AUTONOMOUS ROBOTIC MODEL BASED ON HUMAN ENDOCRINE SYSTEM

By

KHALIQUE REHMAN

M.B., B.S

University of Karachi

Karachi, Pakistan

1983

Submitted to the Faculty of the

Graduate College of the

Oklahoma State University

in partial fulfillment of

the requirements for

The Degree of

MASTER OF SCIENCE

July, 2009

AUTONOMOUS ROBOTIC MODEL BASED ON

HUMAN ENDOCRINE SYSTEM

Thesis Approved:

Dr. Johnson P. Thomas

Thesis Adviser

Dr. Douglas R. Heisterkamp

Dr. Subhash Kak

Dr. A. Gordon Emslie

Dean of the Graduate College

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

LIST OF GRAPHS

Graph Page

Chapter 1
Introduction

Robotics is a very fascinating, extremely challenging and a rapidly growing field that is fast entering the consumer market. This field has undergone tremendous technological advancement attracting manufacturers with large and capable infrastructures to offer innovative industrial as well as consumer products. There are already commercial products available that range from household vacuum cleaner robots to remotely controlled small airplanes (drone) being used in military operations. Individual robots have become quite intelligent and have been provided with a vast variety of sensors and have developed the capability to be remotely controlled from far away.

Collaboration and Coordination between robots has been explored widely and research is going on in this field since decades. In 1994, Tucker Balch and Ronald C. Arkin [6] explored the importance of communication in a multi-agent robot environment and estimated the cost involved with various types of communications and their impact on robot performance.

In another study at Robotic Research Laboratories, University of Southern California [7] the focus was on integrating data from multiple robots exploring the same environment. In this study, they used robots that differed in their exploration capabilities like having different type of sensors, actuators etc.

A relatively recent example is of the work done collectively by Wolfram Burgard, Marks Moors, Cyrill Stachniss, Frank Schneider [8]. Their focus was on efficient exploration of an unknown environment by multiple robots. They studied different ways of task assignment techniques and their effectiveness. However, all robots were basically performing the same type of task; exploring the environment.

So far, we have not seen any work that is done to coordinate different types of robots each independently performing a different task and contributing towards the common goal while asynchronously passing messages to anyone who may be interested and receiving messages of their own interest. In this scenario, there may be one or more robots that perform one specific task and other robots that perform a different task and each one contributes towards a common goal. The key here is that the robots are autonomous and independent of each other, that is, no one is aware of the existence of the other or dependent on the other, yet their work contributes in achieving the common goal.

The idea of the model that we are going to present in chapter 4 was conceived from the study of human physiology. The reason why we turned towards human physiology is that during the last two decades biological systems have attracted a lot of researchers in the field of information technology to explore similarities between the Human system and Computer Systems [2][3]. One notable example is the emergence of Artificial Immune System that is modeled on Human Immunological characteristics [4][5]. Our project is also an example, on the same lines, to apply the principal and characteristics of human physiology to the field of Robotics.

We take as our model, for our study, the human endocrine (hormone) system. As far as we are aware no-one else has applied the human endocrine model to the field of robotics. The hormonal system consists of several hormones of which some are tightly related to each other's impact on the body and their performance. From such groups, we chose the hormone that is perhaps one of most familiar hormone that a common person might have some knowledge of. That is, we studied Insulin (and glucagon) that is the major hormone that controls glucose metabolism. While our example is limited to the hormones mentioned, the principals are mostly common to the entire hormone system.

We have focused on stimuli that cause production/release of insulin, insulin passage to and its pick up by the target tissue, its effect in controlling glucose utilization in the body, and the mechanism of control of insulin production. We also studied Glucagon, an Insulin antagonist (opposing) hormone that is important in glucose utilization.

We provide a detailed description of these hormonal characteristics in chapter 2. In chapter 3 we extract and map some characteristics we learned in chapter 2 to the field of Robotics. We also present a Robotics model in chapter 4 based on the principals learned from the human endocrine system, specifically Insulin. Chapter 5 will cover our implementation scheme and the results obtained.

Chapter 2
Human Endocrine System – Review

2.1 General Characteristics

Hormones are chemical structures produced in certain tissues [3]. They bring about changes in the target tissues and coordinate different activities of cells, tissues and organs in the body. Thus, as such they constitute a chemical messenger system in the body.

Hormones are secreted by specialized cell or glands. Each hormone targets certain type(s) of tissue(s). The manner in which they are carried to their target varies. However, we can broadly classify them into two categories:

- Hormones that are secreted by the cells and act within a very short distance on the neighboring cells and tissues.
- Hormones that are secreted and then are absorbed into the blood and carried to other locations in the body where they exert their effect.

In the majority of cases, the hormone itself does not perform the intended activity. It merely initiates a process that, with help of other chemical structures, brings about the change. Therefore hormones mainly act as messengers.

Hormones production is controlled in many ways. Some are regulated by their concentration in the medium, blood or intracellular fluid providing negative feedback. Some are controlled by other, antagonistic hormones. There are examples of control involving more than 1 additional hormone in a negative feedback mechanism. Some hormones are only produced when the presence of another hormone is detected. Many times there is more than one mechanism active for the control of a certain hormone. In essence, there are multiple ways in which hormonal balance is maintained with the body.

A hormone that is secreted has a certain life span. There are mechanisms in place to remove a hormone from the body either by chemically inactivating it or destroying it. Hence, constant production at an optimal rate and its timely removal is very important for the body to function normally.

2.2 Insulin

2.2.1 Chemical Structure

Insulin is a well known and well studied hormone. It was discovered in 1922. Chemically, it is a protein composed of two amino acid chains attached to each other by disulfide linkages. Its activity is lost when two chains are split apart. Its half life is about 6 minutes.

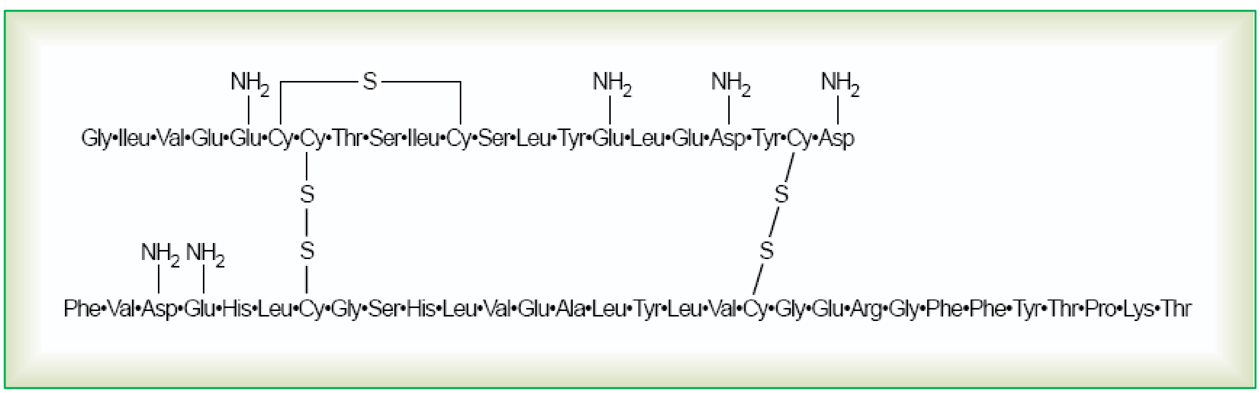


Figure 1 - Human Insulin Molecule

2.2.2 Production & Transport

It is produced by special cell in the pancreas called β-cells. When released, it is picked up by the blood and carried to the destination sites, mainly Liver and Muscles.

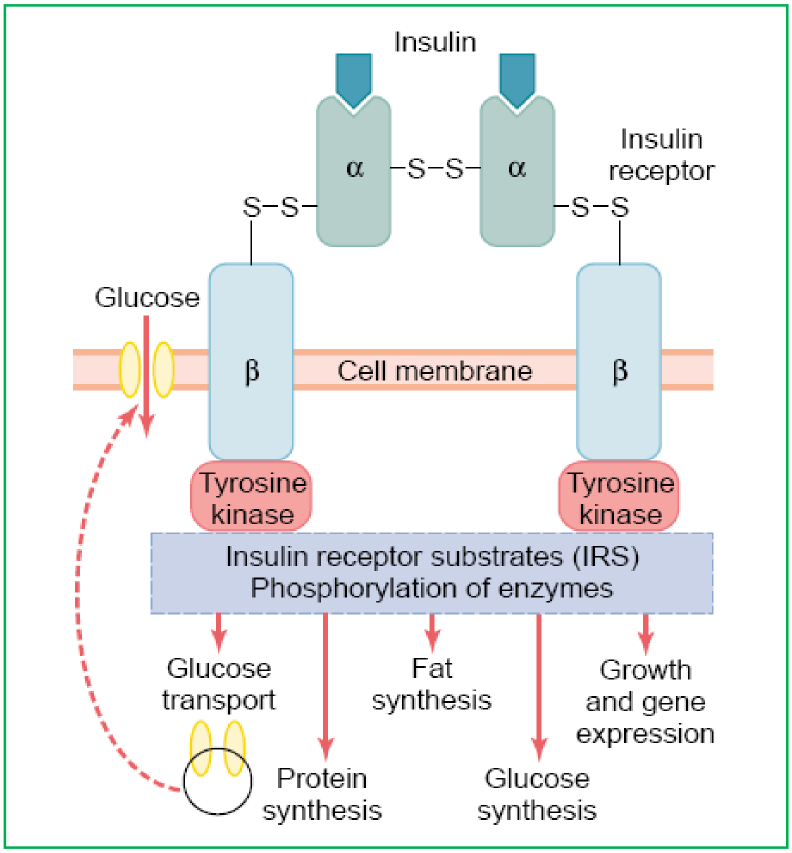


Figure 2 - Schematic of the insulin receptor. Insulin binds to the alpha subunit of the receptor which causes a chemical change in beta subunit of the receptor which in turn induces tyrosine kinase activity. This results in increase permeability of cell membrane for glucose leading to movement of glucose into the cells

2.2.3 Delivery Mechanism

The target cells have special chemical structures sticking out of the cell membrane. These are called insulin receptors. These receptors extend from inside of the cell through the cell membrane and outside to the extracellular space. When an Insulin molecule attaches to this structure outside the cell, it causes a three dimensional change in the shape of the part of the receptor that is inside the cell. This change signals the cell that the message has arrived. From here, a chain of reactions takes place inside the cell that ultimately results in the movement of blood glucose (and to lesser extent amino acids and other molecules) into the cell.

