IMMUNOLOGY-BASED MOTION CONTROL FOR MODULAR HYPER-REDUNDANT MANIPULATORS

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Abstract: Artificial Immune System (AIS) has recently been actively researched with a number of emerging engineering applications that has capitalized from its characteristics including self-organization, distributive control, knowledge mapping and fault tolerance. This paper reports the application of the existing AIS paradigm for the distributive control of a modular multi-jointed, hyper-redundant manipulator. Modular robot usually implemented with simplified mathematical model to cope with the scenario of limited computation power and memory. In this paper, we investigate the viability of a multiagent immunology–based motion control for the trajectory control of modular hyper-redundant manipulators. *Copyright©2005 IFAC*

Keywords: Artificial Immune System, Distributed Control, Hyer-redundant Robot, Robot Control, Robotics, Modular Robot, Biological-inspired Robot

1. INTRODUCTION

Artificial Immune System (AIS) has recently been actively researched with a number of emerging engineering applications that has capitalized from its characteristics including self-organization, distributive control, knowledge mapping and fault tolerance. This paper reports the application of the existing AIS paradigm for the distributive control of a modular multi-jointed, hyper-redundant manipulator. Traditionally, manipulator control is achieved by analytical solutions. Modular robot usually implemented with simplified kinematics model to cope with the scenario of limited computation power and memory. By adopting a multiagent-based control paradigm, a multi-jointed hyper-redundant manipulator can be thought of as a group of separately controlled agents in which the exact mathematical model can be replaced by simplified heuristic rules. In this paper, we investigate the viability of a multiagent immunology–based control framework for the motion control applying to a modular hyper-redundant manipulator.

Artificial Immune System (AIS) has recently been actively researched with a number of emerging engineering applications including the control of mechantronics systems, in particular, robots, which has capitalized from the special characteristics of the immune system including self-organization, distributive control, knowledge mapping and fault tolerance. Some examples of applying AIS in robotics include: Michelan and Von Zuben (2002) investigated an autonomous control system of a mobile robot based on the immune network theory; Lau and Wong (2003) developed a control framework to improve efficiency and robustness of a distributed material handling system; Lau and Ng (2004a) proposed an immunology-based control framework for multi-jointed redundant manipulator.

This paper introduces an AIS-based, multiagent, distributive robot control paradigm for the real-time control of redundant manipulators. In this paper, Section 2 reviews the development of modular robot and Section 3 describes the multiagent-based paradigm. An immunology-based control framework is presented in Section 4 and Section 5 that describe the configurations of the modular hyper-redundant manipulator for the performance of experimental studies. Section 6 presents the experimental results and Section 7 concludes and discusses our findings.

2. MODULAR ROBOT

Modular robots (Bojinov *et. al*, 2000; Castano and Will, 2000; Ko *et. al*, 2004; Rus *et. al*, 2002) are robots made up of many identical but independent mechatronics modules that can autonomously control its joint angle to achieve the tasks and reach a specific goal. Each individual module is a self-contained identical unit which is controlled by its predefined behaviors. Yim *et. al* (2002) suggested there are three promises on modular robots which are versatility, robustness and low cost. Versatility refers to the possible reconfiguration of modular robots which could be catered for different application requirements. Robustness refers to the redundancy and the use of identical modules which could be compensated, replaced and reconfigured easily for every situation. Low cost refers to the relatively cheaper cost for each module even if large amount of identical modules used for particular application. Besides, there are two more advantages worthwhile to mention, redundancy and fault tolerance. Redundancy refers to the existence possible redundant degrees-of-freedom for better manipulation of complete tasks in a more effective and efficient manner, while the better use of redundancy relies on the computation power, neatness and complexity of the control model and possible extension of redundancy. Fault tolerance is another key advantage of modular robots. Modular robots make use of identical module for manipulation, which are usually controlled with a distributed and decentralized control paradigm. It is envisaged that such control framework will compensate faulty module without deteriorating the overall performance severely. Snake configuration is often one of the commonly use configuration for locomotion and reach some particular target point. Snake robot is an active research topic in the last decades while there are many different control methods proposed in the field. Due to the hardware design and the nature of modular robots, using a centralized control requires an accurate kinematics model for the control of the hyper-redundant manipulator which often limits its possible extension and imposes difficulties in model establishment. Some researchers proposed different control frameworks for modular hyper-redundant manipulator. Burdick *et. al* (1993) introduced a means of locomotion for hyper-redundant robots where the robot kinematics model a simplified backbone. Henning *et. al* (1998) used Generalized Voronoi graph for motion planning. Hirose (1993) proposed serpentine motion control which is characterized by every single part of the snake's body that moves on the same trajectory. The snake's head defines the motion movement and the body follows the defined trace.

