Torque Analysis and Motion Realization of Reconfigurable Modular Robot

Bo-Hee Lee[1], In-Hwan Yu[2] and Jung-Shik Kong[3]

[1]*Dept. Of Electrical Eng., Semyung Univ., Shinwaldong, Jechon,Chungbuk, Korea*
[2]*Dept. Of Display Eng.,Doowon Univ.,Paju,Kyungki-do, Korea*
[3]*Dept. Of Mech. Design, Induk Univ., 12 Choansan-ro, Nowon-gu, Seoul, Korea*

bhlee@semyung.ac.kr, tough0507@hanmail.net, jskong@induk.ac.kr

Abstract

This paper deals with design of the intelligent mechanism and working algorithm for a cube-style modular robot. The modular robot changes own shape according to the working environment. Therefore it is suitable to work in the search and rescue area where requires the adaptation of situation with a shape of snake, legged robot or humanoid. Each of modular unit has to install own controller on the body and drive the body to give some mobility autonomously, also combine and separate their modules with docking and unlocking mechanism. In this paper we proposed design concept of our modular robot including the combination, control, and communication algorithm between modules, and also suggest some application movement with respect to various situations after torque consideration. Torque analysis according to the motion were accomplished by generation of trajectory and followed by simulation with respect to walking gait. The motions are verified with some simple action and shown their effectiveness through actual experiment for corporative motion of multiple modular robots such as inchworm, butterfly, crab, and bipedal motion.

Keywords: *Cube-style modular robot, docking mechanism, torque analysis, inchworm, butterfly motion, crab and bipedal motion*

1. Introduction

The robot of various kinds has been developed recently with respect to requirements of application field. Among the application, a walking robot with legs and the mobile robot using wheels are the main research areas. The development of such a robot has taken a close attention at the rehabilitation field in particular and search-rescue area. However, in the most case of such a robot, the restriction for the motion was also existed. Reconfiguration area of robot has a good application since it transforms itself into a form deserving special working, and it makes an appropriate movement according to situation. Therefore, we can expect effectiveness as a modular robot that is possible to be transformed with the adaptability for the circumference environment. The form of such a robot can be effective in lifesaving area and searching environment of the circumference having various obstacles [1]. The active study for the such robot had been done mainly in university and research organization like Swarm-bot [2] of Switzerland EPFL, Polybot G1-G4 [3] series of American PARC, CONRO[4] and SUPERBOT[5] of USC University, M-Trans I,II,III from AIST [6], and these days Sambot [7] from China that has cubic shape using Zigbee has been studied. Swarm-bot is unique form of the bonding and separation structure, but coupled with the complexity of combination, so it is difficult to implement it in a small space. CONRO and Polybot have the combination structure using magnet, but it is overly complicated structure for locking. M-

Trans series has good combination structure, but it requires high cost to implement the structure. And the case of Sambot mechanism for combining and separating mechanism is simple form and good structure to make multiple connections fitting into the structure of modular robots, but has some drawback too large in size. However, the existing reconfiguration robot established the focus on the mobility using recombination process, but it had not adaptability for the complicated ground situations. In addition, since they did not have the mobility of unit cell itself, the module cell came to have a problem to add a module to a robot. They have some limitation to express the high-speed movement for the user demand, and they are impractical to deal with the application under the complicated situation. Moreover they are so heavy that it is difficult to make some creature after combination and it cost a lot to realize many modular cells. To effectively solve this problem, we suggested a modular robot to transform a form and reconfigure its shape with its mobility and light weight. In addition, it comes to realize with low cost because we need lots of module in application. In addition we proposed the intelligent shape transformation that can be taken through some sequential motion like an insect and butterfly action

2. System Design

For the purpose of this reconfiguration, we developed compact a modular unit that can build some creature from the combination. It may have own controller inside to change shapes to the various things. At same time, some connection and moving mechanism is also suggested. To control modular unit, some control logics with intelligent capability is also designed. Figure 1 shows modular unit cell and its function blocks we have designed.

