An Immuno Robotic System for Humanitarian Search and Rescue
(Application Stream)

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Abstract. The unprecedented number and scales of natural and human-induced disasters in the past decade has urged the emergency search and rescue community around the world to seek for newer, more effective equipment to enhance their efficiency. Tele-operated robotic search and rescue systems consist of tethered mobile robots that can navigate deep into rubbles to search for victims and to transfer critical on-site data for rescuers to evaluate at a safe spot outside of the disaster affected area has gained the interest of many emergency response institutions. To fully realize the promising characteristics of robotics search and rescue systems, however, mobile robots must first be free from their tether and be granted the ability to navigate autonomously even when wireless control commands from the operator cannot reach them. For search and rescue robots to go autonomous in exceedingly unstructured environment, the control system must be highly adaptive and robust to handle all exceptional situations.

This paper introduces the control of a low-cost robotic search and rescue system based on an immuno control framework, GSCF, which was developed under the inspiration of the suppression mechanism of the immune discrimination theory. The robotic system can navigate autonomously into rubbles and to search for living human body heat using its thermal array sensor. Design and development of the physical prototype and the control system are described in this paper.

Keywords: Artificial Immune Systems, Emergency Logistics, Humanitarian Search and Rescue, USAR, Robotics.

1 Introduction

Humanitarian search and rescue operations can be found in most large-scale emergency operations. Search and rescue technology to-date rely on search dogs, camera mounted probes, and technology that has been in service for decades. With the increasing demand for scapegoats to go into dangerous environment to carry out reconnaissance and into hazardous environments to perform inspection, robots are being identified as good candidates to step in for their creator – human. Robots

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equipped with advanced sensors have therefore become more and more popular in the search and rescue theatre. To navigate autonomously, search and rescue robots require robust and adaptive fail-soft systems that can ensure calculable reliability desired for operations under unstructured environment.

Human immune system is a robust and adaptive decentralized system; the function of its components and their interactions offer inspiring analogies for solving problems in different disciplines. General Suppression Control Framework (GSCF) based on the suppression mechanism between immune cells was designed to take advantage of the adaptability and robustness of its biological counter part. This research demonstrates the possibility to implement GSCF on a decentralized search and rescue robot system. The goals of the research is to design and develop a decentralized control system based on GSCF to assist a search and rescue robot system to communicate and to navigate in unstructured disaster-affected areas.

This paper begins with an introduction to humanitarian search and rescue and robotics search and rescue systems. Then the paper moves on to describe the mechatronic design of the newly developed robot prototype and its control strategies. An introduction to AIS and the implementation of GSCF into the new search and rescue system is also included in the second half of the paper. Recommendations and conclusions is given at the end of the paper.

2 Humanitarian Search and Rescue

Over the past decade, natural and human-induced disasters claimed millions of lives and demolished astronomical sum of assets around the world. Natural disasters such as the Hurricane Marilyn in 1995 [Centers for Disease Control and Prevention 1995], the Oklahoma Tornado in 1999 [National Severe Storms Laboratory 1999], the Indian Ocean Earthquake [Zubair 2004] and Hurricane Katrina in 2005 [Federal Emergency Management Agency 2005], and the Pakistan Earthquake in 2005 [Birsel 2005], all claimed deadly and costly tolls to the affected communities. Human-induced disasters such as the civil war between Uganda government and the LRA (Lords Resistance Army) that dragged on for nearly two decades since 1987, the long-running Somali civil war since 1986, and the never-ending Palestinian conflict in Hebron and the Gaza Strip caused much more causalities than nature has ever claimed. Natural disasters usually inflict one-off damage to the community. Human-induced disasters continue to inflict damage well after the "main" conflicts have ceased. The Kosovo crisis between Albanians and Serbs as well as the crisis at Timor-Leste (formerly known as East Timor) in 1999, took place for a relatively short period of time but landmines deployed during the conflicts continue to claim lives well after the crises settled. Searching and removing landmines during and after the war can reduce civilian casualty and sooth local tension. De-mining and defusing landmines after the settlement of a war is a humanitarian responsibility that war parties should bear. However, until today, yet-cleared minefields still scatter in countries like Vietnam and Cambodia, claiming lives of ill-fated civilians.

Collapsed buildings are common field environment for humanitarian search and rescue operations. Earthquakes, typhoons, tornados, weaponry destructions, and catastrophic explosions can all generate damaged buildings in large scales. The use of heavy machinery is prohibited because they would destabilize the structure, risking the lives of rescuers and victims buried in the rubble. Only by hand should the pulverized concrete, glass, furniture and other debris be removed (see Figure 1).