3. A MULTIAGENT-BASED CONTROL PARADIGM

Individual robot joints can be thought as spatially distributed agents that are controlled independently and concurrently. This suggests a totally distributed agent control paradigm for manipulator control. An agent (Dastani *et. al*, 2002; d'Inverno *et. al*, 1998; Jennings and Wittig, 1992) can be considered as a logical and autonomous entity that aims to contribute to the overall task achievement based on its own strategy. The agent is assumed to be able to recognize the conditions of the progressing task. Each agent tries to drive the assigned actuators with its own strategy by which it can improve the degree of task achievement. The overall system can be deemed as a set of distributed control variables which are directly or indirectly managed by these agents. Each joint controlling agent decides and carries out their own behaviors in response to external sensory signals. In this context, Lau and Ng (2004b) proposed a multiagent-based control paradigm for the slave arm control in a teleoperator system. Lau and Ng (2004a) also proposed an immunology-based framework for multi-jointed robot arm. This paper is an extension of the control framework to the similar application on a hyper-redundant robot that establishes the generality of the model to the control of different robot applications.

The proposed multiagent-based control paradigm, as shown in Figure 1, is a logically distributed system for manipulator control. Under this control approach, the execution of a trajectory involves the interaction between agents; and a conventional manipulator can therefore be thought of as a system composed of a group of agents, each of which is independently controllable. Conventional methods for hyper-redundant robot control have largely been dependent on a simplified curve model for centralized control which hinders its extension and flexibility. In contrast, a multiagent based paradigm has multiple agents and each agent may have individual goal(s). All cooperating agents may contribute to achieve a particular goal such as to move the end point of a multi-jointed hyper-redundant robot along a particular trajectory. In the proposed control paradigm, cooperative strategies are adopted from the artificial immune system that each joint agent's behavior is suppressed or stimulated by the neighboring agents in order to achieve optimal control.

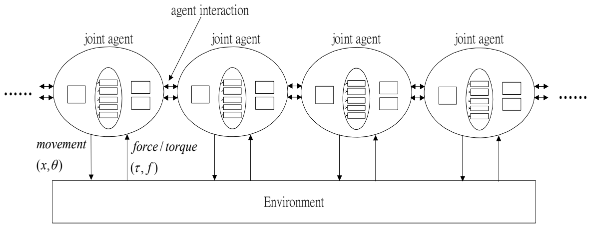
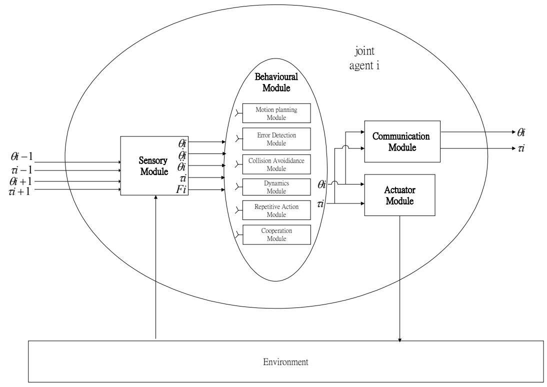


Fig. 1. A multiagent-based control paradigm for the modeling and control of a multi-jointed manipulator

4. AN IMMUNOLOG-BASED CONTROL FRAMEWORK

The biological immune system consists of the tissues, cells and molecules that involve in adaptive immunity and totality of host defense mechanisms. The immune system is a natural, rapid and effective defense mechanism for a given host against various infections. An Immune action can often been classified into innate and adaptive immunity (Janeway *et. al*, 2001; de Castro and Timmis, 2002).

Innate immunity refers to the abilities to recognize all pathogens specifically, where as the enhanced protection against re-infection are the unique features of adaptive immunity that is based on the clonal selection of lymphocytes bearing, antigen-specific receptors. Each lymphocyte carries cell-surface receptors of a single specificity each bearing a distinct receptor so that the total repertoire of receptors can recognize virtually any antigen. Adaptive immunity is initiated when an innate immune response fails to eliminate a new infection and antigens and activated antigen-presenting cells are delivered to the draining lymphoid tissues. Each lymphocyte bears a single type of receptor with a unique specificity. Interaction between a foreign molecules and a lymphocyte receptor capable of bringing that a molecule with high affinity leads to lymphocyte activation. The differentiated effector cells derived from an activated lymphocyte will bear receptors of identical specificity to those of the parental cell from which that lymphocyte was derived. The characteristics of distributed control, distributed memory, specificity, stimulation and suppression of human immune system inspired mathematical analogies for solving engineering problems, in particular, robot control problems described in this paper.



