Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Coordination of Cooperative Search and Rescue Robots for Disaster Relief

Henry Y. K. Lau* and Albert W. Y. Ko**

**Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Hong Kong, PRC*
(Tel: +852-28578255; e-mail: hyklau@ hku.hk).
***Medecins Sans Frontieres, Hong Kong (e-mail:aux1496@gmail.com)*

Abstract: This paper describes the use of modular robots as the next generation search and rescue robots for humanitarian logistics and developed an immunity-based control framework called General Suppression Control Framework (GSCF) for controlling these robots. The application of GSCF on heterogeneous-distributed robotics systems is studied where the behaviors of the search and rescue agents are mirror images of the immunological cell behaviors when the immune system is under attack. While the goal of these agents are to perform rescue tasks, the motivation behind the study was to show GSCF can work equally well on heterogeneous-distributed systems.

1. INTRODUCTION

The increasing number of armed conflicts and unprecedented scales of natural disasters striking around the world in recent years have challenged the competency of traditional logistics systems in emergency relief operations. Humanitarian Logistics for disaster relief encompass traditional logistics functions such as the procurement, storage, and delivery of relief supplies, as well as humanitarian logistics functions that aim to alleviate the suffering of victims during and after an emergency (Beamon, 2004). The unique characteristics of humanitarian logistics systems require effective search and rescue systems to provide timely, professional, coordinated and technically sound international assistance in demanding situations (UN Joint Logistics Center, 2006). Humanitarian search and rescue systems as an integral part of most large-scale emergency responses are carrying an increasingly heavier role in disaster relief missions. Tele-operated search and rescue robots equipped with miniature sensors and powerful microcontrollers are good alternatives to deploy into dangerous environment instead of human. These search and rescue robots can become more effective if they can navigate autonomously to search for human victims and landmines.

Humanitarian search and rescue robots require robust and adaptive fail-soft systems to achieve calculable reliability desired for operations under unstructured environment. Emergency robot systems for such purpose require robustness and flexibility in the physical design of the robot as well as the control algorithms of the system. Human immune system is useful for this purpose as it is a robust and adaptive decentralized system (Sompayrac, 1999); the function of its components and their interactions offer inspiring analogies for solving problems in different disciplines. The suppression mechanism between immune cells, for example, demonstrates the possibility of using simple local signals to generate useful global behaviors in a dynamically changing environment. This research exploits the mechanisms that give our immune system robustness and adaptabilities to develop a decentralized framework for controlling modular robots.

This research proposed the use of modular robots as the next generation search and rescue robots and developed an immunity-based framework for controlling modular search and rescue robots. Modular robots are module-based systems that can be configured to accommodate different operation requirements (Marbach & Ijspeert, 2005; Groß et al, 2006)). The ability to change shape dynamically during operation enables modular robots to navigate across larger gaps, creep through smaller voids and to climb over higher obstacles more effectively than conventional robots. The inherited decentralized nature of modular robots require flexible decentralized control system that can adapt to its topological changes to take full advantages of modular robots' versatility. Immunity-based control systems inspired by the biological immune system exhibits essential characteristics for controlling modular robots. The decentralized nature plus the robustness and adaptability of immunity-based control system enable modular robots to operate effectively under different operation modes.

The operation modes of modular robots are defined into four different classes. They are Homogeneous-connected, Homogeneous-distributed, Heterogeneous-connected, and Heterogeneous-distributed. Homogeneous modular systems contain only one type of modules, whereas heterogeneous modular systems contain two or more types of modules. Connected modular systems are multiple modules operate together as a single robot. Distributed modular systems are collections of disconnected modules navigating on their own in the same mission. A modular robot can change between the four operation modes under specific conditions.

