Insect-scale Robot and Assembly Robotic System

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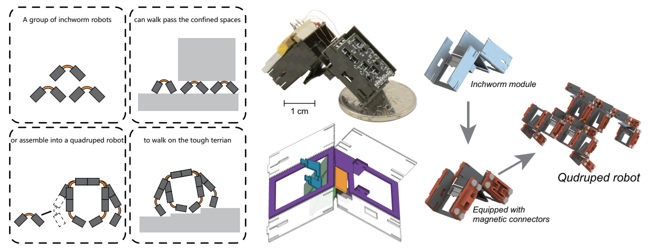
I. Introduction

The insect-scale robot generally takes inspiration from nature insects such as ant [34], bee [5] and cockroach [1]. However, most insect-scale robots are simply actuated mechanisms. When comparing them with their biological counterparts, the capability for locomotion and autonomous operation is far lower than the latter [31]. Building an insect-scale robot is challengeable for its limited scale, complex structure, unconventional fabrication method and high requirements of mobility and autonomy. The efforts of previous works have resulted in many successful attempts. Powerful tools such as Smart Composite Microstructure (SCM) method [32] and 3-D printing [30] have been developed for fabricating the microstructure of the insect-scale robot. Developments of the smart material actuators such as piezoelectric ceramic [33][1], dielectric elastomer [5] and shape memory alloy [34] also promotes the performance of the insect-scale robot. These advances narrowed the gap between robots and insects, which also guide insect-scale robot research.

In parallel with the advances in insect-scale robots, multi-robot systems such as modular robotic systems and swarms had several recent breakthroughs in the last decades. Attribute to the massive quantity and collaboration capability, multi-robot systems promise to be versatile, robust, and low-cost compared with an individual robot system. Previous works of the modular robotic system [25][17] and swarm [28][29][26] have provided instructions on hardware and algorithm design of the reconfigurations and collective behaviors. The swarm robotic system [18] also offers an artificial platform for studying the collective behavior of nature. However, there is a contradiction between the functionality and size of the multi-robot system. For modular and assembly systems, small and light modules can form a largely connected configuration, while the modules generally lack mobility. For a system with large modules, the scale of the assembled system is limited due to the structure's stiffness. Moreover, most assembled configurations of the multi-robot systems are suffering from tardy motion, leading to the underestimation of these systems in practical applications.

My research goal is to build an insect-scale multi-robot system that can assemble from a swarm of insects to another species, for instance, the quadruped. In this research statement, this type of system is named an insect-scale assembly robotic system. The system combines the mobility of both insect-scale robots and quadruped robots. It can pass the confined space as a swarm, or assemble into a quadruped robot to walk on the tough terrain Fig.1(a). This comes to the first vision of the system, which is a swarm of high-performance untethered insect-scale robots with the ability to assemble. Besides, the gait controller of the quadruped configuration should meet the requirement of the limited onboard computing power, thus, novel control architecture is needed. Further, to make the system work as artificial life, we aim to design all the behaviors as insect-level intelligence to achieve the full autonomy of the system, such as gathering, following and making the decision to assemble and disassemble. Extraterrestrial exploration is the most likely application scenario of this system. The spaceship spreads thousands of fast, cheap and insect-level intelligent modules on the planet rather than an expensive Mars rover. The swarm of modules can search the planet rapidly and thoroughly as individuals or assemble into quadrupeds.



(a) System concept (b) Inchworm robot and transmission mechanim (c) Magnetic connection and assembly

Fig. 1. My research goal is to build an insect-scale multi-robot system that can evolve from swarm to quadruped. My current research has focused on designing high-mobility insect-scale inchworm robots as modules [20][21] and controlling the locomotion of the quadruped configuration [19].

Limited by the muscles and neurons, insect swarms can assembly into rafts [24]and bridges [27] but not multi-legged, even though swarms can gain more adaptability from the latter. Artificial systems can conquer the limitations, in other words, can surpass the nature systems. My research route starts with the hardware design of the insect-scale module, then the locomotion control of the assembled quadruped configuration, and finally the collective behavior design of the swarm.

II. Prior Research

A. Assembly Robotic System with Inchworm Modules

My first work proposed and verified the concept of the assembly robotic system [19]. A group of inchworm robots can perform as a swarm to pass the narrow space. To walk on the tough terrain, inchworm modules can gather and assemble into a quadruped robot by remoter control. The concept of the system was proved with a large-scale prototype made by 3D printing and servos (inchworm module spans ∼15cm).

In this paper, we set the basic principles of the final insect-scale assembly robotic system, which are: (1) Inchworm modules play the role of joints of the quadruped configuration. A quadruped configuration consists of eight inchworm modules. (2) The locomotion of the quadruped robot is controlled by the Central Pattern Generator (CPG), which is a dynamic network. (3) All the collective behavior should be automated, such as gathering, assembling and walking as a quadruped.

