Design and Evaluation of a Mobile Instrumentation Platform for Unmanned Vehicle Testing

Brett Anthony Gombar

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Dr. Charles F. Reinholtz, Chairman
Dept of Mechanical Engineering

Dr. Alfred L. Wicks
Dept of Mechanical Engineering

Dr. Dennis Hong
Dept of Mechanical Engineering

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Abstract

Unmanned vehicle systems are becoming more important in the future of the military and in commercial applications. These systems are used to prevent humans from entering dangerous situations or to automate dull tasks. In order to facilitate rapid development of these systems, testing procedures and infrastructure need to be created. Once developed, the performance characteristics of unmanned vehicle systems can be determined and compared to similar systems. This information will be beneficial to system developers and potential customers.

In order to provide the infrastructure and test procedures to the unmanned systems community, the Joint Robotics Program created the National Unmanned Systems Experimentation Environment (NUSE2). NUSE2 consists of a variety of military organizations and academic resources, including the Joint Unmanned Systems Test Experimentation and Research (JOUSTER) site at Virginia Tech. JOUSTER was tasked specifically with creating a mobile instrumentation platform capable of providing wireless communications, data collection, and video coverage of a testing site.

This thesis presents the system designed and created to meet this need. For the first time, a mobile instrumentation platform has been created to specifically support unmanned systems research. Additionally, the performance characteristics of this system have been fully evaluated and will serve as a benchmark for future improvements to the system.
Development of a Mobile Instrumentation Platform has been a challenging and exciting part of my graduate work. It has been my pleasure to work on a project with a scope as large as the MIP and it has added greatly to my skills as an engineer. This project would not have been completed were it not for the continuing efforts those listed here.

My interests in unmanned systems were originally sparked by involvement in the Autonomous Vehicle Team at Virginia Tech and the enthusiasm of Dr. Reinholtz. As an advisor for the project, Dr. Reinholtz has enabled many undergraduate teams to become highly successful. My involvement in JOUSTER would not have been possible if not for the encouragement of Dr. Reinholtz and the skills gained through AVT.

Dr. Wicks has provided me with constant abuse through classes and design reviews during my graduate career. Many have experienced this abuse and have become better engineers and people because of it. Dr. Wicks, thank you for making my graduate career challenging and entertaining.

Dr. Hong first caught my attention while substitute teaching a kinematics class. His enthusiasm for teaching and design is great to experience. In addition his designs and thoughts on alternative locomotion strategies for robots are creative and inspiring. I look forward to seeing these designs evolve in the future.

Critically important to the completion of this project are the efforts of fellow JOUSTER researchers. In particular, I’d like to thank Michael Fleming for creating the concept of a Wireless Instrumented Portable station (aka MIP) and contributing to the design. I’d like to thank Sean Baity for his extensive and extremely thorough work on the CAD models used in the design of the MIP. Were it not for Sean’s professionalism rubbing off the project would not be where it is today. I’d also like to thank Mike Avitabile. While working on AVT and during the creation of the MIP Mike has constantly challenged my every thought for no reason. This attitude caused me to focus on every detail of the MIP in order to pass his scrutiny. If it is meat-hand approved it is a success. His enthusiasm for connectors and electrical design has contributed greatly to the success of the MIP.

I’d like to thank all the members of the JOUSTER research program. Due to the leadership, forethought, and efforts of Dr. Reinholtz, Dr. Wicks, and others the program would have never materialized. From the beginning the program has been fast paced, challenging, and fun. My co-workers have created the ideal work environment that is both fun and hard working. I have been lucky to be a part of all the jokes, late nights, long road trips, and rewarding projects.

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Chapter 1: Introduction and Literature Review

With unmanned systems becoming more prevalent in military operations and civilian enterprises testing and validation procedures and standards are necessary. According to the National Research Council, “no quantitative standards, metrics, or procedures exist for evaluating autonomous mobility performance, particularly off-road” [1]. As a result, competing systems in the market place have little or no basis for comparison.

Currently, few sites have the infrastructure, equipment, and procedures to adequately test unmanned vehicle systems and provide reliable performance data to the developers. Additionally, many sites are located on active military bases which impose strict regulations and have limited availability due to other high priority activities [2]. As a result, the military has recognized the need for dedicated unmanned systems testing environments and is currently developing the technology and practices to fully characterize these systems.

1.1: Project Overview

In 1990 the Office of the Secretary of Defense recognized the need to consolidate all the ground vehicle robotics projects into the Joint Robotics Program (JRP). With the creation of the JRP, all branches of the military had a single point of management and coordination for all robotics related projects [3]. As a result, the goals of the Department of Defense could be managed more efficiently and effectively.

Identified as one of the goals of the JRP was the ability to use Commercial Off the Shelf (COTS) technology to streamline research and development and reduce life cycle costs [4]. In order to advance this goal and provide the unmanned systems community with increased capability to conduct experimentation and promote technology transfer, the National Unmanned Systems Experimentation Environment (NUSE2) was created in 2004 [5]. NUSE2 includes military, experimental, and academic resources of which Virginia Tech is a member.

In June of 2004 Virginia Tech was granted a contract from the Army’s Research, Development & Engineering Command (RDECOM) to develop the JOint Unmanned Systems, Test, Experimentation, and Research (JOUSTER) site. As one
of the assets of NUSE2, one goal JOUSTER was tasked with was the development and implementation of a Mobile Instrumented Platform (MIP) for data collection, video recording, and communications [2]. The work presented in this paper will focus on the development and implementation of a Mobile Instrumentation Platform (MIP) used in the JOUSTER site infrastructure and related experiments.

1.2: Motivation

JOUSTER was created to promote unmanned systems testing and develop standards and metrics for evaluating vehicle performance [6]. To accomplish this goal, JOUSTER was required to develop the infrastructure and practices to perform real world vehicle experiments [7, 8]. One JOUSTER project, the MIP, was established to provide a flexible, portable, and wireless system for site instrumentation and data collection to aid in the development process of unmanned vehicle systems and related technologies.

One application for the use of the MIP technology is within the framework of the Future Combat System (FCS) currently in development by the Army. A main focus of the FCS is the dissemination of battlefield information up and down the command chain. To accomplish this goal, the FCS will rely heavily on high-bandwidth, long range, and secure digital networks. This network, shown in Figure 1.1, is described as:

“The Army’s Future Combat Systems (FCS) network allows the FCS Family-of-Systems (FoS) to operate as a cohesive system-of-systems where the whole of its capabilities is greater than the sum of its parts. As the key to the Army’s transformation, the network, and its logistics and Embedded Training (ET) systems, enable the Army to employ revolutionary operational and organizational concepts. The network enables Soldiers to perceive, comprehend, shape, and dominate the future battlefield at unprecedented levels as defined by the FCS Operational Requirements Document (ORD) [9].”
With the network having a critical role in the combat environment, validation of technology and systems will be absolutely necessary. The capabilities of the MIP will provide a platform for evaluating the components which make up this future network to ensure functionality.

The network described in the FCS is a part of a broad reaching goal of the Department of Defense (DoD) to transition the military from a platform-centric force into a network-centric force. The term network-centric-warfare (NCW) is described by the DoD in a report to Congress as,

“NCW represents a powerful set of warfighting concepts and associated military capabilities that allow warfighters to take full advantage of all available information and bring all available assets to bear in a rapid and flexible manner [10].”

This concept will allow the Armed Forces to enhance military effectiveness by ensuring the information necessary to make wartime decisions is accurate and available to the personnel who need it most. Described as “the single most important contributor to combat power [10],” the NCW concept cannot be achieved easily and will require many years of research and development. The DoD recognized this problem and stated to Congress,

“Far more needs to be done to develop, test, and refine network-centric concepts of operation and co-evolve them with
The MIP is a system designed to provide the functionality and flexibility necessary to aid in the development of network-centric systems. Having the ability to easily collect and record data, be reconfigured to support alternative equipment, and facilitate real-world testing in any locations will provide engineers with the means to fully evaluate their systems.

The Joint Architecture for Unmanned Systems (JAUS) Working Group has experienced this capability firsthand. The Working Group is currently developing a standard messaging set, JAUS, for use in all unmanned vehicle systems associated with the JRP [11]. Using this message set, robotic platforms, controllers, and payloads from different suppliers will be able to communicate to each other through a common language. The Working Group recognized the need for testing and verification of JAUS and requested the use of the MIP during their Operator Control Units and Payloads (OPC) Committee experiment held in August, 2004. Figure 1.2 illustrates how the OPC made use of the MIP’s network communications and data logging capabilities. The recorded information was used to verify proper function of JAUS and OPC members gained valuable feedback on where improvements could be made to the standard.

Figure 1.2: The MIP's role in a JAUS experiment

As the need for testing and validation of systems increases, the importance of equipment such as the MIP becomes critical. The unique ability of the MIP to provide a reconfigurable instrumentation system and scalable communications network will provide the framework necessary for future experiments. This is
consistent with the NUSE2 goal to “provide the unmanned systems community the unprecedented capability to conduct experimentation and promote technology transfer by fostering a synergistic and synchronized relationship between government, contractors, commercial business, small business, and academia with scientists, technologists, product developers, testers, and users [12].”
Chapter 2: MIP Project Objectives

Unmanned systems, in general, contain a considerable number of vehicle types ranging from small aerial vehicles to ground vehicles weighing over 30,000 pounds. With such a broad range of vehicle types, experiments will constantly evolve to meet the needs of the unmanned systems community. The MIP must be able to provide support for ground, aerial, or surface experimentation. With such a broad reaching goal it was necessary to clearly define the project objectives which would guide the design.

Mechanically, JOUSTER management required the MIP to be capable of surviving environments with heavy rain, winds of 30 MPH, ice, temperatures between -20°F and 120°F, sand, mud, and salt water. Management also required the MIP to be deployed and operational by two people in fewer than thirty minutes, ready for transport in less than thirty minutes, and have an expected life of at least five years. These requirements were formed through input from personnel in the unmanned systems community and experience gained during previous experiments. The base platform, shown in Figure 2.1, was chosen due to its transportability, weather resistance, and available space to support test equipment.

![Base trailer used for construction of the MIP](image)

Figure 2.1: Base trailer used for construction of the MIP

Electrically, the MIP should be capable of continuous operation over a 24 hour period, support a wide variety of sensors, provide onboard AC and DC power, and provide over-current protection for all connected components. Additionally, all
of the equipment must be located on the base platform and suitable for transportation on and off-road.

With unmanned systems testing only beginning to evolve, the instrumentation and techniques used to gauge performance are relatively unknown. Therefore, management suggested a basic set of components necessary to meet the requirements of the Statement of Work. This included a pan/tilt/zoom video camera, a weather station (providing temperature, relative humidity, barometric pressure, and wind speed), a Global Positioning System (GPS) system used to provide position corrections, and wireless communications equipment. While this instrumentation would serve to provide basic data associated with the testing site, it was unknown if test engineers would require additional instrumentation. This unknown requirement forced the design of the MIP to be modular and capable of supporting the basic equipment while providing an option for expanding instrumentation. As a result, the electrical and mechanical designs were created with expansion and reconfiguration in mind.

Finally, a key function of the MIP, detailed in the SOW, is to provide communications capabilities to the experimentation site. JOUSTER management expanded upon this and required the communications system to be commercially available, wireless, provide a range of at least 1 mile while supporting a data rate of 11 Mb/s, have the ability to be encrypted, and be reconfigurable. Ideally, in order to provide the best wireless coverage to a testing site, the MIP should be placed in locations with no obstructions, such as trees, which could create dead zones in the wireless coverage. However, in order to provide the most flexible system possible this restriction is unrealistic. Therefore, the MIP should be capable of operation as a stand-alone unit or in conjunction with multiple MIPs networked together to extend the wireless coverage area and eliminate possible dead zones.

2.1: Technical Challenges

Creating a mobile instrumentation platform capable of meeting the needs of multiple users, supporting changing test instrumentation, withstanding a variety of environments, and providing a scaleable communications network introduces
numerous technical challenges. Specifically, areas of consideration are the mechanical design, electrical design, instrumentation, and network architecture.

Mechanically, the MIP must be capable of meeting the demanding needs of testing military equipment. Because many unmanned systems are destined for military use and are designed for operations in rugged areas, the MIP must be capable of operating in these environments. Experiments could be based in cold regions or desert environments with temperatures reaching -20°F to 120°F and anywhere in between. Additionally, experiments could be conducted in any weather condition including rain, snow, sleet, or sun. Such broad ranging environments required a great deal of forethought and planning during the design. Factors such as safety, material selection, durability, cost, human interactions, and packaging were all considered when adding mechanical elements to the design of the MIP.

Simultaneous development of the mechanical and electrical systems of the MIP was a key factor in creating a successful design. While most mechanical elements of the MIP were designed to protect the electrical equipment, the electrical components were still required to meet the environmental specifications set by management. Challenges were encountered when weighing equipment cost with function and intended use of the system. During the design process, it was necessary to fully reconsider the electrical design of the first generation MIP and implement significant changes to improve the modularity of the second generation system. For example, unknown variables, such as the voltage and current requirements of different sensors, required considerable thought to determine a flexible power distribution solution. Additionally, attention to safety, reliability, maintenance, and documentation were balanced with the requirements set forth by management.

