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UNDERSTANDING THE LOCOMOTION AND DYNAMIC CONTROLS FOR MILLIPEDES: PART 1 - KINEMATIC ANALYSIS OF MILLIPEDE MOVEMENTS

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ABSTRACT

An investigation of the biological locomotion and control mechanisms observed in Diplopoda (millipedes) is performed in order to provide design rules for the development of a crawling millipede-inspired robot (millibot). Millipedes have long bodies with numerous pairs of legs, which allows them to perform higher ranges of motion compared to other arthropods traveling in the same environment. The relevant features of millipedes with respect to robotics include: (i) metachronal locomotion, (ii) ability to burrow through different substrates, and (iii) capability to traverse uneven terrains and align themselves swiftly when fallen over. A mathematical model is proposed describing these locomotion features that will provide guidance towards emulating these actions in a millibot.

1 Introduction

There is a growing need for small mobile robots that can navigate through difficult scenarios, unknown terrains and dangerous areas of interest. For operations at the mesoscale, roboticists have been inspired by insects and other arthropods (arachnids and myriapods) for developing locomotion techniques. The efficient and effective movements of arthropods that have evolved over 500 million years demonstrate optimized kinemat-

ics and dynamics with respect to the surrounding environment, and needs to be investigated and mathematically modeled in order to derive representative transitions. A range of bio-inspired ambulatory millibot systems have been designed on quadrupedal or hexapedal platforms inspired from the locomotion of rigid-bodied insects [1–8]. However, much of the prior work has focused upon copying the function of the natural organism rather than understanding the need and utility of such function within the given mechanistic context. Furthermore, a common denominator of these studies is that the locomotion is constrained to 4-6 legs, which while energy efficient, limits burrowing capabilities and other desirable features present in myriapods (e.g., the ability to align their bodies correctly with the plane of motion).

Another morphology that has been explored in literature for crawling robotic systems are myriapods [9–14]. These "many-legged" animals possess an elongated and flexible body. This subphylum most notably comprises the Chilopoda and the Diplopoda, which possess one and two pairs of legs respectively per body segment. The most often studied myriapod for robotic locomotion purposes has been the Chilopoda, commonly known as centipedes. Centipedes are known for their long flexible bodies with many legs, and demonstrate impressive speed resulting from their evolution as predators that need to chase and capture prey. Koh et al. [10] demonstrated a centipede robot "Zinedyn" that emulated the crawling gait of centipedes as a means to tra-

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verse uneven terrains. This platform was much larger than the biological creature itself, of the order of 73cm, and utilized conventional motors and gear systems for locomotion. Hoffman et al., [11–14] developed a centipede-inspired robotic platform of a much smaller scale (millibot). To do so effectively, piezoelectric bimorphs were used to actuate the system, similar to many of the quadrupedal and hexapedal platforms mentioned previously. The work of Hoffman et al. [12] demonstrated the advantages of myriapod morphologies for robotics platform applications such as agility (flexibility allows conformity to uneven terrains and transition from horizontal to vertical surfaces), stability (having many legs increases the number of contact points with the ground), robustness (can still operate even if a leg is damaged) and adaptability (can use a modular design for robotic applications).

While the centipedes have been investigated in the development of "many-legged" ambulatory robots, another myriapod, the Diplopoda (millipedes) have not been explored to the same extent. Similar to centipedes, millipedes are also known for their long flexible segmented bodies with many legs. Despite the similar morphology there are a few distinct differences which make millipede-inspired robots intriguing such as:

(i) Number of legs: Both classes are known for having many legs, however millipedes generally have more legs than centipedes. Millipede adults have a total number of legs that ranges from 22 to 750 with 4 legs (2 pairs) per body segment [15]. Centipedes on the other hand, have a range between 30 to 382 legs, with 2 legs (1 pair) per body segment [21].

(ii) Locomotion: Despite having a large number of legs, millipedes and centipedes exhibit different gaits. In millipedes, each pair of legs (on either side of the body) moves in phase with one another with slight phase differences between the adjacent pairs depending upon the species and situation [17]. This results in an undulation seen along the millipedes legs, referred to as a metachronal gait. In the case of centipedes, a pair of legs has two legs moving with an 180° phase difference, also with slight phase differences between the adjacent leg pairs. This, in part, results in lateral body undulations [19, 20], particularly at high speeds. A visual difference between these locomotion patterns can be seen in Figure 1.

(iii) Body Structural Functions: Both these myriapods display the ability of relative motion between body segments allowing for flexibility. However, millipedes generally exhibit more control of their body having complex and strong musculoskeletal systems needed for burrowing in 3-dimensional space. While centipede bodies tend to be flat as they are designed for speed and 2-dimensional surface activity, they do not have the same strong and rigid musculoskeletal structure, and have actually developed anatomical features of "tergite heteronomy" and "tergal fusion" to reduce gait associated body undulations [16] (e.g., the ubiquitous house centipede, *Scutigera coleoptrata*, possess fused segments to reduce these undulations). Millipedes on the other

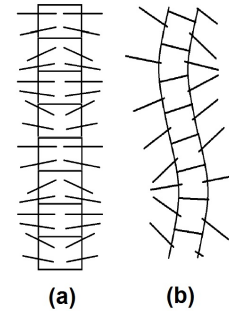


FIGURE 1: Difference in Gait - a) Millipede b) Centipede

hand, generally have cylindrical bodies, and there are a number of burrowing ecomorphs in millipedes (i.e., bulldozers, borers, wedgers and crevice dwellers) that have repeatedly evolved in unrelated lineages that live in the same habitat. Species that have flatter bodies are more surface active, but still demonstrate burrowing abilities using different techniques based upon their anatomy.