Rescue specialists use trained search dogs, cameras and listening devices to search for victims from above ground. Though search dogs are effective in finding human underground, they are as limited as human in the depth they can reach below the surface of rubbles and are unable to provide a general description of the physical environment the victim locates. Camera mounted probes can provide search specialists a visual image beyond voids that dogs cannot navigate through, however their effective range is no more than 4-6 meters along a straight line below ground surface.

Fig. 1. Left: Pakistan earthquake 2005, locals making attempts to search for survivors in a collapsed girl's college. The structure was in unstable condition; excavation and lifting machineries were prohibited from the site. **Right:** Indian Ocean Earthquake 2004. Most buildings were collapsed and roads were blocked by debris. (Pictures taken on site by author during the two relief missions).

3 Search and Rescue Robots

Mobile robots designed for search and rescue operations are rugged in design and offer many features to address current technology constraints. Search and rescue robots can navigate through voids and crevices that are too small for search dogs, and can zigzag between obstacles to reach areas where straight camera mounted probes cannot reach. Search and rescue robots equipped with camera and two way voice communications allows the operator to get a visual image of the victim's surrounding and to speak to the victim to provide psychological support. Moreover, once the location of the victim is identified, another robot can deliver water and food to prolong the victim's life.

Robots for search and rescue had been discussed in scientific literature since the early 1980's [Kobayashi and Nakamura 1983]; however, no actual systems had been developed or fielded until 2001. With the advancement in sensor miniaturizations and exponential increment in the speed and capability of microcontrollers, rescue robots small enough to thread through rubbles are rolling out of experimental laboratories into the catastrophic areas. The first real research on search and rescue robot began in the aftermath of the Oklahoma City bombing in 1995 [Murphy 2004a]. Robots were not used at the bombing response, but suggestions as to how robots might have been applied were taken. In 2001, the first documented use of urban search and rescue robots took place during the 9/11 World Trade Center (WTC) disaster. Mobile robots of different sizes and capacities were deployed. These robots range from tethered to wireless operated, and from the size of a lunch box to the size of a lawnmower [Snyder 2001]. Their primary functions are to search for victims and paths through the rubble that would be quicker to excavate, perform structural inspection and detection of hazardous material.

4 Mechatronic Design

At present, search and rescue robots are typically stand-alone unit focused in obstacle avoidance and object discovery. In real world operations, when these robots are deployed into rubbles to search for victims or into muddled mine fields to locate bombs, they are often deterred by narrow passages. Smaller robots can often reach deeper into rubble pile than larger, bulkier robots; however, smaller robots are more likely to report lost if they drop themselves into large openings. Since search and rescue robots are typically deployed to work in highly unstructured environment, damaging and losing of robots due to uncontrollable external factors should not be considered as failures; instead, all loses should be considered as calculable risk and incorporate the risk into normal operation cost. Following this line of thought, to minimize operation cost, small low-cost search and rescue robots that can be deployed in high volume are more suitable for search and rescue missions in unstructured environment than large complex single unit.

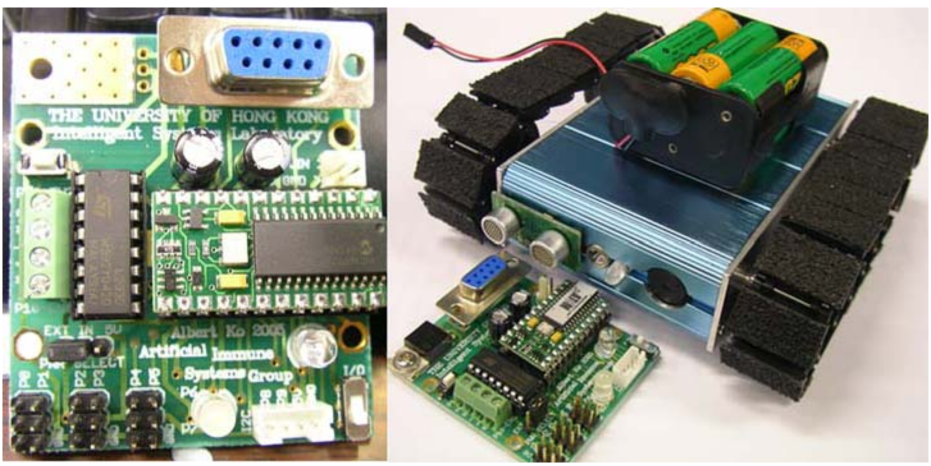

Fig. 2. Left: Custom designed control board for general AIS robot controls. **Right:** The physical prototype of the newly developed robot. The battery pack on top of the robot serves as a scale to show the robots' dimension.