While determining the instrumentation necessary to evaluate unmanned systems was not within the scope of the MIP project, possible equipment had to be considered. Challenges were encountered when trying to provide the flexibility, within the mechanical and electrical systems, to support a variety of instrumentation. Evaluation of the first generation MIP provided significant insight on how to improve the system and overcome these challenges.

One piece of instrumentation within the scope of the MIP project was the communications equipment. As directed by the SOW, the MIP should be capable of providing communications and data collection capabilities to the test environment. Further refinement of this requirement came from project management, however, the
details of the network architecture were left undefined. This required the evaluation of possible network types in order to provide a standard solution for customers and allow for future changes. Two general network types under consideration were a mesh network shown in Figure 2.2, and a point-to-multipoint network shown in Figure 2.3.

![Mesh Network](image)

**Figure 2.2:** Mesh network architecture [13]

![Point-to-multipoint Network](image)

**Figure 2.3:** Point-to-multipoint network architecture

Each network type met the requirements from management, however, the complexities and commercial availability of equipment had to be considered. Selecting the appropriate equipment to fit into the overall design, meet the
requirements of management, and provide reconfigurable equipment proved to be especially challenging.

The combination of components onboard the MIP was designed to provide the most flexible and scalable system possible. Each aspect of the design, from the mechanical, electrical, and network design to the basic instrumentation, was selected to fulfill the requirements of JOUSTER management and the unmanned systems community. Balancing all these elements of the design and producing a finished product was a daunting task. This document will provide the reader with an overview of a developed prototype, its shortcomings, and the design and testing of the next iteration in the design.
Chapter 3: First Generation MIP Overview

In June 2004, JOUSTER received funding to begin research and development of the equipment and procedures necessary for a mobile experimentation site. From the start, JOUSTER was tasked with developing a MIP for an August 2004 experiment which would make use of the network communications, data collection, and video capabilities onboard the MIP. The design, construction, and implementation of the first generation MIP was rushed and mainly created to support the August experiment. This chapter will present an overview of the first generation MIP shown in Figure 3.1.

![Figure 3.1: First generation MIP designed for the JAUS OPC experiment](image)

3.1: Mechanical Design

Mechanically, the first generation MIP was simple, functional, and designed and fielded in a three month period. As shown in Figure 3.1, the base platform on which all instruments would be placed, consists of an extendable aluminum tower from Aluma Tower Inc.. This base platform not only provides the necessary portability, but also outstanding weather resistance due to its all aluminum construction. Initially, the tower rests on the two vertical supports extending from the bed of the trailer, when in use the tower pivots on the rear support and is secured to the base trailer. Outriggers are then extended to provide stability and optional guy wires can be used for operations in high winds. The tower can then be extended
using an electric winch up to a maximum height of 50 feet. In addition to the base tower, Aluma Tower Inc. constructed a three-arm instrumentation tree to be placed onto the top of the tower, shown in Figure 3.2, and a cable reel located on the base trailer.

![Figure 3.2: Three-arm instrumentation tree used on the prototype MIP](image)

Working from the base trailer, the components necessary to support the August experiment were added. Mechanically, these included an electronics enclosure located on the base trailer, shown in Figure 3.3, junction boxes for data and power connections, mounts for instrumentation and communications equipment, and an enclosure for electronics located on the instrumentation tree. The main electronics enclosure (MEE) would protect the electronics equipment which would supply AC and DC power to the entire system. Electrical conduit and junction boxes, shown in Figure 3.4, were used to route DC power to the secondary electronics enclosure (SEE) located on the instrumentation tree and provide a network port at the base of the trailer.
Figure 3.3: Main electronics enclosure (MEE, red) and secondary electronics enclosure (SEE, blue) used to house the electrical system

Figure 3.4: Location of the three junction boxes (a) and a schematic representation of the function of each box (b)

Installation of the MIP is accomplished by first extending four outriggers and leveling the trailer. Once leveled, the instrumentation tree can be installed with the tower in the lowered position. This requires two people to support the tree while a third person positions the tree into the tower and secures it with three retaining pins.
Next, the electrical and network connections from junction box #3 to the Main Electronics Enclosure can be made and any additional instrumentation installed. Having completed the electrical connections the entire tower is then raised, using a hand crank, to its upright position, shown in Figure 3.5, and secured to the trailer with a retaining nut at the base of the tower. An electric winch permits the tower to be extended from 25 feet up its maximum height of 50 feet, however, the addition of guy wires may be necessary for safety when the tower is at its maximum height.

![Figure 3.5: Raised position of the MIP](image)

Securing the MIP for transportation is also an involved process. First, the entire installation procedure is reversed and the instrumentation tree removed. Once removed, the instrumentation tree must be transported in a suitable cargo vehicle as there is no integrated method for transporting it onboard the MIP itself. Next, the tower is lowered using the hand crank and secured to the base trailer supports using a tie-down strap. Finally, the electrical cables are secured and the trailer can be attached to any vehicle with the proper towing capabilities.

### 3.2: Electrical Design

As with the mechanical system, the electrical design of the first generation MIP was created specifically to support the equipment necessary for the August 2004
experiment. With a three month development period, little attention was paid to creating a modular system capable of future expansion. However, the system did function as a proof of concept and provided valuable feedback used in the design of the second generation MIP. The electrical system can be broken down into three main regions, power generation in the Main Electronics Enclosure (MEE), power distribution and computing in the Secondary Electronics Enclosure (SEE), and the instrumentation.

Power generation and conditioning components are located in the electronics enclosure on the base of the trailer and highlighted in Figure 3.6. These electronics, shown in Figure 3.7 provide AC and DC power to the entire MIP system. Detailed in Figure 3.7 (b), a hybrid-power system supplies DC power to the MIP and consists of a generator used to provide continuous power to a four-bank battery charger which maintains the batteries at peak capacity. DC power is then routed from the batteries to separate DC-DC converters supplying the instrumentation with 12 VDC and 48 VDC. The voltage output of the regulators was chosen based on the requirements of the instrumentation used on the MIP. AC power is also supplied by the onboard generator and is distributed using an AC junction box. Inside the AC junction box, ground fault interrupt (GFI) circuit breakers are used for safety and to protect the AC equipment from damage.

![Figure 3.6: The lower electronics enclosure (red) contains the power generation and conditioning equipment](image-url)
Figure 3.7: Inside the main electronics enclosure (a) and schematic representation (b)

From the MEE, DC power is routed to the SEE and used to power the equipment inside the enclosure and components placed on the instrumentation tree. Figure 3.8 highlights the location of the secondary electronics enclosure in reference to the MIP and Figure 3.9 shows a schematic representation of the components inside the enclosure. Power distribution and circuit protection is implemented using automotive style fuse blocks and standard ATO blade fuses. A National Instruments Compact FieldPoint functions as the computing and data acquisition system and allows users to remotely interact with and monitor instruments over the communications network. An 8-port ethernet switch is used to connect the communications equipment, instrumentation, and computer to the same network.
Figure 3.8: Secondary electronics enclosure (red) contains power distribution components and limited computing ability.

Figure 3.9: Schematic representation of the secondary electronics enclosure.
Instrumentation supported by the first generation MIP was selected to meet the needs of the SOW and provide additional basic site monitoring capabilities. As directed by the SOW, the MIP must be able to provide communications capabilities to a testing site. To meet this requirement Cisco Systems communications equipment was chosen due to its industry proven reliability and its wide range of network configuration options. A wireless IEEE 802.11b/g access point is used to provide site coverage with data rates up to 54Mbps (Megabits per second) for data transmission and communications to client devices. In order to relay this information back to a central command center for processing and visualization an IEEE 802.11a bridge capable of data rates up to 54Mbps is used. To supplement the communications equipment a weather station, pan/tilt/zoom camera, and global positioning reference station are included in the prototype system. These instruments were chosen to provide additional site data which could be useful in a testing situation.

Designed and implemented in a three month time frame, the first generation MIP was created to serve as a proof of concept and used to gain valuable knowledge of the capabilities of the MIP. The focus of the design was to create a functional system capable of meeting the requirements described by the SOW and JOUSTER management. The resulting first generation MIP fulfilled these requirements and provided valuable insight into the needs and requirements of test engineers which would be used in the design of the second generation MIP.
Chapter 4: Second Generation MIP

The first generation MIP was a simple system which proved the concept was feasible and provided much needed insight as to how the system should be used. Initially, the MIP was designed with little knowledge of how the product would actually be used during an experiment. After fielding the prototype MIP for a number of experiments the entire system was evaluated and areas in need of improvement were noted. This evaluation identified various mechanical, electrical, and functional drawbacks of the first generation MIP. The following sections will detail the mechanical elements that needed improvement including the overall layout and function of components on the MIP, the design and function of the instrumentation tree, the placement of components in the main electronics enclosure, and attention to providing a finished product.

4.1: Instrumentation Tree Improvements

The instrumentation tree created by Aluma Tower Inc. proved to be problematic when deploying the first generation MIP. First, due to the size of the tree users were unable to leave the tree installed on the tower during transportation because it would hit tow vehicles while turning. Because of this limitation the instrumentation tree had to be installed and removed for each experiment and transported in a separate vehicle. Second, while functional the instrumentation tree did not have adequate space for the addition of future instrumentation. Finally, the design forced the instrumentation to be mounted on the tree prior to installation causing it to be heavy and unevenly weighted. Due to the awkward weight of the tree, three people and an additional ladder were needed to install the tree safely.

To successfully redesign the instrumentation tree, these problems needed to be addressed. The new tree had to be safe, modular, easy to use, and easily transportable. First, the awkward weight and large size of the prototype tree needed to be addressed. In an effort to reduce size and weight the new instrumentation tree was designed to accept removable “instrumentation arms” which slide into the tree and support the instrumentation. Each arm would be responsible for supporting the computing power necessary for the arm, the power conditioning equipment, and the
instrumentation itself. Figure 4.1 shows a comparison of the overall size of the two instrumentation trees.

![Figure 4.1: Size comparison of the two instrumentation trees (dimensions in inches)](image)

Although each instrumentation arm must be installed separately for experiments, single arms would be much easier to manage than a fully equipped tree. The final design of the new instrumentation tree is shown in Figure 4.2.

![Figure 4.2: Redesigned instrumentation tree with removable arms and secondary electronics enclosure](image)

Removable instrumentation arms were a key feature necessary for the reduction in size and functionality of the second generation instrumentation tree. By using stainless steel DE-STA-CO 323-SS toggle clamps in conjunction with a sliding plug and socket joint, shown in Figure 4.3, the arms can be slid into the tree and
secured. With a holding capacity of 360 lbs, the clamps far exceed the weight which should be placed on a single arm. This system has proven itself to be safer to install, easier to manage, and eliminates the difficulty of transporting an entire tree.

Figure 4.3: Toggle clamps used to secure the instrumentation arms once they are slid into the tree socket

4.2: Main Electronics Enclosure Improvements

The Main Electronics Enclosure (MEE) on the base of the trailer was identified as an area in need of redesign. Shown in Figure 4.4, the first generation enclosure contained the equipment necessary for power generation, circuit protection, power conditioning and AC/DC power distribution. Its large size, unprofessional appearance, problematic design, and unintuitive user interface were all reasons for the redesign.
A major problem was encountered with the generator while fielding the first generation MIP. Initially, all the components were placed inside a single enclosure to simplify construction. However, this proved to be problematic in practice as improper routing of the generator exhaust created a build up of carbon dioxide and heat inside the enclosure. This eventually caused the generator to stall and made the enclosure hot to the touch. Without the generator running, the onboard batteries would no longer be continuously recharged and would eventually be drained. In practice this was solved by simply propping open the enclosure to let air in, however, this was an unacceptable solution and needed to be addressed in the redesign.

In addition to the exhaust problem, the user interface with the MIP was unprofessional. In order to turn on DC power to the MIP, and subsequently provide power to the instrumentation, the enclosure had to be unlocked, two hold down clamps had to be unsecured, and the enclosure opened in order to gain access to the DC power switch and generator. This process proved to be an annoyance during operation and had to be changed.

In the redesigned enclosure, much attention was given to equipment placement and user interaction in order to remedy the problems encountered on the first generation MIP. Having all the components located in a single enclosure was beneficial from a manufacturing standpoint because only a single enclosure had to be manufactured and installed. However, the problems encountered with this design on
the first generation MIP were solved by housing the generator in its own enclosure. This step not only eliminated the heat and exhaust problem but also permitted a refined user interface to be created. With the generator located separately, the main electronics enclosure can remain closed at all times excluding maintenance. Therefore, the controls such as the main power switch and accessory switches were moved to the exterior of the enclosure. This improved the safety and appearance of the system and simplified the start up procedure. The final design and overall layout are shown in Figures 4.5 and 4.6.

Figure 4.5: The finished main electronics enclosure with improved user interface

Figure 4.6: Overall layout of components on the base of the trailer with the generator enclosure (red) and lower electronics enclosure (yellow) shown
Finally, the safety and professional appearance of the components located in the enclosure was addressed. In the main electronics enclosure there were potentially hazardous flaws in the design. If Figure 4.4 is examined closely many of these flaws can be recognized. For example, exposed battery terminals are a potential spark hazard if a tool is dropped across the terminals. Combine this with the possibility of spilling gasoline while adding fuel to the generator and there is potential for a large problem. Additionally, the user can be exposed to live AC lines when opening the AC junction box to access the circuit breakers. Each of these problems and the overall appearance of the system were addressed in the next iteration of the design.

