A New Application of Modular Robots on Analysis of Caterpillar-like Locomotion

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***Abstract*— This paper presents the application of developing and employing modular robots for caterpillar-like locomotion research. Firstly an investigation on locomotion kinematics adopted by natural caterpillars is given systematically. From kinematics viewpoint, the caterpillar can be considered as a structure with pitching moving joints and attachment units in total. The kinematics locomotion model can be built with three robotic modules Cube-M in pitching-pitching connections, which is designed by us recently. We concentrate on using flexible and cheap modular robotic system for bio-inspired research and educational purposes in our international consortium. Various bio-inspired locomotion is investigated thoroughly, such as most efficient movement for power consumption, the fastest movement gaits. In the end a conclusion is given and future work is outlined.**

Index Terms—modular robot; bio-inpired technology; caterpillar-like locomotion analysis;

I. Introduction

The research field of robotics has been contributing widely and significantly to industrial applications for assembly, welding, painting, and transportation for a long time. As a new special potential sub-group of mobile technology, modular robotic system features multiplicity functions, strong practicability, flexible expansibility and configuration, and robustness. They are usually composed of multiple building blocks of a relatively small repertoire, with uniform docking interfaces that allow the transfer of mechanical forces and moments, electrical power and communication throughout the whole robot [1].

Since T. Fukuda and his colleagues introduced the first modular robot CEBOT to the research society in the 1980s [2], there has been an increasing interest in developing and employing modular reconfigurable robots for different applications [3] [4] [5]. Many research projects on modular robots were implemented worldwide, most of them in the U.S.A. and Japan. For example, M. Yim has been developing a series of Polybots [6] since the 1990s. A new self-configuration prototype has been presented recently at the IROS2007 conference [8]. CONRO and SuperBot were developed by Information Sciences Institute at University of Southern California (USC) [7]. These projects focus mainly on the control hardware and have a great impact on programming. At CMU, some interesting modular robotic projects are also under development [9].

In Japan, S. Murata and his team designed an impressive M-TRAN robot [10]. It features a hybrid topology and can self-configure autonomously. Each module includes two blocks which can rotate 90 degrees and a link in between. There are two parallel axes for motion and six connectable surfaces. Four controllers are on board to make master-slaver control architecture. The masters are in charge of high-level algorithm computation and communication; while the slaver controllers take care of the locomotion, docking procedure, and sensor organization.

However, the research and development on modular robots in other countries is lagging behind. In Europe, the modular project YaMoR [11] was presented at the Biologically Inspired Robotics Group (BIRG) of the Ecole Polytechnique Federale de Lausanne (EPFL). It consists of several homogeneous modules and can connect normally in a pitch-pitch way. And finally, some modular robotic cooperation projects were implemented recently in Denmark [12].

Currently it is hard to find a real application even if some researchers mentioned modular robots could be used for space exploration and other purposes in future [13]. In our modular robot project, we will concentrate the efforts on developing a modular robotic system that meets the requirements of flexibility, functionality, extensibility, easy handling for bio-inspired research and educational purposes in our international consortium [14].

There are two reasons for using modular robots for inspired research. Firstly, modular robots consist of many identical modules which are able to change the way they are connected. The modular approach enables robots to locomote and reconfigure flexibly, which is very essential for tasks which are difficult for a fixed-shape robot, thus also makes the robotic system versatile, robust, and fast to prototype. New configurations of different inspired robots can be built fast and easily for the exploration, testing and analysis of new ideas. For example, snake-like robots, caterpillar-like robot, four legged robots can be easily built with a low-cost.