The search and rescue robot system being discussed in this paper consists of an operation console and two autonomous robots. The robots are essentially two mechatronically loaded aluminum cases, each fitted with two tread-belts driven by two separate gear-motors. Each of these robots is equipped with a Thermal Array Sensor (TAS), a camera for transmitting visual image to the operator, a microphone for picking up sound under the rubble, an accelerometer to tell the orientation of the robot in respect to gravitational pull, a sonar range finder for obstacle avoidance, a high intensity LED for lighting, 6V rechargeable battery, a custom designed micro controller board designed for general AIS robot controls, and a ZigBee wireless network module for establishing a network between the operator and the robots. The board has two channels for motors up to 2A, 6 servo controllers, one 5V regulator, two LED indicators, one I2C port and a serial port for programming (Figure 2). The prototype has the camera, TAS, and high-intensity LED encased in the aluminum case. Sonar is to be encased in the second prototype.

The operation console consists of a mini-monitor for displaying video images obtained from the robots, a ZigBee wireless network module for communication and a remote control unit for interfacing human inputs to the mechatronic system. Basic layout of the system is illustrated in Figure 3.

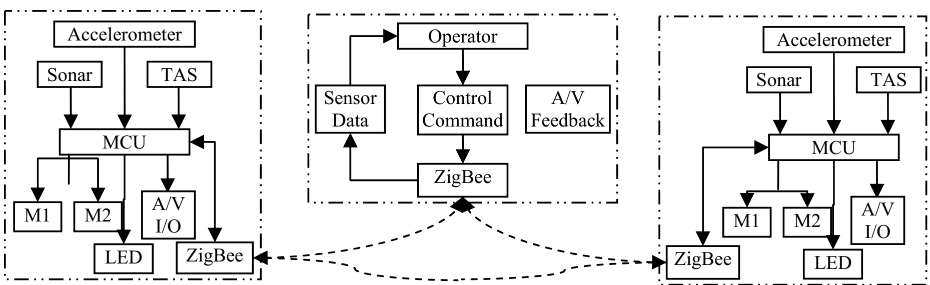

Fig. 3. Mechatronic layout of the system

The designated function of the robots is to navigate autonomously into rubble to search for living bodies using the TAS equipped in front of the robot. The TAS is a thermopile array that detects infrared in the 2μm to 22μm range. The unit has eight thermopiles arranged in a row and can measure the temperature of 8 adjacent points simultaneously. These thermopiles are identical to those used in non-contact infrared thermometers, and can detect heat generated from a human body from 2 meters away regardless of the lighting condition. The robots can avoid obstacles and find passage under rubble autonomously using its sonar range finder, but the operator can, at anytime, choose to control each robot individually using the remote controller with the assistant of the control console's mini-monitor. This alternative control scheme enables the human operator to assist the robot to solve navigation problems based on real-time visual images. Without this alternative control scheme, the robots would require many more onboard sensors and higher computational power to achieve barely comparable results, which in turn adds to the weight and cost of the robots.

The robots are designed with two separate communication channels to minimize power consumption. The A/V channel for audio and video uses 2.4GHz transmission, and is by default turned off to save power. When the robot detects an object with human-body-like temperature or when it has difficulty to navigate out of a trap, it will generate a request for the operator to turn on the A/V channel and assist it to navigate or to determine if the object is a human being. The data channel is for sharing data and transmitting command between robots and the operator. This is done through the second channel using the ZigBee (http://www.freescale.com/ZigBee) communication modules installed in the robots and in the control console. ZigBee is a low-power, short-distance wireless standard based on 802.15.4 that was developed to address the needs of wireless sensing and control applications. ZigBee supports many network topologies, including Mesh. Mesh Networking can extend the range of the network through routing, while self-healing increases the reliability of the network by re-routing a message in case of a node failure. This unique feature is highly desirable for search and rescue robots operating in unstructured environment. The ZigBee communication channel can also be turned off to save power, and can be waken wirelessly with a single command. In fact, it is programmed to stay in standby mode when it is not transmitting or receiving data.