In order to fully address the safety issues found in the prototype design, each component inside the electronics enclosure was evaluated. As noted previously, the generator was relocated on the base of the trailer and is now housed in a separate enclosure solving the problem of potentially spilling gasoline on the electronics and excessive heat build up. Next, the safety and isolation of the batteries was addressed by placing them inside rugged battery holders. These holders protect the battery terminals and eliminate the possibility of accidentally shorting the terminals while the cover is secured. Preventing the user from being exposed to live AC lines was a priority when selecting the replacement AC junction box. The replacement junction box from Square D has a front panel that only exposes the circuit breaker switches and prevents the user from exposure to the live electrical lines. Figure 4.7 shows the result of these improvements. While functionally the electrical system differs only slightly from the prototype system, it is clear that the next generation system is safer, more organized, and professional in appearance than the first generation system.
4.3: Additional Improvements

In addition to changes made to the instrumentation tree and the main electronics enclosure, a significant number of improvements were made to the remaining MIP system. Using feedback gathered from personnel who used the first generation MIP, a detailed list of suggested improvements was compiled. From this list three areas of concern were identified: usability, durability, and security.

Being able to identify the drawbacks of the first generation MIP as they related to the usability of the system was an important step in the design of the second generation MIP. Usability deals with features the first generation MIP was lacking and difficulties encountered during construction, deployment, and transportation. For example, a major difficulty encountered during fabrication of the prototype MIP had to do with the size of the junction boxes used to pass electrical and communications lines. These boxes required that two connectors be placed on them for each outgoing line and a conduit fitting for the incoming lines. The difficulty in fabrication was due to the size of the junction box. Being only 4”x4”x4” it was extremely difficult for the user to maneuver their hand inside the box in order to make the proper connections. As a result, the size of the junction boxes was increased to 6”x6”x4” and assembly of the boxes was found to be much easier.

Another difficulty encountered during construction of the first generation MIP had to do with the use of metallic conduit to protect the electrical lines on the
MIP. This conduit, commonly used in home electrical applications, consists of varying lengths of ½” galvanized steel conduit that was routed underneath the MIP from the main electronics enclosure to junction box 1. The main problem with this conduit was that it was not rated for outdoor use and could possibly fill with water and cause major electrical problems in the future. In addition to poor weather resistance, the conduit was difficult to install. The conduit had to be repeatedly and accurately bent into shape increasing construction time and material costs due to mistakes. The solution to this problem was simple and straightforward. The second generation MIP makes use of a different type of conduit commonly used in the electrical industry and is specifically designed for outdoor applications. This conduit is referred to as liquid-tight and is made of an outer jacket of flexible plastic and may or may not have a flexible internal metallic skeleton to aid in crush resistance. Because this type of conduit is flexible, the difficulties encountered with bending metallic conduit were completely eliminated. Additionally, this type of conduit is rated for wet environments and is used with watertight fittings which terminate the conduit on the junction boxes. Although, the material cost for liquid-tight conduit is greater than metallic conduit, the benefits in weather resistance and installation time far outweighed the additional cost.

Originally envisioned to be a self-contained unit, the design of the first generation MIP did not meet this goal. For example, on the first generation MIP the instrumentation tree had to be removed for transportation and placed in a separate cargo vehicle. A self-contained system in which the MIP would provide for the transportation and storage of all the equipment necessary for operation had to be developed. As described earlier, the new instrumentation tree consists of a central hub with socket joints to accept the instrumentation arms and the two are secured together with a toggle clamp. Due to this new configuration, the central hub can remain fixed to the tower during transportation and will not interfere with tow vehicles because the overall width when the arms are removed is much less than the width of the first generation tree, as seen previously in Figure 4.1. To accommodate the storage of the individual instrumentation arms an adjustable socket assembly was created and fixed to the base of the MIP. Shown in Figure 4.8, this system will store up to three arms and can be adjusted longitudinally by loosening four nuts and sliding the H-shaped base in order to accommodate arms with large equipment. Two of these racks are used on the base of the second generation MIP in order to hold all
the instrumentation arms. From experience, this system has proven to be reliable and has alleviated the transportation headaches associated with the first generation MIP.

Lastly, the use of the first generation MIP also identified some features that could be added to increase the ease of operations. One such feature added to the second generation MIP was two 5-gallon gas tank holders. Previously, the fuel for the onboard generator was transported in a separate vehicle and simply left standing next to the MIP during experiments. The addition of the gas tank holders, highlighted in Figure 4.9, provided a safer and more appealing solution. Another feature that was added was integrated winch power. The first generation MIP required the use of a separate portable power supply that connected to the winch in order to provide the power to raise the MIP to its maximum height. Although this solution was simple and effective, it was considered another piece of equipment that could easily be lost or broken. As a result, the second generation MIP eliminated this piece of equipment and electrical power for the winch was supplied from the onboard electrical system. This improvement, shown in Figure 4.10, serves to provide a more integrated and reliable solution and has eliminated the need for additional equipment. Finally, a critical feature the first generation MIP lacked was provisions for security. With the amount of costly equipment onboard the MIP it was important that the system be secure. The simple solution was to place locks on the main electronics enclosure, the generator enclosure, and to provide a long cable with a lock to secure
the instrumentation arms while they are being transported. The addition of all these features has improved the overall functionality of the MIP and addressed each of the concerns identified in the first generation MIP in order to provide a well designed and easy to operate system.

Figure 4.9: Two 5-gallon gas tank holders (red) installed on the next generation MIP

Figure 4.10: Separate winch power supply (a) used on prototype MIP and replacement integrated power solution (b) on next generation MIP
4.4: Electrical System Overview

While the some aspects of the electrical system have been previously discussed, the system as a whole has not been treated. This section will present the improvements and differences between the electrical systems on the first generation MIP and the second generation MIP while a detailed description of each segment of the design will be provided later. These differences will encompass changes in the function of the electrical system, component upgrades, and system design.

Initially, the first generation MIP sought to provide a one-size-fits-all solution when providing power for the instrumentation. The instrumentation was selected, its power requirements noted, and the electrical system was designed accordingly. Although this system functioned properly it did not leave much room for future additions of instrumentation or components. In order to remedy this design flaw, a new system was created. At its core, the system consists of a similar hybrid power system as in the first generation MIP. An onboard generator supplies power to a battery charger which continuously charges the onboard batteries of the MIP. These batteries in turn provide the DC power for the entire system. The system implemented on the second generation MIP does not provide power conditioning, but rather supplies each instrumentation arm with unregulated 24 VDC. It is then the responsibility of the instrumentation arm to transform and condition the incoming power to the proper levels. This design was chosen to eliminate hard to find and costly DC-DC converters and place the responsibility of power conditioning on each individual arm. This way each arm can be specifically designed to fit into the MIP framework rather than the MIP conforming to instrumentation specifications. The end result is a more modular system.

Improvements over the first generation system were made to increase performance and runtime of the system. The major difference in the main power system is the use of higher capacity batteries. The batteries on both systems are lead acid absorbed glass mat batteries. This type of battery is considered a “dry cell” battery as there is no free flowing acid inside the battery to leak out, thus preventing acid spills if the battery were to rupture. The first generation MIP contained four 12 VDC batteries with two pairs connected in series to obtain 24 VDC and then connected in parallel with the other pair to increase the capacity of the system. This configuration provided a total capacity of 32 Ah. Although effective, this system
was difficult to visualize and challenging to install. As a result, the next generation MIP used two Hawker Odyssey PC 1700 12 VDC batteries connected in series to give an output voltage of 24 VDC and a total capacity of 65 Ah. Increasing the capacity of the batteries provides a much longer run time if operating in silent mode (generator off) or if the generator were to shut off for a period of time, as in the case of neglecting to refill its fuel tank. A system voltage of 24VDC was chosen as a standard power supply due to the requests of users and the wide availability of power converters which accept 24VDC as a standard input.

From the battery bank, power is then fused and routed to the secondary electronics enclosure located on the instrumentation tree and to the onboard winch used for raising the MIP to heights above 25 feet. The electrical lines carrying the power to the instrumentation tree and winch are 10 AWG construction-grade three-conductor power wire commonly used in home construction. This was an upgrade from the prototype MIP which used a similar three-conductor 14 AWG cable. According to an online calculator, a 10 AWG wire is capable of carrying up to 32 Amps of current which is consistent with the maximum current rating of the connectors used in the system [15]. In contrast, a 14 AWG cable has a maximum current rating of 16 Amps. The upgrade to a 10 AWG wire was a simple decision as it would provide the system with increased electrical capacity with minimal changes to the design. From the batteries, two 30 Amp in-line Maxi-blade automotive style fuses are installed to protect the cable and connectors from possible over-current damage. One fuse is used to protect the winch circuit while the other fuse protects the instrumentation circuit.

Following the main power cable through the junction boxes and up the tower to the secondary electronics enclosure, power enters the enclosure and is split to one of eight power ports for the instrumentation arms and individually fused to protect the equipment. This is accomplished using a Cooper Bussmann Rear Terminal Mini Fuse & Relay (RTMR) power distribution module commonly used in automotive applications and shown in Figure 4.11.
This module consists of three slots for automotive style relays (no relays are used) and 10 slots for Mini-ATO automotive style blade fuses that are used for each instrumentation arm. Rated at 80 Amps the RTMR module is more than capable of distributing the power to each instrumentation arm. A 14 AWG power wire, used to provide power for the instrumentation arms, is fused at 3 Amps with the option to increase the rating of the fuse to a maximum of 10 Amps which is the current rating of the connector. However, care must be taken to not exceed a 30 Amp total draw or the main power fuse will blow. From the power distribution module, power and communications lines are routed to panel-mount connectors with a protection rating of at least IP-65. This protection rating is stated to be completely protected from dust and also provides protection from low pressure jets of water from all directions. This was required for all connectors used in the system as the MIP will need to operate and be stored in adverse conditions including high wind and heavy rain.

Moving from the secondary electronics enclosure, power is then carried from the enclosure to a user-constructed power conditioning and computing box located on each instrumentation arm. This user-constructed box houses all the equipment necessary to provide power for the instrumentation located on a single arm. By having the user provide the power conditioning and computing equipment for their instrumentation the need to provide a “one size fits all” solution onboard the MIP was alleviated. Figure 4.12 shows the secondary electronics enclosure with three arms installed on the instrumentation tree.
The components of the electrical system were selected to provide increased safety and better performance. Another major change to the electrical system was the connectors used to distribute power. Originally, MIL-spec connectors were used due to their ruggedness and weather resistance. However, the connectors selected for the first generation MIP proved to be problematic. These connectors were expensive and complex to put together requiring seven pieces in order to assemble one side of a connector. In contrast, the new connectors which provide equivalent weather resistance at a much lower per-connector cost only have a total of 4 pieces necessary for construction. Bulgin 900 series connectors are used for the main power connectors, Bulgin Standard Series connectors are used for the instrumentation arm power connectors, and all communications connectors are Amphenol RJ Field industrial ethernet connectors. During construction and use each of these connectors proved to be reliable, easy to assemble, and easy to use. The main power connectors used on each MIP system can be seen in Figure 4.13 for comparison.
As with any product it was important to properly document the design of the electrical system and follow the design closely during construction. This was accomplished using Microsoft Visio 2003 for the electrical schematics as this provided the ability to easily color code and label wires and components in the second generation MIP system. A sample of the schematic for the main electronics enclosure is shown in Figure 4.14 and the complete set can be seen in Appendix A. The labels associated with each wire in the schematic drawing were reproduced with heat-shrink tubing on the finished system and shown in Figure 4.15.

Figure 4.13: Main power connector on the first generation MIP (a) and equivalent connector on the second generation MIP (b)
Figure 4.14: Electrical schematic for the main electronics enclosure
Figure 4.15: Example of heat-shrink wire labels on all electrical and communications wires

The heat-shrink labels directly correspond to the wires shown in the electrical schematic to aid in construction, maintenance, and understanding of the system. Additionally, a separate document was created to further define the role of each wire in the system. Created in Excel, this system details the wire name, what the wire is used for, where the wire connects from, where it terminates, and the wire gage. A sample is shown in Figure 4.16 and the complete document can be seen in Appendix B. This sheet can be used as a quick reference guide for technicians when repairing or maintaining the system.

<table>
<thead>
<tr>
<th>Wire Label</th>
<th>Description</th>
<th>Connects From</th>
<th>Connects To</th>
<th>AWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP-24V</td>
<td>Main Power 24 VDC line</td>
<td>MP Pin L</td>
<td>BUS-MAIN</td>
<td>10</td>
</tr>
<tr>
<td>MP-GND</td>
<td>Main Power Ground line</td>
<td>MP Pin E</td>
<td>Ground Terminal</td>
<td>10</td>
</tr>
<tr>
<td>MP-EXT</td>
<td>Extra main power line</td>
<td>MP Pin N</td>
<td>nothing</td>
<td>10</td>
</tr>
</tbody>
</table>

Overall, the second generation electrical system is far better than the first generation system. The design is fully documented, easy to understand and troubleshoot, and modular. Additionally, the “one size fits all” solution of the first generation system was found to be impractical and has been completely replaced by the modular system of the second generation MIP. This design will provide the end user with the flexibility to implement any type of instrumentation system they desire.
4.5: Electrical System Detailed Design

The previous section provided the reader with an overview of the entire electrical system with the detail necessary for basic understanding of the system. This section will provide the reader with the full details of the system, its implementation, and the components used.

