. For the triad used in the proposed model, singularity is obtained when the continuations of the three ground legs intersect at a single point as illustrated in figure 3(b).

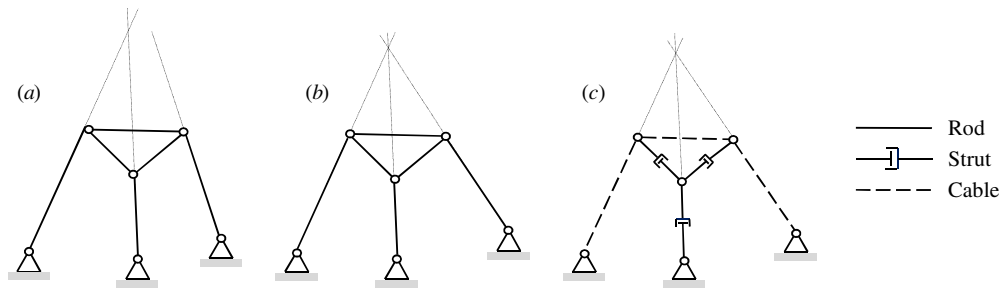
Based on the above, the physical model is as follows. An Assur structure in a singular configuration is employed—in this case a triad. The structure can sustain pre-stress forces and therefore can turn into tensegrity structure: tensioned rods are replaced with cables and compressed rods are replaced with struts. This kind of structure is called an *Assur tensegrity structure*, depicted in figure 3(c).

### 3. Caterpillar robot modeling

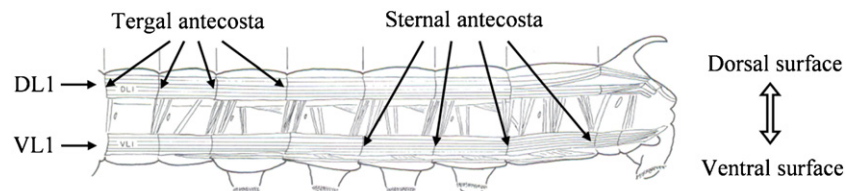
The biological caterpillar has complex musculature. Each abdominal body segment includes around 70 discrete muscles, most of which are contained entirely within the body segment. The major abdominal muscles in each segment are the ventral longitudinal muscle (VL1) and the dorsal longitudinal muscle (DL1) as illustrated in figure 4. The VL1 muscle is not a single muscle that extends the entire length of the caterpillar



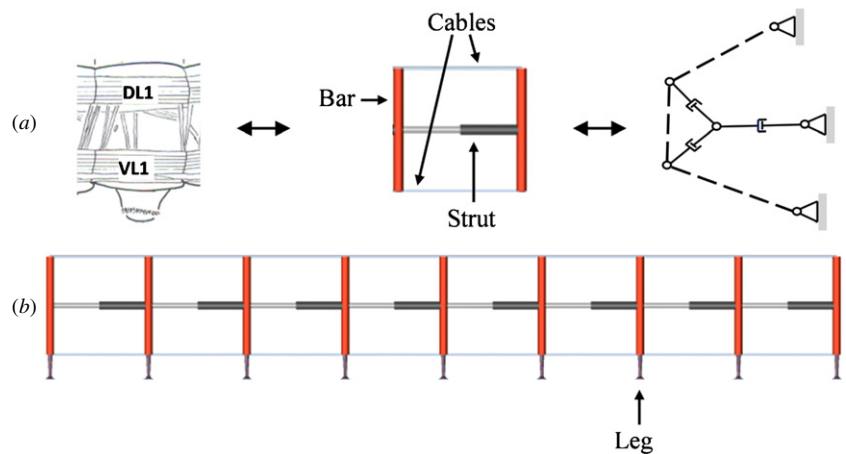
**Figure 2.** Example of two different types of determinate structures: (a) a truss that is not of Assur type and (b) an Assur truss called a triad.



**Figure 3.** Different configurations of a triad: (a) a triad in general configuration, (b) a triad in singular configuration and (c) an Assur tensegrity triad.



**Figure 4.** The caterpillar body and its main longitudinal muscles.



**Figure 5.** Proposed mechanical caterpillar model: (a) comparison between the standard triad, the model segment and the biological caterpillar segment, and (b) the complete caterpillar mechanical model.

