Development of a Low-cost Flexible Modular Robot GZ-I

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***Abstract*— This paper presents a low-cost modular robot named GZ-I which is an improved version based on Y1 modular robot. After a related survey on the previous work, all aspects of the new modular robot are introduced systematically. GZ-I features fast-building mechanical structure, four connecting faces, onboard easy-used electric controller, and friendly programming environment. Each module own one rotation degree of freedom. After connecting in different modes, active joints actuated by RC servos endow the connecting modules with the ability of changing shapes in two dimensions. Then two kinds of modular robots, snake-like robot and three-leg robot are built as examples to confirm the design principle and the robot's capabilities. In the end a conclusion and future work are given.**

I. Introduction

Modular robots are usually composed of multiple building blocks of a relatively small repertoire, with uniform docking interfaces that allow transfer of mechanical forces and moments, electrical power and communication throughout the robot [1]. The last few years have witnessed an increasing interest in modular reconfigurable robotics. Some modular prototypes are quite famous, such as Polybot from Mark Yim [2], SuperBot from Information Sciences Institute and Computer Science [3], M-TRAN robot from Kamimura et al [4]. The applications of modular robots include education [5], inspired robotic research [6], and space applications [7].

In general, the modular robotic system features the following aspects: multiplicity functions, strong practicability, flexible expansibility and configuration, and robustness. Common ideas of modular robots lie in two points. Normally this kind of robots consists of many modules which are able to change the way they are connected. In further the modular approach enables robots the reconfiguration capability which is very essential in such tasks which are difficult for a fixed-shape robot. It also enables the mobile robotic system the characteristics of versatility, robustness, low-cost and fast-prototyping so that new configurations of different robots can be built fast and easily, for the exploration, testing and analysis of new ideas. More exciting advantage is that the robots have the capability of adopting different locomotion to match various tasks and suit complex environments.

In this paper, a new improved modular robot named GZ-I is developed recently, which is based on the cooperation with Juan González-Gómez from the School of Engineering, Universidad Autonoma de Madrid in Spain and Robotics Center at Shenzhen Institute of Advanced Technology in China. It features easy-handling, fast-building and low cost mechanical design and efficient control algorithm for the active joints which endow the robot with the ability of changing shape in two dimensions. Using docking blots, the modules can connect or disconnect easily and flexibly. Each joint actuated by a RC servo is controlled by means of an oscillator with some parameters such as amplitude, frequency, phase and offset. After introducing the mechanical and controlling part of the robot, a snake-like robot and three-leg robot built using GZ-I to show the flexible configuration and easy-handling practicability.

II. Related Work

A. Modular robots research in literatures

A lot of successful research has been carried out in the field of reconfigurable modular robotic systems. A general classification of the different configurations of modular robots is essential but difficult for the study of their properties. It is even worst due to the exponential growths of the number of configurations with the modules.

Firstly we group the modular robots according to their locomotion capability. The first group features active modules which comprises several identical similar modules with full locomotion capability. Every unit or module is an entire robot system that can perform distributed activities. Meanwhile all of them can also connect with each other by some special designed docking joints which enable the adjacent modules to adopt optimized configurations to negotiate difficult terrain or to split into several small units to perform tasks simultaneously.

A sub-classification of this kind of modular robots according to their kinematics modes includes wheeled and chain-track vehicles. Robots with a wheeled and chain-track vehicle are relatively portable due to high adaptability to unstructured environments [8][9]. The application of

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powered tracks to field robots enhances their configurations and improves their adaptability to environments. A serpentine robot [10] from Takayama and Hirose consists of three segments. Each segment is driven by a pair of tracks, but all tracks are powered simultaneously by a single motor located in the centre segment. The special ability of adapting to irregular terrain is passive and provided by springs. The OmniTread serpentine robot [11] for industrial inspection and surveillance was developed by Grzegorz Granosik in 2004. Optimal active joints actuated by pneumatic cylinders make the robot strong and flexible. Even if this prototype is quite adaptable, it is obstructed by a tube for pressurized air and cables for control signals connected to the supporting system on the ground. Another robot KOHGA [12] has recently been developed for rescue purposes by the International Rescue System Institute in Japan. It consists of eight serially interconnected individual units with two tracks except the first and last modules.

