BASE MOLECULE DESIGN AND SIMULATION OF MODULAR ROBOT ROBMAT

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Abstract: This article presents the design of the base molecule for the RobMAT modular robot and the simulation tool MAVES (Modular Agents Virtual Environment Simulator). The base molecule is formed by 3 link atoms, 2-foot accessories and 2 joint atoms with 3 d.o.f. With the developed simulator, it is possible to analyse the kinematics morphology and dynamics behaviour of different configurations. MAVES tool allows evaluating control algorithms in order to minimize some parameters. Denavit-Hartenberg method is applied to calculate the kinematics of the base molecule and from thereon study the singular configuration of the modular robot.

Keywords: Modular Robots, Robot Kinematics, Simulators, Design Systems.

1. INTRODUCTION

A primary designed objective for a self-reconfiguring modular robot is to allow the robot to assume any geometric shape. The modular self-reconfigurable robot is proposed in order to make a system adaptable to the different given tasks and unknown environment. Modular robots are of interest because they permit the construction of a wide variety specialised robots from the set of standard components. This goal is different from other types of shape-changing robots, which may only take one of a small number of shapes.

There are two basic types of modular robot: heterogeneous and homogeneous. In a heterogeneous system, the modules are different while in a homogeneous system all the modules are identical (Rus and Vona, 2000).

In the RobMAT robot, each module is called atom, while the geometric structure formed by these atoms is called molecule (McGray and Rus, 1998).

Where would the modular reconfigurable robots be used? A modular, self-reconfigurable robot is most useful in an unknown complex environment. For example, a building that has been damaged by an earthquake contains a variety of obstructions and may not be suitable for any particular standard robot. A reconfigurable robot, with the ability to locomote over a variety of terrains, through gaps and over obstacles can perform well in this situation.

With the adaptability of the modular robot, it can pass through narrow passageways (in a snake-like configuration), it could reshape into a legged robot and walk over rubble and it can climb stairs or even onto desks by self-reconfiguration. Another application is space/planetary exploration, where unpredictable terrains on a planet have to be explored by a robot before human beings are sent (Jantapremjit and Austin, 2001).

In the literature, it is possible to find several modular designs (Murata et al, 1998, Kotay et al., 1999, Casal and Yim 1999, Fukuda and Nakagawa 1988, Yim et al., 2000, Castaño and Will, 2000, Pamecha et al., 1996, Fukuda and Kawauchi , 1990, Suh et al., 2002, Tomita et al., 1999, Ünsal and Khosla 2000) where authors developed the hardware and the control software. Development of functional self-reconfigurable robots is a significant challenge. Hardware must be designed and built in a manner that it is capable of self-reconfiguration, do autonomous operation and support algorithm that can confer upon the ability to change shape.

This paper shows the design of the RobMAT base molecule. It consists of two joint atoms, each with 3 d.o.f., and 3 link atoms that contain control boards for motors, wireless communication, sensors for environmental perception and batteries. By connecting link and joint atoms, the molecule adopts to the shape needed for the tasks. Different configurations have been analyzed to optimize manipulating and moving. Accessories have been designed for specific task. The simulation tool (MAVES), is used for evaluating the performance of the RobMAT.

This article has been organized in the following manner: section 2 shows a brief description of the RobMAT project. Section 3 presents MAVES, which is the simulation tool developed for evaluating the performance of the robot. Section 4 describes the main components of the base molecule. Section 5 describes the kinematics equations derived for base molecule. Lastly, conclusions and future line of research are presented.

2. THE ROBMAT PROJECT

RobMAT is a self-configurable modular robot and as mentioned above, it has 2 different types of modules named atoms wherein several tools are possible to be connected. These tools are called accessories. With these modules it is possible to form complex structures to carry out specific tasks. On the other hand, different structures can cooperate among themselves.

Next it is defined the basic structure of the RobMAT robot.

Definition: The combination of atoms to form a structure (molecule) with all minimum characteristics required for an autonomous robot is called base molecule.

The base molecule consists of three link atoms that carry control hardware, communications, sensors and batteries make it up. They are connected by joint atoms, each having 3 d.o.f.

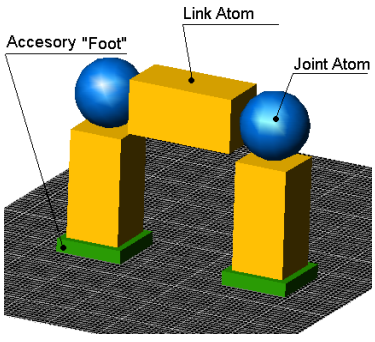

Fig.1 Base Molecule of the RobMAT Self-reconfigurable Modular Robot.