The emulation of millipede locomotion is appealing because it displays a wide range of dynamic functions of interest. Other creatures may display faster speeds but their surface locomotion appears to be the only function that robotic platforms have interest in emulating. Millipedes possess effective locomotive abilities on the surface but can also burrow through substrates by means of utilizing their unique gait and body structure. In addition, they have other advantages as listed above. This makes them quite appealing for millibot architecture.

2 Millipede Movements

In this study, two different species of Diplopoda were investigated. The first species was *Apheloria virginensis* (Figure 3a), which are considered flat-backed millipedes (Polydesmida) and grow to about 5cm in length. With such a body structure, they use a "wedging" method when burrowing. This involves inserting the anterior end into a crack or crevice, and then widening the gap by straightening their body and pushing upwards with their legs [16]. The other species observed was *Narceus americanus* (Figure 3b), which have been found to grow up to 10 cm. This species has a nearly cylindrical body (as do all millipedes in the Juliformia: Julida, Spirobolida, and Spirostreptida) and employ a "bulldozing" burrowing technique, where the head is used as a surface ramming object [16]. Another burrowing mechanism seen in millipedes is "boring", exhibited by species (e.g., in the Polyzoniida) with a narrow anterior end followed by progressively wider body segments enabling further penetration, but are not represented in this study. The two types of millipedes were characterized in similar scenarios and captured with a high speed camera at the rate of 120fps. The recordings were then analyzed using image processing methods of motion tracking on

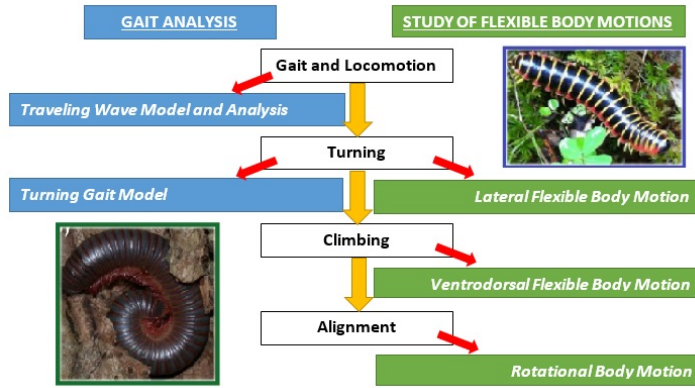


FIGURE 2: Layout of the Paper Describing the Flow of Information

Adobe After Effects and/or key framing on MATLAB. The rest of this paper explores and models the locomotion movements of millipedes with the flow structure illustrated in Figure 2.

2.1 Gait and Locomotion

The traveling wave phenomenon observed in millipede locomotion is a result of their metachronal gait (Figure 3a/b). The wave's characteristics (such as frequency, amplitude etc.) vary depending on the species, number of legs, weight, size and substrate. As previously described, a single pair of legs are always in bilateral phase symmetry with one another, but slightly out of phase with the adjacent pairs, as can be seen in Figure 3c-e.

The metachronal gait of millipedes has captured the attention of several studies, including those done by Sathirapongsasuti et al. [18] and Manton [17]. Sathirapongsasuti et al. [18] developed a model for predicting the position of a millipede's individual leg based on the assumption that the leg trajectory traces

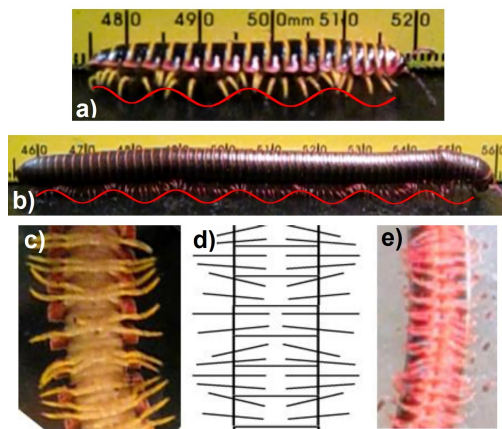


FIGURE 3: Traveling Wave and Metachronal Gait (Side and Bottom Views) - *A. virginianensis* (a, c) *N. americanus* (b, e) Model (d)

a circular path if suspended freely in the air. A visual representation of this motion can be seen in Figure 4a, where the solid blue line indicates the path traveled by an individual leg when crawling. With this assumption, when a millipede walks, the referenced circular path is disrupted by the ground and leads to the forward propulsion. The equations of motion derived for the model [18] are:

$$V_{wave} = \frac{\theta R}{t_T} \quad (1)$$

$$V_{millipede} = \frac{2R\sin(\frac{\theta}{2})}{t_P} \quad (2)$$

$$T = t_T + t_P \quad (3)$$

$$H = R - R\cos(\frac{\theta}{2}) \quad (4)$$

$$\omega = \frac{\theta}{T - \frac{2R\sin(\frac{\theta}{2})}{V_{millipede}}} \quad (5)$$