Another group of reconfigurable modular robots features passive modules [13]. The robotic system comprises several identical modules without any locomotion capability. It can only move after the modules assembled by active joints. New configurations can be achieved very fast and easily using this kind of purely mechanical modules. Our robot GZ-I which will be presented in this paper is in this group. For this kind of reconfigurable modular robots, some researchers established a classification of modular robots in two groups: lattice and chain robots. The former one arranges modules to conform a grid, just like atoms conforming complex 3D molecules or solids. One of the promises of this kind of robots is building solid objects, such as cups or chairs, and then rearranging the atoms to form other solids. The latter structures are composed of chains of modules.

Chain-robots are suitable for locomotion and manipulation since the modular chains are like legs or arms. Here the emphasis is only on the chain-format since it is our focus for discussion. In [14], 1D, 2D and 3D chain robots are classified according to their topology. 1D-chain robots are like snake [15], worms [16], legs, arms or cords [4]. They can change their bodies to adopt different shapes. They are suitable for going though tubes, grasping objects and moving in rough terrain. However, the pitch-connecting robots only can move forward or backward. Its movement can be generated by means of waves that travel the body of the robot from the tail to the head. M-TRAN [17] and Yamour [18] are similar prototypes that can only connect in a pitch-pitch way.

Other kind of modular robot is in yaw-connecting. 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 researches have been done on this kind of robots. It is noted that yaw-connecting robots were first studied by Hirose [19] who developed the Active Cord Mechanism (ACM). Recently some new versions were developed in his group [20]. S. Ma et al. in Japan and his Chinese colleagues at the Robotics Laboratory of Shenyang Institute of Automation also developed their own yaw-connecting robot and studied the creeping motion on a plane [21] and on a slope [22]. Other similar prototypes are SES-2 [23], WormBot [24] and swimming Amphibot I [25].

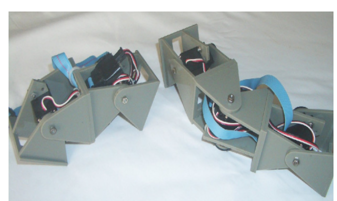
B. Our Research on Modular robots

Since 1999 our international group in TAMS and BUAA has designed two active modular robots. A flexible structure with two linked-track vehicles was proposed firstly [26]. This size of the modular is only 300 mm wide and 300 mm long, the weight is 5 kg. A two-DOF pose-adjusting joint is located between two units which are proposed as a flexible mobile platform carrying a CCD camera and other sensors. This joint can be extended and contracted linearly so that the length of the robot is changeable. The structure can be reconfigured so that the robot can move between surfaces standing at an angle of 0 - 90 degrees due to the pitching DOF actuated by the joint to increase the flexibility. Then based on the formal project, a more flexible novel modular reconfigurable mobile robot named JL-I with various moving modes was proposed [27]. To date, the system consists of three connected, identical modules for crossing grooves, steps, obstacles and traveling in complex environments. JL-I features three-degree of freedom (DOF) active joints for changing shape and flexible docking mechanism. In order to enable adaptive movement, the robot's mechanical structure is employed to drive serial and parallel mechanisms to form active joints for changing shape in three dimensions [28].

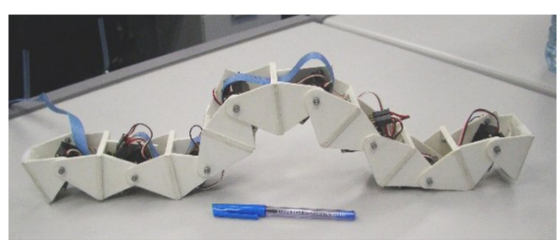
III. Prototype Design of GZ-I

A. Mechanical Design of GZ-I

From 2004, our international group began to work on low-cost passive modular robots. Y1 modular robot with one DOF was designed in 2004 as the first prototype [29], as shown in Fig. 1.