In this paper an immune-inspired distributed control approach based on the General Suppression Control Framework (GSCF) (Ko et al., 2005) that adopts the suppression hypothesis in discrimination theory is presented. The core of GSCF is the Suppression Modulator that contains suppressor cells with different functions. Simulation study is presented to demonstrate the ability of GSCF in controlling heterogeneous-distributed systems. The experiment uses GSCF to determine the basic operations of the immune system to control a distributed group search and rescue robots

978-1-1234-7890-2/08/$20.00 © 2008 IFAC **10.3182/20080706-5-KR-1001.0733**

under a simulated environment. Five classes of AIS agents are introduced representing the robots and the tasks. Apart from demonstrating GSCF's ability to control heterogeneous-distributed systems, the simulation is also used to evaluate the effect of cell diversity on system performance. Experiment setup and results are presented in detail.

2. HUMAN AND ARTIFICIAL IMMUNE SYSTEMS

2.1 Human Immune System

Human immune system (Sharon, 1998) is a robust, efficient, and adaptive system that continuously acquires new knowledge of non-self cells, adjusts its responses against foreign antigens, scales up defense mechanism to foil foreign attacks, suppresses destructive actions against self cells, converts emergent behaviors into organized memories, and stores distributed memories for global access (Elgert, 1996). There are four main functions listed below that contribute to the operation of the entire system these functions form the basis of immune systems and their underlying architectures offer inspiring analogies in many aspects for developing reliable decentralized systems.

Clonal Selection - Specific cells in the immune system produce antibodies that fit only one specific type of antigen. When these specific cells spotted the existence of a recognizable antigen, they proliferate to clone copies of themselves with identical characteristics.

Immunological Memory - Unique antibodies that successfully destroyed foreign invaders are maintained within the system to become part of the distributed immunological memory of the system. These antibodies are activated quickly to protect the body when the same antigen is revisited.

Antibody Diversity - Unique antibodies for specific antigens are produced by a modular design process which mixes and matches segments of cell genes. The result of this mix and match strategy is a small number of gene segments that can create incredible antibody diversity.

Cell Discrimination - This function discriminates non-self cells from self cells. Self cells are the good cells that exist inside our body. Non-self cells are external elements that does harm to the body. The distinction and the recognition of foreign antigens are done by B-Cells and T-Cells. B-cells are lymphocytes that mature in the bone marrow, and T-cells are white blood cells that mature in the thymus. These two kinds of cells allow the system to identify harmful molecules to kill and to leave the good molecules (self-cells) untouched.

2.2 Artificial Immune System

Artificial Immune Systems (AIS) (de Castro & Timmis, 2003) is a computational intelligence paradigm built around inspirations from its biological counterpart. Though the field of AIS is relatively new when comparing to other established systems such as artificial neural networks (Hassoun, 1995), evolutionary algorithms (Bently, 1999), and fuzzy logic systems; its promising underlying biological principles has attracted many researchers from different field. Scientists and engineers have applied AIS to solve a wide variety of problem. Lau & Wong (2006) developed a control framework to improve the efficiency of a distributed material handling system. Wilson et al. [16] presented an immune inspired algorithm that is successful in identifying trends in price time series data. Sahan et al. (2005) applied attribute weighted AIS to diagnosis heart and diabetes diseases. Neal et al. (2006) developed a model for integration of low-level responses to damage and component failure in robots, based on the notion of artificial inflammation and an extensible, sub-symbolic mechanism for modulating high-level behaviour. Dasgupta et al. (2004) exploited negative selection algorithm to detect abnormalities in aircrafts. Cserey et al. (2004) developed an AIS real-time visual analysis system for surveillance based on the behavior of T-cells. Oda & White (2005) developed AIS for detecting junk e-mail and achieved accuracy close to and even exceeded commercial products in certain aspects

AIS exploits and mimics these four main functions in the biological immune system by embedding various computational techniques and algorithms (Sipper, 2002). These functions are further integrated to form decentralized systems with specific advantages to meet application needs. Many of these systems have successfully been implemented as decentralized systems to perform learning, data manipulation, abnormality detection, object classification and pattern matching. Despite the many successful implementations of AIS in various areas, few have attempted to apply AIS to control modular robots. The decentralized nature of AIS and its robustness and adaptability mirror the exact needs for the control systems of modular robots. Though the theme of this research focuses in search and rescue operations, the objective is to develop a generally decentralized control framework for modular robots base on the intuitive analogies that AIS offers.

