Kinematics of An Origami Inspired Millipede Robot*

Chenying Liu, Zhong You and Perla Maiolino

***Abstract*— Millipedes are worm-like arthropods with a relatively hard exoskeleton, a segmented body, and numerous pairs of legs. The appendages help to coordinate the behaviours of multiple body segments so they can generate a peristaltic wave, which have evolved over 500 million years to achieve efficient locomotion on uneven surfaces and limited space. When sensing danger or disturbed, millipedes are capable of curling up into a coil shape to protect themselves against predators. The curling behaviour in millipedes has also been found in some of their close relatives in the arthropod family, such as pill bugs and lobsters. By looking at the peristaltic and curling behaviours, we propose an origami-based concept for a robot that can imitate the motion of a millipede. The mechanism is made with a chain of interlinked modules, mimicking the segments in a millipede. Each module is an assembly of rigid facets with uniform and non-negligible thickness, leading to a reduction in the overall degrees of freedom (DoF). Given its special geometric design, the origami itself can be extended to any number of modules without excessive DoF. Its curling and peristaltic motions are mathematically quantified, which paves a way for a millipede robot design with rather simple actuation and control strategy. In addition, a few other configurations of the proposed origami mechanism and its geometric variants are presented to open up design space for future applications.**

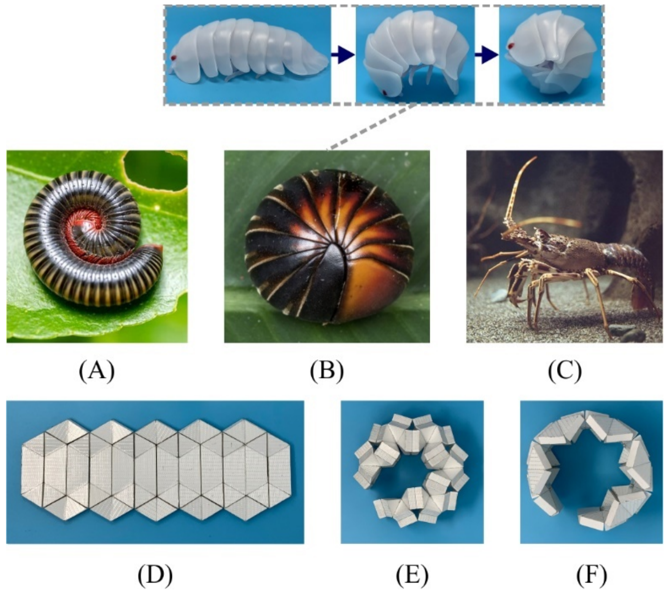
I. Introduction

Taking inspiration from earthworms, inchworms, millipedes, and centipedes, worm-like robots have received great attention due to their ability to navigate through limited space and crawl over uneven surfaces with ease. These living organisms usually consist of several continuous body segments, which can generate wave-like peristaltic motions for locomotion purpose [1]. To mimic such behaviours, roboticists have adopted a variety of approaches to design versatile worm-like robots. For instance, soft materials have already been implemented and controlled to achieve radial and longitudinal expansion on multiple body segments, and thus, a retrograde wave motion is produced [2]. Origami techniques also offer a quicker and easier way to design metameric segmentation that is capable of locomotion through the length variation and body rotation [3]. Both approaches have greatly expanded the scope in design, fabrication and control of worm-like robots.

Chenying Liu and Perla Maiolino are with Department of Engineering Science, University of Oxford and the Oxford Robotics Institute, Oxford, UK (e-mail: {chenying.liu, perla.maiolino}@eng.ox.ac.uk).

Zhong You is with Department of Engineering Science, University of Oxford, Oxford, UK (e-mail: zhong.you@eng.ox.ac.uk).

*The abstract of this work has been accepted as a keynote speech for *15th World Congress on* Computational Mechanics & 8th Asian *Pacific Congress on Computational Mechanics*. A full version work has been submitted to *ASME 2022 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*.



