Seventh International Conference on Control, Automation,
Robotics And Vision (ICARCV'02), Dec 2002, Singapore

Self-Reconfigurable Modular Robot (M-TRAN) and its Motion Design

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Abstract

We have developed a modular robotic system (M-TRAN) which can change its configuration by itself. By using many DOFs of mechanism and self-reconfiguration capability, it can realize several types of motion, and can make various configurations. We have made two models of the system (M-TRAN I & II). In M-TRAN II, various improvements are integrated such as onboard multi-computers, reliable inter-module communication system, low power consumption, precise motor control, etc. Its hardware design, basic experiments and examples of motion are presented in this paper.

1 Introduction

Feasibility of modular robotic systems has been examined on hardware and software [1-13], in order to build a highly autonomous system. Adaptive operation in unpredictable environment is expected by its metamorphic capability, and long-life operation is possible by its homogeneity because a damaged module can be replaced by another module. Such a metamorphic capability and fault torelance is useful to search and rescue operations or exploration on planets.

We have been developing "Modular Transformer (M-TRAN)" as a general-purpose modular system [2], and realized several motions through experiments. Its basic design is aimed to realize easy and reliable connection/ detachment between modules, capability of three-dimensional self-reconfiguration and enough power for versatile motions such as locomotion. By experiments with the first model, we verified its ability of both self-reconfiguration and locomotion, which included a crawler motion and quadrupedal walking [2].

In the second model (M-TRAN II), several improvements have been made, which include downsizing, low power consumption for battery usage, precise motor control, upgraded onboard computation and reliable communication between modules. Especially, performance of the control system is upgraded by using an inter-module network system and a multi-CPU system on each module.

A method for motion control and planning reconfiguration is still a challenging problem for most modular systems and yet there are several studies of distributed [1,8,9] as well as centralized [10,11] methods for reconfiguration. It is difficult to apply them to our system. We developed a software that supports a human operator to make a reconfiguration motion [12], and also developed an automatic planner which generates a reconfiguration sequence among predefined type of configurations [13].

Though a fully automatic planner has not been obtained, we can design various configurations and motions of several modules. Possible motions include locomotion (or walking) along a rough terrain and through a narrow space, obstacle avoidance, making a firm structure and dexterous motions suitable for inspection or manipulation.

This paper describes the hardware design and control architecture of M-TRAN II including multi-CPU and an inter-module communication system in Section 2. In Section 3, an example of configuration by M-TRAN is introduced, which can perform several types of locomotion and dexterous motions. Section 4 summarizes future works.

2 Hardware Design of M-TRAN

The main characteristics of M-TRAN system include a simple design of the module mechanism, easy connection and wide variety of possible three dimensional configurations. We have developed the second model (M-TRAN II) with the same basic design as the first one, aiming at downsizing, precise control of the motors, lower power consumption, and higher performance of the local controller and inter-module communication.

2.1 Concept of Module

The module is composed of three components, two semi-cylindrical parts and a link (Fig. 1). Each semi-cylindrical part can rotate from -90 to 90 degrees independently by a motor embedded in the link. There are four permanent