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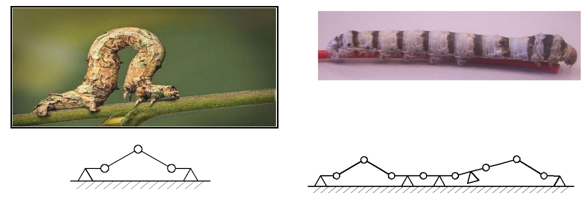
Secondly, normally biologists use expensive devices to capture, memory and analyze two or three dimensional motion of different animals. For example, in order to understand the kinematics of soft-bodied, legged locomotion in Manduca sexta larvae, the moving larvae is illuminated with a high-intensity long-wave ultraviolet lamp and their movements are recorded by two high quality cameras poisoned with some degrees [15]. The experiment data is analyzed only sequences of step in which the markers on the larvae are clearly visible and good enough in both cameras. Now, with the development of modular robots technology, the biologists have an alternative. A caterpillar-like robot built using robust low-cost modules relieves researchers of highly expensive devices and makes the on-site experiment in a real-time way. In principle, the experiment using modular robots should be similar to that of using natural creatures if we can implement the bio-inspired control methods which are adopted by larvae. Application of modular robots in this field makes the experiment easy, thus enable the researcher concentrate on locomotion principle research.

The paper is organized as follows: Section 2 investigates two kinds of locomotion of natural caterpillars. Then our modular robot, Cube-M will be introduced from the mechanical viewpoint in section 3. A caterpillar-like configuration is built to study the inspired locomotion principle. In Section 4, the discussion focuses on the on-site locomotion experiments. Distributed sinusoidal generators are used to produce rhythmic motion of modules. Some interesting issues such as the most efficient locomotion for power consumption and velocity are investigated in detail. In the end, future work and conclusions are given.

II. Locomotion of Caterpillars

Caterpillars are among the most successful climbers and can maneuver in complex three-dimensional environments, burrow, and hold on to the substrate using a very effective passive grasping system [16]. That is one of the reasons why we have such a strong interest not only in understanding their locomotion principle but also in trying to build a robot with a caterpillar-like configuration. Normally, the caterpillars consist of a head and neck part, a body with several segments and a tail end part, as shown in Fig. 1. Their movement depends mainly on the muscle's expansion and contraction. Caterpillars use passive grip to secure themselves to complex branched substrates and can effect multidimensional movements: they are able to bend, twist and crumple in ways that are not possible with a rigid skeleton.

From the kinematics point of view, there are two typical locomotion modes adopted by the different kinds of caterpillars. The corresponding representative worms are the inchworm (Fig.1a) and Manduca sexta larvae (Fig.1b) respectively. If the module idea is taken into account, the bodies of these two worms are considered as a combination of adhesion modules and rotating joint modules. The different quantity and connecting sequence of two modules determine the different locomotion modes. In order to analyze the kinematics of caterpillars, an adhesion module is indicated as " △ " and an active rotating joint module is indicated as " —○— " in the latter discussion [28]. Caterpillar kinematics models are also presented in Fig. 1. Between two adhesion modules, there must be at least one joint module. Otherwise, the two adjacent adhesion modules should be considered as only one.



a. b.

Fig. 1 Two kinds of locomotion adapted by caterpillars.

The body part of an inchworm is totally different since it possesses no proleg at all. A drawing of an inchworm and its kinematics model are also shown in Fig. 1a. Due to its simple body structure, the inchworm has to adopt a simple gait to move. While crawling, it lifts the tail first, contracts the trunk, and then drops the tail a short distance ahead from its original position forward. Then, it lifts the head, stretches the trunk and drops the head. A gait is completed with a certain distance forward movement.

There is other typical locomotion mode adopted by the different kinds of caterpillars, like Manduca sexta larvae, which is the focus of our discussion in this paper. A number of different research achievements on the locomotion principle of a caterpillar's movement on flat surfaces have been presented over the past years from the biological viewpoint [17] [18]. When the caterpillar moves, the tail end part begins to contract after the related proleg retracts; then it bows the tail and releases the muscle to set down the proleg a short distance from its first position in the forward direction. During this step, the caterpillar shapes the tail part into a half wave. After that, the moving wave will transfer from the tail end to the head from the global point of view. As a result, the caterpillar moves the whole body forward one step. When it wants to move faster, more than one half wave will be transferred through the body at the same time.

