Embedded Intelligent Capability of a Modular Robotic System

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***Abstract*—The last few years have witnessed an increasing interest in modular reconfigurable robotics for education, inspired robotic research, and space applications. This paper presents the latest results of the Cube-M modular project. Firstly, an overview of the research achievements in modular robot is given. Then the new modular robot Cube-M with one degree of freedom, an improved version of the Y1 modular robot, is presented. After that, the discussion focuses on the realization of a distributed hardware and control. Each module has embedded intelligent capabilities with an independent onboard controller to enable the realization of completely modular design. In the end, a snake-like robot prototype is built to confirm the feasibility of our design principle.**

I. Introduction

Modular robotic systems feature multiple functions. They are very practical, flexibly extendible, reconfigurable and robust. The last few years have witnessed an increasing interest in modular reconfigurable robotics for education [1], inspired robotic research [2], and space applications [3]. 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 [4].

A general classification of the different configurations of modular robots is essential for the study of their properties, but difficult to make. Some researchers established a classification of modular robots in two groups: lattice and chain robots. The former kind arranges modules to form a grid, just like atoms forming complex 3D molecules or solids.

Chain-robots are suitable for locomotion and manipulation since the modular chains are like legs or arms. In this paper, our focus lies on the chain-format. In [5], 1D, 2D and 3D chain robots are classified according to their topology. 1D-chain robots are like snakes [6], worms [7], legs, arms or cords [8]. They can modify their bodies to adopt different shapes. They are suitable for passing though tubes, grasping objects and moving in rough terrain. However, the pitch-connecting robots can only move forward or backward. Their movements can be generated by means of waves that travel through the body of the robot from the tail to the head.

Another kind of modular robot features yaw-connections. All the joints rotate around the yaw axes. In order to get propelled, these robots creep along a given curve path, but the body should slip in the tangential direction without any sliding in the direction normal to the body axis. A lot of research has been done on this kind of robots [9] [10]. Other similar prototypes are SES-2 [11], WormBot [12] and Amphibot I [13].

Though there have been many research achievements in this field, the fact is that the known reconfigurable modular robots can only assume few configurations due to relatively limited connecting and pose-adjusting mechanisms. For example, YaMoR [14] from the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland consists of several compact segments which can connect using velcros with one DOF. The modules can be connected one by one in a certain manner by hand. The reconfigurable modular robot Millibot train from Carnegie Mellon University in principle has a similar connection design. Two coupling holes and two pins in the front and in the rear of each module respectively are designed specially for connecting two neighboring units. As a result, the DOF is only a pitching movement [15].

Additionally, the intelligent technology in these prototypes is distinct. Modular robots should own enough intelligence to build different autonomous mobile robots easily and quickly. The system consists not only of a mechanical shell with several DOFs but also onboard power and the electrics. However, several real modular robots only have a mechanical system, such as I(CES)-cubes from Carnegie Mellon University [16], and Telecube from Palo Alto Research Laboratory in U.S.A [17]. For example, all modular prototypes built using Y1 have an outside electronic and power supply. The electronic part consists of an 8-bit microcontroller that supplies the Pulse Width Modulation (PWM) signals to the servos. The robots are connected to a PC by a serial port. The other modular prototypes are semi-automatic or controlled by operators even if they have a simple controller onboard. The reason for this situation is that in designing a new modular prototype, attention was too focused on reconfiguration capability or methods of connection.

Another problem in modular robots is that the research is limited to academia. It is hard to find a real application at the

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moment, even if some researchers mention that modular robots could be used for space exploration and bucket of stuff in future. Almost related projects on modular robot were supported by national foundations. As a result, some of the famous prototypes are still too expensive to popularize. For example, Superbot [18] is a wonderful design from the technical viewpoint. Each module consists of two units and features six connecting faces. Also, the related power supply and controllers are onboard. However, one single module already costs more than ten thousand US dollars.

In our modular robot project, the efforts will concentrate on developing our own flexible, functional, extendible, easy-to-handle and cost-effective modular robotic system for practical courses in universities. In 2004, our international group began to work on low-cost passive modular robots. The Y1 modular robot with one DOF was designed as the first prototype [19] (Fig. 1).