where V_{wave} is the velocity of the traveling wave, $V_{millipede}$ is the velocity of the millipede, t_T is the duration of the transfer period (leg in the air), t_P is the duration of the propulsion state (leg on the ground), H is the maximum height of the leg and ω is the angular velocity of the leg tracing the circular reference path. Solving equations (1) to (4), R and θ can be determined. The position of the legs can then be tracked over time:

$$X(t) = \begin{cases} V_{millipede}(t - \phi_t) - R\sin(\omega(t - \phi_t)), & \text{transfer} \\ -V_{millipede}(t - \phi_t), & \text{propel} \end{cases} \quad (6)$$

$$Y(t) = \begin{cases} H - R - R\cos(\omega(t - \phi_t)), & \text{transfer} \\ 0, & \text{propel} \end{cases} \quad (7)$$

where the time phase ϕ_t between adjacent legs is found by $\frac{d}{V_{wave}}$ (d is the distance between pairs).

This model of the millipede gait was compared to the actual leg motion observed for the *A. virginianensis*, using the video processing approach on Adobe After Effects, as shown in Figure 4b. Tracking the motion of a single leg of a walking millipede, indicated that the model developed by Sathirapongsasuti et al. [18] captures the desired aggregate behavior, shown in Figure 4c.

With many legs and small phase differences, continuous constant propulsion (like a wheel) can be easily achieved, unlike 4-6 legged creatures that may require a period of transition depending on the legs' phase differences in order to maintain upright stability. The observed values of the significant parameters used to model the legs end positions of the *A. virginianensis* are shown in Table 1.

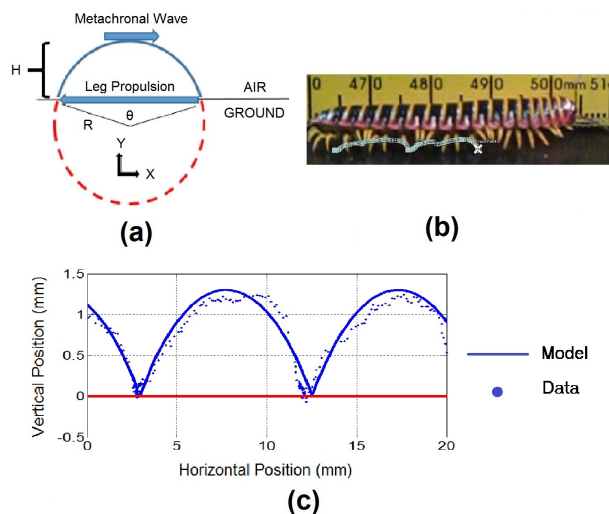


FIGURE 4: Millipede Gait (*A. virginiensis*) - a) Existing Circle Reference Model [18] b) Tracking Method on Adobe After Effects c) Model vs Experimental Data of a Single Leg

TABLE 1: Model Parameters (*A. virginiensis*)

H	1.3 mm
t_T	0.525 s
t_P	0.325 s
V_{wave}	12.6172 mm/s
$V_{millipede}$	13.6986 mm/s

It is worth noting that even though the aggregate behavior of the leg position is determined, the model is certainly a simplification of the actual motion. Looking at Figure 4c, there is a slight discrepancy, likely related to the model assumption that the leg is a single body that moves in a circular motion. The actual leg of a millipede consists of several segments, however for simplicity let us define an upper and lower leg region as seen in Figure 5. The assumption from Sathirapongsasuti et al. [18] was made by observing a circular motion performed by the remaining upper region of a leg that had been broken off. This assumption therefore eliminates any motion contributed by the lower leg region. Noting that the leg leaves and lands on the ground at different angles indicates that the lower leg portion experiences a swinging motion when elevated. The rate of swing or articulation of several joints could potentially relate to the slight discrepancies seen in Figure 4c. However, considering that the difference is minimal and with the aggregate motion captured, developing a more complex multiple segment kinematic model with extra degrees of freedom may not be essential in understanding the utility of its traveling wave gait across its many legs.

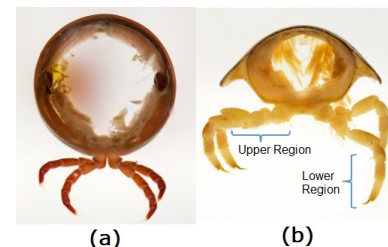


FIGURE 5: Millipede Segment (Ring and Leg) - a) *N. americanus* b) *A. virginiensis*

This model is able to determine the position of individual legs with knowledge of a millipedes' body and wave velocity. However it does not reveal the characteristics of the traveling wave across all the legs. Understanding how the wave properties, such as wavelength and amplitude, are controlled in order to be utilized for effective locomotion on the surface or burrowing activity is of interest. We want to be able to determine the type of waves needed to accomplish locomotion for different terrains, which then could be translated to generating and modeling the appropriate individual leg motions (such as [18]).