3. GENERAL SUPPRESSION CONTROL FRAMEWORK

The General Suppression Control Framework (GSCF) (Ko et al., 2005) is based on the analogy of the immunological suppression hypothesis in the discrimination theory (Aickelin et al., 2003). The major recognition and reaction functions of the acquired immunological response are performed by T-lymphocytes (T-cells) and B-lymphocytes (B-cells) which exhibit specificity towards antigen. B-cells synthesize and secrete into the bloodstream antibodies with specificity against the antigen, the process is termed *Humoral Immunity*. The T-cells do not make antibodies but seek out the invader to kill; they also help B-cells to make antibodies and activate macrophages to consume foreign matters. Acquired immunity facilitated by T-cells is called *Cellular Immunity*

When a T-cell receptor binds to a peptide with high affinity presented by an APC (Antigen Presenting Cells), such as macrophages, the T-cell recognized the antigen become mature and it has to decide whether to attack the antigen aggressively or to tolerate it in peace. An important decision factor is the local environment within which the T-cell resides. The present of inflammatory cytokine molecules such as interferon-gamma (INF-γ) (Sharon, 1998) in the environment tend to elicit aggressive behaviors of T-cells, whereas the anti-inflammatory cytokines like IL-4 and IL-10 tend to suppress such behavior by blocking the signaling of aggression. In brief, a T-cell matured after recognizing an antigen does not start killing unless the environment also contains encouraging factors for doing so. In addition, after a mature T-cell developed the behavior, it will emit humoral signals that have slower transmission speed but longer lasting effect than cellular signals to convert others to join. The mechanism is illustrated in Fig. 1.

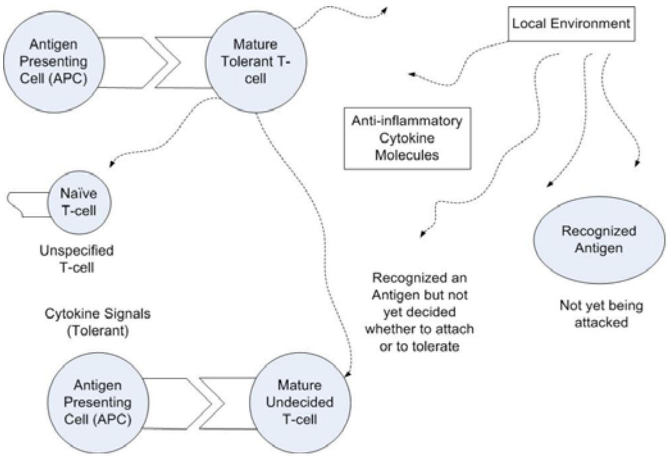

Fig. 1. Cell suppression mechanism of the immune system

Our analogy infers each module of the modular robot is an autonomous T-cell that continuously reacts to the changing environment and affects the functioning of other cells through the environment. The framework consists of five major components. The most notable difference between the natural mechanism shown in Fig. 1 and the proposed framework shown in Fig. 2 is that the T-cell's functions are divided into three separate components, the *Affinity Evaluator*, *Cell Differentiator* and the *Cell Reactor*. Delegating the three unique functions into separate components enables the system to be organized in a modular manner and that when programming for an application, the result and effect of each component can be observed easier. There are five main components in GSCF; they are Affinity Evaluator, Cell Differentiator, Cell Reactor, Suppression Modulator, and the Local Environment. Their functions are explained below.

(1) Affinity Evaluator – evaluates information in the Local Environment against the objective and output an affinity index. The function of this component is similar to the immune discrimination function of biological immune systems, which helps to differentiate between self and non-self cells. Affinity Evaluator can affect the Cell Differentiator in two ways, the first is to directly send a cellular signal that indicates the affinity level, and the second is to send humoral signals to Suppressor Cells (SC) in the Suppression Modulator. The cellular signals give a spontaneous effect that last only one cycle, whereas humoral signals can remain effective until another humoral signal is released to reverse or to neutralize the effect.

