Develop Measures of Effectiveness and Deployment Optimization Rules for Networked Ground Micro-Sensors

A Thesis Presented to

the Faculty of the School of Engineering and Applied Science,

University of Virginia

In Partial Fulfillment of the Requirements for the Degree

Masters of Science (Systems Engineering)

by

Linda M. J. Lamm

May 2001

REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY) 01-05-2001	2. REPORT TYPE Master's Thesis	3. DATES COVERED (FROM - TO) xx-xx-2001 to xx-xx-2001
4. TITLE AND SUBTITLE Develop Measures of Effectiveness and Deployment Optimization Rules for Networked Ground Micro-Sensors Unclassified		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Lamm, Linda M. ;		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME AND ADDRESS University of Virginia School of Engineering and Applied Science Charlottesville , VA 00000		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS ,		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT A PUBLIC RELEASE ,		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

Future combat systems planned for the 2008 timeframe and beyond require medium size armament vehicles that fit onto C-130 airplanes, and smaller deployed forces that are capable of covering a greater area within a complex environment. Command, control surveillance and reconnaissance capabilities are vital to the success of any mission. With this reduction in forces and the armament they use, comes a requirement for increased intelligence and knowledge of the battlefield. Networked ground micro-sensors represent one aspect available to enhance the US Army?s capabilities for covering Beyond Line of Sight (BLOS) areas and joins in with Unmanned Aerial Vehicles (UAV) and Unmanned Ground Vehicles (UGV) for gaining dominant situational awareness across all echelons of the future battlefield. This thesis presents a methodology for determining measures of effectiveness for guidance in developing rules for employing networked ground micro-sensors on the battlefield. These rules and guidelines help users to understand how networked sensors can best be employed on the battlefield. The thesis process: 1) uses a systems engineering framework to understand the problem, 2) literature research to understand networked sensor capabilities, 3) develops a framework for determining measures of effectiveness for a system, 4) demonstrates the application of statistical tools such as Response Surface Methodology (RSM), which is used to develop sensor employment rules, and 6) uses a computer simulation to test experimental designs and obtain outputs (i.e., measures of effectiveness values).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
			Public Release	156	Fenster, Lynn lfenster@dtic.mil
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER International Area Code Area Code Telephone Number 703 767-9007 DSN 427-9007

APPROVAL SHEET

This thesis is submitted in partial fulfillment of the requirements for the degree of Masters of Science (Systems Engineering).

____

Linda Mary Johnson Lamm (Author)

This thesis has been read and approved by the Examining Committee:

____

Professor Donald E. Brown (Thesis Advisor)

____

Professor Christina M. Mastrangelo (Chairperson)

____

Professor Brian L. Smith

Accepted for the School of Engineering and Applied Science:

____

Dean, School of Engineering and Applied Science

May 2001

DEDICATION

I dedicate this thesis to Gregory, my best friend and loving husband, and Shelby, our precious daughter.

ACKNOWLEDGMENTS

I thank my mom and dad for all of their love and guidance through the years.

I thank the Army and West Point for affording me the opportunity to attend graduate school.

I thank Professor Brown for all of his help and guidance.

Most importantly, I thank Greg for his constant love, support and knowledge. He is truly my inspiration.

ABSTRACT

Future combat systems planned for the 2008 timeframe and beyond require medium size armament vehicles that fit onto C-130 airplanes, and smaller deployed forces that are capable of covering a greater area within a complex environment. Command, control surveillance and reconnaissance capabilities are vital to the success of any mission. With this reduction in forces and the armament they use, comes a requirement for increased intelligence and knowledge of the battlefield. Networked ground micro-sensors represent one aspect available to enhance the US Army's capabilities for covering Beyond Line of Sight (BLOS) areas and joins in with Unmanned Aerial Vehicles (UAV) and Unmanned Ground Vehicles (UGV) for gaining dominant situational awareness across all echelons of the future battlefield. This thesis presents a methodology for determining measures of effectiveness for guidance in developing rules for employing networked ground micro-sensors on the battlefield. These rules and guidelines help users to understand how networked sensors can best be employed on the battlefield. The thesis process: 1) uses a systems engineering framework to understand the problem, 2) literature research to understand networked sensor capabilities, 3) develops a framework for determining measures of effectiveness for a system, 4) demonstrates the application of statistical tools such as Response Surface Methodology (RSM), which is used to develop sensor employment rules, and 6) uses a computer simulation to test experimental designs and obtain outputs (i.e., measures of effectiveness values).

List of Acronyms

Acronym	Definition
AOI	Area of Interest
ARL	Army Research Lab
BCT	Brigade Combat Team
FLIR	Forward Looking Infrared
FOV	Field of Vision
IR	Infrared
MOE	Measure of Effectiveness
RSM	Response Surface Methodology
RSTA	Reconnaissance, Surveillance and Target Acquisition
SEDM	Systems Engineering Design Methodology
SEDP	Systems Engineering Design Process
UAV	Unmanned Aerial Vehicle
UGS	Unmanned Ground Sensor
UGV	Unmanned Ground Vehicle
USMA	United States Military Academy

Table Of Contents

List Of Figures

List Of Tables

Chapter 1 Introduction

1.1 Motivation

The Army's new vision for guidance into the 21st century requires a movement towards a new Future Combat System of a full spectrum air Deployable Force (by C-17 and C-130 type aircraft) beyond the 2008 timeframe. In order to accomplish this, a medium weight force must replace the current heavy force structure, which includes heavy armor and reconnaissance vehicles. With the loss in armor and reconnaissance vehicle power comes a critical need for clear situational awareness and integrated protection. In a sense, the Army plans to substitute information for armor and implement a "See First – Shoot First – Kill First" mentality [Milton, 2000].

Survivability of a medium weight force is dependent on sensors and the ability to accomplish a high quality situational awareness in order to avoid unintentional close combat and to support beyond line of sight targeting. The future force plans to utilize a force of unattended, highly automated ground micro-sensors capable of being deployed by ground forces, helicopters and artillery means and joining with other sensor type assets such as unattended aerial vehicles (UAV) and unattended ground vehicles (UGV) in order to provide battlefield commanders with a clear picture of the enemy situation. The Army believes a combination of distributed sensors and the network to interconnect them is critical to capturing this high quality situational awareness on the dynamic battlefield.

1.2 Statement of Need

Networked ground micro-sensors represent a main ingredient for the Reconnaissance, Surveillance and Target Acquisition (RSTA) Squadron of the Brigade Combat Team of the future and are anticipated to play a crucial role in the requirement for high quality situation awareness development. Many Department of Defense agencies and private sector corporations are concentrating their efforts in developing the best and smallest micro-sensors for the dynamic battlefield of the future. However, there is very little research being done on what type of metrics should be used for measuring the effectiveness for configuring these networked micro-sensors on the battlefield, and developing rules and techniques for their emplacement under different situations. The US Army may receive these “high tech” micro-sensors, but if field units do not know the best and most efficient way to emplace the networked sensors, then the sensors are not utilized to their full potential thus hindering the quest for high quality situation awareness development. This thesis presents a Networked Ground Micro-Sensors Systems Engineering Methodology that sets the procedures for determining the most critical measures of effectiveness for determining optimization of a networked sensor field and what emplacement rules are critical for optimized emplacement of networked ground micro-sensors on different types of battlefields and under different type of battlefield scenarios or missions.

1.3 Stakeholders

Stakeholders are individuals and/or organizations who are either actively involved in the project or whose interests may be positively affected as a result of successful project completion [Project Management Institute, 1996]. For this thesis, the major stakeholders are the Army (specifically the Army Research Lab – Sensors Electronic Directorate Division, The Night Visions and Electronic Sensors Directorate and the Operations Research Lab of the United States Military Academy) and the Systems Engineering Community (both academia and industry).

1.4 Problem Statement

Develop a methodology for determining metrics and deployment optimization rules for networked ground micro-sensors on the battlefield.

1.5 Understanding the System

This thesis focuses on the networked sensors and sensor capabilities planned for future configurations of the RSTA squadron at approximately the 2008 time frame. The methodology presented in this thesis breaks the problem of developing measures of effectiveness and the procedures for the deployment of networked sensors into two distinct phases. First, gain and develop an understanding of the system, its interconnectedness in military applications and desired measures of effectiveness. It is desirable to increase the understanding of the relationship between certain controllable input and response variables where this understanding can be codified into rules and policies and evaluated with established measures of effectiveness. Second, apply the system understanding from phase one towards solving the problem of determining optimal or near optimal settings of the factors that can be controlled. Figure 1 serves as a road map for accomplishing the second phase of the thesis.

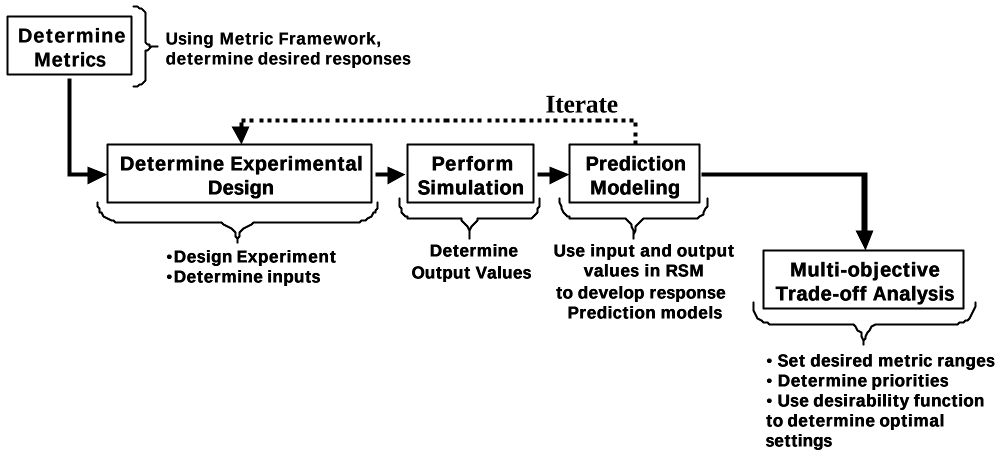


Figure 1: Second Phase Roadmap

1.6 Mathematical definition

Sensor emplacement is a multi-response non-linear problem. The primary purpose is to optimize a system that results in useful rules of employment for networked sensors on the battlefield.

1.6.1 Decision Variables

X_1 = Number of Seismic sensors

X_2 = Number of Acoustic sensors

X_3 = Number of FLIR sensors

1.6.2 Control Variables

C_1 = amount of time, in minutes, sensors must cover the area

C_2 = amount of area, in meters, sensors must cover

C_3 = location of coverage area, (polygon area of terrain)

C_4 = location of each individual sensor (X and Y coordinates)

1.6.3 Random Variables

R_1 = Enemy Wheeled Vehicles

R_2 = Enemy Tracked Vehicles

R_3 = Weather Effects R_4 = Atmospheric Effects

R_5 = Terrain

1.6.4 Multiple Objectives

Minimize Undetected Rate	# of "leakers" / total # of enemy tgts
Minimize Attrition Rate	# sensors attrited / total # of sensors
Maximize Classification Rate	# correctly classified / total # of detections

1.6.5 Constraints

- Amount of Power available ($P_W \leq$ max power) {cost constraint}
- Number of Sensors available

  ([For T = 1 to 3; 1 = Seismic, 2 = Acoustic, 3 = FLIR]

  $\sum_{n=1}^{k} S_{Tn} \leq$ Total of sensor type T available (N_T)
- Maximum effective range of each Sensor type (S_T)

  (For T = 1 to 3; 1 = Seismic, 2 = Acoustic, 3 = FLIR)
- Location of sensor field (Z) (Area of Operations for networked sensors)

- Pay-off cost – cost for emplacing additional sensor (S) compared to the potential increase in metric improvement

1.7 Thesis Tasks and Contributions

1.7.1 Thesis Tasks Completed

1. Formulated a Sensor Emplacement Systems Engineering Methodology.
2. Developed a Metric Framework.
3. Developed a computer simulation that models sensor emplacement
4. Applied RSM techniques in order to develop prediction models and facilitate the ability to conduct multiple response optimization.
5. Used simulations to model the system and obtain metric results or outputs.
6. Provided a comprehensive list of tasks for future work

1.7.2 Thesis Contributions Completed

The major contribution is the development of a methodology to facilitate the decisionmaker's ability to optimize the sensor emplacement system. Other contributions to the thesis are listed below.

Provide Military Community:

1. Methodology for Optimizing Emplacement Rules
2. Framework for Developing Metrics for Units and Organizations
3. Technique for using simulations and systems engineering tools to solve micro-sensor type problems

Provide Systems Engineering Community:

1. Methodology for Determining General Rules for Sensor Emplacement
2. Method for Acquiring Metrics for General Placement Problems
3. Technique for using Multivariate RSM for Simulation-Optimization Problems with Integer-Valued Control Variables

Chapter 2 Methodology

2.1 Overview of Methodology

Due to limited dollars for sensor resources and manpower, methodologies must be developed to reduce the impact on resources for future missions. The major task of this thesis is to develop a methodology that determines optimized networked sensor emplacement rules using a systematic process. The purpose of this methodology is to gain an increased understanding of the complexity, uncertainty, and interconnectedness of networked sensors and to determine an overall model and methodology for determining measures of effectiveness and rules for optimized sensor emplacement.

A methodology is necessary to model this difficult problem in order to develop a road map to follow and provide a systematic approach to accomplish all of the tasks. This is a difficult problem due to the dynamic battlefield that the networked sensors must monitor, the requirement for battlefield awareness, knowledge about future systems and future doctrine, and the fact that technology is always advancing and changing.

Numerous design methodologies currently exist for engineers and scientists to use and tailor to their specific needs for solving real world problems. Although most methodologies are tailored for specific problems, most include defining the problem either mathematically, written or both; generating solution sets; analyzing and comparing the solution sets; and selecting the best solution through qualitative or quantitative means. The sensor emplacement methodology builds on the framework of the design methodology from the United States Military Academy (USMA) known as the Systems Engineering Design Process (SEDP).

Phase	**Step**	**Activity**	**Result**
Formulation	1	Problem Definition	Engineering Problem Statement
	2	Functional Decomposition	Hierarchy of Functions
	3	Value System Design	Value Hierarchy
	4	Alternative Generation	A set of alternative solutions
Analysis	5	Input-Output Modeling	Input-Output Model
	6	Process Flow Diagramming	Process Flow Diagrams
	7	Selection of Models	Models to evaluate alternative performances
	8	Analysis of Alternatives	Completed Raw Data Matrix
Interpretation	9	Decision-making	Completed Decision Matrix/recommendation
	10	Plan for Action	Requirements to implement the selected alternative
	11	Record Results	Technical Report capturing work completed

Table 1: USMA Systems Engineering Design Process [Willis and Davis, 2000a]

The United States Military Academy's SEDP (Table 1) was chosen as the best guideline for developing a methodology for sensor emplacement because it is a proven military systematic problem-solving methodology that is easy to adapt to the problem of networked sensor emplacement. A few modifications to the SEDP were necessary in order to tailor it to the specific real world problem of networked sensor emplacement optimization. Table 2 (Page 9), outlines the differences between the two methodologies. It is important to note that some of the steps from the USMA SEDP were combined into different steps in the sensor emplacement methodology accounting for the change in the required number of steps. The USMA SEDP requires eleven steps while the sensor emplacement SEDM only requires eight steps. The step for input-output modeling is performed during the systems modeling and analysis step of the new methodology, and process flow diagramming is encompassed in the problem definition step. Steps 9, 10 and 11 are all combined into one step of the new methodology. These changes were made to shift the focus to the main requirements for this thesis, performing metrics identification, response surface methodology and simulation.

Phase	USMA SEDP	Networked Sensors SEDM
Formulation	Problem Definition	Problem Definition[2]
	Functional Decomposition	Functional Decomposition
	Value System Design	System Modeling and Analysis[1]
	Alternative Generation	
Analysis	Input-Output Modeling[1]	Metric Identification
	Process Flow Diagramming[2]	Response Surface Methodology
	Selection of Models	Simulation
	Analysis of Alternatives	Analysis of Alternatives
Interpretation	Decision-Making[3]	Plan of Action[3]
	Plan for Action	
	Record Results[3]	

Table 2: SEDP and networked sensors SEDM Comparison

Table Notes:
1. Input-Output Modeling from USMA SEDP is accomplished in System Modeling and Analysis of Networked Sensors SEDM.
2. Process Flow Diagramming from USMA SEDP is accomplished in Problem Definition of Networked Sensors SEDM.
3. Decision-Making and Record Results from USMA SEDP are accomplished in Problem Definition of Networked Sensors SEDM.

The methodology for this thesis is called the networked sensors Systems Engineering Design Methodology (SEDM). The Networked Sensors SEDM (Table 3, Page 10) is the formulation for the rest of this thesis. There are three phases consisting of eight steps with a number of activities to perform and a list of the expected results. Each of the steps, along with their activities, is presented in the remainder of this chapter.

Phase	Activity	Tasks	Results
Formulation	1. Problem Definition	1. Identify Stakeholder Desires 2. Define the Problem 3. Develop Initial Methodology 4. Develop Methodology Flow Diagram	1. Useful Results for Stakeholders 2. Initial Road Map 3. Overall problem understanding 4. Engineering Problem Statement
	2. Functional Decomposition	1. Identify Critical Functions 2. Identify Critical Sub-functions 3. Create Functional Decomposition	1. Filtered Relevant System Components 2. Sub-component Description 3. Defined Parameters
	3. System Modeling and Analysis	1. Develop Mathematical Model 2. Develop Input-Output Model	1. Mathematical Representation of the Problem 2. State Space Representation
Analysis	4. Metrics Identification	1. Develop Metric Framework 2. Identify Relevant Metrics 3. Metric Representation 4. Metric Analysis	1. Generic Metric Framework to follow for future refinements 2. Measures of Effectiveness Developed 3. Generalized List of Metrics for Sensors
	5. Response Surface Methodology	1. Develop Initial Experiment 2. Multiple Response Optimization 3. Develop Initial Sensor Emplacement Rules	1. Initial Variables Identified 2. Significant Variables and their ranges Identified 3. Sensitivity Analysis Multiple Response Optimization 4. Initial networked sensors Emplacement Rules Identified
	6. Simulation	1. Set up Simulation 2. Run Simulation 3. Record Results 4. Iterate Step 5 with new experiment until no improvement	1. Simulation software to use for future tests 2. Improvement = new RSM experiment 3. No Improvement = Test Different Scenarios 4. Generalized networked sensors Emplacement Rules Identified
	7. Analysis of Alternatives	1. Scenario Development 2. Iterate Steps 5 and 6	1. Emplacement Rules for Different Scenarios Identified
Interpretation	8. Plan of Action	1. Make Recommendations 2. Execute Plan 3. Gather Additional Information	1. Road Map Complete 2. Working Process Complete 3. Report Results and Conclusions

Table 3: Sensor Emplacement Systems Engineering Design Methodology

2.2 Methodology Description

2.2.1 Step 1. Problem Definition

The first and most important step in the SEDM is identifying, understanding and defining the problem. For a clear understanding of the problem, one must conduct research into the problem area and interact with the relevant stakeholders in order to determine their needs and objectives. The result of these efforts is an engineering problem statement that captures the essence of the problem. If the wrong problem definition is used, then the remaining steps of the methodology are useless and money and time is wasted. During the Problem Definition step, four major activities are performed: 1) stakeholder identification, 2) engineering problem statement development, 3) initial methodology development and 4) methodology flow diagramming.

The first step is to identify the stakeholders and gain a full understanding of their desires and needs. Stakeholders are individuals and/or organizations who are either actively involved in the project or whose interests may be positively affected as a result of successful project completion. For this thesis, the major stakeholders are the Army, specifically the Army Research Lab – Sensors Electronic Directorate Division and the Operations Research Lab of the United States Military Academy and the Systems Engineering Community.

After gaining an understanding of the stakeholders' needs and desires, one develops the problem resulting in an engineering problem statement. The problem statement is the key task for the entire thesis. If the engineering problem statement does not address the correct problem or goals, then the project fails. Subsequently, if we do not adhere to the problem statement and its implied tasks, then the project fails. So a clear understanding of the problem statement is a must in order for this thesis to result in a useful product for the stakeholders. The engineering problem statement for this thesis is: To develop a methodology for determining measures of effectiveness and deployment optimization rules for networked ground micro-sensors on the battlefield.

The next task is to develop an initial methodology to serve as a "road map" to follow for the remaining thesis process. This chapter as a whole covers the initial methodology and was discussed in great detail in Section 2.1. The methodology flow diagram is developed to visually depict each activity in the sequence they occur (Figure 2).

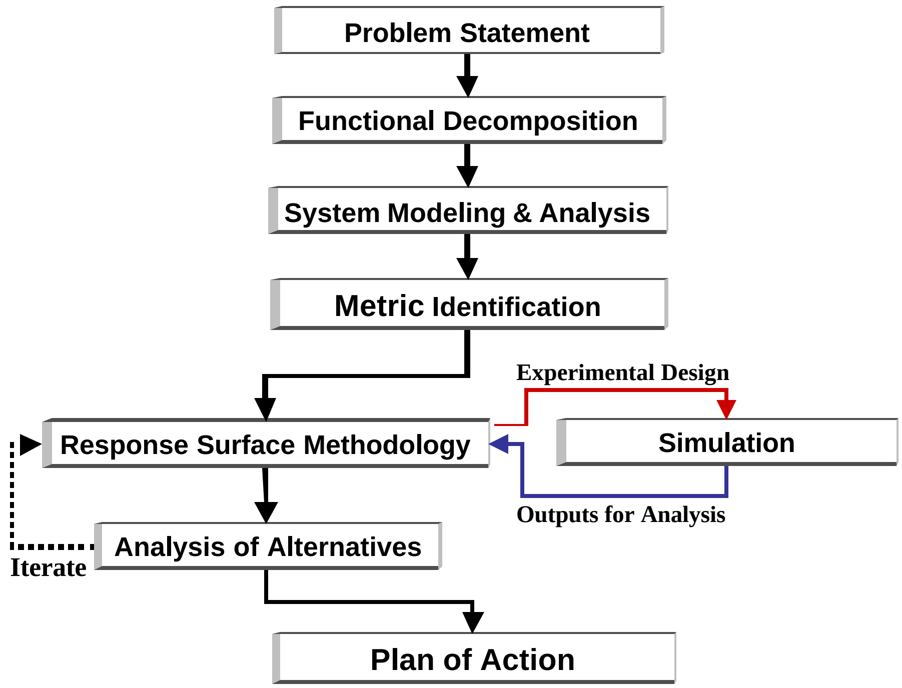


Figure 2: Networked Sensors Methodology Flow Diagram

2.2.2 Step 2. Functional Decomposition

This is the step that helps to understand the complexity and issues involved with the overall system. The primary purpose of this step is to "brainstorm" all of the possible elements interacting with the system and to identify and decompose the critical functions of the entire optimized networked sensor emplacement system. The outcome of a functional decomposition is a large *Hierarchy of Functions* that lists the many characteristics defining unattended ground sensors. During this step, the large functional decomposition is reduced to only depict the critical functions involved in this sensor emplacement methodology. Figure 3 (Page 14) illustrates the critical functions and the critical sub-functions required by the system. There are several other functions involved in the system (e.g., decisionmaking level, resources) but have a minimal effect based on the RSTA's mission and the networked sensors capabilities.

For the functional decomposition, there are five head-topics and 25 subtopics that represent the most critical functions that may have a substantial effect on the system. Over the length of the methodology it is applicable to add and delete topics and subtopics based on an increased knowledge and understanding of the problem.

The sensor type function lists the types of sensors that are available for use in the system. The emplacement function lists most of the possible ways for networked sensors to be emplaced on the battlefield. The environmental function lists the types of environmental effects that may affect sensor collection capabilities. The communication function lists a majority of the communication means the sensor networks may use to communicate their information to the main controllers. The measure of effectiveness function lists the possible metrics to use in evaluating the system.

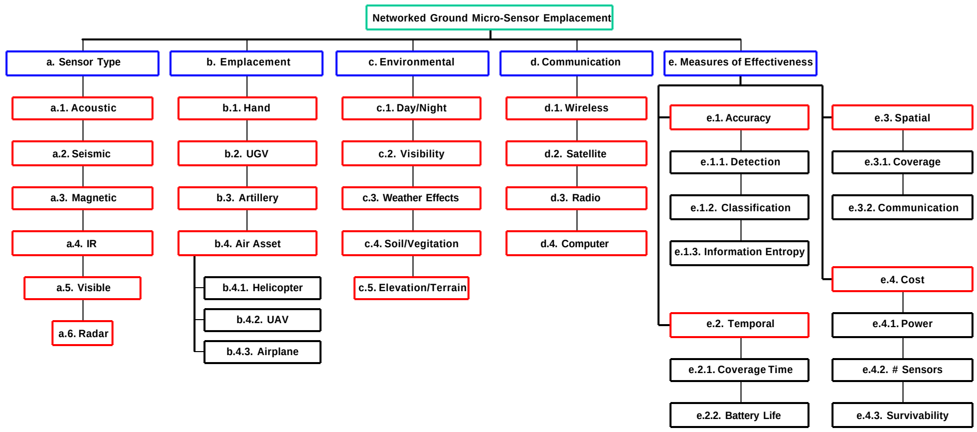


Figure 3: Sensor Emplacement Functional Decomposition

2.2.3 Step 3. System Modeling and Analysis

During the system modeling and analysis step a number of critical activities are performed that layout the basis for the remaining steps of the SEDM. The mathematical model is developed in order to present the mathematical representation of the problem and sets up the initial work for the RSM step. The input-output model for the sensor emplacement system is developed and visually depicts what is going on with the system.

The mathematical model development requires a great deal of development and explanation, and is discussed in much greater detail in Chapter 1, Introduction. This is a multi-response nonlinear problem with the primary purpose of optimizing a system that results in useful rules of employment for networked sensors on the battlefield. The control variables:

X_1 = Number of Seismic sensors
X_2 = Number of Acoustic sensors
X_3 = Number of FLIR sensors

C_1 = amount of time, in minutes, sensors must cover the area

C_2 = amount of area, in meters, sensors must cover

C_3 = location of coverage area, (polygon area of terrain)

C_4 = location of each individual sensor (X and Y coordinates)

The Random Variables:

R_1 = Enemy Wheeled Vehicles

R_2 = Enemy Tracked Vehicles

R_3 = Weather Effects

R_4 = Atmospheric Effects

R_5 = Terrain The Objectives

Minimize Undetected Rate	# of "leakers" / total # of enemy tgts
Minimize Attrition Rate	# sensors attrited / total # of sensors
Maximize Classification Rate	# correctly classified / total # of detections

Subject to:

- Amount of Power available ($P_w \leq$ max power) {cost constraint}
- Number of Sensors available

  ([For T = 1 to 3; 1 = Seismic, 2 = Acoustic, 3 = FLIR]

  $\sum_{n=1}^{k} S_{Tn} \leq$ Total of sensor type T available (N_T)
- Maximum effective range of each Sensor type (S_T)

  (For T = 1 to 3; 1 = Seismic, 2 = Acoustic, 3 = FLIR)
- Location of sensor field (Z) (Area of Operations for networked sensors)
- Pay-off cost – cost for emplacing additional sensor (S) compared to the potential increase in metric improvement

Input-Output modeling helps to define the boundaries and boundary conditions of the system and allows one to analyze inputs and intended outputs. The intended outputs are considered goals or objectives of the system. From these intended outputs, the engineer begins to make a determination of what system inputs are needed. Controllable inputs are used to achieve the intended outputs. Uncontrollable inputs are environmental characteristics or tangibles that influence the performance of the system such as weather or terrain. [Willis and Davis, 2000b]

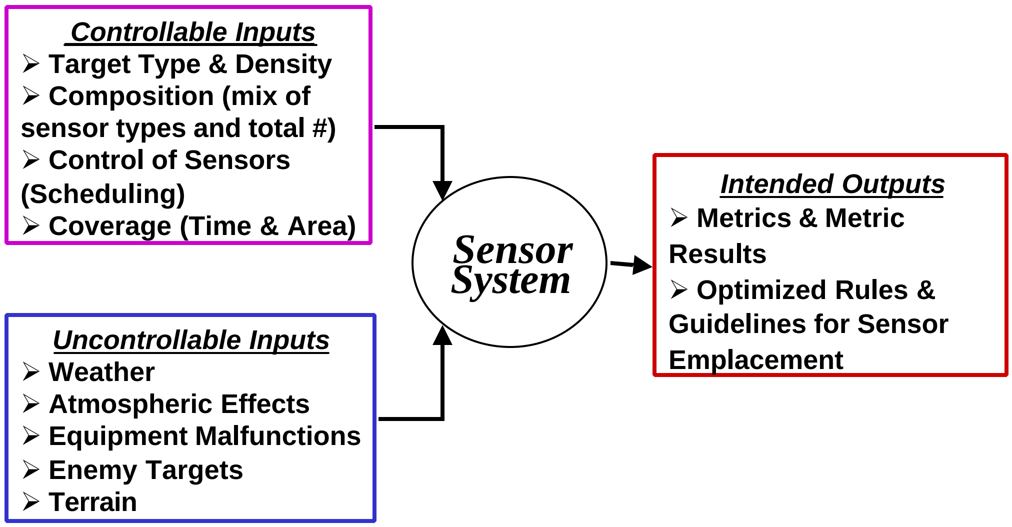


Figure 4: Input-Output Model

2.2.4 Step 4. Metrics Identification

The primary purpose of this step is to identify all of the measures of effectiveness that may play a role in determining the attributes and characteristics of an optimized battlefield sensor network and then determining the most critical ones for the system. Metrics are standalone measures one uses in order to specify and record a situation, compare it to similar past measures and make decisions through figures of merit [Skroch, 1999]. A measure of effectiveness (MOE) is a type of metric and in a generic sense, is any index that indicates the quality of a system [Habayeb, 1987]. Metrics are necessary for measuring the effectiveness of different networked sensor emplacement configurations on the battlefield in order to compare different rules and techniques resulting in optimized employment rules.

In order to determine the proper metrics for the system a framework or "roadmap" must be developed first, in order to lie out the activities or tasks for the remainder of the metric development process (Figure 5, Page 18). The figure is from "Assessing and Managing Risks to Information Assurance: A Methodological Approach" [Lamm, G., 2001] and is adapted for use in the framework presented here. This framework provides guidelines and sets the tasks to accomplish for establishing a consistent baseline for metric development, no matter what the subject is or the goals are, and allows for easy refinements to the system, if necessary in the future.

The framework for generating networked ground micro-sensor metrics includes four basic steps: 1) determine the goals and sub-goals for the system, 2) determine appropriate metrics, 3) determine consequences and impacts if the metric is not accomplished and prioritize metrics, 4) determine metric implementation. This whole process is covered in Chapter 4 Networked Sensor Metrics, so only a brief introduction is discussed here.

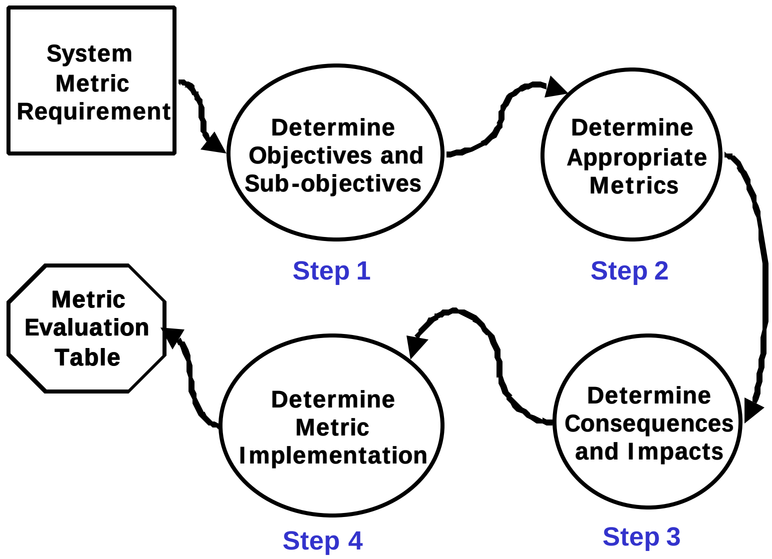


Figure 5: Metric Development Framework

2.2.5 Step 5. Response Surface Methodology

The RSM step determines which variables influence the system most and allows for multi-objective trade-off analysis. From the developed mathematical model and metric development steps, we determine the initial experiments to run during the simulation step. The RSM step is the main step for determining optimized sensor emplacement rules.

There are three main activities for this step. The initial step includes developing the initial experiment or in future iterations, developing new experiments in order to identify the significant variables and their ranges. The metrics developed in the previous step are used in the multi-objective trade-off study performed in this step. The final activity for this step is to develop initial sensor emplacement rules and to refine them as the steps are iterated. Since there is an entire chapter dedicated to this step (Chapter 5), only an introduction to the subject is presented here. Figure 6 illustrates the major steps involved in the RSM process for this thesis.

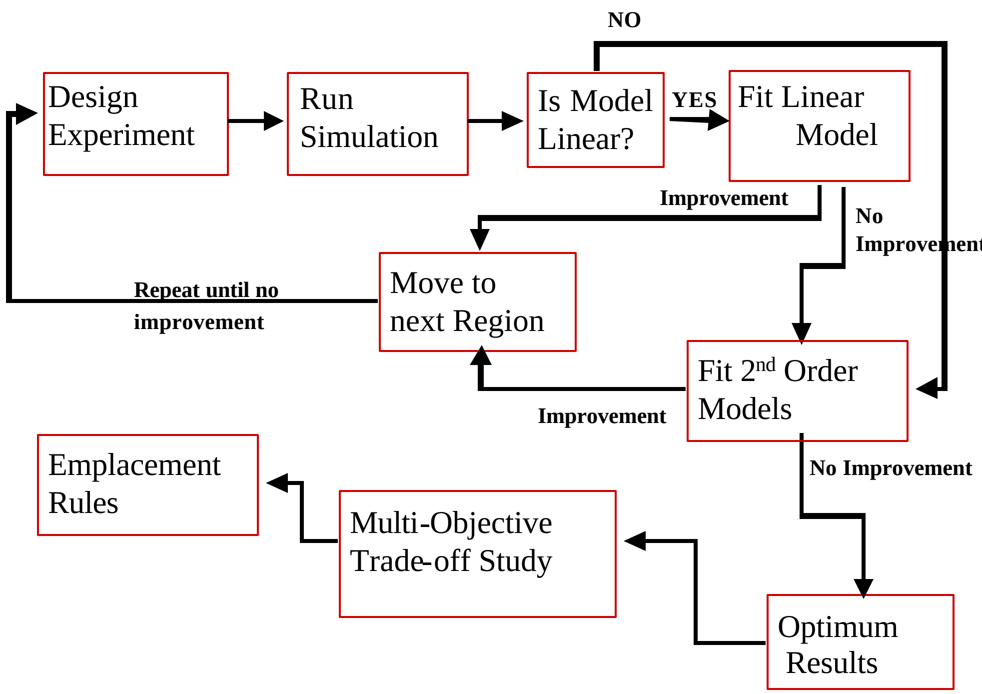


Figure 6: Response Surface Methodology

2.2.6 Step 6. Simulation

The simulation step involves running computer-based simulations that contain or account for as many of the sensor characteristics and requirements as possible in order to obtain results for sensor emplacement performance based on the RSM experiment set from the previous step.

This step is actually a sub-set of the Response Surface Methodology step. The two steps are intertwined and repeated numerous times until optimal generalized emplacement rules are determined (Figure 7, Page 20). These rules are characterized as generalized rules, because they have not been tested against specific scenarios and mission types. These tests are conducted in the analysis of alternatives step.