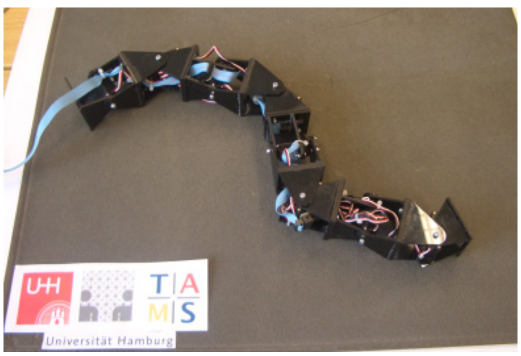


Fig. 1 Y1 modular robot design

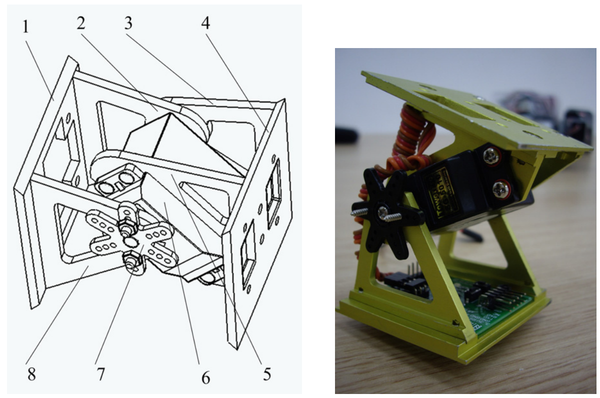
Based on Y1, our following project of 2006 was aimed at developing a real low-cost, robust, fast-prototyping modular robot with an onboard controller, sensors and a friendly, easy-to-use programming environment for testing and evaluating inspired technology.

This paper describes the recently developed, improved modular robot called Cube-M according to its mechanical outlook, which is based on the cooperation with Juan González-Gómez from the School of Engineering, Universidad Autonoma de Madrid in Spain and the Robotics Center at the Shenzhen Institute of Advanced Technology in China. Firstly, our module is called GZ-I [20]. This paper is focused on embedded intelligent system realization including hardware and software. The paper is organized as follows. Section 2 gives an overview of the research achievements on modular robots in the literature. Mechanical development is described briefly in section 3. In Section 4, the distributed hardware system is presented in detail. Some related issues such as the control hierarchy, single controller design and an inspired control model for motion are introduced step by step. To demonstrate our design principle and the robot's capabilities, on-site experiments on a modular snake are presented in the following section. In the end, conclusions are given and future work is outlined.

II. PROTOTYPE DESIGN OF CUBE-M

A. Short Introduction of Mechanical Design of Cube-M

The major challenges in designing this robotic system are the smaller dimension and the flexible connection. From the mechanical point of view, the new design looks similar to the Y1 module.

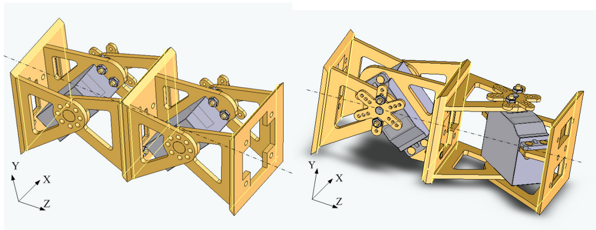


1. Left connecting face; 2. Inboard mechanical ear for rotation output; 3.Outboard mechanical ear for rotation output; 4.Right connecting face; 5. Mechanical bracket for RC servo; 6. RC servo; 7. Rotating plate of RC servo; 8. Mechanical ear for rotating plate

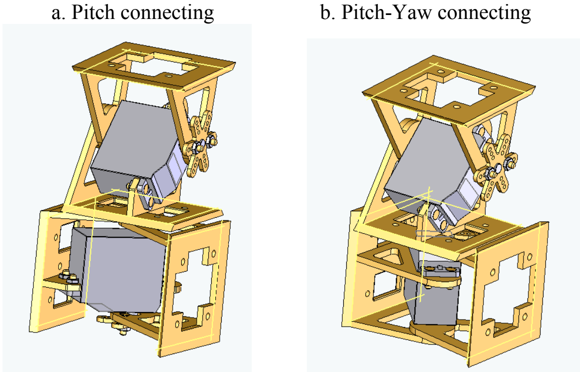
Fig. 2 Mechanical module design and realization

