Autonomous and Self-Sufficient CONRO Modules for Reconfigurable Robots

Andres Castano, Ramesh Chokkalingam, and Peter Will

University of Southern California
Information Sciences Institute
4676 Admiralty way
Marina del Rey, CA 90292
e-mails: andres@isi.edu, rchokkal@isi.edu, will@isi.edu

Abstract. The goal of the Conro project is to build deployable modular robots that can reconfigure into different shapes such as snakes or hexapods. In this paper we present an overview of the first generation of the Conro modules. The modules are designed to work in groups, as part of a larger modular robot. Still, Each module is, itself, a complete autonomous and self-contained robot with its own processor, power supply, communication system, sensors and actuators. We conclude the paper by describing some of the robots that could be built using these modules.

keywords: module, reconfigurable, autonomous, self-sufficient.

1 Introduction

A reconfigurable robot is a robot that can change its own shape. In contrast to modular robots designed to add versatility to a specific type of robot (e.g., [1]-[3]), a reconfigurable robot can change its shape at will. It could turn into a snake to reach into narrow places, into a hexapod to carry a load or it may split into many smaller robots to perform a task in parallel. Reconfigurable robots are classified as homogeneous or heterogeneous depending on whether their modules are identical or not. In a homogeneous robot, the position of the module in the robot defines its function, e.g., the module could play the role of head, leg or spine depending on its location in the robot. In a heterogeneous robot, the function of the module defines its position in the robot. For example, a leg module must be used as a leg and a power module must be located in a part of the robot where it is safe from collisions.

Reconfigurable robots can also be categorized according to whether or not their modules are organized in a lattice (either in the plane or 3D space). Lattice-based robots are usually homogeneous and need to reconfigure in order to move, i.e., as they reconfigure, their center of mass translates accordingly (e.g., [4]-[10],). In contrast, reconfigurable robots that are not based on lattices tend to be heterogeneous and can either translate while reconfiguring or reconfigure and then select a gait that takes advantage of the particular new configuration (e.g., [11]-[14]).

In this paper we discuss the modules of the Conro robots, which are being designed to be homogeneous reconfigurable robots not based on a lattice. These robots are being designed to be self-contained and to support inter-robot metamorphing, i.e., reconfiguration that involves more than one robot and leads to merging of small robots into a larger one or splitting of a large robot into smaller ones. The basic blocks of these robots, the Conro modules, are themselves self-contained small robots. Thus, a Conro robot is a distributed system of independent modules and its actions require their coordinated movement. Although the individual modules are already fully functional, the software for coordinating the reconfiguration and locomotion of these robots is a work in progress and thus, it is not discussed in the paper. The results of our preliminary work on module design and algorithms for reconfiguration as it applies to the Conro robots can be found in [15].

This paper is organized as follows. In Sect. 2 we summarize the philosophy behind the design of the module. In Sects. 3 and 4 we describe the design of the module from the mechanical and electrical points of view, respectively. In Sect. 5 we describe the resulting module and give some examples of possible Conro robot configurations. In Sect. 6 we present our conclusions.

2 Philosophy of Design

The goal of the Conro project is to build deployable reconfigurable robots with inter-robot metamorphic capabilities. The capabilities of these robots are determined by the characteristics and functionality of their modules. A description of the philosophy of design of our modules can be found in [15]. The summary in this section is presented for completeness of the paper.

The specifications of deployability and inter-robot metamorphic capabilities translate into constraints on the levels of self-sufficiency, autonomy and homogeneity of the module, module size and communication capabilities. A deployable robot must be self-sufficient, i.e., capable of untethered operation. In the trivial case, an inter-robot metamorphic split operation may create a robot formed by a single module. Therefore, to guarantee that any robot such created is self-sufficient, each module must be self-sufficient. Likewise, a module must be autonomous with respect to the use of its own resources, e.g., it has exclusive access to its sensors and actuators.