(2) Cell Differentiator – evaluates inputs from the Affinity Evaluator and Suppression Modulator to decide the type of behavior to react. Such behavior is sent to Cell Reactor using cellular signaling. The Cell Differentiator can also send humoral signals directly to influence the Local Environment with its functioning similar to the cell differentiation mechanism, in which cells develop aggressive or tolerant behavior in response to the type of cytokines present in the environment. When being activated, these cells release humoral signals to convert nearby cells to duplicate their behavior. Humoral signals travel slower than cellular signals but their effect last longer than cellular signals. Humoral signals are typically used to broadcast signals to cells distributed in a large area and expect to influence their behavior for an extended period of time.

(3) Cell Reactor – reacts to the cellular signal from the Cell Differentiator and execute the corresponding behaviors which take effect in the Local Environment. It is the part that actually does the killing like activated aggressive T-cells.

(4) Suppression Modulator – consists of Suppressor Cells. The function specific Suppressor Cells continuously react to external stimulants to adjust their specific function, perform proliferation, bond and recombine with other Suppressor Cells to develop new specific functions. The overall function of Suppression Modulator is comparable to the cytokine signaling mechanism that uses INF-γ, IL-4, IL-10, etc. to perform intercellular communication and to cause the environment to inflame, so as to elicit or suppress aggressive behaviors in the T-cells. In this framework, the Suppression Modulator acquires information from the Local Environment and the Affinity Evaluator. This information is available to all Suppressor Cells within the modulator.

(5) Local Environment – is where interactions between different components take place. The importance of this component within the framework is to act as an interface that links to the Global Environment which contains other Local Environments with different sets of Suppression Modulators. In addition, it provides a theoretical space to integrate the physical objects and the abstract system.

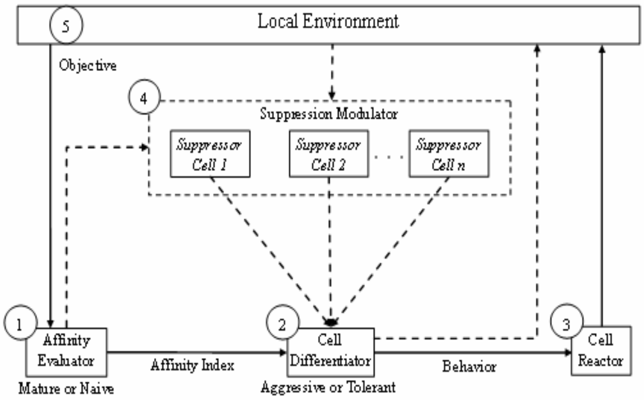

Fig. 2. The General Suppression Control Framework, dashed lines represent humoral signals and solid lines represent cellular signals.

GSCF has been implemented to the four different classes of modular robots. However, this paper will focus on the control of heterogeneous-distributed robots.

4. SIMULATION STUDY

4.1 Heterogeneous Distributed Systems

The overall behavior of an AIS-based system is the result of the emergent behaviors of all elements at the cell levels. In order to develop a formal AIS model that exhibits the benefit of its biological counterpart, an understanding of properties affecting the interaction mechanism is essential. This study develops of a formal AIS model based on GSCF and to study the impact of cell diversity on system performance. A search and rescue operation simulation involving distributed agents that take the functions of immune cells is undertaken to. The simulation consists of five distributive classes of agents working in close cooperation. The application of GSCF for controlling these distributed agents in a simulated environment is identical to the control of a group of heterogeneous-distributed modules. Though the simulation constructed in MATLAB can be used to test a wide spectrum of governing variables, this study will focus on testing system performance against cell diversity.