Some newest research in 2007 is presented. Scientists found there are some phase differences between the neighboring segments of the larvae during the moving [15]. If we only focus on their body part, the caterpillar can be considered as a structure with three pitching moving joints and four attachment units in total. Furthermore, if you equal the length of all links, the kinematics locomotion model in Fig. 2 can be considered like three modules in pitching-pitching connections built with our modular robot Cube-M. From kinematics point of view, the locomotion models of the natural caterpillar and the structure of modular caterpillar-like configuration are in the same principle if the soft-body characteristic of natural larvae is ignored. That is an important reason why in our modular robot project, the efforts will concentrate on using flexible and cheap modular robotic system for a bio-inspired research and educational purposes in our international consortium.

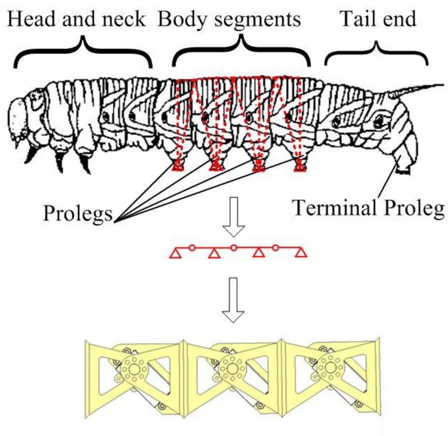


Fig. 2 Caterpillar's locomotion mechanism.

III. Capabilitie-like Configuration Using Cube-M

A. *Cube-M Modular Robot*

In 2004, our international group began to work on modular robots. The Y1 modular robot with one DOF was designed as the first prototype [19]. Using Y1, the minimal configurations for movement are studied in [20]. Then two eight-module robots were built for further research purposes [21]. However, the Y1 module in plastic breaks very easily since all of mechanical parts are glued together without any professional connecting components.

Our following project beginning in 2006 was aimed at developing a robust, fast-prototyping modular robot with an onboard controller and sensors and a friendly easy-to-use programming environment for testing and evaluating inspired technology, as shown in Fig.3. This improved Cube-M module is named according to its mechanical outlook, which is in cooperation with Juan González-Gómez from the School of Engineering, Universidad Autonoma de Madrid in Spain.

A single body module with six parts in aluminum is about 80 mm long, 50 mm wide and 50 mm high. As a result of being actuated by the servo, one degree of freedom (DOF) active rotating joint within ±90 degrees enables the left and right part of the module to carry out pitching movement. This version is called GZ-I at the beginning. The specifications are shown in TABLE I. More details can be found in Ref. [22].

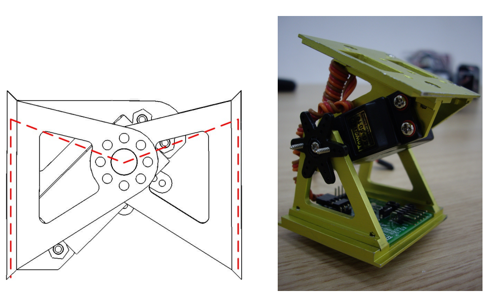


Fig. 3 A CAD design (with a M character in red) and the real module.

TABLE I. Specifications of Cube-M

Module Mass (kg)	150g
Module dimension: Length ×Width ×Height	80×50×50 mm^3
Docking faces:	4
Embedded DOF:	1
Working space:	-90-90°
Maximum working time before recharging:	>30 minutes

B. *Caterpillar-like Configuration and Control Realization*

The proposed caterpillar-like configuration consists of three serial-connected modules for traveling. The connecting mode enables modules to rotate around the pitching axes one by one. From the kinematical viewpoint, the robot will have different locomotion capabilities to move in different directions with various velocities.

Each module has embedded intelligent capabilities with an independent onboard controller. The principle of the control system is shown in Fig. 4. The motion commands can be sent to a certain module individually or broadcast to all modules through the IIC bus according to the task requirements. A PC, which can be considered as a virtual module in the robot system and plays the role of the master or a graphic user interface (GUI), directly connects to the bus through a set of wireless data transmission modules [23].