The level of homogeneity of a module determines its capabilities and the functions that it can fulfill. Each module must have a processor, power, sensors, actuators and communication systems to satisfy the self-sufficiency and autonomy constraints. Other components not needed to satisfy these constraints (e.g., cameras, antennas) can be carried by the robot as a load or are piggy-backed on a given module, driven by a generic port. This trade-off between the necessary and desired components of a module reduces its design, manufacturing, testing and programming costs. All the components must fit into a package that is as small as possible to reduce the effect of inertia of the limbs and increase the relative torque-to-robot weight ratio of the actuators.

Finally, we address the communication needs of the module. During inter-robot metamorphing, two robots need to communicate remotely to agree on the merging operation and need a mechanism to guide themselves toward each other. At the local level, each module needs to communicate with its adjacent modules. An infrared (IR) system can satisfy all these requirements; it could be used for remote and local communication and can double as the directional guiding mechanism for both inter-robot and intra-robot dockings.

3 Mechanical Design

We now describe our work to build a module that satisfies the goals described in Section 2. Our module achieves self-sufficiency, autonomy, a high level of homogeneity, miniature size and IR-based intra-robot communication and docking. However, in the present state, the module does not support long-range inter-robot communication. Also, the module is not completely homogeneous since, although all the modules have the same mechanical and electrical components, half of the modules have their motors and CPUs on their left side while the other half have them on their right side. This asymmetry was introduced to improve the stability of the snake configuration.

Our implementation of the Conro module has three segments connected in a chain: a passive connector, a body and an active connector, as shown in Fig. 1. At the intersection of the body and the two connectors there are joints that give the module yaw and pitch degrees of freedom. The weight of the module is 115 g (including batteries) and its length is 104 mm excluding the length of the pins protruding from the passive connector. We now describe the parts of the module.

3.1 The Module Body

The body is the central part of the module to which the active and passive connectors attach. It is composed of a delrin frame, two servo motors and a printed-circuit board (PCB). The PCB has a hole in its center to allow its accommodation on the frame. When it is in place, the PCB is screwed in position to the frame. The servos fit into cavities of the frame and are held in place by friction.

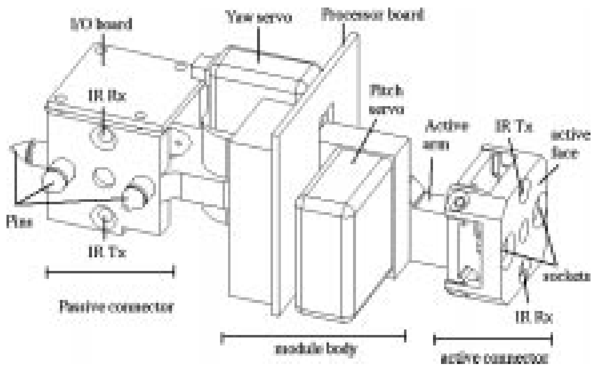

Fig. 1. Parts of the Conro module

Commercial-off-the-shelf servos for radio-controlled devices (RC servos) are connected directly to the processor board using 3-pin connectors. Two of the pins provide power to the servo and one carries a pulse width modulated (PWM) signal that defines the position of the axis. The pitch and yaw servos have a torque of 3.7 and 1.7 kg-cm, respectively, and weigh 21 and 9 g, respectively. The output shafts of the servos are connected directly to the active and passive connectors in a direct drive fashion. The servos are back-drivable and thus, under load, they must be powered continuously to maintain a given attitude. The processor board is a two-layer PCB with surface-mounted components that distributes the control signals and power to the rest of the module and serves as holding place for a small 3 v battery.

3.2 The Passive Connector

The connectors are the parts of the module that allows it to attach to other modules. The passive connector has no moving components. Its frame is a cube of delrin with a side of 2.54 cm. Three of the vertical faces of the cube have two protruding aluminum pins that fit into the sockets of the active connectors of other modules. The cylindrical pins have a lateral groove to allow the active connector to anchor to them. The particular positions of these pins and sockets permit only connections of modules that lie in the same plane, i.e., modules that are tilted 90 degrees with respect to each other cannot be connected. On each of these faces there is an IR pair used by the module for communication and docking. The fourth vertical face of the cube has a tongue that fits on a fork of the body and allows the module to pivot the connector about the yaw axis.