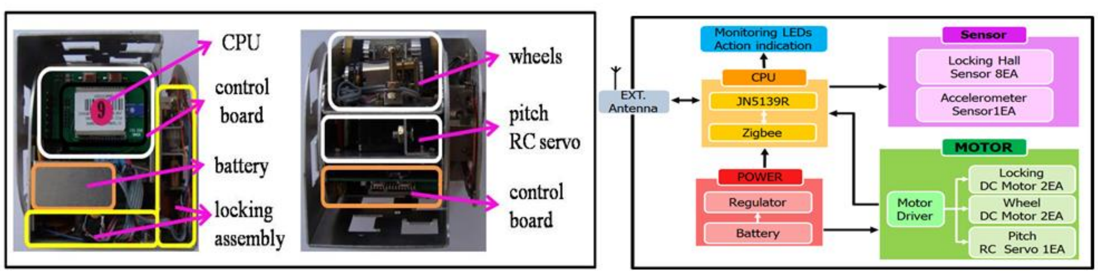

Figure 1. Modular Robot and Function Block Diagram of Main Controller

All of parts are inside in a modular cell including sensors, motors and controllers. Inside of a modular unit, motor controller driving a rotation joint and docking mechanism and sensor parts recognizing the state of the module cell are installed. The module is built with small and compact structure, 7cm in each side, to express the giant structure. Each of modules is divided into four piece of partial structure to attach the internal components like mechanical parts and electronic parts. All of electronic devices from motor controller to battery controller are installed inside module without external wire to give mobility. These modular units are cubic structure, so they can combine modules using four different faces in order to express the various structures. Even though each of module has one DOF and only pitch motion using a single RC motor that has rotation angle ranged from -90~+90 degree, the various docking scene can be made by adjusting movement angle. We can express as a roll movement and a pitch movement according to connection angle. As all of the mechanical and electrical parts are contained inside of unit, we realize the autonomy and compactness, but has also the complexity problem caused from lack of space. Docking and locking process is crucial to develop into a reconfiguration robot. Figure 2 shows the assembly of modular robot we designed [8]. It contains body frame, supporter, motor assembly and controller assembly with wireless networking.

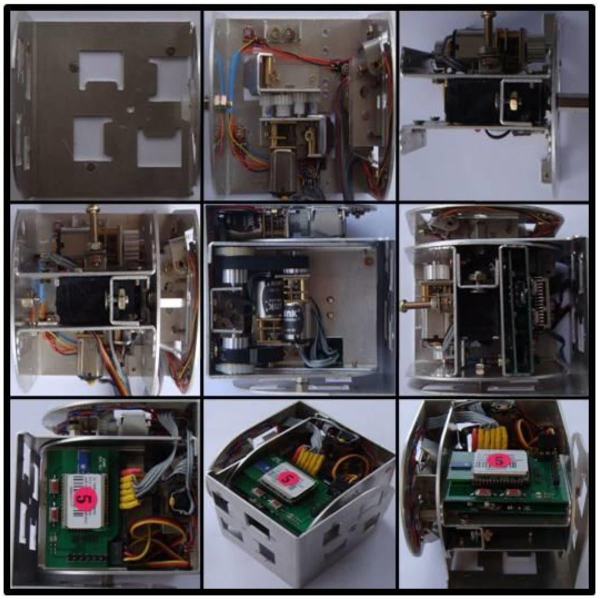

Figure 2. Assembly of Modular Robot

We have designed some kind of mechanism according to the variation of connections. This combination mechanism is based on a hook, some gears, and driving motor. The module consists of body link structures, and gear assembly for docking and locking with custom-made spur gears. The each surface of modular unit has the recognition sensors those are hall sensors. When you start the motor rotating shaft with a gear attached to the gear linkage and locking the structure to rotate in a clockwise direction came to opposite sides of the structure is mounted on the structure has to be combined. And that works by stopping the motor after a period of time, will finish the combination. The stopping time, it takes the motor to a rapid change in current is detected and recognized. In contrast to the combination of separation in the same way, it will release the latch by turning the motor when the direction of motor rotation is opposite. The characteristics of this structure, when combined and separate power supply to the motor and keep the bond because they do not consume enough energy to bring energy-saving advantages. In order to develop to modular robot from modular unit, it is necessary to make some combinations based on face recognition and docking between modules. Each face of cubic has the magnets and hall sensors to recognize the docking face. The connecting face has hall sensors, while connected face has magnets. 3 or 2 magnets on the side are installed. During combination process it is needed to recognize faces and angles. Depending on the number of magnets attached to the docking surface, modular robot recognizes faces and the angle of rotation. A-side magnets come to be attached two position, in contrast B-side three magnets are affixed to detect the rotation angle. If modular robot designed by detecting the angle after rotation of 90 degrees, then each sensor of 4 sides check the bonding angles according to the combination of sensing. In case of sensing two right magnets, it means the combination comes to straight, whereas the case of sensing upper two, it is right-angled combination. Using this combination the robot detects the direction of rotation regardless of the chosen sensors attached to each side. If a module finds a matching face, it starts docking and locking scenario using hook assembly like following. First, the DC motor starts working, gears engaged with the motor are going rotation. At same time the latch moves some locking degrees in clockwise. If the latch reaches locking position, then the motor stops the rotation and all the docking sequence will be finished, and two module units become to bond each other. This sensing mechanism can be realized with the support of magnets and hall sensors. Sensing sensitivity is controlled by adjusting the sensing threshold level of the followed A/D converter. It also needs not to have pins hanging diagonally across the wide area to catch since the two docking latches are rotated inward. Holding and latching at the front side within about 2 ~ 3mm is even able to do because of its flexibility. In order to realize self-assembly structure, each module should have own mobility. Wheel drive system is designed using two motors and pulleys. The two-wheel differential driven system compared to Caterpillar-type moving in straight line changes the direction by the difference in speed of the motor, while caterpillar wheel moves in straights. It moves two separate motors, so the module can move forward or turning to some directions by driving two motors separately.