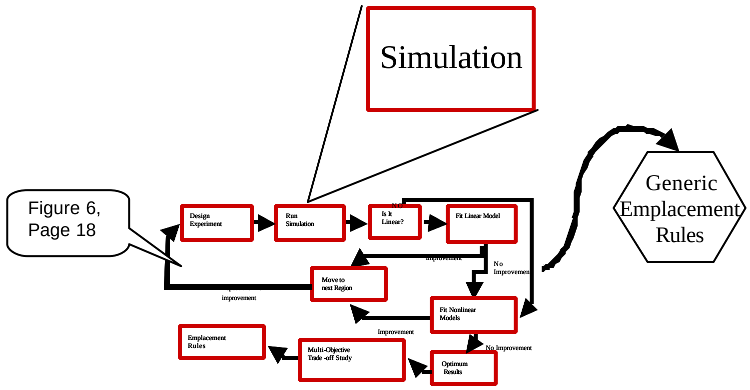


Figure 7: Simulation, RSM Interaction

The computer simulation for this thesis uses Map Info Professional and Map Basic software programs. The terrain information is based off of a black and white image of a small section of ground with its topographical features in Bosnia. Since the image was black and white and there was no elevation data included with the picture, it is hard to differentiate between roads and rivers, so some terrain modifications and approximations were made. Modifications and approximations included adding rivers and hilltops. Since this is a rudimentary, basic simulation, we did not feel that completely accurate terrain was necessary to accomplish our simulation objectives. Figure 8 (Page 21) depicts the layers and the process of building the terrain based model used in this simulation. Several metrics (i.e., undetected, attrition and classification rates) are measured through the simulation, and then evaluated during the RSM process.

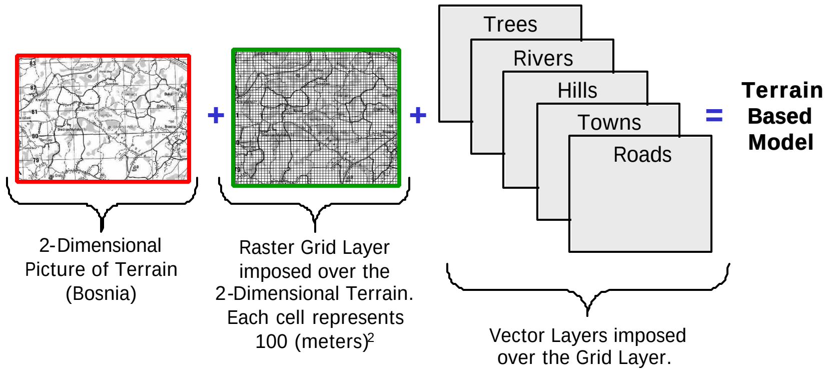


Figure 8: Simulation Layers

The four major activities for this step include setting up the simulation with required data and instructions, running the simulation, recording the results and returning to the RSM step in order to either continue on in the RSM framework or to develop a new experiment or refine the old experiment until no improvement in the results occurs.

2.2.7 Step 7. Analysis of Alternatives

An analysis of alternatives step is crucial because of the Army's dynamic nature, specifying one set of rules will not be all encompassing for all units and all missions. This step is intertwined with the previous two steps (RSM and Simulation), but in a different way (Figure 9, Page 22). Analysis of alternatives is accomplished after the initial completion of the RSM framework (e.g., initial emplacement rules are identified, now they must be tested against different scenarios). The analysis of alternatives step identifies alternative scenarios that the networked sensors might face and the whole RSM process in essence, starts over again. However, the RSM process starts from a more advanced state and more focused experiments. This happens because the generic emplacement rules are already established and are considered the starting baseline for further experiments.

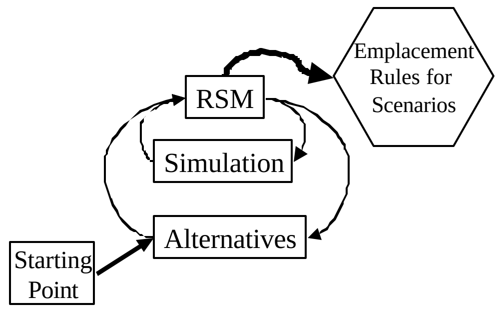


Figure 9: Alternatives, RSM and Simulation Interaction

In this step different basic scenarios are developed in order to determine what sensor emplacement rules will change and how they will change. Some of the different scenarios to test include armor heavy enemy, dismounted enemy, mechanized infantry enemy, reconnaissance elements, offensive operations, defensive operations and different types of terrain. Each of the different scenarios must be tested and ran through the RSM and computer simulation steps again.

2.2.8 Step 8. Plan of Action

This final step binds the whole Sensor Emplacement Systems engineering Design Methodology together and allows for distribution of the findings to the decisionmakers and a reflection on refinements for the methodology. The decisionmakers then plan for action based on the recommendations. Other activities that may be performed in this step include: executing the plan determining more efficient ways for information gathering.

Chapter 3 Background

3.1 Overview

Military transformation into the 21st century requires an increased situational awareness and use of sensor technologies for remote reconnaissance collection on the battlefield. High quality situation awareness is required for the future combat force's various missions and networked sensors help to provide it. This increased importance on the use of networked sensors requires increased knowledge on the best way to employ sensors on the battlefield in order to reap the most benefit from their collection capabilities.

Unattended networked ground micro-sensors come in various sizes and forms, and are constantly undergoing improvements. Each individual sensor may contain one type or multiple types of sensor technologies, is capable of being deployed by several means and posses the capability to report information on or about many different types of targets. Networked sensors perform multiple missions (i.e., general surveillance, early warning, target acquisition) in order to provide remote target detection, location and recognition. This potential gives units improved battlespace knowledge and decisionmaking capabilities. Networked ground micro-sensors are small, low cost, robust and expected to perform their deployment mission on the battlefield for extended periods of time. Elements such as terrain, weather, background noise, and time of day may affect the optimal performance of each micro-sensor.

3.2 Reconnaissance, Surveillance and Target Acquisition Squadron

This thesis focuses on the deployment and utilization of networked ground micro-sensors by the Reconnaissance, Surveillance and Target Acquisition (RSTA) Squadron of the proposed Objective Force Brigade Combat Team (BCT).

The RSTA squadron provides a powerful contribution towards battlespace and information dominance and serves as a significant combat multiplier to commanders. The RSTA squadron performs a number of diverse operations, with most occurring simultaneously within the battlespace. Some of these operations include: collecting information that develops situational awareness, intelligence preparation of the battlefield, indications and warning, situation development, force protection, battle damage assessment, targeting and collection queuing. Given this multi-dimensional capability, the RSTA squadron resources are under the battlefield commander's responsibility, demanding a top-down planning and unity of effort throughout the BCT in order to achieve a synchronized intelligence-operations approach to RSTA employment. The RSTA squadron is required to operate throughout the BCT's area of responsibility, generally a 100 kilometer by 100 kilometer space. [Draft RSTA Squadron O&O, 2000]

The RSTA squadron's Surveillance and Target Acquisition Troop's ground sensor platoon is responsible for the emplacement, monitoring and maintenance of the networked ground micro-sensors. The remotely emplaced networked sensors provide acoustic, seismic, magnetic, and camera type sensor capabilities for monitoring the battlefield and acquiring threat personnel and equipment measurements and signatures as well as monitoring vehicle and personnel traffic. These capabilities provide the RSTA squadron the ability to detect and assess patterns in the operational environment allowing the BCT to conduct anticipatory planning based on predictive analysis. [Draft RSTA Squadron O&O, 2000]

3.3 Networked Ground Micro-Sensors

This thesis concentrates on the networked ground micro-sensors concept. Networked sensors are only a small piece to the puzzle for providing clear situational awareness to battlefield commanders. Network sensor capabilities include: networked, organic unattended ground sensors for beyond line of sight situational awareness and targeting that complement global surveillance that is hampered by shadowing, foliage, cover, concealment and deception (CC&D), moving target indicator thresholds and lag time [Milton, 2000]. Networked ground micro-sensors are utilized in the third layer of a five-layer surveillance plan (Figure 10, Page 26). They are tied in at the Battalion/Company intelligence gathering level or the level that is the responsibility of the RSTA squadron. This layer of surveillance also includes mobile sensor assets such as Unmanned Aerial Vehicles (UAV) and Unmanned Ground Vehicles (UGV). By combining the different sensor assets, multiple look angles and continuous tracking with cross cueing is gained in order to find targets hiding in complex terrain.

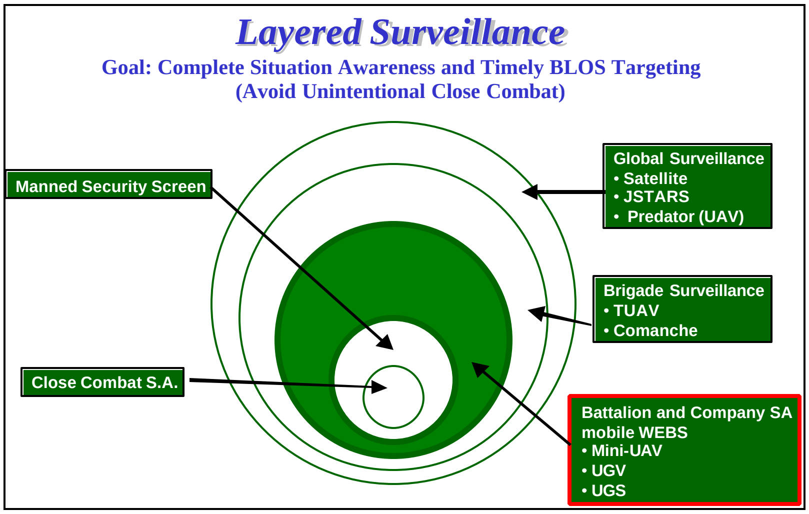


Figure 10: Layered Surveillance [Milton, 2000]

3.3.1 Sensor types

Three types of sensor layers (trip line, pointer and Imager) make up the complete package of networked sensors [Hopkins, 2000].

3.3.1.1 Trip Line Sensor Layer

The trip line sensor is the simplest layer. It consists of the smallest, least expensive and lowest power consumption type of sensors. Trip line sensors are widely scattered and used to cue or wakeup other higher-level sensors. Trip line sensors consist of some combination of acoustic, seismic and magnetic sensors that generate Lines of Bearing (LOB) towards the target of interest and send that information to the next level of sensors (pointer) for processing.

3.3.1.2 Pointer Sensor Layer

The pointer sensor is the next layer of sensors and they collect additional information in order to cue the highest level of the three sensors, the imager node sensors. This high level sensor provides the bulk of the processing information for the networked sensors.

3.3.1.3 Imager Node Sensor Layer

The imager node sensors are platforms of multiple sensor types including IR imager, acoustic, and seismic sensors that locate, classify, identify and visualize (when requested) detected enemy targets and sends the collected information to the sensor controller.

3.3.2 Sensor Technologies and Capabilities

Networked ground micro-sensors use a number of different sensor technologies in order to provide robust target detection, identification and tracking capabilities. These sensor technologies include both imaging and non-imaging sensors. The imaging sensor capabilities are centered on infrared (IR) technologies. Acoustic, seismic and magnetic sensor technologies make up the passive, non-imaging sensors.

3.3.2.1 Acoustic

Acoustic sensors, the most common non-imaging sensor, provide non-line of sight detection and classification capabilities for a number of enemy battlefield targets at significant ranges. They collect sound waves propagating through the air. Acoustic sensors provide long range, remote detection of many types of targets and generally detect targets operating below the 150 Hz range [Hopkins, 2000]. They have a maximum effective range of 50 meters for personnel (if they are talking or making audible noises), 250 meters for wheeled vehicles and 700 meters for tracked vehicles. The range of detection is 360 degrees and the probability of detection for all three types of targets is 95 percent while the probability of classification for all three types of targets is 80 percent [Gerber, 2000]. Some terrain features and environmental factors may hinder the collection capabilities of acoustic sensors (e.g., ambient interferences such as running water and power lines, time of day - sound waves travel further at night and wind).

3.3.2.2 Seismic

The seismic sensor is a low cost, non-line of sight sensor that provides unique detection capabilities in the case of adverse acoustic propagation conditions. Seismic sensors detect vibrations in the ground. The maximum effective range is 30 meters for personnel, 250 meters for wheeled vehicles and 500 meters for tracked vehicles; the range of detection is 360 degrees; the probability of detection and classification of enemy personnel, wheeled and tracked vehicles are all 95 percent [Gerber, 2000]. Some terrain features and environmental factors may hinder the collection capabilities of seismic sensors (e.g., ambient interferences – noise due to earth tremors, soil – hard compacted soil is best and wind).

3.3.2.3 Magnetic

The magnetic sensor is a low cost, non-line of sight sensor that provides early detection of many targets. This sensor offers a highly orthogonal sensing modality from acoustic and seismic sensors [Hopkins, 2000]. The maximum effective range is 3 meters for personnel (provided the person is carrying a metallic object), 15 meters for wheeled vehicles and 25 meters for tracked vehicles; the range of detection is 360 degrees; the probability of detection is 90 percent and it is not possible to classify target type [Gerber, 2000]. Some terrain features and environmental factors may hinder the collection capabilities of magnetic sensors (e.g., ambient interferences – noise due to earth tremors and power lines).

3.3.2.4 IR/Passive Sensor

The IR/Passive Sensor is currently under development, with a goal to create an effective, low cost sensor. The IR/Passive sensor is a line of sight sensor triggered by one of the three low cost, non-line of sight sensors (acoustic, seismic, magnetic) when it detects a target. This sensor is used to look at a target visually to verify the target. The maximum effective range is 20 meters for personnel, 50 meters for wheel vehicles and 50 meters for track vehicles; the range of detection is 40 degrees; the probability of detection is 0.95 for personnel, 0.98 for wheel vehicles and 0.99 for track vehicles [Gerber, 2000].

3.3.2.5 Forward Looking Infra-Red Sensor

The Forward Looking Infra-Red Sensor (FLIR) is an effective, low cost sensor. The FLIR is a line of sight sensor triggered by one of the three low cost, non-line of sight sensors (acoustic, seismic, magnetic) when they detect a target. The FLIR sensor sends a visual image in order to verify the target. The maximum effective range is 100 meters for personnel, 150 meters for wheeled vehicles and 150 meters for tracked vehicles; the range of detection is 25 degrees; the probability of detection is 0.90 for all three types of targets, while the probability of classification for all three types of targets is 0.70 [Gerber, 2000]. Some terrain features and environmental factors may hinder the collection capabilities of Micro FLIR sensors (e.g., trees and hills).

3.3.3 Networked Sensor Mission Types & Capabilities

3.3.3.1 General Surveillance

Surveillance missions for sensors generally include providing surveillance of lines of communications, helicopter landing zones, assembly areas, objectives, key terrain and other named areas of interest [MCWP 2-2.3, 1997].

3.3.3.2 Early Warning

Early warning sensor missions require sensor networks to be placed forward along enemy avenues of approach in order to provide early warning of enemy movement and targets towards friendly positions. For this mission, the sensors are placed as far forward as possible in order to exploit the extended range of the unattended sensor system to provide maximum reaction time. [MCWP 2-2.3, 1997]

3.3.3.3 Target Acquisition

Target acquisition sensor missions include the use of a well-developed sensor networks that monitor key enemy lines of communication and other named areas of interest in order to initiate targeting actions once the sensors are activated by enemy movements. The inability of the sensors to distinguish between hostile, friendly and noncombatant activity is a major limitation of the unattended sensors under this mission. Due to this deficiency, some other surveillance asset prior to any actual targeting missions must confirm the sensor data. The sensors do provide an excellent means of facilitating the targeting process by cueing other target acquisition sources. The sensors also possess the ability to track a positively identified target moving across the battlefield. [MCWP 2-2.3, 1997]

3.3.3.4 Target Detection and Classification

Unattended ground sensors confirm or deny the presence of enemy activity in their assigned mission area and report the general indication of type of target and volume of activity. These sensors usually provide the number, general type, location, direction and speed for the targets they acquire [MCWP 2-2.3, 1997]. Each sensor type (i.e. seismic, acoustic, magnetic) possesses a probability of detection and classification rating based on their capabilities.

3.3.3.5 Continuous Operations

Networked sensors operate in all weather conditions and around the clock. Each individual sensor is battery operated and depending on its power source and the power requirements for operations determines how long its continuous operations last. With continuous technology advancements, soon battery power will not be an issue for most sensors and their accomplishment of their assigned missions. Currently, battery life is the primary factor limiting sensor and communication relay endurance. Battery life is dependent on the number of activations and transmissions required along with weather and other environmental factors.

3.3.4 Planning Considerations

3.3.4.1 Terrain Masking

Networked sensors must maintain line of sight communications with their monitoring and control site in order to maintain communications. Due to these requirements, individual sensors are susceptible to terrain masking (interference in line of sight operations by terrain features such as mountains and forests). Due to this susceptibility, detailed planning is required for sensor, relay and monitoring site locations.

3.3.4.2 Terrain & Weather

Terrain and weather play major roles in the planning for emplacement and the effectiveness of the sensor's collection capabilities. The terrain and weather in the mission area are very influential in determining potential sensor locations, sensor detection radius capabilities and relay requirements (Table 4).

Feature	Effects
Soil	Detection radius (especially seismic)
Ambient Interference (noise due to earth tremors, surf action, running water and power lines)	Degrades quality & detection capabilities (especially seismic & magnetic)
Vegetation	May interfere with radio line of sight communications May hinder antenna placement
Elevated Areas	*May degrade detection radius*
Weather	May degrade sensor detection radius
Atmospheric Effects	May degrade detection radius May degrade line of sight communications
Day/Night	Effects Seismic sensor detection radius (night allows sound to travel further)
Wind	May hinder both seismic and acoustic detection

Table 4: Terrain & Weather Effects on Sensors [MCWP 2-2.3, 1997]

3.3.4.3 Threat

The type of enemy the sensors must detect plays an influential role in planning considerations for emplacement. Enemy vehicles generally follow doctrinal movements and tend to stay on the roads until moving into battle formation allowing for easier planning of emplacement locations. Enemy personnel are very hard for the sensors to detect due to sensor limited capabilities for detecting them and they are harder to predict patterns of movement. The enemy's capability to detect and destroy the unattended sensors must be taken into account. In order to decrease the enemy's capability for detecting sensors, care must be taken to use cover, concealment and deception techniques when emplacing the sensors.

Chapter 4 Networked Sensor Metrics

4.1 Introduction

In order to develop optimized rules for networked sensor emplacement, a number of metrics are developed to make comparisons and assess an optimized sensor network layout for the RSTA squadron. The developed metrics or measures of effectiveness are the most important ingredients for assessing optimization of networked sensors configured on the battlefield. The overall goal of determining the most critical measures of effectiveness for the RSTA Squadron is the core topic of this chapter. This chapter has two sub-goals: 1) determining the metrics for optimized networked sensor emplacement, and 2) present a framework for the general utility of determining metrics for the type of objectives within a sensor system. The chapter presents several figures and tables generated through a four step metric framework in order to accomplish both goals. Networked sensor metrics should possess the following qualities [Skroch, 1999]:

1. Computable within a time frame that is useful to decision makers.
2. Reasonable cost to obtain.
3. Makes intuitive sense and is easily understood.
4. Has consistency across systems and can be repeated.
5. Measures what you think it measures.
6. The scale (bounds on the metric) is meaningful to the user and the decision maker.
7. The quantifiable metrics should have precision within its significant digits and its uncertainty has a known source.

8. Metrics should be useful to meet the goals of the system (i.e., design, operation, etc.).

4.2 Metrics Overview

Metrics are standalone measures one uses in order to specify and record a situation, compare it to similar past measures and make decisions through figures of merit [Skroch, 1999]. There are many different types of metrics associated with sensor systems and this thesis uses metrics as a means to measure the effectiveness of the sensor system. A measure of effectiveness (MOE) is a type of metric and in a generic sense, is any index that indicates the quality of a system [Habayeb, 1987]. An MOE is a quantifiable comparison of results obtained under specific external conditions and decisions, or in other words, a group of metrics that are required to evaluate models and algorithms and to conduct trade-off studies [Wideman, 2000].

4.3 Measurement Theory

In order to understand metrics, it is important to understand the theory of measurement. Measurement theory is the assignment of numbers to a system or event in order to represent or preserve observed relations and involves axioms and rules for governing the process of assigning metrics to a system. To assign measurements to a process, two fundamental issues must be addressed. These issues are representation (finding axioms so measurement can take place) and uniqueness (determining the uniqueness of the resulting measure). [Roberts, 1979]

Two dimensions (performance and temporal) represent a networked sensor metric (Figure 11). Four metric scales (nominal, interval, ordinal and ratio) are characteristics of the performance dimension. The temporal dimension incorporates time, which is defined as a static or dynamic element. A static element is stationary or fixed and a dynamic element changes.

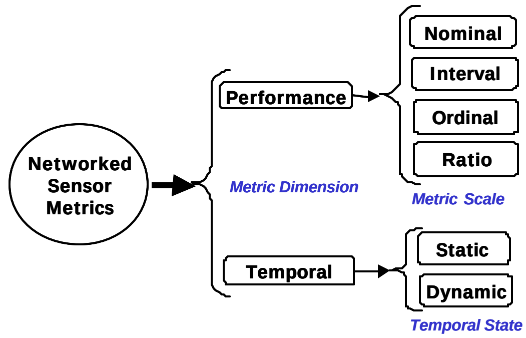


Figure 11: Metric Characteristics

Although there are other types of measurement scales (e.g., absolute, multidimensional), only four scale types are considered when identifying networked sensor metrics and each scale represents different functions and meaningfulness. The highest form of measurement and the most useful is ratio scales followed by interval, ordinal and nominal scales, respectively. The stronger the scale type, the more arithmetic operations can be performed on the data without losing information or meaning.

Nominal scales are the lowest form of measurement and involve the use of numbers or names for classification purposes. Ordinal scales build on nominal scales by introducing an ordering relation between the elements. Interval scales introduce the rule for combining two elements in the form of a difference between the two elements. Ratio scales are the most restrictive and most powerful scale of measurement because they have a natural origin, keeping the ratio of two measurements the same even if the scale is changed. [Chakong and Haimes, 1983]

4.4 Metric Methodology

A major concern for Army leadership is how to formulate metrics for networked micro-sensor systems evaluation and optimized emplacement. In order to generate networked sensor metrics, a framework (Figure 12, page 38) is developed providing answers to the following questions:

- What is the overall system objective?
- What are the systems objectives?
- How to measure those objectives?
- How do the metrics influence the system's mission?
- How are the metrics implemented?

The metric framework allows the user to provide an input (the measurement requirement) and receive outputs (evaluate the objectives of the system) in order to determine the overall effectiveness of the desired system. As a rule of thumb, metrics answer questions about effectiveness and system capability in order to assist the decision makers in selecting the appropriate course of action.

The framework for generating networked sensor metrics includes four basic steps: 1) determine the objectives and sub-objectives for the system, 2) determine appropriate metrics, 3) determine consequences and impacts, and 4) determine metric implementation.

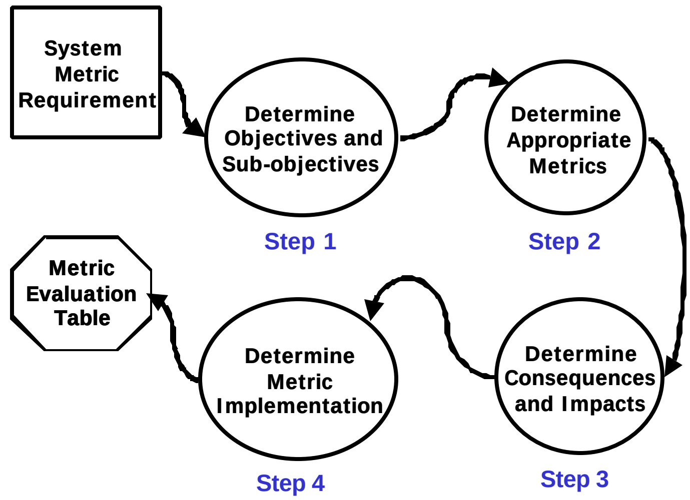


Figure 12: Networked Sensor Metric Development Framework

4.4.1 Step 1

The initial step in metric development is to determine the overall objective of the system along with its sub-objectives (Figure 14, Page 41). One must determine the objectives of the system prior to the metrics in order to avoid the tendency to measure what is easy or convenient rather than measuring what is actually needed.

In order for metrics to have value and meaning, a value hierarchy structure (Figure 13, Page 39) is required. With in the value hierarchical structure, the top represents the overall objective of the system. The next layer represents the objectives of the system and if possible, the next layer represents further development into sub-objectives. All objectives or sub-objectives require a metric or evaluation measure in order to determine their value. The objectives tree as a whole, asks the question, "why" ascending the tree and "how" descending the tree. [Willis and Davis, 2000a]

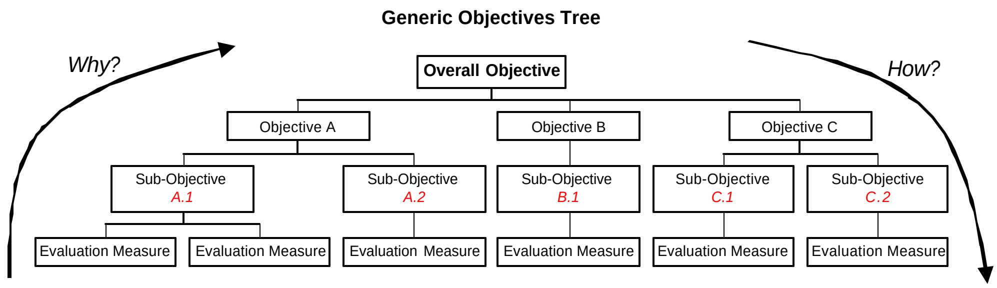


Figure 13: Generic Objectives Tree [Willis and Davis, 2000a]

In order to determine the objectives for the networked sensors, it is important to understand the RSTA squadron's mission. The RSTA squadron develops situational awareness and knowledge in the area of operations, empowering the brigade to anticipate, forestall and dominate threats, ensuring mission accomplishment through decisive action and freedom of maneuver [RSTA, 2000]. It is also important to note that RSTA operations provide extraordinary pay-off in the areas of warning, force protection, combat assessment and prediction of threat actions [RSTA, 2000]. One must extract the portions of the RSTA mission that apply to the networked ground micro-sensors' capabilities and use those portions for the remainder of this process.

From the RSTA mission statement, we determined the primary objective of the networked ground micro-sensors is to provide optimal situation awareness. Situational awareness consists of developing a broader, deeper understanding of the operational environment and all of its facets (including military forces, demographic, social, cultural, political and economic factors) thus creating an umbrella of situational understanding around and within the RSTA squadron's area of responsibility [RSTA, 2000].

The objectives and sub-objectives for networked sensors of the RSTA squadron are summarized in Table 5.

Objective	Meaning
Maximize Situation Awareness	Developing a broader, deeper understanding of the operational environment and all of its facets (including military forces, demographic, social, cultural, political and economic factors) in order to create an umbrella of situational understanding around and within the unit's area of responsibility.
Maximize Stealth	Actions taken for proceeding furtively or secretly in order to avoid contact with enemy elements, includes taking measures to conceal oneself from the enemy such as limiting sensor signatures.
Maximize Time of Operations	Measures taken to conserve power and survivability of the sensor network in order to sustain successful monitoring operations for the mission duration, up to 72 hours.
Maximize Enemy Situation Development	Provide intelligence information for input into analysis of the motives, qualifications and characteristics of the enemy elements in order to make a comprehensive projection of the enemy possible courses of action and capabilities for the decisionmaker.
Maximize Security	Measures taken by military units or elements in order to protect themselves against all acts designed to impair their effectiveness.
Minimize Power Consumption	Measures taken to conserve battery power of the sensor network in order to sustain monitoring operations.
Maximize Survivability	Actions taken to ensure the continuation of life or existence resulting in sustained operability of the micro-sensors, soldiers, weapons and equipment.
Maximize Warning	An early communication of indications and warnings that potential enemy activity is in the area causing such actions as routine defense measures to a substantial increases in readiness and force preparedness.
Maximize Combat Assessment	The determination of the overall effectiveness of force employment during military operations and is composed of three major components: 1) battle damage assessment, 2) munitions effects assessment, and 3) re-attack recommendation.

Table 5: Objectives and Their Meaning

4.4.2 Step 2

This step involves three sub-tasks. First, we determine the number of possible metrics for the system with the described scenario by "brainstorming" or literary research. These metrics form an initial listing (Figure 14) that influences networked sensor systems and the task to emplace the sensors on the battlefield.

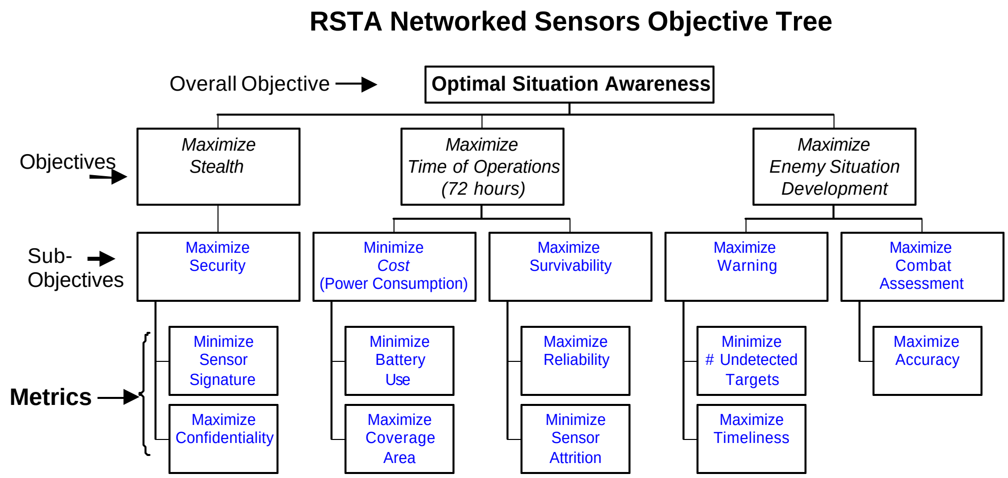


Figure 14: Initial Metrics Chart

The second task involves determining metric characteristics (i.e., meaning, metric dimension and scale (Table 6, Page 20)) for each metric in order to successfully execute the last task within Step 2. It is essential to develop a metric characteristic table due to variability in metric attributes between users and organizations. This table forms the basis for reducing the objectives and metrics within the objective tree.

Metric	Meaning	Performance	Temporal
Maximize Accuracy	Employ measures and techniques in order to ensure or increase the probability of the networked sensors correctly reporting enemy signatures, targets and types.	Interval	Dynamic
Maximize Confidentiality	*Ability of the networked sensors to send information that is not accessible to enemy troops and collection capabilities*	Ordinal	Static
Maximize Coverage Area	The terrain the sensor must monitor taking into account such sensor limitations as terrain, ground cover, maximum range and the sensor's ability to search.	Ordinal	Static
Maximize Reliability	Probability that a sensor observes a target, triggers other sensors and records it.	Interval	Dynamic
Maximize Timeliness	The amount of warning or preparation time the main body of friendly forces has to prepare for enemy elements that are reported by the networked sensors.	Nominal	Dynamic
Minimize # of Undetected Targets	Employ measures and techniques in order to reduce the number of enemy targets passing through the sensor field undetected and coming in contact with the main body of friendly forces.	Nominal	Dynamic
Minimize Battery Use	Employ power conservation measures and techniques in order to ensure adequate battery power for the networked sensor field to accomplish its mission for the prescribed period of time.	Ratio	Dynamic
Minimize Sensor Attrition	Employ measures and techniques in order to prevent or reduce the probability of enemy elements detecting the ground sensors and the subsequent probability that the enemy elements destroy or degrade the sensor's capabilities.	Ratio	Dynamic
Minimize Sensor Signature	The energy emitted or reflected from the micro-sensor.	Nominal	Static

Table 6: Networked Sensor Metric Definitions

The last task in this step involves isolating the critical and most influential objectives by reducing metrics that do not have an immediate impact on the current system scenario. Objective and metric reduction is accomplished through several iterations with the use of expert evidence, knowledge-based systems and analytical abilities.

After further research and an increased knowledge of the system, we determined that Stealth for the networked sensors was not necessary as an independent objective and was covered by the objective of *Survivability*. For the metrics developed to measure the stealth of the system, sensor signature is covered under the survivability objective and its metric of minimize sensor attrition. We determined confidentiality capabilities are set by the sensor hardware and/or software and not influenced by sensor placement on the battlefield.

There were three other metrics that were pruned from the initial objectives tree (i.e., maximize coverage area, maximize reliability and maximize timeliness). Coverage area was deleted because we determined the mission designates the coverage area and it serves as a constraint on the system rather than a metric. Reliability was removed because it is more influenced by the sensor's hardware/software functionality rather than the emplacement of the sensor on the battlefield. Maximize timeliness was determined to be more influenced by the mission and unit standing operating procedures rather than how the sensor was emplaced on the battlefield.

As a result of this step, we determined the most appropriate metrics for networked ground micro-sensor emplacement include: minimize battery use, minimize sensor attrition, minimize number of undetected targets and maximize accuracy and are represented in Figure 15, Page 44.

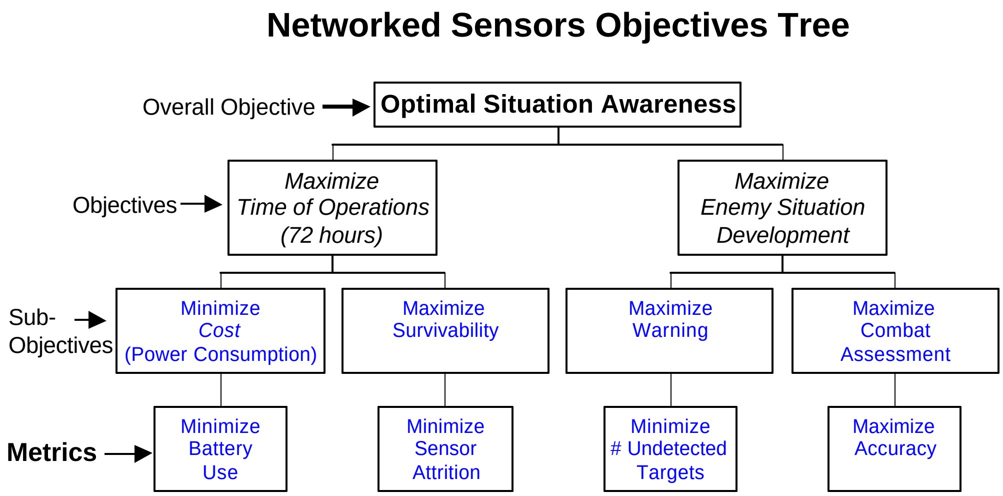


Figure 15: Networked Sensors Critical Objectives Metric Tree

4.4.3 Step 3

The third step in metric development involves determining the consequences and impacts experienced by the system (i.e., networked sensors, the RSTA squadron and the units it supports). This step asks, "What happens if a metric is not measured." First, a list of consequences is determined, keeping in mind that there are an unlimited number of consequences affecting the system. The scope for this thesis is limited to the consequences and their interpretations in Table 7 (Page 45). Next, the mission impacts are determined (Table 8, Page 45). Table 7 and Table 8 are critical elements in building Table 9 (Page 46), which illustrates a mapping of consequences and metrics and the relationship to mission impacts.

Consequence	Interpretation
Loss of Early Warning	Loss of readiness or the "upper hand" - hinders such capabilities as initiative, ability to fight in a "deliberate" setting and the ability to make and communicate sound decisions faster than the enemy.
Loss of Life	US Soldiers die.
Loss of Equipment	Equipment such as vehicles, tanks, and other weaponry are either destroyed or degraded.
Loss of Intelligence Information	Information and enemy situation reports that help the commander to make timely battlefield decisions are lost - hinders such capabilities as superiority, initiative, ability to fight in a "deliberate" setting, the ability to make and communicate sound decisions faster than the enemy and increases the probability of chance encounters with the enemy.
Loss of Sensors	Networked ground micro-sensors are destroyed.

Table 7: Consequences and their Interpretations

Impact	***Interpretation***
Extremely High	Loss of ability to accomplish mission.
High	Significantly degrades mission capability.
Medium	Degrades mission capability.
Low	Little or no impact to mission capability.