A single body module, which is about 80 mm long, 50 mm wide and 50 mm high, consists of six mechanical parts, an RC servo and an electrical controller with enough input and output resources, as shown in Fig.2. Cube-M can be assembled easily. Firstly the driving RC servo is fixed to mechanical ear 5 using bolts through four holes; while the rotating plate of the servo is fixed to mechanical ear 8. Then we fix the mechanical ears 2 and 8 with the rotating plate to the left connecting face by bolts respectively. This completes the left half of the Cube-M module. In the same way, the mechanical ears 3 and 5 with the RC servo will be fixed to the right connecting face. After that, the left half and right half are brought together. Then the two modules will connect automatically as soon as the rotating plate is fixed to the servo again. In this way, Cube-M will be assembled around the horizontal axis. As a result of being actuated by the servo, one DOF active rotating joint within ±90 degrees enables the left and right half of the module to carry out pitching movements.

There are four assembling faces on the Cube-M to implement connections so that the system can be extended to build different kinds of inspired robots. They are attached to the mechanical parts 1, 4, 3, and 7 respectively. They feature holes and screw threads so that any two modules can connect or disconnect easily through bolts. The flexible assembly principles are illustrated in Fig. 3. Two modules can connect in a pitching-pitching way, a pitching-yawing way or lateral ways. The details on mechanical design of our modules are in [20].

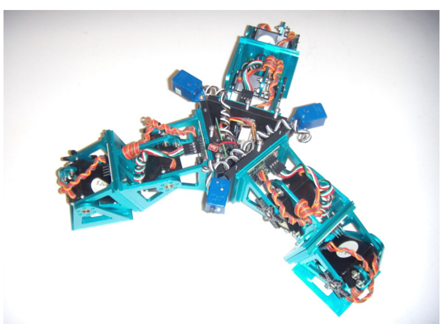


a. Pitch connecting b. Pitch-Yaw connecting

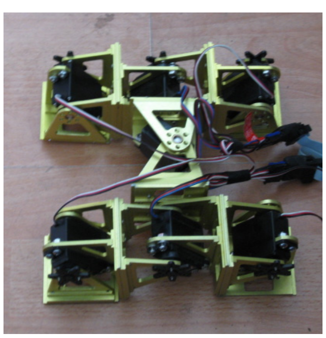


c. and d. Lateral connecting
Fig. 3 Draft of four connecting principles

All connection modes endow the robot with the ability of changing its shape in two dimensions. Some prototypes are built to test different locomotion capability recently, as shown in Fig. 4.



a. Three-legged configuration



b. Four-legged configuration
Fig. 4 Different configurations built using Cube-M

III. Hardware and Software Realization

A. Distributed control system

The modular robot should own enough intelligence to imitate a natural creature. In order to move freely, firstly it is also important for the robot not to be wired or otherwise connected to the environment. That means each module should carry onboard power, the controller, and wireless communication units. Secondly, as we mentioned before, the system should be low-cost to be used for different applications such as locomotion analysis, bio-inspired investigation.