The frame of the passive connector is hollow and holds the wiring of the IR devices of the faces and the main battery of the module, a 6 v lithium battery of the type K28L (9 g, 2.5 cm height, 1.3 cm diameter). The roof of the cube is a two-layer PCB that is screwed directly onto the cube. This PCB has the input-and-output electronics that drive the IR receivers (RX) and transmitters (RX) of the faces of the connector. The PCB also doubles as the positive contact for the battery. A 14-pin connector is used to transfer the power of the main battery to the processor board and receive the control signals. Finally, the connector has a brass latch at the bottom of the cube that keeps the battery in place and serves as its negative contact. The latch can swing about one of its extremes allowing the removal of the battery. The weight of the passive connector, including the battery, is 31 g.

3.3 The Active Connector

The active connector is the part of the module that engages and disengages the pins of the passive connectors of other modules. It weighs 15 g and is composed of an arm and a face frames, both machined in delrin. The body of the module is connected to the active connector by the arm. The active connector can rotate about a pitch axis located at the intersection of the arm and the body. The face of the active connector has the same dimensions as those of the faces of the passive connector. It also has an IR pair but the locations of the transmitter and receiver are the reverse of those of the faces of the passive connector to allow communication between connected modules.

The process of connecting two modules involves the active and passive connectors of the modules. Figure 2a shows a passive connector approaching an active connector in a docking trajectory. The active face has two sockets to

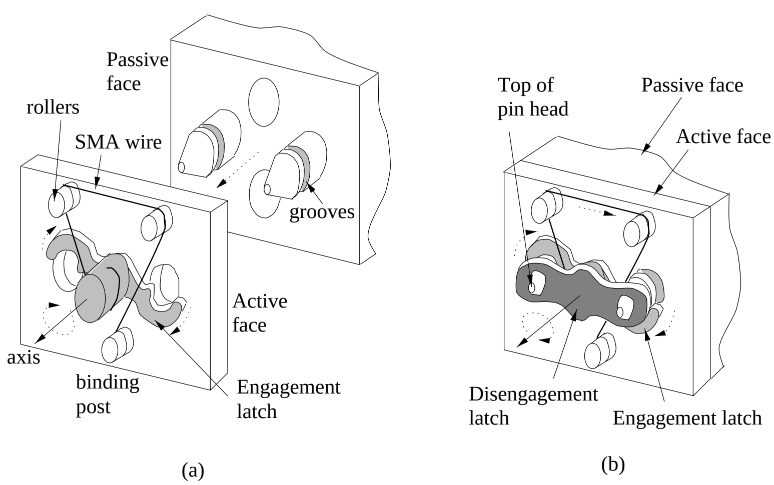

Fig. 2. Stages of the docking procedure. (**a**) Engagement. (**b**) Disengagement

receive the pins of the passive face. As the pins slide inside the sockets, their dome-shaped heads force an engagement latch to rotate in a direction normal to the trajectory of the pins. When the pins are fully inserted, the engagement latch is forced by a spring action into their lateral grooves (the spring is not shown in the figure). This docking process is completely mechanical.

The process of disconnecting two modules is initiated by the active face. As shown in Fig. 2a, the engagement latch can be rotated using a shape-memory alloy (SMA) wire. The wire is attached between a fixed binding post and a cylinder attached to the latch. We use two rollers to establish the path of the SMA wire and to extend its working length. When the SMA is contracted, it pulls the cylinder against a spring, forcing the latch to retract and freeing the pins. However, freeing the pins is not the same as disconnecting the modules. The SMA can be activated only for a fraction of a second because it consumes a large amount of power. Thus, it is possible that the modules fail to move away from each other before the SMA is de-energized, re-engaging the pins.