a. Minimal configurations using Y1 Modular robot



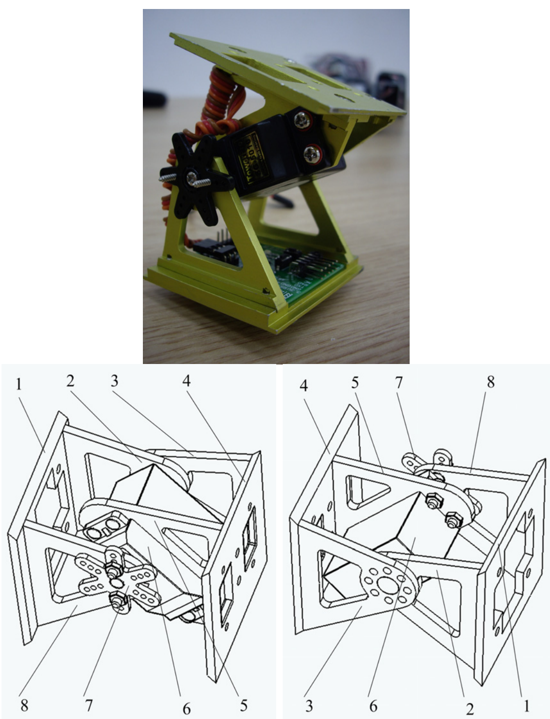
b. Eight modules prototype

Fig. 1 Y1 modular robot design

Using this prototype, the minimal configurations for movement are studied in [30]. Then two eight module robots have been built for further research purposes. One is a pitch connecting modular robot and the other a pitch-yaw connection. However Y1 module is manufactured in plastic so that the stiffness of mechanical structure is quite low. The module is very easy to be broke since all of the mechanical parts are glued together without any professional connecting components. In Fig. 1, all the prototypes built using Y1 have the electronic and power supply outside. The electronic part consists of an 8-bit microcontroller that generates the Pulse Width Modulation (PWM) signals to the servos. The robots are connected to a PC by a serial port. As a conclusion, Y1 is a pure mechanical module not a real intelligent robot prototype.

The most important requirement for modular robots is the extraordinary reconfiguration capabilities. Based on Y1, the following project was aimed at developing a real low-cost, robust, fast-prototyping modular robot with onboard controller and sensors and a friendly easy-used programming environment for testing and evaluating inspired technology.

We have been beginning to improve GZ-I from 2006. Fig. 2 shows pictures of GZ-I robot in the front and back views. This system is developed and currently still under improvement in our consortium.



(a).Front view (b). Back view

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

The major challenges in designing this robotic system are the smaller dimension and the flexible connecting capability. From the mechanical point of view, the new design looks similar to Y1 module. GZ-I features the following aspects:

1) Low-cost mechanical design with only six parts in aluminum for building a strong module;

2) Simple assembling robust modules manually and real fast-building and easy handling design;

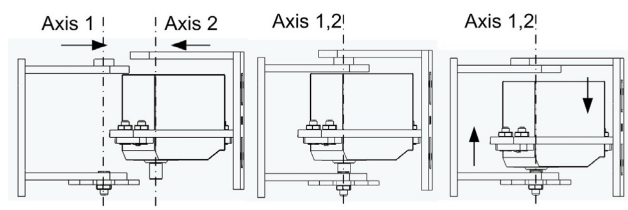
3) Four faces for modules to connect each other to implement pitching and yawing movement and two crossed connecting modes so that the system has the strong extensibility to build different kinds of inspired robots

4) Onboard controller and sensors to make the system complete, then sensor-servo-based active perception of the environment is possible.

While the single body module is about 80 mm long, 50 mm wide and 50 mm high, as shown in Fig. 2. It consists of six mechanical parts, a RC servo and a piece of electrical controller with enough inputs and outputs resources.

GZ-I can be assembled easily. In order to present the building procedure as simple and convenient as possible, we introduce the following steps using of index number in Fig. 2. Firstly the driving RC servo is fixed to the mechanical ear 5 using bolts through four holes; while the rotating plate of the servo is fixed to the mechanical ear 8. Then fix the mechanical ear 2 and 8 with the rotating plate to the left connecting face by blots respectively. Now the left part of GZ-I module is finished. In the same way, the mechanical ear 3 and 5 with RC servo will be fixed to the right connecting face, as shown in Fig. 3a.

