A Bio-inspired Objecct Tracking Algorithm for Minimizing Power Consumption

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Abstract—**This electronic document is a "live" template. The various components of your paper [title, text, heads, etc.] are already defined on the style sheet, as illustrated by the portions given in this document. A wireless sensor network (WSN) is a distributed information processing system with the capabilities of sensing, wireless communication and data processing. Individual sensor modules of such a network sense the environment, perform data processing locally and cooperate with other sensors via communication. One very important issue in the deployment of a wireless sensor network is the problem of optimizing energy consumption as these networks may be deployed in places where energy supply are not readily available such as in a seaport container terminal and they are required to work with a long lifespan.**

The main objective of our research is to develop an algorithm for controlling the power consumption of sensor modules in a wireless sensor network for mobile object tracking. The algorithm determines the actions of an individual sensor module to enter a low power state to conserve energy while maintaining its functionality to track objects and to optimize the lifespan of the entire sensor network by reducing overall power consumption. A control framework and corresponding algorithms for controlling the actions of a sensor is designed and experimentation is done to show its efficiency in controlling power consumption of a sensor network.

I. INTRODUCTION

The rapid development of semiconductor technology has promoted the emergence of low cost wireless communication hardware such as Wi-Fi, Bluetooth, ZigBee and mobile phones that are often incorporated with processing and sensing capabilities. These devices transfer information between one another, and have the functionality of information processing as well as detecting changes in its surrounding environment. Devices such as a mobile phone that is incorporated with a global positioning system (GPS) and a remote weather monitoring unit are typical examples of such devices that are commonly available nowadays.

With these devices, generally known as sensor modules, which are low in cost and small in physical size, a large number of them can be deployed in an area forming a network of sensor modules. These modules collect information from its environment through their sensing capability in an independent manner. When they are allowed to communicate with one another and exchange data and information that they captured and processed with other sensor modules that are assessable within their vicinity using their communication functionality, they form an integrated information processing infrastructure that are commonly known as a sensor network. While such a multi-sensor architecture can be loosely defined as micro-electro-mechanical systems (MEMS), the network that is formed by these sensor modules that are capable to communicate via a wireless means is commonly known as a wireless sensor network (WSN).

While the model of wireless sensor networks has been well-established and been around for some time, problems and issues that are related to their operation and deployment also emerge. In the logistics and transportation industry, the deployment of wireless sensor network for the real-time tracking and management of shipment of cargo and goods in various scales ranging from inter-continental shipment tracking to in-warehouse and factory-based tracking has become popular.

With the properties of the sensor modules that form the wireless sensor network, and through the deployment of a very large number of these sensor nodes in a network that may be distributed over a large physical area, challenges are encountered for their successful applications. In essence, the basic functionality of a sensor module include computation, sensing and communication that are performed onboard of individual hardware devices, namely, the sensor modules consume power. In order for sensor modules to be usable in a sensor network that provides a reasonable lifespan and reliability over time, the management of power consumption and supply is one of the very crucial problems to address. A sensor module not only requires power to perform information processing such as signal processing, data encryption and

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local control, the communication of information requires significant amount of power. With these requirements, strategies for distributing the task of information processing over a number of sensor modules while maintaining a minimum communication overhead is a key issue of power management.

The research will lead to the introduction of an algorithm that effectively maintains the balance between the performance of mobile object tracking and the reduction of the overall energy consumption of a sensor network. The proposed algorithm aims to reduce the power consumption of the overall network by allowing certain sensor nodes to enter a low power state to conserve energy. In this way, the average power consumption of a sensor node could be reduced, and overall lifespan of the sensor network can be extended without scarifying significantly the performance of the network.

The rest of this paper is organized as follows; Section II introduces the different research topics related to WSN that is followed by the descriptions on the human immune system and artificial immune systems (AIS) in Section III. An abstract model of the sensor network is presented in Section IV, and a detail description of the proposed algorithm given in Section V. Experimentation is described in Section VI and discussion given in Section VII. Conclusion is drawn in Section VIII.