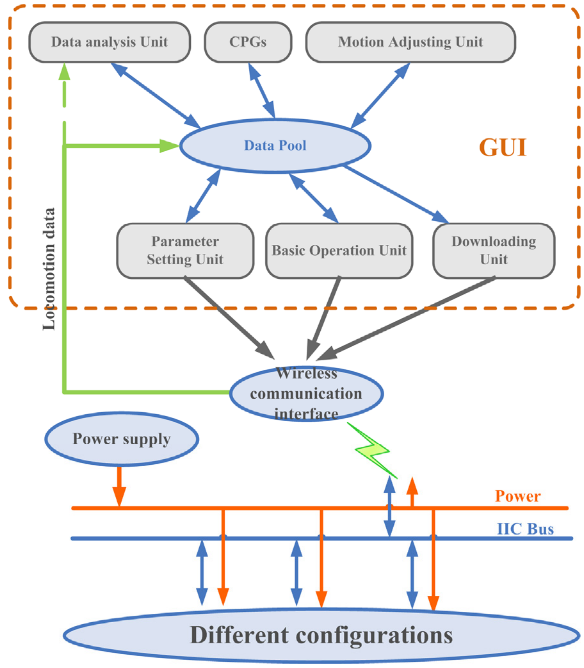


Fig. 5 Control system realization

Fig. 5 shows the principle of the control system in a distributed control structure. Each Cube-M module has embedded intelligent capabilities with an independent onboard controller. One hand, each module is equal from the control view point. According to their different locomotion functions, various programs will run on the signal module respectively. All motion commands can be sent to a certain module individually or broadcast to all modules through the IIC bus according to the task requirements. On the other hand, any module can be nominated as a master control which is charge of high-level control functions such as path planning, navigation, localization.

At the moment, a PC is used as a master controlling node. It can also be directly connected to the bus through a set of wireless data transmission modules. In this way, actually the PC can be considered as a virtual module in the robot system and plays the role of the master or a graphic user interface (GUI). There are six units in total in the PC indeed. Except GUI, the parameter setting unit is used to configure the communicate protocol; the basic operation unit is needed for normal operation. For motion control, a Central Pattern Generators (CPGs) [21] unit is to control the oscillation of the RC motors. Due to the mechanical assembly errors and the different qualities of RC motors, a motion adjusting unit is very necessary to make sure that the CPGs can be implemented on each module. In the end, the downloading unit is for the data transformation.

B. *Cube-X controller*

The core part of the system is a CubeX controller, as shown in Fig. 6. P89LPC922 is used as a micro processor with a two-clock 80C51 core. Many system-level functions have been incorporated into this processor in order to reduce the number of components, board space, and the system cost. In our system, we use In-Application Programming (IAP-Lite) supported by P89LPC922 to store non-volatile parameters, such as the motion data, without an outside EEPROM. 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.

There are only two layers of actuating functions in each onboard controller. The high-level is the CPGs; the other one is the PWM generator. The lowest control function detail, the drivers for the RC servo, is closed to the general users to ensure the safety and flexibility of the programming.

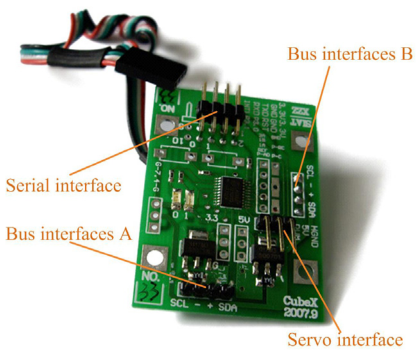


Fig. 6 Control electrics

The controller board features different kinds of interfaces to guarantee flexible functions. There are two IIC bus interfaces for communication and powering. They are equivalent, but generally, a 4-pin connector is soldered with bus interface A to connect to the bus cable from the former neighboring module. Interface B is used to connect to the next module. A servo interface is used to safely connect to the RC motor. A ferrite bead is also installed to suppress high frequency noise in the electronic circuit. The serial interface on the board is used for debugging and programming, but not necessary for the general operation. Besides the interfaces mentioned above, the board contains others such as the power output and unused I/O pins.

The motion data of a certain gait can be downloaded and stored in each module distributively. At the beginning of a certain gait mode, all the Cube-M modules will rotate to their initiating positions. Then the PC or an assigned module will broadcast a synchronization command through the bus 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 by to the GUI to analyze according to the requirements.

Currently, the controller can use the serial bus and the IIC bus for communication and controlling. However, the serial interface is mainly designed for debugging. Each controller will be identified with a 7-bit ID (1-127) for communication. The ID value can be seen on the upper-left corner and bottom-left corner of the PCB board. For example, the ID of the board in Fig. 6 is 33 (0x21). When the ID is zero, the command will be broadcasted to all modules in the system.