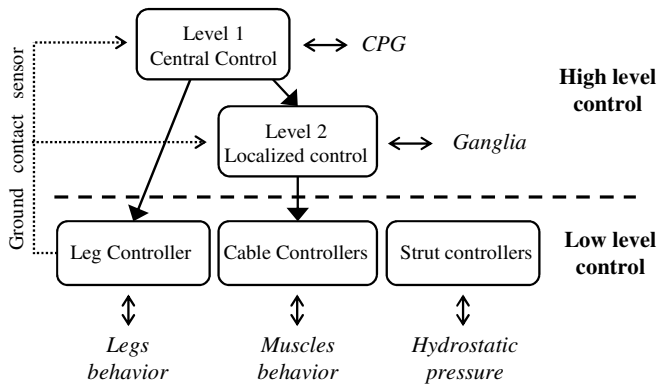
body. Rather, each segment has its own distinct VL1 muscle, which is controlled separately. The same is true for the DL1 muscle (and virtually all other caterpillar muscles). Each VL1 and DL1 muscle is attached to the sternal and tergal antecosta, respectively (the antecostae are stiff ridges formed at the primary segmental line and provide a surface for the attachment of muscles) [22].

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 allow them to assume some of the control tasks that would otherwise be performed by the nervous system [11].

The caterpillar model presented here is a 2D model and therefore allows only planar locomotion. Each segment of the biological caterpillar is represented in the model by a planar tensegrity triad consisting of two cables and a strut

which connects two bars. Note that compared to the standard tensegrity triad shown in figure 3(c), the model triad has a few modifications that were made to simplify the model and to enable direct connection between segments: the model, i.e. the triad is rotated 90°; the top triangle (two struts and a cable) is replaced with an un-actuated rigid bar and the ground supports are replaced by another bar (figure 5(a)). The whole caterpillar model consists of several such segments connected in succession, with legs connected to the bottom of each bar (figure 5(b)). The structure of the model segment is inspired by the biological caterpillar. The cables assume the role of the two major longitudinal muscles: the upper cable represents DL1 while the lower cable represents VL1. The strut, which is always subjected to compression forces, represents the hydrostatic skeleton (figure 5(a)). Also, legs are not used as propulsive limbs; rather, they are used for support and grip, similar to the biological caterpillar prolegs [23].





**Figure 6.** Control scheme: high-level and low-level controls and corresponding caterpillar functions.

#### 4. Control algorithm

The control scheme of the caterpillar model is also inspired by the biological caterpillar and is divided into two levels: high-level control and low-level control.

Low-level control is inspired by the mechanical characteristics of the caterpillar. It is composed of localized controllers for each of the strut, cable and leg elements. Each controller is independent of all the others: the controller output of an element is calculated using only the inputs of that specific element. The strut controllers simulate the internal pressure of the hydrostatic skeleton, the cable controllers simulate the elastic behavior of the muscles and the leg controllers simulate leg behavior.

High-level control simulates the function of the nervous system. The role of the high-level control unit is to deliver commands to the cable and leg controllers in order to coordinate motion. Just as the internal pressure of the caterpillar is not directly controlled by the nervous system, struts are not driven by high-level control.

High-level control is also divided into two levels: levels 1 and 2. Level 1 is the central control unit and is inspired by the caterpillar's central pattern generator (CPG) for locomotion. Its role is to control the timing of movements and to activate the relevant cables and legs. Level 2 control mediates between level 1 control and the cable controllers of each segment, adjusting level 1 control for each segment according to terrain. Segment control is thus local as inspired by caterpillar segmental ganglia. An essential property of high-level control is that the coordination of locomotion is triggered by the contact of the legs with the ground. Figure 6 summarizes the control hierarchy.

Because the details of high-level control are not essential to understand the concept of *structural softness*, this paper will focus on low-level control. More details on high-level control appear in [24].

##### 4.1. Low-level control

In general, robot degrees of freedom (DOFs) can be controlled by one of two control types: motion control or force control. In motion control the controlled variables are kinematic (position, velocity and acceleration); in force control the controlled

variable is the force the robot exerts on the environment. Motion control is useful for many industrial applications because of its high accuracy: each joint position is calculated and monitored at each point in time [25]. Nevertheless, this type of control is not well fitted to the nature of soft robotics. Soft robots deform by external and internal forces, which 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 our model, cables and struts employ a force control scheme based on impedance control [26]. The general control law for the low-level controllers is

$$F_{\text{out}} = F_0 + k(l - l_0) - bv. \quad (1)$$

The output force  $F_{\text{out}}$  is a sum of three terms:  $F_0$  is a constant and initial force which has the role of maintaining the pre-stress forces inside the tensegrity segments.  $F_0$  is negative for cables (tension forces) and positive for struts (compression forces). The term  $k(l - l_0)$  is the static (or elastic) relationship between the 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 is controlled by changing the stiffness coefficient ( $k$ ). Finally,  $bv$  is the relationship between the 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 as explained below.