4.2 Simulation Design

The simulation developed closely mimics our body's immune responses against foreign substances. The purpose of the simulation is to provide a platform to examine the effect of varying factors associated with interactive heterogeneous systems. The simulation is designed in a way that allows different factors to be isolated for investigation and it involves a diverse group of AIS agents with different capacities to perform search and rescue operation. The behaviors of these agents are similar to the different types of cell behaviors in the immune system.

The function of our immune system is complicated and involves coordination between cells with different capacities. When a white blood cell called *macrophage* encounters a virus, it will consume the virus, digest it and displays pieces of virus on its surface. These pieces are called antigens. One of the many *helper T-cell* with the specific affinity will recognize the antigen displayed and binds to the macrophage. This binding stimulates the macrophage and the helper T-cell to produce chemical substances that work like communication signals at cellular level. These signals (chemical substances) cause other classes of T-cells, such as *killer T-cells* to multiply. While killer T-cells proliferate, they release additional chemical substances that cause *B-cells* to multiply and produce *antibodies*. Killer T-cells will begin to destroy infected cells while antibodies tag themselves to the viruses to facilitate macrophages to destroy viruses. This process continues until all antigens are destroyed.

As seen above, human immune system relies much on intercellular communication and coordination, which, at a glance, is very similar to many artificial network systems for control, sensing and communication; but because the immune system communicates using long lasting signals to cell classes form of many identical cells, malfunction of individual cell or bad reception of intermittent signals would not impair system stability. This characteristic alone is highly desirable for systems that require robustness.

The search and rescue simulation builds on the immune mechanisms has four active and one passive agent classes. Active agents include Search Expert, Rescue Expert, Paramedics, and Backup Agent, together with the Victim representing the virus. Table 1 summarizes the biological counterparts of these agents whereas Fig. 3 outlines the action sequence of the search and rescue operations.

Table 1. Immune cells represented by AIS agents

Immune system	**AIS agents**
Pathogens	Victims
Macrophages	Search Experts
Helper T-cells	Rescue Experts
Killer T-cells	Paramedics
B-cells	Backup Agents

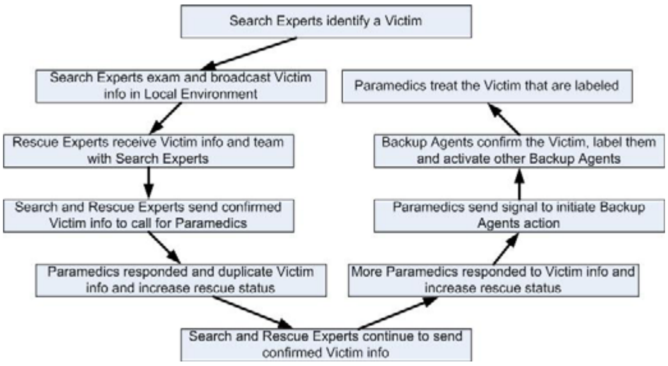

Fig. 3. The search and rescue operation performed by the AIS agents

4.3 GSCF on Heterogeneous Distributed Systems

In the simulation study, GSCF is adopted to control the coordination of heterogeneous distributed modular robots. The objective of the search and rescue robot system is to find and rescue the Victims that are randomly distributed in the simulated environment. The actions of the active agents are characterized by the immune mechanisms under GSCF.

In studying the coordination of heterogeneous AIS agents, the behaviors of these agents are treated as interdependent suppressor cells inside the suppression modulator. Fig. 4 illustrates the structure of the GSCF-based control system. The five types of AIS agents are represented by the five suppressor cells. The affinity evaluator is used to monitor number of iterations the simulation performed before completion of the search and rescue operation. The cell differentiator collects behavioural status of the AIS agents in the suppression modulator and forwards the results to the cell reactor, and the local environment provides a platform for agents' interaction.