As mentioned, the traveling wave characteristics in millipede locomotion has been observed to vary based on the species and environmental conditions such as substrate [17]. An example of such variation is seen in Figure 6a, where *N. americanus* reveals three distinctly different gait patterns when placed in three different scenarios. It can be seen that there is a difference in the number of legs in contact with the ground per wavelength. The *N. americanus* in Figure 6ai is crawling on a flat horizontal surface (0°). Figures 6aii and 6aiii show the millipede on inclined surfaces of 35° and 55° , respectively. Given the change in scenarios, the adjustment in gait would be due to a resistant force opposite to the direction of motion (gravity), in combination with a behavioral response to reducing traction.

In Figure 6a, the blue regions consist of legs that are in contact with the ground propelling the body forward (backward strokes), while the red regions consist of the legs off the ground in the transfer stage that create the traveling wave like phenomenon (forward strokes). The red and blue regions combined form one wavelength.

Manton [17] conducted experiments that provided resistance to the motion of millipedes using weights, and a few of the traveling wave variations that were observed are also present in Figure 6a. First of all there is a difference in wavelength, with 13 legs per wavelength when crawling on a horizontal surface (Figure 6ai), 16 legs per wavelength on an inclined surface of 35° (Figure 6aii), and 23 legs per wavelength on an inclined surface of 55° (Figure 6aiii). The change in wavelength is a result of adjusting the phase difference between leg pairs. Manton [17] indicated that there could be slight variations in wavelengths across the body due to the fact that the legs at the anterior and posterior ends tend to be a little shorter than those along the rest of the

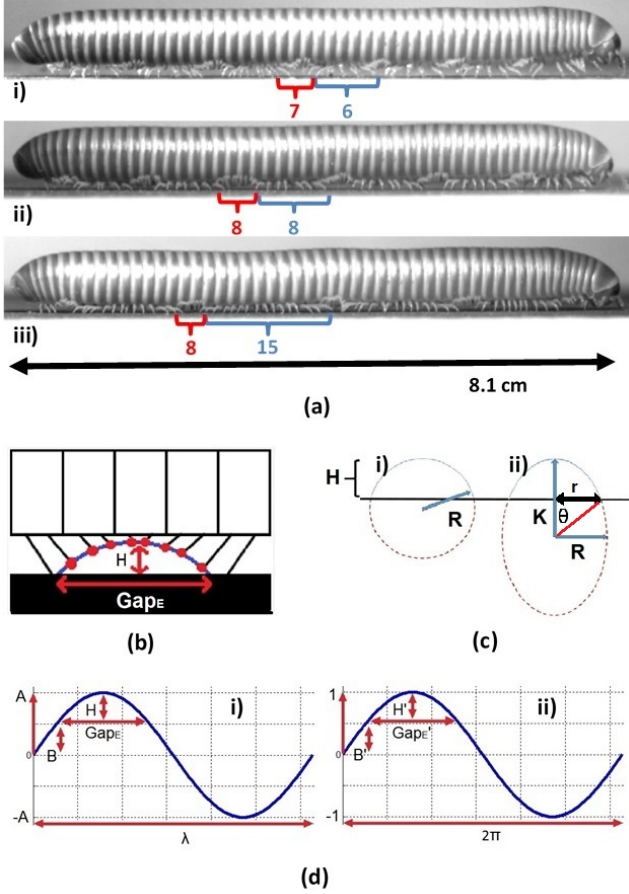


FIGURE 6: a) Observed Gait Variations (*N. americanus*) b) Constant Forward Strokes Profile c) Circle vs Elliptical Reference d) Amplitude Modeling

body.

Figure 6a shows that there are variations in wavelength and ratio of legs performing forward to backward strokes. The data is consistent with Mantons [17] findings of a "constancy in forward strokes" that is consistently at 7-8 legs, relative to the backward strokes that range between 6-15 legs. This profile of forward strokes, for this specimen, can be represented with Figure 6b. H is the elevation height and Gap_E is the distance between the two legs in contact with the ground. From this observation, a model to characterize the effective wave amplitude can be developed.

A traveling wave can be characterized by its wavelength, amplitude, and velocity. Given that the wavelength and wave velocity can be directly observed when the millipede is walking, the amplitude of wave is the only thing that needs to be calculated.

In order to determine the amplitude, the position of all the legs need to be known. The model proposed by Sathirapongsasuti et al [18] is capable of determining these positions as each leg follows the same motion, however requires solving a

system of nonlinear equations 1 - 4. This process can be avoided by removing the temporal nature of their model, which is acceptable because we are only looking to define the amplitude at defined instances. This involves more than taking the anti-derivatives of equations 6 and 7. This is because the circle reference model [18] involves two differently defined velocity regions during the transfer and propelling stages. Therefore, the time phase between legs can not directly translate to an angular phase difference nor can a circular reference be used, shown in 6ci. To capture the correct placement of legs, an elliptical model is used to maintain the leg tip arc motion while implementing an angular phase difference. This is accomplished by defining the leg positions using 6cii and equations:

$$X(\tau) = R \cos(\tau) \quad (8)$$

$$Y(\tau) = H - K - K \sin(\tau) \quad (9)$$

where τ is the angle ranging from 0 to 2π . While R and K are calculated as:

$$\lambda = V_{wave} T \quad (10)$$

$$n_{wave} = \frac{\lambda}{d} \quad (11)$$

$$n_{elevated} = \frac{V_{wave} t_f}{d} \quad (12)$$

$$\phi_A = \frac{2\pi}{n_{wave}} \quad (13)$$

$$\theta_{initial} = \frac{\phi_A n_{elevated}}{2} \quad (14)$$

$$r = \frac{V_{millipede} t_p}{2} \quad (15)$$

$$k = \frac{r}{\tan(\theta)} \quad (16)$$

$$K = H + k \quad (17)$$

$$R = \sqrt{\frac{r^2}{1 - \frac{k^2}{K^2}}} \quad (18)$$

where n_{wave} and $n_{elevated}$ are the number of legs per wave and the number of legs elevated in the forward strokes profile, respectively. Note that $\theta_{initial}$ for a circular case, but is then incrementally adjusted until the propelling leg velocity is within a desired tolerance of the body velocity and has the correct number of elevated legs.

With this model explicitly taking into account the forward strokes profile, the amplitude of the effective wave is determined as:

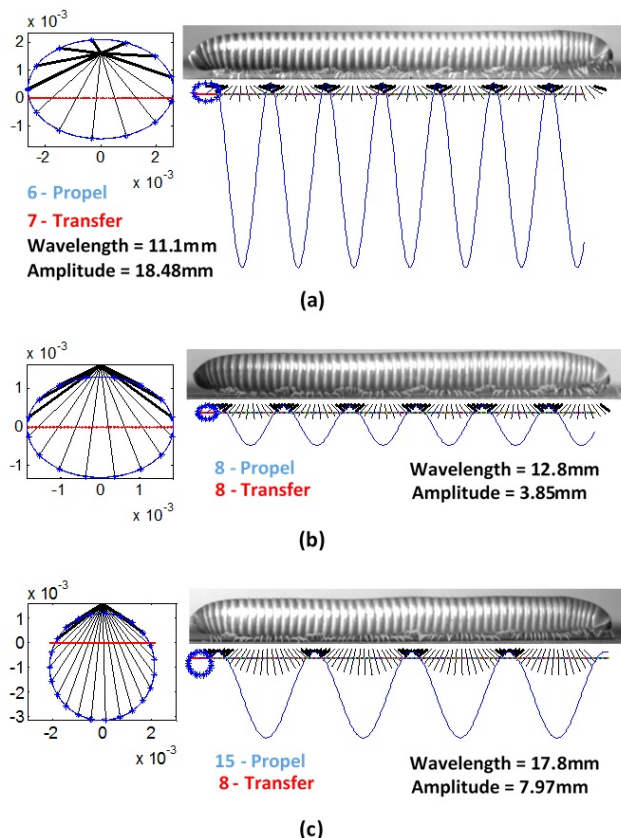


FIGURE 7: Comparing Gait Model with Actual Gait - a) 0°incline b) 35°incline c) 55°incline

$$Gap_E = (n_{elevated} + 1) \frac{\lambda}{n_{wave}} - 2r \quad (19)$$

$$\frac{Gap'_E}{2\pi} = \frac{Gap_E}{\lambda} \quad (20)$$

$$B' = \sin\left(\frac{\pi}{2} - \frac{Gap'_E}{2}\right) \quad (21)$$

$$H' = 1 - B' \quad (22)$$

$$A = \frac{H}{H'} \quad (23)$$

As mentioned, the positions of the legs needed to determine the amplitude could be found using the model of Sathirapongsasuti et al [18], however this requires solving a set of nonlinear equations that can be time consuming. The elliptical model proposed is able to determine the amplitude without solving a nonlinear system. Both models were computed using MATLAB and the average computation times were compared. The circle reference model took 112.9 seconds, while the elliptical model

took 0.496 seconds and still clearly captured the millipedes' position as shown in Figure 7. This is significantly relevant when considering the limited computing power of miniature robotic platforms.

Figure 7 directly compares the results from the elliptical model to that of the three gait variations introduced in Figure 6a. It is interesting to see the variation in the wave characteristics. It is worth noting that in Figure 7a (flat surface) the *N. americanus* was found to be significantly faster than the other cases, moving at 17.1mm/s. While in Figure 7b (35°incline) and Figure 7c (55°incline) the millipede moved at 9.2mm/s and 5.3mm/s, respectively. These initial observations and results would indicate that there is a relationship between the traveling waves characteristics, in combination with body shapes (Figure 5), with thrusting power. This is of great relevance for understanding burrowing capabilities.

Millipede gaits have evolved to maximize the resultant force applied in the direction of motion. With a means of increasing the number of pairs of legs in contact with the ground by adjusting its metachronal gait (by modulating the effective traveling wave's wavelength and amplitude) millipedes can vary the amount of force to thrust the body forward. While this model can capture the kinematic motion of variation in gaits, and is consistent with observations and literature [17], no direct relationships between the traveling wave characteristics and propulsion have been derived or modeled. Future studies on dynamic analysis needs to be conducted in dynamically controlled environments to determine the mathematical relationships.