First, it is necessary to discuss the electronics located in the main electronics enclosure as this is where the power is generated and distributed to the entire system. The heart of the system is the hybrid power generation system. This consists of a generator, battery charger, and batteries. These are coupled together to provide power for the entire MIP system. The generator, shown in Figure 4.17, is a Honda EU 2000i portable generator with a maximum AC output of 2000 Watts and a rated output of 1600 Watts. The rated output is what will be used when designing and calculating the performance of the system. With an integrated gas tank with a capacity of 1.1 gallons, the generator will run for 4 hours at its rated output and 15 hours at \( \frac{1}{4} \) the rated output.

![Honda EU 2000i generator](image)

**Figure 4.16:** Honda EU 2000i generator used on the MIP

From the generator AC power is routed to the main electronics enclosure and distributed to the battery charger, work lights, optional flood lights, and accessory outlet using a Square D AC distribution panel. This panel, shown in Figure 4.18, has up to six breaker slots, of which the MIP makes use of four. Each breaker is a ground fault interrupt (GFI) breaker rated at 20 Amps. While the GFI option adds cost to the system, the safety benefits of using a GFI breaker far outweigh the added cost because the system will detect a short and automatically trip the breaker. The
flood light circuit and work light circuit are switched on through individual toggle switches located on the exterior of the main electronics enclosure while the accessory outlet circuit is always “on” so long as its breaker is not in the “off” position.

Figure 4.17: AC distribution box used on the MIP

AC power from the distribution panel is then routed directly to a Dual Pro Pro Series battery charger shown in Figure 4.19. Capable of providing a maximum of 15 Amps of charging current to each battery bank the charger’s function is to keep the onboard batteries at peak capacity. Typically used in marine environments, the charger is completely waterproof and temperature compensated to assure a full charger under all atmospheric conditions; a key requirement for the MIP system.

Figure 4.18: Dual Pro Pro series battery charger

Two cables from the Dual Pro charger carry the power to the batteries. As described previously, the batteries are Hawker Odyssey 12 VDC batteries with a capacity of 65
Amp-hours each. By using two batteries connected in series, a final system voltage of 24 VDC is achieved. Additionally, the charger is a dual bank system which means it can charge two banks of batteries individually. Therefore, in the MIP system each battery is charged independently to insure peak capacity and nominal system voltage.

Next, power is taken from the batteries and routed to two automotive style relays. These relays are Tyco Electronics VF4-15F11-S05, used to switch 12 VDC for the winch circuit, and VF4-15H-S05, used to switch 24 VDC for the main power circuit. Each relay is rated switch up to 60 Amps at its normally open contact and contains a 12 VDC coil which is used to activate the relay. Controlling the two relays are the main power switch and the winch power switch. The winch power switch is wired such that the main power switch must be “on” in order for the winch switch to receive power and be capable of activating the winch relay. This was done to prevent the winch from being left on inadvertently and draining power from the electrical system. While the winch power switch, flood light switch, and work light switch are standard toggle switches, the main power switch is a keyed toggle switch. It also has the unique feature of the key having to remain in the switch during operation. This feature was selected to give the user a visual indication that the system is turned “on” as opposed to indicators such as LEDs that would be difficult to see in direct sunlight. The current ratings of the switch are minimal due to the fact that the main power switch and winch switch are only activating the coil on the relay and not switching the high currents that the main power and winch circuits would draw.

As described previously, the main power line passes through the relay and then fed into an automotive style fuse rated at 30 Amps. The fuse used was a standard Maxi Blade fuse held securely in place by a Bluesea Maxi Blade fuse holder. This configuration can be seen in Figure 4.20 which includes the main power and winch relays and corresponding fuses.
After the fuse, power is then routed to the main power cable. This cable is then passed through liquid tight conduit to the first junction box located on the base of the MIP. Here the line is terminated in a panel mount connector that mates with the cable assembly that connects the junction box 1 to junction box 2 located on the base of the tower assembly. The main power and communications cable are contained in corrugated liquid tight conduit that provides superior flexibility and permits the cable to be stored on the cable reel located on the base of the MIP. The cable reel and junction box 1 can be seen in Figure 4.21.
From junction box 2 the main power cable continues up to the secondary electronics enclosure in corrugated liquid tight conduit. The cable assembly terminates in junction box 3 where a separate cable assembly is needed to bridge the gap between junction box 3 and the secondary electronics enclosure. Although the addition of this small cable assembly adds to the number of parts in the system, and thus its complexity, it was necessary in order to facilitate the easy removal of the instrumentation tree and secondary electronics enclosure for maintenance. Once installed, this small cable assembly will mate to the secondary electronics enclosure completing the power connections from the main electronics enclosure up to the secondary electronics enclosure.

Inside the secondary electronics enclosure power is distributed to individual power connections for each instrumentation arm. As described previously this is accomplished using a Cooper Bussmann RTMR power distribution module. This module also distributes power to DC-DC power converter used to power the two network switches. A V-Infinity VDZ400-D24-S12 encapsulated DC to DC converter is used to step down 24 VDC to 12 VDC which can be used by the network switches. From the output of the DC-DC power is connected to a generic automotive style 4-circuit fuse center which uses standard ATO blade style fuses. Here, power is distributed, fused at 3 Amps, and sent to the network switches. The switches are two Netgear FS108 models which have a maximum current draw of 1.2 Amps each. This is consistent with the rated output of the DC-DC converter which has a rated output of 16.7 Amps, which is more than capable of providing the required power and any additional 12VDC lines which may be added at a later date. The inside of the secondary electronics enclosure can be seen in Figure 4.22.
Inside the secondary electronics enclosure the power and communications connections terminate in separate panel mount connectors. From these connectors power and communications lines are distributed to the individual instrumentation arms. A full schematic of the secondary electronics enclosure can be seen in Figure 4.23 and Appendix A. In designing the electrical system it was important to avoid “hot male” connectors. What this means is that none of the male connectors (which have protruding pins) could be connected to live power. This is a safety feature which prevents accidental shorting of the electrical connector with a tool or simply by dropping it across a conducting object. Therefore all live power connectors used on the MIP are female in gender, meaning that they have no protruding pins but rather receptacles for accepting the male pins. An overall connector diagram, shown in Figure 4.24 was helpful in determining the connector gender and creating a master parts list of connectors.
Figure 4.22: Electrical schematic of the secondary electronics enclosure
Figure 4.23: Connector schematic for the MIP system
Looking at the connector schematic diagram, green colored rectangles are ethernet connectors and hardware and red and black colored rectangles are power connectors and hardware. For clarity, red color rectangles are considered “hot” meaning that when power is turned on these connection points are live. Therefore a red rectangle corresponds to a female connection while a black rectangle corresponds to a male connection. Similarly, a light green rectangle corresponds to a female connector while a dark green rectangle corresponds to a male connector. Lighter shades of red, black, and green correspond to the dust caps for the connector that they are adjacent to. For additional clarity and replacement part purchases the manufacturer’s part number is included in each colored rectangle. This document proved to be invaluable during the design phase of the project as the number and gender of each connector could be established without mistake long before construction of the system began.

The entire electrical system of the MIP was completely designed before construction using knowledge gained from the first generation MIP’s drawbacks and limitations. The resulting system has been created to be modular, easy to maintain, simple to construct, and fully documented to aid in future manufacturing and repair efforts.

**4.6: Network Architecture**

One of the most critical functions of the MIP system is to provide wireless coverage to an experimentation site. In order to accomplish this goal the MIP must be capable of supporting the proper network equipment used to provide wireless coverage for a given area. The equipment used on the MIP consists of two separate units for providing wireless coverage and transmitting collected data back to a central command center as illustrated in Figure 4.25. Providing the wireless coverage is a Cisco Aironet 1300 series outdoor access point. This unit broadcasts in the 2.412 to 2.462 GHz range which is common for IEEE 802.11b (802.11b) systems and is capable of supporting IEEE 802.11b and IEEE 802.11g (802.11g) standards. For clarification, 802.11b and 802.11g operate in the same frequency range but differ in the type of modulation used to transmit the signals and supported data rates. 802.11b is capable of data rates up to 11 Mbps and 802.11g is capable of rates up to 54 Mbps.
Based on the supported standard on the client side, the Cisco equipment will automatically adjust the signal modulation to accommodate the use of 802.11b and 802.11g signals within the same network. Additionally, the Cisco equipment will automatically handle error checking and data retransmission if necessary.

Another Cisco unit, an Aironet 1400 wireless bridge, manages the transmissions to and from the central command center. Operating in the 802.11a frequency range corresponding to 5.725 to 5.825 GHz this unit was chosen because it would not interfere with the 802.11b/g signals. The data transmission rates are equivalent to the 802.11g rates of up to 54Mbps. Used together these two components provide the wireless coverage capability to the experimentation site.

![Figure 4.24: Representation of overall MIP network structure](image)

In order to begin the selection of additional components, such as antennas and client equipment, it is first necessary to discuss how the Cisco equipment will initially be configured. To construct a simple network between the MIP, a client, and the command center a “flat” network architecture was implemented. In this type of network every component is on the same subnet. This configuration requires no external routing as each component on the network has its own unique IP address and is individually addressable by every other component on the network. A flat network can be thought of as a neighborhood where each person in the neighborhood can talk to each other. Continuing with this analogy, if a person in the neighborhood wished to send a letter to a person in another neighborhood (or subnet) the person would
have to go through the post office, who would have to route the letter to the proper location. Due to the complexities associated with routing, the MIP networking equipment was configured to be a “flat” network. For additional clarification the MIP does not use a Dynamic Host Configuration Protocol (DHCP), which automatically assigns IP addresses. Alternatively, each client is individually assigned a unique IP address which identifies it on the network and allows other clients on the network to communicate with it. Cisco equipment allows the user to easily configure this type of network architecture while providing options for more complex architectures if necessary.

An important consideration when selecting the networking components was the antennas that would be used to provide the wireless signal to the site. Ideally, the antennas should have a high gain to provide long range capability and be omnidirectional to provide an uninterrupted coverage zone around the site. The antenna used on the client, or mobile robot, is also an important consideration because that antenna will have its own radiation characteristics which need to be accounted for. However, the primary concern is selecting the proper antenna for the networking equipment on the MIP in order to permit the client to use almost any antenna available. With these considerations in mind, the antennas selected for the Aironet 1300 802.11b/g access point is a Cisco AIR-ANT24120 12 dBi omnidirectional antenna. The vertical and horizontal radiation patterns can be seen in Figure 4.26.
Examining Figure 4.26 will show that the horizontal radiation pattern is clearly omnidirectional, meaning that the coverage will be 360° around the antenna. The vertical radiation pattern however is not omnidirectional but is focused in certain directions to achieve a high antenna gain. From this pattern, it can be determined that the strongest signal the antenna will transmit/receive will be along the vertical plane corresponding to angles of 0° and 180°. The -3dB beam width in the vertical plane is 7° and 360° in the horizontal plane as specified in the antenna data sheets and confirmed by examining the plots. To help visualize this specification, Figure 4.27 illustrates the vertical beam width of the 12 dBi antenna used on the MIP. Assuming an equal distribution of the 7° beam width about the centerline of the vertical plane (the line from 0° to 180°) the resulting radiation angled towards the ground would be at a 3.5° angle. This corresponds to the antenna radiating half its power at approximately 408 feet away from the base of the MIP. Figure 4.28 clarifies this result. This is important to note because the radiated power

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Figure 4.25: Cisco AIR-ANT24120 vertical (a) and horizontal (b) radiation patterns (www.cisco.com)

The interpretation of the vertical radiation plot can be visualized as looking onto the side of the antenna while the horizontal radiation plot can be visualized as looking onto the top of the antenna. Along the abscissa of each graph is a scale in -dB which indicates a reduction in radiated power. For example, at -10dB there is approximately a 10X reduction in radiated power. One important piece of information gathered from the plots is the -3dB beam width, a common specification given with antennas, which describes the width of the radiated beam at half the maximum antenna power. Examining Figure 4.26 will show that the horizontal radiation pattern is clearly omnidirectional, meaning that the coverage will be 360° around the antenna. The vertical radiation pattern however is not omnidirectional but is focused in certain directions to achieve a high antenna gain. From this pattern, it can be determined that the strongest signal the antenna will transmit/receive will be along the vertical plane corresponding to angles of 0° and 180°. The -3dB beam width in the vertical plane is 7° and 360° in the horizontal plane as specified in the antenna data sheets and confirmed by examining the plots. To help visualize this specification, Figure 4.27 illustrates the vertical beam width of the 12 dBi antenna used on the MIP. Assuming an equal distribution of the 7° beam width about the centerline of the vertical plane (the line from 0° to 180°) the resulting radiation angled towards the ground would be at a 3.5° angle. This corresponds to the antenna radiating half its power at approximately 408 feet away from the base of the MIP. Figure 4.28 clarifies this result. This is important to note because the radiated power
drops off significantly at angles below 177° which will be closer to the MIP. This could result in possible dead zones in coverage in areas within 408 feet of the MIP.