Table 8: Mission Impacts Explanation

MOE / Mission Impact / Consequence	Minimize # Undetected Targets	Minimize Battery Power	Minimize Attrition	Maximize Accuracy
Loss of Early Warning	Extremely High	High	High	High
Loss of Life	Extremely High	Medium	Medium	Medium
Loss of Equipment	Extremely High	Medium	Medium	Medium
Loss of Intelligence Information	High	Extremely High	High	High
Loss of Sensors	Medium	Extremely High	Extremely High	Low

Table 9: Metric Consequences and Impacts

As a result of the consequences and impacts table, it is easy to determine the order of priority for the metrics in Table 9. The order of priority is: 1) Minimize number of undetected targets; 2) Minimize battery use; 3) Minimize attrition; 4) Maximize accuracy. Depending on the acceptable thresholds placed on the system, the metric *maximize accuracy* may fall out of consideration during the multi-objective trade-off portion in Chapter 5. This metric may not play a large enough role in the overall mission to warrant consideration based on the current impacts on the system

4.4.4 Step 4

The fourth step in metric development involves determining implementation rules for each metric by obtaining values and results from an experiment or scenario, allowing comparisons among different options, and generating formulas or functions for measuring each metric.

4.4.4.1 Minimize Number of Undetected Targets

- Maximize the amount of terrain covered by the networked sensors in the mission area
- Employ redundancy measures
- Employ a mix if different sensor types in order to increase detection probability

4.4.4.2 Minimize Battery Power

- Set schedule turn on and off – programmed to accomplish scheduled mission time
- Triggering system
- Multiple modes – ultra-low power until something triggers sensor to switch to high power
- Random turn on schedule

4.4.4.3 Minimize Attrition

- Emplace sensors utilizing CC&D measures (cover, concealment & deception)
- Avoid possible high traffic areas (run over sensors, step on sensors)
- Dig in or hand emplace sensors under foliage
- Test hardware for defects prior to emplacement

4.4.4.4 Maximize Accuracy

- Multiple sensor types collect and report on same target
- Use of imager sensor to look at target

Chapter 5 Response Surface Methodology (RSM)

5.1 Response Surface Methodology Definition

Response surface methodology (RSM) is a collection of statistical and mathematical techniques that are used for developing, improving and optimizing processes such as engineering and industrial optimization problems [Myers and Montgomery, 1995]. The methodology is mostly utilized in situations where several input variables may potentially influence the response or performance measure of the system. It includes determining the most important variables to the system, performing sets of experiments to produce a response, modeling the response surface and using the results to plan the next set of experiments until the optimum or near optimum is reached.

5.2 Response Surface Methodology Procedure

The steps executed during the Response Surface Methodology included (Figure 16, Page 49):

Step 1: Design the experiment
Step 2: Run Simulation
Step 3: Fit linear models
Step 4: If improvement, move to the next region to explore
Step 5: Repeat until no improvement occurs (near optimal results)
Step 6: Fit second order models
Step 7: If improvement, move to the next region to explore, return to step 1
Step 8: Repeat until no improvement occurs
Step 9: Conduct multiple Response Optimization
Step 10: Determine Emplacement Rules

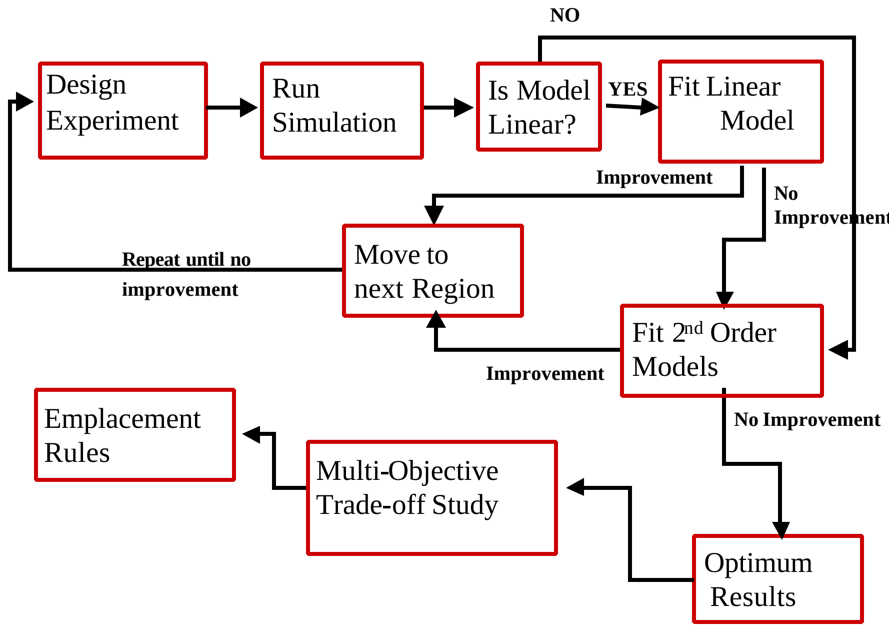


Figure 16: RSM Procedure

5.3 Step 1: Design The Experiment

The general steps for designing RSM experiments include: determine the input variables, transform the input variables, determine the appropriate levels for the input variables, determine the responses and measurement implementation and determine the experimental design type [Box and Draper, 1987].

5.3.1 Determine the input variables

The input variables for the experiments include enemy tracked vehicles and enemy wheeled vehicles from a type of motorized rifle battalion. The remaining input variables are the three main types of networked micro-sensors (i.e., seismic, acoustic and FLIR sensors). Magnetic sensors are not included, because their maximum effective range is much less than the error distances involved in the simulation.

Input Variables
Tracked Enemy Target
Wheeled Enemy Target
Seismic Sensor
Acoustic Sensor
FLIR Sensor

Table 10: Initial Input Variables

5.3.2 Determine the appropriate levels for the input variables

Based on this experiment, the input variables are not transformed and the appropriate input variable levels are determined. With the limited information available, the input variables and their levels were an approximation based on experience, expert evidence and literary research. The enemy vehicle levels are based on the approximate size of a motorized rifle battalion. The number of sensors is based on the chosen simulation area and sensor detection ranges.

Table 11 shows the input variables and their levels. In order to code the variables to +1 and –1 levels, the following equation is used: $x_i = (x_i - x_{i0})/S_i$, where x_i is the coded variable, x_i is the actual numeric variable, x_{i0} is the center of the region and S_i is the distance from the center point to the outer edges. The remaining two columns of the table show the "high" and "low" values for each variable.

Input Variable	**Coded Variable (Equation)**	**High (+1)**	**Low (-1)**
Tracked Vehicle	$[x_i - 12]/4$	16	8
Wheeled Vehicle	$[x_i - 36]/12$	48	24
Seismic Sensor	$[x_i - 4]/2$	6	2
Acoustic Sensors	$[x_i - 4]/2$	6	2
FLIR Sensors	$[x_i - 3]/1$	4	2

Table 11: Input variables and their levels

5.3.3 Determine the Responses and Measurement Implementation

The responses for this experiment include the percentage of undetected enemy targets that move through the simulation area, the attrition rate for the number of micro-sensors that are found and destroyed by enemy forces, and the percentage of times that the sensors correctly identify the enemy targets after they are detected. The responses are depicted in Table 12 along with information on how the responses are measured.

Response	Measured
Undetected	# enemy tgts undetected / total # of enemy tgts
Attrited	# sensors attrited / total # of sensors emplaced
Classified	# correct classifications / total # of detections

Table 12: Response Variables

5.3.4 Experimental Design

The initial experimental design is a screening experiment to see which variables are important. After obtaining results from the initial screening experiment (two levels of each variable and four center points), subsequent experiments are planned based on the significant variables and any requirements for second-order designs.

Two types of independent experimental runs are planned. One run consists of placing the networked ground micro-sensors in open areas in order to maximize collection range, labeled *Open*. The other run consists of placing the networked ground micro-sensors in the tree lines in order to reduce enemy detection capabilities, labeled *Obstacles*.

For the screening experiments, a factorial design with two levels for each variable and four center point runs, or as this type of design is commonly referred to as a 2^K factorial design is used. The factor K represents the number of input variables in the system. For our initial screening experiment, we ran a 2^5 factorial design (the K value is 5 because we have five input variables). Each variable is ran at a “high” and “low” level in combination with all of the other variables resulting in 32 experimental runs plus four center point runs, totaling 36 experimental runs. The center point runs are used to check for curvature in the system and to obtain an independent estimate of error. The center point runs are effective because they do not impact the effect estimates of the design. For more information on 2^k factorial designs, consult Myers and Montgomery [1995].

Screening Experiment – 2^5 factorial design with three responses

Standard Order	Tracked	Wheeled	Seismic	Acoustic	FLIR
1	8	24	2	2	2
2	16	24	2	2	2
3	8	48	2	2	2
4	16	48	2	2	2
5	8	24	6	2	2
6	16	24	6	2	2
7	8	48	6	2	2
8	16	48	6	2	2
9	8	24	2	6	2
10	16	24	2	6	2
11	8	48	2	6	2
12	16	48	2	6	2
13	8	24	6	6	2
14	16	24	6	6	2
15	8	48	6	6	2
16	16	48	6	6	2
17	8	24	2	2	4
18	16	24	2	2	4
19	8	48	2	2	4
20	16	48	2	2	4
21	8	24	6	2	4
22	16	24	6	2	4
23	8	48	6	2	4
24	16	48	6	2	4
25	8	24	2	6	4
26	16	24	2	6	4
27	8	48	2	6	4
28	16	48	2	6	4
29	8	24	6	6	4
30	16	24	6	6	4
31	8	48	6	6	4
32	16	48	6	6	4
33	12	36	4	4	3
34	12	36	4	4	3
35	12	36	4	4	3
36	12	36	4	4	3

Variables	**Responses**
Tracked	Undetected
Wheeled	Attrited
Seismic	Classified
Acoustic	
FLIR	

Figure 17: Initial Screening Experimental Design

5.4 Step 2: Run the Experiments in a Computer Simulation

This step forms a major contribution of this thesis and is addressed in great detail in Chapter 6 (Simulation). Two types of experiments were planned for the computer simulations: sensors in the open and sensors in obstacles. The remaining steps are explained by experiment.

5.5 Experiment – Sensors in the Open

5.5.1 Step 3: Fit Linear Models (Open)

Linear models are justified for simple systems containing interaction between variables. Variables (A, B, C) containing interdependencies with other variables (e.g., AB or BC) or itself (A^2, B^2 or C^2) requires at least a second order model. The goals of this step are to determine the appropriate order of the variables (e.g., first or second order) and the appropriate transformations for each variable.

Analysis of the data is compiled in the Analysis of Variance (ANOVA) table, which for our purposes was compiled in a Response Surface Modeling software program by STAT-EASE. The ANOVA table is based on a decomposition of the total variability in the response variable *y*. If curvature is significant (F-ratio less than $\alpha = .05$) in the ANOVA table, there are indications that there is curvature present in the system and a linear model is not appropriate for modeling the system. The alpha level for the significance test may be set at different levels, we chose the most common level of $\alpha = .05$ for testing significance. Lack of fit is one part of the residual sum of squares calculations and is a weighted sum of squared deviations between the mean response y_i at each x_i level and the corresponding fitted value. If lack of fit is found to be significant (F-ratio less than α = .05) then one concludes that the regression function is not linear. [Myers and Montgomery, 1995]

Once a linear model is fit to the system, model adequacy checking is performed. This involves examining the fitted model to ensure it is an adequate approximation to the true system and checking to ensure none of the least squares regression assumptions are violated. Tools to accomplish model adequacy checking include constructing a normal probability plot of the residuals to ensure the normality assumption stands, checking for outliers (individual points that may influence the model) and checking Cook's distance (measure of the squared distance between the least squares estimate based on all *n* points and the estimate obtained by deleting the i^{th} point) looking for points that have large values ($D_i > 1$) indicating the least squares estimate is sensitive to the i^{th} data point. Other tools for checking model adequacy include R^2 and adjusted R^2 values. R^2 (a value between 0 and 1) is a measure of the amount of reduction in the variability of *y* obtained by using the regressor variables in the model. Due to the fact that R^2 always increases with the addition of terms, the adjusted R^2 value is preferred and is defined as: $R^2_{adj} = 1 - \frac{SS_E/(n-p)}{S_{yy}/(n-1)}$. [Myers and Montgomery, 1995]

The results for the initial screening experiment indicate that the response values for undetected must be transformed with the natural log transform.

Because the F-ratio is below 0.05 for both curvature and lack of fit, they are both significant indicating a second order model is necessary.

The results from the natural log transform of the response *undetected* (Figure 18) indicate that curvature and lack of fit are still significant making it necessary to abandon attempts to fit a linear model and turn to looking at a second order model.

We did obtain some results from the initial screening experiment. It appears that the significant variables for the response *undetected* are wheeled vehicles, seismic and acoustic sensors. Further experiments focus on those three variables.

ANOVA Table Natural Log Transform of Response: Undetected

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	8.25	3	2.75	110.86	< 0.0001
B	*0.70*	*1*	*0.70*	*28.30*	*< 0.0001*
C	*4.59*	*1*	*4.59*	*185.08*	*< 0.0001*
D	*2.96*	*1*	*2.96*	*119.19*	*< 0.0001*
Curvature	**0.82**	**1**	**0.82**	**32.94**	**< 0.0001**
Residual	0.77	31	0.025		
Lack of Fit	***0.76***	***28***	***0.027***	***19.68***	***0.0155***
Pure Error	*.0042*	*3*	*.0014*		
Cor Total	9.84	35			

Std. Dev.	0.16	R-Squared	0.9147
Mean	-1.19	Adj R-Squared	0.9065
C.V.	-13.19	Pred R-Squared	0.8977
PRESS	1.01	Adeq Precision	28.310

Final Equation in Terms of Actual Factors:
Ln(Undetected) = -0.21946 + 0.012342 * Wheeled - 0.18938 * Seismic - 0.15198 * Acoustic

Figure 18: Results from 2^k Open – Natural Log (Undetected)

The results for the response *attrited* indicate that curvature and lack of fit are not significant and an appropriate linear model is fitted (Figure 19). By performing model adequacy checking, it was determined that the adjusted R^2 value of 68% is reasonable, the normality plot of the residuals shows that the normality assumption stands and there are no outliers or influential points that impact the model. The next step for this response is to explore the next region to see if we experience any improvement.

ANOVA Table for **Response: Attrited**

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.090	1	0.090	72.90	< 0.0001
B	*0.090*	*1*	*0.090*	*72.90*	*< 0.0001*
Curvature	**.000935**	**1**	**0.000935**	**0.76**	**0.3898**
Residual	0.041	33	0.00123		
Lack of Fit	***0.038***	***30***	**0.00*128***	***1.62***	***0.3911***
Pure Error	0.00*236*	*3*	0.000*788*		
Cor Total	0.13	35			

Std. Dev.	0.035	R-Squared	0.6884	
Mean	0.25	Adj R-Squared		0.6789
C.V.	13.92	Pred R-Squared		0.6364
PRESS	0.048	Adeq Precision		10.457

Final Equation in Terms of Actual Factors:
Attrited = 0.091375 + 4.41406E-003 * Wheeled

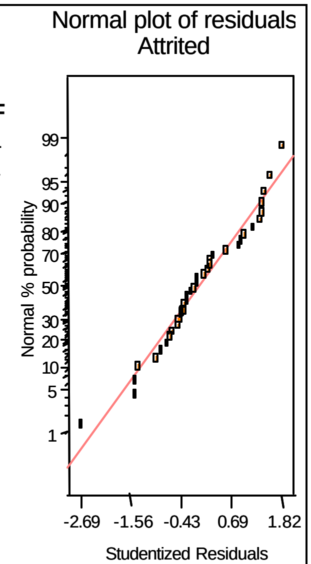


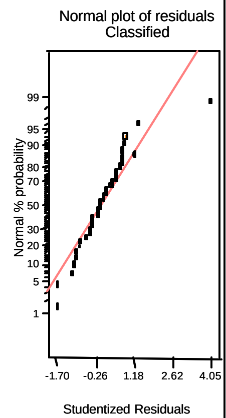
Figure 19: Results from 2^k Open – Attrited

The results for the response *classified* indicate that curvature and lack of fit are not significant and an appropriate linear model is fitted (Figure 20, Page 57). By performing model adequacy checking, it is determined that the adjusted R^2 value of 91.8% is very good (indicating almost 92% of the variation about the mean is explained by the fitted model), the normality plot of the residuals shows that the normality assumption stands. There is one outlier that may be influential to the model, however the cook's distance check is less than one and it does not appear to be influential to the model. The next step for this response is to explore the next region to see if we experience any improvement.

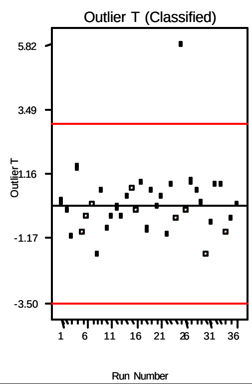
ANOVA Table for Response: Classified

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.040	3	0.013	127.17	< 0.0001
C	*0.024*	*1*	*0.024*	*233.91*	*< 0.0001*
D	*0.015*	*1*	*0.015*	*140.86*	*< 0.0001*
CD	0.000*703*	*1*	0.000*703*	*6.73*	*0.0143*
Curvature	**0.000168**	**1**	**0.000168**	**1.61**	**0.2140**
Residual	0.00324	31	0.000104		
Lack of Fit	**0.00*304***	***28***	**0.000*109***	***1.67***	***0.3781***
Pure Error	0.0001*954*	*3*	0.0000*649*		
Cor Total	0.043	35			

Std. Dev.	0.010	R-Squared	0.9248
Mean	0.86	Adj R-Squared	0.9176
C.V.	1.19	Pred R-Squared	0.9001
PRESS	4.319E-003	Adeq Precision	25.768



Final Equation in Terms of Actual Factors:
Classified = 0.830 + 0.0185 * Seismic -.00603125 * Acoustic - .00117188 * Seismic * Acoustic



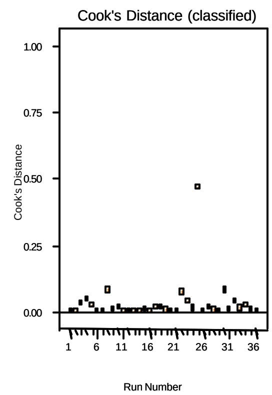


Figure 20: Results from 2k Open - Classified

5.5.2 Step 4: If Improvement, Move to Next Region to Explore

5.5.2.1 Overview

Since the responses Attrited and *classified* are both linear models, we plan a new set of experiments to explore the next region in an attempt to find improvement in the response results. Since we determined that the three significant variables are wheeled vehicles, seismic sensors and acoustic sensors and in order to make the simulation work correctly those three variables are also the minimum number to run for further experiments. So even though the model for the response *attrited* is only concerned with the number of wheeled vehicles, the two sensors must be included in the simulation in order to obtain any results.

The number of variables used for all future designs is reduced to the three significant variables (Wheeled, Seismic, Acoustic). The desirability function and graphical optimization is used to determine the next region to explore. The desirability function and graphical optimization procedures are explained in detail in Section 5.7, Page 82. Instead of trying to optimize each response individually and determining new regions for each of the three responses, the optimization method enables us to conduct more efficient experiments. The three responses are all inter-related and it did not make sense to try to do each one individually. For example, if we tried to optimize the response attrition alone, we would keep moving to new regions that involved less wheeled vehicles until no vehicles remained.

5.5.2.2 Experimental Design

Based on the results from the desirability plot (Figure 21, Page 59), the optimal value range for the sensors in this experiment is six seismic and four acoustic sensors. Testing the next region, involves new variable values, listed in Table 13, Page 59. A factorial design with 2^3 variables is designed for the next experiment (Table 14, Page 59). Figure 22, Page 60 is a visible representation of the 2^3 factorial design.

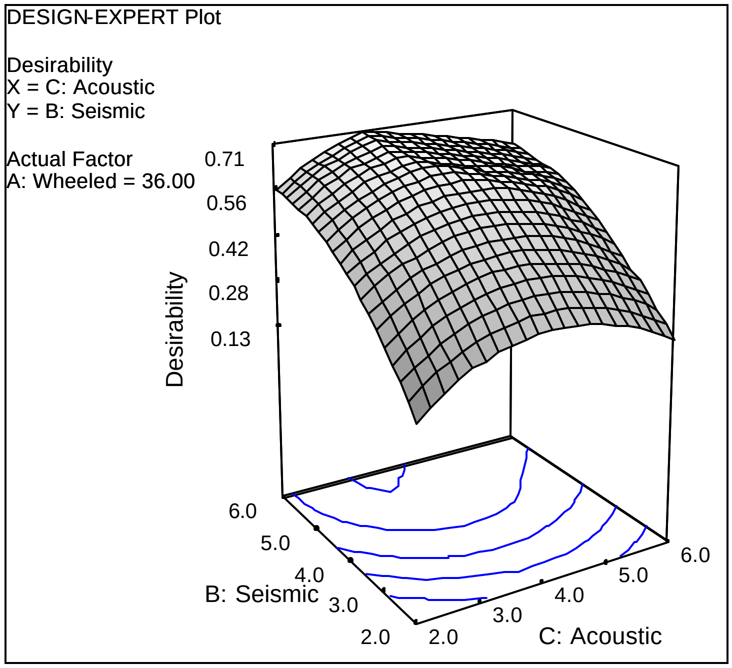


Figure 21: Region One Optimal Setting – Open

Input Variable	Coded Variable (Equation)	High (+1)	Low (-1)
Wheeled Vehicle	$[x_i - 36]/12$	48	24
Seismic Sensor	$[x_i - 8]/2$	10	6
Acoustic Sensors	$[x_i - 6]/2$	8	4

Table 13: Region 2 Variable Levels

Run #	Wheeled	Seismic	Acoustic
1	24	6	4
2	48	6	4
3	24	10	4
4	48	10	4
5	24	6	8
6	48	6	8
7	24	10	8
8	48	10	8
9	36	8	6
10	36	8	6
11	36	8	6

Table 14: Region 2 Experimental Design

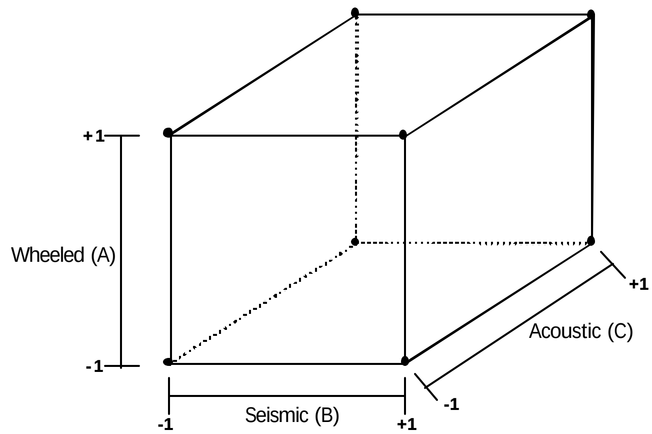


Figure 22: 2^3 Factorial Design Schematic

5.5.2.3 Results

Initial analysis indicate that the response values for *undetected* must be transformed with the natural log transform. The results from the natural log transformation of the response *undetected* (Figure 23, Page 61) indicate that curvature and lack of fit are not significant and an appropriate linear model is fitted. By performing model adequacy checking, it was determined that the adjusted R^2 value of 95% is very good (indicating 95% of the variation about the mean is explained by the fitted model) and the normality plot of the residuals shows that the normality assumption stands. There appears to be no outliers that influence the model.

ANOVA Table Natural Log Transform of Response: Undetected
Region 2, 2^3 Factorial Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	6.79	3	2.26	62.11	< 0.0001
A	*0.39*	*1*	*0.39*	*10.73*	*0.0169*
B	*4.57*	*1*	*4.57*	*125.28*	*< 0.0001*
C	*1.83*	*1*	*1.83*	*50.30*	*0.0004*
Curvature	0.00852	1	0.00852	0.23	0.6458
Residual	0.22	6	0.036		
Lack of Fit	*0.15*	*4*	*0.038*	*1.10*	*0.5286*
Pure Error	*0.069*	*2*	*0.034*		
Cor Total	7.02	10			

Std. Dev.	0.19	R-Squared	0.9688
Mean	-3.10	Adj R-Squared	0.9532
C.V.	-6.16	Pred R-Squared	0.8925
PRESS	0.75	Adeq Precision	22.614

Final Equation in Terms of Actual Factors:
Ln(Undetected) = 0.71421 + 0.0184 * Wheeled - 0.378 * Seismic - 0.239 * Acoustic

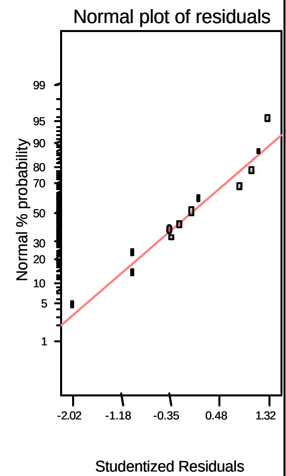


Figure 23: Results – Region 2, 2^3 Design (Open) for Undetected

The results from the response *attrited* (Figure 24) indicate that curvature is significant there fore a second order model must be fitted. Lack of fit is not significant, but the significant curvature indicates a linear model is not appropriate. Curvature is considered significant, because the Prob>F value of 0.0029 is less than the significance test alpha value of 0.05.

ANOVA Table of Response: Attrited
Region 2, 2^3 Factorial Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.022	3	0.00721	106.20	< 0.0001
A	*0.021*	*1*	*0.021*	*301.89*	*< 0.0001*
B	0.000*231*	*1*	0.000*231*	*3.40*	*0.1146*
C	0.000*903*	*1*	0.000*903*	*13.30*	*0.0108*
Curvature	0.00158	1	0.00158	23.20	0.0029
Residual	0.000408	6	0.0000679		
Lack of Fit	0.000*366*	*4*	0.0000*914*	*4.35*	*0.1955*
Pure Error	0.0000*42*	*2*	0.0000*21*		
Cor Total	0.024	10			

Std. Dev.	8.241E-003	R-Squared	0.9815
Mean	0.20	Adj R-Squared	0.9723
C.V.	4.07	Pred R-Squared	0.9341
PRESS	1.556E-003	Adeq Precision	23.982

Figure 24: Results – Region 2, 2^3 Design (Open) for Attrited

The results from the response *classified* (Figure 25) indicate that curvature is significant therefore a second order model must be fitted. Lack of fit is not significant (the Prob>F value is greater than the 0.05 significance level), but the significant curvature (the Prob>F value is less than the 0.05 significance level) indicates a linear model is not appropriate.

ANOVA Table of Response: Classified
Region 2, 2^3 Factorial Experiment

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	0.00350	3	0.00117	45.03	0.0002
A	0.000*242*	*1*	0.000*242*	*9.33*	*0.0224*
B	0.000*882*	*1*	0.000*882*	*34.00*	*0.0011*
C	0.00*238*	*1*	0.00*238*	*91.75*	*< 0.0001*
Curvature	0.00018	1	0.00018	6.94	0.0388
Residual	0.000156	6	0.00002594		
Lack of Fit	0.0000*81*	*4*	0.0000*203*	*0.54*	*0.7292*
Pure Error	0.0000*747*	*2*	0.0000*373*		
Cor Total	0.00384	10			

Std. Dev.	0.00509	R-Squared	0.9575
Mean	0.91	Adj R-Squared	0.9362
C.V.	0.56	Pred R-Squared	0.8719
PRESS	0.000492	Adeq Precision	19.365

Figure 25: Results – Region 2, 2^3 Design (Open) for Classified

5.5.3 Step 6: Fit Second Order Models (Open)

The Central Composite Design (CCD) is the most popular design for second-order models and therefore, is used in this experiment. The CCD involves the use of a two-level factorial design combined with $2k$ axial points and n_c center runs (Figure 26, Page 63). The factorial points provide the optimal design for first-order models as well as the two factor interactions of first-order type models. Center runs identify the existance of curvature in the system. If curvature exists, the axial points provide the ability to estimate the pure quadratic terms. The flexibility areas of the CCD are the α value for the axial points and n_c, the number of center point runs. The values for the axial points are determined in a number of ways, varying from the value of one to the square root of *k*. For this experiment, whole number values are required, so the axial point alpha value that allowed this to happen was α = 1.5. This α value is different from the α value used for the significane test, it is the term used when determining the axial point values for the CCD. For more information on CCD designs, consult [Myers and Montgomery, 1995].

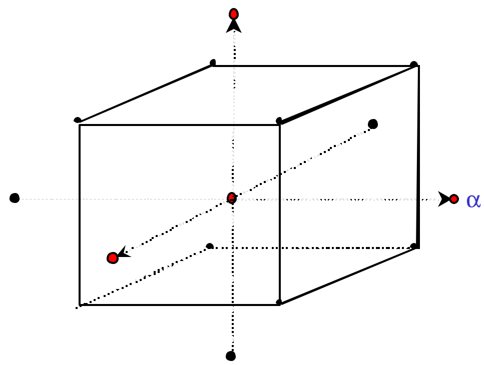


Figure 26: CCD Design Schematic

The planned CCD experiment is summarized in Figure 27.

Central Composite Design – three variables, α = 1.5

Standard Order	Wheeled	Seismic	Acoustic
1	24	2	2
2	48	2	2
3	24	6	2
4	48	6	2
5	24	2	6
6	48	2	6
7	24	6	6
8	48	6	6
9	18	4	4
10	54	4	4
11	36	1	4
12	36	7	4
13	36	4	1
14	36	4	7
15	36	4	4
16	36	4	4
17	36	4	4

Variables	Responses
Wheeled	Undetected
Seismic	Attrited
Acoustic	Classified

Figure 27: CCD Experimental Design

5.5.4 Sensors in the Open Experiment

The results for the CCD experiment indicate that the response values for *undetected* must be transformed with the natural log transform. For the developed model, curvature and lack of fit are not significant, indicating the model is a good second order model and the appropriate second order model is fitted (Figure 28).

Model adequacy checking determined that the adjusted R^2 value of 96% is really good and the normality plot of the residuals shows that the normality assumption stands and there are no outliers or influential points that may impact the model. The next step for this response is to explore the next region to see if we experience any improvement.

ANOVA Table for Response: LN(Undetected)

CCD Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	5.91	6	0.99	70.30	< 0.0001
A	*0.099*	*1*	*0.099*	*7.080.0239*	
B	*3.00*	*1*	*3.00*	*214.28*	*< 0.0001*
C	*1.09*	*1*	*1.09*	*77.93*	*< 0.0001*
A2	*0.30*	*1*	*0.30*	*21.69*	*0.0009*
B2	*0.79*	*1*	*0.79*	*56.50*	*< 0.0001*
C2	*1.08*	*1*	*1.08*	*77.14*	*< 0.0001*
Residual	0.14	10	0.014		
Lack of Fit	***0.12***	***8***	***0.015***	***1.47***	***0.4668***
Pure Error	*0.020*	*2*	*0.010*		
Cor Total	6.05	16			

Std. Dev.	0.12	R-Squared	0.9768
Mean	-1.53	Adj R-Squared	0.9629
C.V.	-7.72	Pred R-Squared	0.9178
PRESS	0.50	Adeq Precision	23.348

Final Equation in Terms of Actual Factors:

Ln(Undetected) = 3.47924 - 0.086751 * Wheeled - 0.85303 * Seismic - 0.85819 * Acoustic + .00130796 * Wheeled2 + 0.075997 * Seismic2+ 0.0888 * Acoustic2

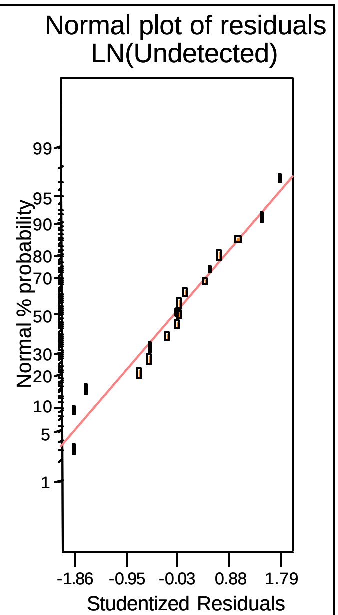


Figure 28: Results from CCD Open – Natural Log (Undetected)

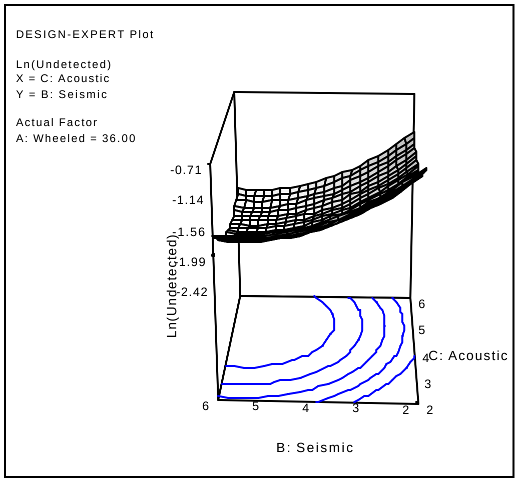


Figure 29: 3-D Model Graph – Natural Log (Undetected)

5.5.5 Step 7: If Improvement, Move to Next Region to Explore

5.5.5.1 Overview

Since the response Natural Log (Undetected) results in an appropriate second order model, we plan a new set of experiments to explore the next region in an attempt to find improvement in the response results. Since region two linear models for the responses *attrited* and *classified* were not appropriate due to significant curvature in the model, they are also analyzed in a CCD model. During region two exploration and fitting linear models, we discovered an appropriate linear model for the response *undetected* with very good model adequacy checks, however we still plan to fit a second order model and compare the results of the two before we decide which model is appropriate.

5.5.5.2 Experimental Design

Based on the results from the desirability plot (Figure 21, Page 59), the optimal value ranges for the sensors in this experiment are six seismic and four acoustic sensors. In order to test the next region, the variable values are listed in (Table 15). For this experiment, a CCD design was planned with an axial point alpha value of 1.5 and three center point runs (Table 16).

Input Variable	**Coded Variable (Equation)**	**High (+1)**	**Low (-1)**	**Axial Points**
Wheeled Vehicle	$[x_i - 36]/12$	48	24	18, 54
Seismic Sensor	$[x_i - 8]/2$	10	6	5, 11
Acoustic Sensors	$[x_i - 6]/2$	8	4	3, 9

Table 15: Region 2 CCD Variable Levels

Run #	Wheeled	Seismic	Acoustic
1	24	6	4
2	48	6	4
3	24	10	4
4	48	10	4
5	24	6	8
6	48	6	8
7	24	10	8
8	48	10	8
9	18	8	6
10	54	8	6
11	36	5	6
12	36	11	6
13	36	8	3
14	36	8	9
15	36	8	6
16	36	8	6
17	36	8	6

Table 16: Region 2, CCD Experimental Design (Open)

5.5.5.3 Results

The results from this CCD experiment indicate that the response values for *undetected* must be transformed with the natural log transformation. For the developed model, lack of fit is not significant, and the resulting model is actually a linear model (Figure 31, Page 68). These results are similar to the results from the 2^3 factorial design for region 2 that was performed in step four (Figure 23, Page 61), exept that model resulted in a little higher acuracy rating.

Model adequacy checking for this CCD model determined that the adjusted R^2 value of 90% is good, but not as high as the results from region one. The normality plot of the residuals indicates that there may be some problems with the normality assumptions for this model. There is one outlier that may influence the results and impact the normality plot results.

The undetected rate is very low for this region (approximately 1.5% of the targets make it through the region undetected). There was improvement experienced in this region and the next step is to move to another region, but by using the constraints that were stated in the mathematical model portion (Section 1.6 , Page 5) no further improvements are really possible. The pay-off cost for emplacing additional sensors in order to reduce the undetected rate even further is extremely low. For example the extra dollars spent on additional sensors emplaced in the area and the increased attrition rate of those sensors is not worth lowering an already extremely low rate of 0.015.