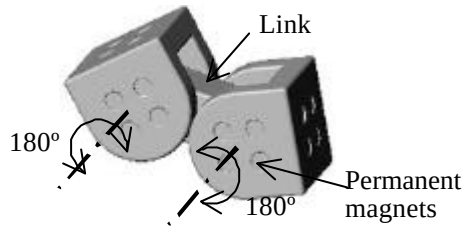


Figure 1: Schematic view of the module

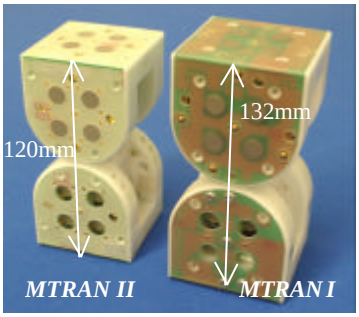


Figure 2. Comparison of MTRAN I and II

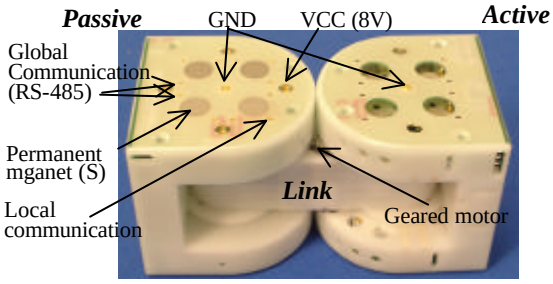


Figure 3. Photo of the module

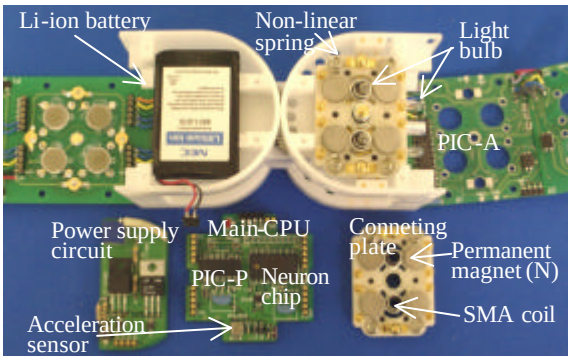


Figure 4. Inner structure of the module

magnets on each of three connecting surfaces of each semi-cylindrical part. As the polarity of the magnets between two parts is different, the module can connect to other modules by magnetic force. As each connecting surface can be connected to the surface of another module in orthogonal relation, a lattice structure is easily formed by modules. This structure can be reconfigured by repeating a primitive process as releasing some connections, changing positions of the semi-cylindrical parts, and connecting again.

Table 1. Specifications of M-TRAN II

Dimension	60x120x60mm
Weight	400 g (including battery)
CPU	Neuron chip (TMPN3120FE5M, Echelon Corporation) Three PICs (PIC16F873/877)
Global communication	LonWorks & RS-485 (39kbps)
Local communication	Asyncronous serial 4,800 bps
Torque of each axis	19.8 kg cm (rating)
Connection force	85 N
Power supply	DC 8V~20VDC (external) 3.8V (battery)
Battery	Li-ion (3.8V, 700mAh)
Power consumption	0.4W - 4W (detachment)
Sensor	Acceleration sensor (3 axes)

2.2 Mechanical and Electrical Design

Figure 2 shows our two types of M-TRAN models and Figs 3 and 4 are photos of the appearance and the inner structure of the M-TRAN II module respectively. Table I shows the specifications of M-TRAN II.

There are two semi-cylindrical parts called a passive part and an active part (Fig. 3). The passive part has four permanent magnets (S pole outside) on each of three surfaces. On the same surface, electrodes are placed symmetrically for power supply (VCC, GND), global communication (RS-485) and local communication between neighbor modules. Inside the passive part, there are circuit boards for control and power supply.

The control circuit board (Fig. 4) includes a microprocessor (Neuron chip, TMPN3120FE5M, Echelon Corporation) for global inter-module communication, called the Main-CPU hereafter, another microprocessor (PIC16F873, Microchip Technology, Inc.), called PIC-P, and acceleration sensors (ADXL202E, Analog Devices, Inc.). The acceleration sensors will be used to detect the orientation of the module.

There are two ways of supplying power to the modules. When the host computer, descibed later, is included in the system, a single set of tethers is connected to one of the modules. These tethers include power lines and communication lines. In this case, power is supplied from outside to one of the modules and delivered from a module to another via electrodes on the modules' surfaces. The power supply circuit inside each module converts the supplied voltage to 8V and 5V for internal usage.

In addition, each module works autonomously by using a lithium-ion (Li-ion) rechargeable battery (3.8V, 700mAh, 29.5 x 47.0 x 6.7mm, NEC Co.,Ltd) as shown in Fig. 4. We have verified its capability by experiments of connection detachment using two modules.