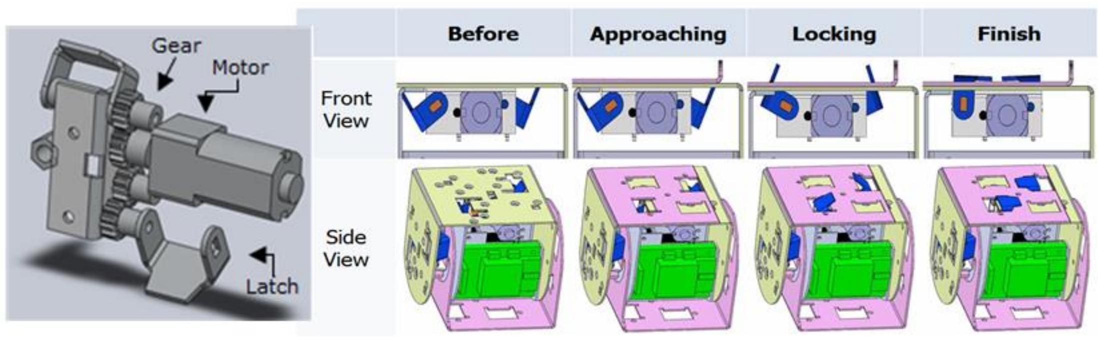

Figure 3. Docking Mechanism and Combination Process

Each modular robot should make lots of combination and separation. In this situation, they have to share the information for the module such as sensor status, and surface information related with shape representation. We realized this function using wireless communication called Zigbee, which was loaded on CPU as program stack [9]. So the communication between the modular robots is automatically solved by using the Zigbee protocol.

Function of each module in the network is classified into three categories; a Host controller that sends user command and collects the status information from modular robot, a Command Module for the network setup and user application, and Action Module as unit modular cell. CM starts the Zigbee network and maintains the network. It is located between HOST and AM and it dispatches the command from HOST to AM and vice versa, sends the status. It can search the moveable module after initializing a total network, and then it translates user command and distributes some modular work to the AM. If an available module is detected in the network, then it stores the module ID, and transmits the new ID to HOST. AM gathers robot status and sends to CM periodically to indicate the status of modular robot to user. The present status of AM is transmitted to HOST via serial channel like RS232C. The overall function can be expressed as follows. As a general, modular robot system consists of one HOST, one CM, and lots of AM, and they operate as a living organic with information exchange.

Algorithm CommandModule()

```
 Initializing network
Search for AM and send ID to HOST
  While true do
    Get command
    If command is 'M', then send it AM and send rcv data to HOST
    In case of 'L', pass it to AM
    In case of 'T', pass it to AM
    In case of 'C', pass it to AM
    In case of 'R', start the application motion
    End while
```

Algorithm ActionModule()

```
Finding network
     Send ID to CM
Wait until receiving command
    Analyze command
    If command is 'M', send status to CM
    In case of 'L', initialize locking process
    In case of 'R', then check if it is inchworm or butterfly movement and do action
    In case of 'C', check if docking or separation, and do operation
  In case of 'T', check if the hardware is valid or not
  End while
```

3. Torque Analysis

In order to analysis the motion of structure, it is required to find the trajectory of motion based on kinematics. Moreover we should find the torque requirement of module joint when the modules are connected with others. Through this process we can find the good motion and application job using allowable torque for a modular robot. For this purpose, the coordinate system of modular robot is defined as follows, based on Denavit-Haretenberg representation. The trajectory planning of the modular robot is created at joint space using via points. The reason used this method is to reduce the computational power. In order to make trajectory, we use a fifth order s-pline polynomial and get mid points from the result.

$$\lambda(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \tag{1}$$

The best equation for a given physical conditions is the acceleration function, so it has the merit not having a function of the third impulse (Jerk). For reliable operation of the structure on the system dynamics analysis is also needed. For kinetic analysis of the modular structure with a total of four mass center, Newton-Euler [10] formulation were applied through a chain of mechanical methods to interpret the dynamics that are expected to spend on each module structure inferred torque. Using Newton-Euler method dynamic solution can be expressed as follows.

$$^{i}R_0\dot{\omega}_i = {}^{i}R_{i-1}[({}^{i-1}R_0\dot{\omega}_{i-1}) + z_o\ddot{q}_{i-1} + ({}^{i-1}R_0\omega_{i-1}) \times z_0 q_i \tag{2}$$

$$^{i}R_0 f_i = {}^{i}R_{i+1}({}^{i+1}R_0 f_{i+1}) + m_i {}^{i}R_0 a_i \tag{3}$$

$$\begin{aligned} {}^{i}R_0 n_i &= {}^{i}R_{i+1}[{}^{i+1}R_0 n_{i+1} + ({}^{i+1}R_0 p_i^*) \times ({}^{i+1}R_0 f_{i+1})] + ({}^{i}R_0 p_i^* + {}^{i}R_0 s_i) \\ &\quad \times {}^{i}R_0 F_i + (R_0 I_0 R_i)(R_0 \omega_i) + (R_0 \omega_i) \times [({}^{i}R_0 I_i {}^{0}R_i)({}^{i}R_0 \omega_i)] \end{aligned} \tag{4}$$

$$\tau_i = ({}^{i}R_0 n_i)^T (R_{i-1} z_0) + b_i \dot{q}_i \tag{5}$$

Where, ${}^{i}R_0$ means rotation matrix with respect to base coordinate. f_i, F_i, n_i, b_i, I_i, and τ_i are internal force, external force, moment, viscous damping constants, inertia, joint torque, respectively. We can calculate the required torque of the joints using MATLAB for the various applications that use many modules as follows. First they are applied in crab motion that has small vertical movement but large movement in horizontal direction. Four modules are combined cascade each other. To express this motion, the moving area are divided into five parts every 0.3 second intervals at the points of (90˚,85˚,90˚,100˚,90˚), (0˚,10˚,22˚,10˚,0˚), (0˚,0˚,0˚,0˚,0˚), and (90˚,70˚,60˚,70˚, 90˚), respectively. After simulation we could find the trajectory and joint torque requirements like Figure 4, and know that the required torque is less than 0.2Nm. The joint motor HITEC (HS-85MG)[11] of the module has 5.3kgcm, so it is enough to drive this motion.