The design of different accessories that can be fitted to the atoms for performing tasks has been taken into account. For example, base molecule has 2 “foot” accessories for displacement. The foot-link joint is rigid. The foot permits adaptable movements necessary to absorb the contact force with the ground. Fig. 1 shows the base molecule.

The foot accessory has an electromagnetic circuit to hold onto the floor. The electromagnetic circuit conditions the terrain where the robot is to move so, in the development phase, the floor is made of metal.

Fig. 2 shows a series of possible postures, which the robot can adopt. It is possible to use a gripper as accessory in order to do some manipulation tasks.

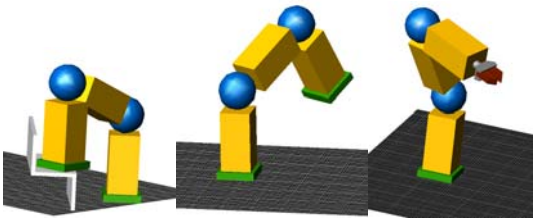

Fig. 2 Possible postures of Base Molecule

Another possibility is the cooperation among molecules and atoms to do more specific tasks as shown in Fig. 3.

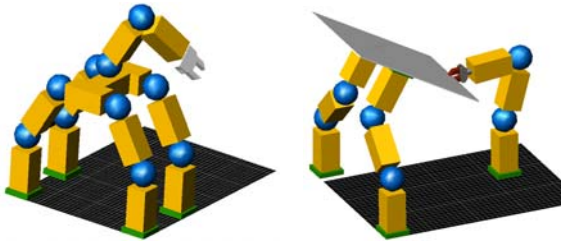

Fig. 3: Cooperation between molecules and atoms

3. SIMULATION PLATFORM: MAVES

Before designing any prototype, it is necessary to perform simulations and calculations thereby requiring a suitable simulation environment.

Since, the RobMAT is a self-reconfigurable modular robot; the simulation tool must support different molecule configuration so as to decide what kind of atoms is to be developed. This virtual environment allows analyzing and solving problems related to multi-agent systems such as: kinematics configurations, cooperation strategies among agents and docking and undocking actions. MAVES (Modular Agents Virtual Environment Simulator) has client-server architecture, it is developed under ANSI C++ and its kernel is based on ODE (Open Dynamic Engine) library that is available in http://ode.org. Such libraries collect functions to do dynamic simulation of rigid body and detect collision. They also show simulation results in 3D using OpenGL. Fig. 4 displays a snapshot of MAVES with two base molecules.

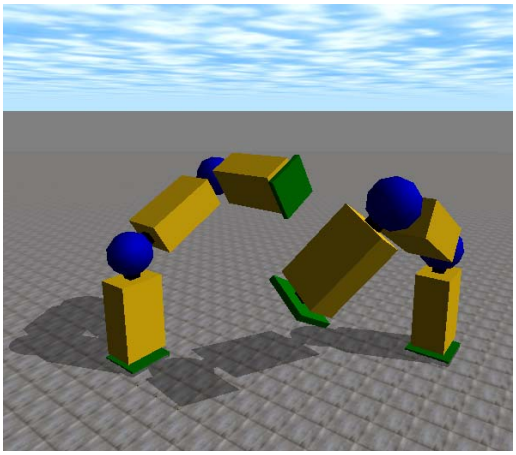

Fig. 4. MAVES 3D

MAVES's server philosophy consists of simulating a physic environment (gravity, inertia, collision) which is transparent to the user. On the other hand, the client (agent) defines a robot that is included in the virtual environment. It is created for the server. The user quickly defines the robot in a text file using developed mark-up pseudo-language. It is then possible to add the mechanical structure (bodies and joints), actuators and sensors as done in a real robot.
The client has to control the robot inside the virtual environment through the data from the sensors. Therefore, once the robot is defined, it is sent to the server that adds it to the environment and begins to send information from the sensors (which have been defined in the robot) to the client.
The algorithms of control are implemented to the client and the result is sent to the server, thereby the loop is closed. The client can be implemented in any programming language since the connection between the client and server is done through TCP. It only requires respecting data structure. In this manner, algorithm of control can be checked faster and more precise. Fig. 5 shows MAVES components.