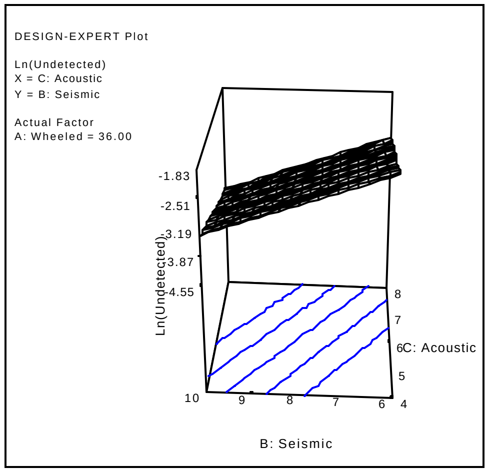


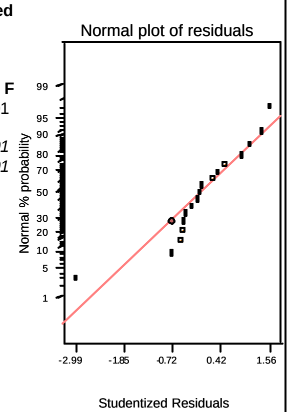
Figure 30: 3-D Model Graph, Region 2, Natural Log (Undetected)

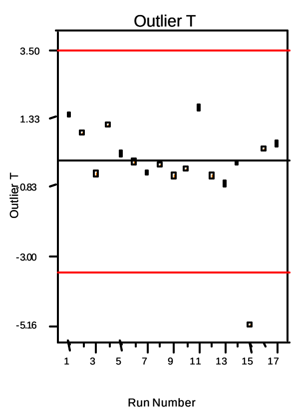
ANOVA Table Natural Log Transform of Response:Undetectted
Region 2, CCD Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	12.24	3	4.08	50.17	< 0.0001
A	*0.54*	*1*	*0.54*	*6.65*	*0.0229*
B	*7.25*	*1*	*7.25*	*89.12*	*< 0.0001*
C	*4.45*	*1*	*4.45*	*54.74*	*< 0.0001*
Residual	1.06	13	0.081		
Lack of Fit	*0.99*	*11*	*0.090*	*2.62*	*0.3083*
Pure Error	*0.069*	*2*	*0.034*		
Cor Total	13.30	16			

Std. Dev.	0.29	R-Squared	0.9205
Mean	-3.19	Adj R-Squared	0.9021
C.V.	-8.95	Pred R-Squared	0.8579
PRESS	1.89	Adeq Precision	22.645

Final Equation in Terms of Actual Factors:
Ln(Undetected) = +1.024 + 0.0173 * Wheeled - 0.381 * Seismic – 0.298 * Acoustic





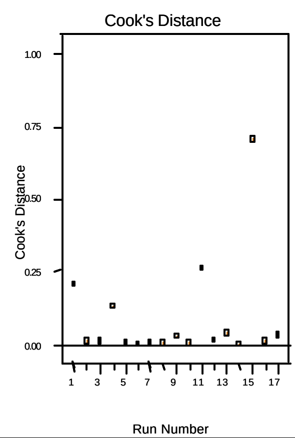


Figure 31: Results from Region 2 CCD Open – Natural Log(Undetected)

The results from the 2^3 factorial design experiments in region two determined that the response attrition and *classified* required second order model fitting due to the fact that curvature was significant for both responses with the attempted linear model fit. So both responses, *attrited* and *classified*, were tested using the CCD experiment in region two.

The results from this CCD experiment indicate that the fitted model is significant and lack of fit is not significant (Figure 33, Page 70). Model adequacy checking for this CCD model determined that the adjusted R^2 value of 91% is good, but the normality plot of the residuals indicates that there may be some problems with the normality assumptions for this model. There are no significant outliers, but the Cook's Distance check indicates there is one point that may influence the results and impact the normality plot results.

The 3-dimensional model plot for the results of the response *attrited* (Figure 32) indicate no improvement can be obtained by moving to another region and perfoming additionall experiments.

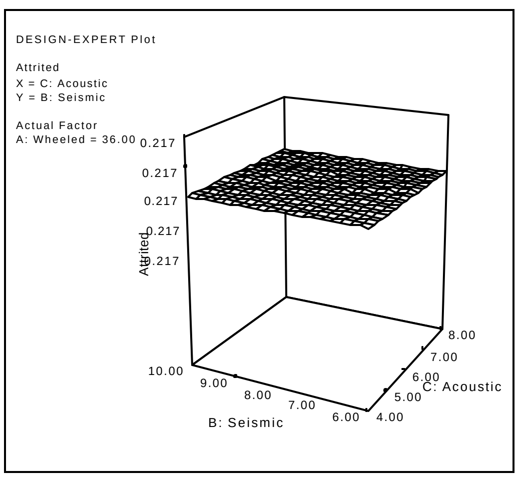


Figure 32: 3-D Model Graph, Region 2 - Attrited

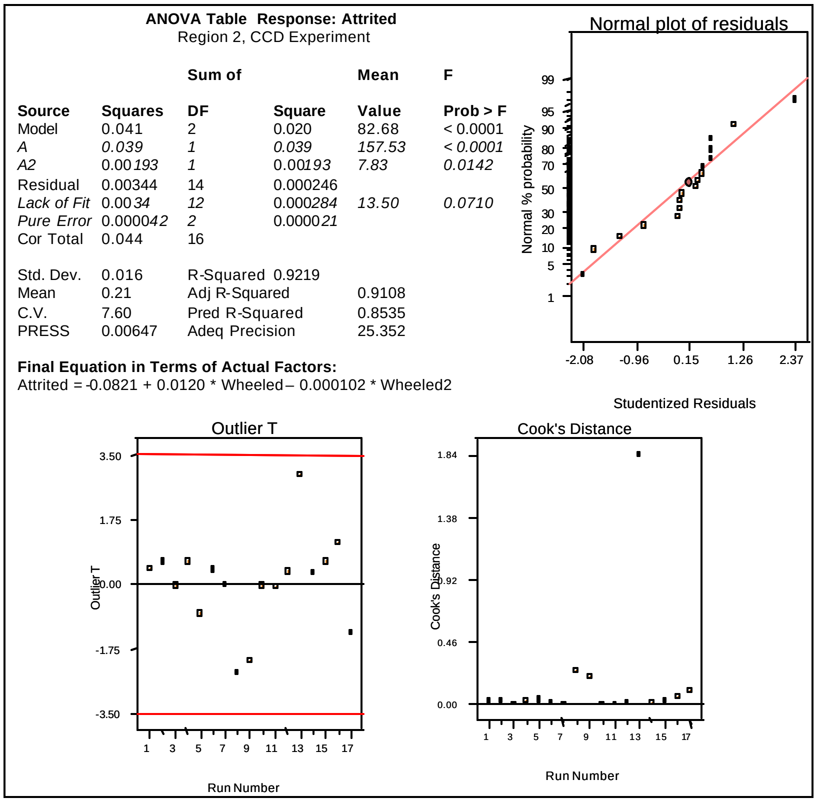


Figure 33: Results from Region 2 CCD Open – Attrited

The results for the response *classified* in the CCD experiment indicate that the fitted model is significant and lack of fit is not significant and the resulting model is actually a linear model (Figure 34, Page 71). Model adequacy checking for this CCD model determined that the adjusted R^2 value of 93% is good and the normality plot of the residuals demonstrates that the normality assumption stands. There are no significant outliers influencing the model.

The 3-dimensional model plot for the results of the response *classified* (Figure 35, Page 71) indicate the more seismic sensors and less acoustic sensors, the better the results for this response will be, no matter what region we move to therefore, there are no further experiments planned for this response in other regions. This is intuitive, because seismic sensors have a much higher correct classification rate than acoustic sensors.

ANOVA Table Response: Classified
Region 2, CCD Experiment

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	5.380E-003	3	1.793E-003	27.39	< 0.0001
A	*2.785E-004*	*1*	*2.785E-004*	*4.25*	*0.0598*
B	*8.323E-004*	*1*	*8.323E-004*	*12.71*	*0.0035*
C	*4.269E-003*	*1*	*4.269E-003*	*65.19*	*< 0.0001*
Residual	8.513E-004	13	6.548E-005		
Lack of Fit	*7.766E-004*	*11*	*7.060E-005*	*1.89*	*0.3964*
Pure Error	*7.467E-005*	*2*	*3.733E-005*		
Cor Total	6.231E-003	16			

Std. Dev.	8.092E-003	R-Squared	0.8634
Mean	0.91	Adj R-Squared	0.8319
C.V.	0.89	Pred R-Squared	0.7605
PRESS	1.493E-003	Adeq Precision	15.979

Final Equation in Terms of Actual Factors:
Classified = 0.917 + 0.000393 * Wheeled + 0.00408 * Seismic – 0.00924 * Acoustic

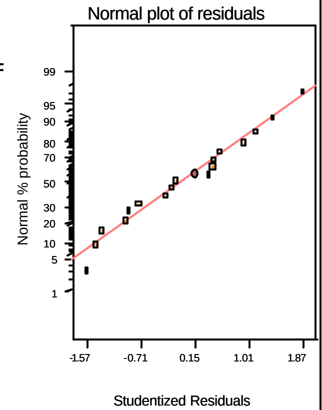


Figure 34: Results from Region 2 CCD Open – Classified

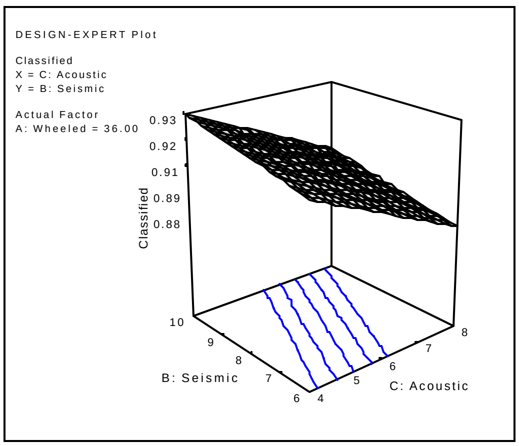


Figure 35: 3-D Model Graph, Region 2 – Classified

5.5.6 Final Response Models for Open Experiment

Figure 36 (Page 72) summarizes the prediction models chosen to represent each of the responses. For more in depth information on the statistical results for each of these models, consult Appendix A.

Response Models, Open Experiments

- Region 1: {0 to 6 Seismic Sensors and 0 to 6 Acoustic Sensors}
  - **Undetected** = Exponential(3.479 - .0868(Wheeled) – 0.853(Seismic) – 0.858(Acoustic) + 0.00131(wheeled)^2 + 0.0760(Seismic)^2 + 0.0888(Acoustic)^2
  - **Attrited** = 0.0914 + 0.00441(Wheeled)
  - **Classified** = 0.830 + 0.0185(Seismic) – 0.00603(Acoustic) – 0.00117(Seismic)(Acoustic)
- Region 2: {6 to 10 Seismic Sensors and 4 to 8 Acoustic Sensors}
  - **Undetected** = Exponential(0.714 + 0.0184(wheeled) – 0.378(Seismic) – 0.239(Acoustic)
  - **Attrited** = -0.0821 + 0.0120(wheeled) – 0.000102(Wheeled)^2
  - **Classified** = 0.917 + 0.000393(Wheeled) + 0.00408(Seismic) – 0.00924(Acoustic)

Figure 36: Response Models for Open Experiments

5.6 Sensors in Obstacles Experiment

5.6.1 Step 3: Fit Linear Models (Obstacles)

The results for the initial screening experiment indicated that the response values for undetected must be transformed with the square root transform. Because the F-ratio is well above 0.05 for both curvature and lack of fit, they are both not significant indicating the proposed linear model is an appropriate model (Figure 37, Page 73).

When performing model adequacy checking, it was determined that the adjusted R^2 value of 95% is very reasonable, the normality plot of the residuals shows that the normality assumption stands and there are no outliers or influential points that may impact the model. The next step for this response is to explore the next region to see if we experience any improvement.

ANOVA Table for Response Sqrt(Undetected)
Screening Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.91	4	0.23	171.92	< 0.0001
B	*0.030*	*1*	*0.030*	*23.13*	*< 0.0001*
C	*0.43*	*1*	*0.43*	*323.12*	*< 0.0001*
D	*0.43*	*1*	*0.43*	*329.18*	*< 0.0001*
CD	*0.016*	*1*	*0.016*	*12.24*	*0.0015*
Curvature	0.00312	1	0.00312	2.37	0.1340
Residual	0.039	30	0.00132		
Lack of Fit	*0.032*	*27*	*0.00119*	*0.49*	*0.8687*
Pure Error	*.00731*	*3*	*0.00244*		
Cor Total	0.95	35			

Std. Dev.	0.036	R-Squared	0.9582
Mean	0.53	Adj R-Squared	0.9526
C.V.	6.80	Pred R-Squared	0.9386
PRESS	0.058	Adeq Precision	35.445

Final Equation in Terms of Actual Factors:
Sqrt(Undetected) = 0.9908 + 0.00257 * Wheeled - 0.0801 * Seismic – 0.0806 * Acoustic + 0.00561 * Seismic * Acoustic

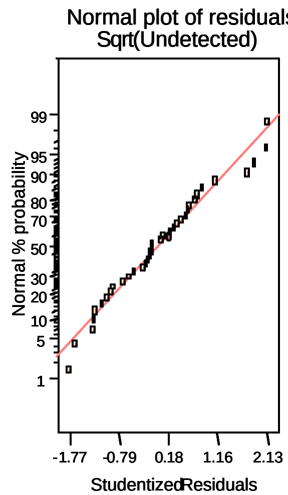


Figure 37: Results from 2^k Obstacles – Square Root (Undetected)

The results for the response *attrited* indicate that curvature is not significant, but lack of fit is significant so the proposed linear model is not appropriate and a second order model is explored (Figure 38).

ANOVA Table for Response: Attrited
Screening Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.032	1	0.032	103.63	< 0.0001
B	*0.032*	*1*	*0.032*	*103.63*	*< 0.0001*
Curvature	0.000657	1	0.000657	2.11	0.1561
Residual	0.010	33	0.000312		
Lack of Fit	***0.010***	***30***	***0.000425***	***64.23***	***0.0027***
Pure Error	*0.000016*	*3*	*0.00000533*		
Cor Total	0.043	35			

Std. Dev.	0.018	R-Squared	0.7585
Mean	0.12	Adj R-Squared	0.7512
C.V.	14.83	Pred R-Squared	0.7291
PRESS	0.012	Adeq Precision	12.468

Final Equation in Terms of Actual Factors:
Attrited = 0.02525 + .00264844 * Wheeled

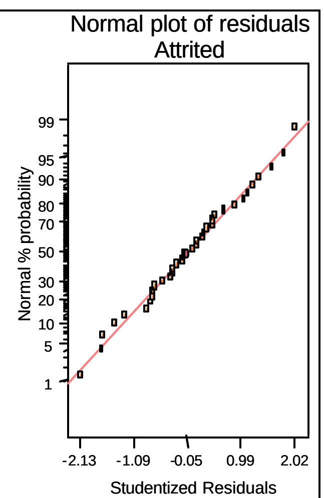


Figure 38: Results from 2k Obstacles - Attrited

The results for the response *classified* indicate that curvature and lack of fit are not significant and an appropriate linear model is fitted (Figure 39). By performing model adequacy checking, it was determined that the adjusted R^2 value of 85% is good (indicating almost 85% of the variation about the mean is explained by the fitted model) and the normality plot of the residuals shows that the normality assumption stands. There is one outlier that may be influential to the model, however the cook's distance check is less than one, therefore it does not appear to be influential to the model. The next step for this response is to explore the next region to see if we experience any improvement.

ANOVA Table for Response: Classified

Screening Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.034	2	0.017	116.22	< 0.0001
C	*0.022*	*1*	*0.022*	*147.41*	*< 0.0001*
D	*0.012*	*1*	*0.012*	*85.03*	*< 0.0001*
Curvature	0.0000132	1	0.0000132	0.090	0.7665
Residual	0.0047	32	0.0001468		
Lack of Fit	*0.00457*	*29*	*0.000158*	*3.67*	*0.1552*
Pure Error	*0.000129*	*3*	*0.0000429*		
Cor Total	0.039	35			

Std. Dev.	0.012	R-Squared	0.8790
Mean	0.87	Adj R-Squared	0.8714
C.V.	1.39	Pred R-Squared	0.8508
PRESS	5.793E-003	Adeq Precision	22.658

Final Equation in Terms of Actual Factors:

Classified = 0.860 + 0.0130 *Seismic - .00988 * Acoustic

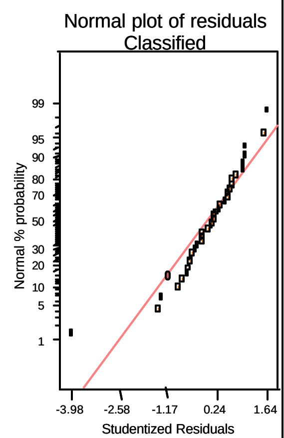


Figure 39: Results from 2k Obstacles – Classified

5.6.2 Step 4: If Improvement, Move to Next Region to Explore (Obstacles)

5.6.2.1 Overview

Since the responses *undetected* and *classified* are both linear models, we planned a new set of experiments to explore the next region in an attempt to find improvement in the response results. The three responses are all inter-related and a multi-objective trade-off is conducted to determine optimized results, the desirability function and graphical optimization in order to determine the next region to explore. These procedures are explained in great detail in Section5.7, Page 82.

5.6.2.2 Experimental Design

Based on the results from the desirability plot (Figure 40), the optimal value ranges for the sensors in this experiment are six seismic and five acoustic sensors. In order to test the next region, the variable values are listed in (Table 17). A factorial design with 2^3 variables was designed for the next experiment (Table 18, Page 76).

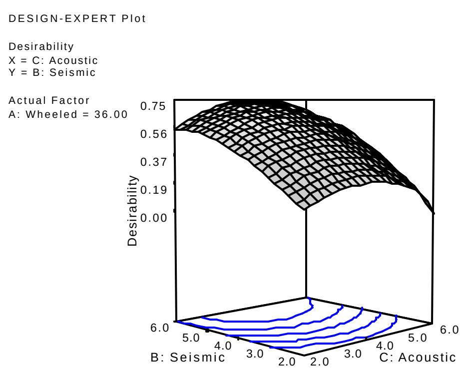


Figure 40: Region One Optimal Setting – Obstacles

Input Variable	Coded Variable (Equation)	High (+1)	Low (-1)
Wheeled Vehicle	$[x_i - 36]/12$	48	24
Seismic Sensor	$[x_i - 8]/2$	10	6
Acoustic Sensors	$[x_i - 7]/2$	9	5

Table 17: Region 2 Variable Levels

Run #	Wheeled	Seismic	Acoustic
1	24	6	5
2	48	6	5
3	24	10	5
4	48	10	5
5	24	6	9
6	48	6	9
7	24	10	9
8	48	10	9
9	36	8	7
10	36	8	7
11	36	8	7

Table 18: Region 2 Experimental Design (Obstacles)

5.6.2.3 Results

Initial analysis indicate that the response values for *undetected* must be transformed with the square root transform. The results from the square root transformation of the response *undetected* (Figure 41, Page 77) indicate that curvature and lack of fit are not significant and an appropriate model is fitted. By performing model adequacy checking, it was determined that the adjusted R^2 value of 93% is very good (indicating 93% of the variation about the mean is explained by the fitted model) and the normality plot of the residuals shows that the normality assumption stands. There appears to be no outliers that may influence the model.

By inspecting the 3-dimensional model plot for the response *undetected* (Figure 42, Page 77), the undetected rate is very low for this region, it is down to only approximately 1.0% of the targets making it through the region undetected. There was improvement experienced in this region and the next step is to move to another region, but by using the constraints that were stated in the mathematical model portion (Section 1.6 , Page 4) no further improvements are really possible. The pay-off cost for emplacing additional sensors in order to reduce the undetected rate even further is extremely low. For example the extra dollars spent on additional sensors emplaced in the area and the increased attrition rate of those sensors is not worth lowering an already extremely low undetected rate of approximately 1.0%.

ANOVA Table Response: Sqrt(Undetected)
Region 2, 2^3 Factorial Experiment

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	0.090	3	0.030	40.24	0.0002
B	*0.063*	*1*	*0.063*	*84.71*	*< 0.0001*
C	*0.020*	*1*	*0.020*	*27.20*	*0.0020*
BC	*6.614E-003*	*1*	*6.614E-003*	*8.82*	*0.0249*
Curvature	4.194E-003	1	4.194E-003	5.59	0.0559
Residual	4.497E-003	6	7.496E-004		
Lack of Fit	*1.640E-003*	*4*	*4.101E-004*	*0.29*	*0.8670*
Pure Error	*2.857E-003*	*2*	*1.429E-003*		
Cor Total	0.099	10			

Std. Dev.	0.027	R-Squared	0.9527
Mean	0.21	Adj R-Squared	0.9290
C.V.	13.32	Pred R-Squared	0.8690
PRESS	0.013	Adeq Precision	15.122

Final Equation in Terms of Actual Factors:
Sqrt(Undetected) = 1.129 - 0.0949 * Seismic - 0.0828 * Acoustic + 0.00719 * Seismic * Acoustic

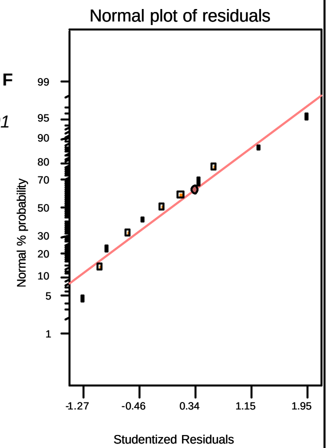


Figure 41: Results – Region 2, 2^3 Design (Obstacles) for Undetected

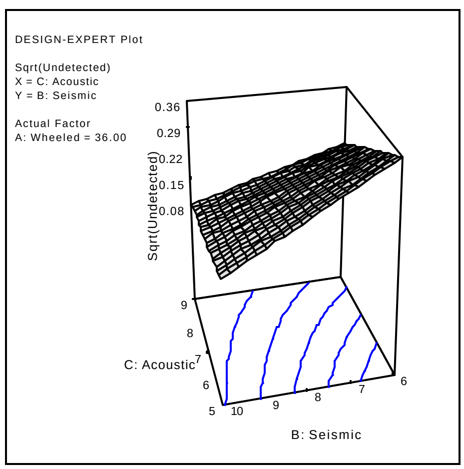


Figure 42: 3-D Model, Region 2 (Obstacles) - Undetected

Initial analysis indicate that the response values for attrited must be transformed with the square root transform. The results from the square root transformation of the response *attrited* (Figure 43) indicate that curvature and lack of fit are not significant and an appropriate model is fitted. By performing model adequacy checking, it was determined that the adjusted R^2 value of 79% is adequate (indicating 79% of the variation about the mean is explained by the fitted model) and the normality plot of the residuals shows that the normality assumption stands. There appears to be no outliers that influence the model.

The 3-dimensional model plot for the results of the response *attrited* (Figure 44, Page 79) indicate no improvement can be obtained by moving to another region and perfoming additional experiments.

ANOVA Table Response: Sqrt(Attrited)
Region 2, 2^3 Factorial Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	9.976E-003	3	3.325E-003	12.20	0.0058
A	*7.069E-003*	*1*	*7.069E-003*	*25.94*	*0.0022*
B	*6.328E-004*	*1*	*6.328E-004*	*2.32*	*0.1784*
AB	*2.274E-003*	*1*	*2.274E-003*	*8.35*	*0.0277*
Curvature	8.476E-005	1	8.476E-005	0.31	0.5972
Residual	1.635E-003	6	2.725E-004		
Lack of Fit	*1.185E-003*	*4*	*2.963E-004*	*1.32*	*0.4745*
Pure Error	*4.498E-004*	*2*	*2.249E-004*		
Cor Total	0.012	10			

Std. Dev.	0.017	R-Squared	0.8592
Mean	0.33	Adj R-Squared	0.7888
C.V.	5.01	Pred R-Squared	0.5081
PRESS	5.753E-003	Adeq Precision	8.372

Final Equation in Terms of Actual Factors:
Sqrt(Attrited) = 0.480 - 0.00314 * Wheeled - 0.0297 * Seismic
+ 0.0007025 * Wheeled * Seismic

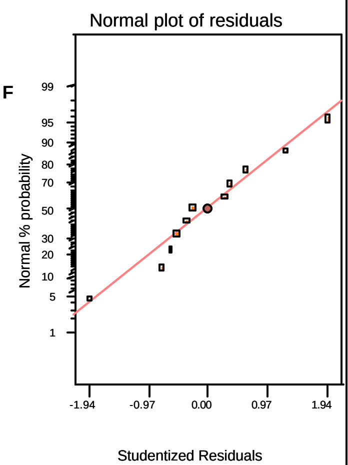


Figure 43: Results – Region 2, 2^3 Design (Obstacles) for Attrited

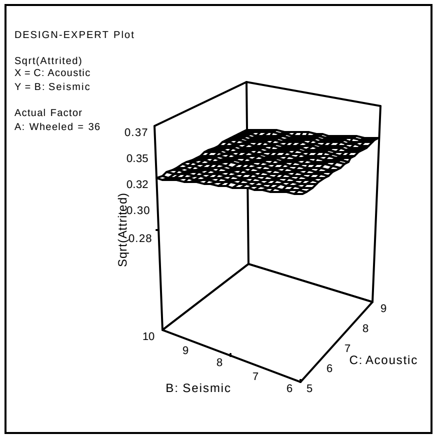


Figure 44: 3-D Model, Region 2 (Obstacles) - Attrited

The results for the response *classified* (Figure 45, Page 80) indicate that curvature and lack of fit are not significant and an appropriate model is fitted. By performing model adequacy checking, it was determined that the adjusted R^2 value of 99% is excellent (indicating 99% of the variation about the mean is explained by the fitted model) and the normality plot of the residuals shows that the normality assumption stands. There appears to be no outliers that influence the model.

The 3-dimensional model plot for the results of the response *classified* (Figure 46, Page 80) indicate the more seismic sensors and less acoustic sensors, the better the results for this response will be, no matter what region we move to therefore, there are no furthe experiments planned for this response in other regions. Again, this is intuitive, because seismic sensors have a much higher correct classification rate than acoustic sensors.

ANOVA Table Response: Classified
Region 2, CCD Experiment

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	2.927E-003	3	9.758E-004	362.15	< 0.0001
A	*1.711E-004*	*1*	*1.711E-004*	*63.51*	*0.0002*
B	*1.378E-003*	*1*	*1.378E-003*	*511.47*	*< 0.0001*
C	*1.378E-003*	*1*	*1.378E-003*	*511.47*	*< 0.0001*
Curvature	6.402E-007	1	6.402E-007	0.24	0.6433
Residual	1.617E-005	6	2.694E-006		
Lack of Fit	*1.150E-005*	*4*	*2.875E-006*	*1.23*	*0.4940*
Cor Total	2.944E-003	10			

Std. Dev.	1.641E-003	R-Squared	0.9945
Mean	0.88	Adj R-Squared	0.9918
C.V.	0.19	Pred R-Squared	0.9808
PRESS	5.650E-005	Adeq Precision	55.797

Final Equation in Terms of Actual Factors:
Classified =0.859 + 0.000385 * Wheeled + 0.00656 * Seismic
 - 0.00656 * Acoustic

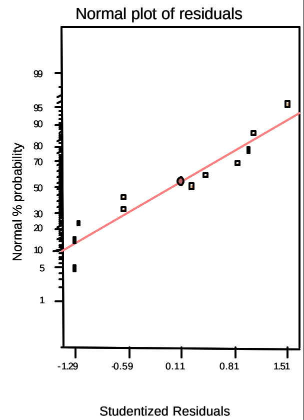


Figure 45: Results – Region 2, 2^3 Design (Obstacles) for Classified

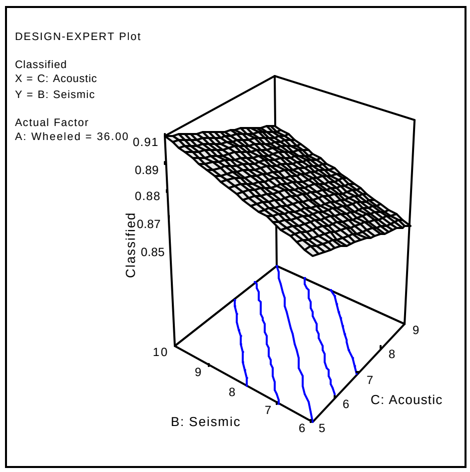


Figure 46: 3-D Model, Region 2 (Obstacles) - Classified

5.6.3 Step 6: Fit Second Order Models (Obstacles)

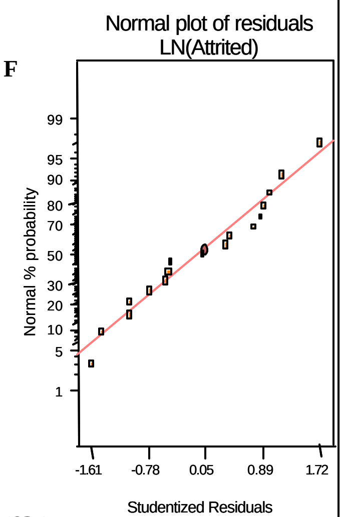
The results for the CCD experiment indicate that the response values for *attrited* must be transformed with the natural log transformation. For the developed model, curvature and lack of fit are not significant, indicating the model is a good second order model and the appropriate second order model is fitted (Figure 47, Page 81).

Model adequacy checking determined that the adjusted R^2 value of 68% is adequate and the normality plot of the residuals shows that the normality assumption stands and there are no outliers or influential points that may impact the model. The next region for this response was explored as part of the factorial design that was accomplished in (Section 5.6.2) above. The resulting model was a linear model and the model adequacy checks were good, so no CCD experiment was planned.

ANOVA Table for Response Natural Log(Attrited)

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	1.68	3	0.56	12.43	0.0004
A	*1.28*	*1*	*1.28*	*28.53*	*0.0001*
C	*0.046*	*1*	*0.046*	*1.03*	*0.3281*
C^2	*0.35*	*1*	*0.35*	*7.73*	*0.0156*
Residual	0.58	13	0.045		
Lack of Fit	*0.35*	*11*	*0.031*	*0.26*	*0.9443*
Pure Error	*0.24*	*2*	*0.12*		
Cor Total	2.26	16			

Std. Dev.	0.21	R-Squared	0.7415
Mean	-2.29	Adj R-Squared	0.6819
C.V.	-9.26	Pred R-Squared	0.6016
PRESS	0.90	Adeq Precision	10.297



Final Equation in Terms of Actual Factors:

Ln(Attrited) = -4.016 + 0.0267 * Wheeled + 0.425 * Acoustic - 0.0493 * $Acoustic^2$

Figure 47: Results from CCD Obstacles – Attrited

5.6.4 Final Response Models for Obstacle Experiment

Figure 48 (Page 82) summarizes the prediction models chosen to represent each of the responses. For more in depth information on the statistical results for each of these models, consult Appendix A.

Response Models, Obstacle Experiments

- Region 1: {0 to 6 Seismic Sensors and 0 to 6 Acoustic Sensors}
  - **Undetected** = (0.991 + 0.00257(Wheeled) – 0.0801(Seismic) – 0.0806(Acoustic) + 0.00561(Seismic)(Acoustic))^2
  - **Attrited** = Exponential(-4.016+.0267(Wheeled) + 0.425(Acoustic) – 0.0493(Acoustic)^2
  - **Classified** = 0.860 + 0.013(Seismic) – 0.00988(Acoustic)
- Region 2: {6 to 10 Seismic Sensors and 5 to 9 Acoustic Sensors}
  - **Undetected** = (1.129 – 0.0949(Seismic) – 0.0828(Acoustic) + 0.00719(Seismic)(Acoustic))^2
  - **Attrited** = (0.480 + 0.00314(Wheeled) – 0.0297(Seismic) + 0.000703(Wheeled)(Seismic))^2
  - **Classified** = 0.859 + 0.000385(Wheeled) + 0.00656(Seismic) – 0.00656(Acoustic)

Figure 48: Response Models for Obstacles Experiments

5.7 Step 9: Multiple Response Optimization

5.7.1 Overview

The multiple response optimization technique used in this thesis is a method used by Derringer and Suich [1980] that makes use of a desirability function where the researchers set the priorities and desires on the response values, which are then built into the optimization procedure. The Derringer and Suich method is described in detail in Myers and Montgomery [1995].

The desirability function takes into account all *n* responses and chooses the conditions ***x*** on the design variables that maximize D and consists of the following function:

$$D = (d_1 \times d_2 \times .. \times d_n)^{\frac{1}{n}}$$

where n is the number of responses and d_i reflects the desirable ranges for each response *(i).* The desirability function technique requires that each response receive a low and high value as well as a goal (e.g., minimize or maximize) assigned to each response in order to perform simultaneous optimization. For a maximize goal the desirability is defined by the following formulas:

Goal = Maximize

$d_i = 0$	$Y_i \leq Low_i$
$d_i = [(Y_i - Low_i)/(High_i - Low_i)]^{wti}$	$Low_i < Y_i < High_i$
$d_i = 1$	$Y_i \geq High_i$

For a minimize goal the desirability is defined by the following formulas:

Goal = Minimize

$d_i = 1$	$Y_i \leq Low_i$
$d_i = [(High_i - Y_i)/(High_i - Low_i)]^{wti}$	$Low_i < Y_i < High_i$
$d_i = 0$	$Y_i \geq High_i$

The formulation of D is only one possibility and other functions of the d_i may work just as well. There are multiple ways to incorporate the desirability function and the way we chose to use it includes using a Microsoft Excel spreadsheet and calculating all the values for certain variables and choosing the variable combination that simultaneously maximizes the desirability function. The spreadsheet is set up in such a way that only whole number variables are used, because you cannot emplace a part of a sensor. The formulas used for calculating each of the response values are the response models that were determined earlier in the chapter Figure 36 (Page 72) and Figure 48 (Page 82).

Some assumptions are made in order to perform this multiple objective trade-off study.

1. The wheeled variable represents the number of enemy wheeled targets moving through the area and is uncontrollable in the "real world", so it is set to three levels in order to find the desired variable settings at each of those three points (28, 36, 44).
2. The undetected rate is the most important response and it is assigned a weight of 2.
3. The goals for the responses include an undetected rate less than 10%, an attrition rate less than 25% and a classified rate greater than 88% (these goals come from the simulation scenario in section 6.4. (Page 93).

5.7.2 Results

The results from the multiple objective trade-off study are summarized in Table 19 and Table 20. Table 19 shows the highest desirability value or optimal results from each experiment and region. Table 20 shows the lowest variable settings that may be used in order to accomplish the stated goals. The Excel spreadsheets that were used to determine the results are located in Appendix B.

		Wheeled	Optimal Variable Settings 28	36	44
Open	Region 1	*Desirability*	0.013	0	0
		Seismic	6		
		Acoustic	4		
	Region 2	*Desirability*	0.398	0.296	0.106
		Seismic	10	10	10
		Acoustic	5	5	5
Obstacles	Region 1	*Desirability*	0	0	0
		Seismic			
		Acoustic			
	Region 2	*Desirability*	0.445	0.446	0.439
		Seismic	10	10	10
		Acoustic	5	5	5

Table 19: Optimal Desirability Response for Goal Settings

		Wheeled	Optimal Variable Settings 28	36	44
Open	Region 1	*Desirability*	0.013	0	0
		Seismic	6		
		Acoustic	4		
	Region 2	*Desirability*	0.077	0.093	0.038
		Seismic	7	7	8
		Acoustic	4	5	4
Obstacles	Region 1	*Desirability*	0	0	0
		Seismic			
		Acoustic			
	Region 2	*Desirability*	0.185	0.190	0.193
		Seismic	8	8	8
		Acoustic	4	4	4

Table 20: Minimum Variable Settings to Accomplish Goals

5.7.3 Sensitivity Analysis

When using computer simulations to model “real world” applications, there is always a certain degree of uncertainty and a need for sensitivity analysis. The example presented in this thesis made a number of assumptions and premises, allowing for a great deal of uncertainty in the results. The uncertainty is addressed in order to identify the major sources of possible error in the results and to understand the variability within the model. This entire process is called sensitivity analysis and is necessary whenever one is trying to make decisions based on mathematical models. Uncertainty is represented in the variables used in the evaluation, the variables that were excluded, and variable capability settings. There is also uncertainty in the decisionmaking process for the optimal variable settings.

For the variables included in the model, questions to ask and explore include: 1) Were these the right variables to use? 2) Did we look at realistic levels for each of the variables? 3) What happens if the enemy variables are much higher in value?