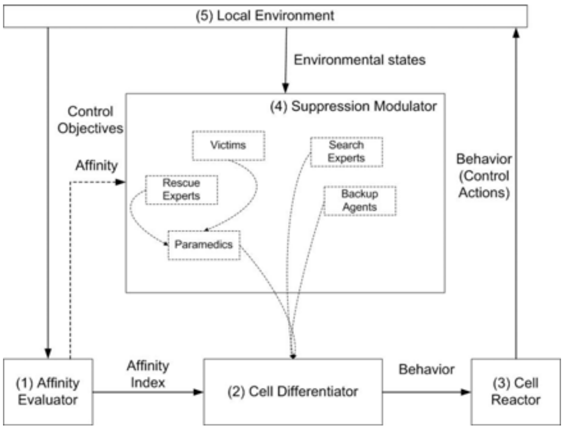

Fig. 4. The GSCF-based search and rescue system

5. EXPERIMENT AND RESULTS

As described in the previous section, the simulation developed can model interactions of large scale heterogeneous-distributed systems. Studies on specific factors affecting overall system performance is done by isolating the targeted variables or by eliminating changes in other variables. The focus of this work is to study the overall system performance with respect to the changes in number of agents in different agent classes. The experiments examine each of the five agent classes, Search and Rescue Experts, Paramedics, Backup Agents and Victims. In the simulation, except for the agent class under investigation where the number of agents is incremented for each simulation run, all other agent classes are set to have twenty agents each. To add reliability to the experiment results, the same set of experiment is repeated ten times.

In this simulation, system performance is measured by the number of iterations required to rescue all victims. Test result on system performance against number of Paramedics is shown in Fig. 5. The graph at the upper left hand corner is a plot of all raw data collected. The x-axis is the number of Paramedics in the system, where y-axis is number of iterations required to rescue Victims. The simulation ran from one to twenty Paramedics and each column in the graph has ten points, denoting the ten trials with the same number of Paramedics. To obtain a more representative result, the highest and lowest results are deleted to produce the graph on the upper right hand corner labeled "High-low Cut-off".

The middle graph on the right hand side shows the average iterations required to rescue all Victims, the decrease in average iterations taken as the number of Paramedics increases fits an exponential curve. The "High-low Cut-off Average" graph shows that when the number of Paramedics increases to about five, its effect on improving system performance starts to flatten out.

Fig. 6a (left) shows that the exponential curve (middle-right) rapidly flattened as the number of Search Experts increase to two. In fact, the "High-low Cut-off Semi-log graph suggests that quantity changes in Search Experts plays a minimal role in the overall system performance. One possible explanation to this phenomenon is that Search Experts are the first batch of agents in the search and rescue operation therefore it is not affected by the performance of other agents. The reason why the number of iterations drops significantly after the first trial is because even when there are only two Search Experts in the environment, the chances of them to find a Victim are basically the same as when there are twenty Search Experts, therefore Search Experts will not become a bottle neck to the even when initial number of agents in this class is low.

Fig. 6b (right) further explains the above observation. As the Search and Rescue Experts are both in the front line of the operation, their quantity in the environment does not affect the overall performance. Notice the "High-low Cut-off Average" graph at middle-right of Fig. 6b (right) shows that the number of iterations relating to the number of Rescue Experts presence in the environment fluctuates significantly. This shows that probability has a significant effect on system performance.

The results of varying the number of Backup Agents and Victims presented in Fig. 7a (left) and Fig. 7b (right) are more predictable. This is because these classes' performances are highly dependable on the number of agent presence in the case of Victims and the number of other agents in the case of Backup Agents.

Note that the shapes of curves shown in Fig. 7b (right) are inverted along the x-axis in contrast to the results from other agent classes. This is because the Victim class is considered as the targeted class that defines the number of tasks to complete. Therefore the smaller number of Victims in the environment means fewer tasks to complete. Further, as the chance of a Victim being found by a Search Expert is identical, therefore, the results of these two classes of agents are closely related.