**Figure 4.26:** Representation of the beam width of the Cisco AIR-ANT24120 12 dBi antenna in relation to the MIP

The range of the 12 dBi antenna is also an important specification. Using a range calculator available from Cisco Systems, Inc the outdoor range could be estimated [17]. This calculator assumes line-of-sight between the host and client antennas, no losses due to cables and connectors, the use of Cisco equipment on the host and client, and takes into account FCC regulations on power output with respect to antenna gain. The results are intended for theoretical estimations only. Real world ranges will vary and can be expected to be less than the theoretical values.
Entering the equipment specifications used on the MIP, an Aironet 1300 access point with an AIR-ANT2410 12 dBi omnidirectional antenna on the host side, and a Cisco PCI card 802.11b adapter with a 5.2 dBi omnidirectional antenna on the client the resulting maximum distance achievable was found to be 3.62 miles with an estimated data rate of 11 Mbps. Calculating the maximum distance achievable with a data rate of 11 Mbps and using an antenna gain of 3 dBi, the resulting distance is reduced to 0.89 miles. This range is important to remember because it was calculated using the same antenna gain which will be used when testing wireless performance in a later chapter. Additionally, it is important to remember that this is the line-of-sight range assuming that the two antennas are on the same plane which is not normally the case with the MIP erected and providing coverage to a testing site. Therefore, the real world distance will be less than this ideal value.

Although the 12 dBi antenna will provide coverage over a long range the close range coverage can be improved. This is possible due to a feature of the Cisco access point being able to support the use of two antennas. As a result a Cisco AIR-ANT3351 2 dBi dipole antenna was added to the second antenna input of the Cisco access point. The corresponding radiation patterns for this antenna are shown in Figure 4.29.

![Figure 4.28: Vertical (a) and horizontal (b) radiation patterns for the Cisco AIR-ANT2251 2 dBi dipole antenna (www.cisco.com)](image)

This antenna has a beam width of 70° which means about 35° of the beam is directed towards the ground. The resulting distance from the MIP to be within half the radiated power of the antenna is 36 feet, as shown in Figure 4.30. It is important to
note that a wireless signal will still be achievable directly under the MIP, however, it will be less than half the radiated power of the antenna. Additionally, for safety reasons a mobile client should not be allowed to enter within 36 feet of the MIP to prevent accidents and maintain good signal quality. The Cisco access point transparently determines which antenna to use to maintain the best signal quality. The use of this second antenna serves to eliminate poor wireless coverage in close proximity to the MIP while the 12 dBi antenna serves to provide long range coverage.

![Combined coverage patterns for the two antennas on the Cisco access point](image)

**Figure 4.29:** Combined coverage patterns for the two antennas on the Cisco access point

The two antennas described previously handle the communications between the MIP and a mobile client and operate in the 802.11 b/g frequencies of 2.412 to 2.426 GHz. In order to communicate from the MIP back to the command center a Cisco 1400 series wireless bridge was chosen due to its ability to operate in the 802.11a frequency range of 5.725 to 5.825 GHz. Operating in the 802.11a frequency range is important because it does not interfere with the 802.11b/g equipment used to communicate to mobile clients. Identical equipment is placed on the command center and the MIP instrumentation tree. A Cisco AIR-ANT58G9VOA-N 9 dBi antenna is used with a radiation pattern as shown in Figure 4.31 and a -3dB beam width of 6°. Using the Cisco range calculator with a Cisco 1400 series bridge on the MIP and command center with the same 9 dBi antenna a theoretical range of 0.57 miles at a data rate of 54 Mbps is achievable. If the data rate is reduced to 12 Mbps the range is increased to 2.56 miles. This range can be increased dramatically by
using directional antennas which would be necessary for MIPs located far away from the command center or if the maximum data rate is absolutely necessary. For example, the use of a Cisco dish antenna with a gain of 28 dBi the range can be theoretically extended to almost 20 miles at a data rate of 54 Mbps. However, to achieve this range significant installation time would be needed to properly align the two dishes.

![Figure 4.30: Cisco AIR-ANT58G9VOA-N antenna vertical (a) and horizontal (b) radiation patterns (www.cisco.com)](image)

Networking is a critical component to the MIP system. It is important to be able to provide long range uninterrupted coverage to a test site while maintaining high data rates. Use of Cisco Systems, Inc equipment has enabled the network to be configured easily while providing the option for more complex network architectures to be used if necessary. Additionally, the variety of antennas available for both the 802.11b/g and 802.11a equipment permits users to customize the site coverage for each experimentation site simply by swapping antennas and properly installing them. The resulting system is highly flexible, configurable, and uses industry proven technology to achieve these results.

**4.7: Predicted Performance**

Having described in detail the entire MIP system and associated components it is important to estimate its performance characteristics. This will include estimates of system run time, environmental capabilities, set up/tear down time, and wireless
performance. During the design process these characteristics were clearly defined in order to guide component selection. The following section will describe the design goals and resulting predicted performance based on the selected components.

One of the most important performance characteristics of the MIP is the system run time. During the design process it was determined that the MIP should be capable of running continuously. This has been achieved by the implementation of the hybrid power system which includes an onboard generator. To operate continuously, the gas tank on the generator must simply be kept full. However, in a worst case scenario, where there is no gas to refill the tank, the run time should be estimated in order to know the capabilities of the system. Run time estimation will consider two scenarios. First, the scenario where there is the maximum load on the system will be considered. This case assumes that the generator is running at its rated load and the instrumentation tree is drawing the maximum power through the system. Second, the scenario where the MIP is solely providing the network infrastructure will be considered. This is assuming that the only load on the generator is due to the battery charger and the system is only required to power the networking equipment.

Considering the first scenario it is important to clearly define the inputs and outputs of the AC and DC power system. The complete electrical system is summarized in Figure 4.32. Beginning with the generator, which is capable of a maximum output power of 1600 Watts, the loads on the AC electrical system include the work lights, flood lights (optional), accessory items (optional), and the battery charger. Table 4.1 provides a summary of power requirements of the AC electrical system.
Figure 4.31: Summary of the MIP electrical system

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Lights</td>
<td>300</td>
</tr>
<tr>
<td>Flood Lights (optional)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Accessory Outlet (optional)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Battery Charger</td>
<td>720</td>
</tr>
</tbody>
</table>

| Total Load on System           | 1020          |
| Generator Output               | 1600          |
| Remaining Power                | 580           |

Two unknowns in the system are the optional flood lights and accessory equipment, however for this scenario it can be assumed that the combined power used by these two components will be equivalent to the remaining power of 580 Watts. Next, it is
necessary to define the maximum power draw on the DC electrical system. The DC system is solely responsible for powering the onboard winch, used when raising the tower, and the instrumentation tree. For this scenario the electrical load provided by the winch will not be considered as it is only used during the initial set up of the MIP and not during normal operation. This leaves the electrical load due to the instrumentation. Because the power requirements of the instrumentation placed on the MIP are unknown, the analysis will assume that the system is drawing 80% of the maximum allowable current (30 Amps). Therefore, the system will be drawing 24 Amps at 24 VDC which is equivalent to a power consumption of 576 Watts. Now that both the AC and DC loads on the system have been established the run time estimation can proceed.

Because the maximum power output of the battery charger is greater than the 80% of the maximum load on the DC system, the charger is able to maintain the batteries at their current state of charge during operation. Therefore, with the generator running the batteries will not be depleted by the DC system and, once the generator stops, the batteries will be at peak capacity. The run time of the generator at its rated capacity is 4 hours [18]. At this point, the AC system will shut down and only the DC system will be operational. The batteries have a rated capacity of 65 Ah and run time estimation will consider a depth of discharge of 80%. This means that the capacity of the DC system has a de-rated value of 52 Ah. Using the de-rated capacity, a system voltage of 24 VDC, and a draw of 576 Watts the estimated run time can be calculated using Equation 4.1.

$$\text{Runtime} = \frac{(\text{System Voltage})(\text{Battery Capacity})}{\text{Wattage Draw}}$$

Equation 4.1: Calculating estimated DC system run time

This results in an estimated system run time of 2.2 hours resulting in a total estimated run time slightly over 6 hours.

Next, it is necessary to consider the second scenario where the MIP is only used for its networking equipment. This scenario can be considered the minimum functionality of the MIP. The DC system is only supporting the networking equipment and the AC system is only supporting the battery charger. Run time estimation will proceed in the same manner as the first scenario. First, the load on
the generator will be established and the corresponding run time estimated. Next, the load on the DC system will be presented and the run time estimated. Finally, the two estimations will be combined into a total run time estimation.

When running at its minimum functionality there is only one load on the AC electrical system. This is due to the battery charger which can require up to 720 Watts of power during operation. Typically, this will not be the case as the charger is not drawing full power all the time, but this will be assumed for the estimation. With a maximum power draw on the AC system of 720 watts, which is 45% of the rated load, the generator should run about 11 hours. Although this may seem to be a generous estimate, the generator will most likely be running at nearly a quarter of the rated load. At a quarter of the rated load (400 Watts) the generator has a specified run time of 15 hours [18].

The DC electrical system also has a load on it due to the networking equipment. This consists of the Cisco access point, Cisco Bridge, and two network switches. The total power consumption for these four components is about 96 Watts. While the generator is running the batteries are maintained at their state of charge by the battery charger. Therefore when the generator stops, the AC power system shuts down and only the DC power system is operational. At this point the networking equipment will be powered by the batteries until they are depleted. Using the same procedure discussed previously to determine the run time of the DC system with a system voltage of 24 VDC, de-rated battery capacity of 52 Ah, and a wattage draw of 96 Watts, the system is estimated to run for nearly 13 hours. This results in a total estimated run time of 24 hours when the MIP is running in its minimal configuration.

In addition to the run time estimation of the MIP it is necessary to consider the types of environments the MIP is capable of operating in. The temperature range of the components on the MIP will be presented in order to define a suitable operational temperature range. Next, the weather protection provided by the components on the MIP will be discussed to determine the allowable operational environmental conditions. Finally, the recommended installation procedures for the tower will be discussed.

Table 4.3 details the operational temperature ranges for each of the major components of the MIP system. Looking at the table, the operational temperature range of the MIP system is from 32°F to 104°F. Constraining this temperature range are the two network switches used in the secondary electronics enclosure. These
units are commercial products normally used in household environments. If a greater temperature range were required these two components could easily be replaced by more industrial switches, although at a much greater cost. However, it should be noted that for cold environments these components are inside an enclosure and will generate heat and the actual minimum temperature range could be expected to be much lower. Additionally, if operations in extreme cold were required the MIP enclosures and components could be fitted with insulation and heaters if necessary. In contrast, operations in extreme heat would require more involved modifications in the form of ventilation fans or cooling units. For the majority of environments the MIP is capable of supporting experiments. Only in the most extreme environments would modifications to the MIP be necessary.

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Operational Temperature Range (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cisco Access Point</td>
<td>-22° to 131°</td>
</tr>
<tr>
<td>Cisco Bridge</td>
<td>-22° to 131°</td>
</tr>
<tr>
<td>Network Switches</td>
<td>32° to 104°</td>
</tr>
<tr>
<td>Automotive Relays</td>
<td>-40° to 311°</td>
</tr>
<tr>
<td>Batteries</td>
<td>-40° to 176°</td>
</tr>
<tr>
<td>Generator</td>
<td>-22° to 120°</td>
</tr>
<tr>
<td>Battery Charger</td>
<td>-40° to 176°</td>
</tr>
<tr>
<td>Power converter for network equipment</td>
<td>-13° to 185°</td>
</tr>
</tbody>
</table>

In the initial design phase, the MIP was required to be operational in heavy rain and high winds. Because of this requirement much attention was given to properly protecting the onboard equipment. On the base of the MIP the generator enclosure and main electronics enclosure are constructed of aluminum due to its resistance to corrosion. These two enclosures provide resistance to heavy rains as dictated in the design goals of the MIP. All other components on the MIP including connectors and enclosures have an International Protection (IP) rating of at least 65 (IP-65). This means that the equipment is fully protected from dust and low pressure...
jets of water from all directions. All of the components on the MIP have provided superior protection when the MIP has been repeatedly exposed to the weather common to Blacksburg, Virginia.

In any experimental setting the ability to begin an experiment promptly is important to maximizing useful time running the experiment. As a main design goal, the MIP was required to be installed by two people and operational in less than thirty minutes. This goal would help to maximize useful experiment time and increase the MIP’s value as a portable system. Installation of the MIP is considered to be the procedure to have the MIP operational once it has been placed in its location and removed from the tow vehicle. This assumes that the networking equipment has been preconfigured to meet the needs of the experiment. This is a valid assumption as the network environment for an experiment should be established prior to performing the actual experiment.

To begin the installation the MIP must first be stabilized and leveled on the ground. This involves placing outriggers on four corners of the base trailer and leveling the trailer using the onboard level. Having completed this step, the instrumentation arms can be removed from their holders and secured into the instrumentation tree. Next, the electrical and networking connections between the secondary electronics enclosure and the instrumentation arms need to be established using the included cable segments. Having installed the instrumentation arms, the tower is ready to be erected and the final electrical connection made. Using the manual winch the tower is then raised into its vertical position and secured in place. Next, the electrical connection from junction box 1 to junction box 2 is made and the electrical connections are complete. Finally, the generator is started and the key switch is turned to the “on” position and the MIP is now fully operational. This entire procedure should be completed by two people familiar with the MIP system in less than thirty minutes. For those unfamiliar with the MIP an installation guide is provided which will aid in the installation procedure. Using this guide, shown in Appendix C two inexperienced personnel should be capable of installing the MIP in nearly thirty minutes.