To effectively achieve the designated function, the robots are instructed to behave in two distinct modes in respond to external stimulations. These two distinct modes govern the robots' actions in victim searching and in exception handling. When the robot is behaving in search mode, it uses its sonar to identify open passages and navigates autonomously into the rubble to look for possible victims using its TAS. While in this mode, the robot shuts down all onboard devices that are not directly related to its objective to conserve energy for navigation and exploration. In practice, the A/V system and the high intensity LED for illumination are deactivated under exploration mode. When the robot identifies a possible victim based on data obtained from the TAS, or when the robot believes it has trapped itself in the rubble, it will switch to the exception-handling mode to request for operator assistance. While in exception-handling mode, the robot would first send all data related to its current situation (i.e. the most current set of data from TAS and sonar) plus its current status (i.e. possible victim identified or trapped) to the operation console. Then it shuts down all energy consuming devices, put the ZigBee communication module to standby mode and wait for the operator's assistance. The human operator can reactivate the robot wirelessly by responding to the console. Once the robot is reactivated in exception-handling mode, it would reinitiate the A/V device, the LED, the sonar, the TAS, and the motor controllers to assist the human operator to determine whether the object identified is a living human body. The human operator can also remotely control the robot to navigate out of a trap with the assistant of the video feedback. The robot can switch back to exploration mode at the operator's command. External interruptions (operator commands or help requests) received through ZigBee communication module can also cause the robot to enter exception-handling mode.

5 Biological and Artificial Immune Systems

Human immune system is a robust, efficient, and adaptive system. The immune system 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. Artificial Immune Systems (AIS) [de Castro and Timmis 2003] is a new computational intelligence paradigm built around inspirations from its biological counterpart. This new computational paradigm, in general, focuses to exploit and mimic the four main functions in the biological immune system by embedding various computational techniques and algorithms. These artificial functions are further integrated to form decentralized systems with specific advantages to meet application needs. Many of these systems had successfully implemented to decentralized systems to perform learning, data manipulation, abnormality detection, object classification and pattern matching. Though AIS is still in its infancy when compared to other well-established computational intelligence paradigms such as, evolutionary algorithms, artificial neural network and fuzzy 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 2004] developed a control framework to improve the efficiency of a distributed material handling system. [de Castro & Timmis 2002] presented the application of AIS in computer network security, machine learning, and pattern recognition. [Sahan et. al 2005] applied attribute weighted AIS to diagnosis heart and diabetes diseases. [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. In an effort to develop robust and decentralized control systems for modular robots, [Ko et al. 2004a] developed a General Suppression Control Framework (GSCF) for designing control systems for modular robots based on the suppression mechanism in AIS. The framework has also been applied to design control systems for controlling a two-wheeled self-balancing robot in heterogeneous-connected mode [Ko et al. 2005]. This paper, continuing from previous works, describes the application of GSCF in designing robust decentralized control systems for a small platoon of search and rescue robots.

6 General Suppression Control Framework

The General Suppression Control Framework (GSCF) [Ko et al. 2005a] is based around 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.

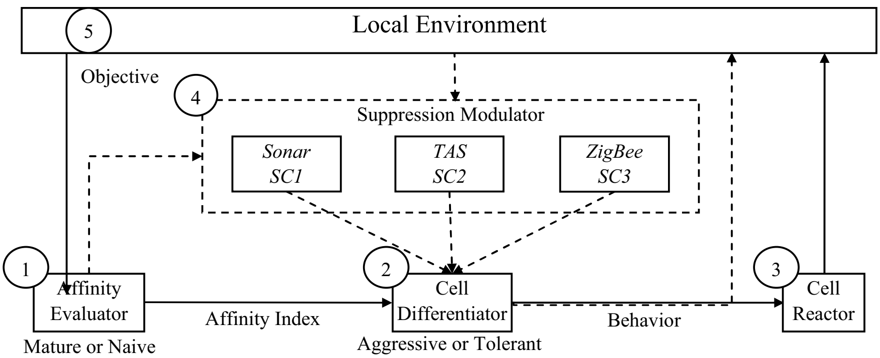

Fig. 4. The General Suppression Control Framework. Dashed lines represent humoral signal transmissions, where solid lines represent cellular signals. The suppression modulator can host any number of suppressor cells.

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 mechanism shown in Figure 4 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.

Affinity Evaluator – evaluates information in the *Local Environment* against the objective and output an affinity index.

Cell Differentiator – evaluates inputs from the *Affinity Evaluator* and *Suppression Modulator* to determine the type of behavior to react.