II. Wireless sensor networks

As mentioned previously, wireless sensor networks (WSN) have been recognized as feasible means for object tracking [10] and its research can be traced back to 1980s when a program called Distributed Sensor Networks (DSN) was started in 1980 [4]. Over the years, however, power consumption is still a major concern of their usage in standalone environment. Efforts have been made by various researchers to derive ways to extend the lifetime of power storage. The other direction is to minimize the use of energy in the tracking process. Ye et al. [15] proposed an adaptation named Sensor Media Access Control (SMAC) in the medium access control layer to minimize energy consumption of the sensor nodes and to better handle collision in wireless channels. Fuemmeler and Veeravalli [8] worked in a different way in which their direction is to make sensor nodes sleep longer, and to balance the tradeoff between sleeping and tracking errors.

In particular, Park and Lee [12] analyzed a number of Media Access Control (MAC) protocols [3] that are developed based on the IEEE 802.15.4 protocol. By building on top of the IEEE standard, many protocols have been proposed so as to be compatible with devices that are commercially available or having applications building on this standard. Park and Lee classified the protocols into two types: (i) on beacon mode and (ii) non-beacon mode. The protocols for each type differ by the mechanisms for transmitters to wait for receivers (or vice versa) in data transmission, and they concluded that there is no one winner algorithm, and the most efficient algorithm is highly dependent on the particular application.

III. Artificial Immune Systems (AIS)

A. *Background*

The biological immune system protects a living organism against various kinds of attacks which causes diseases where many of these are caused by pathogens. To safeguard against pathogens, the immune systems develop multiple levels of protection mechanism.

Interestingly, the human immune system exhibits its functionalities through several mechanisms, which engineers found inspiration to designing algorithms for engineering applications. It provide inspirations for creating novel and efficient algorithms for generating solutions to complex problems that are generally difficult to solve by analytical methods. The engineering analogy of human immune system is named artificial immune systems or AIS. This computation paradigm adopts the mechanisms and theories of biological immune systems to solve important engineering problems. One of the most profound properties of AIS is the ability of these immune entities to solve a problem in a distributed manner. In an immune system, lymphocytes are cells circulating throughout the body. They do not have a centralized control but can coordinate to achieve a common goal.

Various applications have been proposed and developed by adopting the ideas of AIS. Examples include deriving optimization algorithms, process control and intrusion detection. Sarafijanović and Le Boudec [13] proposed an AIS-based algorithm for detecting misbehaviors in an ad-hoc network. By using the negative selection mechanism of AIS, the system can be trained to understand and remember normal behaviors. Whenever behaviors that are out of the normal set are being detected, they are regarded as misbehaviors.

B. *Immune Network theory*

Jerne [9] proposed the immune network theory to explain the mechanism of maintaining constant overall population of B cells while some types of B cells stimulated by antigens can proliferate and memorise antigens. Inspired by the theory of Jerne, Farmer et al. [7] proposed a mathematical equation relating the concentrations of various kinds of antibodies. Concentrations of each kind may cause stimulation or suppression to other kinds of antibodies. Such an equation takes the following form:

$$\dot{x}_i = c\left[\sum_{j=1}^{N} m_{ji}x_i x_j - k_1\sum_{j=1}^{N} m_{ij}x_i x_j + \sum_{j=1}^{n} m_{ji}x_i y_j\right] - k_2 x_i \quad (1)$$

In (1), the first m_{ji} is the stimulating affinity between *j-th* and *i-th* antibody, and m_{ij} is the suppressing affinity between *i-th* and *j-th* antibody. The second m_{ji} is the affinity between *j-th* antibody and *i-th* antigen. x_i and x_j are concentrations, x_i is stimulus, k_2 is natural death coefficient. The equation defines the four factors affecting the change in concentration of an antibody, i.e. affinity with antigen, stimulus and suppression from other antibodies, and natural death.