B. Novel Transmission Mechanism for Inchworm Robot

After the concept of the assembly robotic system is established and verified, we started our work on insect-scale inchworm modules[20]. Our work is inspired by the HAMR project [1, 9, 16], which is a famous series of four-legged cockroach-like robots. The literature on the HAMR project provides an experienced driving system for an insect-scale robot, that is, and SCM-made transmission mechanism driven by a piezoelectric actuator, and the most recent prototype HAMR-F [9] is widely regarded as the state of the art.

The target of our research is an inchworm robot, the requirements of the module are universal locomotion(moving forward and making turns), high mobility and high stiffness to support the assembled configuration. We can learn from HAMR but we need a novel transmission mechanism with 2-DoF. According to the survey [23], the 2-DoF transmission mechanism is rare and existing mechanisms are not appropriate for us. To fill this gap, we applied the screw theory [2] and type synthesis method [13, 12] to design a novel 2-DoF transmission mechanism specified for inchworm robot. SCM method is introduced here to fabricate the transmission mechanism as an origami structure. The insect-scale inchworm prototype equipped with the 2-DoF origami transmission mechanism spans 4.1 cm and weighs 4.34 g (Fig. 1(b)). The top speed of the prototype achieves 27.4 cm/s. Compared with the HARM-F (Size:4.5cm, Mass:2.8g, Speed: 17.2 cm/s) at the same scale, both achieve untethered locomotion and our prototype is **60% faster**.

C. High Speed Inchworm Robot

In our recent work [21], we further improved the mobility performance of the inchworm robot through singularity analysis. As the 2-DoF transmission mechanism is made of the SCM method, which could be regarded as an origami structure, the singularity problem is found in the stiffness test. We applied Grassmann-Cayley algebra (GCA)[3, 4, 7] to solve all the singular conditions of the transmission mechanism. The structure of the new prototype is also fabricated and tested. The modification between the new version and the last version is only a simple geometric adjustment, while **the speed of the new version is 170% faster than the previous, reaching 75 cm/s, 18.8 body length per second**. The speed is dramatically high for an untethered insect-scale robot. We attribute the improvement to the singularity-based SCM modification. The method we proposed can be widely applied to improve the performance of other projects with SCM structures.

So far, we have proposed a complete route for building high performance insect-scale robots, that is designing the transmission mechanism through the type synthesis method and optimizing the mechanism through the singularity analysis with GCA. Stiffer transmission mechanism promotes the mobility and load-capacity of inchworm robots as individuals and assembled units, respectively. They are ready for the next step, which is to assemble to a quadruped (Fig. 1(c)).

III. ONGOING AND FUTURE DIRECTIONS

A. Central Pattern Generator

My ongoing research is constructing a CPG network for locomotion control of the assembled quadruped robot. CPG is widely applied to achieve bionic locomotion control in robotics [22, 15, 14]. This part of the research is based on the symmetry of the dynamic network [11, 10]. In CPGs, gait rhythms are described by spatiotemporal symmetries, which is a model-independent phenomenon [6]. My ongoing research focuses on designing the symmetries of an eight-cell network to generate eight signals for the modules of the assembled quadruped robot. We have already found an eight-cell network with global and local symmetry to support both spatiotemporal symmetries of the gaits and the hip-knee phase locking.

The obtained eight-cell network is capable of executing multiple gaits and full gait transitions. My immediate future work will focus on programming the network controller into the onboard electronics of the insect-scale inchworm modules. The modules are equipped with magnetic connections to form a quadruped robot for verifying this CPG network.

B. Autonomy and Collective Behavior

The final goal is to build an insect-scale assembly robotic system with full autonomy. For individual modules, full autonomy implies the inchworm robot is equipped with onboard power, control and sensing system [31]. For the swarm, automatic algorithms of all collective behaviors should be embedded in each module [29, 34, 18]. Individual autonomy is the basis of collective behavior since communication is receiving and sending information, which could be regarded as individuals sensing each other.

Achieving sensing at the insect-scale is limited by the load capacity. I plan to add a photosensitive resistor array at the head of the inchworm robot to achieve phototaxis. Considering that collective behavior requires individuals to communicate, a LED could be added at the tail of the robot, like a firefly. The array can receive light signals of different wavelengths to achieve information decoupling.

In nature, the complex behaviors of a swarm can be classified as combinations of four basic behaviors [8]: Coordination (#1), Cooperation (#2), Deliberation (#3) and Collaboration (#4). In our system, the most complex behavior is when facing the tough terrain, inchworm modules decide to gather and assemble. We separate this behavior into sub-steps and classify them with the above basic behaviors: STEP-1-Spontaneous Aggregation (#1 and #3); STEP-2-Align and Connect (#2) ; STEP-3-Self identify (#1 and #2); STEP-4-Simultaneous stand (#1 and #2). Further research will focus on coding these basic behaviors to achieve the autonomy at system level.

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