Cell Reactor – reacts to the cellular signal from the *Cell Differentiator* and executes the corresponding behaviors that take effect in the *Local Environment*.

Suppression Modulator – is a collection of *Suppressor Cells* that are sensitive to predefined external stimulants.

Local Environment – is where interactions between different components take place and a theoretical space to integrate the physical objects and the abstract system in an analyzable form.

7 Control Design and System Integrations

The search and rescue robot control system presenting in this paper is based on the GSCF [Ko et al. 2004b] developed for controlling decentralized systems. In general, the first step in designing a GSCF based control system is to identify the system objective and system constraints. For the search and rescue robots in this research, the primary objective is to search for human body under rubbles using their TAS. Therefore searching for human-body-temperature-like heating object is the system objective. Next, for the robot to navigate through rubbles to search for heat, the robots must be able to avoid obstacles and to ask for help when it is stuck. Therefore avoiding obstacle is a crucial condition that the robots must satisfy before pursuing the system objective; hence obstacle avoidance is a system constraint. In addition, operator commands and help requests, made by other robots within the system, received through ZigBee communication module are also treated as external constraints.

With system objective and constraints identified, the next step is to organize these conditions into system solvable form. For GSCF, the fundamental idea is to let Affinity Evaluator to decide whether there is a problem to solve (an system objective to pursue), and then consult the Cell Differentiator to decide whether the system has the resources to solve the problem under imposed constraints. For the search and rescue robot, the Affinity Evaluator is responsible for monitoring the status of the system objective. The system objective is said to have achieved when a human-body-temperature-like heating object is detected. The Affinity Evaluator would produce a high affinity index when the system object is achieved to encourage the system to behave aggressively. When a robot is in aggressive mode, it would remain in its position and perform a series of actions to alarm the operator for assistant. Otherwise, the Affinity Evaluator would produce a low affinity index to allow the system to continue exploring the surrounding to search for heating objects. When the affinity index is low, Cell Differentiator would actively evaluate various system constraints to see how the robot should behave. These constraints being evaluated may be predefined system constraints or newly developed constraints due to changes in the environment. GSCF define these constraints as suppressor cells (SC), these cells may evolve to adapt to new changes and may proliferate to increase their sensitivity to specific stimulants. The search and rescue robots under discussion have two main sensors that determine the robots' behaviors. The sonar range finder helps the robot to avoid obstacles, and the TAS helps to locate heating objects. Suppressor cells that have high sensitivity to these sensors are situated in the Suppression Modulator.

Suppression Modulator is a very important component in GSCF; it contains suppressor cells that are sensitive to particular sensors and can be viewed as representations of external constraints reacting inside the control system. The function of Cell Differentiator, on the other hand, is similar to the biological cell differentiation mechanism, in which cells develop aggressive or tolerant behavior in response to the type of cytokines present in the immune system. Similar to Suppression Modulator, Cell Differentiator is also an important component of GSCF; it is responsible for integrating complex information from different sources into simple instructions and converts intricate problems into quantitative outputs. The decision flow of the Cell Differentiator can be summarized in a flow chart as shown in Figure 5.