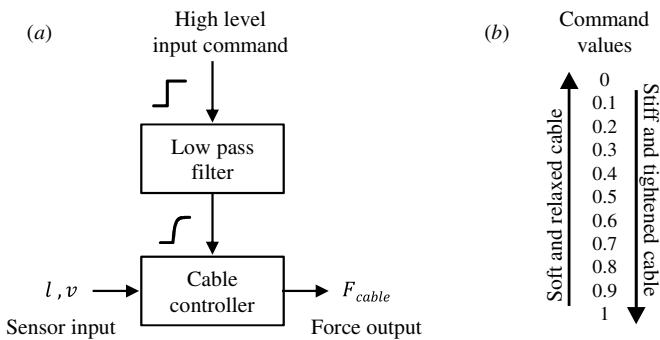
**4.1.1. Control of cables.** As mentioned above, cables simulate the function of caterpillar muscles. Biological caterpillar muscles have a large, nonlinear, deformation range and display viscoelastic behavior [11].

If all controller parameters ( $F_0$ ,  $k$ ,  $l_0$  and  $b$ ) remain constant, the model will remain in steady state and will not move. Cable behavior is controlled by input signals from high-level control to cable controllers (which we call a high-level command).

As high-level control simulates the nervous system and cables simulate muscles, the high-level command simulates nerve stimulation. The 'command' input receives values between 0 and 1. A command value of 0 indicates that the cable should be 'relaxed' (i.e. a low value of  $k$  and a high value of  $l_0$ ). A command value of 1 indicates that the cable should be 'tightened' (i.e. a high value of  $k$  and a low value of  $l_0$ ). Intermediate values indicate intermediate behavior.

A low-pass (LP) filter is placed between the command and the cable controller. This LP filter slows down cable reaction, which simulates the slow reaction of the caterpillar muscle. Figure 7 summarizes the characteristics of the cable controller.

**4.1.2. Control of struts.** Struts have simpler behavior than cables. As mentioned above, struts simulate the internal pressure of the hydrostatic skeleton. In the biological caterpillar, the internal pressure is not isobarometric and the fluid pressure changes do not correlate well with movement [11]. For simplicity, our model assumes nearly constant



**Figure 7.** The cable controller: (a) high-level command is passed through a low-pass (LP) filter, and (b) command values between 0 and 1 control cable behavior.

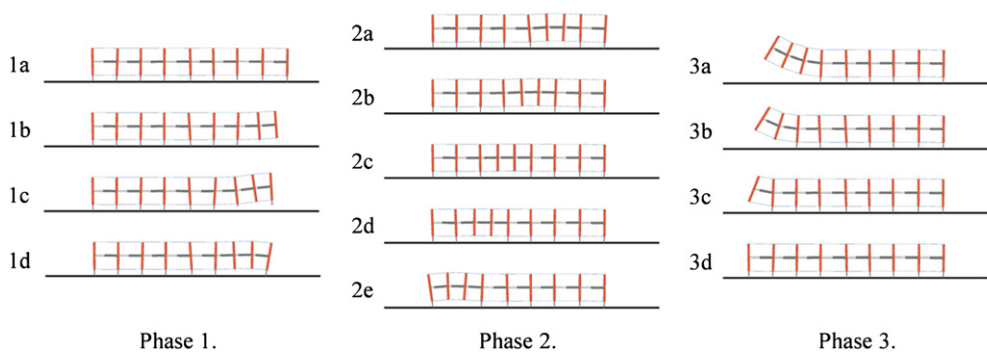
pressure. The stiffness coefficient ( $k$ ) is set to zero, and the control law for struts is reduced to  $F_{out} = F_0 - bv$  with positive values of  $F_0$  (compression force). Strut parameters stay constant during locomotion and are not driven by high-level control.

**4.1.3. Control of legs.** Legs are not part of the tensegrity triad and are not impedance controlled. In our model, legs have only two positions: lifted and lowered. The transition between these positions is controlled by a simple motion controller. When a leg touches the ground it is ‘planted’ and cannot be lifted until the next stride. This behavior is, again, modeled after the biological caterpillar [23].