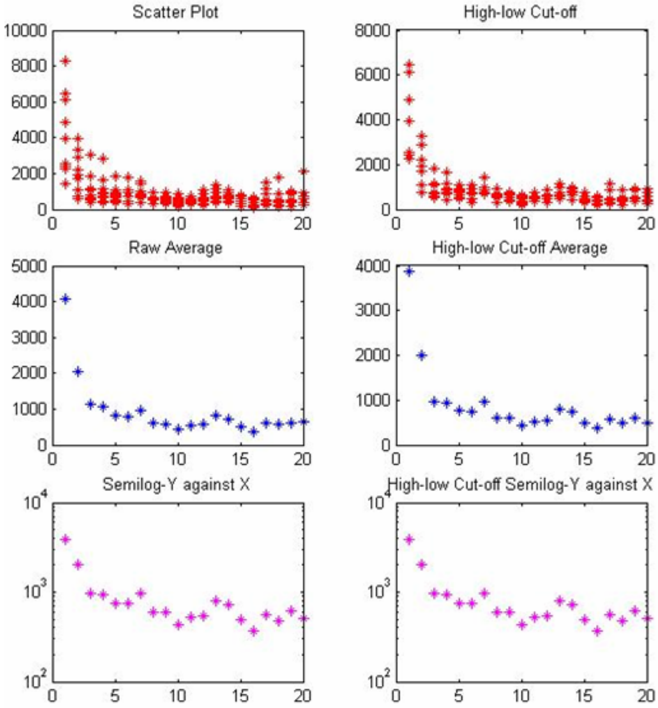

Fig. 5. Number of iterations required to rescue all Victims with the Paramedics as the test subject.

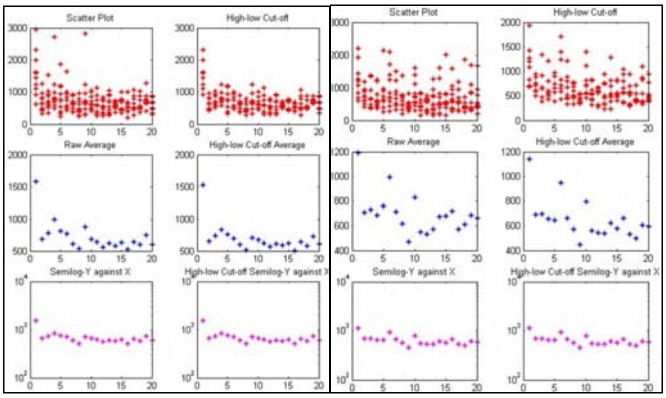

Fig. 6a. (Left) Number of iterations required to rescue all Victims with the with the Search Expert class as the test subject. Fig. 6b. (Right) Number of iterations required to rescue all Victims with the Rescue Expert class as the test subject.

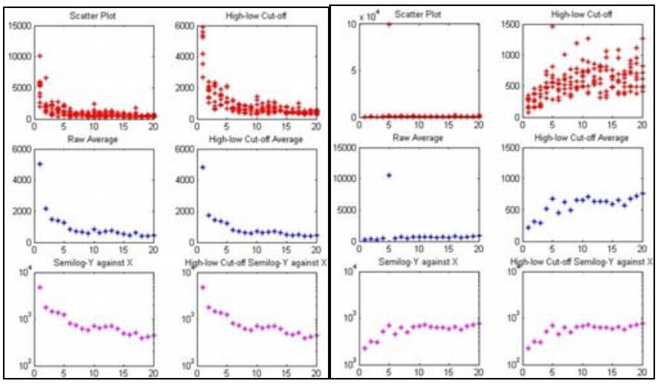

Fig. 7a. (left) Number of iterations required to rescue all Victims with the Backup Agent class as the test subject. Fig. 7b. (Right) Number of iterations required to rescue all Victims with the Victim class as the test subject

6. CONCLUSIONS

This paper has presented the GSCF for the coordination of cooperative agents under the formalism of artificial immune system. A search and rescue operation simulation that mimics the control of a typical heterogeneous system is performed to study the characteristics of the framework and the impact of agent diversity on overall system performance. The behaviors of the search and rescue agents are designed with respect to the cell behaviors of the immune system. The results indicate that GSCF works equally well on heterogeneous-distributed systems. The characteristics exemplified by the search and rescue agents can well be applied to other tasks and objective oriented relief efforts in humanitarian logistical systems. The results presented provide an understanding the effect of cell diversity versus system performance.