Inside the active part, there are a connection mechanism and a microprocessor (the same one as in the passive part), called PIC-A, for controlling detachment and communicating with connected modules locally. The connecting plate in Fig. 4 has four permanent magnets (N pole outside), which can connect to a passive surface of another module without external force. Also there are electrodes for the power supply, global and local communication corresponding to those on the passive part. These come out from inside the casing when two parts are connected by magnetic force. A sensor for detecting completion of detachment is also implemented.

Inside the link part, there are two geared motors which rotate the active and passive parts. The circuit board to control these motors are also in the link, which includes a microprocessor (PIC16F877) called PIC-M and motor driver chips. A PID position control program is implemented and the static torque of the motor can be estimated. Maximum torque of each motor is 19.8 Kg cm which is enough to support and lift up other two modules.

2.3 ConnectionMechanism

The connection mechanism of the module is based on an IBMU [14] (Internally Balanced Magnetic Unit.) and coil actuators made of shape memory alloy (SMA). The IBMU mechanism includes a connecting plate with permanent magnets and non-linear springs as shown in Fig. 5. When the magnets are connected face to face, the repulsive force of the non-linear springs is internally balanced inside the casing and firm connection by magnets is realized. The connection is automatically released when the SMA coils generate enough force to move the plate.

Different methods are used in the two models, M-TRAN I and II, to heat the SMA coils. In M-TRAN I, electric current is applied directly through the SMA coils but as the electric resistance of the coil is too small, much power is consumed by the driving circuits. In M-TRAN II, we have implemented miniature light bulbs inside the SMA coils to heat them as shown in Fig. 4 and Fig. 5. The power needed for detachment is 36 W (0.5 A current with 8V voltage), which is far less than the power needed in M-TRAN I. Currently, there is a problem with the speed as detachment and reconnection requires 1 and 3 minutes respectively. Finetuning of the non-linear spring is necessary to reduce these values.

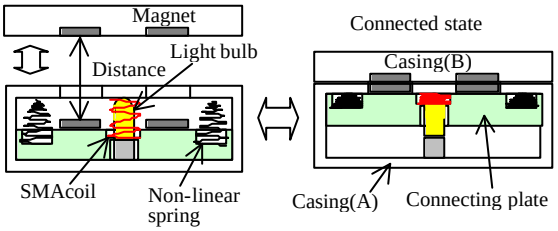


Figure 5. Connection mechanism

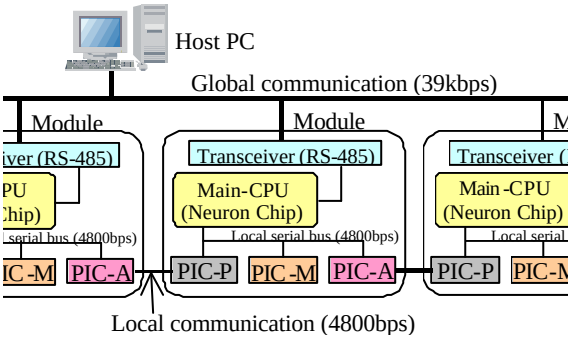


Figure 6. Multi-CPU and communication system

2.4 Multi-CPU and Communication System

The control system of the M-TRAN II contains two layers of multi-CPU system (Fig. 6). The lower layer consists of a main CPU (Main-CPU in Fig. 6) and three local controllers (PIC-P, -M, and -A) inside each module. The upper layer is a computer-network system with the host PC, the Main-CPUs in the modules and a communication line among them.

The Main-CPU is the Neuron Chip which currently works as an interface between the host PC and other three processors. All the control of the modular system in total is managed by the host PC and delivered to each module's Main-CPU.

An interface board with the same Neuron Chip is installed in the host PC and all the Neuron Chips are connected via the global communication line (Fig 6), which is a two-wire bus based on RS-485. Its speed is restricted to 39kbps because the network topology changes dynamically and there is no terminator-circuit. The communication is achieved by the LON protocol that is implemented on the Neuron Chip as firmware. In the LON protocol, network variables are shared with other neuron chips and users do not need to consider the network. In the network, all the chips are equivalent in their priority, and the communication program is designed so that any modules can turn into the host.