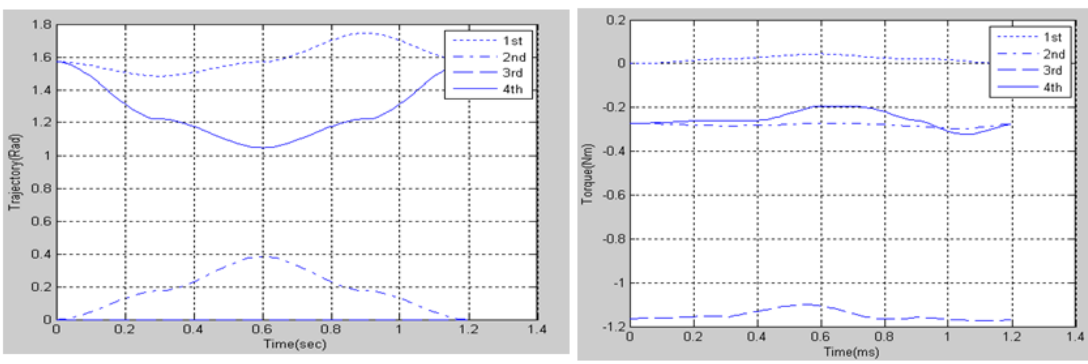

Figure 4. Trajectory and Joint Torque of Modular Robot at Crab Gait

Second simulation is acquired from bipedal motion that has via points at (90˚,45˚,90˚,90˚,90˚),(90˚,90˚,0˚,0˚,90˚),(90˚,90˚,180˚,180˚,90˚),and (90˚,90˚,0˚,90˚,90˚).

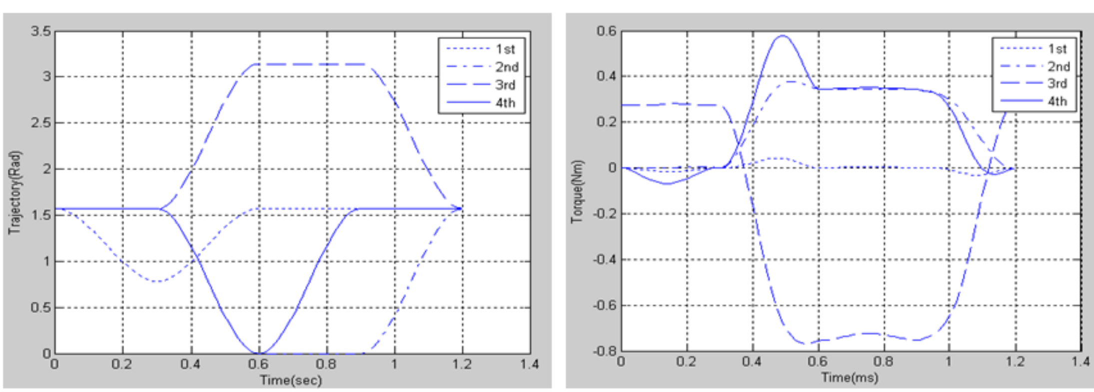

Figure 5. Trajectory and Joint Torque of Modular Robot at Bipedal Walking

Figure 5 shows the result of trajectory generation and torque analysis. In the Figure, the maximum torque of the joint is 0.6Nm or 8kgcm, and one module torque is not enough to lift the other three modules, and notice the lack of action. The cooperation with the other modules required was found by power distribution. They should attach their body on the floor to cooperate and need to distribute the required torque.

In order to check the torque variation with the consideration during close chained operation that meets at real situation when it is applied in case of two points contact. We use different tool to analyze the dynamic properties using RecurDyn [12], which can analyze some multiple flexible body dynamics on CAE. Test motions are chosen with basic pattern of insects and realized by combining the 4 modules cascade as shown from Figure 6. The rear module behind the first 3 modules moves first and follows with some forward movement. Eventually, the robot moves forward periodically. The simulation is doing over 1.2 sec with 3 different times at 0,0.3,0.6,0.9, and 1.2 second. Each positions for that time are (90˚, 45˚, 90˚, 90˚, 90˚), (90˚, 90˚, 70˚, 70˚, 70˚), (90˚, 90˚, 80˚, 90˚, 80˚), (90˚, 90˚, 0˚, 90˚, 90˚), respectively.

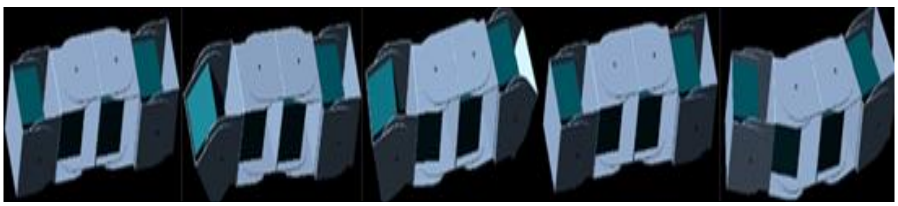

Figure 6. Snapshots of Inchworm Motion

Throughout the simulation with dynamic program, we can find the torque requirement for the movement like Figure 7. The maximum motor torque is 3.5kgcm of joint motor, and the maximum torque of simulation is less than 0.4Nm. Therefore the torque is same as the required value, and it is enough to drive modules under assumption doing ground contact by torque distribution.