θ	Joint angle
$\theta^{\cdot}$	Joint velocity
$\theta^{\cdot\ \cdot}$	Joint acceleration
τ	Joint torque
F	Force

Fig. 2. Principal components of a joint agent in the immunology-based control framework

An intelligent joint agent in the proposed immunology-based control framework for multi-jointed manipulator control, as shown in Figure 2, is a distributed control, distributed memory and specific behavioral control agent for each joint of a robot. Each joint agent models a self-contained entity requiring minimal information from others. The framework consists of a number of basic modules including sensory module, behavioral module, communication module and an actuator. The sensory module and the actuator interact with the environment. The sensory module can be considered as a group of sensors such as encoders which are used to obtain the joint position or the joint torque sensor for deriving the joint torque via the motor current. The sensory module includes filters for filtering the noises and also includes the abstraction model for abstracting the actual sensed data to some sensory states. The actuator is used to output commands to the joint motor. The communication module is used for the communication between neighboring agents.

In this control framework, communication between neighboring joint agents are considered, where information are not gained or communicated beyond its two nearest neighbors. The behavioral module obtains sensory information from the sensory module and output to the communication module for stimulation and suppression of its neighboring agents for the actuation of the individual robot joint. The behavioral module is derived according to the artificial immune system. Each generic behavior is specialized for different categories of tasks where the interaction between the behavior and the relevant sensory state that initiate such behaviors imitate the mechanism of clonal selection. The behavior set refers to the capabilities of joint agent in association with robot manipulation tasks that imitate the antigen receptor repertoire storing the pattern for recognized antigens. Repetitive actions are learnt and stored in the behavior module which can be retrieved for tackling similar tasks that may come up subsequently. The mapping between the immune system and the AIS-based multi-jointed robot control framework is given in Table 3.

Table 3 Mappings between the biological immune system and the AIS-based multi-jointed robot control framework

Immune System	Artificial Immune System
Antigen	Sensory states
Antigen recognition	Behavior initiate condition
Behavior set	Antigen receptor repertoire
Behavior	Antibody
Repetitive actions	Immuno-memory

In the proposed intelligent joint agent, four modules are defined for the behavioral module, namely, the Motion Planning Module, Error Detection Module, Obstacle Avoidance Module and Cooperation Module.

The Motion Planning Module is designed for the trajectory generation for each joint agent. The trajectory generator adopted by the control framework, namely, is straight-line interpolation. The inputs to the module are the current locations of the end-effector, $\vec{x}$, the target location, $\vec{s}$ and the distance $|\vec{s}\text{-}\bar{\mathrm{x}}|$, the module then computes the trajectory in Cartesian coordinate using Cartesian trajectory interpolation. The Motion Planning Module produces output for the Error Detection Module.

Given a target S_i:

$$\mathrm{S_i} = [\mathrm{x} \quad \mathrm{y} \quad \mathrm{z}]^{\mathrm{T}} \tag{1}$$

with reference to local frame $\{\mathrm{i}\}$ $s.t.\ \mathrm{S_i} = \mathrm{S_w} T_1^0 \ldots\ldots T_i^{i-1}$

where

$\vec{\mathrm{S}}_{\mathrm{w}}$	The set point in the world frame
T_i^{i-1}	The i^th^ Denavit-Hartenberg transformation matrix

Straight Line Interpolation:

$$\vec{y} = nk(\vec{s} - \vec{x}) + \vec{x} \tag{2}$$

Where

n	represents the coefficient
k	represents the cycle
$\vec{s}$	represents the set point
$\vec{x}$	represents the current position

The Error Detection Module is designed to derive the joint output for each joint agent with a view to minimize the error between the set point and the current position. The module controls the movement of the single joint variable (θ_i) that moves within the joint limit (θ_{si}).

The module has knowledge about the link dimension of the joint and the corresponding joint range. It can be informed of the locations of the end-effector ($\vec{x}_i$) and target ($\vec{\mathrm{S}}_{\mathrm{i}}$) and the distance $|\vec{S}_{\mathrm{i}}\text{-}\vec{\mathrm{x}}_{\mathrm{i}}|$. It also controls the joint angle according to its objective function and it stimulates the activities of the Motion Planning Module such that the Motion Planning Module then generates the next control set point to achieve the desired movement.