Of lesser importance is the time needed to put the MIP into “storage” and “ready to transport” states. Placing the MIP into a “storage” state, where it can sit overnight and be ready to deploy in the morning, the tower simply needs to be lowered and secured. Once secured, the instrumentation arms and electrical
connections can remain in place and the generator and main power should be turned off. The time needed to accomplish this procedure should be less than ten minutes. In order to place the MIP into a “ready to transport” state, the installation procedure must be reversed and should take approximately thirty minutes. The total set up and tear down time associated with the MIP system is minimal and will prove to be a valuable feature when the MIP is used in the field.

Another main feature of the MIP is its ability to provide wireless coverage to a given testing field. Although a great deal of detail has been presented on this topic in the Network Architecture section, the main points will be reiterated here. The MIP system uses Cisco Systems networking equipment to provide wireless coverage to a test site and communicate recorded data back to a central command center. Providing the wireless coverage in the 802.11b frequency range is a Cisco Aironet 1300 Access point with a 12 dBi omnidirectional antenna and a 2 dBi dipole antenna. These two antennas work in conjunction to provide short and long range wireless coverage. In addition to the access point, a Cisco Systems Aironet 1400 Wireless Bridge is used to communicate to the command center. The bridge uses a single 9 dBi omnidirectional antenna. These two systems provide the backbone for the wireless coverage and it is important to estimate their performance before use in the field.

As discussed previously, the estimated performance of the wireless equipment was accomplished using an online calculator provided by Cisco Systems. Using the calculator to estimate the performance of the 802.11b/g system resulted in a maximum range of 3.62 miles at a data rate of 11 Mbps when using a Cisco Systems client card with a 5.2 dBi omnidirectional antenna. If this range is recalculated using the antenna gain of the equipment to be used during experimentation the wireless range drops to 0.89 miles. Range drops significantly as the data rate increases because the signal to noise ratio must remain high for increased data rates. For example, a data rate of 54 Mbps reduces estimated range to 0.46 miles. This is because the system needs more power to support the higher data rate and as distance increases power is lost. The performance of the 802.11a system was calculated to be 0.57 miles with a data rate of 54 Mbps using identical equipment on the MIP and the command center (9 dBi omnidirectional antennas).

These values for wireless range should only be used as an estimation of performance. Actual range at a test site will vary dramatically as environmental
factors will affect the signal quality. Therefore, it is necessary to test the system in a real environment to gain a better understanding of how well the system will provide coverage for a given area.

4.8: Safety Analysis

Throughout the design of the MIP much attention was given to safety. As described previously, the electrical system and instrumentation tree were redesigned in order to be safer and easier to operate. In addition to improvements to MIP subsystems, it is important to address the safety of the entire MIP. Of primary concern is the ability of the MIP to remain stable in high winds.

The safety analysis of the MIP in high wind conditions will try to characterize the allowable wind speed before the MIP will begin to tip over. The analysis will assume an equivalent flat plate area due to the installed instrumentation, which will contribute a drag force due to wind speed. This force will act at the top of the tower where the instrumentation tree is located. Basic illustrations of the scenarios under analysis are shown in Figure 4.32 and Figure 4.33. Additionally, a brief analysis of the tower structure will be done to determine the maximum allowable wind speed before tower failure.
Figure 4.32: Forces on MIP when viewed from the side

Figure 4.33: Forces on MIP when viewed from the rear
Given these two scenarios, an analysis of the static condition where the moment due to the drag force causes the MIP to just begin to tip over. The resulting drag force that causes the static condition to be satisfied will then be correlated to an estimated wind speed using a flat plate assumption. This is accomplished by applying Equation 4-2 shown below.

\[
F = C_d \left( \frac{\rho V^2}{2} \right) A
\]

**Equation 4-2:** Calculating the drag force due to wind velocity

Where \( F \) is the resulting force, \( C_d \) is the drag coefficient for a flat plate, \( \rho \) is the density of air at standard ambient temperature and pressure, \( V \) is the velocity of the wind, and \( A \) is the frontal surface area of the flat plate [19].

To begin the analysis the location of the center of gravity (CG) of the MIP had to be located and determined. From the factory the MIP weighed 1790 lb and 218 lb of additional equipment was added to the base of the MIP. Additionally, the tower itself and additional components have a maximum allowable combined weight of 245.5 lb. These two components were used to estimate the CG of the MIP to be 118” from the rear outrigger and located along the centerline of the base of the MIP.

Using the resulting CG location and a total weight of 2254 lb an equation for the static equilibrium condition can be written as shown in Equation 4-3.

\[
(F_{\text{wind}})D_1 = (W_{\text{MIP}})D_2
\]

**Equation 4-3:** Moment balance to find the force necessary to satisfy static condition

Where \( F_{\text{wind}} \) is the force to be determined, \( D_1 \) is the moment arm from the outrigger to the center of the flat plate, \( W_{\text{MIP}} \) is the weight of the MIP, and \( D_2 \) is the distance from the CG to the outrigger. After solving for the force of the wind, Equation 4-3 is then used to find the wind speed which produces this force for a given flat plate surface area. Table 4-4 details the results from these calculations.
Table 4-4: Summary of maximum allowable wind speeds for a given surface area

<table>
<thead>
<tr>
<th>MIP Orientation</th>
<th>MIP Height (ft)</th>
<th>Required $F_{\text{wind}}$(lb) to meet static condition</th>
<th>Max Wind Speed (MPH, 7.6 ft$^2$ frontal area)</th>
<th>Equivalent flat plate area (ft$^2$) for 150 MPH wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side</td>
<td>26</td>
<td>852</td>
<td>156</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>434</td>
<td>111</td>
<td>4.2</td>
</tr>
<tr>
<td>Rear</td>
<td>26</td>
<td>455</td>
<td>114</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>232</td>
<td>81</td>
<td>2.2</td>
</tr>
</tbody>
</table>

The orientation of the MIP corresponds to the views shown in Figures 4.32 and 4.33 at a specific MIP height. The force due to the wind was calculated using an equivalent flat plate area calculated from summing the largest dimensions of the equipment currently on the MIP. This includes the secondary electronics enclosure, empty instrumentation arms, networking arms, and the instrumentation tree. This resulted in a maximum frontal surface area of 1095 in$^2$ (7.6 ft$^2$). This area was used in conjunction with the coefficient of drag for a flat plate of 1.9 [19] to calculate the wind speed necessary to produce the required force. Next, the equivalent flat plate area that would survive 150 MPH wind speeds was calculated and shown for comparison.

Looking at the above information, when the MIP is raised to its typical height of 25 feet, the maximum wind speed is 114 MPH before the MIP will begin to tip over. For comparison, if the equivalent frontal surface area of the instrumentation were reduced from 7.6 ft$^2$ to 4.4 ft$^2$ the maximum wind speed is raised to 150 MPH. If the MIP were extended to its maximum height of 50 feet, the allowable wind speed is reduced to 81 MPH given a surface area of 7.6 ft$^2$.

These results will provide users with a good estimate of wind speeds the MIP can survive, care should be taken regardless of wind speed. Performance of the MIP in high winds could be improved by adding additional weight on the base of the trailer, extending the outriggers, limiting the amount of large equipment on the instrumentation tree, or by using the included guy wires.

While the concern that the MIP will tip over is important, it is also necessary to consider the structural integrity of the tower itself. This involves determining the maximum allowable wind load the MIP is capable of withstanding before failure. To
simplify the analysis and provide a conservative estimate of the maximum wind load a few assumptions were made. First, it was assumed that the force of the wind is acting as in Figure 4.34, in order to place all the stress on one member of the triangular truss. Second, the stresses were assumed to be solely axial, as shown in Figure 4.35, and the effects of the truss structure were not evaluated. Finally, the evaluation considered that the tower was fixed to the ground, as shown in Figure 4.36.

Figure 4.34: Cross section of the triangular truss of the MIP tower

Figure 4.35: Free body diagram of MIP truss under wind load (axial forces only)
Figure 4.36: Diagram of MIP truss used for stress analysis

With the tensile force acting axially in one of the outer members of the truss the stress analysis was straightforward. First, from the manufacturer’s specification the tower is constructed of two types of aluminum, 6063T832 and 6061T6, with a yield strength of 39000 and 40000 psi respectively. Each of these materials will be evaluated separately and the results tabulated.

To begin the analysis it was first necessary to determine the cross sectional area of the outer member of the truss. For this analysis the cross sectional area will be the area of the outer member of the truss which is 0.54 in². Using Equation 4-4, the maximum tensile force can be calculated.

\[
\sigma = \frac{F}{A}
\]

**Equation 4-4:** Calculating maximum tensile stress in MIP tower

Where F is the axial force being applied, A is the cross sectional area, and \(\sigma\) is the yield strength of the material. Using the yield strength figures from the manufacturer, this corresponds to maximum tensile force of 21,060 and 21,600 psi for 6063T832 and 6061T6 respectively.
These values were then used with the free body diagram shown previously in Figure 4.35 to determine the maximum allowable force due to the wind using Equation 4-5.

\[
(F_w)(D_1) = (F_T)(D_T)
\]

**Equation 4-5:** Moment balance for stress analysis of MIP tower

Where \( F_w \) is the force of the wind, \( D_1 \) is the moment arm from the top of the tower to the base, \( F_T \) is the calculated maximum allowable tensile force, and \( D_T \) is the perpendicular distance from the truss to the summation point. This distance was different for the individual material under analysis. That is because the inner triangle of the tower is constructed of 6063T832 aluminum while the outer triangle of the tower is constructed of 6061T6 aluminum. Table X.X summarizes the results for the maximum allowable wind force.

<table>
<thead>
<tr>
<th>MIP Material and yield stress (psi)</th>
<th>MIP Height ((D_1, \text{feet}))</th>
<th>Maximum allowable wind force (lb)</th>
<th>Maximum allowable wind speed (MPH) for current area (7.6 ft(^2))</th>
<th>Equivalent flat plate area (ft(^2)) to produce force, (F_w) at 150 MPH</th>
<th>Equivalent flat plate area (ft(^2)) to produce force, (F_w) at 100 MPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>6063T632/39,000</td>
<td>25</td>
<td>882</td>
<td>158</td>
<td>8.5</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>441</td>
<td>112</td>
<td>4.2</td>
<td>9.5</td>
</tr>
<tr>
<td>6061T6/40,000</td>
<td>25</td>
<td>1216</td>
<td>186</td>
<td>11.7</td>
<td>26.25</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>608</td>
<td>131</td>
<td>5.8</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Looking at the results from the stress and stability analysis, it is clear that the MIP will tip over before it fails. In each case the force necessary to tip the MIP over is less than the force necessary to cause failure in the tower structure. Therefore, it is important to note the surface area of the equipment placed on the instrumentation tree as well as the wind speed during testing.
Chapter 5: Experimental Results

Characterization of the performance of the MIP through experimental results will serve to provide users with real world performance data. This data will become helpful when designing experiments that involve the MIP as its capabilities will be known beforehand. The previous section provided predicted performance specifications for system run time, environmental constraints, installation/tear down time, and wireless coverage. While each of these factors is important to test, some metrics such as the maximum allowable wind speed before failure are impractical to test because it will harm the MIP. This section will focus briefly on the environmental constraints, system run time, and installation/tear down time. The majority of the information presented in this section will discuss the wireless performance of the MIP.

System run time is an important metric as it will dictate how long the MIP is capable of performing and under what loads. This metric will consider two scenarios: a maximum and minimum load on the system. At this point it is only possible to perform an experiment which considers the minimum load on the system. This is due to the lack of additional instrumentation to place on the MIP in order to stress the electrical system. Therefore, only the minimum load on the system will be tested. This considers the MIP to be supporting only the networking equipment necessary for communications and the battery charger. Because the estimated run time of the MIP while operating at a minimum load is 24 hours, an automated procedure for testing the run time was necessary. This system consisted of two computers connected via an ethernet connection to the MIP. One computer was configured to send out a message over UDP (a common networking protocol) which includes a time stamp to the second computer which reads the message and logs the time the message was sent and when it was received. When the MIP loses power these messages will not reach the second computer and the log file will indicate when the last message was received. It is then a simple task to determine when the system started sending messages and when it stopped receiving message which corresponds to the total system run time. Upon completion of this test, the MIP was capable of supporting the wireless equipment for 23 hours. At this point the test was halted to prevent any possible damage to the batteries. The batteries had voltage levels of 11.73 and 11.43 VDC when the test was stopped. These voltage levels were still
within the manufacturer discharge limit of 10.02 VDC, therefore it is safe to assume that the system could have continued to run for some time. However, at this point the MIP had proven its ability to support the wireless equipment for an extended period of time and further testing was unnecessary.