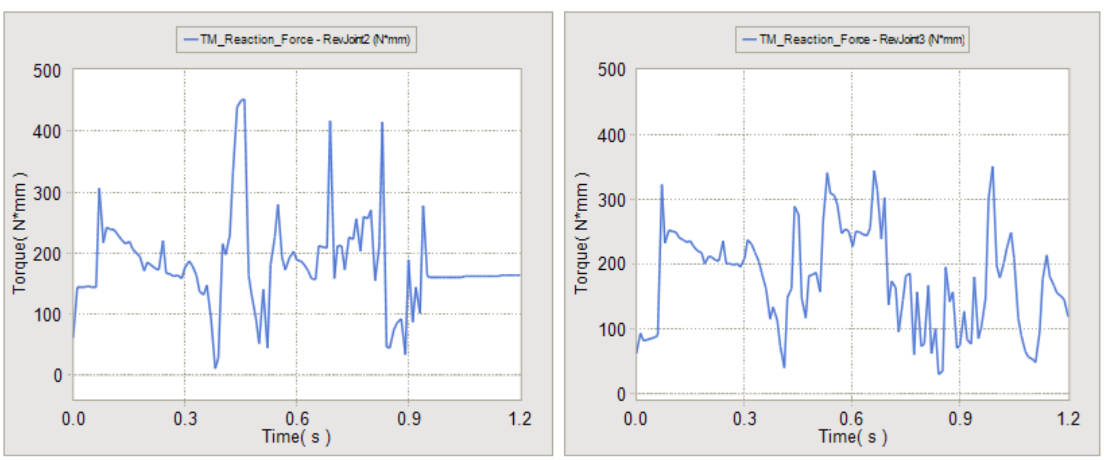

Figure 7. Torques of 2nd and 3rd Module at Inchworm Motion

Next we performed the butterfly movement. Eventually, a combination of 4 modules is same as simulation before. This motion include strong stroke the middle modules, so the required torque might be large. The simulation is doing over 1.2 sec with 4 via points like

0,0.3,0.6,0.9, and 1.2 second. Each position for the time is (90˚, 40˚, 40˚, 110˚, 90˚), (90˚, 90˚, 0˚, 0˚, 90˚), (90˚, 90˚,0˚, 0˚, 90˚), (90˚, 40˚, 40˚, 110˚, 90˚), respectively.

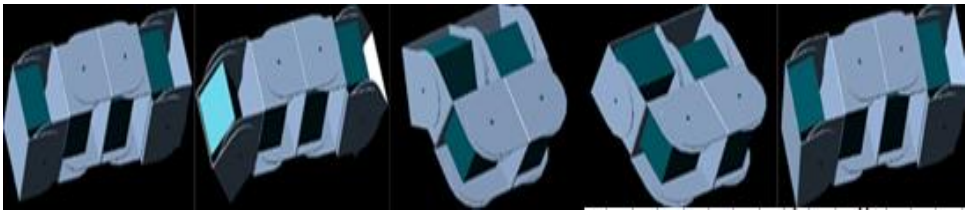

Figure 8. Snapshots of Butterfly Motion

Throughout the simulation with dynamic program, we can find the torque requirement for the movement like Figure 9. In the Figure, the required torques stayed under limited values like inchworm motion, so the joint motors in the modules can drive the modules to express butterfly motion.