For the variables excluded from the model, questions to ask and explore include: 1) Is the variable significant if the levels are higher? 2) Are higher values realistic? 3) How do the results change if the variables were included?

For the variable capabilities, questions to ask and explore include: 1) Are the capability assumptions realistic? 2) How do the results change if the capabilities change (e.g., if the enemy vehicle probability of detection is much higher, what adjustments to the results must be made)? 3) If terrain features degrade the sensor's capabilities significantly more than the original assumptions, how does that affect the results?

The uncertainty in the chosen optimal variable settings are in the decision making process. For the optimal variable settings, questions to ask and explore include: 1) Who set the goals? 2) Are the goals correct? 3) What happens if one goal is weighted more than the others? 4) How does different weightings on the goals affect the results? 5) How much does each goal need to be changed in order to change the results?

In order to show the process for sensitivity analysis, we only degraded the enemy's detection capabilities by 25% instead of 50% in the obstacles experiment. After adapting the enemy detection capability formula, the simulation experiments were conducted. The results were analyzed and the same settings turned out to have the highest desirability.

There are a number of sensitivity experiments that are applicable for checking the uncertainty of sensor emplacement models. The goal of this section is to illustrate an example sensitivity analysis process and the analysis that is necessary when conducting simulation experiments.

5.8 Overall RSM Results and Conclusions

Based on the results from Table 19: Optimal Desirability Response for Goal Settings (Page 85), placing the sensors in the tree lines and using the variable settings 10 seismic sensors and 4 acoustic sensors from the region 2 experimental design results scores the highest desirability values. The model functions and optimal response values are summarized in Table 21. Figure 49 (Page 88) and Figure 50 (Page 89) show three-dimensional graphics for the optimization of the three responses based on both 28 enemy wheeled vehicles and 36 enemy vehicles moving through the area of responsibility.

Optimized Results				
Models	Undetected	(1.13 – 0.0958(Seismic) – 0.083*(Acoustic) + 0.0072*(Seismic)*(Acoustic))^2		
	Attrited	(0.48 – 0.0031*(Wheeled) – 0.03*(Seismic) + 0.0007*(Wheeled)*(Seismic))^2		
	Classified	0.86 + 0.00039*(Wheeled) + 0.0066*(Seismic) – 0.0066*(Acoustic)		
Results	Wheeled	28	36	48
	Undetected	0.016	0.016	0.016
	Attrited	0.085	0.104	0.137
	Classified	0.903	0.906	0.910

Table 21: Optimized Results

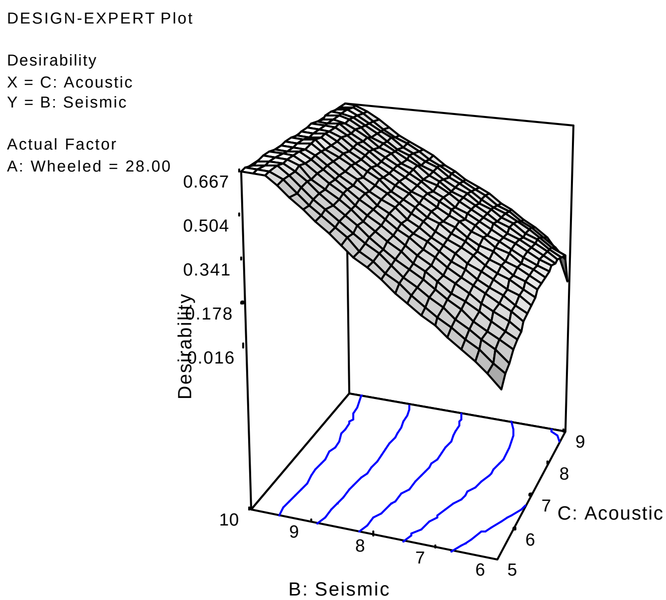


Figure 49: Desirability (28 Wheeled Vehicles)

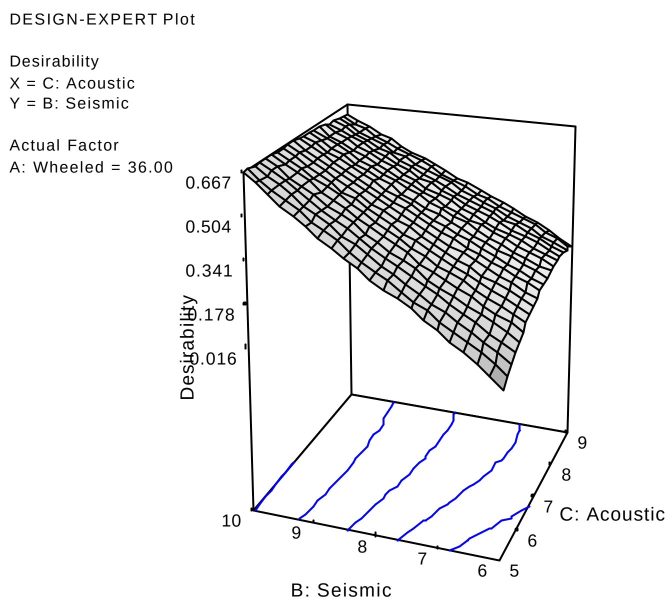


Figure 50: Desirability (36 Wheeled Vehicles)

Based on the scenario presented in Chapter 6 (Simulation), the minimum number of sensors required to accomplish the mission of an undetected rate of less than 0.10 is 6 seismic sensors and 5 acoustic sensors placed in open areas. By placing 6 seismic sensors and 5 acoustic sensors the sensor platoon only just accomplishes the commander’s goal of an undetected rate less than 0.10, but does not take into account the attrition rate or the classification rate. The results for the simulation presents a fictitious scenario and the process one may perform in order to accomplish the desired objectives stated in that scenario.

Chapter 6 Simulation

6.1 Overview

Simulation is the second step of the RSM process discussed in the previous chapter, Chapter 5. An entire chapter is dedicated to the simulation step, because of the important role it plays in the whole methodology process.

6.2 Simulation Introduction

A collection of “real world” processes or entities that act and interact together towards the accomplishment of a logical end is called a system. In order for that system to be studied scientifically, one must make a set of assumptions about the working processes of the system. The resulting assumptions, usually mathematical or logical relationships, formulate the model that is used to gain system behavior insight. Most “real world” systems are very complex and cannot be modeled with basic mathematical methods like algebra or probability theory. These complex systems must be studied by means of simulations. In a simulation, data is gathered in order to closely resemble the true characteristics of the “real world” model and a computer is used to evaluate a model graphically. [Law and Kelton, 1991]

Simulations range in type from extremely sophisticated models to basic rudimentary spreadsheet models. They are relatively inexpensive compare to the cost of actually using or testing the “real world” system. There are static (one particular time) and dynamic (systems as it evolves over time) simulation models.

Simulations may be deterministic (contains no probabilities) or stochastic (possesses some random input components). [Law and Kelton, 1991]

For this thesis, a Monte Carlo type simulation is used to model networked micro-sensors. A Monte Carlo simulation incorporates random numbers to solve both deterministic and stochastic problems. The problem of modeling networked sensors is a dynamic, stochastic process. The route enemy targets travel, is probabilistic as well as the probability of detection for both the sensors detecting the enemy and vice versa and the correct classification by the sensors of enemy targets. The simulation is dynamic, because each time the enemy targets move new calculations and outputs are performed and this continues over time until the target is out of the area of interest.

6.3 Background

There are many simulation programs that approximate real world conditions. The problem of modeling networked ground micro-sensors requires a simulation package that is very flexible (i.e., terrain, enemy forces and random variables), easily adaptable, terrain-based, table-based and easy to code. Due to limited programming experience, time resources and knowledge, we required a package that was easy to code and adaptable to our specific requirements and needs. Several software simulation packages were explored including very high level simulation packages available at the Night Vision and Electronic Sensors Directorate in Fort Belvoir, Virginia and very basic computer simulation packages such as Microsoft’s Excel with a Visual Basic Application combination, Arc View, Map Info Professional and Visual Basic. Through my literary research, I was presented with a dissertation entitled, “Estimating the Probability of Mine Contamination in a Non-combat Environment” [Riese, 2001]. The dissertation used Map Info Professional to predict mine fields on grid squares within a predefined area of operation. The goal of the predicting probability of minefields on a map parallels predicting detection, attrition and classification rates for sensors on the battlefield. Stephen Riese explained his simulation and provided us with his code allowing us to gain initial knowledge on what was needed and expected to write simulation code in Map Basic in order to produce a simulation that met our thesis requirements for output information.

Map Info Professional meets the requirements for an initial attempt at simulating sensors on the battlefield. The simulation package contains the base program, which aids in graphically depicting terrain, visualizing detection ranges, and setting up the location of sensors, obstacles and the grid dimensions. Figure 51 (Page 93) illustrates the five layers of the simulation program. The base program represents the foundation for the simulation. The middle layers represent stacked tiers that are superimposed on each other. The two-dimensional map is a depiction of the actual layout from an atlas or military map. The next layer is the grid layer and forms a square region segregated into smaller defined cells. In this simulation each cell represents a 100-meter by 100-meter area, which forms over 4700 cells for the 5-kilometer by 5-kilometer region. The cell size is a user defined option in the initial set up parameters and each cell then represents a cellblock in a database table. The table illustrates values of objects on the grid. Each kind of object depicts a separate vector layer (i.e., trees, hills, town, rivers, and roads), which is imposed on top of one another. This is useful for control and simulation application within this thesis.

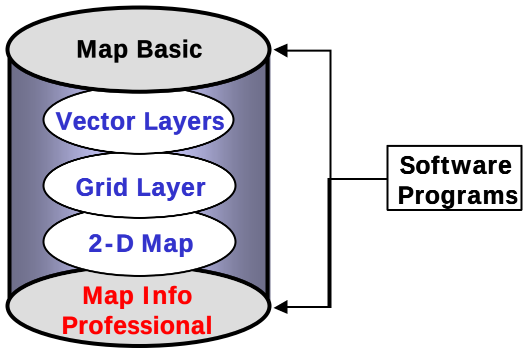


Figure 51: Map Info Professional Simulation Layers

6.4 Simulation Scenario

The following scenario is a fictitious based example used as a conduitto illustrate the methodology presented in this thesis.

The sensor platoon of the 1st RSTA Squadron is monitoring area Blue in the 2nd Brigade Combat Team's (BCT) sector. The BCT is currently responsible for Area Team as depicted in the schematic (Figure 52, Page 94). The area covers approximately a five-kilometer by five-kilometer area in Bosnia central to Route Arizona. The area encompasses two small towns; several mixed surface roads; four small rivers and three hilltops. The region is characterized by a mix of open and heavily wooded areas.

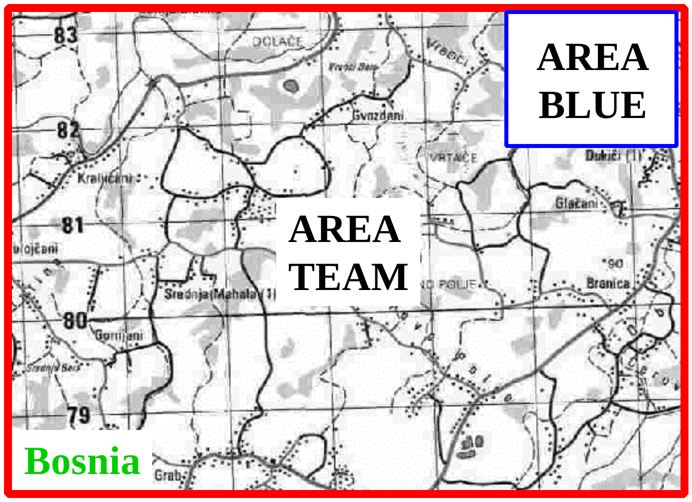


Figure 52: Area Team Sector (5 km by 5 km)

Higher intelligence is predicting a division-sized enemy element attack through Area Team in 36 hours. BCT intelligence predicts approximately a battalion sized motorized element supplemented with tanks to move through the sensor platoon's area. The senor platoon's mission is to emplace the available sensors to minimize the number of undetected targets passing through the area and maximizing the correct classification rate. This forms a trade-off with another objective, which is to minimize the number of sensor lost due to attrition. For example, emplacing the sensors in open terrain affords the sensor platoon the ability to utilize the maximum detection and classification rates for the sensors but increases the attrition rate of the sensors. On the other hand, concealing the sensor behind obstacles decreases the attrition rate and degrades the detection and classification rates.

Intelligence reports predict 8 to 16 tracked vehicles and 24 to 48 wheeled vehicles passing through Area Blue. The sensor platoon's supplies are depleting rapidly because of logistical and maintenance issues. For the mission, they have six seismic sensors, six acoustic sensors and four FLIR sensors available. The RSTA commander states that there might be follow-on missions and the platoon should use the minimum number of sensors to cover Area Blue and accomplish their objectives. The platoon decides that at a minimum they can use two of each sensor with a maximum number equaling the number of available sensors.

The commander wants to know several things about the sensor platoon's mission:

1. What is the emplacement plan (e.g., sensors in open terrain, or in the tree lines)?
2. What is the expected sensor undetected, classification and attrition rates for the sensor network based on the emplacement plan.

The commander's desired detection rate is greater than 90%. Minimizing the undetected rate is the most important mission because resources are allocated based on the capability to detect enemy targets. The BCT is taking risks with no reserve forces or air assets available to support them for the next 48-72 hours. Limiting the attrition rate and maximizing the correct classification rate are secondarily important to the commander.

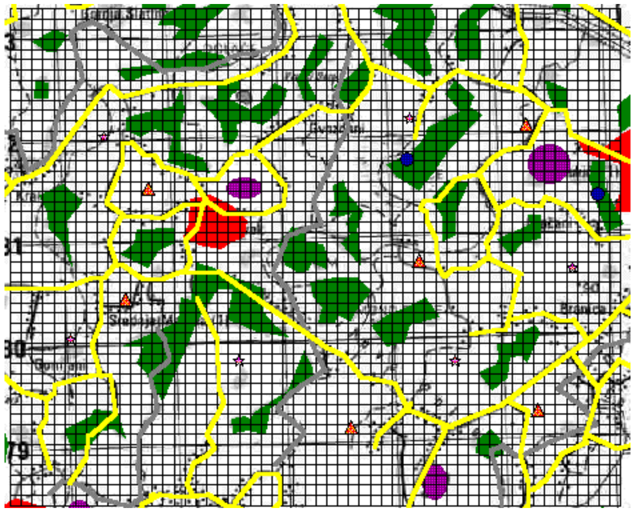


Figure 53: Computer Visualization of Area Blue

The senior platoon leader, Lieutenant Johnson and platoon sergeant, Sergeant First Class Jones are assigned the mission for emplacement of the micro-sensors. The RSTA's Intelligence officer, Captain Green, assists them by depicting Area Blue on the computer (Figure 53). Captain Green mentions that the unit has a simulation package that helps the section train on different intelligence scenarios. The simulation system randomly moves vehicles through a sector and evaluates the section on several attributes. Sergeant Jones tells the lieutenant that they can adapt the simulation package to answer the commander's questions and allow the platoon to maximize resources for future missions. The lieutenant and the sergeant rewrite the code in tandem over the next 12 hours. Currently, the platoon has 24 hours before sensor emplacement must start; both decide to run a multitude of simulation scenarios for the next six hours. After six hours, both report to the commander on their emplacement plan. After guidance from the commander the platoon executes sensor emplacement.

6.5 Simulation Specifics

6.5.1 Overview

The networked ground micro-sensor simulation utilizes Map Info and Map Basic software programs. The terrain information is based off of a black and white image of a small section of ground in Bosnia. Since the image was black and white and there was no elevation data included with the picture, it is hard to differentiate between roads and rivers, so some modifications and guesses were made as to what the actual terrain really consisted of. Modifications included adding rivers and hilltops. Since this is a rudimentary, basic simulation, we did not feel that completely accurate terrain was necessary to accomplish our simulation objectives.

This simulation combines both raster terrain tables and vector terrain tables into one model in order to represent the spatial information and requirements to model the sensor emplacement system. The status of the terrain (an assignment of a probability of detection to each grid square) is described with a raster model while all the features, such as rivers, towns, hills, forested areas and roads, are represented by vector models.

The resolution of the raster grid layer, in itself represents a topic for in-depth research and is beyond the scope of this thesis. In order to achieve a feasible model that is useful and does not take an enormous amount of computer time to run the simulation, a trade-off occurs with the amount of information that is lost due to the resolution of the raster grid cells. The resolution of the raster grid layer for this simulation is 100 meters by 100 meters and the specifications are listed in Table 22. This resolution enables us to perform our simulations in a timely manner and limits the amount of information loss to an adequate level for our purposes. The raster grid table covers an experimental region of approximately a 5 km by 5 km area of land in Bosnia.

r(m)	N_{rows}	N_{cols}	n
100	49	56	2744

Table 22: Raster Grid Table Specifications

Table Notes:
1. *r* = resolution (meters)
2. *n* = total number of cells (observations)

The feature data used in the simulation comes from a black and white photo of a 1:50,000 scale map of a region in Bosnia. Using MapInfo Profession, the raster image helps convert all feature data into digital vector maps and each of these vector maps is stored as a separate table. Figure 54 (Page 99), depicts the layers and the process of building the terrain based model used in this simulation.

While conducting queries to determine which raster grid cells to reduce the probability of detection in based on any feature data existing in that cell, three geographic operators were used: contains, within and intersects. These geographic operators allow one to select objects on the basis of their spatial relationship to another specified object. Contains is used when one desires to select the raster grid cell that possesses the feature data of concern's centroid anywhere with in its boundary. Within is used when one desires to select the raster grid cell whose centroid is inside the feature data of concern's boundary. Intersects is used when one desires to select the raster grid cells that have at least on point in common with the feature data of concern. Specific geographic operators used in the simulation include: within (for trees, hills and towns) and intersects (for rivers and roads). [MapInfo Professional Corporation, 1998]

Because this is a Monte Carlo type of simulation, each designated experimental run is performed in 25 independent randomly generated simulations. The desired metrics or responses (i.e., undetected, attrition and classification rates) are measured at the conclusion of each of these 25 independent simulations the results are recorded. After each set of 25 simulations is concluded, the results of the 25 simulations are evaluated in Microsoft's Excel spreadsheet program. The mean values for each response are calculated and then used in the response surface modeling process.

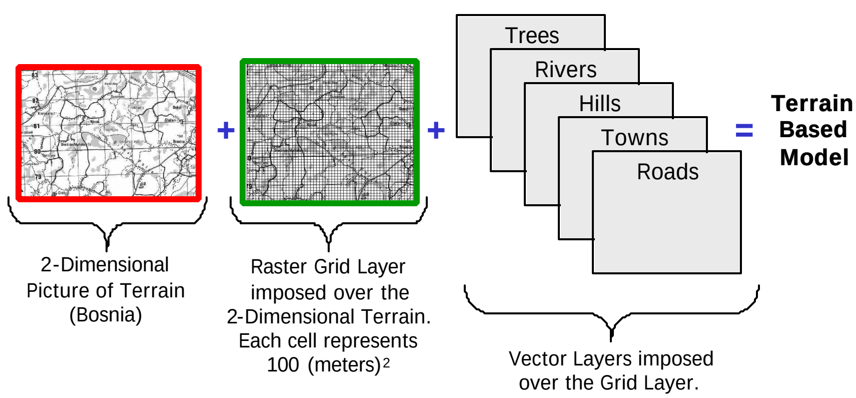


Figure 54: Simulation Layers

6.5.2 Simulation Framework

Current information on sensor capabilities and how certain terrain features degrade their capabilities is not readily available. Therefore, in order to design and run a simulation, a number of assumptions and guesses were made determining how terrain features degrade the sensor capabilities and to what extent. Table 23 summarizes the capabilities and degradation percentages used in the simulation in order to account for terrain feature affects on the micro-sensors.

	Capability			
Feature	*Seismic*	*Acoustic*	*FLIR*	*Enemy*
Open	100%	100%	100%	100%
Water	50%	75%	100%	N/A
Trees	90%	60%	75%	75%
Hills	65%	25%	25%	50%
Towns	10%	10%	25%	10%

Table 23: Terrain Feature Degradation of Sensor Capabilities

In order to determine sensor detection ranges and subsequent enemy detection capabilities of the sensors, a number of additional assumptions and modifications were made. An initial listing of each sensor's maximum effective range and capabilities at that range was provided by ARL [Gerber, 2000] and is in Appendix D. Because the simulation is based on distances and we assume that the detection capability decreases as the distance to the object increases, we created natural log models in order to determine values at different distances. Figure 55 (Page 101), depicts the mathematical models used to determine the probability of detection at different distances and portrays the subsequent plots for the sensor capabilities based on the type of target it is trying to detect.

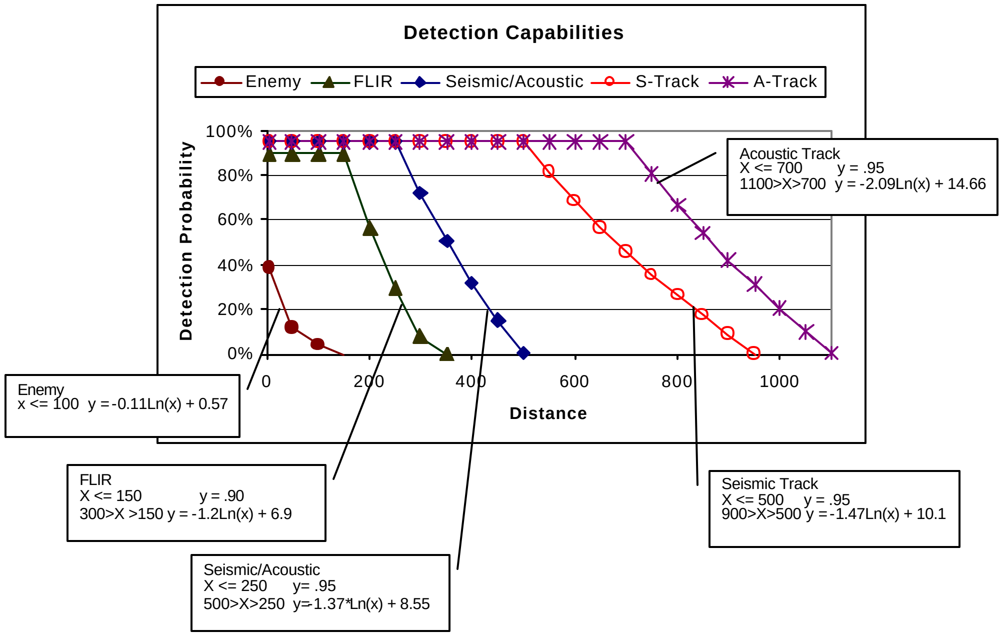


Figure 55: Sensor Detection Capabilities

In order to move enemy targets through the experimental area probabilities for each direction of movement from one cell on the raster layer to another was determined. Figure 56 (Page 102) portrays enemy movement probabilities and Table 24 (Page 102) shows the direction of movement based on the random number that is generated in the simulation. Due to the fact that these are enemy vehicles moving through the area, we assumed their main focus is to keep moving forward through the sector and we set the probabilities for movement accordingly.

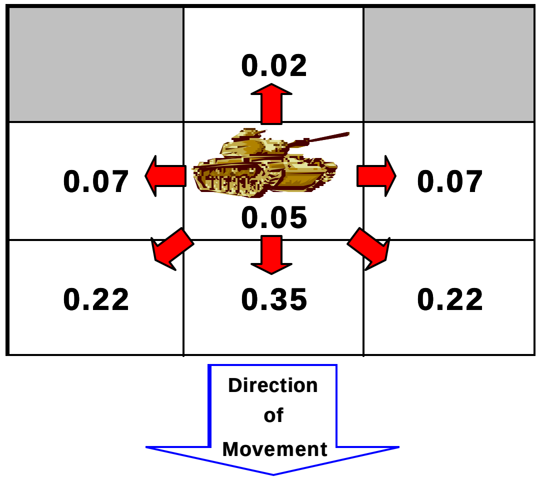


Figure 56: Enemy Wheeled and Tracked Vehicle Movements

	Range of Probabilities		
Direction of Movement	**Low Value**	**High Value**	**Total Probability**
Backwards	0.00	0.02	0.02
Left	0.03	0.09	0.07
Right	0.10	0.16	0.07
Stays	0.17	0.21	0.05
Forward-Right	0.22	0.43	*0.22*
Forward	0.44	0.78	*0.35*
Forward-Left	0.79	1.00	*0.22*

Table 24: Probability Ranges used for Enemy Targets

6.5.3 Simulation Limitations

Due to the newness of using unattended micro-sensors, the rapid developing technologies in this area and the limited sensor capability information we were able to obtain, a number of limitations exist in the simulation. A number of limitations also exist do to other factors such as a variety of software issues and simulation specific limitations. Table 25 (Page 103) outlines the limitations we feel currently exist and if corrected enable the simulation to operate much more effectively producing more accurate and realistic results.

Head-topic	Subtopic	Specific Simulation Limitation
Capabilities	Sensor	Information about sensor power capabilities (i.e., total usage, transmitting and receiving messages)
		Information on what voltage does partial power degradation occur for each type of sensor
		Accurate information on terrain and obstacle degradation data for each type of sensor
		Information on failure rates for all sensor components
		Information about terrain and obstacle degradation on each sensor's communication components
	Enemy	More accurate information on the enemy's sensor detection capabilities, which affect sensor attrition rates
		Incorporate emerging and changing enemy doctrine into the simulation
	Communication	Understand line of sight sensor communication capabilities and incorporate that data into the simulation
	Environment	Atmospheric effects on sensors capabilities
		Weather effects on sensors capabilities
		Elevation effects on sensors capabilities
Simulation	Software	Ability to incorporate weather effects, consistent with regional data
		Ability to incorporate environmental effects, consistent with regional data
		The ability to turn sensors on and off based on enemy situation in order to conserve battery life
		Account for sensor hardware, communication relay and base station failures
		Develop probability sensor distribution patterns for artillery and air emplacement
		Hand sensor emplacement options should take on user-defined preferences (i.e., W-formation, half circle and line formations)
		Understand when multiple sensors detect the same target
		Allow for redundancy requirements and sensors working together in tandem
		Incorporate magnetic sensors
		Incorporate a FLIR rotatable camera angle based on intelligence and allow the user to change the angle during the simulation
		Incorporate sensor offset probabilities that remain in effect on the other side of terrain features
	Layers	Raster Grid limitations allow Boolean logic leading to assumptions about terrain in a particular grid square.
		decreasing the grid size leads to a significant increase in simulation run times.
	Model	Understand the interconnectedness and interdependencies of the sensors and their effect on the model.

Table 25: Sensor Capabilities and Simulation Limitations

6.5.4 Simulation Pseudo Code

Pseudo code gives an abstract view of the simulation programming language. It is the starting point for a program and is written in plain English in order to portray the steps required to achieve the program goals. Table 26 below presents the simulation pseudo code and Figure 57 (Page 106) portrays the pseudo code schematic for this simulation.

#	Section	Description	Code
1	Initialize Map	Get User Input	Evaluate FLIR Vision Evaluate Program Options
		Open Grid and assorted Tables	Table Open All
		Reset Map Tables	Table Cells = 0
		Reset Sensor Tables	Table Cells = 1
2	Initialize Variables	Set attrition counter to zero	Attrit=0
		Set correct classification counter to zero	CorrectC=0
		Set wheeled targets to zero	w_tgt=0
		Set tracked targets to zero	t_tgt=0
		Set undetected targets to zero	Undetect=0
		Set total targets	i=w_tgt + t_tgt
3	Sensor Distances	Calculate centroid to the nearest sensor of each grid. Distances are related to probability of detection.	x2=CentroidX(object) y2=CentroidY(object) this_dist=Distance (x1, y1, x2, y2, "m")
4	FLIR Vision	Set FLIR Vision Look Angle. Delete probability of detection information for all other camera angles.	Select From Grid Table Choose FLIR_Look_Angle= 1 for West 2 for North 3 for East FLIR=FLIR*0 for other two angles
5	Offset Probability	Calculate adjusted probability based on terrain degradation.	*Example: For Trees* Select from Trees, Grid Where Tree objects, Grid objects Set Trees Column to 1 Update Grid Columns where

			Trees Column = 1 Seismic=Seismic*0.90 Acoustic=Acoustic*0.60
			Begin
6	Target Movement	Move selected number of wheeled and tracked vehicles through the area of operations	Move first target Initial Random Number Adjust RowID based on Rand(1) Loop Until Last Target

7	Attrition Probability	Calculate nearest sensor attrition probability	If attrition POD >0 then
			If Rand(2)<attrition POD then
			attrit=attrit+1
			Delete sensor if attrited

8	Detection Probability	Calculate sensor detection probability bands.	Based on calculated distances, estimate POD Update Grid columns Initial Random Number If Rand()<POD then counter=counter+1

9	Sensor Classification	Calculate nearest sensor correct classification probability	If detected then
			If Rand()<classification rate then
			correctC=correctC+1

10	Write Data	Append undetected and classification rates to file	Write rates, and number of targets
			End

Table 26: Pseudo Code Block Diagram

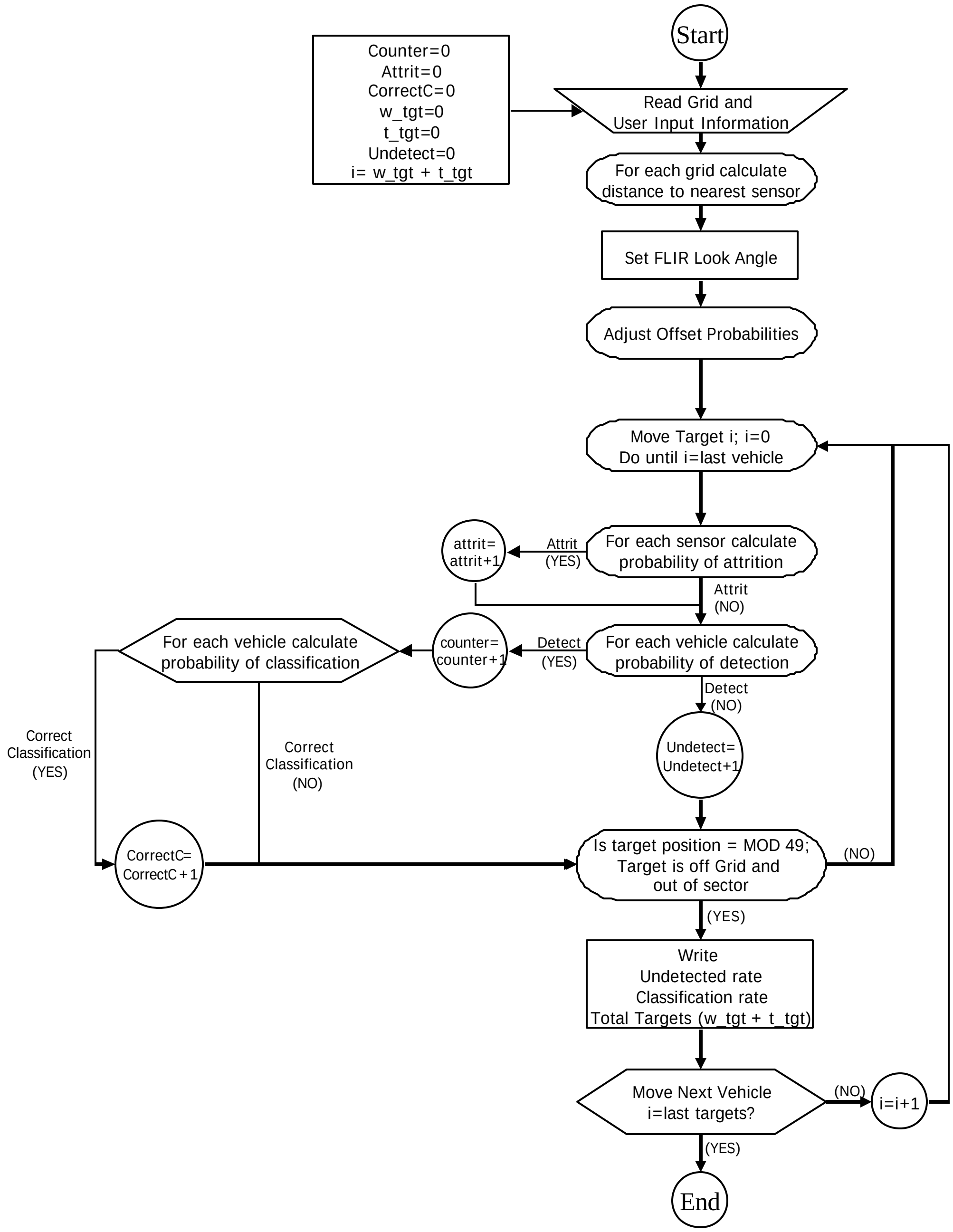


Figure 57: Pseudo Code Schematic

Chapter 7 Analysis of Alternatives

7.1 Introduction

Due to the scope and size of this problem and lack of sensor capability information, this chapter only illustrates the means to perform analysis of alternatives within the Sensor Emplacement Systems Engineering Design Methodology. When additional knowledge is available about sensor capabilities and their interaction with terrain, weather and other factors that affect them on the battlefield, this step will be fully developed.

7.2 Statement of Need

An analysis of alternatives step is crucial to this problem and the overall results. Due to the Army's dynamic nature, specifying only one set of rules based on one terrain setting is of no use and does not encompass the requirements of all units and all missions. Therefore, it is necessary to test any optimization rules and measures of effectiveness on different types of terrain and under different types of conditions.

7.3 Analysis of Alternatives Procedure

This step is intertwined with the previous two steps (RSM and Simulation), but in a different way (Figure 58, Page 108). Analysis of alternatives is accomplished after the initial completion of the RSM framework (e.g., initial emplacement rules are identified and then tested against different scenarios). The analysis of alternatives step identifies alternative scenarios that the networked sensors might face and the whole RSM process, in essence, starts over again. However, the RSM process starts from a more advanced state and more focused experiments. This happens because the generic emplacement rules are already established and are considered the starting baseline for further experiments.

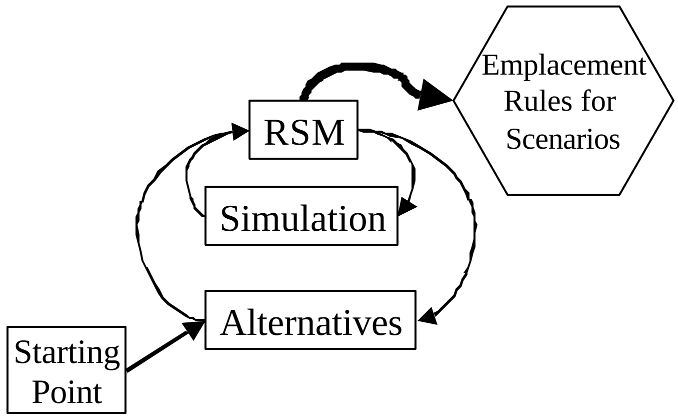


Figure 58: Alternatives, RSM and Simulation Interaction

In this step, a number of different basic scenarios are developed in order to determine what sensor emplacement rules change and how they change based on terrain factors or other factors that influence the system. Examples of different scenarios to test include an armor heavy enemy, dismounted enemy, mechanized infantry enemy, reconnaissance elements, offensive operations, defensive operations and different types of terrain. Each of the different scenarios must be tested and run through the RSM and computer simulation steps again.

Chapter 8 Conclusions and Future Research

8.1 Conclusions

Unattended micro-sensors are important to both the military and civilian communities; they are a fast, developing technology that plays an important role in all infrastructures. Unattended micro-sensors are used to develop situation awareness on the battlefield in order to reduce the number of reconnaissance soldiers placed in harms way thus reducing the risk of loss of life. They are used to monitor stress in buildings and bridges in order to avoid accidents and a subsequent threat to human lives; and they are used in security systems in a number of different ways in order to reduce the threat of robbery and other crimes.