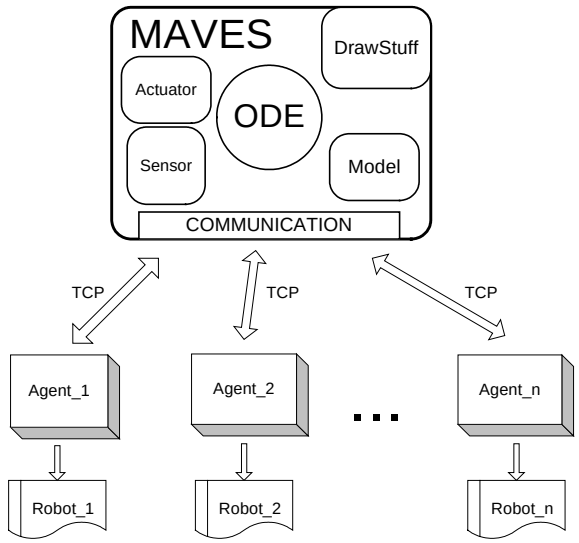

Fig. 5: MAVES Components

Software components of MAVES have been developed. They include sensors such as torque and force. From the data obtained, optimal motors can be selected. Encoders are also implemented to close control loop inside the virtual environment. Actuators have been also programmed besides the ones that carry ODE such as grippers or foot support to hold on the ground. New sensor and actuator could be included easily using C++ inheritance mechanism.
MAVES also incorporates a communication system that lets agents communicate among themselves or with other sources such as control stations. It is also possible to simulate cooperation among different agents. Movement displacement of the base molecule is currently being studied. Strategies for the connection of various molecules are also being looked into. The possibility of including uncertainties in the sensor that defines reading closer to reality will obtain a more advanced control.

4. COMPONENTS DESCRIPTION

In the following, the basic elements of RobMAT's base molecule are described.

4.1 Link Atom

The link atom is a prism of 80x60x60 mm. It is light because of the plastic material *Tecadur*. It is a semi-crystalline engineering thermoplastic with very high strength and good rigidity, excellent machinability and versatility of application. The link atom carries all control boards and batteries.
Some characteristics are detailed next:

- Very strong and rigid
- Tough
- Good sliding properties
- Abrasion resistant
- Resistant to many acids, cleaning agents, numerous solvents.
- Very good electrical insulation
- Easily machined and polished
- Not resistant long term to hot water over 60^{o}C
- Easily bonded
- Easily welded

4.2 Joint Atom

The joint atom has three motors whose axes are orthogonal and intersect in a given point, thereby, giving the joint atom 3 d.of. Fig. 6 shows all parts of the joint atom. It is made of aluminium, stainless steel and plastic. The joint atom is shown in Fig.7.

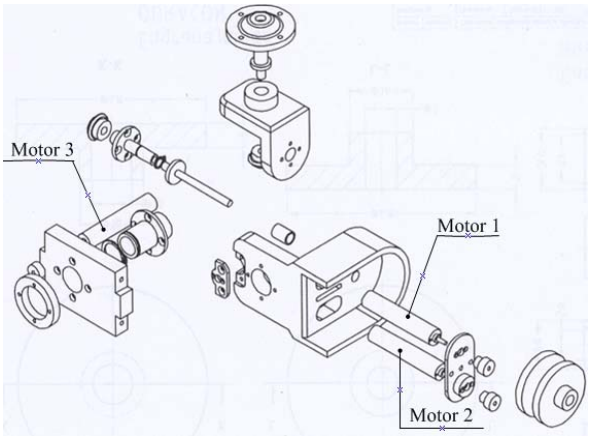

Fig. 6. Exploded view of the joint Atom

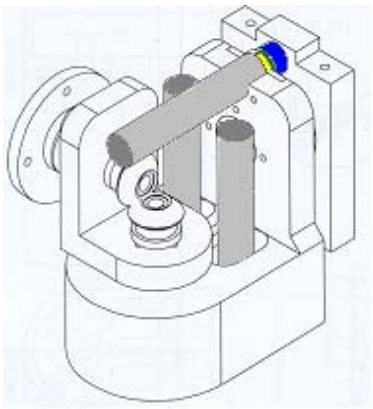
Fig. 7. Assembled view of the Joint Atom with Motors

4.3 Actuators

The DC motors selected are the Maxon Motor® RE 13. One of the motors located in the joint atom is shown in Fig. 8. It is also possible to see the gearbox and the encoder. It is 13 mm in diameter and 3 Watts. The whole length of the set is 72.2 mm taking into account all assembly parts. Some characteristics of the motor are detailed in Table 1 where L is the length of the motor, W is the weight, τ_A is the maximum permanent torque and η is the efficiency.

The gearbox has a reduction ratio of 275:1. The digital encoder has 16 pulses per round and this is enough due to reduction ratio.