Although the effect of insulin is to promote entry of glucose into cells from the blood, the final effect this is somewhat different in each type of cell.

- In muscles, if there is an immediate need to burn the fuel, as in the case of exercise. Here the absorbed glucose is immediately utilized. At other times, this glucose is converted to Glycogen, a storage form of glucose, and stored for later use.
- In liver, all the glucose is converted to Glycogen and stored.
- In fat cells, this glucose is utilized as required component to build fat molecules.

2.2.4 Control of Insulin Production

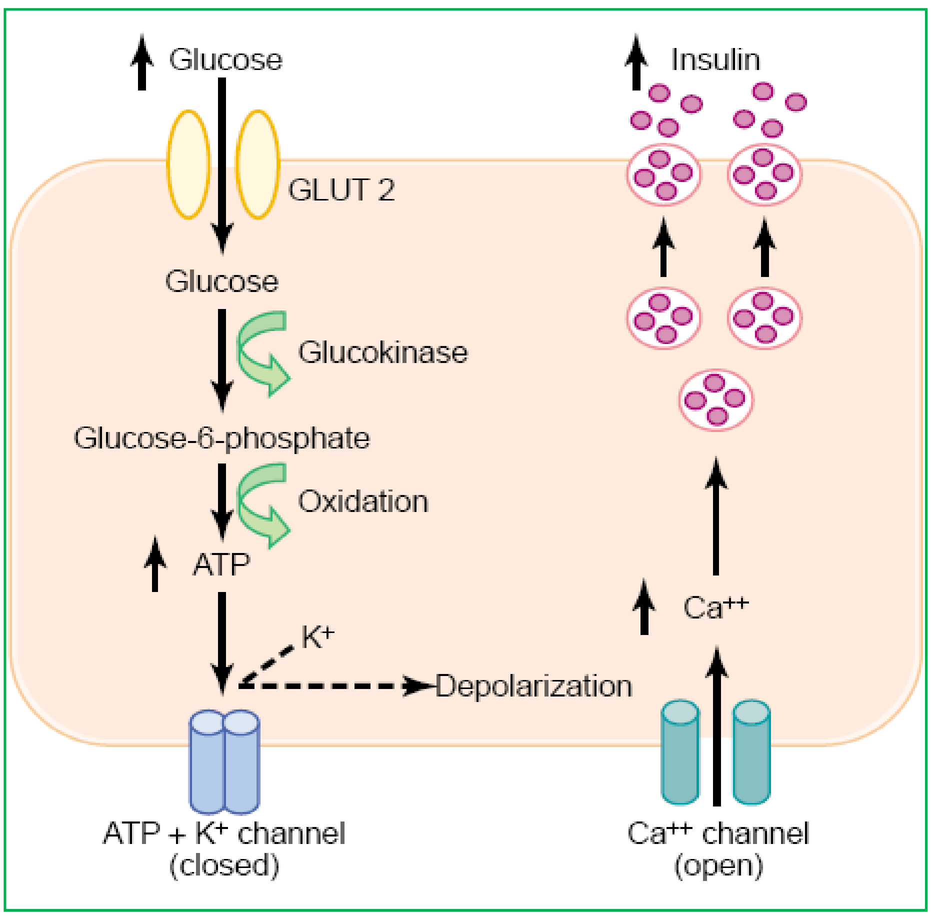


Figure 3 - Basic mechanism of glucose stimulation of insulin secretion by beta cell of pancreas. GLUT, glucose transporters

The amount of circulating insulin is controlled by the rate at which it is secreted into the blood and the rate at which it is removed from it. Insulin is secreted mainly in response to a high blood glucose level. A high carbohydrate meal causes a substantial increase in blood glucose. It is this raised blood glucose level that triggers the release of insulin from the pancreatic cell into the blood. The mechanism of its action is depicted in Figure 3.

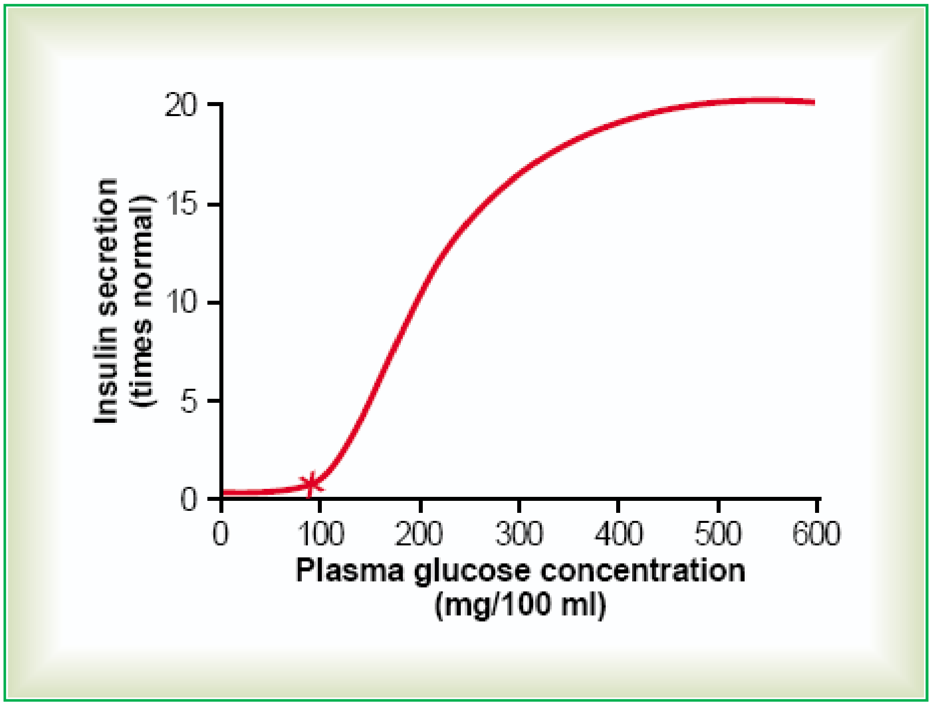


Figure 4: Approximate insulin secretion at different blood glucose levels.

β-cells in the pancreas have a large number of *glucose transporters* (GLUT-2) that permit glucose to enter the cell. This transport of glucose into the cell is proportional to the concentration of glucose in the blood. After its entry into the cell, glucose is converted to glucose-6-phosphate by an enzyme, glucokinase. This step appears to be the rate limiting factor for glucose metabolism in the β-cells and is considered the major mechanism for glucose sensing and adjustment of the amount of secreted insulin in response to the blood glucose levels.

As the secreted insulin reaches the target cell, mainly liver and muscles, it initiates glucose transfer from blood into those cells. As blood glucose is taken up by the cells in response to insulin, its level starts to fall thus sending a negative feedback signal to the β-cells. Hence insulin secretion also decreases as blood glucose level falls.

The insulin that goes into the blood is also being removed effectively from circulation mainly by the liver cells and also, to a lesser extent, by the muscles cells. Hence, by the time blood glucose level returns to normal, excess insulin secretion also stops and blood insulin level returns to normal. Between meals, insulin is produced in small quantities and does not manifest any significant effect.

Other factors that that play a role in insulin production include some amino acids and hormones. Among amino acids, arginine and lysine have considerable effect on insulin secretion. However, their effect is manifested mainly in the presence of high blood glucose level. In other words, these amino acids potentiate the effect of high blood glucose level on insulin production instead of causing increased insulin production by themselves. Some digestive system hormones also cause an increase in insulin secretion. These hormones are secreted mainly to facilitate and coordinate digestive functions mainly after a meal. Their effect on insulin is in anticipation of the forthcoming rise in blood glucose level.

Growth hormone and some others also affect insulin. Again, their affect is mainly of synergetic nature.

There are other aspects of insulin that are important from its functional point of view. However, for simplicity, we have taken only a subset of its characteristics which are among the most important ones.

Chapter 3
Human Endocrine Model

3.1 Blood Glucose Control System – The Human Model

In this chapter our aim is to describe the human endocrine system and formulate certain rules that can be applied or mapped to Robotics and then develop a robotic model that utilizes these same rules.

The first thing that we notice is that insulin producing cells and the target cells where insulin is supposed to act are two physically and functionally separate entities. Neither is aware of the existence of the other. The insulin producing cells are found within the pancreas while the cells that insulin acts are spread all over the human body. One of the most important types of these cells is the muscle cell.

We first take the example of interaction between blood glucose (molecules) and the insulin producing cell. The usual source of blood glucose is the end result of digestion and absorption of food (carbohydrates) in the gastrointestinal system. The insulin producing cells apparently do not have any knowledge of this source or control on the mechanism of entry of glucose into the blood stream. However, these insulin producing cells can identify blood glucose molecules when they encounter them and are capable of responding to such exposure. Here in this case we may assume that glucose is an input to the insulin producing cell and insulin released into the blood stream is an output in response to the input. The rate of input determines the rate of output.

The second example of a similar mechanism is of insulin (molecule) and the target cell e.g. muscle cell. The basis of their relationship is the fact that an insulin molecule can attach to the receptor at the target cell membrane. The important factor here is that the beta cells in the pancreas have the knowledge, not only of how to construct this message (input) but also of affixing a correct address on it so that it can be recognized by the receptor on the target cell membrane. Even though beta cells have the knowledge of the construction and addressing of these messages, they have no knowledge of the location or impact of the message at the target site. The same is true of the target cells. They have the knowledge to produce membrane receptors that will correctly recognize insulin molecules; however, they have no idea of where the insulin is coming from and what is the mechanism of insulin production and control.

Insulin secretion starts when beta cells detect an increase in the blood glucose level. This insulin secretion is proportional to the increase in blood glucose level. Again beta cells do not care where the glucose is coming from. All they are supposed to do is detect the level of glucose in the blood and adjust the output of insulin. Since each glucose molecule is the same, each one delivers the same message to beta cells. For the control of insulin production, it is not the message itself, rather the frequency of the message at which it arrives at the destination that is the rate controlling factor.