The left part and right part approach to each other and make axis 1 and 2 superposition (Fig.3b). Then two modules will setup together automatically when the rotating plate is fixed to the servo again, as shown in Fig. 3c. In this way, GZ-I will be assembled around the horizontal axis. As a result actuating by the servo, one DOF active rotating joint within ±90 degrees enables the left and right part of the module to adopt pitching movements.



(a) (b) (c)

Fig. 3 Assemble procedure (From the top view)

TABLE I
SPECIFICATIONS SUMMARY

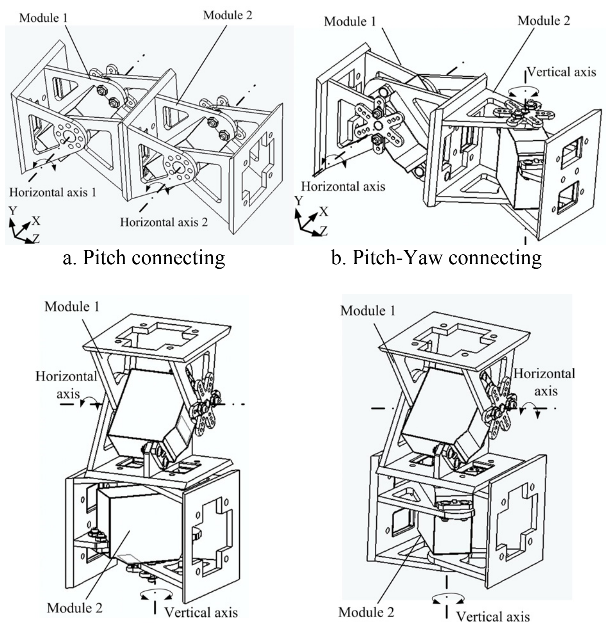
Module Mass	150 g
Module dimension:	80×50×50 mm3
Docking faces:	4
Embedded DOF	1
Working space:	-90-90°
Maximum unchangeable working time:	30 Minutes
Cost:	Less than 50 Euros

To ensure its ability of performing tasks individually and keep the extensibility, there is enough space in each module for sensors, the onboard controller, and batteries. In order to achieve a dexterous movement mechanism, considerable stress is laid on weight reduction as well as on construction stiffness. The total module weighs approximately 150 g. The specifications of GZ-I modular robot is shown in Table I.

B. Assemble realization

The mechanical structure can be reconstructed and is flexible due to its special connection faces design. As mentioned before, there are four assembling faces on the GZ-I to implement connection. They are on the mechanical parts 1, 4, 3, and 7 respectively. Some holes and screw threads are designed and manufactured on them so that any two modules can connect together or disconnect easily through bolts.

The flexible assemble principles are shown in Fig. 4. Firstly two modules can connect in succession. After assemble, two axes of the modules are parallel. We can also call this connecting as pitching-pitching way (Fig. 4a). Compared to the first one, the second way is pitching-yawing way. The module 2 will be rotated 90 degrees; then be cross-connected with module 1 (Fig.4b). We can see the two axes in horizontal and vertical respectively. As a result this connecting endows the robot with the ability of changing shape in two dimensions.



a. Pitch connecting b. Pitch-Yaw connecting

c. and d. Lateral connecting

Fig. 4 Draft of four connecting principles

Other two assembling modes are still valid, as shown in Fig. 4c and Fig. 4d. They are called as lateral connecting ways. Some screw threads are designed on mechanical ear 3; while a number of inherent holes are on the rotating plate of the RC servo. The mechanical part 5 can connect to mechanical ear 3 and rotating plate through two special designed holes.

Based on four assembling modes, a lot of inspired robots can be built easily, such as snake-like robot, four-leg robot and humanoid robot, as shown in Fig. 5 and Fig. 6. Here the snake-like robot will be introduced as an example from the mechanical point of view. The proposed snake robot consists of eight cross-connected modules for traveling. The connecting mode enables some modules to rotate around the pitch axes and others around the yaw axes alternately. From kinematics view point, the robot will have different locomotion capabilities, like side-winding, rotating and rolling. Each joint actuated by a RC servo is controlled by means of an oscillator with four parameters: amplitude, frequency, phase and offset to achieve various moving modes.