The robot system is powered by a 7.4v Li-Poly rechargeable battery. The low dropout regulator (LDO) unit maintains a 3.3v voltage for the control unit and a 5v voltage for the servo. Different kinds of control interfaces are valid to guarantee the flexible functions.

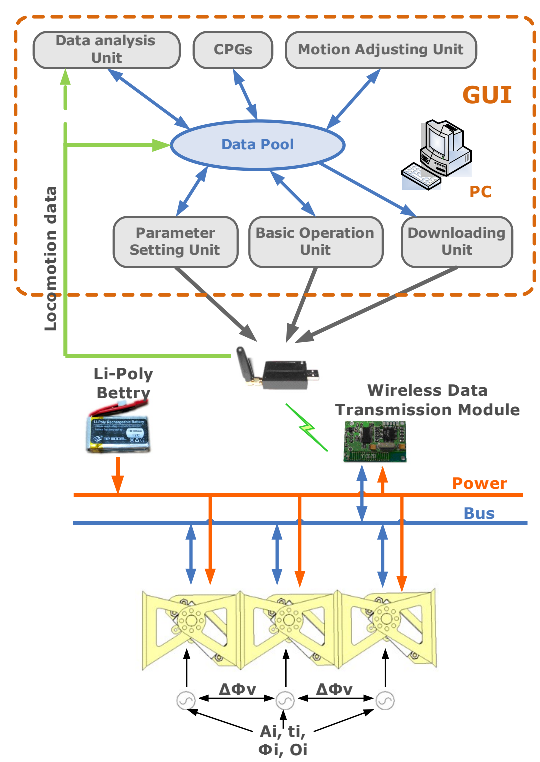


Fig. 4 Sketch map of control mechanism.

The motion data of a certain gait can be downloaded and stored in each module distributively. At the beginning of a certain gait mode, the PC or an assigned module will broadcast a synchronization command continually with an assigned frequency, and all modules will oscillate rhythmically and independently to negotiate the locomotion. During the moving, all locomotion data can be saved onboard and also can be sent back to the GUI to analyze according to the requirements.

The control of caterpillar-like modular robot is based on sinusoidal generators to produce rhythmic motion. From the biological point of view, these generators act like the Central Pattern Generators (CPGs) [24] to control variation of the rotation angle of each module. When the steady state is reached, the CPG acts with a fixed frequency, thus makes it possible to be replaced by simple waves. Our model is described by the following equation (1) [25]. The sinusoidal generators produce very smooth movements and have the advantage of making the controller much simpler.

$$y_i = A_i \sin(\frac{2\pi}{T} t + \phi_i) + O_i \tag{1}$$

Where y_i is the rotation angle of the corresponding module; A_i is the amplitude; T is the control period; t is time; Φ_i is the phase; O_i is the initial offset; i means the module number; $\Delta\Phi_V$ is the phase difference between two adjacent vertical pitching modules.

IV. Analysis of Inspired Locomotion Capabilities

In this section, the discussion will be focused on caterpillar-like locomotion analysis. It is noted that the motion of the caterpillar-like robot is dependent on four parameters: amplitude, frequency, phase and offset to achieve various moving modes, described in (2). While the initial offset O_i is not the focus for investigation in this paper even it is important for locomotion too. Here we only investigate the relationships of the movement and the amplitude, phase difference respectively.

$$(A_i, t, \phi_i, O_i) \quad i=1,2,3 \tag{2}$$

According to research achievements in biology, for any individually independent movement, the frequency of rhythmic gaits is equal [26]. Meanwhile, the phase difference is the same to all neighboring oscillators [27]. We also equal the amplitudes of all our modules in order to consider them as the same muscles' CPGs. To simplify the investigating procedures, the following constraints (3), (4), and (5) have been applied. As a result, all three sinusoidal generators are same functions with the same phase difference (PD) between any two neighboring modules.

$$T_1 = T_2 = T_3 \tag{3}$$

$$\Delta\phi = \phi_3 - \phi_2 = \phi_2 - \phi_1 \tag{4}$$

$$A_1 = A_2 = A_3 \tag{5}$$

Some other constraints are also applied for the following experiments: $\Delta\Phi$ is changed from 0 to 175 degrees with a step of 25 degrees; A_i is set from 10 to 70 with a step of 10.