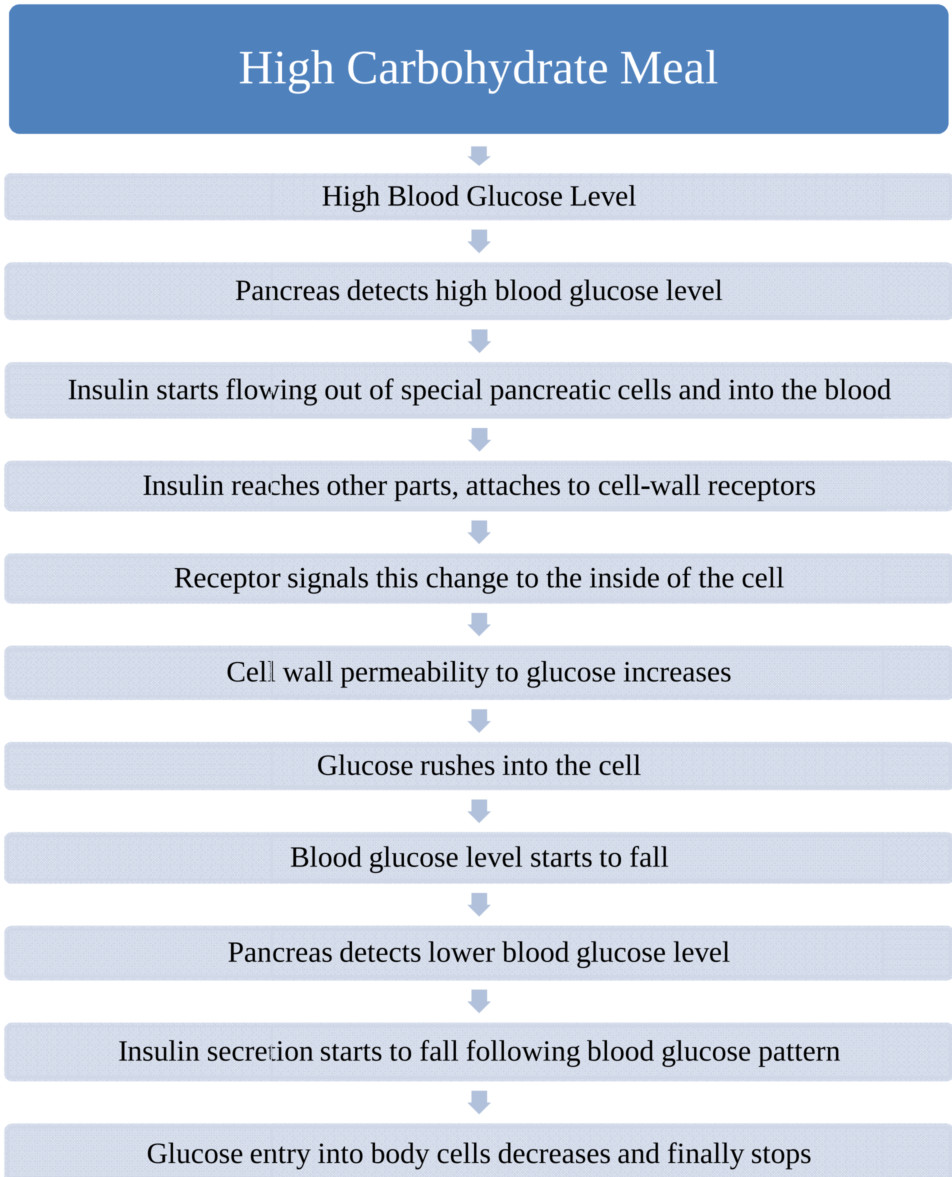


Figure 5 - Sequence of events in blood glucose control process

When target cells in the liver and muscles receive the message in the form of insulin, they respond by activating the glucose transport mechanism within the cell and the cell membrane thus allowing glucose to enter into the cell thus reducing the amount of glucose in the blood. Since blood glucose acts as the message to produce insulin, the lowering of blood glucose in this way appears to slowdown the rate at which insulin producing beta cells respond. This is like sending a negative feedback signal.

We also saw that, other than blood glucose level, some amino acids also play a role in insulin production. Their role is basically to potentiate the effect of blood glucose on insulin production. It means, in other words, the original message attains higher importance when some other appropriate message is received at the same time and, although this does not change the nature of the response, it does change its rate of production. Therefore, it brings about a quantitative change in the response.

3.1.1 Characteristics of human model

With this knowledge, we are able to define certain characteristics that may help us prepare a model; a model that we may apply to our Robotics project comprising of more than one robot (mentioned next chapter).

1. The functional unit (insulin producing β cell, muscle and liver cells) is a separately and independently identifiable entity.
2. There may be more than one unit of one specific type of entity (β cell); entities that accept and generate similar messages are considered of one type.
3. The entities communicate with each other with a predefined message pattern agreed on and understood by both the sender and the receiver.

4. Communication between a pair of entities is specific to both the sender and receiver type. A message sent by one entity type can only be understood by the intended recipient type.
5. A specific instance of a message sent by an entity can be picked up by any one of many entities belonging to the intended entity type.
6. An instance of a message, after its receipt at the destination, is destroyed.
7. The internal working of the unit is not known to the outside world.
8. Entities do not know if their messages are being received by the others or even if should be received.
9. The entities are not aware of the existence of other entities in the world whether of the same type or of different type.
10. All messages flow through the same medium.
11. A received message may cause the recipient to initiate a response.
12. The rate at which responses are initiated is directly proportional to the rate of receipt of incoming messages.
13. A response may consist of a new message to another entity and could possibly be directed to the original sender as feedback.
14. The medium through which messages flow (transportation / delivery system) does not differentiate between messages. It merely transports them to every possible location where recipients pick up messages addressed to them.

Next, we will describe a robotic model that is based on the above characteristics.

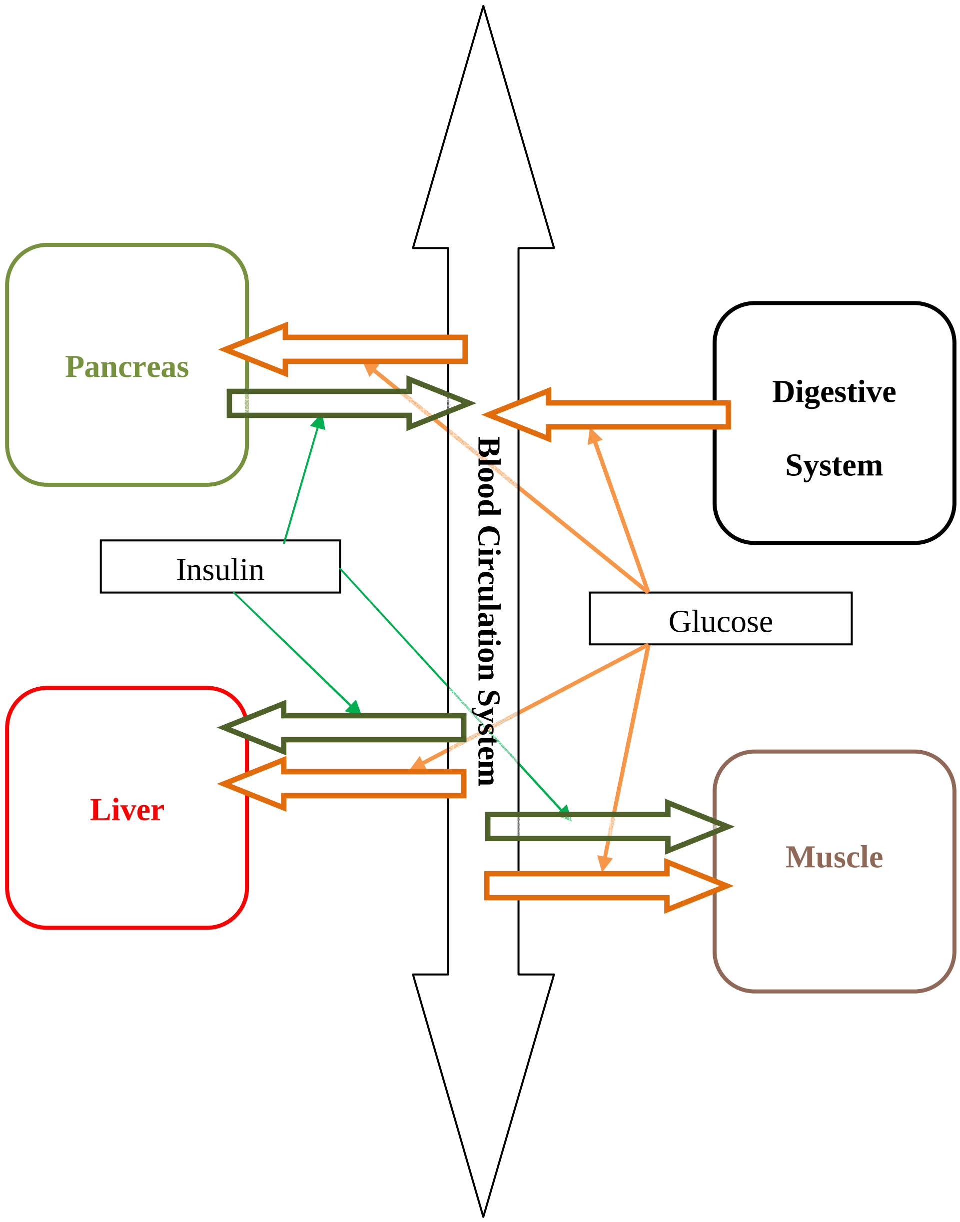


Figure 6 - Human Model showing message transfer between various entities.

Chapter 4
Human Endocrine Model Applied to Robotics

4.1 Mines Detection and Removal System – The Robotics Model

We will apply this human model to the field of robotics. We look at a specific application, namely, the detection and removal of mines from a battle field, with the detection and removal being performed by autonomous robots. It is important to note that our proposed robotics coordination model based on the human endocrine system can be applied to other robotic applications also.

The scenario that we want to model is a simulated field of mines. The robots will go out in the field and detect the presence of mines, record their locations, update a central data repository and remove those mines from the field.

The rules that govern the functioning of robots are derived from our human model. To simulate the human model we will have two types (based on their function) of robots as well as some other services that provide the necessary plumbing for our model. A description of each follows.