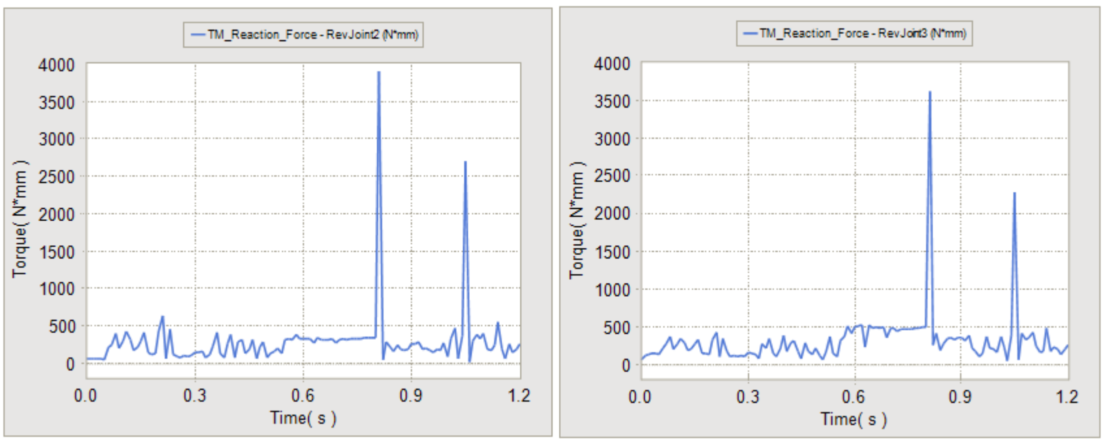

Figure 9. Torques of 2nd and 3rd Module at Butterfly Motion

Finally we combine 4 modules to mimic the complex motion like snakes as shown in Figure 10. At a first step, both ends of the bridge module support the floor and inside two modules have the role to move forward. Each holding end of the module was pushed forward to support the module. The next step on the floor at both ends of the module support, and support modules, pulling pushing forward makes the module. Finally, for the support module pull forward again to repeat the following action on the motion was expressed. Each time is (90˚, 45˚, 90˚, 90˚, 90˚), (90˚, 90˚, 0˚, 0˚, 90˚), (90˚, 90˚,180˚, 180˚, 90˚),(90˚, 90˚, 0˚, 90˚, 90˚) , respectively.

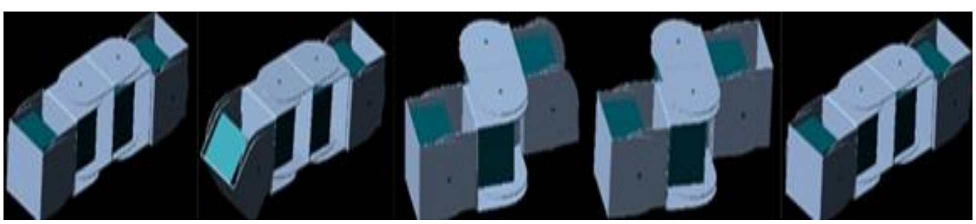

Figure 10. Snapshots of Snake Motion

Throughout the simulation with dynamic program, we can find the torque requirement for the movement like Figure 11.

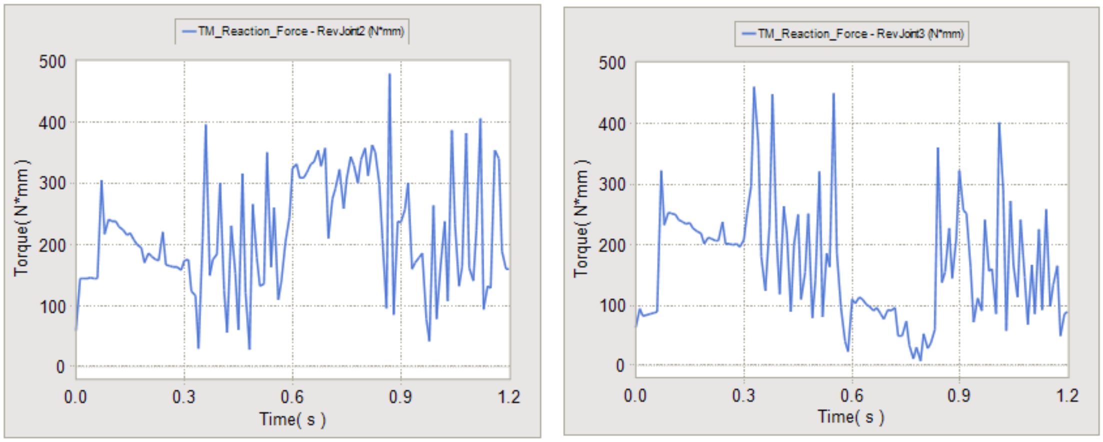

Figure 11. Torques of 2nd and 3rd Module at Snake Motion

As mentioned before the maximum torque of joint motor is 3.5kgcm and our simulation shows the applied torque varied from 200 to 400Nmm. That means we can realize the movement with this motor.

4. Motion Experiments

As referred in the previous section, all modular units operate independently or in cooperation. Figure 12 shows the process of connection for two modular robots using wheels. It starts to move independently, make connection after docking, and perform the cooperative action. After combination of two modules, it performs a sequential operation like inchworm's motion successfully.

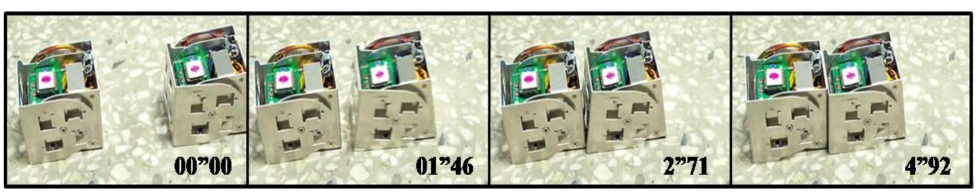

Figure 12. Moving Independently, Docking, and Inchworm Motion

Figure 13 shows the snapshots of combined movement including inchworm and snake motion with wheels. To move the robot forward, a left module flips its link with following a motion of right module (to 34”87:snake motion) up-down and left-right motion of third modules(45”86 to 51”74:butterfly motion). After doing this operation repeatedly, a modular robot moves forward, backward or turns some direction using velocity difference of two wheels(51’’74 to 60”29). This motion showed the snake motion and application motion like changing directions. Through these experiments, we could not only verify basic motion of two modular units like connection, locking, and pitch motion, but also we could extend the basic operation into complex function of snake or worm's motion which can be used in the various application fields