## 5. Results

The biological descriptions of this section pertain to the *Manduca sexta* species of caterpillar in its fifth instar (the last developmental stage before it becomes a pupa). In this stage, the caterpillar weights about 2 g and its dimensions are about 60 mm in length and 5 mm in height [5]. When divided into 11 segments (3 thoracic + 8 abdominal, neglecting the small head), each segment weights about 0.18 g with an average length of around 5.5 mm. While our model maintains consistency with the height and weight of the biological caterpillar, there is considerable discrepancy in the segment length which will be discussed below.

The model was constructed using MATLAB® Simulink and SimMechanics, and simulations include full dynamics.



**Figure 8.** A stride is divided into three phases.

**Table 1.** Time of force development under a tetanic stimulus at a resting length.

|                   | Caterpillar muscle (s) | Model cable (s) |
|-------------------|------------------------|-----------------|
| 50% of peak force | 0.27                   | 0.26            |
| 80% of peak force | 0.41                   | 0.56            |

Results are divided into kinematic results (which deal with lengths and velocities) and dynamic results (which deal with internal forces inside the model). In addition, sharp-incline crawling is illustrated, and the effect of internal force is discussed.

### 5.1. Kinematic results

In order for effective locomotion to occur, the model’s stride is divided into three phases as shown in figure 8. In the first phase, the three posterior segments of the caterpillar are lifted and shrunk. This phase ends when the most posterior leg is lowered and touches the ground. In the second phase, the crawling wave passes through the body. In the third and final phase, the three anterior segments are lifted and expanded one after the other.

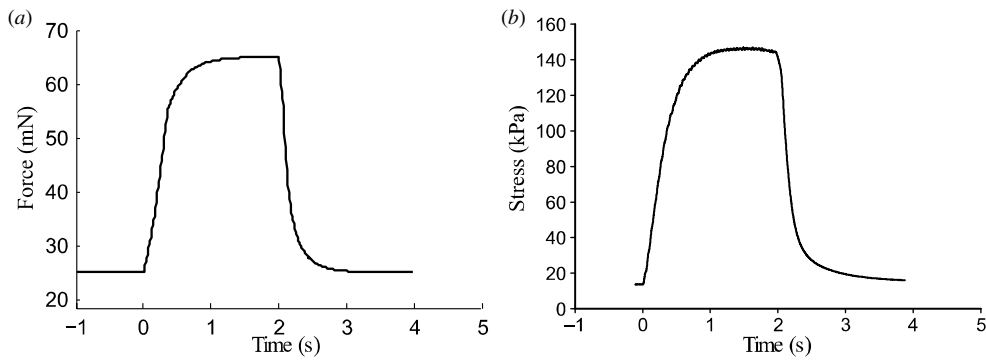
The simulation is programmed such that the next stride begins before the previous one is completed (once the stride reaches the position shown in image 3b of figure 8). For clarity, the figure does not show the beginning of the next stride.

When crawling, the segment length changes by an average of 31%. This result is consistent with the observation of caterpillar muscles, which exhibit comparable shortening to 30% of the resting length [27]. The duration of one model stride is also very close to that of the biological caterpillar—2.71 and 2.78 s, respectively (a difference of 2.5%).

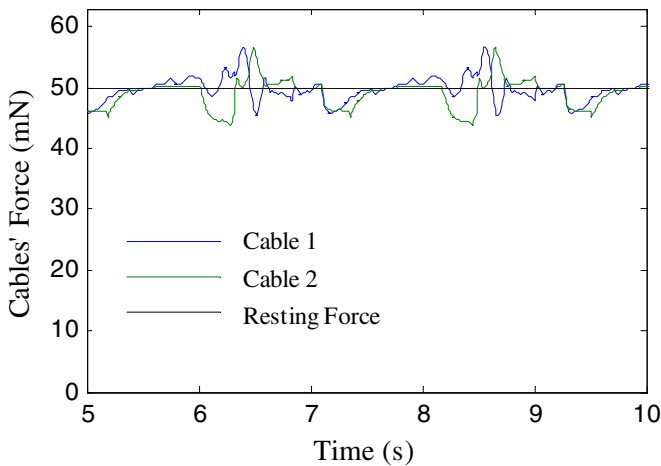
In contrast, the average resting length of a model segment is about 4.5 mm, which is significantly different from the approximate 5.5 mm length in the biological caterpillar. Also the average stride length of the model is 4.19 mm, which is less than half that of the biological caterpillar (8.52 mm) [28].