4.1.1 The Robots:

- One type of robot will perform the duty of detection. We call them Detectors. Every time these robots detect a mine, they send a notification to a central data repository (Coordinator Service, described later) where all the data is kept.
- A second type of robot, named Remover, performs the mine removal service. They receive notification from the Controller Service about the presence and location of mines.

After each removal they send a notification to the Coordinator Service to update the mine database.

4.1.2 The Services:

- The Coordinator Service controls the overall functions. It decides when and how many robots of each type should be recruited at any particular moment. The Coordinator service receives notifications from the Detector and Remover Services each time a record is created (a mine is detected) or updated (a mine is removed). The service operates under an arbitrary logic as to when a new Detector or Remover should be commissioned or decommissioned. Additionally, this service performs initial mines setup in the field and also provides a visual display.
- All the messages use a Message Service for message transport and delivery. Every entity hands the message to this service which determines the destination based on the type of the message.

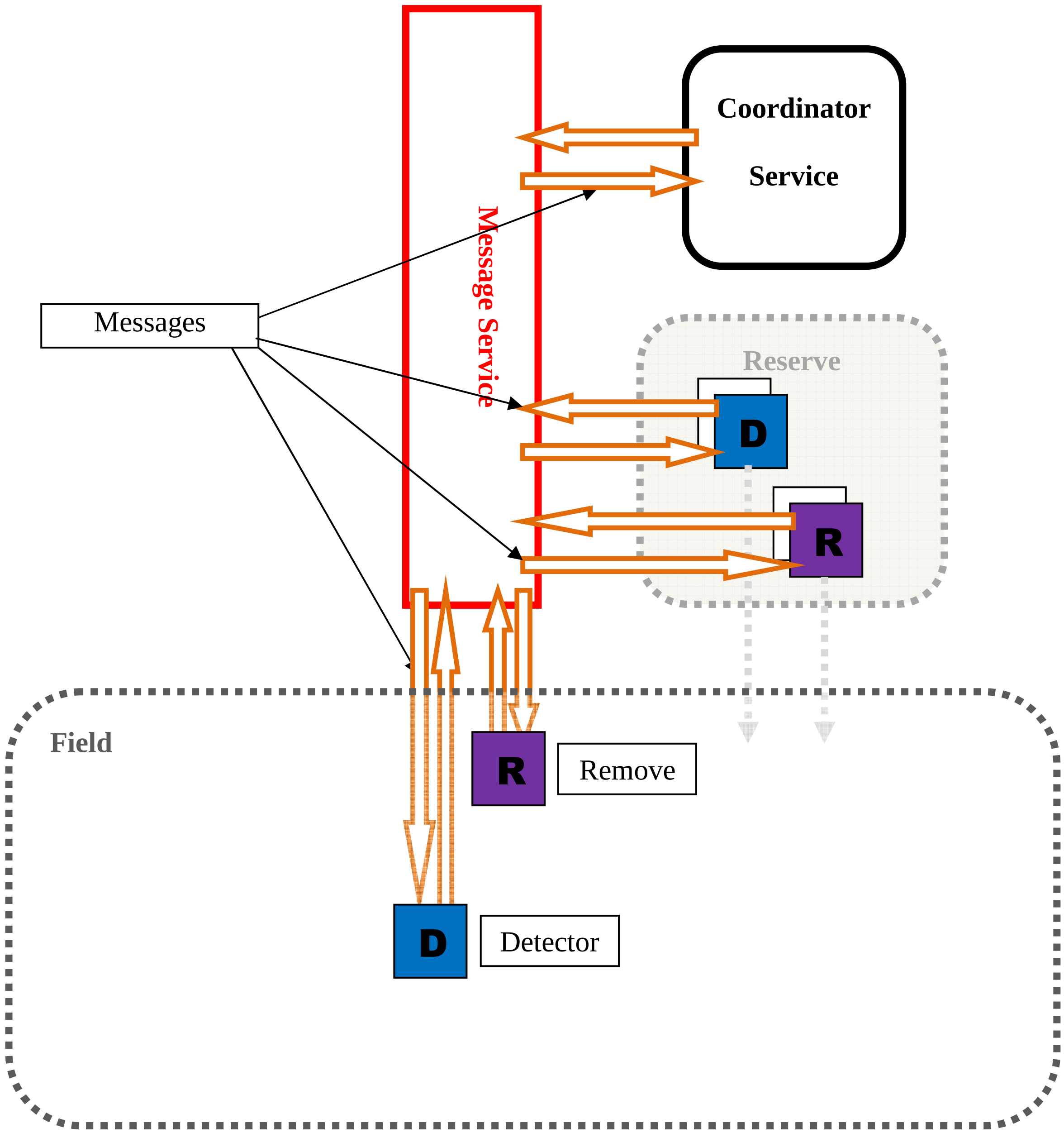


Figure 7 - Robotics Model depicting the communication among various entities (services).

From a programming point of view, our robots and services are one and the same thing. Each one is considered a service that performs a certain task and sends and receives messages.

The model consists of two types of robots and there are two robots of each type, i.e. two of the robots are modeled as Detector and other two as Remover.

To demonstrate this idea, we will use simulation. We will simulate all the functionality in software program utilizing Microsoft platform and technologies. During this simulation we will be able to inspect each service as it is created, check messages sent or received and monitor the system as it runs. We will also be able to log all activity for the entire operation.

4.2 Correlation between Human and Robotic Model

1. The two types of robots, Detectors and Remover, are functionally distinct units and independently identifiable. Each type of Robot performs one function and has no knowledge of the existence of other robot whether it belongs to its own type or the other type.
2. There may be multiple Detectors and multiple Removers active at any given moment during the operation. The maximum number of robots of a single type is fixed at two in this model.
3. The message pattern is predefined and specific to each pair of sender and receiver. Each of the Detectors and Remover can act as sender or receiver or both.
4. Message transfer is specific to sender and receiver pair.
5. A specific instance of a message can be picked up by anyone of the intended recipient types. For example, a message from a Detector to a Remover can be picked up by any one of the two Removers, if both have been commissioned.
6. Once delivered, a message is no longer available for redelivery.
7. The Internal working of any of the Detector and Remover or other support services is not visible to others in the model.

8. Sender of a message does not know if its message was delivered unless recipient sends a response.
9. Services are not aware of the nature of destination of the messages they sent. They just send messages based on the logic they have been programmed for.
10. All messages use the same message delivery service, the Message Service.
11. Upon receipt, a message may or may not cause a response. The response may be another message that is sent out.
12. The Coordinator Service is responsible for monitoring the activity level and recruiting more Detectors or Removers (or removing them from service) based on the amount of work at any given moment.
13. A message, sent in response to the receipt of a message, may be addressed to any other entity. For example, the Coordinator Service may receive a message from the Detector Service and Send a response to a Remover. Or the Coordinator Service may receive a message from a Remover and updates data internally (no message sent out).
14. The message delivery service treats all messages equally with equal priority.

In blood glucose control process, pancreatic beta cells detect presence of glucose in the blood. In our model, Detector robots detect the presence of underground mines. The difference is that beta cells of pancreas are stationary and glucose molecules move around them and come in contact with them. In our model, Detectors are in motion and mines are stationary.

In blood glucose control process, on glucose detection, beta cells dispatch a message for the target cells in liver and muscles in the form of insulin molecules. In our model, upon detection of a mine, Detector robots send a message for Remover robots.

In blood glucose control process, liver and muscle cells receive the message (insulin molecule) and start removing the glucose from the blood stream. In our model, Remover robots receive the message and go out in the field and remove the mine.

Table 1: Blood Glucose Control versus Mine Detection & Removal

Blood Glucose Control	Mine Detection and Removal
Glucose molecule (moving)	**Underground mine (stationary)**
Beta cells in pancreas (stationary)	**Detector robots (moving)**
Insulin molecules	**Message from Detector to Removers**
Liver & muscle cells (stationary)	**Remover Robots (moving)**

Chapter 5
Implementation

5.1 Tools and Framework

As mentioned earlier in the last chapter, to implement this model we used Microsoft tools and technology. Microsoft's Robotics Development Studio [MRDS] is an integrated development, simulation and test environment that provides all the features that we may need in our implementation. The programming language that we have chosen is C# (C-Sharp) that is the preferred language of the Robotics Development Studio. The recent improvements and inclusion of new features in this language offer a multi threaded programming model that fits our needs for this project. It handles multi-threaded program execution in a non-blocking manner and enables writing sequential programs that behave like a real-time event based concurrent programming model.

Although MRDS provides its own simulation environment, we didn't utilize it and instead build our own simulation. This allowed us to keep our code relatively simple and brief.

5.2 Field Setup

For this implementation, a field of size 400m x 400m was chosen. This corresponds to a screen size of 400 pixel x 400 pixel.