The disconnection process must guarantee that the modules are be free when it is finished. Figure 2b shows the faces of two connected modules. We have added a view of the disengagement latch, a plate with two holes that, during engagement, allows the heads of the pins to go through. When the modules are connected, the engagement latch is pressed against the pins, into their grooves. To disconnect the modules, we contract the SMA wire as described before. As both latches rotate together, first the engagement latch frees the pins and then the disengagement latch pushes the dome-shaped heads of the pins out of the sockets. The latch pushes the pins about 0.125 mm. This displacement is enough to guarantee that the latch will not be able to re-engage the pins when the SMA relaxes. After this process, the modules are disconnected and can be moved away from each other at any moment.

4 Electrical Design

The electrical system of the Conro module must support the control of the sensors and actuators, a communication system and a power system. The objectives of the design of the system are to minimize the number of discrete components, their overall weight and their power consumption while preserving the self-sufficiency and autonomy of the module.

A functional diagram of the electric system of the Conro module is shown in Fig. 3. Each module has a processor that gives it control over its sensors and actuators. The processor is defined by the use of one of three different single-chip micro-controllers: a stamp II based on a PIC16C57 processor, a stamp II-SX based on a SCENIX SX28AC/SS processor or a Basic-X based on a ATMEL AT90S8535. The use of a zero-insertion force socket allows for the manual removal of the processor for replacement or programming. The

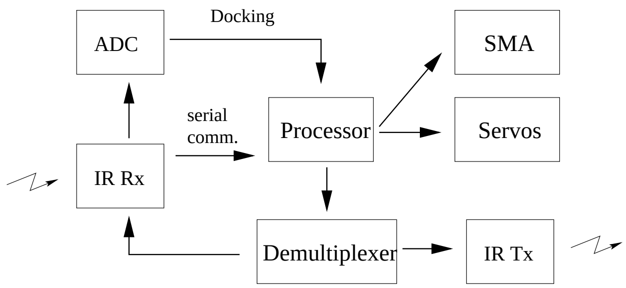

Fig. 3. Functional block diagram of a module

three processors are pin-compatible but differ in speed, memory capacity, programming capabilities and power consumption. Thus, the micro-controller of the module can be selected to suit a particular application.

The processor has exclusive access to the actuators of the module. The SMA wire is activated with a fixed current during a programmable period of time. The servos require a PWM signal generated in software because none of these micro-controllers has a suitable PWM circuit. The number of digital outputs was increased using a demultiplexer that is used to control the IR devices. The micro-controllers can set any of their port pins to behave as serial receivers or transmitters. The receiver circuit can direct the input signals to either a low-impedance input pin of the micro-controller or to a high-impedance input pin of an 8-bit analog-to-digital converter (ADC), depending on whether the IR receiver is being used for serial communication or as an IR sensor. This latter state is used during the docking of two modules, where a module uses its IR transmitter as a beacon and the other module uses its IR receiver as an analog directional sensor. The two modules that are docking can belong to the same robot or to two different robots. The combined use of these IR pairs provides the feedback necessary for the modules (or the robots) to approach to each other and dock. However, the working range of the docking sensors is too small (in the order of cms) to serve the general purposes of inter-robot communication.

The Conro module uses two lithium batteries: a 6 v K28L battery and a 3 v K58L cell, each one with a capacity of 160 mA-h. The batteries set up a 9 v high-voltage low-current node to power the micro-controller and a 6 v low-voltage high-current node to power all other components. The use of the two batteries prevents large voltage drops at the micro-controller that would appear when devices like the SMA or the servos are used. The batteries were selected for their voltage, size, weight, capacity, drain and the flatness of their discharge curves; lithium batteries are a good compromise between these features. Rechargable batteries, although desirable for a robotics project, have an energy density that is very inferior to that of the lithium chemistry.