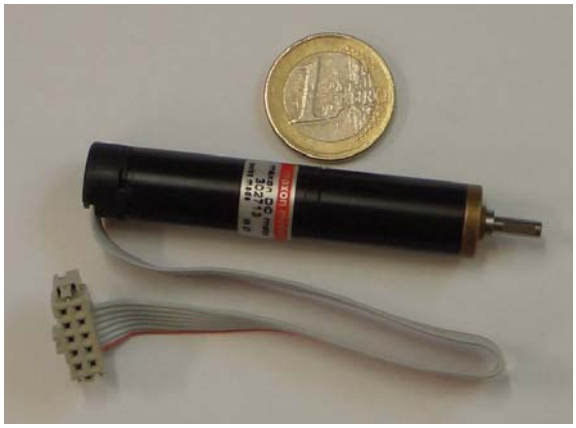
Fig. 8 Motor of joint atoms

Table 1: Characteristcs of the Maxon Motor used

Actuator	L [mm]	W [gr]	τ_a [mNm]	η [%]
118639	36.9	26	3.08	67

4.4 Control Hardware

The control hardware which has been designed for base molecule of the RobMAT requires great quantity of calculations and managing a great number of analogical and digital signals. It also requires reading communications protocol among the atoms of a molecule and among molecules in order to communicate.

Therefore, DSP made by Texas Instrument has been selected as the nucleus of the control hardware. It is characterized by:

- Great calculating capacity (150 MPIS).
- CPV fixed command emulating from floating command.
- External Interface (Xintf), allows access in a determined memory zone and bus data to external device.
- Interruption Management (up to 45 interruptions of peripherals and 3 external).
- Digital-Analogical converter with 16 channels and 12 bits.
- Up to 56 in/out signals.
- Different ports of communication (2 channels, Bus-CAN, SPI).

Fig. 9 shows the electronic board used for module control. It includes all sensors and actuator signals. New functions are being developed to include wireless communication.

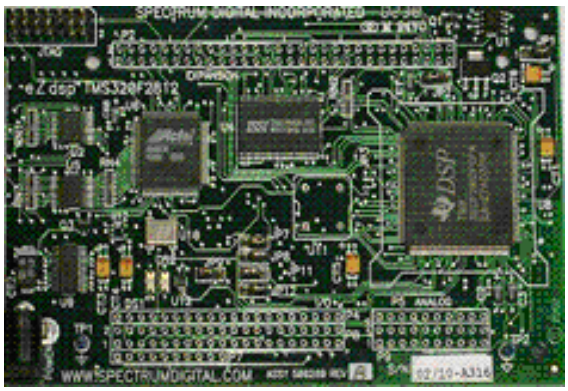

Fig. 9: Electronic board based on a Texas DSP.

5. KINEMATIC MODEL

Kinematic equations of the robot in a single-support are obtained in this section. Single-support means one foot holds onto the ground while the other is free.

The base molecule of the RobMAT is a connection of bodies joined by articulated parts. Articulated parts have 3 d.o.f., however, the joint atoms were presumed to be formed by 3 articulated parts of 1 d.o.f. whose axes have been cut in a point. Considering this

hypothesis, it complies with Denavit-Hartenberg proposal in literature (Craig, 1986).

Therefore, in order to perform a kinematics study, the following have been presumed:

1. Modular robot is symmetric.
2. Accessories are rigid.
3. The foot accessory that acts as the support holds firmly onto the terrain. It cannot slip while on contact with the ground.
4. No equilibrium problem exists on the robot while performing some movements.

5.1 Direct Kinematic

The base molecule of the robot has a 6 d.o.f., two of them upon the same axis, therefore making the robot redundant. Fig. 10 shows the robot with its 6 d.o.f.. It can be observed that axes λ and γ are co-linear.

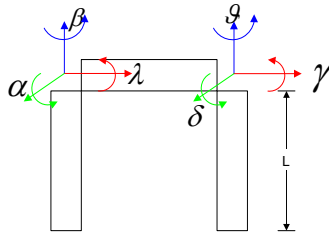

Fig. 10 Joint Axes

Acting upon axes λ and γ, the superior link atom can be oriented with respect to the other link atoms. Acting upon axis γ, the extreme end of the link atom can be oriented and consequently, orient the accessory.

Orienting the superior link atom is of no major relevance as the sensors are to orient it. However, considering workspace for the robot to move or perform its task, this degree of freedom does not contribute any advantage.

Due to prior statements, the relation between joint and Cartesian space is defined through a 5 d.o.f.