A. *Relationship of the Locomotion and the Ampulitude*

Fig. 5 shows that the displacement per cycle with the same phase difference for each line in different colors increases with the increment of the amplitude. It is interesting that the locomotion capability is the most efficient when the phase difference is around 125 degrees; on the opposite, the displacement is tiny and negligible when the phase difference is approaching to 0 or 180 degrees.

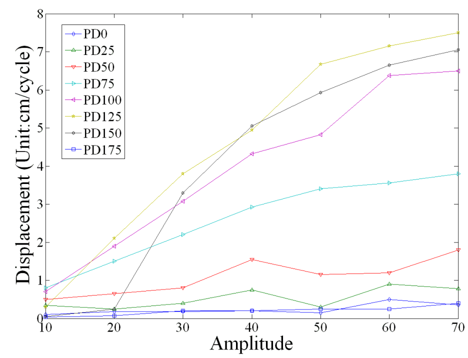


Fig. 5 Relationship of the locomotion and ampulitudes

B. *Relationship of Locomotion and the Phase Difference*

Fig.6 shows that the relationship of the locomotion and the phase difference. The difference in phases determines the coordination between the connecting joints. The experiment data show a consistency of the tendency.

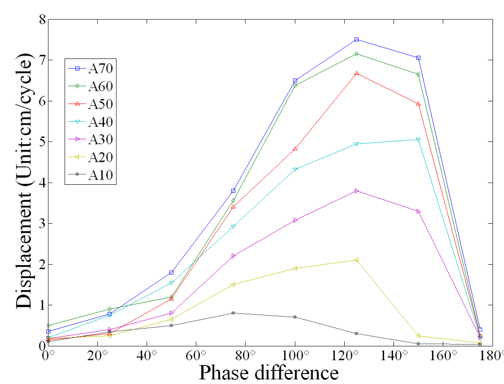


Fig. 6 Relationship of locomotion and phase difference

Firstly the amplitude is fixed; then we only increase the phase differences. For all different amplitudes except A is equal to 10, the displacement per cycle reaches maximum when PD is 125 degrees. Since the phase difference is increased with a 25-degree per step, it is sure that the best coordinated locomotion can be obtained when the phase difference are between 110 to 130 degrees. While the phase differences are 0 and 180, there is no movement at all.

C. *Relationship of the Power Consumption and Amplitudes*

Other important issue is the power consumption during the movement. From biological control point of view, caterpillars should move effectively and efficiently as a result of thousands years of evolution. Obviously, the natural caterpillar rarely adopts large amplitudes to the normal locomotion. We cannot assume the fastest moving gate as the most consumption-efficiency one as a matter of course. A series of experiments are tested to investigate the relationship of power consumption and the amplitudes, as shown in Fig. 7.

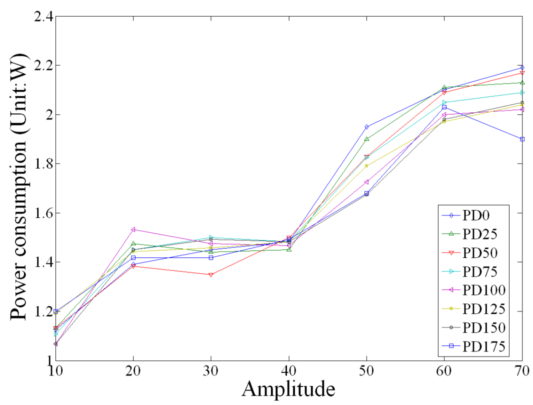


Fig. 7 Relationship of power consumption and the ampulitudes

The power consumption increases with the increment of the amplitude linearly mostly except when the amplitude is around 40. With this amplitude, relatively low-power consumption occurs.

D. *Relationship of the Power Consumption and the Phase Difference*

When the amplitudes are fixed, the power consumption is changed with the phase difference, as shown in Fig. 8. The power consumption is relatively low when the phase difference is between 80 to 130 even the changing is not so dramatic in each line.