### 5.2. Dynamic results

Woods *et al* [27] examined the force development of a caterpillar muscle under tetanic stimulus at resting length. To compare these results, a similar test was conducted on the model cable. Results are shown in figure 9 and table 1 which



**Figure 9.** Force development under a tetanic stimulus of 2 s at resting length: (a) model cable and (b) caterpillar muscle.



**Figure 10.** The change of cable force in the third segment while crawling in comparison to pre-stress cable force at rest ( $F_0$ ).

demonstrate that the behavior of the model cable is close to the behavior of the caterpillar muscle and has a similar time constant.

The change of cable forces in the third segment while crawling relative to the initial pre-stress force ( $F_0$ ) is shown in figure 10. Note that the initial pre-stress force is the cables force while the caterpillar is at rest. The value of this force used in the simulation is 49 mN. It was calculated by the product of the biological caterpillar body pressure (1.3 kPa) and its cross-sectional area (37.4 mm<sup>2</sup>) [5]. The maximum change in cable forces is only 13.8% relative to the pre-stress force. Other segments demonstrate similar behavior.

### 5.3. Different terrains

The locomotion of the model was tested on various terrains. Figure 11 shows snapshots from a simulation of the model climbing a sharp incline. The complete video of this simulation and others can be found at <http://www.eng.tau.ac.il/~shai/studentlist.htm>. Because the legs are programmed to grip the ground, the model is able to crawl vertically and can even function when upside down. It is important to realize that the model is able to navigate such different terrains without changing the control characteristics.

### 5.4. Internal pressure

The model was tested with varying internal pressures. Simulations showed that, above a threshold value, performance is not affected by changes in pressure. As a result, changes in the scale do not require corresponding changes in internal pressure. The importance of this fact will be discussed in the following section.

## 6. Discussion

We will first discuss the use of impedance control for Assur tensegrity structures in general. Secondly, we will focus on the caterpillar model and what can be learnt from it.

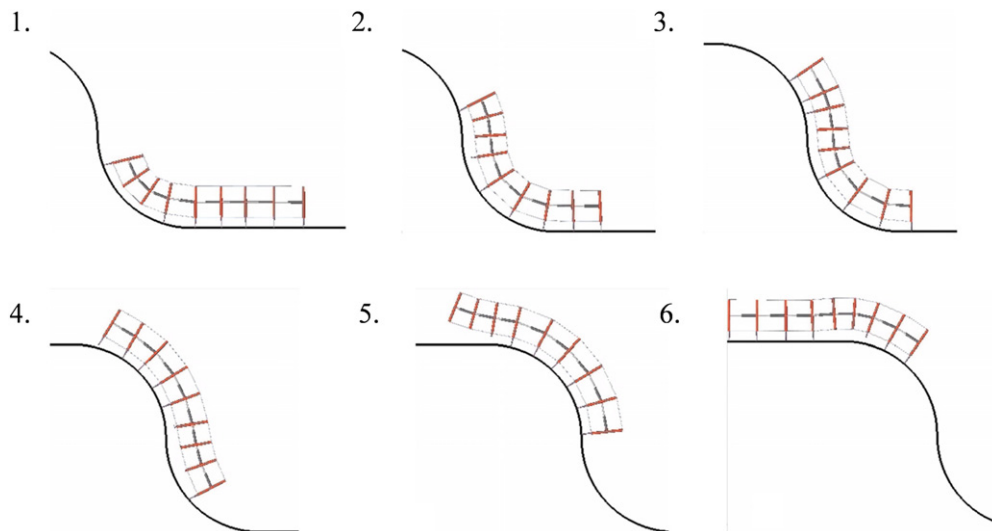
### 6.1. Controlling Assur tensegrity structures using impedance control

Impedance control is a well-known control scheme [26]. Nevertheless, no work has been done on its application to tensegrity structures. We found that impedance control keeps the Assur tensegrity structure in a singular configuration, thus maintaining the stability of the structure. In addition, impedance control enables us to produce a soft model with a controllable degree of softness.

While impedance control is complex in typical industrial robotics, it is much simpler to implement in tensegrity structures. For reasons outlined below, impedance control is a ‘natural’ choice for our model.

1. In tensegrity structures, each element is controlled separately and independently. This is in contrast to a standard industrial robot in which all DOFs are conjugated.
2. There is no need to transform end-point forces to actuator forces, and there is no need to consider robot dynamics in the impedance control law; the equation is used as is.
3. All tensegrity structures have infinitesimal motion in their singular configuration. The actual motion around this point is determined, among other things, by the elasticity of the materials (cables and struts). Impedance control can be thought of as a way to increasing this elasticity (where the stiffness coefficient  $k$  is equivalent to Young’s modulus).