2.2 Turning and Lateral Body Motion

A model of the millipede gait has been discussed and verified by actual millipede observations, however only for straight line locomotion. Sathirapongsasuti et al. [18] extended their model and developed it to account for turning using the assumption that the trajectories of the 2 legs for a pair are scaled inversely to each other. To achieve a turning motion, one leg traverses less (inner leg) while the other increases the distance it travels (outer leg). Both the scaling factors (P) and duration of the turn are functions of the angle ϕ and radius L of the circular arc the millipede is turning [18].

$$\frac{L}{(L + \frac{l}{2})} = P_{in} \quad (24)$$

$$\frac{(L + l)}{(L + \frac{l}{2})} = P_{out} \quad (25)$$

$$\frac{(L + \frac{l}{2})\phi}{V_{millipede}} = t_{turn} \quad (26)$$

where l is the width of the millipedes body. The scaling factors P_{in} and P_{out} are multiplied to equations 8 and 9. It is worth noting

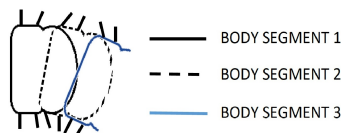


FIGURE 8: Ball and Socket Turning Mechanism of Segment Joints

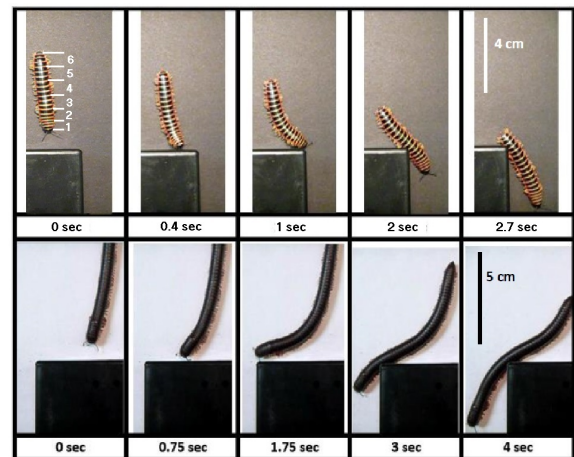
that modeling the turning gait in this fashion is consistent with the observations that leg pairs always stay in bilateral phase with each other.

For millipedes to exhibit effective turning with many legs and a long body, other than utilizing the turning gait as described, they need to have flexible bodies. The flexible bodies of millipedes consist of several body segments that are capable of motion relative to each other. In Manton's [17] work, an in-depth study of the musculoskeletal structure of millipedes was performed. The relative motion of body segments is accomplished by use of a "ball and socket" like joints in between them. The anterior ends of each segment is tapered and inserted into the wider posterior end of the segment ahead of it. A complex musculature, in combination with the structure, allows for the rigidity needed for burrowing. Even though there are variations between species, a visual example of Manton's general description [17] of the joints between body segments can be seen in Figure 8.

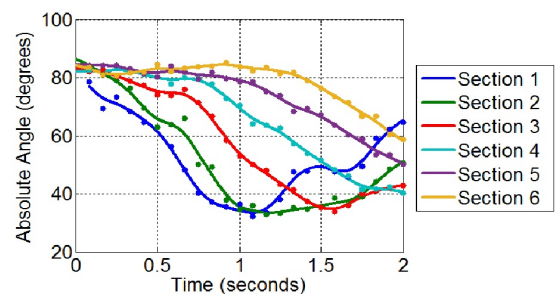
To further understand how millipedes perform a turning motion, millipedes were placed in scenario with a large obstacle in their path. Footage was taken of both the *A. virginiensis* and *N. americanus* in similar situations, as shown in Figure 9a. As it can be seen, the bodies of both species display a lateral bending while turning, in the manner where all the body segments tend to follow the path initially traversed by the first segment (head). To capture data that represents these movements, several points along the *A. virginiensis*'s body were tracked. By tracking seven points, the position and angle of six sections could be determined. The points were selected so that each section represented three body segments. For the purposes of capturing the aggregate behavior, it was assumed that the angle of a given section was the summation of the angles between the internal segments. From the data collected from the key framing image process, the trajectories in Figures 9b and 9c were generated with smooth splines by using MATLAB's cftool function. Figure 9b displays the absolute angle of the body sections. From this data, a sequential behavior of the body sections changing angles over time, and of similarly followed trajectories, is evident. This is consistent with the motions expected from Manton's description and the "follow the leader" observation of the body segments. The relative lateral angular motion between sections during the turning period was determined and these trajectories are seen in Figure 9c. The maximum relative angular displacement between adjacent sections, during the turn by the *A. virginiensis* in Figure 9a, was 15° , which for three body segments is representative of

approximately 5° per body segment. The particular turn captured was certainly conservative to its maximum capabilities, which Manton [17] determined to be up to 35° per segment depending on the species.

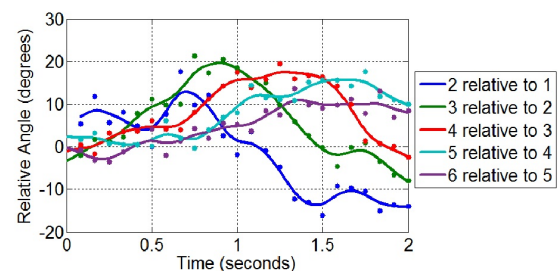
Lastly, across the different species of millipedes, some have eyes to help with sensing their environments, while others are completely blind. However, regardless of having vision or not, millipedes generally rely on the use of antennae to indicate direction of motion. As seen in Figure 9a, both the blind *A. vir-*



(a)



(b)



(c)

FIGURE 9: Tracking a Millipedes Turning Motion - a) *A. virginiensis* and *N. americanus* Turning b) Absolute Body Segment Angles of *A. virginiensis* c) Relative Body Segment Angles of *A. virginiensis*

giniensis and *N. americanus* that has eyes, begin to turn once the antennae make contact with the obstacle, towards the path of least resistance. Combining the turning gait model and the determined "ball and socket" like joint allowing relative lateral motion between body segments, provides an understanding of the turning locomotion. This provides a sound basis for developing approaches and means to emulate this turning locomotion on a millipede robot.