5.3 Mines

The number of mines was selected randomly with a maximum limit of 15 with no limit on the minimum number of mines. For each run, a new random number was generated for this purpose. Similarly, mines were placed randomly in the field with a minimum clearance of 20m from another mine and minimum clearance distance of 10m from the boundary of the field. Each time

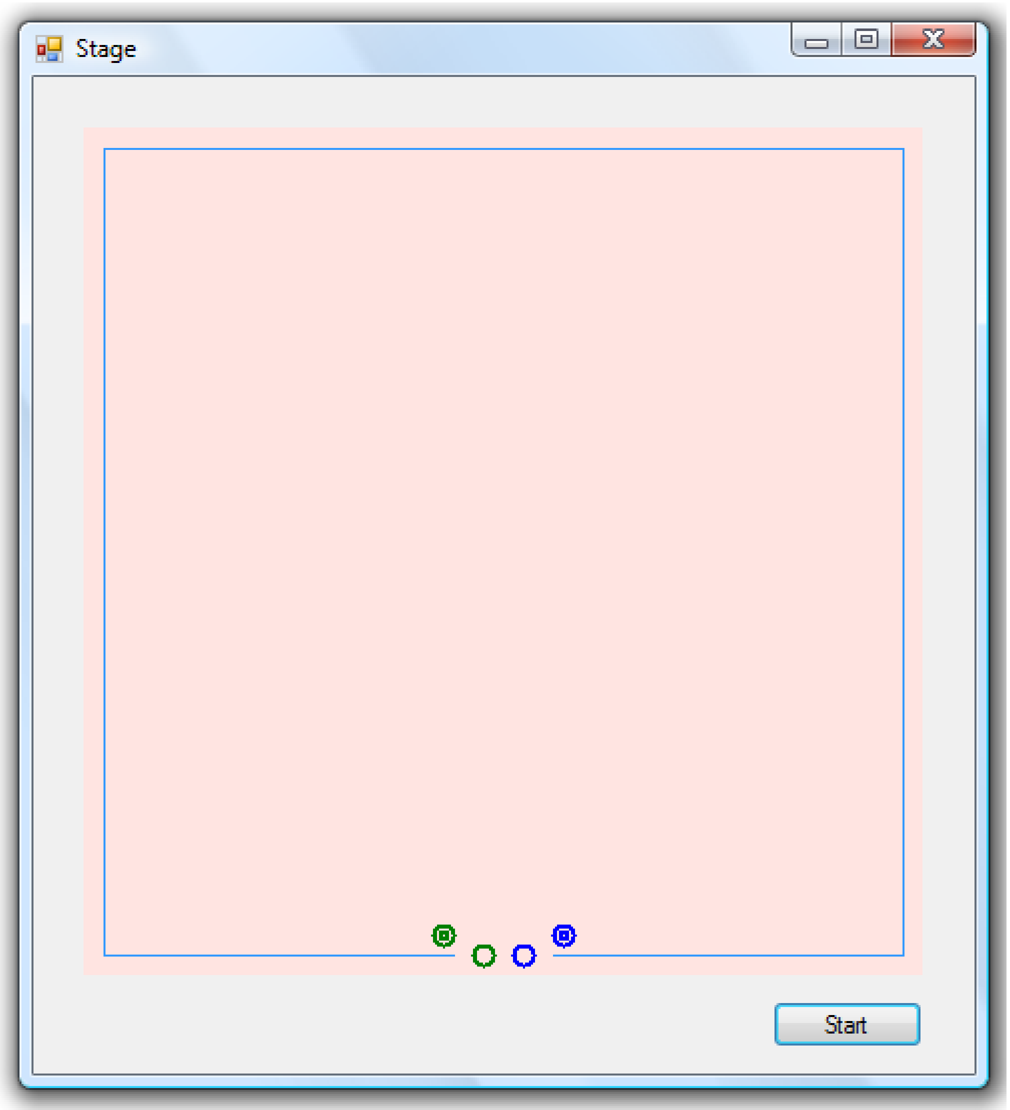


Figure 8: Initial position of Detectors (with a dot in the center) and Removers (without the central dot

the program is run, it displays a different number of mines placed in the field

5.4 Detectors

This is one of the two main services that demonstrate the main idea. As previously decided, there are two detectors which are initially positioned near the mid-point of the lower boundary in the

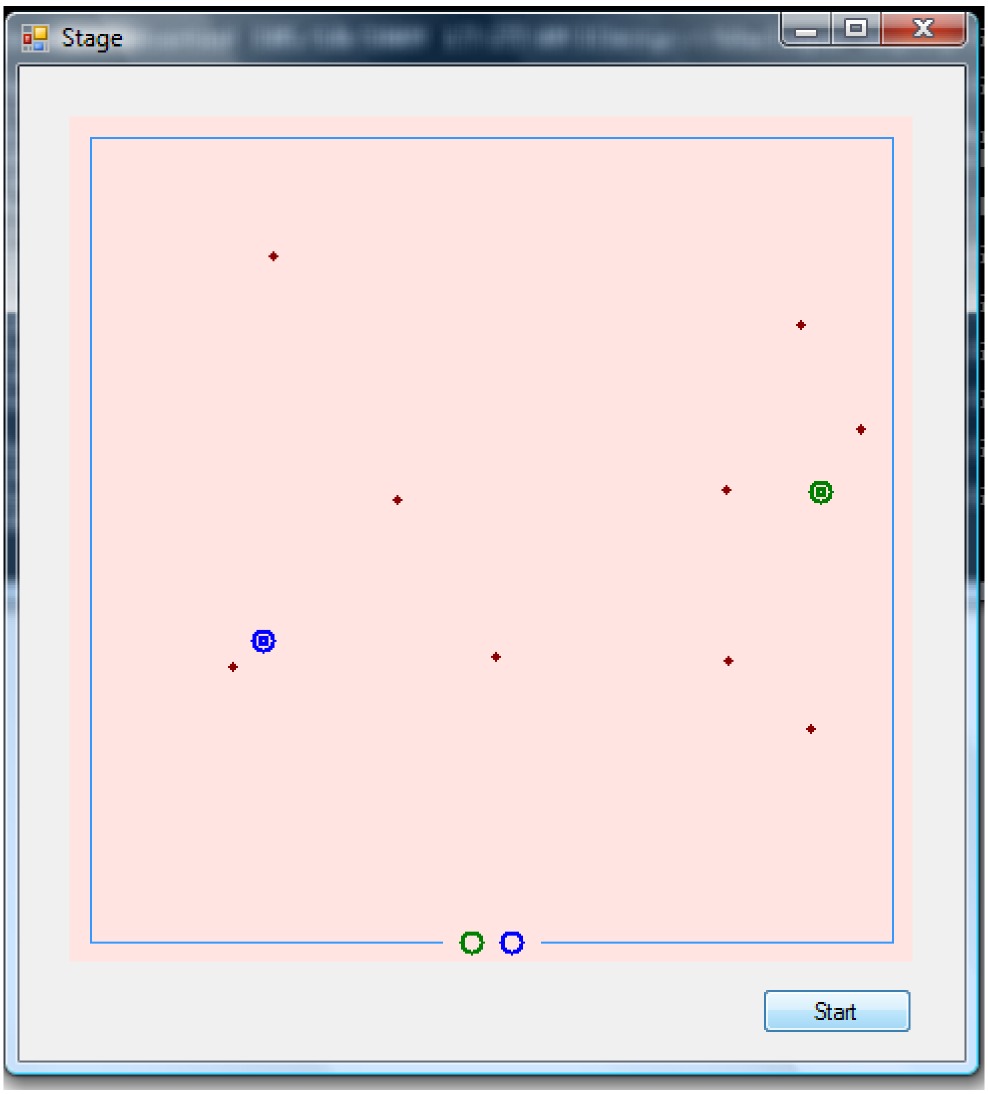


Figure 9: Detectors have started their job and moving the field. No mines have been detected so far and Removers are still at their initial position waiting to receive a message.

visual display. The footprint of the detector was 2m x 2m. The Detectors start their movement after the mines are placed and move along a straight line whose angle is based on a randomly generated number. They move at a speed of 5m per minute. When they hit the boundary, they bounce off it and continue their motion in a straight line. If two detectors run into each other, they change their direction in order to avoid a collision. Similarly, detectors change their direction to avoid collision with Removers.

The mine detection process is simple. At each position, Detector determines if it is right over a mine. If it is, it sends a message to the Controller Service that it has detected a mine. The

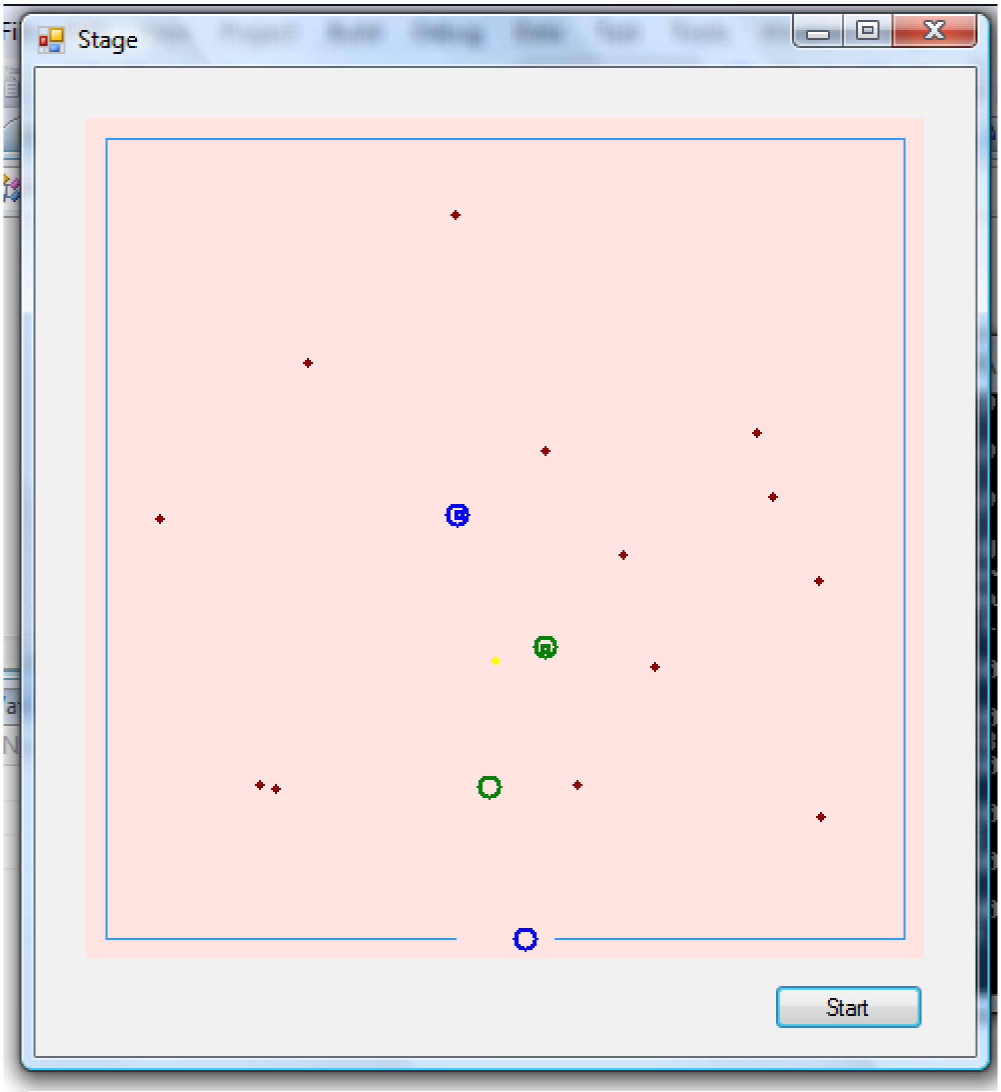


Figure 10: First mine detected (yellow). The first Remover is moving towards its target.

message includes the location information of the detected mine.