1. source: source: https://www.callnorthwest.com/tag/how-to-get-rid-of-millipedes/

2. source: https://www.hobbyfarms.com/roly-poly-pill-bug-garden-roles/

3. source: https://www.gettyimages.co.uk/photos/underwater-lobster

Figure 1. (A) A millipede curl up into a spiral[1]; (B) a pill bug curl into a coil, with a toy version dipleyed above[2]; (C) a lobster curl its abdomen[3]; (D) – (F) top view of the origami mehcanism and its two curling configurations.

From a perspective of biology, while millipedes resemble worms in many ways, they are, in fact, not worms but arthropods with legs and shells [4]. Their multi-segment bodies are normally covered by hard outer skins. They have numerous pairs of legs on both sides of body segments, which help to coordinate body motions and generate peristalsis for locomotion. When sensing danger, millipedes can curl into a spiral as shown in Fig. 1(A), which is a self-defensive mechanism and protect them against predators. Similar curling behaviours have been found in the bigger arthropod family, i.e., crustaceans, which include pill bugs and lobsters. Their coil-like configurations are displayed in Figs. 1(B) and 1(C), respectively, which both help with their survival in nature. Pill bugs, commonly known as roly-polies or pill millipedes, can quickly switch into the coil shape when disturbed. Lobsters or shrimps use the curling mechanism for a rapid change in their swimming directions.

There has been extensive research on the peristaltic motions of millipedes [5], and thus, we pay more attention to the imitation and modeling of the curling mechanism. To understand how it works kinematically, we look into the curling motions of a roly-poly toy and a lobster as they are larger in size compared to millipedes while sharing similar biological features to curl up. A pill bug toy is shown upon Fig. 1(B), which has seven body segments connected by simple rotational joints one after another, resulting in a curling motion. The lobster's abdomen, shown in Fig. 1(C), comes into a coil in a similar way. The adjacent hard shells overlap and are connected by two symmetric spherical joins on both sides of the shells. The shells are further connected by a flexible film on the top, which seals up the body and restrict its curling angle as the film itself is not extensible. The whole mechanism is equivalent as a rotational joint, just like the pill bug toy. The motion of these arthropods is similar to that of worms, but the former have a body made from rigid segments, making it ideal to imitate using rigid origami.

Inspired by these specific organisms, our research is to develop an origami-based concept for a robot that replicates the motion of a millipede. It should be able to generate peristalsis and curl into a coil or spiral shape.

To date, a soft-material robot has already been developed to imitate a millipede's behaviour. It crawls on a hard surface using the travelling metachronal wave, and can curl up and roll to move forward [6]. Despite the highly-customizable potential, soft material itself makes it challenging to model, actuate, and control the robot [7]. In contrast with the existing material-based approach, our proposed mechanism, shown in Fig. 1(D), is made with a chain of interlinked origami modules, mimicking segments in a millipede. Thin materials like paper or polymer films have already been used for worm-like robot design. The have shown substantial advantages to simplify the design and control, while such base materials are prone to fatigue and may not be suitable to carry considerable loads.

Different from the usual origami approach where near-zero-thickness sheet materials are employed, our module is an assembly of rigid facets with uniform and non-negligible thickness, which are connected along their upper or lower edges by creases, forming an origami pattern of thick panels. The increase material thickness has not only opened up more design space for desirable properties, but also introduced mechanical coupling to reduce unwanted motions [8]. Kinematically, a segment is composed of two types of Bricard linkages, known as one of the spatial overconstrained linkages [9]. Since consideration of thickness in origami facets is known to reduce the overall degrees of freedom (DoF) of the mechanism, our mechanism has only single DoF with different bifurcation paths. Moreover, the proposed origami pattern is specially designed so that it can be extended to have any number of modules while its peristaltic and curling motions always remain single mobility. Two types of curling motions, as shown in Fig. 1(D), can be achieved when all segments come to an identical bifurcation path. Switching between different states of a certain curling motion generates peristaltic motions. A combination of different bifurcation paths leads to wave-like, bench-like, and heart-like shapes that can be used for multi-modal locomotion.