ACKNOWLEGEMENT

The work described in this paper was partly supported by the Research Grant Council of the Hong Kong Special Administrative Region, PRC under the CERG Project No. HKU7142/06E.

REFERENCES

Aickelin, U., Bentley, P., Cayzer, S., Kim J. and Mcleod, J. (2003). Danger theory: the link between AIS and IDS. In: *Proceeding of 2nd International Conference on Artificial Immune Systems, (ICARIS 2003)*, pp. 147 – 155.

Beamon, B. M. (2004). Humanitarian relief chains: issues and challenges. In: *Proc. of 34th International Conference on Computers and Industrial Engineering*, San Francisco.

Bently, P. J. (1999). *Evolution Design by Computers*, Morgan Kaufmann, Bath, U.K.

de Castro, L. N. and Timmis, J. (2003). Artificial immune systems as a novel soft computing paradigm. *Softing Computing*, **7(8)**, pp. 526 – 544.

Cserey, G., Porod, W. and Roska, T. (2004). An artificial immune system based visual analysis model and its real-time terrain surveillance application. In: *Proc. of 3rd International Conf. on Artificial Immune Systems (ICARIS 2004),* Catania, Italy, 13 – 16 September, pp. 250 – 262.

Dasgupta, D., KrishnaKumar, K., Wong, D. and Berry, M. (2004). Negative selection algorithm for aircraft fault detection. In: *Proceedings of 3rd International Conference on Artificial Immune Systems (ICARIS 2004),* Catania, Italy, 13 – 16 September. pp. 1 – 13.

Elgert, K. D. (1996). *Immunology: Understanding the Immune System*, New York: Wiley-Liss.

Groß, R., Tuci, E., Dorigo, M., Bonani, M. and Mondada, F. (2006). Object transport by modular robots that self-assemble. In: *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, Orlando, Florida, May, pp. 2558- 2565.

Hassoun, M. H. (1995). *Fundamentals of Artificial Neural Networks*, MIT Press, Cambridge, Massachusetts.

Lau, H. Y. K. and Wong, V. W. K. (2006). An immunity-based distributed multiagent control framework. *IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans*, **36(1)**.

Marbach, D. and Ijspeert, A. J. (2005). Online optimization of modular robot locomotion. In: *Proceedings of the IEEE International Conference on Mechatronics & Automation*, Niagara Falls, Canada, July.

Neal, M., Feyereisl, J., Rascun`a, R. and Wang, X. (2006). Don't touch me, I'm fine: robot autonomy using an artificial innate immune system. In: *Proc. of 5th Int. Conf. on Artificial Immune Systems (ICARIS 2006).* pp. 349 – 361.

Oda, T. and White, T. (2005). Immunity from spam: an analysis of an artificial immune system for junk email detection. In: *Proceedings of 4th International Conference on Artificial Immune Systems (ICARIS 2005),* pp. 276 – 289.

Sahan, S., Polat, K., Kodaz, H. and Gunes, S. (2005). The medical applications of attribute weighted artificial immune system (AWAIS): diagnosis of heart and diabetes diseases. In: *Proceedings of 4th International Conference on Artificial Immune Systems (ICARIS 2005),* pp. 65 – 79.

Sharon, J. (1998). *Basic Immunology*, Williams & Wilkins, Pennsylvania, USA.

Sipper, M. (2002) *Machine Nature, the Coming Age of Bio-inspired Computing*, McGraw-Hill, New York.

Sompayrac, L.M. (1999). *How the Immune System Works*, Blackwell Publishing, Massachusetts, USA.

United Nations Joint Logistics Center (2006). Retrieved on June 27, Available: http://www.unjlc.org/