In the module, the Main-CPU works as the master and the others as slaves. The PIC-M controls two motors and the PIC-A controls the light bulbs to detach the connection as described in 2.3. The PIC-A and the PIC-P of neighboring modules locally communicate with each other for exchanging the ID of each module and internal states. Such local communication is necessary to reduce the load of the global communication when the number of modules increases in the future. Also, the PIC-A and the PIC-P can detect the states of connection and the orientation of the connected surface. Communication between those four internal computers are made by asynchronous serial lines.

The Main-CPU currently sends request commands to three PICs repeatedly and receives internal states of the PICs such as the angles of the motors, the states of connection and so on. These internal states of the module are specified as network variables and shared with all the modules and the host PC.

3 Motion Planning

A group of M-TRAN modules can make various configurations and motions suitable for a variety of tasks. Possible tasks include locomotion, forming a firm structure, and dexterous motions for inspection and manipulation.

To realize such tasks, there are two kinds of research subjects. One is to find a suitable configuration and design an appropriate control method for such a multi-DOF mechanism. The other is to find a reconfiguration sequence from one configuration to another.

Generally speaking, reconfiguration sequences from one configuration to another are sometimes very difficult to find and sometimes impossible to realize. We have been developing various programs to design configurations, reconfiguration sequences and motions.

In the followings, the software study for the M-TRAN system is briefly introduced, and next an example of a module cluster, its possible motions and reconfigurations are presented in detail to show its capability for several tasks.

3.1 Software

We developed a utility program for designing M-TRAN motion [2, 12]. A human operator can design a configuration and a sequence of modules' motion using GUI of the program. This program confirms whether the total system is connected and whether it is stable under gravity, and outputs commands to the real hardware to realize the corresponding motion. In addition, it supports a macro function, which is defined as a series of motions with modules. Such a macro sequence is applicable when the structure contains the same local configurations of modules.

We have also developed an automatic planner for reconfiguration between a specific class of configurations [13]. The structure of this class is a serial chain of several four-module blocks and can move in three dimensional space as a series of block transportation from the tail to the head along the side of the chain. This planner program automatically generates a sequence of module motions.

A research study is continuing to realize a general method to obtain reconfiguration sequence between arbitrary configurations.

3.2 Motion Design

Let's show examples of configurations and motions. Figure 7 (a) shows the initial configuration for all the following motions (Fig. 7 (b), (c), ..., (h)). It consists of double module chain of arbitrary length and additional two modules with axis different from others. As the main structure is a chain with the same axis direction, it can generate either a worm-like motion (Fig. 7 (b)) or a crawler motion (Fig. 7 (c)) to realize locomotion. Reconfiguration between three configurations (Fig. (a), (b), and (c)) is simple and in either motion, self-reconfiguration is unnecessary and each module's motion can be defined as a periodic motion. Locomotion is also possible by a multi-legged centipede-like configuration with many two DOF legs (Fig. 7 (d)).

Figure 7 (e) shows another type of locomotion for this configuration. It is a series of module transportations from the tail to the head. Compared with previous three motions, this requires repetitive self-reconfiguration. This type motion can follow a rough terrain or the surface of an obstacle by controlling angles of modules (Fig. 7 (f)). Also this type motion is applied to make a tower-like structure (Fig. 7 (g)).

For any of the above configurations, a four-DOF manipulator can be formed by using two modules (Fig. 7 (g)). This is suitable for tasks such as inspection.

By using a pair of modules attached to the side of the main body, the whole body can change its heading direction after a series of reconfiguration (Fig. 7 (h)). Thus, the module cluster of this structure can move to any direction even along a rough terrain or stairs, and make a structure such as a tower.

Though the detailed sequences of each motion from (b) to (h) have been manually designed for clusters of specific length, a general sequence for each motion for arbitrary length clusters can be easily made because they mainly consist of the same types of primitive motions.