Our work so far focuses on the kinematic modeling of a millipede robot design using origami techniques. A detailed kinematic analysis of the origami mechanism is to be presented, where both curling and peristaltic motions are quantified in detail. The motion paths are given, with bifurcation configurations identified for motion change. In addition to two typical millipede motions, three more configurations of our mechanism are displayed, which brings potential for locomotion mode change and also opens further design space with targeted applications. Our proposed mechanism is analytically calculated, simulated in SOLIDWORKS® 2020 and experimentally validated by prototypes made from polyvinyl chloride (PVC) foam sheets with uniform thickness. The work paves a way for the realisation of millipede-like robots in the future with actuation and control elements integrated.

II. Selected Work

Two curling motions of the proposed origami mechanism are displayed in Fig. 2.

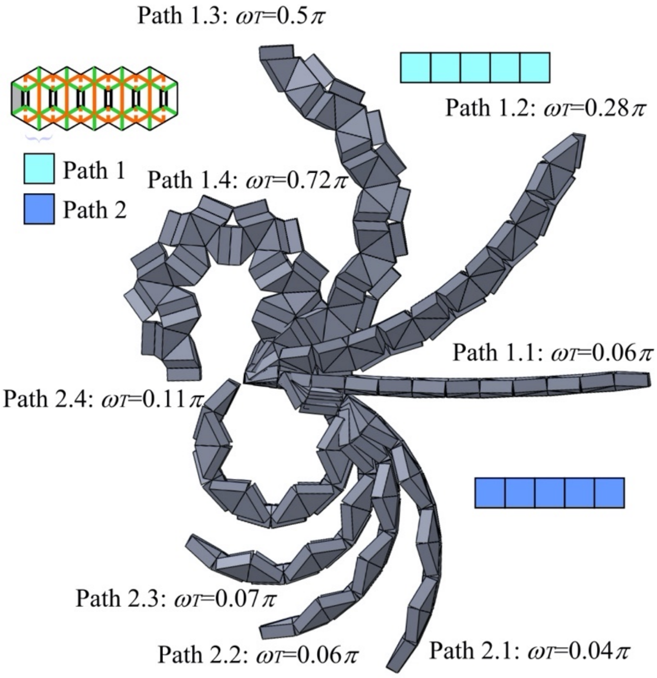


Figure 2. Side view of two curling motions with an incremental dihedral angle, with the whole origami partern displayed as well. The light blue square represents one particular motion path while the dark blue square represents the other. Their combinations generate two curling motions.

References

[1] Chapman, G., 1976. The Locomotion of Soft-Bodied Animals. E. R. Trueman. *The Quarterly Review of Biology*, 51(3), pp.452-452.

[2] Pfeil, S., Henke, M., Katzer, K., Zimmermann, M. and Gerlach, G., 2020. A Worm-Like Biomimetic Crawling Robot Based on Cylindrical Dielectric Elastomer Actuators. *Frontiers in Robotics and AI*, 7.

[3] Bhovad, P., Kaufmann, J. and Li, S., 2019. Peristaltic locomotion without digital controllers: Exploiting multi-stability in origami to coordinate robotic motion. *Extreme Mechanics Letters*, 32, p.100552.

[4] Vanden Spiegel, D. and Golovatch, S., 2012. The millipede family Ammodesmidae in western Africa. *ZooKeys*, 221, pp.1-17.

[5] Garcia, A, Priya, S, & Marek, P. "Understanding the Locomotion and Dynamic Controls for Millipedes: Part 1 — Kinematic Analysis of Millipede Movements." *Proceedings of the ASME 2015 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, Colorado, USA. September 21–23, 2015. V002T06A005.

[6] Gu, H., Boehler, Q., Cui, H. et al. Magnetic cilia carpets with programmable metachronal waves. *Nat Commun*, 11, 2637 (2020).

[7] Iida, F., and Laschi, C. Soft robotics: Challenges and perspectives. *Procedia Computer Science*, 7 (2011): 99-102.

[8] Chen, Y., Peng, R. and You, Z., 2015. Origami of thick panels. *Science*, 349(6246), pp.396-400.

[9] Chen, Y., Feng, H., Ma, J., Peng, R., and You, Z., 2016, Symmetric waterbomb origami. *Proceedings of Royal Society A*, 472:20150846.