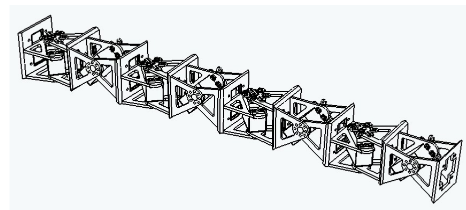
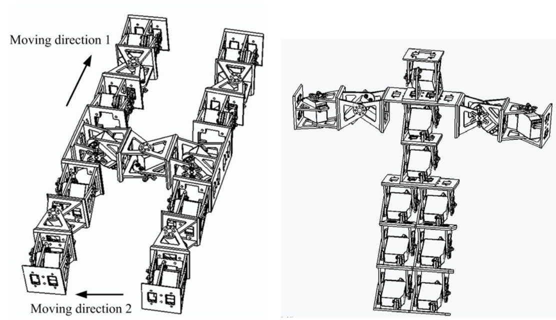


Fig. 5 Snake-like robot

More interesting inspired robot is four-leg robot, shown in Fig.6a. We also call it as "H" structure. Actually there are five chains in the robot, each of which has three cross-connected modules. The robot can imitate dog's movement in direction 1. In moving direction 2, the robot will move like reptiles. This prototype can also be considered as two biped robots in parallel. A lot of interesting research work can be done on this design.



a. Four-leg robot b. Humanoid robot

Fig. 6 Other possible prototypes

C. Hardware and software realization

As a modular robot system for inspired research, it should own enough intelligence to imitate a real natural creature. In order to move freely, it is also important for the robot not to be wired or otherwise connected to the environment. The robot should carry onboard power, the controller, and wireless communication units. Meanwhile the robot should be easy to use and cheap enough.

Each GZ-I module has the embedded intelligent capability with an independent onboard controller. The principle of the control system is shown in Fig. 7. The lowest control function detail such as the drivers for RC servo is closed to user in order to improve the programming safety and flexibility. The motion commands can be sent to a certain module individual or be broadcasted to all modules through the I^2C bus according to the task requirements. PC can also be connected to the bus through a set of wireless data transmission modules directly. In this way, 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).

As the core part of the controller in GZ-I, P89LPC922 is an 8-bit micro processor with two-clock 80C51 core. Many system-level functions have been incorporated into this processor in order to reduce component count, board space, and system cost. In our system, we use In-Application Programming (IAP-Lite) supported by P89LPC922 to store some 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.

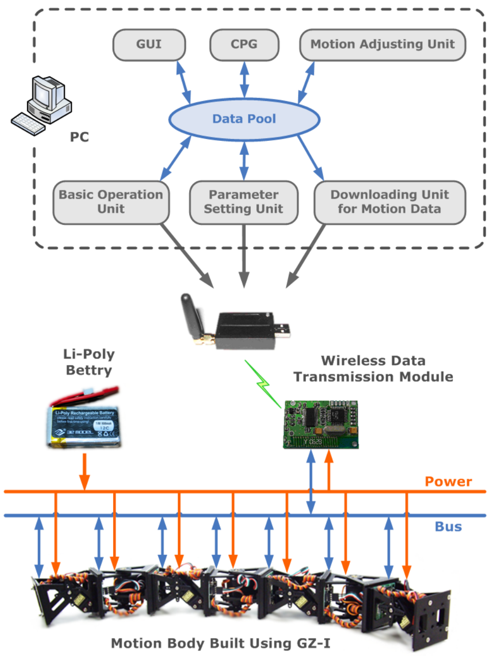


Fig. 7 Control system realization

The motion data of a certain gait can be downloaded and stored in each GZ-I distributively. At the beginning of a certain gait mode, all the GZ-I modules will rotate to their initiate positions. Then PC or an assigned module will broadcast a synchronization command through the bus continually with an assigned frequency, all GZ-I modules will oscillate rhythmically and independently to negotiate the locomotion.