**Figure 11.** Model climb with sharp incline.

In addition, Assur tensegrity structures, unlike most other tensegrity structures, are statically determinate structures which allow simple shape change.

These two characteristics (simple control and softness) make this combination (Assur tensegrity and impedance control) very useful for soft robotics. In contrast to using soft materials, this method requires relatively simple control; in contrast to using rigid bodies, it manifests robotic softness.

### 6.2. The caterpillar model

The model exhibits several characteristics which are analogous to those of the biological caterpillar as described in the following sections.

Empirical testing of the model has demonstrated that effective crawling requires that each stride be executed in three different phases. Trimmer *et al* [6] examined the kinematics of the biological caterpillar and found kinematic differences between three anatomic parts of the caterpillar: the thoracic segments, the midbody segments and the posterior segments. This distinction is similar to the three stride phases of the caterpillar model. The caterpillar model can navigate different terrains and in different directions using the same crawling pattern without adjusting the control scheme. This is made possible by slow stride speed and firm ground planting. The same is true for the biological caterpillar [28].

The internal pressure of the biological caterpillar is not a function of its size. During growth, its body mass is increased 10 000-fold, while internal pressure remains constant [5]. In the same way, our model is able to use the same pre-stress forces regardless of the model size (although the pre-stress forces must exceed a certain force threshold).

It was proposed above that the mechanical properties of caterpillar muscles may assume responsibility for some of the control tasks otherwise carried out by the nervous system. Our model demonstrates that using impedance control for each cable (which mimics the mechanical properties of caterpillar muscles) does indeed simplify high-level control. Also, caterpillar muscle develops force slowly. For comparison,

caterpillar muscle force development is about four to seven times slower than that of an insect flight muscle [11]. The model shows that adding the low-pass filter to the cable controller, which makes the cable react slower, eases high-level control and results in smoother motion. Note that the time constant of the filter was determined empirically in order to optimize results. Only afterward was the comparison made to the biological muscle (figure 9), both of which exhibited similar time constants. In addition, other crawling parameters related to time (e.g., the duration of one stride) are comparable in both the model and the biological caterpillar.

On the other hand, there is a discrepancy between the stride length of the model and that of the biological caterpillar. There are two reasons for this discrepancy. Firstly, the biological caterpillar has longer segments. Secondly, the biological caterpillar can contract up to four segments at a time. In our model, only three segments are contracted at a time. The reason for this limitation is that, when four segments are contracted and lifted together, the impact of gravity becomes much larger (especially in phases 1 and 3). This makes it difficult to program locomotion in a way that will be robust in all crawling directions (vertical and upside-down). This discrepancy should be improved in future versions of the model.

In summary, our model is consistent with many of the actual biomechanical attributes of the *Manduca sexta* caterpillar. Our research further suggests a few characteristics that the biological caterpillar may possess.

In the model, stride timing is strongly dependent on the signals that the legs send when touching the ground. Without those signals, locomotion is not robust—it tends to be inefficient and many times unstable. Observations show that feedback from the legs is not essential for maintaining locomotion gait in fast insects like the cockroach, while it is critical in slow insects like the phasid (the stick insect) [29]. Although we were not able to find similar information on caterpillars, their slower gait makes it reasonable to assume that they also need leg feedback. The model introduced in this paper strongly supports this hypothesis.

Another important observation is that cable forces do not change significantly during motion (figure 10). They have more-or-less the same magnitude while crawling and while at rest. This suggests that caterpillars invest little additional energy when crawling as opposed to resting. This conclusion may inspire follow-up biological research.

## 7. Further research

Future research can follow three directions. Firstly, the model can be improved in a number of ways. It should be optimized by increasing stride length. To do so, gravitational sensors would need to be added, which would allow for better control and better performance. In addition, the ability to control stride frequency would allow for variable velocity, and a more complex control algorithm could be designed to enable the model to navigate through obstacles and over gaps. Secondly, the model can be expanded into three dimensions. The transition from two to three dimensions is possible but would present several complications, particularly because Assur graph theory for three-dimensional structures is not yet fully complete. Finally, the construction of a physical mechanical model will greatly help to increase our understanding of these types of soft/rigid robots.

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This work was funded by ISF grant 1668/11. Figure 4 is taken from [22] and reproduced with the permission of John Wiley & Sons, Inc. Figure 9(b) is taken from [27] and reproduced with permission of the Journal of Experimental Biology.

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