C. *AIS-based sensor network control methods*

Works have been done using AIS to control the activities of sensor networks. Drozda et al. [5] focussed on the ability of immune systems for fault detection. They demonstrated that a few set of misbehaviours can be detected through their algorithm. In [6], they performed an analysis on the performance of such algorithm and pointed out some design considerations. However, their main focus is a self-healing architecture, which is expected to detect faults and recover from those faults. Atakan and Akan [2] focussed on control. They proposed an algorithm using immune network theory to selectively choose nodes to participate in the data transmission process to transmit information to the sink. They adjusted the reporting frequency to further reduce energy consumption of the whole sensor network.

Xue and Chi [14] treated the computation of routing path as an optimisation problem. They proposed a scheme for routing data from sensors to sensors. They treat the entities in a WSN as entities in immune systems, and perform optimisation to aim for minimum power consumption. As the calculation involves all entities in a WSN, the implementation is a centralised one. Fuemmeler and Veeravalli [8] studied the effect on the accuracy of object tracking when sensor nodes may sleep to reduce energy consumption. They concluded an optimal solution cannot be found but suboptimal solutions can obtain performance close to optimal.

IV. SENSOR NETWORK MODEL

Assume the following exists in our sensor network model:

- There are m sensor nodes (N_1 to N_m) located in a two-dimensional space (P).
- There are n objects (O_1 to O_n) to be tracked in P.
- Distance is measured as their Euclidean distance.
- There is a maximum limit in distance, R between two communicating sensor nodes. Two sensor nodes N_i and N_j can communicate only when the (Euclidean) distance between them is less than or equal to R.
- There is a maximum limit in distance, r between an object and a sensor node. A sensor node N_j is able to track an object O_i only when the (Euclidean) distance between them is less than or equal to r.

Sensor nodes are placed before objects are detected. Depending on hardware capabilities, some sensors can work independently to measure distance and direction of movement of an object. However, others solely rely on Received Signal Strength Indication (RSSI) values to determine the distance between themselves and the tracked object. In such a case, information is needed from other sensor nodes for locating the position of the tracked object. Following this concept, the proposed model uses measurements from multiple sensor nodes to compute the exact position of an object.

In our proposed energy efficient object tracking algorithm, objects and active sensor nodes are key components of the system. Active nodes refer to the sensor nodes which are active in detecting objects and communicating with other sensor nodes. Inactive nodes closes down wireless communication for most of the time, thus to communicate with inactive nodes is difficult.

V. AN IMMUNE NETWORK-BASED ALGORITHM

A. *Overview*

The tracking algorithm involves two types of nodes, sensor nodes and object nodes. Location estimation of target objects and a decision making process are required to be achieved in a sensor node. Under normal operation, a sensor node may enter a low power state or going into a sleeping state, which in effect will reduce the node's energy consumption. The process controls the entering of the low power state and the length of time that the sensor is engaging in this state. The length of time has to be specified in advance when the command for entering low power state is issued. The mechanism of the proposed algorithm is developed based on the inspiration from the Immune Network Theory discussed earlier and the algorithm determines the best sleeping policy in order to optimise the power consumption of the entire sensor network.

B. *Outline of the object tracking algorithm*

Under the proposed WSN model, there are two types of agents, namely, sensor nodes and object nodes (or objects). Both of them are intelligent agents. To track the movement of a target object, an object node is attached to the target. The location of object nodes represents the location of target objects. Each sensor node execute in the way as follows:

(1) The sensor network initializes itself with each node pick a random time to start a loop which is described in the following steps.

(2) In one round of activity, a sensor node listens for other sensor nodes that are within its communication range and objects within sensing range for certain fixed period of time. The sensor node collects and stores the information, in preparation for decision making later on.

(3) The sensor node broadcasts its own beacon to let other sensor nodes detect the current node. The beacon also includes a list of object nodes that is detected by the current node, so that other nodes may realize the existence of other object nodes that they do not detect directly.

(4) An immune-inspired decision making task is performed. It determines if the node should enter sleep mode, and if so, for how long. If the node is not going to sleeping, it returns to Step (2) immediately.