3.3 Experiment

We have developed 10 modules of the first model (M-TRAN I) and 20 of the second model (M-TRAN II). Some parts of the above motions have been verified by experiments. By M-TRAN I, reconfiguration from a plane configuration to a quadrapedal robot via a crawler and

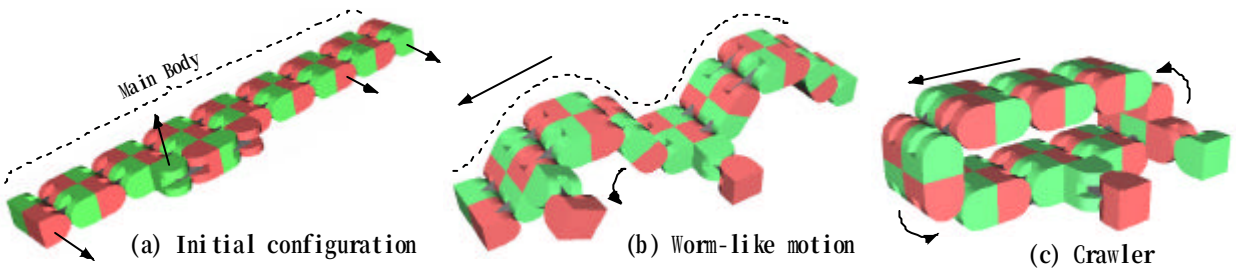


Fig. 7 Reconfiguration and motions

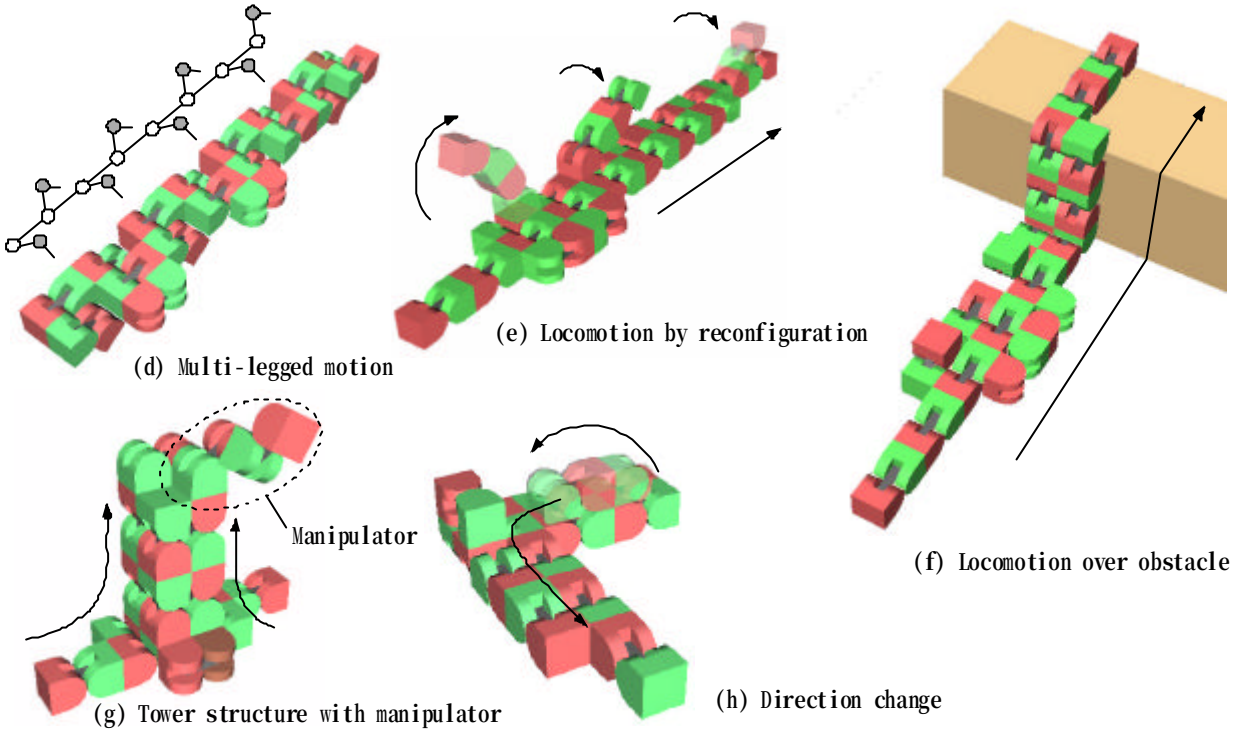


Fig. 7 (Continued)