$$\theta_i(\mathrm{t}) = \vec{\mathrm{k}}_{\mathrm{i}} \left[\vec{S}_{\mathrm{i}}(\mathrm{t}) - \vec{\mathrm{x}}_{\mathrm{i}}(\mathrm{t}-1) \right] \tag{3}$$

where

$\vec{\mathrm{x}}_{\mathrm{i}}(\mathrm{t}) = \mathrm{fwdkinematics}(\theta_1, \theta_2, \theta_3, \theta_4)$

$\vec{\mathrm{k}}_{\mathrm{i}} = [\mathrm{k_{ix}} \quad \mathrm{k_{iy}} \quad \mathrm{k_{iz}}]$

s.t. $\vec{\mathrm{k}}_{\mathrm{i}}$ is the row vector and is a constant for $\mathrm{agent_i}$

Obstacle Avoidance Module provides the capability to maintain a safety distance from an obstacle in order to prevent collision. This module provides the capability to maintain a safety distance, D_s, from an obstacle, $\vec{\mathrm{o}}$, in order to prevent collision. This module has the capacity to suppress other behaviors when it is initiated.

$$|\vec{\mathrm{x}} - \vec{\mathrm{o}}| < D_s \tag{4}$$

$$\theta_i = k_o(\vec{\mathrm{x}} - \vec{\mathrm{o}}) \tag{5}$$

where

$\mathrm{k_o}$	is the obstacle avoidance coefficient
$\vec{\mathrm{o}}$	is the obstacle position

Cooperation Module is activated when the head is close to the target such that the distance between the target and the current position is smaller than a predefined distance. The module generates suppression signal to deactivate the activities of its neighboring agents. If the head is far away from the target such that the distance between the target and the current position exceeds a predefined distance, the cooperation module then stimulates the activities of neighboring agents to achieve optimal control. The detail model description has been presented in Lau and Ng (2004a).

5. SYSTEM CONFIGURATION

A six-module MSR hyper-redundant robot arm is constructed to verify the generality of the immunology-based control framework and to evaluate the practicability of the proposed control framework. The snake robot consists of six modules as shown in Figures 4 and 5, each has one degree-of-freedom actuated by a standard servomotor with built in potentiometer for position feedback. The control of each module is a BasicATOM Pro 24-M microcontroller as shown in Figure 6, which supports 8 analogue-to-digital pins and 24 high-resolution servo outputs that can also be used as input for position feedback. The microcontroller can has 32K of flash memory that can cater for 2k bytes of user RAM execute 100,000 instructions/second, and can be programmed using basic, C, C++, or Java through the RS-232 serial port. The BasicATOM Pro runs on 9V DC. Access to the microcontroller is through the console application which has an integrated compiler and a function library. The console application can be run on different platforms, including Windows, MacOS X, Palm OS, WinCE, and Linux. The BasicATOM Pro has an internal clock and the motion regeneration program is written to instruct the servomotor to adjust its position every second according to the preloaded data in the RAM. The whole snake will therefore generate synchronized motion at 500Hz.