Next, the environmental conditions the MIP is capable of operating in will be discussed. Failure testing of the MIP system was not conducted as it would ruin the onboard equipment or the entire tower itself. Therefore, the experimental results will focus on only the environments the MIP has successfully survived. These conditions are mainly those of Blacksburg, Virginia. While stored in Blacksburg, the MIP has experienced heavy rains, snow, and high heat. Each of these environmental conditions has proven to be no problem for the MIP as it has remained operational without any apparent damage. When considering the maximum sustainable wind speed for having the tower erected, the specification from Aluma Tower should be respected. An Aluma Tower engineer recommended maximum allowable wind speed of 40 MPH at a height of 25 feet and 30 MPH at a height of 50 feet. In the case that the MIP should be required to exceed these specifications for wind speed, the included guy wires should be installed according to the installation instructions included with the tower. Aluma Tower also recommends that the instrumentation tree and corresponding components do not exceed 200 pounds. This restriction stems from the manual winch used to erect the tower which is rated at 1000 lb. Currently, the instrumentation tree and two instrumentation arms (access point and bridge) have a combined weight of 92 lb. Therefore, any additional instrumentation should not exceed 108 lb in total weight.

Set up and tear down time is another important metric of the MIP. This will provide users with an estimation of how quickly an experiment can be started and finished. Installation of the MIP system will consider only the time taken to remove the MIP from a tow vehicle until the MIP is fully operational. This does not include the time necessary for the networking equipment to be configured properly as this will vary between experiments. Going back to the original requirement set forth by management, the MIP should be capable of being deployed in less than 30 minutes. Given an experienced user, the MIP is deployable in less than 20 minutes. This result has been tested numerous times and each time the goal of 30 minutes has been beaten. Inexperienced users tasked with deploying the MIP have turned in times closer to the 30 minute goal. Tear down time is the reverse of the installation
procedure. From experience, the time taken to complete this step is roughly the same as the installation procedure. The total time for installation and tear down is minimal considering the time necessary to perform possible experiments. Potential users of the MIP system should be thrilled with the ease of installation and removal from a testing site.

The most important metric for the MIP system is the wireless coverage it provides to a test site. The following section will discuss the results of experiments involving the site coverage for the 802.11b/g Access Point. Testing of the 802.11a wireless bridge coverage could not be conducted as the proper equipment was unavailable. However, the results for the 802.11a system should be comparable to the 802.11b/g system.

5.1: Wireless 802.11b/g Performance

Performance of the 802.11b/g system will be evaluated using Ekahau Site Survey (Ekahau) software. This software package enables users to merge wireless signal data collected from a wireless client card with aerial images of a test site. Figure 5.1 shows an example of a completed site survey. Details of this specific site survey will be discussed later, however, it is important to note that the black and white line track the GPS position of the vehicle, the push pins on the image are GPS reference points taken before the survey, and the colors (specific to this image) represent signal strength measured from the wireless client.
While the Ekahau software provides excellent visualizations of the coverage provided by the wireless equipment, the values reported are only estimations. The mechanism used for measuring the signal strength at the wireless card is the Received Signal Strength Indicator (RSSI) common to most wireless equipment. This indicator is automatically calculated by the wireless card and reported to the software. Implementation of this indicator is optional and is defined in the 802.11 specification to be:

*The receive signal strength indicator (RSSI) is an optional parameter that has a value of 0 through RSSI Max. This parameter is a measure by the PHY sublayer of the energy observed at the antenna used to receive the current PPDU. RSSI shall be measured between the beginning of the start frame delimiter (SFD) and the end of the PLCP header error check (HEC). RSSI is intended to be used in a relative manner. Absolute accuracy of the RSSI reading is not specified [20].*

After reading this specification it is important to note that implementation of this indicator is optional and that the absolute accuracy of the measurement is not
specified. Because manufacturers implement RSSI in different ways, the Ekahau software normalizes the recorded data to the RSSI scale used by Cisco Systems 305 series client adapters. This allows different client card RSSI values to be converted to an equivalent scale from -100 dBm to 0 dBm for visualization purposes. The normalized RSSI value is used in the Ekahau software for the signal strength visualization and the data rate estimation, both of which will be discussed in detail in the following pages.

Signal strength is an important factor in estimating data throughput and determining if the client card can actually read a signal. A contributing factor to signal strength is the receive sensitivity of the client card. For example, a card with a receive sensitivity of -93 dBm will require roughly half the signal strength of a card with a receive sensitivity of -90 dBm due to the increased sensitivity. The client card used for the wireless coverage experiments was a Proxim Orinoco 11b/g Gold PC card adapter with an optional external antenna. Table 5.1 details the receive sensitivity of the client card for various data rates. It is easy to see that with lower receiver sensitivity the data rate also decreases. This is due to the fact that increasing amounts of power are needed to support higher data rates [21].

Orthogonal frequency-division multiplexing (OFDM) and Complementary code keying (CCK) are two types of signal modulation. Typically, CCK is used for lower data rates up to 11 Mbps while OFDM is used for data rates up to 54 Mbps. Knowledge of the signal modulation is not necessary for the understanding of the results provided by the Ekahau software but it is important to note that the wireless equipment automatically handles the transition from one data rate and modulation scheme to the next based on the RSSI value. Therefore, given the RSSI value for a particular reading the data rate can be estimated. This result is the basis for the Ekahau software visualization of signal strength and data rates.
Table 5-1: Receiver sensitivity and corresponding data rates [22]

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Wireless site surveys were conducted at Kentland Farms located near Blacksburg, Virginia. This location provided the land necessary to conduct two types of surveys in an ideal setting with little interference. The first survey was to characterize the wireless coverage over a variety of terrain (referred to as test 1). The second survey was conducted to characterize the wireless coverage over a long range with few obstructions and limited variations in terrain (referred to as test 2). Analyzing these two results will provide the users with a good picture of how the MIP performs over a wide range of terrain and conditions. Figure 5.2 and 5.3 show the test sites and location of the MIP for test 1 and test 2 respectively. The area for test 1 spans about 0.5 miles from the location of the MIP while the area for test 2 spans about 1 mile from the location of the MIP.
Figure 5.2: Test site for the wireless coverage experiment (test 1) and location of the MIP (red "X")

Figure 5.3: Test site for the wireless range experiment (test 2) and location of the MIP (red "X")
Once the location for the test sites had been determined the wireless equipment was selected. As described previously, the equipment on the MIP consists of a Cisco Aironet 1300 access point with a 12 dBi omnidirectional antenna and a 2 dBi dipole antenna. On the client side, a Proxim Orinoco 11b/g Gold PC card was used with a 3 dBi omnidirectional external antenna mounted to a moving vehicle. Radiation patterns for the 12 dBi and 2 dBi antennas have been previously presented and Figure 5.4 shows the radiation patterns for the 3 dBi antenna. One interesting feature of the vertical radiation pattern is the sharp cut off along the centerline of the image. This is due to the antenna being constructed to support a magnetic mount for placement on a vehicle or other magnetic surface. Figure 5.6 shows the antenna mounted on the vehicle used during the tests.

Figure 5.4: Radiation patterns for the 3 dBi antenna used during testing (www.hyperlinktech.com)
Figure 5.5: 3 dBi antenna mounted on the vehicle used during wireless coverage tests

For the experiment, a Ford Excursion was used with the 3 dBi antenna mounted to the roof of the vehicle as shown in Figure 5.5. This configuration placed the antenna roughly 77 inches off the ground. For the most accurate survey possible the Ekahau manual recommends walking the test site and covering as many points on the map as possible. This however is impractical considering the size of the test areas and given that some of the farmland is currently being used to grow crops. Therefore, a maximum vehicle speed of 5 MPH was chosen and the vehicle was permitted to travel on the drive rows between each plot of land. Figure 5.6 illustrates the path of the vehicle on the field used for test 1. A Novatel GPS unit was used in conjunction with the Ekahau software to map the path of the vehicle over the test site automatically. When the Ekahau software was reading the GPS and wireless equipment correctly the site survey was started.
Test 1 was conducted to provide users with a good idea of how the MIP performed over a variety of terrain. Figure 5.7 shows the test 1 field with areas of interest marked. These include elevation changes both above and below the height of the antenna on the MIP, trees, and structures. Figure 5.8 shows the results of the site survey conducted for test 1 with the visualization showing the signal strength at each location. The values used for signal strength are shown in dBm and are based on the normalized RSSI value as discussed previously. Figures 5.9-5.12 highlight the view from the vehicle in the areas of interest marked in Figure 5.7. At location 1, shown in Figure 5.7 and detailed in Figure 5.9 it is clear that the signal may be obstructed by the trees lining the field. However, in some places along the tree line, there are clearings within the trees which allow the signal to be stronger. This is also reflected in the survey image where there are areas of high signal strength beyond the tree line. An area where this is particularly apparent is at location 2. At location 3 where there is a steep hill, shown in Figure 5.11, the signal strength drops off significantly as would be expected without line of sight to the MIP antennas. Finally, location 4, shown in Figure 5.12 highlights the generally flat area surrounding the MIP. As expected this area contains a fairly high signal strength measurement. It should be
noted however, that there are some regions which show an unexpected drop in signal strength. With no apparent obstructions or interfering signals in the area this should be attributed to errors in the interpolation done in the Ekahau software or RSSI readings from the client card.

**Figure 5.7:** Aerial view of test 1 site with terrain features highlighted and MIP location (red “X”)**
Figure 5.8: Survey results illustrating signal strength (dBm)

Figure 5.9: View from vehicle at location 1 during test 1
Figure 5.10: View from vehicle at location 2 during test 1

Figure 5.11: View from vehicle at location 3 during test 1
Using the signal strength measurements and any possible interference the Ekahau software can provide an estimate of the data rate for the surveyed site as shown in Figure 5.13. The data rates shown are in Mbps and it is clear that for most of the regions outside location 4 the data rate is close to 1 Mbps. For experiments that require information to be transmitted/received from a vehicle regions where the data rate is 1 Mbps are unacceptable because the signal is frequently lost and there are high error rates when transmitting/receiving data. Therefore, for the best coverage and optimal data rate it is recommended to stay within the areas with good signal strength and high data rates. From the two surveys these qualities are achieved in the generally flat region (location 4) with a clear line of sight to the MIP antennas.

**Figure 5.12:** View from vehicle at location 4 during test 1
Upon completion of test 1, which gave wireless performance characteristics over a variety of terrain, a second test (test 2) was conducted in order to characterize the wireless performance over long ranges. Test 2 was also conducted at Kentland farms due to the availability of large areas of land and relatively flat terrain. Figure 5.14 shows the test location and the position of the MIP during data collection. The majority of the test site was flat open terrain with limited obstructions that was ideal for testing long range line-of-site links.

Analyzing the results from the Ekahau software many interesting features can be noted. For example, in the signal strength visualization, shown in Figure 5.15, there are two empty regions in close proximity to the MIP. These formed because active plots in this location lacked drive rows and prevented data collection. The bridge across these two regions is due to interpolation done within the Ekahau software and not actual measurements. The first area of interest is the region to the left of location 1, shown in Figure 5.14. When driving away from the MIP along the road, there is a hill which rises up and obstructs the MIP as shown in Figure 5.15.
Examining Figure 5.16, the resulting drop in signal strength along the road near location 1 is due to this hill obstructing the line-of-sight connection to the MIP. Contrast this with locations 2 and 3, which have clear line-of-sight to the MIP, the signal strength remains excellent. Locations 2 and 3 are shown in Figures 5.17 and 5.18 respectively. Moving onto location 4 presents another interesting change in terrain. At this location not only does the signal strength improve over the surrounding areas but the distance away from the MIP is significant. Shown in Figure 5.19, the vehicle is roughly level with the antennas on the MIP putting the client antenna in the best location for reception. Recalling the radiation pattern for the 12 dBi antenna placed on the MIP, the main lobe has a beam width of 7° meaning that anything within this region will experience the best reception. At location 4 the two antennas are clearly within this region and the distance to the MIP is roughly 0.90 miles. Location 5, shown in Figure 5.20 and roughly 1 mile from the MIP, begins to reach the limits of the wireless coverage area. At this location there is still line-of-sight to the MIP and no large obstructions or other types of interference therefore the reduction in signal strength can be attributed mainly to the inverse square law. This law states that the received power decreases in proportion to the square of the distance between the two antennas [23]. This effect can be visualized with the analogy of dropping a pebble into still water. As the ripples in the water radiate away from the entry point of the pebble their amplitude decreases. As with test 1, the results obtained from the signal strength visualization so no major surprises and the performance is close to what was expected. With line-of-sight to the MIP and moderate distances, the signal strength at the receiver can be expected to be good. Only when the distances to the MIP increase to about 0.80 to 1 mile or when line-of-sight is obstructed does the signal strength begin to drop off to unacceptable levels.
Figure 5.14: Aerial view of test 2 site with terrain features highlighted and MIP location (red “X”).