5 The Conro Module

We have built twenty modules that follow the description discussed in this paper. Figure 4a shows a close view of a module. Because each module is

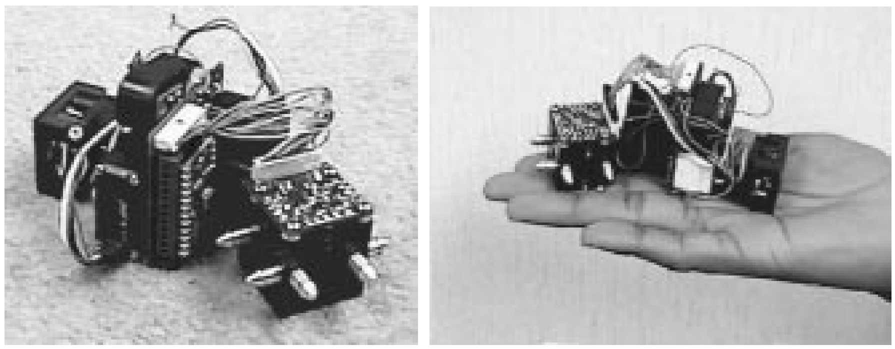

Fig. 4. The Conro module. (**a**) Close-up view. (**b**) Executing motions while untethered

self-contained and autonomous, it is a robot by its own right and thus, it is possible to program it to execute motions and to react to stimuli. Figure 4b shows the module, completely untethered, running a program that rotates its connectors in sequence. Using the PIC-based micro-controller, the program can run for 35–40 mins continuously. The module consumes 50–70 mA-h at 6 v when it is not moving. The use of the motors adds 70–80 mA-h to this total. Due to the high cost of running experiments using non-rechargable batteries, the modules are tested using external power supplies.

Although the modules can run by themselves, they were designed to work in groups, connected to each other forming large robots. We now give a brief overview of the present state of the robots and the work in progress. At this moment, the robots are configured manually but our goal is to achieve automatic robot reconfiguration eventually. The priority of the modules of a robot is to communicate efficiently with their adjacent modules. The modules do not share a clock signal and thus, robot actions that require the synchronized motions of different modules rely on the quality of the communication. The programming of the communication network is complex because, due to the lack of interrupt mechanisms in our micro-controllers, the module has to poll the ports in a round-robin fashion. At this moment, the IR communication between adjacent modules is a 9600 Bd inverted serial connection with flow control. We are in the process of modifying the modules to support 68HC12 processors that support interrupt-driven communication.

The control of a set of modules can be performed using a distributed control or a centralized control based on a master-slave hierarchy. The robots shown in Fig. 5 are controlled using a master-slave approach where the master is a remote host with a large computational capability. The snake Conro robot

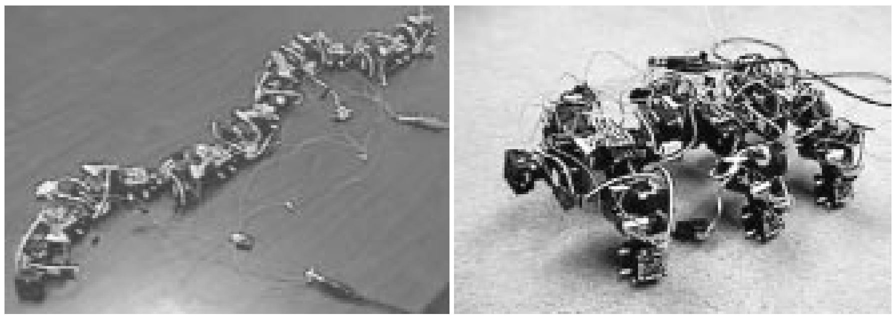

Fig. 5. Conro robots executing motions. (**a**) Snake. (**b**) Hexapod

shown in Fig. 5a is formed by eight modules connected in series. This particular head-to-tail configuration simplifies the communication mechanism because each module needs to communicate to, at most, two other modules. Figure 5a shows the snake while executing sinusoidal motions which are the basic steps of the traveling wave gait (e.g., see [16]).

Figure 5b shows a Conro hexapod after standing up by its own means. It is composed of nine modules: six modules play the role of legs and three modules form the spine. In this case, the distribution of the communication load is uneven because the modules that form the spine have to handle up to four communication ports while the modules that form the legs need to handle a single port.