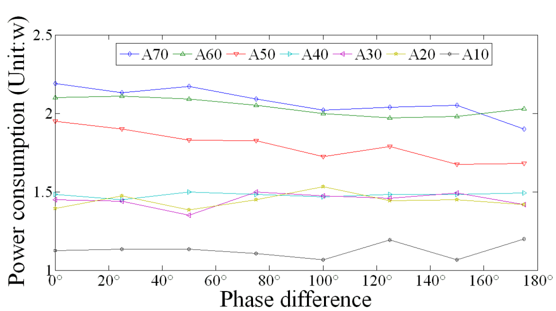


Fig. 8 Relationship of power consumption and phase difference

E. *Summary of the Experiments*

According to above experiments, the locomotion behaviors are summed up and synthesized in Fig. 9. When the phase difference changes from 80 to 130 degrees and the amplitude lies between 35 to 50 degrees, there is a compromise between the required parameters for locomotion and power consumption. After zooming in the up-part of Fig. 9, the most efficient control parameters are shown in the low-part of Fig. 9. The conclusion is described in (6).

$$\begin{bmatrix} A \\ \Delta\phi \end{bmatrix} = \begin{bmatrix} 40 \\ 125 \end{bmatrix} \tag{6}$$

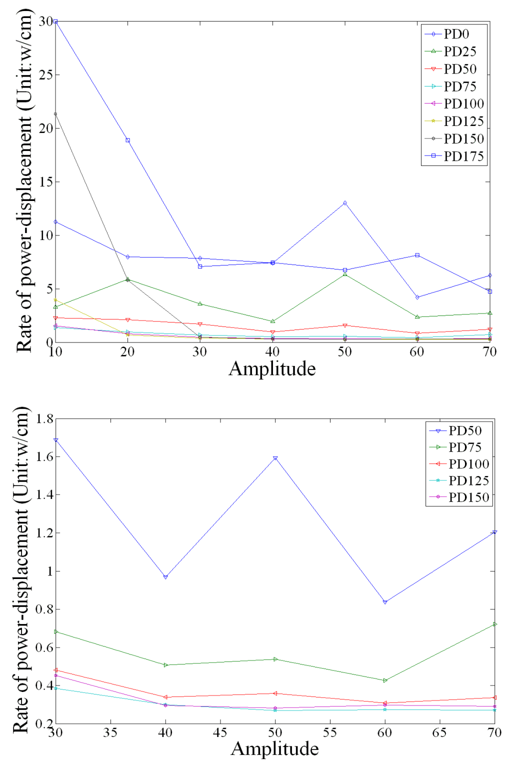


Fig. 9 Relationship of rate of power-displacement and amplitude.

V. Future Work and Conclusions

Modular robotic system features multiplicity functions, strong practicability, flexible expansibility and configuration, and robustness. In contrast to conventional theoretical research, the project introduced in this paper successfully completes the following innovative work:

1. We investigated the caterpillar-like locomotion principle using our robust, cost-efficient modular robot Cube-M. As a new application of modular robot research, one hand it makes the bio-inspired research easy and relatively simple. Furthermore, it will enhance the modular robotic technology level and also encourage us to go forward on related issues.

2. Some useful on-site experiments are implemented to uncover the mystery of caterpillar-like movement even if the modular robot is stiffness while the natural caterpillar is with a soft-body characteristic. When the phase difference is around 125 degrees between the adjacent modules, the movement is the most smooth and fastest. While the power consumption for

the whole system is lowest. The results are significative for related biological research counteractively.

Currently, we just do a first step on bio-inspired research using modular robots. According to the experimental results we are working on the further elaborate testing in order to find the optimized parameters for locomotion control. Meanwhile considering the importance and difficulty of the movement harmony among segments of natural caterpillars in order to move in different gaits on surfaces of various materials, we are starting to focus on adding different sensors, such as touch sensors and torque sensors on the module to get more related moving information. This prototype will enhance the system capability for future research remarkably.

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