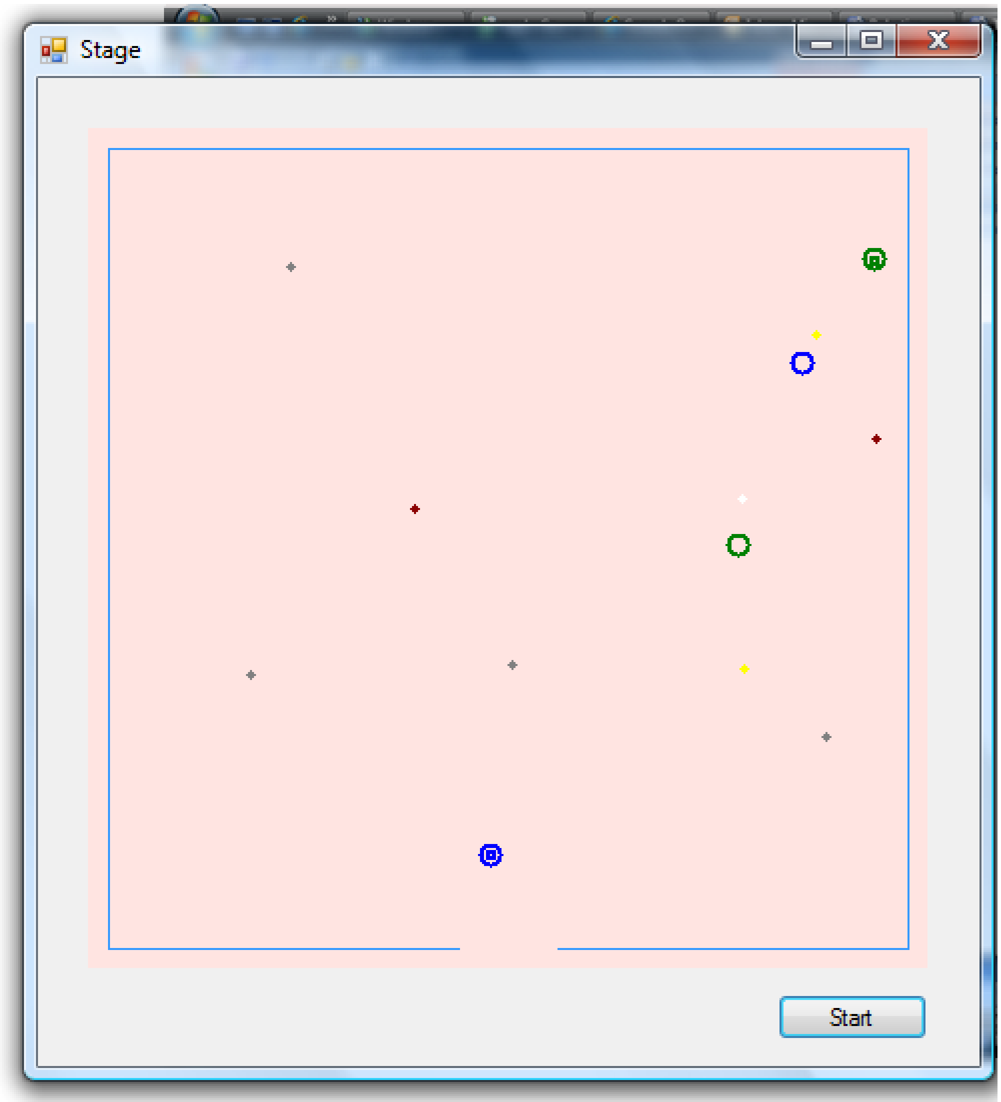


Figure 11: Both the Removers have been called in. Some of the mines have been removed (white), some are pending removal (grey) and some are yet to be detected.

5.5 Removers

Remover is the other main component of this idea. There are two Removers in this implementation. The footprint of the Remover is 2m x 2m. Initially they positioned near the lower boundary of the field like Detectors. They stay there until they receive a message from the data center to remove a mine. The message contains location information of the mine to be removed. Upon receipt of such message, Remover starts moving straight towards the mine at a speed of 0.5m per minute. The Remover moves at a much slower speed than the Detector. The assumption here is that Remover carries special heavy equipment to remove mines while Detector's is lighter and its needs in terms of equipment are limited. Additionally, in our source model (human) not all component work at the same speed.

The mine is supposed to be removed once Remover reaches that location. Upon removal, Remover sends a message to the Data Center that the mine has been removed. The remover stays at that position until it receives another message to remove a mine.

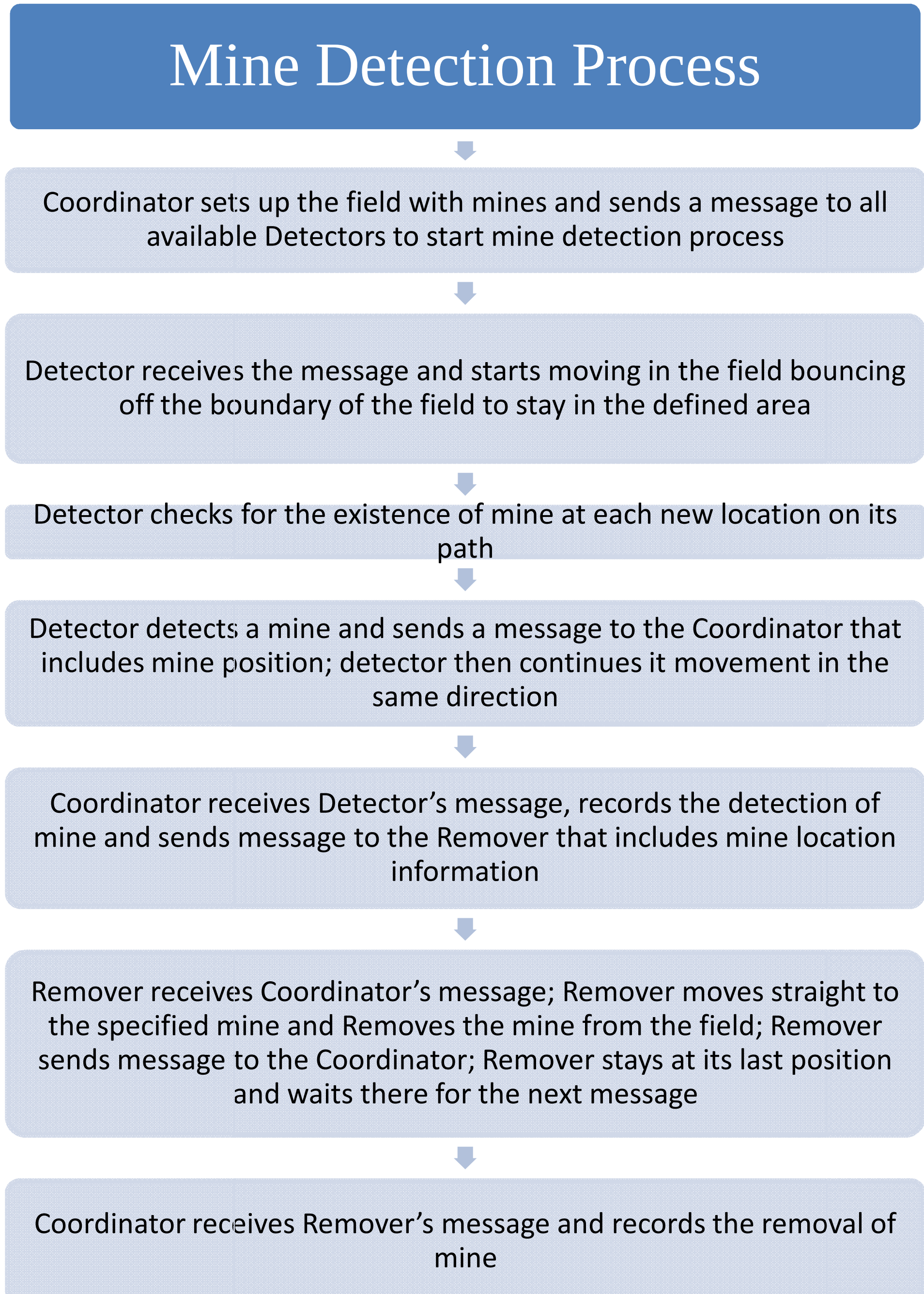


Figure 12: Sequence of events and message passing between various entities during mine detection process

5.6 Coordinator Service

The Coordinator Service mainly plays a role of message coordinator. For this demonstration, this provides the services of field setup, visual display and message coordination between Detectors and Removers. It also monitors the completion of the detection and removal process.

5.7 Limitations and Differences

Since we were operating under a simulated environment, we needed to introduce a Coordinator in the system. In an actual field, there would be no need to setup a field and then monitor completion of the process. In our simulation, however, we needed to set up the field with varying number of mines and also monitor the process to determine if all of the mines have been eliminated. In a real world system we would run the operation for a predetermined amount of time to achieve a certain degree of confidence that all mines have been removed. Determination of such a time period would most likely take into account the size of the field and speed of Detectors and Removers.

The human model employs negative feedback mechanism to throttle the activity level of the system. For example, when glucose concentration in the blood falls as a result of its movement into liver and muscle cell, it acts as a negative feedback signal to the pancreas which slows down insulin secretion. Our model lacks this feature though it certainly can benefit from it. For example, during detection process a point may come where most of the mines are expected to be detected and therefore, at that time some of the Detectors may be pulled off the field.

5.8 Results

The program code was successfully compiled and tested. The program also logged the time for each message sent or received as well as when the detection of all mines was completed and when the removal of all mines was completed.

For each run of the program we recorded the number of mines in the field, the time it took to detect all of the mines and the time it took to remove all of the mines. The averages were calculated from 5 different run for each row in the following table. Actual speed was much faster than the stated speed of detectors and removers. This was necessary in order to complete the collection of data in a reasonable amount of time. The speed and thus the time were then scaled to match the stated speed of the Detectors and Removers. The data is shown in the following table.