The methodology presented in this thesis utilizes systems engineering tools for determining optimization of a sensor emplacement system and is easily adaptable to other generic sensor problem. Sensor emplacement is a multi-dimensional issue and requires a methodology that: 1) establishes a consistent baseline for metric development, 2) allows users to tailor the methodology to their specific needs, 3) allows sensor capabilities and emerging sensor technologies to be incorporated into the process, 4) provides a process for taking a problem with an unlimited number of combinations or settings and reduces it to a manageable number of experiments in order to obtain results for optimizing the system, and 5) provides the ability to take a “real world” problem and model it in a computer simulation in order to obtain results in a faster, cheaper way than actually performing the tests.

With the US Army focused on a future force with an increased emphasis on emerging technologies, such as unattended micro-sensors, processes for implementing and managing these systems is paramount. Within information systems, sensors provide an increased situational awareness on the battlefield while reducing the risks and resources associated with military operations. The methodology presented in this thesis is an example of how to model emerging technology in order to determine the full potential of the desired system.

8.2 Future Research

Networked ground micro-sensors on the battlefield as well as micro-sensors in the civilian world are such new and developing technologies, that there is an immense amount of future work to be done in this area. My focus for future work concentrates on the military aspect of sensors, specifically simulation enhancements and required information to create a more realistic simulation for creating and testing sensor emplacement metrics and rules. The overall focus is to reduce or eliminate the limitations identified in Table 25 (Page 103) by improving sensor modeling and metric implementation, overcoming current simulation limitations and improving the simulation interface. Once all of these tasks are accomplished the methodology possesses the ability to accomplish what it was developed for: develop optimized emplacement rules and perform analysis of alternatives in order to provide the system with robustness.

1. Modeling: Obtain more current and accurate information on sensor capabilities and how their capabilities are degraded by such factors as

terrain features, weather effects, atmospheric effects and elevation in order to model sensors more accurately.

2. Metric Implementation: Conduct personal interviews and more in-depth research in order to determine all of the objectives and sub-objectives for the system's organization and obtain all the required information for measuring the metrics in order to obtain results and perform more accurate optimization trade-off studies.
3. Simulation Limitations: Learn more about programming and modeling sensor capabilities in a computer simulation environment. Incorporate any new information obtained in the two previous steps into the simulation in order to reduce the limitations listed in Table 25: Sensor Capabilities and Simulation Limitations (Page 103).
4. Improve Simulation Interface: Learn more about computer programming and take time to improve the simulation interface by animating the simulation so one may watch the enemy vehicles as they move across the experimental region. Create a way for the user to click directly on the map and place the sensors in different locations just prior to each simulation run as well as a way to pause the simulation so the user may change the field of vision for a FLIR sensor based on intelligence reports from the other sensors.
5. Develop Optimized Emplacement Rules: By overcoming the simulation limitations listed in Step 3, obtaining the additional information listed in Step 1 (modeling) and improving metric implementation (Step 2), the tools

will be in place to test different emplacement rules and guidelines in order to develop emplacement rules with confidence.

6. Analysis of Alternatives: Implement different terrain scenarios, sensor missions in order to test the emplacement rules and refine the rules for specific types of terrain and missions.

Appendix A: RSM Statistical Results

1. Open Experiment, Region 1

1.1. Statistical Results for the Fitted Model, Undetected

ANOVA for Response Surface Reduced Quadratic Model

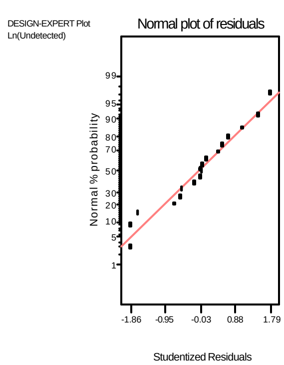
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	5.91	6	0.99	70.30	< 0.0001
A	*0.099*	*1*	*0.099*	*7.08*	*0.0239*
B	*3.00*	*1*	*3.00*	*214.28*	*< 0.0001*
C	*1.09*	*1*	*1.09*	*77.93*	*< 0.0001*
A^2	*0.30*	*1*	*0.30*	*21.69*	*0.0009*
B^2	*0.79*	*1*	*0.79*	*56.50*	*< 0.0001*
C^2	*1.08*	*1*	*1.08*	*77.14*	*< 0.0001*
Residual	0.14	10	0.014		
Lack of Fit	***0.12***	***8***	***0.015***	***1.47***	***0.4668***
Pure Error	*0.020*	*2*	*0.010*		
Cor Total	6.05	16			

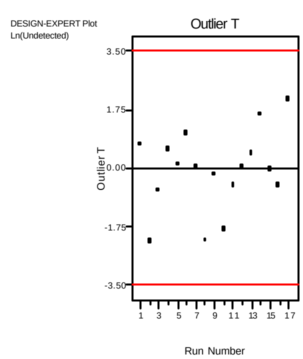
Std. Dev.	0.12	R-Squared	0.9768
Mean	-1.53	Adj R-Squared	0.9629
C.V.	-7.72	Pred R-Squared	0.9178
PRESS	0.50	Adeq Precision	23.348

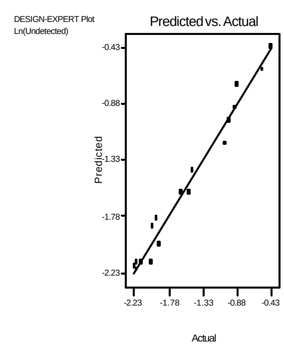
Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-2.16	1	0.066	-2.30	-2.01	
A-Wheeled	0.089	1	0.033	0.014	0.16	1.00
B-Seismic	-0.49	1	0.033	-0.56	-0.42	1.00
C-Acoustic	-0.30	1	0.033	-0.37	-0.22	1.00
A^2	0.19	1	0.040	0.098	0.28	1.04
B^2	0.30	1	0.040	0.21	0.39	1.04
C^2	0.36	1	0.040	0.27	0.45	1.04

Final Equation in Terms of Actual Factors:

$$\text{Ln(Undetected)} = 3.47924 - 0.086751 * \text{Wheeled} - 0.85303 * \text{Seismic} - 0.85819 * \text{Acoustic} + .00130796 * \text{Wheeled}^2 + 0.075997 * \text{Seismic}^2 + 0.0888 * \text{Acoustic}^2$$







1.2. Statistical Results for the Fitted Model, Attrited

ANOVA for Selected Factorial Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F

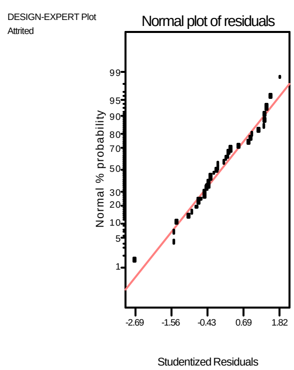
Model	0.090	1	0.090	72.90	< 0.0001
B	*0.090*	*1*	*0.090*	*72.90*	*< 0.0001*
Curvature	**9.353E-004**	**1**	**9.353E-004**	**0.76**	**0.3898**
Residual	0.041	33	1.232E-003		
Lack of Fit	***0.038***	***30***	***1.276E-003***	***1.62***	***0.3911***
Pure Error	*2.365E-003*	*3*	*7.883E-004*		
Cor Total	0.13	35			

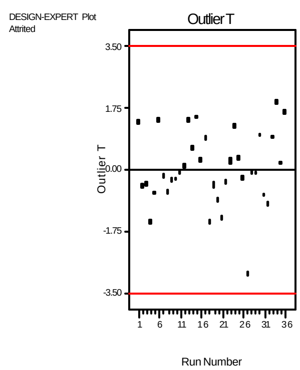
Std. Dev.	0.035	R-Squared	0.6884
Mean	0.25	Adj R-Squared	0.6789
C.V.	13.92	Pred R-Squared	0.6364
PRESS	0.048	Adeq Precision	10.457

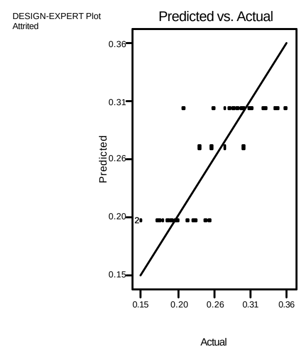
Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.25	1	0.0062	0.24	0.26	
B-Wheeled	0.053	1	0.0062	0.040	0.066	1.00
Center Point	0.016	1	0.019	-0.022	0.054	1.00

Final Equation in Terms of Actual Factors:

Attrited = 0.091375 + 4.41406E-003 * Wheeled







1.3. Statistical Results for the Fitted Model, Classified

ANOVA for Selected Factorial Model

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	0.040	3	0.013	127.17	< 0.0001
C	*0.024*	*1*	*0.024*	*233.91*	*< 0.0001*
D	*0.015*	*1*	*0.015*	*140.86*	*< 0.0001*
CD	0.000*703*	*1*	0.000*703*	*6.73*	*0.0143*
Curvature	**0.000168**	**1**	**1.681E-004**	**1.61**	**0.2140**
Residual	0.00324	31	1.044E-004		
Lack of Fit	**0.00*304***	***28***	***1.086E-004***	***1.67***	***0.3781***
Pure Error	0.000*195*	*3*	*6.492E-005*		
Cor Total	0.043	35			

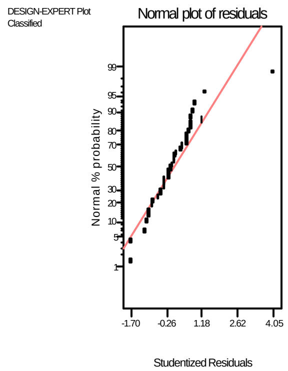
Std. Dev.	0.010	R-Squared	0.9248
Mean	0.86	Adj R-Squared	0.9176
C.V.	1.19	Pred R-Squared	0.9001
PRESS	0.00432	Adeq Precision	25.768

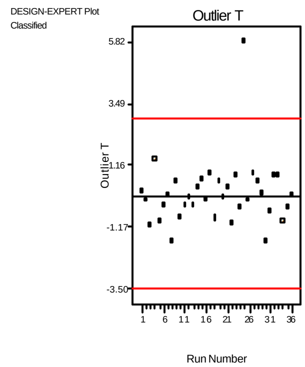
Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept	0.86	1	1.806E-003	0.86	0.86	

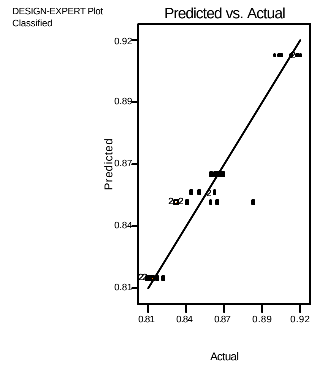
C-Seismic	0.028	1	1.806E-003	0.024	0.031	1.00
D-Acoustic	-0.021	1	1.806E-003	-0.025	-0.018	1.00
CD	-.004688	1	1.806E-003	-.00837	-.001004	1.00
Center Point	-.006875	1	5.419E-003	-0.018	.004177	1.00

Final Equation in Terms of Actual Factors:

Classified = 0.830 + 0.0185 * Seismic -.00603125 * Acoustic - .00117188 * Seismic * Acoustic







2. Open Experiment, Region 2

2.1. Statistical Results for the Fitted Model, Undetected

Response: Undetected Transform: Natural log

Analysis of variance table [Partial sum of squares]

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	6.79	3	2.26	62.11	< 0.0001
A	*0.39*	*1*	*0.39*	*10.73*	*0.0169*
B	*4.57*	*1*	*4.57*	*125.28*	*< 0.0001*
C	*1.83*	*1*	*1.83*	*50.30*	*0.0004*
Curvature	0.00852	1	0.00852	0.23	0.6458
Residual	0.22	6	0.036		
Lack of Fit	*0.15*	*4*	*0.038*	*1.10*	*0.5286*
Pure Error	*0.069*	*2*	*0.034*		
Cor Total	7.02	10			

Std. Dev.	0.19	R-Squared	0.9688
Mean	-3.10	Adj R-Squared	0.9532
C.V.	-6.16	Pred R-Squared	0.8925
PRESS	0.75	Adeq Precision	22.614

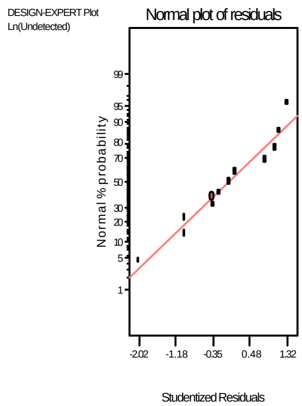
Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept	-3.08	1	0.067	-3.25	-2.92	
A-Wheeled	0.22	1	0.067	0.056	0.39	1.00
B-Seismic	-0.76	1	0.067	-0.92	-0.59	1.00
C-Acoustic	-0.48	1	0.067	-0.64	-0.31	1.00
Center Point	-0.063	1	0.13	-0.38	0.25	1.00

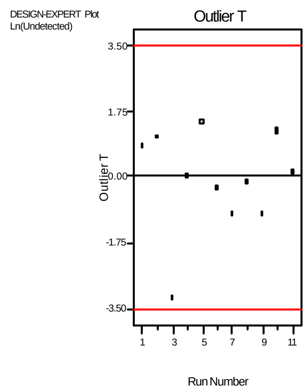
Final Equation in Terms of Actual Factors:

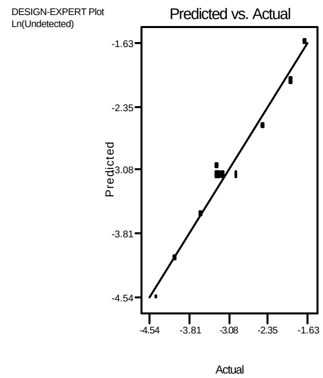
Ln(Undetected) = 0.71421 + 0.0184 * Wheeled - 0.378 * Seismic - 0.239 * Acoustic

Diagnostics Case Statistics

Std Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t
1	-1.91	-2.07	0.16	0.500	1.161	0.270	1.204
2	-1.65	-1.63	-0.025	0.500	-0.187	0.007	-0.171
3	-3.58	-3.58	0.00265	0.500	0.020	0.000	0.018
4	-3.27	-3.14	-0.13	0.500	-0.994	0.198	-0.993
5	-3.30	-3.02	-0.27	0.500	-2.016	0.813	-3.241
6	-2.44	-2.58	0.14	0.500	1.042	0.217	1.051
7	-4.42	-4.54	0.11	0.500	0.835	0.140	0.811
8	-4.07	-4.09	0.019	0.500	0.139	0.004	0.127
9	-2.94	-3.14	0.21	0.333	1.318	0.174	1.427
10	-3.19	-3.14	-0.051	0.333	-0.329	0.011	-0.304
11	-3.30	-3.14	-0.15	0.333	-0.988	0.098	-0.986







2.2. Statistical Results for the Fitted Model, Attrited

ANOVA for Response Surface Reduced Quadratic Model
Analysis of variance table [Partial sum of squares]

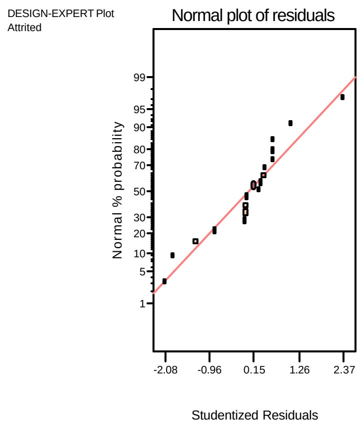
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.041	2	0.020	82.68	< 0.0001	
A	*0.039*	*1*	*0.039*	*157.53*	*< 0.0001*	
A^2	0.00*193*	*1*	0.00*193*	*7.83*	*0.0142*	
Residual	0.00344	14	0.000246			
Lack of Fit	0.00*34*	*12*	0.000*284*		*13.50*	*0.0710*
Pure Error	0.0000*42*	*2*	0.0000*21*			
Cor Total	0.044	16				

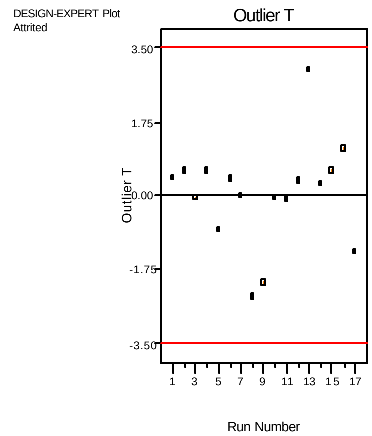
Std. Dev.	0.016	R-Squared	0.9219
Mean	0.21	Adj R-Squared	0.9108
C.V.	7.60	Pred R-Squared	0.8535
PRESS	0.00647	Adeq Precision	25.352

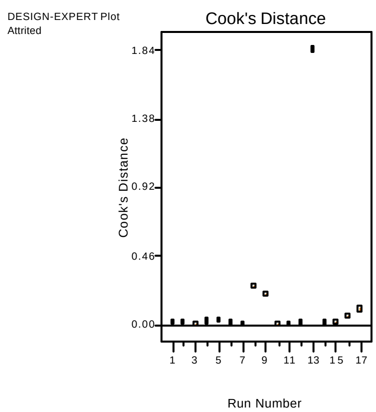
Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.22	1	0.00542	0.21	0.23	
A-Wheeled	0.056	1	0.00444	0.046	0.065	1.00
A^2	-0.015	1	0.00525	-0.026	-0.00343	1.00

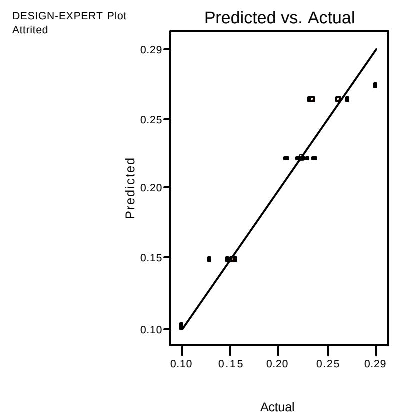
Final Equation in Terms of Actual Factors:

Attrited = -0.0821 + 0.0120 * Wheeled – 0.000102 * Wheeled^2









2.3. Statistical Results for the Fitted Model, Classified

Response: Classified

ANOVA for Response Surface Linear Model

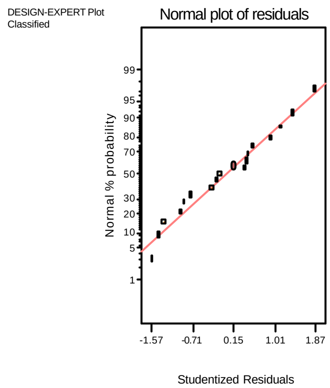
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	5.380E-003	3	1.793E-003	27.39	< 0.0001
A	*2.785E-004*	*1*	*2.785E-004*	*4.25*	*0.0598*
B	*8.323E-004*	*1*	*8.323E-004*	*12.71*	*0.0035*
C	*4.269E-003*	*1*	*4.269E-003*	*65.19*	*< 0.0001*
Residual	8.513E-004	13	6.548E-005		
Lack of Fit	*7.766E-004*	*11*	*7.060E-005*	*1.89*	*0.3964*
Pure Error	*7.467E-005*	*2*	*3.733E-005*		
Cor Total	6.231E-003	16			

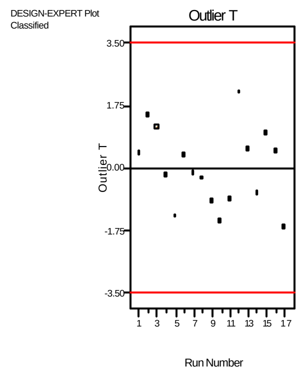
Std. Dev.	8.092E-003	R-Squared	0.8634
Mean	0.91	Adj R-Squared	0.8319
C.V.	0.89	Pred R-Squared	0.7605
PRESS	1.493E-003	Adeq Precision	15.979

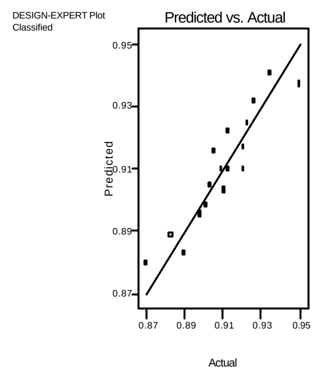
Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.91	1	1.963E-003	0.90	0.91	
A-Wheeled	4.720E-003	1	2.289E-003	-0.000225	0.00967	1.00
B-Seismic	8.160E-003	1	2.289E-003	3.215E-003	0.013	1.00
C-Acoustic	-0.018	1	2.289E-003	-0.023	-0.014	1.00

Final Equation in Terms of Actual Factors:

Classified = 0.917 + 0.000393 * Wheeled + 0.00408 * Seismic – 0.00924 * Acoustic







3. Obstacle Experiment, Region 1

3.1. Statistical Results for the Fitted Model, Undetected

ANOVA for Selected Factorial Model

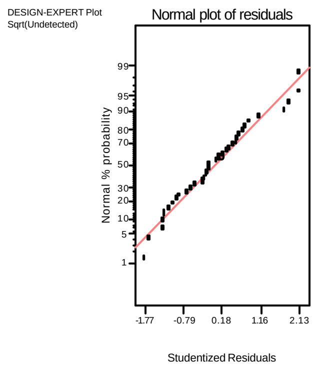
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.91	4	0.23	171.92	< 0.0001
B	*0.030*	*1*	*0.030*	*23.13*	*< 0.0001*
C	*0.43*	*1*	*0.43*	*323.12*	*< 0.0001*
D	*0.43*	*1*	*0.43*	*329.18*	*< 0.0001*
CD	*0.016*	*1*	*0.016*	*12.24*	*0.0015*
Curvature	0.00312	1	0.00312	2.37	0.1340
Residual	0.039	30	0.00132		
Lack of Fit	*0.032*	*27*	0.00*119*	*0.49*	*0.8687*
Pure Error	0.0*731*	*3*	0.0*244*		
Cor Total	0.95	35			

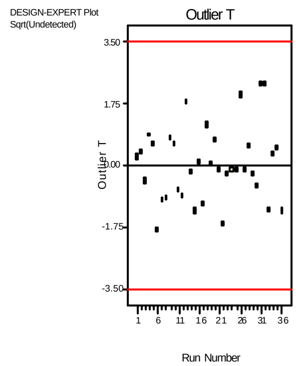
Std. Dev.	0.036	R-Squared	0.9582
Mean	0.53	Adj R-Squared	0.9526
C.V.	6.80	Pred R-Squared	0.9386
PRESS	0.058	Adeq Precision	35.445

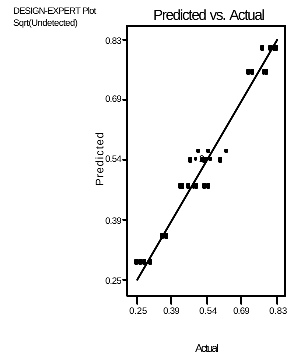
Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.53	1	0.00641	0.52	0.54	
B-Wheeled	0.031	1	0.00641	0.018	0.044	1.00
C-Seismic	-0.12	1	0.00641	-0.13	-0.10	1.00
D-Acoustic	-0.12	1	0.00641	-0.13	-0.10	1.00
CD	0.022	1	0.00641	0.00934	0.036	1.00

Center Point	0.030	1	0.019	-0.00966	0.069	1.00

Final Equation in Terms of Actual Factors:
Sqrt(Undetected) = 0.99079 + .00257 * Wheeled - 0.080093 * Seismic - 0.080632 * Acoustic
+ .00561045 * Seismic * Acoustic







3.2. Statistical Results for the Fitted Model, Attrited

ANOVA for Response Surface Reduced Quadratic Model

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	1.68	3	0.5612.43	0.0004	
A	*1.28*	*1*	*1.2828.53*	*0.0001*	
C	*0.046*	*1*	*0.046*	*1.03*	*0.3281*
C^2	*0.35*	*1*	*0.357.73*	*0.0156*	
Residual	0.58	13	0.045		
Lack of Fit	*0.35*	*11*	*0.031*	*0.26*	*0.9443*
Pure Error	*0.24*	*2*	*0.12*		
Cor Total	2.26	16			

Std. Dev.	0.21	R-Squared		0.7415
Mean	-2.29	Adj R-Squared		0.6819
C.V.	-9.26	Pred R-Squared	0.6016	
PRESS	0.90	Adeq Precision		10.297

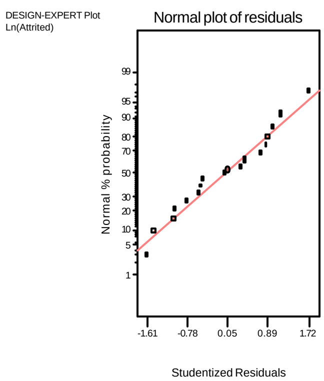
Factor	**Coefficient Estimate**	**DF**	**Std Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept-2.14	1	0.073	-2.30	-1.99		
A-Wheeled	0.321	0.060	0.19	0.45	1.00	
C-Acoustic	0.061	1	0.060	-0.069	0.19	1.00
C^2	-0.20	1	0.071	-0.35	-0.044	1.00

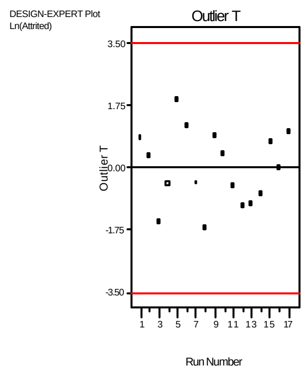
Final Equation in Terms of Actual Factors:
Ln(Attrited) =-4.016 + 0.0267 * Wheeled + 0.425 * Acoustic - 0.0493 * $Acoustic^2$

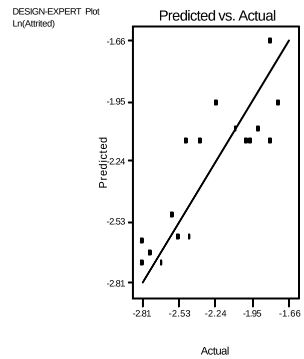
Diagnostics Case Statistics

Std	**Actual**	**Predicted**				**Student**	**Cook's**	**Outlier**		
Order	**Value**	**Value**	**Residual**		**Leverage**		**Residual**		**Distance**	**t**
1	-2.81	-2.72	-0.091	0.227	-0.487	0.017	-0.472			
2	-1.90	-2.08	0.19	0.227	0.993	0.072	0.992			
3	-2.66	-2.72	0.063	0.227	0.340	0.008	0.328			
4	-2.08	-2.08	0.00272	0.227	0.015	0.000	0.014			
5	-2.53	-2.60	0.075	0.227	0.403	0.012	0.389			

6	-1.74	-1.96	0.22	0.227	1.166	0.100	1.184
7	-2.44	-2.60	0.16	0.227	0.853	0.053	0.843
8	-2.23	-1.96	-0.27	0.227	-1.473	0.159	-1.551
9	-2.81	-2.62	-0.19	0.299	-1.064	0.121	-1.070
10	-1.80	-1.66	-0.14	0.299	-0.777	0.065	-0.765
11	-2.00	-2.14	0.15	0.119	0.750	0.019	0.737
12	-2.35	-2.14	-0.21	0.119	-1.054	0.038	-1.059
13	-2.75	-2.68	-0.069	0.496	-0.461	0.052	-0.447
14	-2.58	-2.50	-0.080	0.496	-0.534	0.070	-0.519
15	-2.47	-2.14	-0.32	0.119	-1.613	0.088	-1.733
16	-1.80	-2.14	0.34	0.119	1.722	0.100	1.882
17	-1.97	-2.14	0.18	0.119	0.896	0.027	0.888







3.3. Statistical Results for the Fitted Model, Classified

ANOVA for Selected Factorial Model

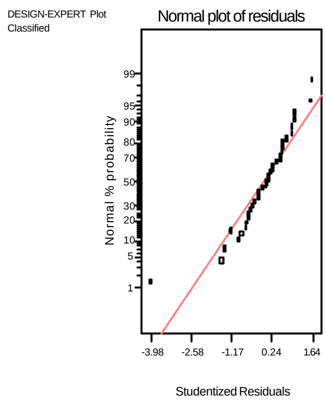
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**	
Model	0.034	2	0.017	116.22	< 0.0001	
C	*0.022*	*1*	*0.022*	*147.41*	*< 0.0001*	
D	*0.012*	*1*	*0.012*	*85.03*	*< 0.0001*	
Curvature	0.0000132	1	0.0000132		0.090	0.7665
Residual	0.00470	32	0.000147			
Lack of Fit	0.00*457*	*29*	0.000*158*		*3.67*	*0.1552*
Pure Error	0.000*129*	*3*	0.0000*429*			
Cor Total	0.039	35				

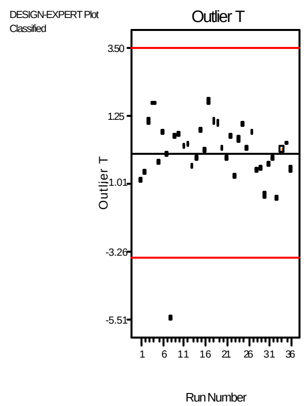
Std. Dev.	0.012	R-Squared	0.8790
Mean	0.87	Adj R-Squared	0.8714
C.V.	1.39	Pred R-Squared	0.8508
PRESS	5.793E-003	Adeq Precision	22.658

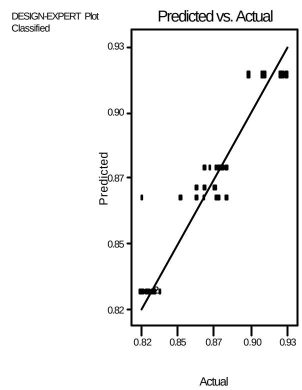
Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**Low**	**95% CI High**	**95% CI VIF**
Intercept0.87	1	0.00214	0.87	0.88		
C-Seismic	0.026	1	0.00214	0.022	0.030	1.00
D-Acoustic	-0.020	1	0.00214	-0.024	-0.015	1.00
Center Point	-0.001931	0.00643	-0.015	0.011	1.00	

Final Equation in Terms of Actual Factors:

Classified = 0.85966 + 0.013004 * Seismic - .00987615 * Acoustic







4. Obstacle Experiment, Region 2

4.1. Statistical Results for the Fitted Model, Undetected

ANOVA for Selected Factorial Model

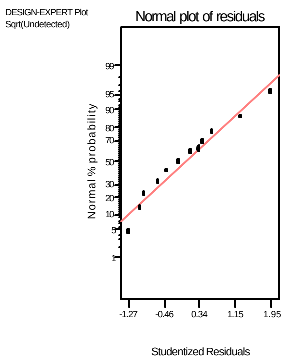
Source	**Squares**	**DF**	**Sum of Square**	**Mean Value**	**F Prob > F**
Model	0.090	3	0.030	40.24	0.0002
B	*0.063*	*1*	*0.063*	*84.71*	*< 0.0001*
C	*0.020*	*1*	*0.020*	*27.20*	*0.0020*
BC	*6.614E-003*	*1*	*6.614E-003*	*8.82*	*0.0249*
Curvature	4.194E-003	1	4.194E-003	5.59	0.0559
Residual	4.497E-003	6	7.496E-004		
Lack of Fit	*1.640E-003*	*4*	*4.101E-004*	*0.29*	*0.8670*
Pure Error	*2.857E-003*	*2*	*1.429E-003*		
Cor Total	0.099	10			

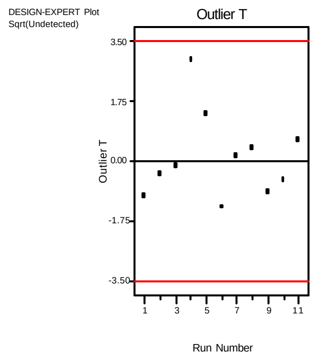
Std. Dev.	0.027	R-Squared	0.9527
Mean	0.21	Adj R-Squared	0.9290
C.V.	13.32	Pred R-Squared	0.8690
PRESS	0.013	Adeq Precision	15.122

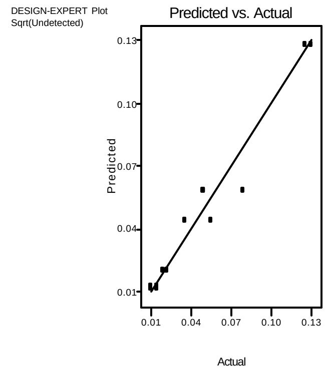
Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**Low**	**95% CI High**	**95% CI VIF**
Intercept	0.19	1	9.680E-003	0.17	0.22	
B-Seismic	-0.089	1	9.680E-003	-0.11	-0.065	1.00
C-Acoustic	-0.050	1	9.680E-003	-0.074	-0.027	1.00
BC	0.029	1	9.680E-003	5.068E-003	0.052	1.00
Center Point	0.044	1	0.019	-1.513E-003	0.089	1.00

Final Equation in Terms of Actual Factors:

Sqrt(Undetected) = 1.129 -0.0949 * Seismic - 0.0828 * Acoustic
+ 0.00719 * Seismic * Acoustic







4.2. Statistical Results for the Fitted Model, Attrited

ANOVA for Selected Factorial Model

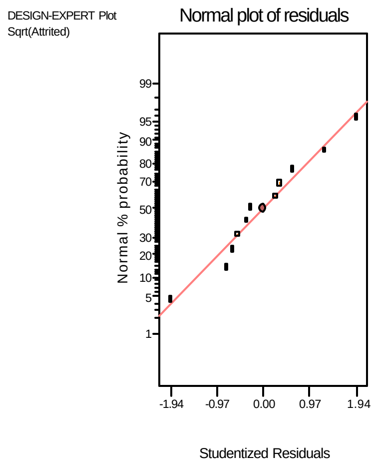
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	9.976E-003	3	3.325E-003	12.20	0.0058
A	*7.069E-003*	*1*	*7.069E-003*	*25.94*	*0.0022*
B	*6.328E-004*	*1*	*6.328E-004*	*2.32*	*0.1784*
AB	*2.274E-003*	*1*	*2.274E-003*	*8.35*	*0.0277*
Curvature	8.476E-005	1	8.476E-005	0.31	0.5972
Residual	1.635E-003	6	2.725E-004		
Lack of Fit	*1.185E-003*	*4*	*2.963E-004*	*1.32*	*0.4745*
Pure Error	*4.498E-004*	*2*	*2.249E-004*		
Cor Total	0.012	10			

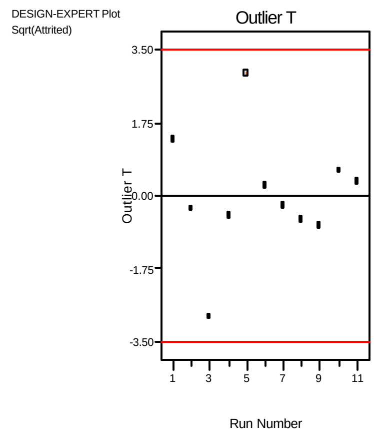
Std. Dev.	0.017	R-Squared	0.8592
Mean	0.33	Adj R-Squared	0.7888
C.V.	5.01	Pred R-Squared	0.5081
PRESS	5.753E-003	Adeq Precision	8.372

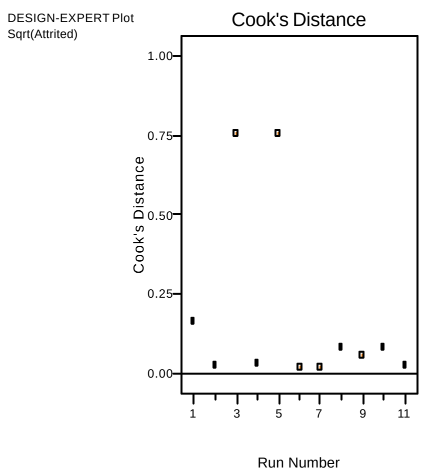
Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept0.33	1	5.836E-003		0.32	0.35	
A-Wheeled	0.030	1	5.836E-003	0.015	0.044	1.00
B-Seismic	-8.894E-003	1	5.836E-003	-0.023	5.388E-003	1.00
AB	0.017	1	5.836E-003	2.579E-003	0.031	1.00
Center Point	-6.233E-003	1	0.011	-0.034	0.021	1.00