(5) Otherwise, it sleeps for some pre-defined time before it finishes the round and repeats Step (2).

The loop of execution in an object node is quite similar, with only Steps (1), (3), and (5). The sleeping duration for an object node is the time when the object node is not in Step (3). That is, whenever the object node is not broadcasting, it should go to sleep.

C. *Decision making*

The decision making process that is adopted by the proposed algorithm is developed by modelling the activities of a small immune network that is defined by the Immune Network Theory of AIS. We model the decisions made by a candidate node as types of antibodies which are associated with a population within the immune network, and the properties of the environment in which the sensors operate in plus the associated changes of environmental condition modelled as antigens. In the decision process, the dynamic equation that specifies the changes in a specific immune entity concentration of Farmer et al. [7] (Section III.B) is adapted to evaluate the changes in the population of each candidate decision. Equation (2) is the modified dynamic equation that is adopted by proposed algorithm.

$$\dot{x}_i = \sum_{j=1}^{n} m_{ji} x_i d_{ij} + \sum_{j=1}^{N} m_{ji} x_i x_j \tag{2}$$

In the context of biological immune system, the first term in (2) represents the effects of antigens and the second term represents the interaction between antibodies meaning that the presence of antibodies of type A may affect the population of antibodies of type B, and vice versa. More specifically, in the immune network, the effectiveness of each type of antibodies is measured by their population. In (2), the term x_i represents the population of antibodies of type i. The term d_{ij} represents the population of certain kind of antigen. In the proposed framework, an antigen is correlated to a target object that is approaching a sensor node or moving away. We adopt the Euclidean distance from the target object as a measure of the effectiveness of this antigen, which in turn is modeled by the population in the equation. We denote this distance by d.

The term m_{ji} is the affinity. In the original Farmer's equation, there should be separate matrices representing the affinities between different types of antibodies and antigens, and between antibodies and antibodies. In this way, the change in concentration of any type of antibodies can be calculated and its effect reflected in the immune network by cloning the particular type of antibodies.

In the context of the proposed control algorithm for the domain WSN, Farmer's equation is simplified with the term representing natural death of an immune entity being ignored. Instead, normalization of the concentrations of immune entities is deployed to reduce the population of different kinds of antibodies. A small population of every type of antibodies is injected to improve diversity of the solution population. This prevents those types of antibodies with a small population to be totally eliminated.

VI. EXPERIMENTATION

A. Simulation tools

In this research, computer-based simulation is deployed for the experimentation, in which the proposed immune-inspired sensor control algorithm and the always-on scheme are compared in different scenarios. In this study, a computer simulation package called Repast Simphony [11] is adopted for hosting the simulation. The application itself is a toolkit which is primarily for agent-based simulations.

B. Parameters

In the experimentation, all the settings of parameters are identical for all the simulation runs. Environment settings for individual experiment would differ where planned and they will be documented in association with each experiment. Otherwise, the environment settings are the same as mentioned below. Table I lists parameter settings having numeric values.

C. Results

By altering the density of sensor nodes in the field, the average power consumption of the WSN are captured and studied. In the experiment, the result of deploying an always-on sensor network is compared with the results obtained from the immune-inspired sensor control framework.

As shown in Figure 1, the average power consumption reduces when the number of sensors is increased for the proposed framework, since increasing the density of sensor node allows sensors to enter the low power states more frequently. Compared with the always-on network, the average power consumed for each sensor node is significantly lower. As such, the proposed algorithm reduces the overall power consumption in a great extent.

Another factor being studied in the simulation is the communication radius of the sensor nodes. In practice, the communication distance is closely related to antenna power, which is in turn a function of the energy consumption. In this experiment, we assumed that the variation of communication distance is small enough that will not impose a significant effect to the overall power consumption of individual sensors. As seen from Figure 2, a reduction of average power consumed is observed.