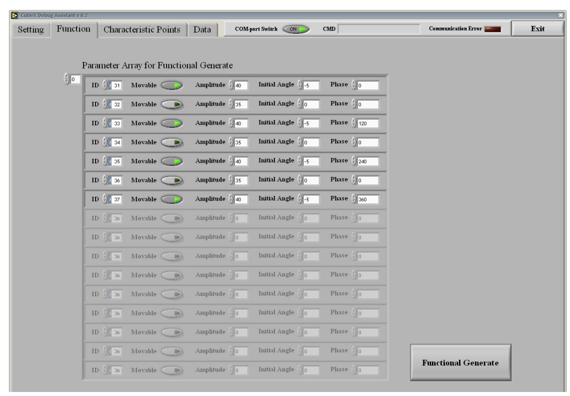
IV. Implementation and Experiments

GZ-I modular robot is still under improvement in our consortium up to now. Modular approach enables the robotic system to obtain the characteristics of versatility, robustness, low-cost and fast-prototyping. Those are also the basic requirements to be met in our design.

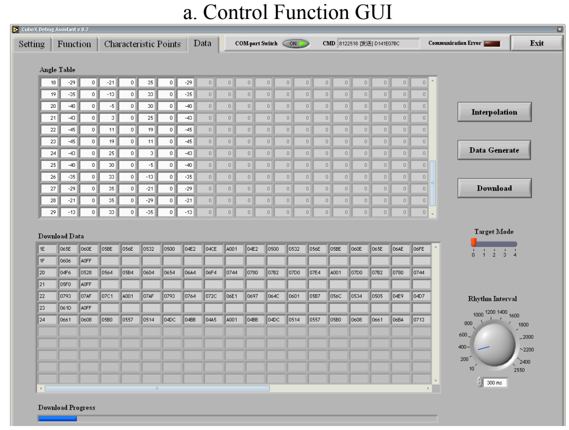
A series of the successful experiments with a modular reconfigurable robot (Fig. 8) were carried out recently, confirming the principles and controlling described above.

Fig. 8 Snake-like robot and three-leg robot as demonstrators

A brief introduction of programming is given to show the flexibility and friendly user environment. To debug and control the robot, we developed an assistant software using NI LabVIEW. In the "Function" page (Fig.9a), the user can set up the parameters of the required gates. After click the "Functional Generate" button, the motion data will be generated and shown in the "Data" page (Fig. 9b). Then click the "Data Generate" button, the motion data will be compressed and transformed to the format that can be read by GZ-I. Next step is to click the "Download" button 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 the on-site test, the user can reprogram the robot to improve the control parameters.



a. Control Function GUI



b. Data GUI

Fig. 9 The assistant software for debugging

Some prototypes of our modular robots have been exhibited in the China Hi-Tech Fair 2007 and attracted many visitors, as shown in Fig. 10.

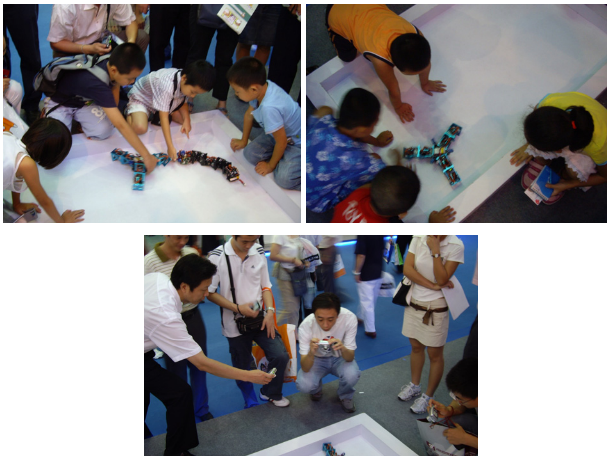


Fig. 10 On-site experiments for education

V. Conclusion and Future Work

Our work in this paper involves highly integrated robotic systems such as modular robot and inspired technology. Based on the former Y1 modular robot, we designed the GZ-I version including the electrics and embedded software so that the whole system is integrality. After a great number of on-site tests, GZ-I robot can meet the requirements of versatility, robustness, low-cost and fast-prototyping.

There is still a great amount of work for future research. Recently considering the importance and difficulty of the movement harmony among modules for realizing different gaits on surfaces of various materials, we are focusing on adding different sensors on the module to improve the intelligent level of the system. The "H" robot is also on the way. This prototype will be used as an intelligent demonstrator and test bed for the implementation of cognitive functions in robotic systems.

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