2.3 Climbing and Ventrodorsal Body Motion

One movement of interest introduced by myriapods is the ability to conform to uneven surfaces and climb. Adding this degree of freedom to the lateral motion allows the body to easily traverse 3-dimensional terrains. In particular, it allows the change from horizontal to vertical surfaces without much adjustment of its walking gait, by controlling its body position instead. This myriapod morphology becomes clearly advantageous over rigid bodied insects, which would require significant changes in gaits to accomplish the same task.

Like the experiment conducted for capturing the turning locomotion, both millipedes were placed in situations that encouraged a climbing behavior. Figure 10a shows both performing the task in similar fashions. Again, data was collected from the footage of the *A. virginiensis*, tracking the absolute and relative angles of the six sections consisting of three body segments each. Figure 10b clearly indicates a similar sequential angular motion of body segments as before but in the ventrodorsal plane.

Observing the relative angular ventrodorsal motion (Figure 10c), the degree of freedom allows motion in both directions in the plane. Also, that for *A. virginiensis* to achieve a 90° bend in the ventrodorsal direction, each segment bends a maximum of about 17°. Again, this motion captured is conservative relative to its maximum capabilities. The range of motion varies among different species of Diplopoda. For instance, juliform millipedes (e.g., *N. americanus*) are capable of a large range of motion in the ventrodorsal, when curling up tightly into a spiral for defensive purposes, seen in Figure 2.

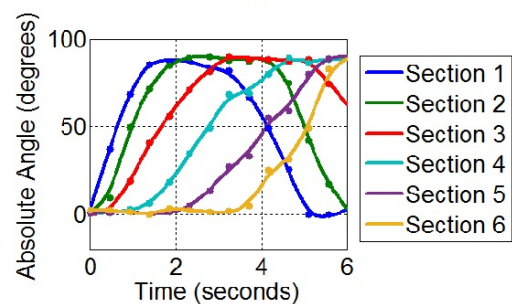
Several species demonstrate the ability to climb on rough surfaces reasonably well, however millipedes are not the most effective climbers. The ability of millipedes to climb is dependent on their morphology of numerous legs providing many points of contact for support and their flexible bodies to transition to crawling on steep surfaces with relative ease. Despite these desirable characteristics for effective climbing, they do not have adhesion techniques seen in other arthropods like ants, beetles and spiders. A few species of millipedes possess claw adaptations for climbing and living in caves, but not *A. virginiensis* or *N. americanus*.

2.4 Righting and Twisting Body Motion

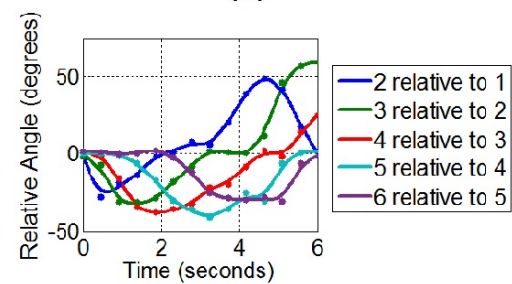
One conspicuous movement exhibited by millipedes is the ability to rotate individual body segments relative to each other



(a)



(b)



(c)

FIGURE 10: Tracking a Millipedes Climbing Motion - a) *A. virginiensis* and *N. americanus* Climbing b) Absolute Body Segment Angles of *A. virginiensis* c) Relative Body Segment Angles of *A. virginiensis*

about the long axis of its body. Again, this motion is possible with the presence of the "ball and socket" like joint in between segments combined with strong musculature.

Manton described that such motion was not demonstrated in open surfaces, and postulated that its function was for burrowing

purposes as species that burrow more effectively, for example a juliform millipede could rotate more than surface active species like the flat-backed millipedes in the Polydesmida.

During the experimental process of collecting video footage of the millipedes crawling, it was found that they would use the ability to rotate body segments to right itself back on its feet. Rigid body insects, such as beetles, would not be able to right themselves if fallen. The ability to perform this motion on a robotic platform would be desirable, if traversing in dangerous and unknown terrains. Similar key framing techniques that were