In the serial command protocol, the motion data is represented as the PWM control signal for the servo. The signal data ranges from 0x01F4 (500d) to 0x09C4 (1500d). However, in the IIC command protocol and data storage, motion data are converted to the range of -3687 to 3687 representing angles from -90 to 90 degree.

There are two control modes for CubeX: the single-point mode and the tempo-sync mode with preinstalled motion data. In the single point mode, the user can actuate a certain module or all modules to rotate to an assigned position. While for the tempo sync mode, the user should set up the parameters of the gaits to generate a motion data table; then download motion data to each Cube-M module separately in advance. When a certain CubeX module receives the download command from outside or the other module through the serial bus, the command will be converted and forwarded to the target module through the IIC bus. After that, the motion data will be retained onboard even when the controller is off power. To date, each CubeX can store five sets of gait data, each of which contains 32 data points.

The PC or an assigned module broadcasts a sync command continually with an assigned frequency. Then each single module just oscillates independently from the local point of view. However, from the global viewpoint, all Cube-M modules will oscillate rhythmically to negotiate certain locomotion.

IV. Modular Prototype Implementation

A. *Snake-like robot*

A recent series of successful experiments on a modular reconfigurable robot in the shape of a snake has confirmed the modular principles and controlling described above. Fig. 7 shows a CAD design and a real photo of a modular snake.

The proposed snake robot consists of eight cross-connected modules. The connecting mode enables some modules to rotate around the pitch axes and others around the yaw axes alternately. From the kinematical viewpoint, the robot will have different locomotion capabilities, like side-winding, rotating and rolling. Each joint actuated by an RC servo is controlled by means of an oscillator with four parameters: amplitude, frequency, phase and offset to achieve various moving modes.

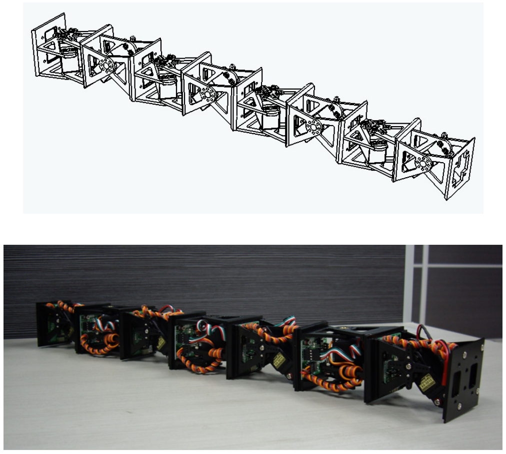


Fig. 7 CAD design and a real photo of the snake-like robot

The control of the snake-like modular robot is based on sinusoidal generators to produce rhythmic motion. From the biological point of view, these generators act like the CPGs located in the spinal cord of the animals to control the variation of the rotation angle of each module. The sinusoidal generators produce very smooth movements and have the advantage of making the controller much simpler. Our model is described by the following equation (1) [22]. 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.

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

Fig. 8 shows a sketch map of the control algorithm. Eight sinusoidal generators are represented that set all modules in rotating motion.

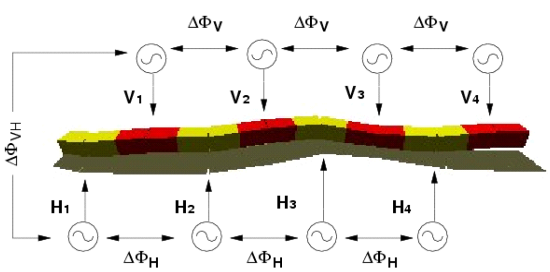
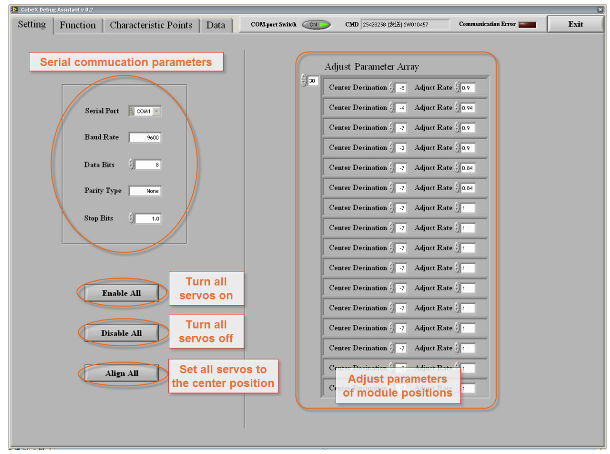