locomotion with both of the configurations were realized experimentally [2]. Figure 8 (a) shows a crawler configuration in that experiment. It consists of 9 modules in total, two closed loops of 4 modules with one module connecting these two loops. Locomotion by this configuration is similar to that in Fig. 7 (c).

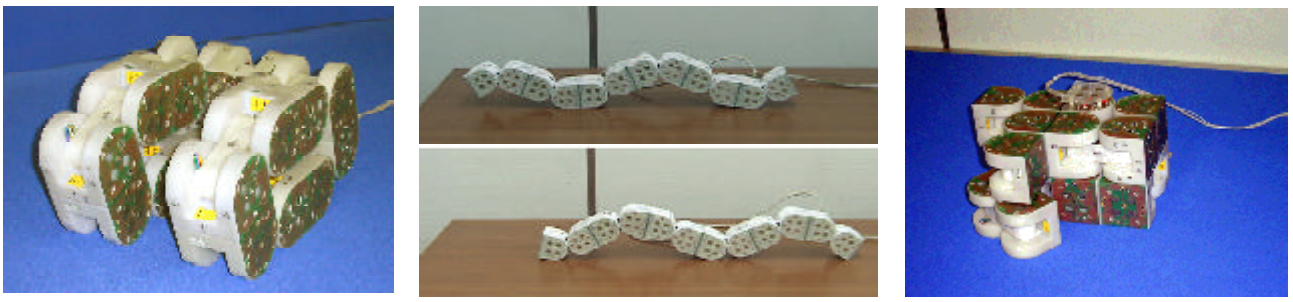
We have tested worm-like locomotion by 6 M-TRAN II modules (Fig. 8 (b)) to confirm the feasibility of the motion in Fig. 7 (b). In this experiment, the total chain generated a propagating wave by changing each angle with a sinusoidal function of different phase. The wave length was set to three module length and a frequency of 2 Hz was tried.

The current M-TRAN II has a problem of reconfiguration speed as described in Section 2.3, and experiments including reconfiguration were carried out only by M-TRAN I. Figure 8 (c) shows reconfiguration for tranporting modules from the tail of the block to the head [13]. Repetitive reconfiguration motions were made in this experiment which are applicable to the motion in Fig. 7 (e).

With the current specification, connecting force between modules and the motor torque could be critical in some of the above motions. In such cases, modification of the reconfiguration process will be necessary. Upon solving the problem of reconfiguration speed, all the motions in Fig. 7 will be tried by 20 of M-TRAN II modules. Sophisticated controls will be necessary such as a stiffness control of the structure when the modules perform any of the above motions in the real world. For controls such as locomotions along a rough terrain or stairs, the system needs more sensors to detect the environment such as a touch sensor or a force sensor.

4 Concluding Remarks and Future Works

We described the concept of the modular robot, M-TRAN, and the hardware design of the new model, MTRAN II.



(a) Crawler (b) Worm-like locomotion (c) Module transportation

Fig. 8 Experiment for basic function

The improvement of the module is achieved especially with its computation and communication capability, low energy consumption and precise motor control. We also introduced an example of configuration, which can perform various tasks such as locomotion, structure forming and dexterous motions by using self-reconfiguration.

As future work, we will execute various experiments using 20 modules, which include reconfiguration and locomotion while being powered from batteries. In order to realize the autonomous motions, each module needs to have more sensors to detect the environment. Moreover, the control system must become more intelligent and autonomous in order to select an appropriate configuration and a motion by itself according to the environment.

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