In order to obtain the equations that describe the kinematics behaviour of the robot, Denavit-Hartenberg procedure has been used. Through this procedure, the relative orientation and position of 2 consecutive bodies are defined. Fig. 11 shows the reference systems that correspond to every articulation complying with conventional D-H. The parameters are shown in Table 2.

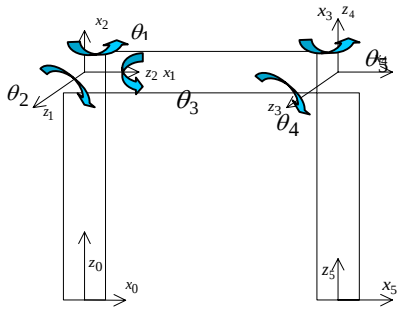

Fig. 11 D-H Convention

Table 2 D-H Parameters of the Base Molecule

i	a_i	α_i	θ_i	d_i
1	0	$\pi/2$	θ_1	L
2	0	$-\pi/2$	$\theta_2 - \pi/2$	0
3	0	$\pi/2$	θ_3	L
4	0	$-\pi/2$	$\theta_4 + \pi/2$	0
5	0	0	θ_5	$-L$

The matrix of transformation which relates joint space to Cartesian space is $\mathbf{T}_5^0 = \mathbf{A}_1^0\mathbf{A}_2^1\mathbf{A}_3^2\mathbf{A}_4^3\mathbf{A}_5^4$. Where $\mathbf{A}_j^i$ represents the matrix of homogeneous transformation of the system j with respect to system i.

5.2 Singularities

The Jacobean matrix $\mathbf{J}$ counts on more columns than rows, which makes the robot redundant. Fig. 11 shows axes θ_5 are only applied in case the foot that supports onto the given terrain is to be turned and does not affect the final position of the end effector. Therefore, $\theta_5 = 0^o$ which makes $\mathbf{J} \in \Re^{3\times4}$ having a redundancy of one degree. Evaluating manipulability over the robot in (1) (Sciavico and Siciliano 2001), singularities of the robot can be obtained.

$$m = \sqrt{\det\left(\mathbf{J}^T\mathbf{J}\right)} \qquad (1)$$

It is evident that the points of singularities of the robot are in the points where the links stay aligned. This corresponds to $\theta_2 = 0$ and $\theta_4 = \pi/2$ or $\theta_4 = 0$ so as with $\theta_2 = \pi/2$ and $\theta_4 = \pi/2$. Fig 12 shows all these points. Fig. 13 shows the manipulability results in each singularity position.

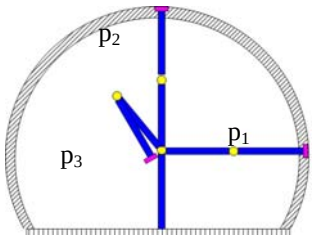

Fig. 12 Singular Positions

Poses that correspond to remaining axes do not produce singularities because they make a change of plan in the movement of the robot.

In spite of poses p_1 and p_2 are singular, the robot can reach these points because velocity in the operating extreme is within the permissible values, which is $\nu \in \Re(\mathbf{J})$.

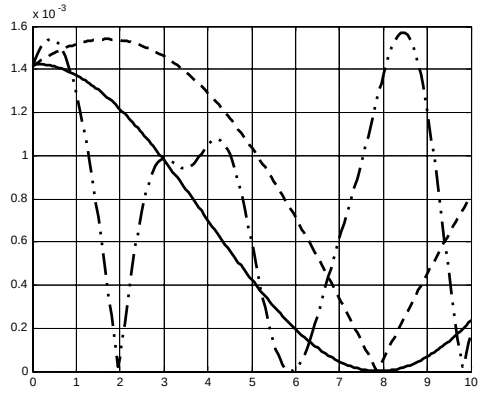

Fig. 13 Manipulability Results

CONCLUSIONS

In this paper, the ROBMAT´s base molecule is presented. It consists of 2 joint atoms, 3 link atoms and 2 foot accessories. The joint atoms have 3 d.o.f. and the link atom has a prism shape of 80x60x60 mm. On the other hand, the simulation tool MAVES is also presented. MAVES allows to analyze and to evaluate the robot performance (different configuration, docking/undocking action, cooperation strategies) and to display 3D scenes of the agents in a virtual environment.

The kinematics model has been derived from Denavit-Hartenberg method. With the theoretical model and the simulation tool, it has been possible to determine singular configurations of the base molecule.

The assembly of the robot is currently being done and soon to validate the kinematics and dynamics model calculated and the movement strategies.

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