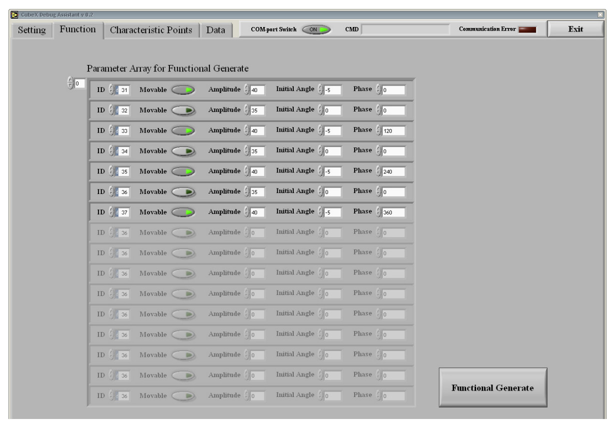
Fig. 8 Representation of the control algorithm

According to the connecting relationship of the modules, they are divided into horizontal and vertical groups, which are described as H_i and V_i respectively. Where i means the module number; $\Delta\Phi_V$ is the phase difference between two adjacent vertical modules; $\Delta\Phi_H$ is the phase difference between two adjacent horizontal modules; $\Delta\Phi_{HV}$ is the phase difference between two adjacent horizontal and vertical modules. By controlling the above parameters, different gaits like linear movement or a turning movement can be achieved.

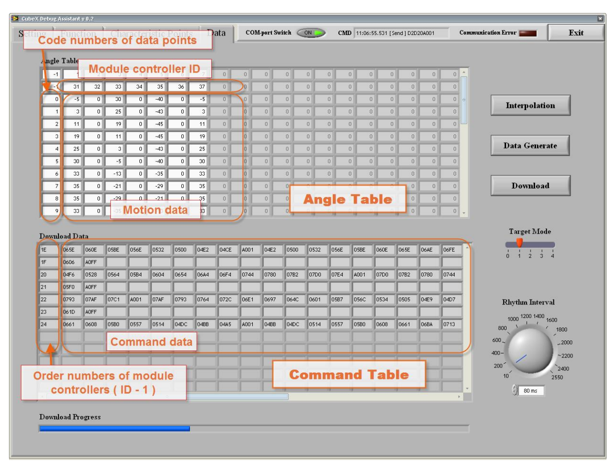
An assistant software was developed to program, debug and control the robot flexibly and easily. Firstly, you should configure the communicate interface in order to transfer data with different modules, as shown in Fig.9a. On the right side of this GUI, there is an adjusting part for calibrating all modules. After that, on the "Function" page (Fig.9b), the user can set up the parameters of the required gates. After clicking the "Functional Generate" button, the motion data will be generated and displayed on the "Data" page (Fig. 9c).



a. Setting GUI



b. Control Function GUI



c. Data GUI

Fig. 9 Assistant software for debugging

Then, by clicking the “Data Generate” button, the motion data will be compressed and transformed to the format that can be read by Cube-M. In the next step, the “Download” button is clicked to download the data to the robot. In the end, the robot can move as designed. The whole procedure is quite simple and easy-to-use indeed. After evaluating the robot movement through an on-site test, the user can reprogram the robot to improve the control parameters.

V. CONCLUSION

Based on the former Y1 modular robot, we designed the Cube-M version including the electrics and embedded software so that the whole system is integrated. Each module has an independent onboard controller. 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. After a large number of on-site tests, the Cube-M and especially its control system has proven to be versatile, robust, inexpensive and easy-to-use. The new control system has improved the system’s intelligence and competence.

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