6 Conclusion

We have introduced the Conro module, the basic block of a reconfigurable robot that is designed for deployability and inter-robot reconfiguration. It is, to our knowledge, the first module for reconfigurable robots that is self-sufficient and autonomous. The module shows a large potential as the building block for deployable reconfigurable robots.

The Conro modules are homogeneous, self-contained, autonomous, miniature and use an IR system for communication that doubles as a tracking system. We have described the implementation of the design in the form of actual modules that can be used to build large robots. These robots are already being used as a research platform for both distributed and centralized control systems. At the moment, we are implementing the gaits for snake and hexapod robots and the automatic reconfiguration algorithms that were tested on robot prototypes and are discussed in our preliminary work [15].

7 Acknowledgments

We thank Robert Kovac and Behrokh Khoshnevis for their contributions to the development of the module. This research is being sponsored by DARPA/MTO under contract number DAAN02-98-C-4032.

References

1. Will P., Grossman D. (1975) An experimental system for computer controlled mechanical assembly. IEEE Trans Computers, **(C-24)9**:879-888
2. Fukuda T., Kawauchi Y. (1990) Cellular robotic system (CEBOT) as one of the realization of self-organizing intelligent universal manipulator. In Proc. IEEE Intl. Conf. Robot. Autom., 662-667
3. Schonlau W. J. (1999) MMS: A Modular robotic system and model based control architecture. In Proc. SPIE, vol. 3839, 289-296
4. Murata S., Kurokawa H., Kokaji S. (1994) Self-assembling machine. In Proc. IEEE Intl. Conf. Robot. Autom., 441-448
5. Pamecha A., Chiang C. J., Stein D., Chirikjian G. (1996) Design and implementation of metamorphic robots. In Proc. ASME Design Engineering Tech. Conf. and Comput. in Engineering Conf., aug, 1-10
6. Chirikjian G., Pamecha A., Ebert-Uphoff I. (1996) Evaluating efficiency of self-reconfiguration in a class of modular robots. J. Robotic Systems **(13)5**:317-338
7. Murata S., Kurokawa H., Yoshida E., Tomita K., Kokaji S. (1998) A 3-D self-reconfigurable structure. In Proc. IEEE Intl. Conf. Robot. Autom., 432-439
8. Kotay K., Rus D., Vona M., McGray C. (1998) The self-reconfiguring robotic molecule. In Proc. IEEE Intl. Conf. Robot. Autom., 424-431
9. Yim M., Lamping J., Mao E., Chase J. G. (1997) Rhombic dodecahedron shape for self-assembling robots. Xerox PARC, SPL TechReport P9710777
10. Ünsal C., Kiliççöte H., Khosla P. (1999) I(CES)-cubes: a modular self-reconfigurable bipartite robotic system. In Proc. SPIE, vol. 3839, 258-269
11. Fujita M., Kitano H., Kageyama K. (1998) Reconfigurable physical agents. In Proc. Intl. Conf. Autonomous Agents, 54-61
12. Farritor S., Dubowsky S., Rutman N., Cole J. (1996) A systems-level modular design approach to field robotics. In Proc. IEEE Intl. Conf. Robot. Autom., 2890-2895
13. Hamlin G., Sanderson A. C. (1995) Tetrobot: A modular system for hyper-redundant parallel robotics. In Proc. IEEE Intl. Conf. Robot. Autom., 154-159
14. Yim M. (1994) New locomotion gaits. In Proc. IEEE Intl. Conf. Robot. Autom., 2508-2514
15. Castano A., Shen W-M., Will P. (2000) CONRO: Towards deployable robots with inter-robot metamorphic capabilities. Accepted for publication in Autonomous Robots Journal **(8)3**
16. Poi G., Scarabeo C., Allota B. (1998) Traveling wave locomotion hyper-redundant mobile robot. In Proc. IEEE Intl. Conf. Robot. Autom., 418-423