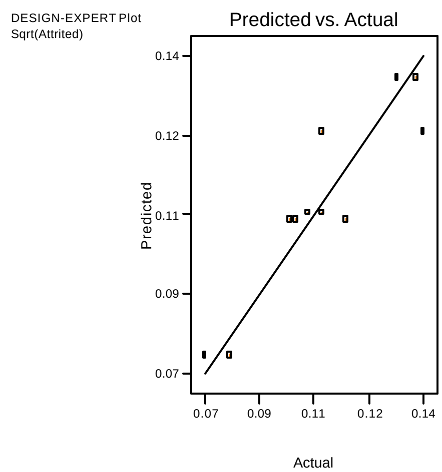
Final Equation in Terms of Actual Factors:

Sqrt(Attrited) = 0.480 - 0.00314 * Wheeled - 0.0297 * Seismic + 0.0007025 * Wheeled * Seismic









4.3. Statistical Results for the Fitted Model, Classified

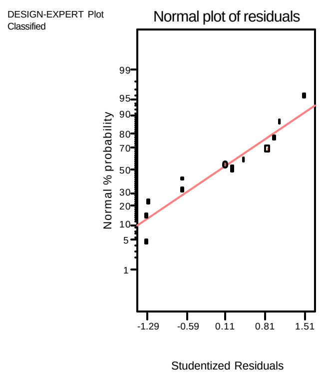
ANOVA for Selected Factorial Model

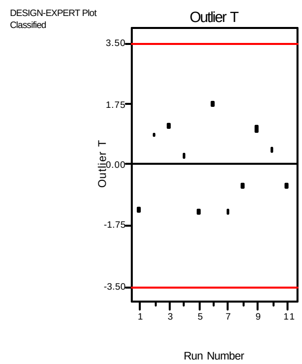
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	2.927E-003	3	9.758E-004	362.15	< 0.0001
A	*1.711E-004*	*1*	*1.711E-004*	*63.51*	*0.0002*
B	*1.378E-003*	*1*	*1.378E-003*	*511.47*	*< 0.0001*
C	*1.378E-003*	*1*	*1.378E-003*	*511.47*	*< 0.0001*
Curvature	6.402E-007	1	6.402E-007	0.24	0.6433
Residual	1.617E-005	6	2.694E-006		
Lack of Fit	*1.150E-005*	*4*	*2.875E-006*	*1.23*	*0.4940*
Cor Total	2.944E-003	10			

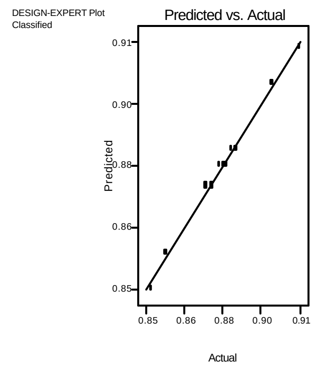
Std. Dev.	1.641E-003	R-Squared	0.9945
Mean	0.88	Adj R-Squared	0.9918
C.V.	0.19	Pred R-Squared	0.9808
PRESS	5.650E-005	Adeq Precision	55.797

Factor	Coefficient Estimate	DF	Error	Standard Low	95% CI High	95% CI VIF
Intercept	0.88	1	5.803E-004	0.88	0.88	
A-Wheeled	4.625E-003	1	5.803E-004	3.205E-003	6.045E-003	1.00
B-Seismic	0.013	1	5.803E-004	0.012	0.015	1.00
C-Acoustic	-0.013	1	5.803E-004	-0.015	-0.012	1.00
Center Point	5.417E-004	1	1.111E-003	-2.178E-003	3.261E-003	1.00

Final Equation in Terms of Actual Factors:
Classified =0.859 + 0.000385 * Wheeled + 0.00656 * Seismic - 0.00656 * Acoustic







Appendix B: Desirability Function Results

Input values			
Wheel	28		
	Low	High	Weight
Undetected	0	0.1	2
Attrited	0	0.25	1
Classified	0.88	1	1

Seismic	Acoustic	Undetect	d(und)	Attrit	d(Attrit)	Class	d(class)	Desire
2	2	0.503	0.000	0.215	0.140	0.850	0.000	0.000
2	3	0.332	0.000	0.215	0.140	0.842	0.000	0.000
2	4	0.262	0.000	0.215	0.140	0.834	0.000	0.000
2	5	0.247	0.000	0.215	0.140	0.825	0.000	0.000
2	6	0.279	0.000	0.215	0.140	0.817	0.000	0.000
3	2	0.313	0.000	0.215	0.140	0.866	0.000	0.000
3	3	0.207	0.000	0.215	0.140	0.857	0.000	0.000
3	4	0.164	0.000	0.215	0.140	0.847	0.000	0.000
3	5	0.154	0.000	0.215	0.140	0.838	0.000	0.000
3	6	0.174	0.000	0.215	0.140	0.828	0.000	0.000
4	2	0.227	0.000	0.215	0.140	0.883	0.021	0.000
4	3	0.150	0.000	0.215	0.140	0.872	0.000	0.000
4	4	0.119	0.000	0.215	0.140	0.861	0.000	0.000
4	5	0.112	0.000	0.215	0.140	0.850	0.000	0.000
4	6	0.126	0.000	0.215	0.140	0.840	0.000	0.000
5	2	0.192	0.000	0.215	0.140	0.899	0.156	0.000
5	3	0.127	0.000	0.215	0.140	0.887	0.057	0.000
5	4	0.100	0.000	0.215	0.140	0.875	0.000	0.000
5	5	0.094	0.003	0.215	0.140	0.863	0.000	0.000
5	6	0.106	0.000	0.215	0.140	0.851	0.000	0.000
6	2	0.189	0.000	0.215	0.140	0.915	0.291	0.000
6	3	0.125	0.000	0.215	0.140	0.902	0.182	0.000
6	4	0.099	0.000	0.215	0.140	0.889	0.073	0.013
6	5	0.093	0.005	0.215	0.140	0.876	0.000	0.000
6	6	0.105	0.000	0.215	0.140	0.863	0.000	0.000

Figure 59: Desirability Table for Open Experiment, Region 1

Input values			
Wheel	36		
	Low	High	Weight
Undetected	0	0.1	2
Attrited	0	0.25	1
Classified	0.88	1	1

Seismic	Acoustic	Undetect	d(undetect)	Attrit	d(Attrit)	Class	d(class)	Desire
6	4	0.158	0.000	0.218	0.129	0.919	0.322	0.000
6	5	0.124	0.000	0.218	0.129	0.909	0.245	0.000
6	6	0.098	0.001	0.218	0.129	0.900	0.168	0.022
6	7	0.077	0.053	0.218	0.129	0.891	0.091	0.086
6	8	0.061	0.155	0.218	0.129	0.882	0.014	0.066
7	4	0.108	0.000	0.218	0.129	0.923	0.356	0.000
7	5	0.085	0.022	0.218	0.129	0.914	0.279	0.093
7	6	0.067	0.109	0.218	0.129	0.904	0.202	0.142
7	7	0.053	0.223	0.218	0.129	0.895	0.125	0.153
7	8	0.042	0.342	0.218	0.129	0.886	0.048	0.129
8	4	0.074	0.068	0.218	0.129	0.927	0.390	0.150
8	5	0.058	0.174	0.218	0.129	0.918	0.313	0.192
8	6	0.046	0.293	0.218	0.129	0.908	0.236	0.208
8	7	0.036	0.408	0.218	0.129	0.899	0.159	0.203
8	8	0.028	0.512	0.218	0.129	0.890	0.082	0.176
9	4	0.051	0.243	0.218	0.129	0.931	0.424	0.237
9	5	0.040	0.361	0.218	0.129	0.922	0.347	0.253
9	6	0.031	0.470	0.218	0.129	0.912	0.270	0.254
9	7	0.025	0.566	0.218	0.129	0.903	0.193	0.242
9	8	0.019	0.648	0.218	0.129	0.894	0.116	0.213
10	4	0.035	0.426	0.218	0.129	0.935	0.458	0.293
10	5	0.027	0.528	0.218	0.129	0.926	0.381	0.296
10	6	0.022	0.616	0.218	0.129	0.917	0.304	0.289
10	7	0.017	0.689	0.218	0.129	0.907	0.227	0.273
10	8	0.013	0.751	0.218	0.129	0.898	0.150	0.244

Figure 60: Desirability Table for Open Experiment, Region 2

Input values			
Wheel	36		
	Low	High	Weight
Undetected	0	0.1	2
Attrited	0	0.25	1
Classified	0.88	1	1

Seismic	Acoustic	Undetect	d(undetect)	Attrit	d(Attrit)	Class	d(class)	Desire
2	2	0.616	0.000	0.091	0.638	0.866	0.000	0.000
2	3	0.511	0.000	0.108	0.567	0.856	0.000	0.000
2	4	0.417	0.000	0.117	0.531	0.846	0.000	0.000
2	5	0.332	0.000	0.115	0.540	0.837	0.000	0.000
2	6	0.257	0.000	0.102	0.591	0.827	0.000	0.000
3	2	0.512	0.000	0.091	0.638	0.879	0.000	0.000
3	3	0.425	0.000	0.108	0.567	0.869	0.000	0.000
3	4	0.346	0.000	0.117	0.531	0.859	0.000	0.000
3	5	0.275	0.000	0.115	0.540	0.850	0.000	0.000
3	6	0.212	0.000	0.102	0.591	0.840	0.000	0.000
4	2	0.418	0.000	0.091	0.638	0.892	0.102	0.000
4	3	0.346	0.000	0.108	0.567	0.882	0.020	0.000
4	4	0.281	0.000	0.117	0.531	0.872	0.000	0.000
4	5	0.223	0.000	0.115	0.540	0.863	0.000	0.000
4	6	0.172	0.000	0.102	0.591	0.853	0.000	0.000
5	2	0.334	0.000	0.091	0.638	0.905	0.210	0.000
5	3	0.276	0.000	0.108	0.567	0.895	0.128	0.000
5	4	0.224	0.000	0.117	0.531	0.885	0.046	0.000
5	5	0.177	0.000	0.115	0.540	0.876	0.000	0.000
5	6	0.135	0.000	0.102	0.591	0.866	0.000	0.000
6	2	0.259	0.000	0.091	0.638	0.918	0.319	0.000
6	3	0.214	0.000	0.108	0.567	0.908	0.236	0.000
6	4	0.172	0.000	0.117	0.531	0.898	0.154	0.000
6	5	0.136	0.000	0.115	0.540	0.889	0.072	0.000
6	6	0.103	0.000	0.102	0.591	0.879	0.000	0.000

Figure 61: Desirability Table for Obstacle Experiment, Region 1

Input values			
Wheel	36		
	Low	High	Weight
Undetected	0	0.1	2
Attrited	0	0.25	1
Classified	0.88	1	1

Seismic	Acoustic	Undetect	d(undetect)	Attrit	d(Attrit)	Class	d(class)	Desire
6	5	0.131	0.000	0.116	0.536	0.879	0.000	0.000
6	6	0.103	0.000	0.116	0.536	0.873	0.000	0.000
6	7	0.080	0.042	0.116	0.536	0.866	0.000	0.000
6	8	0.059	0.170	0.116	0.536	0.860	0.000	0.000
6	9	0.041	0.347	0.116	0.536	0.853	0.000	0.000
7	5	0.091	0.007	0.113	0.548	0.886	0.050	0.059
7	6	0.073	0.074	0.113	0.548	0.879	0.000	0.000
7	7	0.056	0.190	0.113	0.548	0.873	0.000	0.000
7	8	0.042	0.336	0.113	0.548	0.866	0.000	0.000
7	9	0.030	0.494	0.113	0.548	0.860	0.000	0.000
8	5	0.059	0.166	0.110	0.560	0.893	0.104	0.213
8	6	0.048	0.275	0.110	0.560	0.886	0.050	0.197
8	7	0.037	0.395	0.110	0.560	0.879	0.000	0.000
8	8	0.028	0.517	0.110	0.560	0.873	0.000	0.000
8	9	0.020	0.636	0.110	0.560	0.866	0.000	0.000
9	5	0.034	0.435	0.107	0.571	0.899	0.159	0.341
9	6	0.028	0.523	0.107	0.571	0.893	0.105	0.315
9	7	0.022	0.609	0.107	0.571	0.886	0.050	0.259
9	8	0.017	0.690	0.107	0.571	0.879	0.000	0.000
9	9	0.013	0.765	0.107	0.571	0.873	0.000	0.000
10	5	0.016	0.710	0.104	0.583	0.906	0.214	0.446
10	6	0.013	0.755	0.104	0.583	0.899	0.159	0.412
10	7	0.011	0.796	0.104	0.583	0.893	0.105	0.365
10	8	0.009	0.835	0.104	0.583	0.886	0.050	0.289
10	9	0.007	0.870	0.104	0.583	0.879	0.000	0.000

Figure 62: Desirability Table for Obstacle Experiment, Region 2

Appendix C: MapBasic Code for MapInfo Professional 5.0

This Appendix represents the actual simulation code used in this thesis. Each page is arranged in two columns per page and reads first from the top to bottom on the left-hand side of the page and then top to bottom on the right-hand side of the page.

```
Include "MapBasic.def"
Include "icons.def"
Declare Sub Main
Declare Sub Startup()
Declare Sub Get_User_Input
Declare Sub Assign_Columns()
'Resets all columns to zero
Declare Sub Reset_Sensor_Tables
'Places a 1 in the columns of the sensor tables for
initial set up and to reset for multiple runs
Declare Sub seismic()
'Calculates initial Seismic POD not adjusted for
terrain
Declare Sub Acoustic()
'Calculates initial Acoustic POD not adjusted for
terrain
Declare Sub FLIR()
'Calculates initial FLIR POD not adjusted for terrain
Declare Sub FLIR_Vision()
'Adjusts for the 25 Degree Field of vision of the
camera
Declare Sub Enemy_Detection()
'Calculates Enemy POD of sensors
Declare Sub Offset_probability()
'Adjusts PODs for all sensors based on terrain
Declare Sub SQL_Query_wheel()
'Combines wheeled table with Grid table
Declare Sub SQL_Query_track()
'Combines tracked table with Grid table
Declare Sub Movement_wheeled()
'Main part of the simulation - wheeled
Declare Sub Movement_tracked()
'Main part of the simulation - tracked
Declare Sub Detection_track()
'Checks for enemy detection (tracked) at current grid
Declare Sub Detection_wheeled()
'Checks for enemy detection (wheeled) at current
grid
'After adjusting for terrain
Declare Sub Thematic_map()
'Shows detection probability rings (adjusted for
terrain)
Declare Sub Thematic_map_track()
Declare Sub reset_sub
'resets dialog to default settings
Declare Sub okhandler
'notes values when user clicks OK
Declare Sub Cancelhandler
'Ends program when user clicks cancel
Declare Sub FLIR_Vision_Click()                 'Not
operable yet
Declare Sub tool_sub
'The following functions calculate each grid cell's
center to the nearest sensor
Declare Function Distance_Attrition(x1, y1 As Float,
table_name As String) As Float
Declare Function Distance_Seismic(x1, y1 As Float,
table_name As string) As Float
Declare Function Distance_acoustic(x1, y1 As Float,
table_name As string) As Float
Declare Function Distance_Flir(x1, y1 As Float,
table_name As string) As Float

'The following functions do the same as the distance
functions, except the RowID value is 'recorded for
the closest sensor in order to delete the appropriate
sensor
Declare Function Sensor_to_Update_Seismic(x1, y1
As Float, table_name As String) As SmallInt
Declare Function Sensor_to_Update_Acoustic(x1, y1
As Float, table_name As String) As SmallInt
Declare Function Sensor_to_Update_Flir(x1, y1 As
Float, table_name As String) As SmallInt
Declare Function Sensor_to_Update_attrition(x1, y1
As Float, table_name As String) As SmallInt

Global showthematic, execute_assign_zeros as
Logical
Global i_seismic_tree_prob, i_seismic_rivers_prob,
i_seismic_towns_prob, i_seismic_hills_prob as Float
Global undetected_rate, classification_rate,
attrit_sensor, correct_class, w_tgt, t_tgt,
        i_row_global, counter, counter_wheel,
counter_track, undetected, total_tgts As float
Global FLIR1_Look_Angle,FLIR2_Look_Angle,
FLIR3_Look_Angle, FLIR4_Look_Angle as Integer
Global Path_location, Path, Path2 as String
Global number_of_tables, tables (13) as Integer
'*********************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Main
Dim s as SmallInt
i_row_global = 0
s = 0
        Call Get_User_Input
        Call Startup ()
        Call Reset_sensor_tables
        Call Assign_Columns()
        Call Flir()
        Call Flir_vision()
        Call seismic()
        Call acoustic()
        Call Enemy_Detection ()
        Call Offset_probability()
        Call Thematic_map_track()
```

```
Call Thematic_map()
Call SQL_Query_wheel()
Call SQL_Query_track()

Do until s = 25
'Number of simulations to perform
counter = 0
attrit_sensor = 0
correct_class = 0
w_tgt = 0
t_tgt = 0
undetected = 0
Call Reset_sensor_tables  'Resets sensor
tables to all ones
Call Movement_wheeled()
Call Movement_tracked()
undetected_rate = (undetected)/(w_tgt + t_tgt)
classification_rate = (correct_class/counter)
total_tgts = w_tgt + t_tgt

Open File path + "Results.txt"
'Writes results to a text file
For Append As #1
Write #1, undetected, undetected_rate,
attrit_sensor, correct_class, counter, total_tgts,
classification_rate
Close File #1
s = s + 1
Print " "
print "Run # " + s + " completed"      'Prints
completed simulation run
Print " "
Loop
End Sub 'main
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Startup()
Close Window Legend
Print Chr$(12)      'This statement clears the
Message window
Set Window Message
Position (5.15, 3.25)
Width 1.5
Height 2.5
'Part I -- Set Path and Map Attributes.
'Print Path_location
Path = Path_location
path2 =
"C:\Sensor_simulation\Simulation_Run_Area\"
'Part II -- Open Tables.
Print "Opening existing tables"
Open table path2 + "Grid"
Open table path2 + "trees"
Open table path2 + "hills"
Open table path2 + "roads"
Open table path2 + "towns"
Open table path2 + "rivers"
Open table path + "attrition"
Open table path + "tracked"
Open table path + "wheeled"
Open table path + "seismic"
Open table path + "acoustic"
Open table path + "flir"

Dim win_id as Integer
Map From Grid, attrition, trees, hills, roads,
towns, rivers, tracked, wheeled, seismic,
acoustic, flir
win_id = FrontWindow()
Set Window win_id Width 5 Height 5
Set Distance Units "m"
Set Map Zoom Entire Layer 1
'Layer 1 should be the Grid
Set Map Distance Units "m"
Set Map Area Units "sq km"
End Sub 'Startup()
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Reset_Sensor_Tables
'Places a 1 in the sensor columns
Select * From Seismic, Grid
Where Seismic.Obj Within Grid.Obj
Into Query500
Update Query500 Set SeismicCol = 1
Close Table Query500
Select * From Acoustic, Grid
Where Acoustic.Obj Within Grid.Obj
Into Query501
Update Query501 Set AcousticCol = 1
Close Table Query501
Select * From Flir, Grid
Where Flir.Obj Within Grid.Obj
Into Query502
Update Query502 Set FlirCol = 1
Close Table Query502
Select * From attrition, Grid
Where attrition.Obj Within Grid.Obj
Into Query503
Update Query503 Set attrition = 1
Close Table Query503
End Sub           'reset_sensor_tables
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Assign_Columns()           'Assign zeros to
all columns in the Grid Table.
If execute_assign_zeros = 0 then Exit Sub
Else
End If
Select * From Grid
Update Grid Set wheeledCol = 0
Update Grid Set trackedCol = 0
Update Grid Set Seismic =0
Update Grid Set Acoustic = 0
Update Grid Set FLIR = 0
Update Grid Set TreesCol = 0
Update Grid Set HillsCol = 0
Update Grid Set TownsCol = 0
Update Grid Set RiversCol = 0
Update Grid Set Attrition = 0
Update Grid Set Seismic_track = 0
Update Grid Set Acoustic_track = 0
End sub 'Assign_Columns()
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
```

```
Sub SQL_Query_wheel()
select * From Wheeled, Grid
        'SQL Query to join Grid & Wheeled Tables
        Where Wheeled.Obj Within Grid.Obj
        Into Query100
        Update Query100 Set WheeledCol = 1
        Close Table Query100
End Sub 'SQL_Query_wheel ()main
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub SQL_Query_track()
select * From tracked, Grid                    'SQL
Query to join Grid & Tracked Tables
        Where tracked.Obj Within Grid.Obj
        Into Query105
        Update Query105 Set trackedCol = 1
        Close Table Query105
End Sub 'SQL_Query_track()main
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Function Distance_seismic(x1, y1 As Float,
table_name As string) As Float
'Determines the distance from the center of a grid
cell (x1, y1) to the nearest seismic sensor.
        Dim     x2, y2, this_dist, shortest As Float
        Dim     table_alias, column_value As Alias
        table_alias = table_name
        column_value = seismic.seismicCol
        shortest = 7500
        'arbitrarily large value
        Fetch First From table_alias
                Do While Not EOT(table_alias)
                'check each object in the table
If column_value = 1 then
'If value = 0 then the sensor was already destroyed
        x2 = CentroidX(seismic.obj)
        y2 = CentroidY(seismic.obj)
        this_dist = Distance(x1, y1, x2, y2, "m")
                If this_dist < shortest Then
                        shortest = this_dist
                                End If
                        End If
                Fetch Next From table_alias
        Loop
Distance_Seismic = shortest
End Function
'*************************************************************
Function Distance_Acoustic(x1, y1 As Float,
table_name As string) As Float
'Determines the distance from the center of a grid
cell (x1, y1) to the nearest acoustic sensor.
        Dim     x2, y2, this_dist, shortest As Float
        Dim     table_alias, column_value As Alias

        table_alias = table_name
        column_value = acoustic.acousticCol
        shortest = 7500   'arbitrarily large value
        Fetch First From table_alias
                Do While Not EOT(table_alias)
        'check each object in the table
                If column_value = 1 then
'If value = 0 then the sensor was already destroyed
                x2 = CentroidX(acoustic.obj)
                y2 = CentroidY(acoustic.obj)
        this_dist = Distance(x1, y1, x2, y2, "m")
                If this_dist < shortest Then
                        shortest = this_dist
                                End If
                        End If
                Fetch Next From table_alias
        Loop
Distance_acoustic = shortest
End Function
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Function Distance_flir(x1, y1 As Float,
table_name As string) As Float
'Determines the distance from the center of a grid
cell (x1, y1) to the nearest FLIR sensor.
        Dim     x2, y2, this_dist, shortest As Float
        Dim     table_alias, column_value As Alias
        table_alias = table_name
        column_value = flir.flirCol
        shortest = 7500
                'arbitrarily large value
        Fetch First From table_alias
                Do While Not EOT(table_alias)
        'check each object in the table
                        If column_value = 1 then
'If value = 0 then the sensor was already destroyed
                x2 = CentroidX(flir.obj)
                y2 = CentroidY(flir.obj)
        this_dist = Distance(x1, y1, x2, y2, "m")
                If this_dist < s hortest Then
                        shortest = this_dist
                                End If
                        End If
                Fetch Next From table_alias
        Loop
Distance_flir = shortest
End Function
'****************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Function Sensor_to_Update_Seismic(x1, y1 As
Float, table_name As String) As smallInt
'This function determines which sensor to delete if
enemy detects a seismic sensor.
        Dim x2, y2, this_dist, shortest As Float
        Dim table_alias, column_value As Alias
        Dim closest_sensor, j as SmallInt
        table_alias = table_name
        column_value = seismic.seismicCol
        shortest = 7500   'arbitrarily large value

        Fetch First From table_alias
        j = 1
        Do While Not EOT(table_alias)
        'check each object in the table
                If column_value = 1 then
'If value = 0 then the sensor was already destroyed
        x2 = CentroidX(seismic.obj)
        y2 = CentroidY(seismic.obj)
        this_dist = Distance(x1, y1, x2, y2, "m")
                If this_dist < shortest Then
```

```
                    shortest = this_dist
                    closest_sensor = j
                    End If
                End If
                Fetch Next From table_alias
                j = j + 1
        Loop
Sensor_to_Update_Seismic = closest_sensor
        'RowID in seismic table to update as a zero
End Function 'Sensor_to_Update_seismic
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Function Sensor_to_Update_Acoustic(x1, y1 As
Float, table_name As String) As smallInt
'This function determines which sensor to delete if
enemy detects a acoustic sensor.
        Dim x2, y2, this_dist, shortest As Float
        Dim table_alias, column_value As Alias
        Dim closest_sensor, j as SmallInt
        table_alias = table_name
        column_value = acoustic.acousticCol
        shortest = 7500
        'arbitrarily large value
        Fetch First From table_alias
                j = 1
                Do While Not EOT(table_alias)
                'check each object in the table
                If column_value = 1 then
'If value = 0 then the sensor was already destroyed
                x2 = CentroidX(acoustic.obj)
                y2 = CentroidY(acoustic.obj)
        this_dist = Distance(x1, y1, x2, y2, "m")
                If this_dist < shortest Then
                    shortest = this_dist
                    closest_sensor = j
                    End If
                End If
                Fetch Next From table_alias
                j = j + 1
        Loop
Sensor_to_Update_acoustic = closest_sensor
        'RowID in acoustic table to update as a zero
End Function 'Sensor_to_Update_Acoustic
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Function Sensor_to_Update_Flir(x1, y1 As Float,
table_name As String) As smallInt
'This function determines which sensor to delete if
enemy detects a FLIR sensor.
        Dim x2, y2, this_dist, shortest As Float
        Dim table_alias, column_value As Alias
        Dim closest_sensor, j as SmallInt
        table_alias = table_name
        column_value = flir.flirCol
        shortest = 7500
        'arbitrarily large value
        Fetch First From table_alias
                j = 1
                Do While Not EOT(table_alias)
                'check each object in the table
                    If column_value = 1 then
'If value = 0 then the sensor was already destroyed
                x2 = CentroidX(flir.obj)
                y2 = CentroidY(flir.obj)
        this_dist = Distance(x1, y1, x2, y2, "m")
                If this_dist < shortest Then
                    shortest = this_dist
                    closest_sensor = j
                    End If
                End If
                Fetch Next From table_alias
                j = j + 1
        Loop
Sensor_to_Update_flir = closest_sensor
        'RowID in FLIR table to update as a zero
End Function 'Sensor_to_Update_Flir
'*****************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Function Distance_Attrition(x1, y1 As Float,
table_name As string) As Float
'This function determines the distance from the
center of a grid cell (x1,
'y1) to the nearest sensor.  This function is used to
determine enemy's
'detection capabilities to find and destroy the
sensors.
        Dim x2, y2, this_dist, shortest As Float
        Dim     table_alias, column_value As Alias
        table_alias = table_name
        column_value = attrition.attrition
        shortest = 7500   'arbitrarily large value
        Fetch First From table_alias
                Do While Not EOT(table_alias)
        'check each object in the table
                    If column_value = 1 then
'If value = 0 then the sensor was already destroyed
        x2 = CentroidX(attrition.obj)
        y2 = CentroidY(attrition.obj)
        this_dist = Distance(x1, y1, x2, y2, "m")
                If this_dist < shortest Then
                    shortest = this_dist
                        End If
                    End If
                Fetch Next From table_alias
        Loop
Distance_attrition = shortest
End Function    'distance_attrition
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Function Sensor_to_Update_Attrition(x1, y1 As
Float, table_name As String) As smallInt
        'This function determines which sensor to
delete if one is attrited.
        Dim x2, y2, this_dist, shortest As Float
        Dim table_alias, column_value As Alias
        Dim closest_sensor, j as SmallInt
        table_alias = table_name
        column_value = attrition.attrition

        shortest = 7500
        'arbitrarily large value
        Fetch First From table_alias
                j = 1
```

```
			Do While Not EOT(table_alias)
			'check each object in the table
				If column_value = 1 then
'If value = 0 then the sensor was already destroyed
			x2 = CentroidX(attrition.obj)
			y2 = CentroidY(attrition.obj)
		this_dist = Distance(x1, y1, x2, y2, "m")
			If this_dist < shortest Then
				shortest = this_dist
				closest_sensor = j
				End If
			  End If
			Fetch Next From table_alias
			j = j + 1
		Loop
Sensor_to_Update_attrition = closest_sensor'RowID in attrition table to update with a zero
End Function 'Sensor_to_Update_attrition
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Seismic()
'Sub Seismic - calculates probability of detection for seismic
'(with no terrain incorporated yet) and places in appropriate column in grid table.
		Dim nearestsensor as Float
		Dim POD, X_center, Y_center as Float
		Dim table as String
		Dim i as integer
		table = "Seismic"
		Fetch first from Grid
		i = 0
		Do while EOT(Grid) = False
			X_center = CentroidX(Grid.obj)
			Y_center = CentroidY(Grid.obj)
			nearestsensor =
Distance_Seismic(X_center, Y_center, table)
		'******Calculates for wheeled target**********
			If nearestsensor <= 250 Then
					POD = .95
			ElseIf nearestsensor <= 500 then
POD = ((-1.3738*(Log(nearestsensor))) + 8.5464)
				Else
				POD = 0
				End If
				Update Grid Set Seismic
= POD Where RowID = i
		'*****Calculates for tracked target************
			If nearestsensor <= 500 Then
				POD = .95
		ElseIf nearestsensor <= 900 then
POD = ((-1.4704*(Log(nearestsensor))) + 10.092)
				Else
				POD = 0
				End If
				Update Grid Set
Seismic_track = POD Where RowID = i
			Fetch next from Grid
			i = i + 1
		Loop
Commit table grid
End Sub 'Seismic()
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Acoustic()	'calculates probability of detection for Acoustic - (with no terrain incorporated.
		Dim nearestsensor as Float
		Dim POD, X_center, Y_center as Float
		Dim table as String
		Dim i as integer
		table = "Acoustic"
		Fetch first from Grid
		i = 0
		Do while EOT(Grid) = False
			X_center = CentroidX(Grid.obj)
			Y_center = CentroidY(Grid.obj)
			nearestsensor =
Distance_Acoustic(X_center, Y_center, table)
		'******Calculates for wheeled target**********
			If nearestsensor <= 250 Then
				POD = .95
			ElseIf nearestsensor <= 500 then
POD = ((-1.3738*(Log(nearestsensor))) + 8.5464)
				Else
				POD = 0
				End If
				Update Grid Set Acoustic
= POD Where RowID = i
		'*****Calculates for tracked target************
			If nearestsensor <= 700 Then
				POD = .95
			ElseIf nearestsensor <= 1100 then
POD = ((-2.0922*(Log(nearestsensor))) + 14.656)
				Else
					POD = 0
				End If
				Update Grid Set
Acoustic_track = POD Where RowID = i
			Fetch next from Grid
			i = i + 1
		Loop
Commit table grid
End Sub 'Acoustic()
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub FLIR()	'calculates probability of detection for FLIR with no terrain incorporated.
		Print " In Sub Flir"
		Dim nearestsensor as Float
		Dim POD, X_center, Y_center as Float
		Dim table as String
		Dim i as integer
		table = "FLIR"
		Fetch first from Grid
		i = 0
		Do while EOT(Grid) = False
			X_center = CentroidX(Grid.obj)
			Y_center = CentroidY(Grid.obj)
			nearestsensor =
Distance_Flir(X_center, Y_center, table)
		'******Calculates for wheeled target**********
			If nearestsensor <= 150 Then
				POD = .95
			ElseIf nearestsensor <= 300 then
```

```
POD = ((-1.1955*(Log(nearestsensor))) + 6.8983)
                        Else
                                POD = 0
                        End If
                        Update Grid Set FLIR =
POD Where RowID = i
        '*****Same values tracked target************
                Fetch next from Grid
                i = i + 1
        Loop
Commit table grid
End Sub 'FLIR()
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Enemy_Detection()  'calculates probability of
enemy detecting sensors.
        Dim nearestsensor as Float
        Dim POD, X_center, Y_center as Float
        Dim table as String
        Dim n as SmallInt
        Print "In Sub Enemy_Detection"
        table = "attrition"
        Fetch first from Grid
        n = 0
        Do while EOT(Grid) = False
                X_center = CentroidX(Grid.obj)
                Y_center = CentroidY(Grid.obj)
                nearestsensor =
Distance_Attrition(X_center, Y_center, table)

                        If nearestsensor <= 100
Then
                                POD = ((-
0.1135*(Log(nearestsensor))) + 0.5656)
                        Else
                                POD = 0
                        End If
Update Grid Set Attrition = POD Where RowID = n
                Fetch next from Grid
                n = n + 1
        Loop
Commit table grid
End Sub 'Enemy_Detection()
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Movement_wheeled()          'Moves wheeled
targets through the grid.
Dim w_enemy As Alias
Dim i_row_num As SmallInt
w_enemy = grid.wheeledCol
i_row_num = 0
Fetch First from Grid
        Do While Not EOT(Grid)
                i_row_num = i_row_num + 1
                i_row_global = i_row_num
        If w_enemy = 1 Then                'Finds
first wheeled enemy target to move.
                        w_tgt = w_tgt + 1
                        Call Detection_wheeled()
                End If
        Fetch rec i_row_num + 1 from Grid
        Loop
End Sub 'Movement_wheeled()
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Movement_Tracked()
Dim t_enemy As Alias
Dim i_row_num As SmallInt
t_enemy = grid.trackedCol
i_row_num = 0
Fetch First from Grid
        Do While Not EOT(Grid)
                i_row_num = i_row_num + 1
                i_row_global = i_row_num
                If t_enemy = 1 then
                        t_tgt = t_tgt + 1
                        Call Detection_track()
                End If

        Fetch rec i_row_num + 1 from Grid
        Loop
End Sub         'Movement_tracked
'************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Detection_wheeled()
'Moves wheeled vehicles through the grid, checks
'for sensor detection and enemy detection after each
move and then moves the
'targets and performs the checks again and so on.
Dim Rand_enemy, Rand_POD, Rand_class,
Rand_move As Float
Dim s_sense, a_sense, f_sense, att_enemy As Alias
Dim Table_s, Table_a, Table_f, Table_att As String
Dim nearest_seismic, nearest_acoustic, nearest_Flir,
sensor_row as Float
Dim X_center, Y_center as Float
Dim target_row, target_status As SmallInt
s_sense = grid.seismic
a_sense = grid.acoustic
f_sense = grid.FLIR
att_enemy = grid.attrition
Randomize
Table_s = "seismic"
Table_a = "acoustic"
Table_f = "flir"
Table_att = "attrition"
        target_row = i_row_global  'RowID of the
current grid row the target is on.
        target_status = 0  'Sets teh target status to
zero, if target is detected the value is
        'switched to one.
        Do
'Move enemy target through the grid one target at a
time.
        Fetch rec target_row from grid
        'Fetches all values for the row in the gird
        Rand_POD = Rnd(1)
        Rand_class = Rnd(1)

        If att_enemy > 0 then        'checks POD for
the enemy detecting the sensor
                Rand_enemy = Rnd(1)
                If Rand_enemy <= att_enemy then
                Fetch rec target_row from grid
```

```
                    X_center = centroidX(grid.obj)
                    Y_center = centroidY(grid.obj)
' Determines which senor was destroyed by the
enemy
nearest_seismic = Distance_Seismic(X_center,
Y_center, table_s)
nearest_acoustic = Distance_Acoustic(X_center,
Y_center, table_a)
nearest_flir = Distance_Flir(X_center, Y_center,
table_f)
IF nearest_seismic = 7500 and nearest_acoustic =
7500 and nearest_flir = 7500 then
          Print "All Sensors are deleted!!!!"
'This checks to ensure there is at least one sensor
reminng to be deleted so the simulation
'doesn't get stuck.  If there are no sensor left, the
senemy target continues to move
'to the end of the grid.
                              GOTO JumpHere
                    End If
          attrit_sensor = attrit_sensor + 1
'counter for # of sensors attrited.
sensor_row = Sensor_to_Update_Attrition(X_center,
Y_center, table_att)
Update attrition set attrition = 0 where RowID =
sensor_row
commit Table attrition
'Deletes closest sensor on attrition tabel in oder to
adjust enemy PODs
          IF nearest_seismic < nearest_acoustic and
nearest_seismic < nearest_Flir then
          sensor_row =
Sensor_to_Update_Seismic(X_center, Y_center,
table_s)
          Update seismic set seismicCol = 0 where
RowID = sensor_row
          Print "A seismic sensor was attrited"
          commit Table Seismic
call seismic()       '0 means sensor was destroyed
call Enemy_Detection()      'recalculated PODs with
the destroyed sensor removed
call offset_probability()
          ElseIf nearest_acoustic < nearest_seismic
and nearest_acoustic < nearest_Flir then
                              sensor_row =
Sensor_to_Update_acoustic(X_center, Y_center,
table_a)
                              Update acoustic set
acousticCol = 0 where RowID = sensor_row
          Print "An acoustic sensor was attrited"
                    commit Table Acoustic
call acoustic()       '0 means sensor was destroyed
                              call Enemy_Detection()
          'recalculated PODs with the destroyed
sensor removed
                    call offset_probability()
                    Else
          sensor_row =
Sensor_to_Update_flir(X_center, Y_center, table_f)
                              Update Flir set Flircol = 0
where RowID = sensor_row
          Print "A Flir sensor was attrited"
                              commit Table Flir
          call flir()  '0 means sensor was destroyed
                              call flir_vision()
                              call Enemy_Detection()
          'recalculated PODs with the destroyed
sensor removed
                              call offset_probability()
                    End If
          End If
End If
If s_sense > 0 then          'checks POD for seismic
                    If Rand_POD <= s_sense then
                              counter = counter + 1
          'counter for detections (there may be
multiple detections of the same target
                    target_status = 1
                    IF Rand_class <= .95 then
correct_class = correct_class + 1     '# correctly
classified
                              End If
                    End If
          End If

          If a_sense > 0 then          'checks POD for
acoustic
                    If Rand_POD <= a_sense then
                              counter = counter + 1
          'counter for detections (there may be
multiple detections of
          'the same target
                              target_status = 1
          '# correctly classified
                    IF Rand_class <= .80 then
                    correct_class = correct_class + 1
                                        End If
                              End If
                    End If
If f_sense > 0 then          'checks POD for FLIR
                    If Rand_POD <= f_sense then
                              counter = counter + 1
          'counter for detections (there may be
multiple detections of
                    'the same target
                              target_status = 1
          '# correctly classified
                    IF Rand_class <= .7 then
                    correct_class = correct_class + 1
                                        End If
                              End If
                    End If
          Rand_move = Rnd(1)

          If Rand_move <= .02 then
                    target_row = target_row - 1
          'target moves back 1 grid cell
                              IF target_row < 0 then
                    target_row = target_row + 1
          'target stays to avoid leaving grid
                              End If
                    ElseIf Rand_move <= .09 then
                    target_row = target_row - 49
          'target moves left 1 grid cell
```

```
                        IF target_row < 0 then
        target_row  = target_row + 49          'target
stays to avoid leaving grid
                        End If
                'Print target_row '+ " Left"
                elseif Rand_move <= .16 then
                target_row = target_row + 49
        'target moves right 1 grid cell
                        IF target_row > 2744 then
                target_row = target_row - 49
        'target stays to avoid leaving grid
                                End If
        '       Print target_row '+ " Right"
                elseif Rand_move <= .21 then
                        target_row = target_row
        '       Print target_row '+ " Stays"
                elseif Rand_move <= .43 then
                target_row = target_row + 50
        'target moves foward right 1 grid cell
                IF target_row > 2744 then
                target_row = target_row - 50
        'target stays to avoid leaving grid
                                End If
        '       Print target_row '+ " Fwd_rt"
                elseif Rand_move <= .78 then
                target_row = target_row + 1
        'target moves forward 1 grid cell
                IF target_row > 2744 then
                target_row = target_row - 1
        'target stays to avoid leaving grid
                                End If
                'Print target_row '+ " Forward"
                else
                target_row = target_row - 48
        'target moves forward left 1 grid cell
                        IF target_row < 0 then
                target_row = target_row + 48
        'target stays to avoid leaving grid
                                End If
                'Print target_row '+ " Fwd-lft"
                End If
        Loop Until target_row MOD 49 = 0
        JumpHere:
'If all sensors are deleted the targets move freely off
the grid
        IF target_status = 0 then
                undetected = undetected + 1
        End If
```