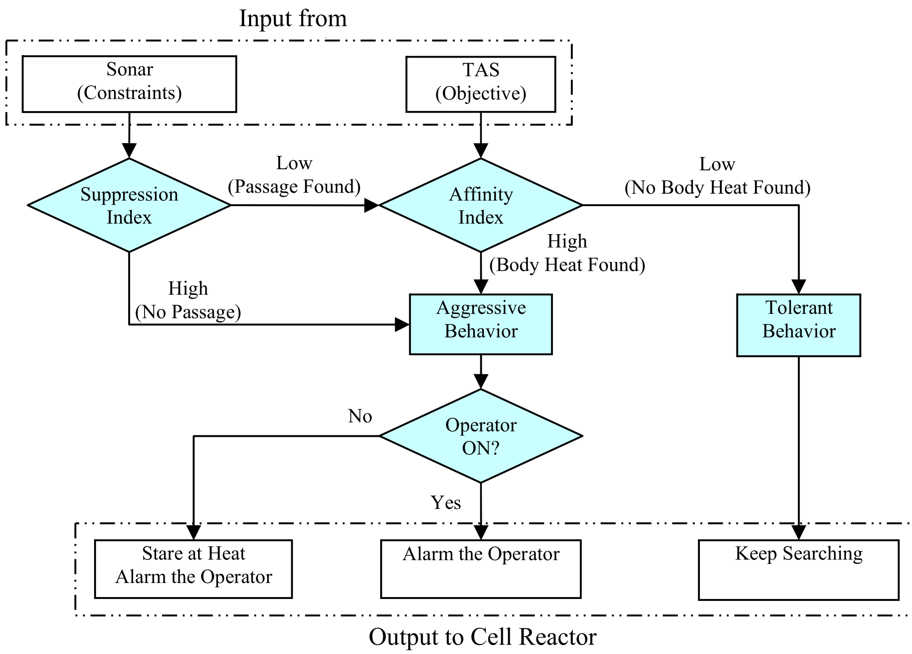

Fig. 5. Decision scheme in the Cell Differentiator of each modular fireguard

The suppression indices from the suppressor cells have priority over all others, it is being evaluated first to see whether the robot is blocked by obstacles or has found a heating body. If the suppression index is high, meaning the system has detected something unusual; the suppressor modulator can force the robot to behave in aggressive mode instantly. On the other hand, when the suppression index is low, the system will check the affinity index and follow the normal procedures to determine how the robot should behave.

Since the Cell Differentiator in GSCF is only responsible for producing high-level behavioral instructions such as “sound the alarm”, “stand fast”, “search for heat”, etc. There has to be a component to interpret these high level commands into lower level commands for the mechanical controllers. This component is called Cell Reactor. Since mechanical control schemes varies greatly between different operation platforms, GSCF delegates this work to Cell Reactor, so the high level design of other components can remain platform independent.

8 Observation Test

To evaluate the performance of a field system and to determine points of improvement, the GSCF-based search and rescue robot system is put to test in a semi-unstructured environment. The test environment is a dumpsite for old furniture and equipment; the piling of chairs, broken pallets, and construction debris resembles a condition close to an earthquake-affected indoor environment. The purpose of this test is to observe how GSCF handles the robots' different behaviors based on simple suppression mechanism. The robots ability to transform between aggressive and tolerant behavior in response to the external condition is also of the experiment's main focus.

The robot deployed into the test environment performed as designed. The robot navigates autonomously into the rubble to search for heat emitting objects that are close to the temperature of heat emitted from a living human body. The robot stopped and switched into tolerant mode after it detected the operators hand. The operator then took over the control of the robot, navigated it to a different location, and let the robot resume its patrolling. Mobility of the robot is biased towards certain terrain. The small size of the robot inherently handicapped its mobility over terrains with large holes, as the robots would simply fall through them as it strolls over. When in front of narrow passages, the robot demonstrated good mobility. The equipped accelerometer helped the robot to determine if it is flipped over and allow the control system to change its motor directions accordingly, so the robot can continue to move in the same direction after being flipped in an accidental event. This feature proves to be very useful over rough terrain and narrow passages, as the operator does not need to know which side of the robot is up to drive the robot forward.

Since this is only a prototype for testing the concept of controlling low-cost autonomous search and rescue robots with GSCF based system, it is fair to say the performance of the robot is inline with design expectation and the GSCF based control system works well as the backbone of the system. To further develop the current prototype system, certain improvements can be made. Suggestions and recommendations derived from this research are discussed in the concluding section.

9 Recommendations and Conclusions

This paper presented a low-cost search and rescue robot system that can navigate into voids in rubbles, avoid obstacles, detect living human body temperature, transfer video image, and communicate in a low-power ZigBee network. The robot system consists of two robots and one operator console and can be expended to consist any number of robots. The GSCF based control system enables the system to be controlled in decentralized manner using very simple commands and limited communication power.

In spite of the technological challenges and mistrust of new technologies in human nature, search and rescue robots will become an indispensable tool in future rescue operations. Starting to develop and field search and rescue robots with regular rescue teams can help scientists to better understand the strength and weaknesses of different robot designs under different situations. Having robots working in parallel with regular rescue team can also help scientists to investigate how robots should behave to comply with their operators' instructions and to best assist the rescue effort in general.

Simple user control interface allows amateur rescuers to be trained to operate the robot in a short period of time, eliminating the need to occupy limited professionals to look after each robot. Low manufacturing cost allows robots to be deployed in mass quantity to increase the chance of finding survivors. Battery is the heart of robots; it keeps electricity pumping inside the robots. Lighter, smaller and more powerful battery is also an important constituent of effective search and rescue robots. Emergency wireless network for communication is also important for coordinating actions between robots, collecting visual image from the robots, and to communicate with the victim when the robot finds one.

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