TABLE I. NUMERICAL SETTINGS OF THE KEY PARAMETERS IN THE SIMULATION MODEL

Setting	Value
Sensor field	
Length	350 metres
Width	350 metres
Number of objects	10
Number of sensors	200
Communication radius (applicable to objects and sensors)	50 metres
Maximum movement speed of objects	10 metres per second
Broadcasting interval	0.5 second
Length of simulation	600 seconds

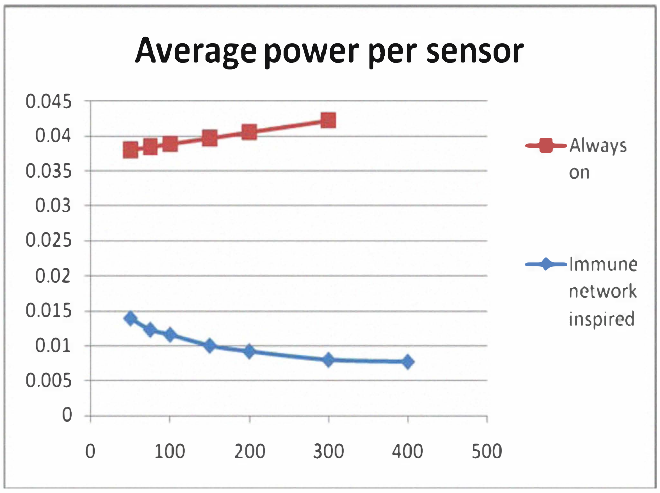

Figure 1. Average power consumption for different number of sensors deployed

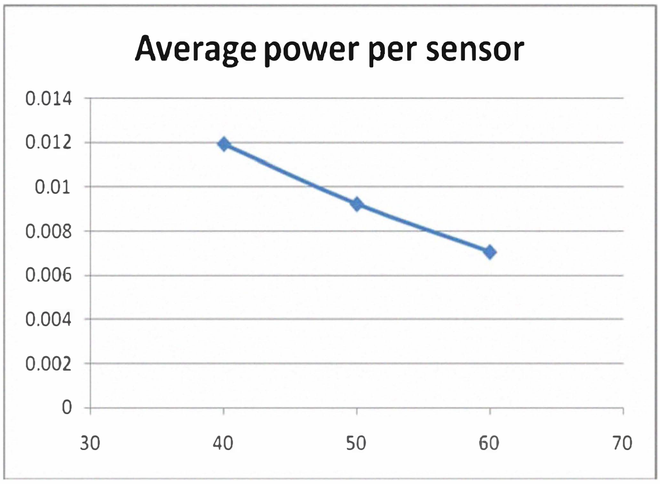

Figure 2. Average power consumption of each sensor for different communication radii

VII. Discussion

From the experimentation of the proposed sensor control algorithm and the result obtained through the comparison with a traditional always-on sensor control scheme, a number of factors affecting the efficiency of a wireless sensor network are concluded.

The density of sensor node deployed in a sensor field is obviously very important in determining the efficiency of the overall sensor network for tracking moving objects that are present in the sensor field. As seen from the results described in Section VI, when the number of sensors deployed in a sensor field and thus the corresponding density of sensor nodes increases, the average power consumption per sensor decreases.

A larger communication radius in general improves the efficiency of the network. This result is apparent and is clearly reflected from the study as a larger communication radius will enlarge the coverage of a single sensor node making the overall network more effective in detecting the moving objects.

There are a number of aspects that the proposed algorithm can be improved. Firstly, the affinity values between antigens and antibodies and between antibodies can be improved by generating them dynamically. Secondly, the diversification of the types of antibodies may not be sufficient. Thirdly, the introduction of the different types of antigens may not be sufficient as there are many possible types of antigens that are not deployed in the proposed algorithm.

VIII. Conclusion

We proposed a control algorithm to enable sensor nodes in a wireless sensor network to individually determine their working status. By reducing the number of active nodes, communication and hence collision are reduced. The proposed algorithm has been verified using realistic dataset, and through the results, the algorithm can be seen to improve the overall energy efficiency of a wireless sensor network.

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