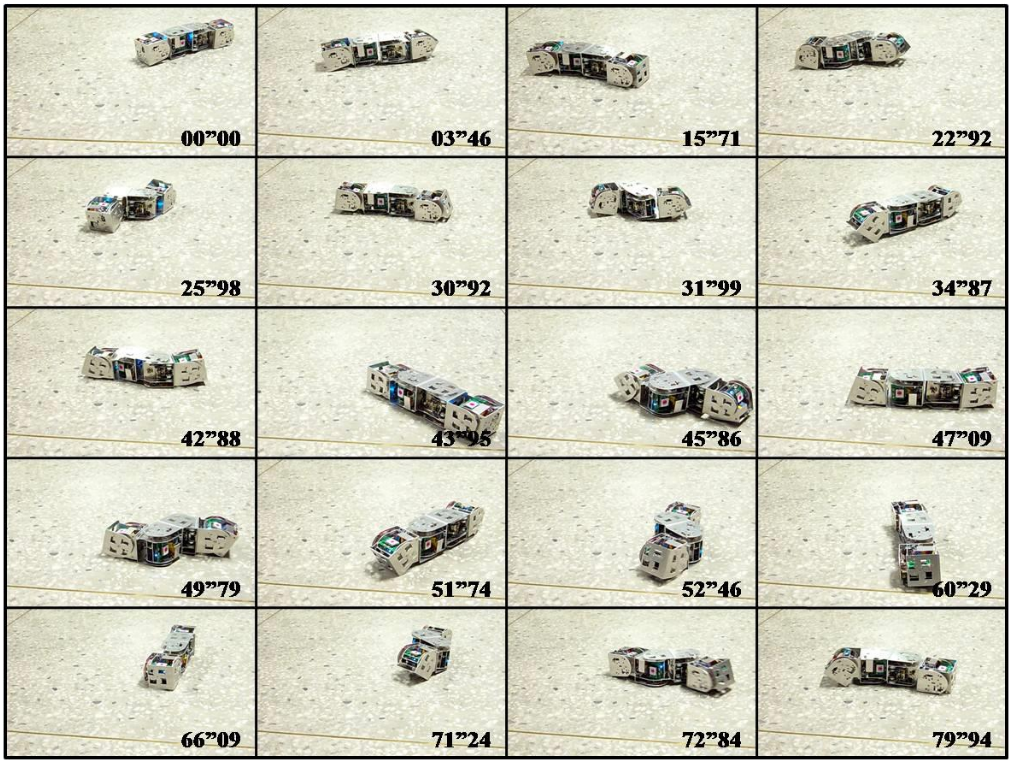

Figure 13. Combined Motions including Snake Motion

Now we implement crab walking that require some horizontal action. The entire operation was performed 80 seconds like Figure 14. During the operation clearance occurs, but latch structure compliance of the module complements the inter-module gap, and can be able to solid combination. The motion repeats at the cycle of approximately 1.2 minites moving from the left to right. As a result we could realize crab walking using 4 modules.

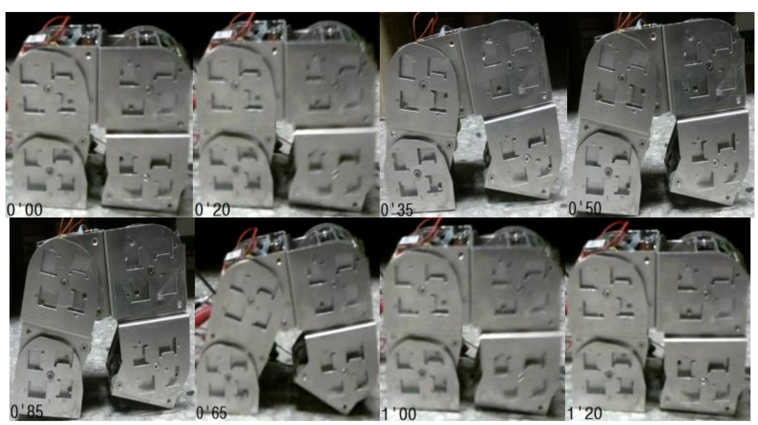

Figure 14. Crab Gait

To perform the more effective gait using angular displacements of each module in spite of small driving torque for the joints, we need the motion that can be modified to expand big displacement in the direction of gravity. So simple bipedal walking is considered with four modules as shown in Figure 15.

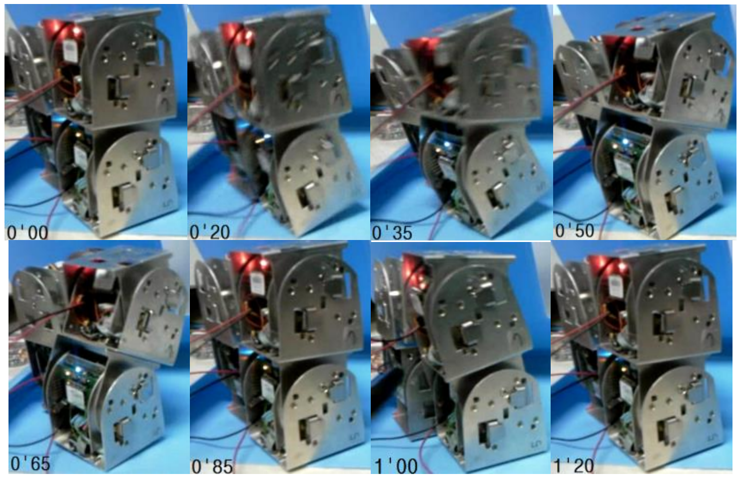

Figure 15. Bipedal Walking

The action step of crab walking is only from the left to right, but bipedal behavior indicates the movement in all directions. From the results of experiments, it was shown that built-in torque of the driving motor could perform a given deformation behavior, but it was still effective in various operation. And when we combine more coupling between modules, the module expression will be expected good mobility because of the increment of the degree of freedom.