End Sub 'Detection_wheel

```
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
```

Sub Detection_track()

```
'All comments form Sub Detection_wheeled() apply
to this section.  The only
'changes is tracked targets are moving and the
values associated with tracked targets.
Dim Rand_enemy, Rand_POD, Rand_move,
Rand_class As Float
Dim s_track, a_track, f_sense, att_enemy As Alias
Dim nearest_seismic, nearest_acoustic, nearest_Flir,
sensor_row as Float
Dim X_center, Y_center as Float
Dim Table_s, Table_a, Table_f, Table_att As String
Dim target_row, target_status as smallInt
s_track = grid.seismic_track
a_track = grid.acoustic_track
f_sense = grid.FLIR
att_enemy = grid.Attrition
Randomize
Table_s = "seismic"
Table_a = "acoustic"
Table_f = "flir"
Table_att = "attrition"
        target_row = i_row_global
        target_status = 0
        Do                              'Move enemy
target through the grid one target at a time.
        Fetch rec target_row from grid
        Rand_POD = Rnd(1)
        Rand_class = Rnd(1)
If att_enemy > 0 then       'checks POD for enemy
                Rand_enemy = Rnd(1)
                If Rand_enemy <= att_enemy then
                Fetch rec target_row from grid
                X_center = centroidX(grid.obj)
                Y_center = centroidY(grid.obj)
                nearest_seismic =
Distance_Seismic(X_center, Y_center, table_s)
                        nearest_acoustic =
Distance_Acoustic(X_center, Y_center, table_a)
                        nearest_flir =
Distance_Flir(X_center, Y_center, table_f)
                IF nearest_seismic = 7500 and
nearest_acoustic = 7500 and nearest_flir = 7500
then
                Print "All Sensors are deleted!!!!"
                        GOTO JumpHere
                        End If
                attrit_sensor = attrit_sensor + 1
                'Print "Enemy detected sensor! "
'Print "Total Sensors Attrited =" + attrit_sensor
                        sensor_row =
Sensor_to_Update_Attrition(X_center, Y_center,
table_att)
                Update attrition set attrition = 0
where RowID = sensor_row
                        commit Table attrition
        IF nearest_seismic < nearest_acoustic and
nearest_seismic < nearest_Flir then
        sensor_row =
Sensor_to_Update_Seismic(X_center, Y_center,
table_s)
                        Update seismic set
seismicCol = 0 where RowID = sensor_row
        Print "A seismic sensor was attrited"
                        commit Table Seismic
                        call seismic()
                        call Enemy_Detection()
                        call offset_probability()
                ElseIf nearest_acoustic <
nearest_seismic and nearest_acoustic < nearest_Flir
then
```

```
                    sensor_row =
Sensor_to_Update_acoustic(X_center, Y_center,
table_a)
                    Update acoustic set acousticCol =
0 where RowID = sensor_row
          Print "An acoustic sensor was attrited"
                         commit Table Acoustic
                         call acoustic()
                         call Enemy_Detection()
                         call offset_probability()
                    Else
                    sensor_row =
Sensor_to_Update_flir(X_center, Y_center, table_f)
                         Update Flir set Flircol = 0
where RowID = sensor_row
          Print "A Flir sensor was attrited"
                         commit Table Flir
                         call flir()
                         call flir_vision()
                         call Enemy_Detection()
                         call offset_probability()
                    End If
          End If
End If
If s_track > 0 then           'checks POD for seismic
                    If Rand_POD <= s_track then
                         counter = counter + 1
                         target_status = 1
                    IF Rand_class <= .95 then
                    correct_class = correct_class + 1
                              End If
                         End If
                    End If
If a_track > 0 then           'checks POD for acoustic
                    If Rand_POD <= a_track then
                         counter = counter + 1
                         target_status = 1
                    IF Rand_class <= .80 then
                    correct_class = correct_class + 1
                              End If
                         End If
                    End If
If f_sense > 0 then           'checks POD for FLIR
                    If Rand_POD <= f_sense then
                         counter = counter + 1
                         target_status = 1
                         IF Rand_class <= .7 then
                    correct_class = correct_class + 1
                              End If
                         End If
                    End If
          Rand_move = Rnd(1)
          If Rand_move <= .02 then
                    target_row = target_row - 1
                         IF target_row < 0 then
          target_row = target_row + 1
                    'target stays to avoid leaving grid
                         End If
                    ElseIf Rand_move <= .09 then
                    target_row = target_row - 49
                         IF target_row < 0 then
                    target_row = target_row + 49
          'target stays to avoid leaving grid
                              End If
               '         Print target_row '+ " Left"
               elseif Rand_move <= .16 then
               target_row = target_row + 49
                         IF target_row > 2744 then
               target_row = target_row - 49
               'target stays to avoid leaving grid
                              End If
          '    Print target_row '+ " Right"
               elseif Rand_move <= .21 then
                         target_row = target_row
          '    Print target_row '+ " Stays"
               elseif Rand_move <= .43 then
               target_row = target_row + 50
                         IF target_row > 2744 then
               target_row = target_row - 50
               'target stays to avoid leaving grid
                              End If
          '    Print target_row '+ " Fwd_rt"
               elseif Rand_move <= .78 then
               target_row = target_row + 1
                         IF target_row > 2744 then
               target_row = target_row - 1
               'target stays to avoid leaving grid
                              End If
          '    Print target_row '+ " Forward"
               else
               target_row = target_row - 48
                         IF target_row < 0 then
          target_row = target_row + 48
               'target stays to avoid leaving grid
                              End If
          '    Print target_row '+ " Fwd-lft"
               End If
          Loop Until target_row MOD 49 = 0
          JumpHere:                'If all sensors are
deleted the targets move freely off the grid
          IF target_status = 0 then
               undetected = undetected + 1
          End If
End Sub 'Detection_track
'*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Offset_probability()
'Calculates the degradation in detection capability
based on the type of terrain
'feature and adjusts the probability of detection for
that grid cell accordingly.
'SQL Query Grid and Trees (Within)
          Select * From Trees, Grid
               Where Grid.obj Within Trees.obj
               Into Query100
          Update Query100 Set TreesCol = 1
' Offset POD Columns based on Terrain (Trees)
          Select * From Query100
                         Where TreesCol = 1
                              Update
Query100 Set Seismic = Seismic * .90
Update Query100 Set Acoustic = Acoustic * .60
Update Query100 Set Seismic_track = Seismic_track
* .90
```

```
Update Query100 Set Acoustic_track =
Acoustic_track * .60
Update Query100 Set FLIR = FLIR * .75
Update Query100 Set Attrition = Attrition * .75
'SQL Query Grid and River (Contains)
        Select * From Rivers, Grid
        Where Grid.obj Contains Rivers.obj
                Into Query101
        Update Query101 Set RiversCol = 1
'Offset POD Columns based on Terrain (Rivers)
        Select * From Query101
                        Where RiversCol = 1
Update Query101 Set Seismic = Seismic * .50
Update Query101 Set Acoustic = Acoustic * .75
Update Query101 Set Seismic_track = Seismic_track
* .50
Update Query101 Set Acoustic_track =
Acoustic_track * .75
Update Query101 Set Attrition = Attrition * .75
'SQL Query Grid and Hills (Within)
        Select * From Hills, Grid
                Where Grid.obj Within Hills.obj
                Into Query102
                Update Query102 Set HillsCol = 1
'Offset POD Columns based on Terrain (Hills)
        Select * From Query102
                        Where HillsCol = 1
Update Query102 Set Seismic = Seismic * .65
Update Query102 Set Acoustic = Acoustic * .25
Update Query102 Set FLIR = FLIR * .25
Update Query102 Set Seismic_track = Seismic_track
* .65
Update Query102 Set Acoustic_track =
Acoustic_track * .25
Update Query102 Set Attrition = Attrition * .5
'SQL Query Grid and Towns (Within)
        Select * From Towns, Grid
                Where Grid.obj Within Towns.obj
                Into Query103
        Update Query103 Set TownsCol = 1
'Offset POD Columns based on Terrain (Towns)
        Select * From Query103
                        Where TownsCol = 1
Update Query103 Set Seismic = Seismic * .10
Update Query103 Set Acoustic = Acoustic * .10
Update Query103 Set FLIR = FLIR * .25
Update Query103 Set Seismic_track = Seismic_track
* .10
Update Query103 Set Acoustic_track =
Acoustic_track * .10
Update Query103 Set Attrition = Attrition * .10
'Close all Queries
        Close Table Query100
        Close Table Query101
        Close Table Query102
        Close Table Query103
Commit table grid
End Sub         'Offset_Probability
'*******************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Thematic_map()
'Calculates and creates a thematic map for sensor
detection ranges
'and enemy detection ranges of the sensors.
        If showthematic = 0 then Exit Sub
                Else
        End If
'Calculates Seismic ranges
Dim range_limits() as Float
Dim brush_styles() As Brush
Dim col_name as Alias
col_name = "Seismic"
        Create Styles
                From Brush (2, CYAN, 0)
        'Style for Low Range
                To Brush (2, BLUE, 0)
                'Style for High Range
                Vary Color by "RGB"
                Number 4
                Into Variable brush_styles
        Create Ranges From Grid
                With col_name
                Use "Equal Ranges"
                Number 4
                Round 0.001
        Into Variable range_limits
Shade Grid
        With col_name
        Ignore 0
Ranges
                From Variable range_limits
                Style Variable brush_styles
'Calculates and creates a thematic map for sensor
detection ranges (Acoustic).
Dim col_name1 as Alias
Dim range_limits1() As Float
Dim brush_styles1() As Brush
col_name1 = "Acoustic"
        Create Styles
                From Brush (17, Red, 0)
        'Style for Low Range
                To Brush (17, Yellow, 0)
                'Style for High Range
                Vary Color by "RGB"
                Number 4
                Into Variable brush_styles1
        Create Ranges From Grid
                With col_name1
                Use "Equal Ranges"
                Number 4
                Round 0.001
        Into Variable range_limits1
        Shade Grid
                With col_name1
                Ignore 0
        Ranges
                From Variable range_limits1
                Style Variable brush_styles1
'Calculates and creates a thematic map for sensor
detection ranges (FLIR).
Dim col_name2 as Alias
Dim range_limits2() As Float
Dim brush_styles2() As Brush
```

```
col_name2 = "FLIR"
        Create Styles
                From Brush (2, RED, 0)
        'Style for Low Range
                To Brush (2, MAGENTA, 0)
        'Style for High Range
                Vary Color by "RGB"
                Number 4
                Into Variable brush_styles2
        Create Ranges From Grid
                With col_name2
                Use "Equal Ranges"
                Number 3
                Round 0.001
        Into Variable range_limits2
        Shade Grid
                With col_name2
                Ignore 0
        Ranges
                From Variable range_limits2
                Style Variable brush_styles2
'Calculates and creates a thematic map for attrition
column.
Dim col_name3 as Alias
Dim range_limits3() As Float
Dim brush_styles3() As Brush
col_name3 = "Attrition"
        Create Styles
                From Brush (38,YELLOW, 0)
                'Style for Low Range
                To Brush (38, BLUE, 0)      'Style
for High Range
                Vary Color by "RGB"
                Number 2
                Into Variable brush_styles3
        Create Ranges From Grid
                With col_name3
                Use "Equal Ranges"
                Number 2
                Round 0.001
        Into Variable range_limits3
        Shade Grid
                With col_name3
                Ignore 0
        Ranges
                From Variable range_limits3
                Style Variable brush_styles3
'Displays Active Thematic Legend
        Set Window Legend
                Font ("arial", 0, 10, black, white)
                Position (6.75, .25)
                Height 5.25
                Width 1.60
                Show
        Open Window Legend
        Set Map Redraw On
End Sub 'Thematic Map
'***********************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Thematic_map_track()
'Calculates and creates a thematic map for sensor
detection ranges
'and enemy detection ranges of the sensors.
        If showthematic = 0 then Exit Sub
                Else
        End If
'Calculates Seismic ranges
Dim range_limits() as Float
Dim brush_styles() As Brush
Dim col_name as Alias
col_name = "Seismic_track"
        Create Styles
                From Brush (2, CYAN, 0)
        'Style for Low Range
                To Brush (2, BLUE, 0)
                'Style for High Range
                Vary Color by "RGB"
                Number 4
                Into Variable brush_styles
        Create Ranges From Grid
                With col_name
                Use "Equal Ranges"
                Number 4
                Round 0.001
        Into Variable range_limits
'Map From Grid
Shade Grid
        With col_name
        Ignore 0
Ranges
                From Variable range_limits
                Style Variable brush_styles
'Calculates and creates a thematic map for sensor
detection ranges (Acoustic).
Dim col_name1 as Alias
Dim range_limits1() As Float
Dim brush_styles1() As Brush
col_name1 = "Acoustic_track"
        Create Styles
                From Brush (2, YELLOW, 0)
                'Style for Low Range
                To Brush (2, GREEN, 0)
                'Style for High Range
                Vary Color by "RGB"
                Number 4
                Into Variable brush_styles1
        Create Ranges From Grid
                With col_name1
                Use "Equal Ranges"
                Number 4
                Round 0.001
        Into Variable range_limits1
        Shade Grid
                With col_name1
                Ignore 0
        Ranges
                From Variable range_limits1
                Style Variable brush_styles1
'Displays Active Thematic Legend
        Update Window Legend
End Sub 'Thematic_map_track()
'***********************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Get_User_Input
```

```
        'This subroutine should be the only one that
the user needs to change to
        'run the program.  Eventually, this will be
replaced by a run-time user
        'interface.
        Dim s_title as String
        Dim i_details as SmallInt
        Dim i_seismic_tree_prob as SmallInt
        Dim i_scope as SmallInt
        Dim sym_variable as Symbol
Print Chr$(12)    'This statement clears the
Message window
        Dialog
                Title "Sensor Input"
                Control GroupBox
                        Title "Simulation Level"
                        Calling reset_sub
        Position 5, 7   Width 70   Height 55
                Control RadioGroup
        Title "&Full Grid;&Half Grid;&First 100 Cells"
                        Value 3
                        Into i_details
                        ID 1
                Position 10, 18    Width 60
                Control StaticText
                        Title "Show Results For:"
                        Position 85, 10
                Control MultiListBox
                Title "Seismic;Acoustic;FLIR;"
                        Value 3
                        ID 2
        Position 85, 21    Width 65  Height 30
                Control StaticText
                        Title "Seismic Sensor"
                        Position 5, 66
                Control GroupBox
                        Title "Offset Probability:"
                Position 2, 75  Width 75  Height 75
                Control StaticText
                        Title "Roads:"
                        Position 5, 89
                Control PopupMenu
                        Title "0.90;0.85;0.80;0.75"
                        Value 1
                        Into i_seismic_tree_prob
                        ID 3
        Position 32, 87    Width 40  Height 7
                Control CheckBox
        Title "Run Thematic Maps"
                        Value 0
                        Into showthematic
                        ID 4
                        Position 5, 170
                Control StaticText
                        Title "Rivers:"
                        Position 5, 104
                Control PopupMenu
                        Title "0.80;0.70;0.60;0.50"
                        Value 4
                Into i_seismic_rivers_prob
                        ID 5
        Position 32, 102  Width 40  Height 7
                Control StaticText
                        Title "Hills:"
                        Position 5, 119
                Control PopupMenu
                        Title "0.50;0.60;0.65;0.70"
                        Value 3
                        Into i_seismic_hills_prob
                        ID 6
        Position 32, 117  Width 40  Height 7
                Control StaticText
                        Title "Towns:"
                        Position 5, 134
                Control PopupMenu
                        Title "0.05;0.10;0.15;0.20"
                        Value 2
                Into i_seismic_towns_prob
                        ID 12
                        Position 32, 132   Width
40  Height 7
'FLIR Vision Control Boxes
                Control StaticText
                        Title "FLIR Camera"
                        Position 105, 66
                Control GroupBox
                        Title "Focus Angles:"
                        Position 102, 75  Width
75  Height 75
                Control StaticText
                        Title "FLIR 1:"
                        Position 105, 89
                Control PopupMenu
                        Title "West;North;East"
                        Value 2
                        Into FLIR1_Look_Angle
                        ID 7
        Position 132, 87  Width 40  Height 7
                Control StaticText
                        Title "FLIR 2:"
                        Position 105, 104
                Control PopupMenu
                        Title "West;North;East"
                        Value 2
                        Into FLIR2_Look_Angle
                        ID 8
                        Position 132, 102
        Width 40  Height 7
                Control StaticText
                        Title "FLIR 3:"
                        Position 105, 119
                Control PopupMenu
                        Title "West;North;East"
                        Value 2
                        Into FLIR3_Look_Angle
                        ID 9
                        Position 132, 117
        Width 40  Height 7
                Control StaticText
                        Title "FLIR 4:"
                        Position 105, 134
                Control PopupMenu
                        Title "West;North;East"
                        Value 2
```

```
                        Into FLIR4_Look_Angle
                        ID 10
        Position 132, 132 Width 40  Height 7
'End FLIR Vision Control Boxes
                Control CheckBox
                Title "Clear Grid Columns"
                        Value 1
                        'Calling Checker
                Into execute_assign_zeros
                        ID 11
                        Position 5, 158

                Control StaticText
                        Title "Enter PATH:"
                        Position 5, 197
                Control EditText
                        Value
"C:\Sensor_simulation\Simulation_Run_Area\Simulat
ion_Open_no_group\Exp_02\"
                        Into Path_location
                        ID 13
                Position 47, 195   Width 200
                Control Button
                        Title "&Reset"
                        Calling reset_sub
                        Position 10, 220
                Control OKButton
                        Position 65, 220
                        Calling okhandler
                Control CancelButton
                        Position 120, 220
                        Calling cancelhandler
        If CommandInfo(CMD_INFO_DLG_OK)
Then
'....then the user clicked OK.
        Else
                '....then the user clicked Cancel.
        End if
End Sub 'Get_User_Input
'***************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub reset_sub
'reset the controls to their original state.
'Alter Control 1 Value 3
End Sub
'***************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub Cancelhandler
'Ends Program
        End program
End Sub
'**************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub okhandler
'Call Startup()
End Sub
'**************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
Sub FLIR_Vision()
'This sub compensates for field of vision on the FLIR
sensor.
'Rather than 360 degrees capability of other sensors,
FLIR cameras
'only have 25 degrees (field of vision; FOV).
                        Open Table path + "FLIR_Vision"
                        Add Map Layer FLIR_Vision
                        Set Map Layer 1 Selectable On
'Polygon = 25 equates to field of vision behind the
camera and is deleted now
                Select * From Grid, FLIR_Vision
                Where FLIR_Vision.Obj Intersects Grid.Obj
                        Into Query98

                select * From Query98
                        Where FLIR_Vision = 25
                        Into Query99
                Update Query99 Set FLIR = FLIR * 0
                select * From Query98
                        Where FLIR_Vision = 0
                        Into Query100
                Update Query100 Set FLIR = FLIR * 0
'Delete other camera angles based on intelligence
'FLIR1_Look_Angle is either 1, 2, 3
                '1 for west focus
                '2 for north focus
                '3 for east focus
                select * From Grid, FLIR_Vision
                        'SQL Query to join tables
                Where FLIR_Vision.Obj Intersects Grid.Obj
                        Into Query200
'Delete other look angles(For FLIR West)
                If FLIR1_Look_Angle = 1 Then
                        select * From Query200
                        'SQL Query to join tables
                        Where FLIR_Vision = 2 Or
FLIR_Vision = 3
                        Into Query201
                Select * From Query201
                        Where FLIR_Vision = 3 And
FLIR_Vision = 2
                Update Query201 Set FLIR = FLIR * 0
                ElseIf FLIR1_Look_Angle = 2 Then
                select * From Query200
                'SQL Query to join tables
                        Where FLIR_Vision = 1 Or
FLIR_Vision = 3
                        Into Query201
                Select * From Query201
                        Where FLIR_Vision = 1 And
FLIR_Vision = 3
                Update Query201 Set FLIR = FLIR * 0
                ElseIf FLIR1_Look_Angle = 3 Then
                select * From Query200
                'SQL Query to join tables
                Where FLIR_Vision = 2 Or FLIR_Vision = 1
                        Into Query201
                Select * From Query201
Where FLIR_Vision = 1 And FLIR_Vision = 2
                Update Query201 Set FLIR = FLIR * 0
                Else
                End if
'FLIR2_Look_Angle is either 1, 2, 3
                '1 for west focus
```

```
            '2 for north focus
            '3 for east focus
            select * From Grid, FLIR_Vision
                        'SQL Query to join tables
            Where FLIR_Vision.Obj Intersects Grid.Obj
                        Into Query202
            If FLIR2_Look_Angle = 1 Then
            select * From Query202
            'SQL Query to join tables
            Where FLIR_Vision = 5 Or FLIR_Vision = 6
                        Into Query203
            Select * From Query203
Where FLIR_Vision = 5 And FLIR_Vision = 6
            Update Query203 Set FLIR = FLIR * 0
            ElseIf FLIR2_Look_Angle = 2 Then
            select * From Query202
            'SQL Query to join tables
            Where FLIR_Vision = 4 Or FLIR_Vision = 5
                        Into Query203
            Select * From Query203
Where FLIR_Vision = 4 And FLIR_Vision = 5
            Update Query203 Set FLIR = FLIR * 0
            ElseIf FLIR2_Look_Angle = 3 Then
            select * From Query202
            'SQL Query to join tables
Where FLIR_Vision = 4 Or FLIR_Vision = 6
                        Into Query203
            Select * From Query203
Where FLIR_Vision = 4 And FLIR_Vision = 6
            Update Query203 Set FLIR = FLIR * 0
            Else
            End if
'FLIR3_Look_Angle is either 1, 2, 3
            '1 for west focus
            '2 for north focus
            '3 for east focus
            select * From Grid, FLIR_Vision
                        'SQL Query to join tables
            Where FLIR_Vision.Obj Intersects Grid.Obj
                        Into Query204
            If FLIR3_Look_Angle = 1 Then
            select * From Query204
            'SQL Query to join tables
                        Where FLIR_Vision = 8 Or
FLIR_Vision = 9
                        Into Query205
            Select * From Query205
                        Where FLIR_Vision = 8 And
FLIR_Vision = 9
            Update Query205 Set FLIR = FLIR * 0
            ElseIf FLIR3_Look_Angle = 2 Then
            select * From Query204
            'SQL Query to join tables
            Where FLIR_Vision = 7 Or FLIR_Vision = 8
                        Into Query205
            Select * From Query205
Where FLIR_Vision = 7 And FLIR_Vision = 8
            Update Query205 Set FLIR = FLIR * 0
            ElseIf FLIR3_Look_Angle = 3 Then
            select * From Query204
            'SQL Query to join tables
                        Where FLIR_Vision = 7 Or
FLIR_Vision = 9
                        Into Query205
            Select * From Query205
Where FLIR_Vision = 7 And FLIR_Vision = 9
            Update Query205 Set FLIR = FLIR * 0
            Else
            End if
'FLIR4_Look_Angle is either 1, 2, 3
            '1 for west focus
            '2 for north focus
            '3 for east focus
            select * From Grid, FLIR_Vision
                        'SQL Query to join tables
            Where FLIR_Vision.Obj Intersects Grid.Obj
                        Into Query206

            If FLIR4_Look_Angle = 1 Then
            select * From Query206
            'SQL Query to join tables
                        Where FLIR_Vision = 11 Or
FLIR_Vision = 12
                        Into Query207
            Select * From Query207
Where FLIR_Vision = 11 And FLIR_Vision = 12
            Update Query207 Set FLIR = FLIR * 0
            ElseIf FLIR4_Look_Angle = 2 Then
            select * From Query206
            'SQL Query to join tables
Where FLIR_Vision = 10 Or FLIR_Vision = 11
                        Into Query207
            Select * From Query207
Where FLIR_Vision = 10 And FLIR_Vision = 11
            Update Query207 Set FLIR = FLIR * 0
            ElseIf FLIR4_Look_Angle = 3 Then
            select * From Query206
            'SQL Query to join tables
                        Where FLIR_Vision = 10 Or
FLIR_Vision = 12
                        Into Query207
            Select * From Query207
                        Where FLIR_Vision = 10 And
FLIR_Vision = 12
            Update Query207 Set FLIR = FLIR * 0
            Else
            End if
Close Table Query206
Close Table Query207

Close Table FLIR_Vision
End Sub 'FLIR_Vision()
''*************************************************************
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
```

Appendix D: Sensor Max Effective Range and Capabilities

	Maximum Effective Range (meters)			Probability of Detection (Pd)			Probability of Classification (Pc)			Field of View (degrees)
Sensor Type	P[1]	W[2]	T[3]	P	W	T	P	W	T	360
Seismic	30	250	500	0.95	0.95	0.95	0.95	0.95	0.95	360
Acoustic	50[4]	250	700	0.95	0.95	0.95	0.80	0.80	0.80	360
Magnetic	3[5]	15	25	0.90	0.90	0.90	[6]			40
IR/Passive	20	50	50	0.95	0.98	0.99				25
Micro FLIR	100	150	150	0.90	0.90	0.90	0.70	0.70	0.70	15
FLIR	800	1100	1100	0.90	0.90	0.90	0.70	0.70	0.70	25
IR-Alpha	250	400	400	0.90	0.90	0.90	0.70	0.70	0.70	15

[1] Indicates Personnel Column
[2] Indicates Wheeled Column
[3] Indicates Tracked Column
[4] Detection occurs if persons are talking or making audible noises. Cannot detect stealth soldiers.
[5] Detection occurs if person is carrying metallic object.
[6] Confirming the size of the magnetic object (people, heavy or light armor, etc.) depends on the relative position of the sensor and whether the target description is known.

References

Box, George E.P. and Norman R. Draper. Empirical Model-Building and Response Surfaces. John Wiley & Sons, Inc., New York, 1987.

Brendley, Keith W. "A quantitative Methodology for Examining the Military Utility of a Mixture of Sensor Systems". Report AR-016-00. Artis, LLC. Arlington, Virginia, January 2001.

Brown, Donald E., Clarence L. Pittard and Andrew R. Spillane. "ASSET: a Simulation Test Bed for Data Association Algorithms". Computers Ops Res. Vol.19, No.6, pp. 470-493, 1992. Pergamon Press Ltd, Great Britain, 1992.

Chankong, Vira and Yacov Y. Haimes. Multiobjective Decisionmaking: Theory and Methodology Series. Volume 8. North-Holland, New York, 1983.

Derringer, G., and Suich, R. (1980, "Simultaneous Optimization of Several Response Variables," Journal of Quality Technology, 12, 214-219.

DRAFT IBCT Organizational and Operational Concept, v 4.0, 18 April 2000. Online. Internet. 6 February 2001. Available: http://contracting.tacom.army.mil/majorsys/brigade/ formalrfp/BCTOandO/Chapter%203%20IBCT%20OO%2018%20April%2000.doc.

DRAFT RSTA Squadron Organizational and Operational Concept, Chapter 7, 18 April 2000. Online. Internet. 6 February 2001. Available: http://contracting.tacom.army.mil/majorsys/brigade/formalrfp/BCTOandO/Chapter%207%20IBCT%20O&O%20Draft%2018%20April.doc.

Environmental Systems Research Institute, Inc., "The Role of Geographic Information systems on the Electronic Battlefield". An ESRI White Paper—February 1998. Online. Internet. 11 September 2000. Available: http://www.esri.com/library/ whitepapers/pdfs/batt0298.pdf.

Fenton, Norman E. and Shari L. Pfleeger. Software Metrics: A Rigorous & Practical Approach 2nd Ed. PWS Publishing Company, Boston, MA, 1997.

FM 44-48 Tactics, Techniques and Procedures for the Sensor Platoon. September 1993. Online. Internet. 9 March 2001. Available: http://www.adtdl.army.mil/cgi-bin/atdl.dll/fm/44-48/fm44-48.htm.

Gerber, Jerry. Army Research Lab, Sensors and Electronic Devices Directorate. Personal Interview. “Sensor Characteristics.” August 2000.

Habayeb, A.R. Systems Effectiveness. Pergamon Press, Oxford, 1987.

Haimes, Yacov Y. Risk Modeling, Assessment and Management. John Wiley and Sons, Inc., New York, 1998.

Hopkins, John W., Brian T. Mays, David B. Hillis, Hao Q. Vu and James C. Brown. "Warrior Extended Battlespace Sensors (WEBS)." US Army Research Laboratory, Adelphi, MD, 2000.

Joint Publication 1-02. “Department of Defense Dictionary of Military Terms”. Online. Internet. 9 February 2001. Available: http://www.dtic.mil/doctrine/jel/doddict/.

Joint Vision 2010, *Army Joint Vision Component Briefing*. Online. March 2000. Available: http:/www.dtic.mil/JV2010/jvpub.htm.

Kang, C.W. and M.W. Golay. "An Integrated Method for Comprehensive Sensor Network Development in Complex Power Plant Systems." Reliability Engineering & System Safety. (Jan, 2000): 17-27.

Keeney, Ralph L. and Howard Raiffa. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press, New York, 1993.

Lamm, Gregory A. "Assessing and Managing Risks to Information Assurance: A Methodological Approach." Thesis University of Virginia. 2001.

Law, Averill M. and W. David Kelton. Simulation Modeling and Analysis, 2nd ed. McGraw-Hill, Inc., New York, 1991.

MapInfo Professional Corporation. MapInfo Professional Version 5.0. Reference Manual. MapInfo Professional Corporation, 1998.

MCWP 2-15.1. US Marine Corps Warfighting Publication, *Remote Sensor Operations.* April 1997. Online. Internet. 9 March 2001. Available: http://www.doctrine.usmc.mil/mcwp2151/mcwp2151.pdf.

Meyers, Raymond H., and Douglas C. Montgomery. Response Surface Methodology. John Wiley & Sons, INC., New York, 1995.

Milton, A. Fenner. Night Vision and Electronic Sensors Directorate. “Sensor Technologies for the Objective Force”. A Briefing presented at the MSS Battlefield Acoustics and Seismic Specialty Group Conference, 17 October 2000. Personal Document (Only available from the author).

Montgomery, Douglas C. and Vernon M. Bettencourt Jr. “Multiple Response Surface Methods in Computer Simulation” Simulation Magazine, October 1977: 113-121.

Project Management Institute. A Guide to the Project Management Body of Knowledge, 1996 ed. Newtown Square, PA: Project Management Institute, 1996.

Riese, Stephen R. "Estimating the Probability of Mine Contamination in a Non-combat Environment." Dissertation University of Virginia. 2001.

Roberts, Fred S. Measurement Theory with Applications to Decisionmaking, Utility, and the Social Sciences. Addison-Wesley Publishing Company, Massachusetts, 1979.

Schamburg, Jeffrey B. "Deployment of TDOA/DD Sensors." Thesis, University of Virginia. 1995.

Schiff, Lauren A., “Sensor Placement Optimization.” Thesis University of Virginia. 1998.

Skroch, Michael, “Development of a Science-Based Approach for IA”. May 1999. Online. Internet. 5 January 2001. Available: http://www.darpa.mil/iso/iaset/iaset.htm.

US Army Research Laboratory. Nino Srour. “Unattended Ground Sensors A Prospective for Operational Needs and Requirements”. Sensor and Electron Devices Directorate, US Army Research Laboratory. Maryland, 1999.

Wass de Czege, Huba, Brigadier General, US Army, Retired. “New Paradigm Tactics: The Rapid Evolution of Army Tactical Capabilities and Methods.” Online. Internet. 26 Feb 2001. Available: http://www.ida.org/DIVISIONS/sctr/cpof/Hub%20Papers%20-%20New%20Paradigm%20P1.DOC.

Willis, John B., Major, US Army and Mark J. Davis, LTC, US Army. "Design of the Reconnaissance, Surveillance, and Target Acquisition Squadron for the US Army's Brigade Combat Team", USMA Operations Research Center Technical Report, New York, 2000a.

Willis, John B., Major, US Army and Mark J. Davis, LTC, US Army. "Distributed Sensor Networks on the Future Battlefield." USMA Operations Research Center Technical Report, New York, May 2000b.

Young, David F., Donald E. Brown and William T. Scherer. “A Polynomial Induction Network Approach to Engineering Design.” University of Virginia. 2000.