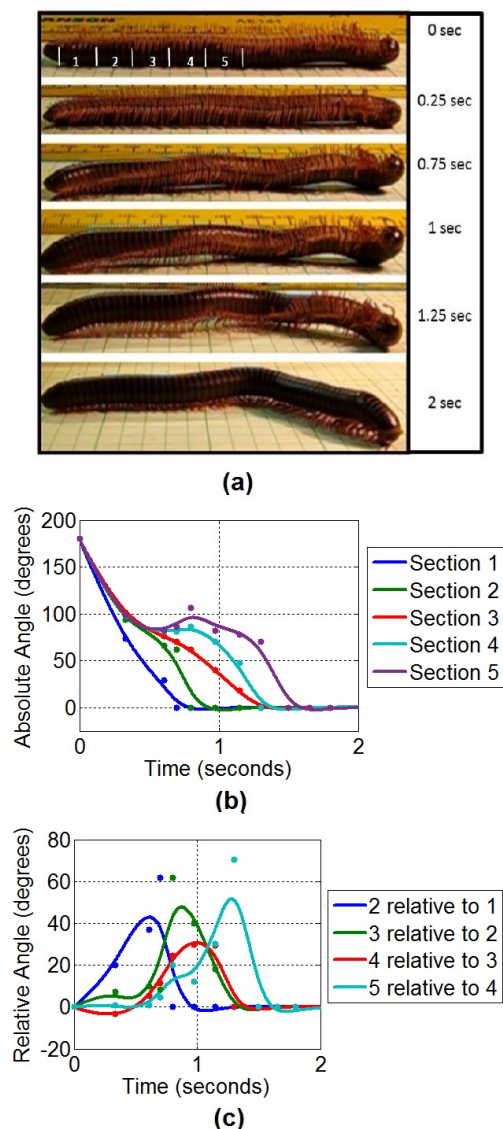


FIGURE 11: Tracking a Millipedes Righting Motion - a) *N. americanus* Righting Itself b) Absolute Body Segment Angles of *N. americanus* c) Relative Body Segment Angles of *N. americanus*

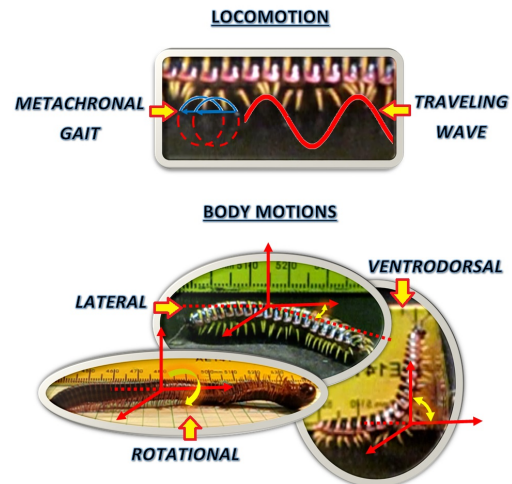


FIGURE 12: Millipede Locomotion Kinematics Summary

used in collecting data for the turning and climbing scenarios were performed for the twisting motion of the millipedes righting themselves. The movement displayed can be seen in Figure 11a. Data was collected from the *N. americanus*, because there was a larger region of its body that displayed only twisting of body segments without other lateral or ventrodorsal flexions, simplifying the key framing process.

Five sections of 1 cm intervals were tracked, each section consisting of six body segments. The angle was determined by tracking the position of the attachment point of the legs to the body relative to the rotational axis along the body (assumed to be halfway up the body from the side). The results of the absolute and relative angles of the body sections selected are seen in Figure 11b and 11c. Looking at the absolute angles, again we see the sequential behavior of body segments rotating. However, it is interesting to note how the millipede gets back on its feet. At about 0.75s the fifth section begins to rotate back upwards. Watching the motion (as seen in Figure 11a) the *N. americanus* would rotate the anterior and posterior ends in opposite directions until one end plants its legs on the ground. The grounded legs then act as an anchor, while the adjacent body segments rotate sequentially until the other end is in the same configuration. Similar motion was observed for the *A. virginianensis*. The relative rotation of segments from the bottom plot of Figure 11c shows that the maximum relative angle between adjacent segments to complete this motion was approximately 9° ($55^\circ / 6$ body segments). This result appears to be relatively consistent to the 11° observed by Manton on another species of juliform millipede [17].

3 Conclusion and Future Works

In this paper, the mechanisms for the locomotion and other conspicuous movements displayed by millipedes were explored

for inspiration of a crawling robotic platform. An already existing model of the metachronal gait creating a traveling wave like phenomenon was discussed, adjusted and verified with video and image processing. We found that our proposed elliptical model of leg motion is biological realistic and reduces the computational burden needed to determine leg amplitude and position, which is a desirable quality given the limited computing power of miniature robotic platforms. Furthermore the "ball and socket" like mechanism existing in between the individual body segments allows flexible bending motions. It was demonstrated that these joints introduce relative motion between body segments in the lateral and ventrodorsal planes which is advantageous when traversing uneven terrains. The relative rotation of body segments about the long-axis of the millipede's body was observed to allow the ability to align itself. A visual summary of the millipede movements discussed can be seen in Figure 12.

From the video footage, we have studied their motions and modeling the traveling wave gait. The next stages of this work towards developing a millipede-inspired robotic platform include performing some dynamic analysis of the millipedes. By understanding fundamental kinematic principles in nature, we now have an informative basis for dynamic analysis and implementation for robotics. In particular, more analysis of performance when applying resistance to its motion to quantify and understand how modulation of the gaits traveling wave and different body shapes relate to thrusting and burrowing ability. In addition, concepts of emulating the motions discussed on a millibot, by means of piezoelectric ceramics or shape memory alloys, are to be developed in the future.

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