In this experiment, the modules at upper structure did not give the severe influence of the action, but lower modules gave large impact to the operation property like power consumption or more complicated control problem like stabilization. Throughout the various realizations, we can verify the effectiveness of the reconfiguration structure and it can be used at the field of various construction fields. And also we can extend to complicated motion such as walking with quadruped robot or humanoid robot in the future.

5. Conclusions

In this paper, we suggested a light(180g), compact(6cm cubic), and simple modular unit having easy combination and separation with simple docking structure based on intelligent combination structure using just 7 components such as 2 hook parts, 4 small plastic gears and one driving motor. Also it has a capability of self-assembly with wheels, so it can be used as a unit module as well as the combined modules, and expandable to more complicated huge robot with its own joint. Using this combination, we can express the various robot representation that can be used the various application field. We have suggested the intelligent combination algorithm using 3 or 4 modules and analyzed dynamic properties of their motions through numerical analysis or simulation tool. The proposed method was verified and realized through experimental motions like inchworm or butterfly, crab, and bipedal movement after simulation. In the future, the more effective graphical expression method for the multiple modular combination and shape representation accepting the environment of the circumference will be continued with precise and effective method. In addition more intelligent structure of the transformation robot with various forms will be studied in order to express the emotional motion like human.

Acknowledgements

This paper was supported by the Semyung University Research Grant of 2012.

References

[1] A. Kamimura, "Automatic Locomotion Design and Experiments for a Modular Robotic System", IEEE Transaction on Mechatronics, vol. 10, no. 3, **(2005)**, pp. 314-325.
[2] F. Mondata, "Swarm-Bot: A New Distributed Robotic Concept: Autonomous Robots", Kluwer Academic Publisher, vol. 17, **(2004)**, pp. 193-221.
[3] M. Yim, D. G. Duff and K. D. Roufas, "Polybot: A modular reconfigurable robot", Proc. IEEE Int. Conf. on Robotics and Automation, **(2000)**, pp. 514-520.
[4] A. Castano, "The Conro Modules for Reconfigurable Robots", IEEE Transaction on Mechatronics, **(2002)**, pp. 100-106.
[5] B. Salemi, M. Moll and S. Wei-Min, "SUPERBOT: A Deployable, Multi-Functional, and Modular Self-Reconfigurable Robotic System", Information Sciences Institute, University of Southern California, Marina del Rey, USA. IEEE/RSJ International Conference, **(2006)** October, pp. 3636-3641.
[6] S. Murata, E. Yoshida, A. Kamimura, H. Kurokawa, K. 9Tomita and S. Kokaji, "M-TRAN: Self-Reconfigurable Modular Robotic System", IEEE/ASME Transactions on Mechatronics, vol. 7, no. 4, **(2002)**, pp. 431-441.
[7] H. Wei, Y. Cai, H. Li, D. Li and T. Wang, "Sambot: A Self-assembly Modular Robot for Swarm Robot", 2010 IEEE ICRA, **(2010)**, pp. 66-71.
[8] B. Hee Lee, C. Lee, K. S. Choi, J. Y. Oh, S. K. Lee and J. K. Kyung, "Modular Robot and Its Control Method", Korea Patent 10-2010-0135607, **(2010)** December 27.
[9] Zigbee Solution, http://www.jennic.com/products/protocol_stacks/zigbee.
[10] K.S. Fu et al ,Robotics, McGraw-Hill inc.,(1987).
[11] RC Servo motor, http://hitecrcd.co.kr.
[12] RECURDYN CAE software for multi-physics solutions http://recurdyn.infinik.com.

Authors

BoHee Lee received the B.S. degree in Electronics Engineering from Inha University, Incheon, Korea, in 1985, and the M.S. degree and the Ph.D. degree in Electronic Engineering from Inha University, Incheon, Korea, in 1991 and 1996, respectively. From 1984 to 1987, he was a researcher at telecommunication system of Samsung Electronics Co. Ltd. Since 1997, he has been with the Department of Electrical Engineering at Semyung University. His main research interests are in the areas of automation, modular robotics, and embedded system applications.

InHwan Yu received the B.S. degree in Appication Electronics and Technology from Kwangwoon University,Korea, in 1979. The M.S. and the Ph.D.degree in Electrical and Electronics Eng.from Semyung University, Korea, in 2008 and 2011, respectively. He was teacher of Semyung Computer Highschool, 1983~2012. Since Sep. 2012, he is Tech Dir. of KCD and prof. of Doowon Technical University. His main research is modular robotics.

JungShik Kong received the B.S. and the Ph.D. degree in Industrial Automation from Inha University, Incheon, Korea, in 1998 and 2006 respectively. He was full-time lecturer in micro-robot at Daeduk College from 2007 to 2008. Since 2009, he has been with the Department of Mechanical Design at Induk University. His main research is robotics, intelligent and robust control algorithm and control system application.