Figure 5.15: View from location 1 during test 2
**Figure 5.16:** Signal strength results for test 2 (dBm)

**Figure 5.17:** View from location 2 during test 2
Figure 5.18: View from location 3 during test 2

Figure 5.19: View from location 4 during test 2
Data rates for test 2 are estimated in the same way as test 1. Given a signal strength measurement and any possible interference, the Ekahau software provides an estimated data rate at each measurement location. The data rate visualization for test 2 can be seen in Figure 5.21. Results from this visualization are not surprising. However, in location 4 the signal strength and resulting data rate are unexpectedly good with an estimated data rate of 11 to 24 Mbps. In all other regions, the data rates are as expected with rates dropping below usable levels of 5 Mbps to 1 Mbps in locations where line-of-sight is obstructed and staying between 24 Mbps and 54 Mbps where line-of-sight is maintained. The major result gained from the data rate estimation for test 2 is the range possible with moderate data rates. Examining Figure 5.21 the data rate is estimated to be 24 Mbps to 11 Mbps at a line-of-sight range of 0.90 miles. To maintain a reliable connection between a roving vehicle and the MIP the vehicle should not venture out of the range where data rates drop below 11 Mbps. This will help to eliminate dropped packets and retransmissions of data resulting in a more reliable and functional connection.
Figure 5.21: Data rate estimation provided by the Ekahau software (Mbps)

Wireless surveying is a critical component to understanding the capabilities of the MIP system. Tests 1 and 2 have shown that the MIP is capable of providing wireless network coverage over a variety of terrain and over long distances while maintaining good signal quality and high data rates. If the already strong performance of the system must be improved the selection and placement of the antennas used should be examined. Longer ranges and higher data rates will be achievable if the rover antenna has a higher gain value. However, care must be taken when using antennas with higher gain values because as the gain increases so does the directivity of the antenna. Therefore, while having a higher gain antenna may increase the range, the antenna would need to be continuously pointed at the MIP in order to maintain the best signal. Another source of improvement could be the placement of the antennas on the MIP itself. As shown in the network architecture section the 12 dBi antenna used on the MIP has its main lobe centered around the vertical plane with a beam width of 7°. When placed 25 feet above ground this main lobe, which can be thought of as having the best signal, may not reach the client antenna. Being outside this main lobe would result in an attenuation of the signal.
and a drop in signal strength. A possible solution to this problem would be to place a second 12 dBi antenna closer to the ground to place the main lobe of the antenna closer to the same level of the antenna used on the client. This solution, however, may be impractical considering the cabling associated with temporarily placing an antenna at the base of the MIP and maintaining a removable system. Considering the configuration of the MIP used during tests 1 and 2, the wireless performance is excellent and possible improvements would only be needed for customized scenarios. The information gathered and visualized during tests 1 and 2 will prove valuable to test designers. Information regarding wireless coverage over a wide variety of terrain and resulting data rates will enable the accurate placement of single or multiple MIPs and provide the most robust wireless network possible.
Chapter 6: Conclusion

From the initial concept, the MIP was developed to support unmanned systems testing and experimentation. The design was to be portable, modular, and capable of supporting any type of instrumentation that would be required by test engineers. Additionally, it had to be capable of operations in a wide variety of environmental conditions and be able to support long duration experiments. These broad requirements are a challenge for any system and careful design, development, and testing were critical to the success of the MIP.

Creation of an initial prototype was an important step in the design process and allowed for further refinement of the design goals and expectations of the MIP system. Designed and implemented in a short three-month period, the prototype MIP was intended to be a proof of concept and demonstrate its basic capability. Supported instrumentation on the initial prototype included networking equipment, a GPS base station, weather monitoring equipment, and a pan/tilt/zoom video camera. The prototype MIP can be seen in Figure 6.1. After supporting a number of initial experiments the prototype MIP was carefully evaluated for its strengths and weaknesses. This information was used to redefine the design goals of the MIP in order to make it more modular and user friendly. During the redesign phase, the changes to the prototype MIP centered on providing a modular system to support additional instrumentation, producing a finished user friendly system, and improving the durability of the entire system.
After a significant redesign period with input from numerous users of the MIP a final design for the next generation MIP was established. Major improvements to the system included a modular system for adding or removing instrumentation, a redesigned electrical system, and improvements in the durability and usability of the system. The completed next generation MIP, shown in Figures 6.2 and 6.3, is fully documented in order to facilitate easy reproduction and the detail contained within these documents will allow technicians to quickly troubleshoot the system in case of problems. Upon completion of the next generation MIP, it was critical to test the system to characterize its performance and identify any possible improvements.
Testing of the next generation MIP included run time testing and estimation, environmental testing, wireless coverage characterization, and deployment time. In each of these categories the MIP was able to meet or exceed the required specifications. System run times are unlimited due to the hybrid power system’s charge sustaining capabilities. Users only need to maintain a proper fuel level in the
onboard generator to ensure continuous operation. The MIP has also been exposed to a variety of environmental conditions and has been stored outdoors for over 6 months with no damage to the components on the system. Additionally, temperature constraints and operational considerations have been identified. While the MIP was designed for operation in most weather conditions, the system is flexible and additional components could be added for operations in extreme environments. Another important feature of the MIP to undergo extensive testing was the wireless coverage provided by the networking equipment. This equipment was shown to be capable of providing high data rate coverage to areas within 0.5 miles and maintaining good connectivity approaching ranges of nearly 1 mile line-of-sight. This range should be more than adequate especially when considering that many experimental systems require visual monitoring.

Overall, the next generation MIP is a complete success. Numerous improvements over the prototype MIP combine to form a professional and highly configurable system that can be used to support many different areas of research. The modular instrumentation system onboard the MIP will allow the system to support not only unmanned systems experimentation but any type of research where portability and configurability are paramount. For this reason, the MIP can be expected to continue supporting experiments for years to come.

6.1: Future Work

In the creation of the MIP, the need for configurable instrumentation was paramount. Providing a portable base platform to support any type of instrumentation would be beneficial to many areas of research. This paper has discussed the creation and functionality of one MIP and future work should focus on the interactions between multiple MIPs.

Central to the functionality of the MIP system is its networking capabilities. The current configuration of the MIP is equipped with Cisco Systems networking equipment. While highly functional, configurable, and reliable this equipment is also limited. For example, the ability for multiple MIPs to be used during a testing scenario must be carefully evaluated. If the current equipment was used each MIP would need to have a line-of-sight connection back to the command center. Ideally, data could be collected from a distant MIP and passed through an intermediate MIP.
then onto the command center as shown in Figure 6.4. This type of network configuration is much more complex than the current configuration and may not be possible with the Cisco equipment. However, the modularity of the MIP system will allow future users to swap the Cisco equipment with other equipment which may be capable of providing this type of functionality.

Figure 6.4: Current multiple MIP functionality (a) and ideal multiple MIP functionality (b)
Another area for future work would be to scale the system down. As stated previously, the main function of the MIP currently is to provide wireless connectivity to a test site. Again, as the need arises for multiple MIPs it may not be cost effective to construct an entire MIP when its purpose is to only provide wireless connectivity and support no other instrumentation. Therefore, it is suggested that a scaled down version of the MIP be created. This would be a portable unit which supports only networking equipment. For example, the mast system shown in Figure 6.5 could be adapted to a small vehicle such as an ATV or a deployable stand alone base containing the electrical system. Such a system would provide the networking capabilities in a lower cost package but would not be able to support additional instrumentation.

![Figure 6.5: Will-Burt Night Scan Chief light tower (www.willburt.com)](image)

Lastly, careful observations should be made when fielding the MIP. While the next generation MIP is a successful product, it is far from perfect. It is important to record any design problems, features that users request, and usability issues as this type of information is invaluable to the refinement of any product. After a reasonable period of use, the MIP should be evaluated and the recorded information taken into consideration.
List of References


Appendix A: Electrical Schematics of second generation MIP
Figure A.0.1: Main electronics enclosure electrical diagram
Figure A.0.2: Secondary electronics enclosure electrical diagram
Figure A.0.3: Connector diagram for second generation MIP
Appendix B: Cost breakdown of second generation MIP

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**Main Electronics Enclosure Total**

$3,432.99

**Total for construction**

$26,463.85

### Networking Equipment

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**Network Total** $5,448.57

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<td>24V-48V DC-DC for wireless arms</td>
<td>VDZ200-D24-S48</td>
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<td>Aluminum plate 48&quot;x48&quot; 0.063” thick</td>
<td>89016K53</td>
<td>$108.86</td>
<td>$217.72</td>
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<td>Fuses for wireless arms</td>
<td>846-4012</td>
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<td>$1.50</td>
<td>LittleFuse</td>
<td>Allied</td>
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<td>$17.40</td>
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**Total for Wireless Arm Construction** $778.04

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<th>Description</th>
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<th>Price 1</th>
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106
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<tr>
<th>Item</th>
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<td>System Testing</td>
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**Total Construction Time (hours)** 480
Appendix C: MIP Installation Guide

This installation guide assumes that the MIP has been removed from the tow vehicle and placed in its final installation location. Additionally, if the use of guy wires is required consult the proper documentation in the Aluma Tower manual.

1. Install the four outriggers on the MIP
   a. The first two outriggers are to be placed on the supports welded to the front left and right side of the base trailer
      i. Remove the retaining pin from the outrigger
      ii. Place each outrigger on the support welded to the frame of the base trailer
      iii. Install the retaining pin through both the support and the outrigger holes
      iv. The installation of the first two outriggers is now complete
   b. For the remaining outriggers two support beams must be extended
      i. Locate the support beams on the left and right rear sections of the base trailer
      ii. Remove the retaining pins in the support beams and extend the beams until the second hole can be seen
      iii. Line up the hole in the support beam with the hole in the welded support on the base of the trailer and install the retaining pin.
      iv. With the support beams extended and secured install the outriggers on the end of the support beams.
   c. With the outriggers installed be sure the included retaining pins are also installed to hold the outriggers in place.

2. Remove the ladder from the side of the trailer and secure it to the tower near the instrumentation tree

3. Remove the instrumentation arms from the instrumentation arm holders

4. Using the ladder install the instrumentation arms into the instrumentation tree and secure with the toggle clamps

5. Obtain and install the electrical and networking jumper cable
   a. Locate an open electrical and networking port on the secondary electronics enclosure and remove the dust cap from the connectors
   b. Match the connectors on the jumper cable with the open connectors on the secondary electronics enclosure and secure the connector
   c. Match the connectors on the jumper cable with the open connectors on the electronics enclosure on the instrumentation arm and secure the connectors.

6. Obtain and install the main jumper cable
   a. Match the connectors on the main jumper cable with the corresponding connectors on the secondary electronics enclosure and secure the connectors.
b. Match the connectors on the main jumper cable with the corresponding connectors on junction box 3 and secure the connectors

8. Erect the tower
   a. Remove the green retaining strap from the top of the tower
   b. Using the manual winch crank the tower to its vertical position
   c. Put the retaining bolt through the slotted retainer plate welded to the rear tower support and secure the retaining nut
   d. Be sure that the tower is as plumb as possible

**NOTE** It may be necessary to install guy wires if the tower is erected higher than 25’ and if the winds exceed 45 MPH at 25’ and 30 MPH at 50’

9. Install the main power cable
   a. Remove the main cable assembly from the cable reel
   b. Match the connectors on the main cable assembly to junction box 1 and secure the connectors
   c. Match the connectors on the main cable assembly to junction box 2 and secure the connectors

10. OPTIONAL: Raise the tower to heights from 25-50 feet
   a. Remove the red security strap from the base of the tower
   b. Obtain the winch controller from the tool box and plug it into the electrical winch
   c. Turn the Main Power keyed switch to the “on” position
   d. Toggle the “winch power” switch to the “on” position
   e. Using the winch controller raise the tower to the desired position paying attention to unexpected noises
   f. If any unexpected noises are encountered stop using the winch and determine the cause of the problem
   g. Do not continue to raise the MIP above its maximum position as the winch is capable of damaging the tower

11. Turn on main power
    a. Open the generator enclosure and start the generator
       i. Toggle the choke control to the “on” position
       ii. Turn the gas tank ventilation cap to the “on” position
       iii. Turn the generator power switch to the “on” position
       iv. Remove any AC cables connected to the generator
       v. Using the pull start cord start the generator and toggle the choke control to the “running” position
       vi. Plug in any AC cables
    b. Turn the Main Power keyed switch to the “on” position

12. The MIP is turned on and ready to use
Troubleshooting

- The instrumentation arms are not receiving power
  - Check the electrical connections from junction box 1 up to the secondary electronics enclosure to be sure that all the proper cables are installed and secured
  - Check the jumper cables from the secondary electronics enclosure to be sure that the electrical connections from the secondary electronics enclosure to the electronics enclosure on the instrumentation arm are connected and secured
  - Check the Main Power switch to be sure that it is in the “on” position
  - Check the Main power fuse inside the main electronics enclosure to be sure it has not blown
  - Check the fuses in the secondary electronics enclosure to be sure that they have not blown
  - Check the fuse in the instrumentation arm electronics enclosure to be sure that it has not blown
  - Check the charge on the batteries to be sure that they have power
- The AC equipment is not working
  - Check the breakers inside the main electronics enclosure to be sure they have not tripped
- The toggle clamps on the instrumentation arms do not fit the instrumentation tree
  - Adjust the nuts on the toggle clamp to the proper position for a secure connection
VITA

Brett Anthony Gombar was born on December 11, 1980 in Springfield, Massachusetts. He is the son of Robert and Deborah Gombar. He grew up in the town of Montclair, VA and enjoyed swimming in the lake and driving around in his sister’s car. After attending C.D. Hylton high school he then enrolled at Virginia Tech where he received both his bachelor and master of science degree in mechanical engineering.