Table 2: Average time to detect and remove one mine from the field

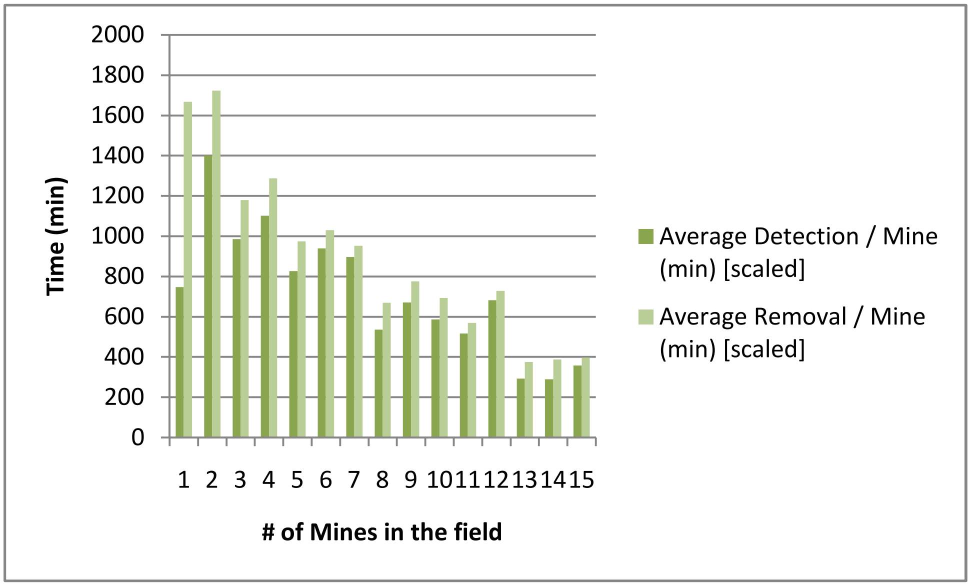
Number of Mines	Average Time / Mine	
	Detection	Removal
1	748	1668
2	1400	1724
3	985	1180
4	1102	1288
5	826	974
6	940	1031
7	897	953
8	535	669
9	672	776
10	586	692
11	516	569
12	681	728
13	292	375
14	290	389
15	358	397

We see a pattern here in the collected data, that is, the average detection and removal time decreases as the number of mines in the field increases. This is understandable because with more mines in the same field, there is a higher probability that the next detector position will be a mine location. We also see that removal time is higher than the detection time. This is because removal does not start until a mine is detected and continues for a short while after the last mine is detected.

As the number of mines in the field increases, the average removal and detection time per mine decreases. In the chart below, when the number of mines reaches 13, we do not see any improvements in average detection or removal time /mine. In fact there is slight increase in the time. This may be the sign that the system has reached close to its maximum performance. This characteristic is good in a sense that the system can achieve best performance with reasonably small number of mines.

There are some values in the table that do not agree with the overall pattern. This is partly because detector movement is random and the algorithm used to move them around is very simple and partly because our sample size was small.

Appendix B consists of a table of data that was collected during these runs.



Graph 1: The graph showing number of mines and the average time to detect and remove one mines

As we have seen, the model demonstrates coordination of independent entities mainly using a loosely coupled messaging system. Entities define the messages that they would send as well as the message types that they are interested in receiving. The message format is very flexible and completely user definable. The structure & format of different messages is defined in Appendix C.

At the start, entities send out a few messages to setup the stage. After that, each Detector sends out one message for each mine detected. There is one message sent to a Remover for each mine assigned. A confirmation message is sent out by the Remover on successful mine removal. Therefore, for each mine detected and removed, there are 3 messages that are sent out.

Chapter 6
Conclusion

The implementation of this model demonstrates the possibility that this model may be successfully implemented in a real world. Although we only created a simulation, the actual idea of the model was clearly demonstrated. The main advantage of this model is its scalability feature, its robustness and freedom from a single point of failure. Depending upon the resource availability and the size of the load, units can be added or removed without making changes to the system or even while the system is in operation. The functionality of the system scales well with the change in requirements. Moreover, removal or failure of one unit does not halt the system though throughput might be affected.

A lot of work still needs to be done to achieve a practical solution based on this idea. The next logical step would be to implement it with real robots in a laboratory environment. Next, the same can be tested in an outdoor, more realistic environment. With the recent advances and current focus in this field (robotics), it is relatively easy to visualize such a solution in near future, if further work in this direction is continued. With the availability of global positioning solutions, localizing software, wireless communications, practically all component technologies are available today to achieve this goal.

References

1. Guyton and Hall, **Textbook of Physiology,** Eleventh Edition, *Unit XIV Endocrinology and Reproduction*. Published by Saunders, 2005.
2. Dipankar Dasgupta, Z. Ji. University of New Memphis, Memphis TN. **Artificial Immune Systems (AIS) Research in the Last Five Years.** *Proceedings of the Congress on Evolutionary Computation Conference (CEC),* Volume 1, pp 123-130, 2003.
3. Steven A. Hofmeyr & Stephanie Forrest. **Immunity by Design: An Artificial Immune System.** *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO),* pp. 1289-1296, 1999.
4. Dipankar_Dasgupta, Senhua Yu, and Nivedita Sumi Majumdar. **MILA – Multilevel Immune Learning Algorithm.** *Proceedings of the Genetic and Evolutionary Computation Conference(GECCO),* Volume 2723, pp 201, 2003.
5. Dipankar Dasgupta, S. Yu, N. S. Majumdar. **MILA – multilevel immune learning algorithm and its application to anomaly detection.** *Soft Computing Journal* Volume 9 Issue 3 pp 172-184, 2003.
6. Tucker Balch, Ronald C. Arkin, **Communication in reactive multiagent robotic system**, Autonomous Robots, Volume 1, Issue 1 pp. 27 – 52**,** 1994
7. Stergios I. Roumeliotis, George A. Bekey, **Distributed Multi Robot Localization**, *IEEE Transactions on Robotics and Automation*, Volume 18, Issue 5 pp781-795, 2002
8. Wolfram B., Mark M., Cyrill S., Frank S., **Coordinated Multi Robot Exploration**, *IEEE Transactions on Robotics*, Volume 21, Issue 3, pp 376-386, 2005

Bibliography

1. Warren E. Levinson and Ernest Jawetz, **Medical Microbiology & Immunology,** fourth edition, published by Appleton & Lange, 1996.
2. Arthur G. Johnson, Richard J. Zeigler, Thomas J. Fitzgerald, Omelan A.Lukasewycz, Louise B.Hawley. **Microbiology and Immunology.** Lippincott Williams & Wilkins, fourth edition, 2001.
3. F. Esponda, S. Forrest, and P. Helman. **A Formal framework for positive and negative detection.** *IEEE Systems, Man, and Cybernetics, Part B: Cybernetics, Transactions on*, Volume 34, Issue 1, pp 357-373, 2004.
4. Jeffrey O. Kephart, David M. Chess, Steve R. White, High Integrity Computing Laboratory, IBM Thomas J. Watson Research Center, NY. **Computers and Epidemiology.** *IEEE SPECTRUM*, May 1993
5. S. A. Hofmeyr, A. Somayaji, and S. Forrest. **Intrusion Detection using Sequences of System Calls.** *Journal of Computer Security* Vol. 6, Issue 3 pp 151-180, 1998.
6. S. Forrest, A.S. Perelson, L. Allen, and R. Cherukuri. **Self-nonself discrimination in a computer.** *Proceedings IEEE Symposium on Research in Security and Privacy*, pp. 202-212, 1994.

Appendix A

Log of messages and other state information during a typical run.

Typically, a few messages are exchanged at the start of the process. After that, each detection and removal comprises of one message.

* Controller: OnLoad message recevied [05/19/2009 12:31:08][http://khaliquerehman.com:50000/krcontroller]
* Controller: OnStart message recevied [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krcontroller]
* Controller: SetupStage executed [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krcontroller]
* Controller: Calling subscribe method [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krcontroller]
* Detector_1: Ready to work [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krdetector/52975c9f-b74b-4f56-b0d8-e0176637d1ad]
* Controller: Response to Subscribe message received from First Remover KRRemover.Proxy.KRRemoverOperations [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krcontroller]
* Controller: Response to Subscribe message received from First Remover KRRemover.Proxy.KRRemoverOperations [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krcontroller]
* Detector_2: Ready to work [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krdetector/fced62ac-b00d-4a3d-b762-3ae099598e04]
* Controller: Activation of Second Remover succeeded [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krcontroller]
* Detector_1: Mines count: 15 [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krdetector/52975c9f-b74b-4f56-b0d8-e0176637d1ad]
* Controller: Activation of First Remover succeeded [05/19/2009 12:31:10][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=322,Y=177}, changed color to Color [Gray] [05/19/2009 12:31:20][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 14, PendingRemovalCount: 1 [05/19/2009 12:31:20][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=322,Y=177} received [05/19/2009 12:31:22][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: Detected Mine {X=366,Y=155}, changed color to Color [Gray] [05/19/2009 12:31:27][http://khaliquerehman.com:50000/krcontroller]

* Controller: PendingDetectionCount: 13, PendingRemovalCount: 2 [05/19/2009 12:31:27][http://khaliquerehman.com:50000/krcontroller]
* Remover_1: ReceiveTarget message {X=366,Y=155} received [05/19/2009 12:31:27][http://khaliquerehman.com:50000/krremover/ba2eb3fc-6dd4-4dd3-a360-d401a47af537]
* Controller: Detected Mine {X=225,Y=220}, changed color to Color [Gray] [05/19/2009 12:31:38][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 12, PendingRemovalCount: 3 [05/19/2009 12:31:38][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=29,Y=138}, changed color to Color [Gray] [05/19/2009 12:31:52][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 11, PendingRemovalCount: 4 [05/19/2009 12:31:52][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=80,Y=170}, changed color to Color [Gray] [05/19/2009 12:32:02][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 10, PendingRemovalCount: 5 [05/19/2009 12:32:02][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=151,Y=163}, changed color to Color [Gray] [05/19/2009 12:32:04][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 9, PendingRemovalCount: 6 [05/19/2009 12:32:04][http://khaliquerehman.com:50000/krcontroller]
* Controller: TargetRemoved message {X=322,Y=177} received from Remover_2 [05/19/2009 12:32:26][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=225,Y=220} received [05/19/2009 12:32:26][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: TargetRemoved message {X=366,Y=155} received from Remover_1 [05/19/2009 12:32:41][http://khaliquerehman.com:50000/krcontroller]
* Remover_1: ReceiveTarget message {X=151,Y=163} received [05/19/2009 12:32:41][http://khaliquerehman.com:50000/krremover/ba2eb3fc-6dd4-4dd3-a360-d401a47af537]
* Controller: TargetRemoved message {X=225,Y=220} received from Remover_2 [05/19/2009 12:32:44][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=80,Y=170} received [05/19/2009 12:32:44][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: Detected Mine {X=116,Y=373}, changed color to Color [Gray] [05/19/2009 12:32:46][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 8, PendingRemovalCount: 4 [05/19/2009 12:32:46][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=79,Y=105}, changed color to Color [Gray] [05/19/2009 12:33:04][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 7, PendingRemovalCount: 5 [05/19/2009 12:33:04][http://khaliquerehman.com:50000/krcontroller]