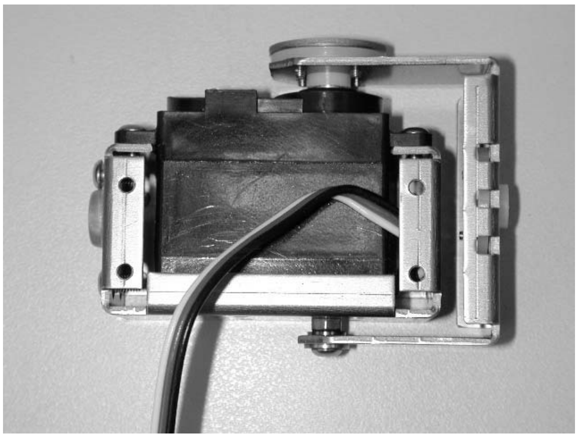


Figure 4 A single module of the modular robot

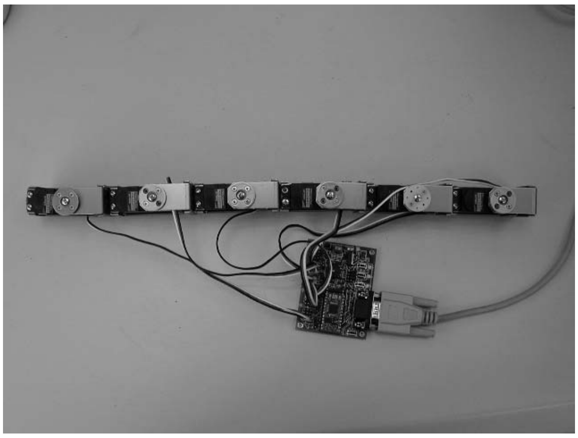


Figure 5 A Multi-jointed hyper-redundant modular robot used in the experiment

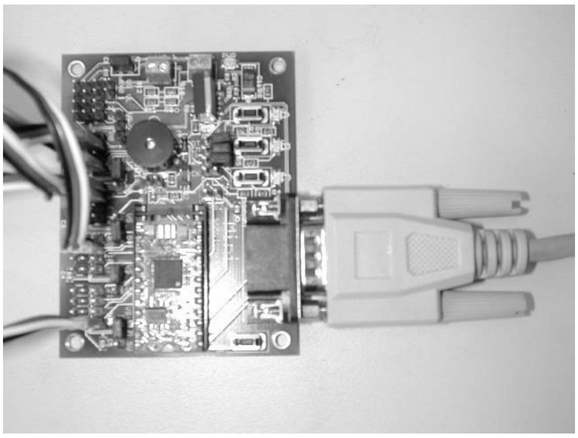


Figure 6 BasicATOM Pro Micro-controller

6. RESULTS

Figure 7 shows the pseudo-code for the implementation of the joint agent. It can show that the control algorithm is relatively simple which it could suit the restriction of micro-controller. There are 100 lines of code for the implementation and 134 bytes used for the maximum of 2 Kbytes. It shows that it is computational plausible for the control framework applying on microcontroller. It is also show that the control framework could apply to both complicated multi-jointed redundant robot and also simpler planar hyper-redundant robot.

```
Main
   count var interger
   joint var float
   currentposition=f(joint)
   error=f(desireposition,
              currentposition)
   deltamove = gain * error
goto main
```

Figure 7 Pseudo-code for implementation of BasicAtom Pro

Figure 8 shows the trajectory plot of the end point of hyper-redundant robot. It shows that the control framework produces steady and smooth trajectory. The control framework produces efficient trajectory to the target point with only 7 cycles. With the restriction of the microcontroller, each output is similar interval that the velocity is constant in this experiment. Figure 9 shows the final configuration for the experiment. It shows that each joint share some efforts to contribute to the goal attainment. It shows that each joint agent configure themselves with its own behavior to control the end point to the target that realized the truly distributed control under the multiagent paradigm.

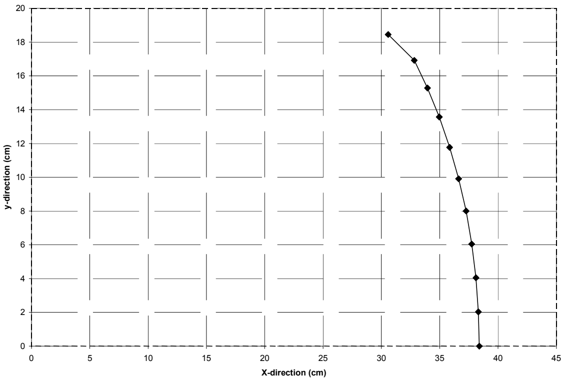


Figure 8 The trajectory described by the end point of the hyper-redundant manipulator

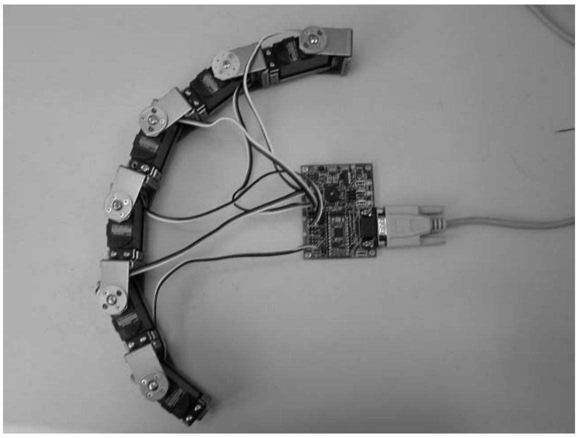


Figure 9 Final configuration of the hyper-redundant robot for the experiment

7. CONCLUSION

This paper presents an AIS-based control paradigm. The immunology-based motion control is described with the essential algorithms deployed outlined in the paper. Experimental studies were carried out to establish the practicability of the multiagent immunology-based motion control and it is shown that this approach required less computational effort that conforms to the requirement of microcontroller. The experimental study shows that desirable joint trajectories were produced to control the modular hyper-redundant manipulator. These findings indicate that the proposed multiagent immunology-based control provides a promising approach to the control of redundancy. The behavior for reconfiguration and docking mechanism is currently been investigated to complete the control model for such modular robots for future implementations. Further studies to investigate the coordination and cooperation between the joint agents under the full AIS framework are also being undertaken.

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