* Controller: TargetRemoved message {X=80,Y=170} received from Remover_2 [05/19/2009 12:33:13][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=29,Y=138} received [05/19/2009 12:33:13][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: TargetRemoved message {X=151,Y=163} received from Remover_1 [05/19/2009 12:33:22][http://khaliquerehman.com:50000/krcontroller]
* Remover_1: ReceiveTarget message {X=79,Y=105} received [05/19/2009 12:33:22][http://khaliquerehman.com:50000/krremover/ba2eb3fc-6dd4-4dd3-a360-d401a47af537]
* Controller: TargetRemoved message {X=29,Y=138} received from Remover_2 [05/19/2009 12:33:23][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=116,Y=373} received [05/19/2009 12:33:23][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: Detected Mine {X=213,Y=316}, changed color to Color [Gray] [05/19/2009 12:33:37][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 6, PendingRemovalCount: 3 [05/19/2009 12:33:37][http://khaliquerehman.com:50000/krcontroller]
* Controller: TargetRemoved message {X=79,Y=105} received from Remover_1 [05/19/2009 12:33:37][http://khaliquerehman.com:50000/krcontroller]
* Remover_1: ReceiveTarget message {X=213,Y=316} received [05/19/2009 12:33:37][http://khaliquerehman.com:50000/krremover/ba2eb3fc-6dd4-4dd3-a360-d401a47af537]
* Controller: TargetRemoved message {X=116,Y=373} received from Remover_2 [05/19/2009 12:33:40][http://khaliquerehman.com:50000/krcontroller]
* Controller: TargetRemoved message {X=213,Y=316} received from Remover_1 [05/19/2009 12:34:03][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=302,Y=343}, changed color to Color [Gray] [05/19/2009 12:34:25][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 5, PendingRemovalCount: 1 [05/19/2009 12:34:25][http://khaliquerehman.com:50000/krcontroller]
* Remover_1: ReceiveTarget message {X=302,Y=343} received [05/19/2009 12:34:27][http://khaliquerehman.com:50000/krremover/ba2eb3fc-6dd4-4dd3-a360-d401a47af537]
* Controller: TargetRemoved message {X=302,Y=343} received from Remover_1 [05/19/2009 12:34:44][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=158,Y=38}, changed color to Color [Gray] [05/19/2009 12:34:45][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 4, PendingRemovalCount: 1 [05/19/2009 12:34:45][http://khaliquerehman.com:50000/krcontroller]
* Remover_1: ReceiveTarget message {X=158,Y=38} received [05/19/2009 12:34:45][http://khaliquerehman.com:50000/krremover/ba2eb3fc-6dd4-4dd3-a360-d401a47af537]

* Controller: TargetRemoved message {X=158,Y=38} received from Remover_1 [05/19/2009 12:35:13][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=273,Y=287}, changed color to Color [Gray] [05/19/2009 12:35:38][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 3, PendingRemovalCount: 1 [05/19/2009 12:35:38][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=273,Y=287} received [05/19/2009 12:35:40][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: TargetRemoved message {X=273,Y=287} received from Remover_2 [05/19/2009 12:36:11][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=303,Y=125}, changed color to Color [Gray] [05/19/2009 12:36:20][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 2, PendingRemovalCount: 1 [05/19/2009 12:36:20][http://khaliquerehman.com:50000/krcontroller]
* Remover_1: ReceiveTarget message {X=303,Y=125} received [05/19/2009 12:36:20][http://khaliquerehman.com:50000/krremover/ba2eb3fc-6dd4-4dd3-a360-d401a47af537]
* Controller: TargetRemoved message {X=303,Y=125} received from Remover_1 [05/19/2009 12:36:48][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=344,Y=303}, changed color to Color [Gray] [05/19/2009 12:37:41][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 1, PendingRemovalCount: 1 [05/19/2009 12:37:41][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=344,Y=303} received [05/19/2009 12:37:42][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: TargetRemoved message {X=344,Y=303} received from Remover_2 [05/19/2009 12:37:56][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detected Mine {X=259,Y=337}, changed color to Color [Gray] [05/19/2009 12:41:14][http://khaliquerehman.com:50000/krcontroller]
* Controller: Detection of all mines completed [05/19/2009 12:41:14][http://khaliquerehman.com:50000/krcontroller]
* Controller: PendingDetectionCount: 0, PendingRemovalCount: 1 [05/19/2009 12:41:14][http://khaliquerehman.com:50000/krcontroller]
* Remover_2: ReceiveTarget message {X=259,Y=337} received [05/19/2009 12:41:14][http://khaliquerehman.com:50000/krremover/49cb11de-f2c8-4cdb-b3d9-593a889b9d61]
* Controller: Removal of all mines is completed [05/19/2009 12:41:30][http://khaliquerehman.com:50000/krcontroller]
* Controller: TargetRemoved message {X=259,Y=337} received from Remover_2 [05/19/2009 12:41:30][http://khaliquerehman.com:50000/krcontroller]

Appendix B

Project Data Collected

Time (min) [scaled]										
Mine Count	First Run		Second Run		Third Run		Fourth Run		Fifth Run	
	Detection	Removal	Detection	Removal	Detection	Removal	Detection	Removal	Detection	Removal
1	60	1420	420	1160	1200	1360	1880	3520	180	880
2	3940	4580	2800	3600	3700	4700	2260	2400	1300	1960
3	4900	5260	3080	3680	3100	3760	2640	3040	1060	1960
4	7400	8400	1620	2480	4180	4700	4580	5500	4260	4680
5	1900	2600	2420	2620	6360	7120	6000	7040	3980	4980
6	6240	7200	7680	8560	7200	7280	4140	4360	2940	3520
7	6140	6480	11360	11520	4900	5800	5840	6320	3160	3220
8	4420	4640	5640	7980	2160	3880	6480	6760	2700	3500
9	6280	8100	5380	6020	7840	8520	4760	5540	5960	6740
10	5820	6920	6120	7540	6740	7500	7780	8100	2840	4560
11	5520	6220	6900	7400	7700	8080	4000	4780	4260	4840
12	5540	6140	9200	9440	15020	15560	5020	5520	6100	7000
13	3420	5140	3400	4460	5660	5900	3280	4800	3220	4060
14	6100	7460	4100	4440	3420	4820	3800	4500	2860	5980
15	3600	4600	4560	5280	8140	8320	6380	6780	4200	4800

Appendix C

Message Format

Message sent by Detector
1. Id [integer]
2. Current Location [Point(x, y)]
3. Direction [0 to 2π]
4. At Work [Boolean flag]

Message received by Remover
1. Id [integer]
2. Target Mine [Point(x, y)]

Message sent by Remover
1. Id [integer]
2. Target Location [Point(x, y)]

VITA

Khalique Rehman

Candidate for the Degree of

Master of Science

Thesis: AUTONOMOUS ROBOTIC MODEL BASED ON HUMAN ENDOCRINE SYSTEM

Major Field: Computer Science

Biographical:

Education:

M.B., B.S.
University of Karachi, Karachi Pakistan 1983

Postgraduate Diploma in Computer Science
University of Karachi, Karachi Pakistan 1995

Completed the requirements for the Master of Science in Computer Science at Oklahoma State University, Stillwater, Oklahoma in July, 2009.

Experience:

Database Programmer	Flightsafety International, Simulation Systems Broken Arrow, OK (Since 2004)
Application Programmer	Enhanced Communication Group Bartlesville, OK (2003-2004)
Consultant	Williams Communications Tulsa, OK (1991-2002)
Application Programmer	Image Analysis Columbia, KY (1997-1999)
Manager IT	Lens Lab Karachi, Pakistan (1992-1995)
Manager IT	Mercury Garments Karachi, Pakistan (1990-1992)

Name: Rehman, Khalique Date of Degree: July, 2009

Institution: Oklahoma State University Location: Tulsa, Oklahoma

Title of Study: AUTONOMOUS ROBOTIC MODEL BASED ON HUMAN ENDOCRINE SYSTEM

Pages in Study: 41 Candidate for the Degree of Master of Science

Major Field: Computer Science

Scope and Method of Study:

Robots are being used in industry for quite some time and have evolved into much sophisticated autonomous agents. Now, with the advancement in technology, robots are fast entering daily life. This highlights some important aspects of their use; that is collaboration among robots and human-robot interaction. This thesis concentrates on robotic collaboration and presents a model that is based on human endocrine system.

In another area of research, namely Computer Immune System, researchers have used human immune system as the basis for their research model. This led us to look for answer to our problem inside human physiological systems. We chose Blood Glucose Control Mechanism as our source from among other systems because it is simpler and has the characteristics that our robotic collaboration model can be based on.

Findings and Conclusions:

We implemented the model in a hypothetical field of underground mines where two types of robots were used for mine detection and removal. A visual simulation was also developed. The data was then analyzed in terms of average time required to detect and to remove a single mine. We repeated the experiments 5 times, with number of mines varying from 1 through 15, and then calculated the average time. The results show that, as the number of mines increases, the average detection and removal time decreases.

The implementation of this model showed that this model may be implemented with real robots. The model is scalable, robust and has no single point of failure. Robots can be added and / or removed while in operation without affecting overall system. This may provide the basis for future work where this model may be implemented with real robots.

ADVISER’S APPROVAL: Dr. Johnson P. Thomas