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THESIS

SYSTEMS ENGINEERING APPROACH TO DEVELOP GUIDANCE, NAVIGATION AND CONTROL ALGORITHMS FOR UNMANNED GROUND VEHICLE

by

Eng Soon Lim

September 2016

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Despite the growing popularity of unmanned systems being deployed in the military domain, limited research efforts have been dedicated to the progress of ground system developments. Dedicated efforts for unmanned ground vehicles (UGV) focused largely on operations in continental environments, places where vegetation is relatively sparse compared to a tropical jungle or plantation estate commonly found in Asia. This research explore methods for the development of an UGV that would be capable of operating autonomously in a densely cluttered environment such as that found in Asia. This thesis adopted a systems engineering approach to understand the pertinent parameters affecting the performance of the UGV in order to evaluate, design and develop the necessary guidance, navigation and control algorithms for the UGV. The thesis uses methodologies such as the pure pursuit method for path following and the vector field histogram method for obstacle avoidance as the main guidance and control algorithm governing the movement of the UGV. The thesis then considers the use of feature recognition method of image processing to form the basis of the target identification and tracking algorithm.

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SYSTEMS ENGINEERING APPROACH TO DEVELOP GUIDANCE, NAVIGATION AND CONTROL ALGORITHMS FOR UNMANNED GROUND VEHICLE

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Despite the growing popularity of unmanned systems being deployed in the military domain, limited research efforts have been dedicated to the progress of ground system developments. Dedicated efforts for unmanned ground vehicles (UGV) focused largely on operations in continental environments, places where vegetation is relatively sparse compared to a tropical jungle or plantation estate commonly found in Asia. This research explores methods for the development of an UGV that would be capable of operating autonomously in a densely cluttered environment such as that found in Asia. This thesis adopted a systems engineering approach to understand the pertinent parameters affecting the performance of the UGV in order to evaluate, design and develop the necessary guidance, navigation and control algorithms for the UGV. The thesis uses methodologies such as the pure pursuit method for path following and the vector field histogram method for obstacle avoidance as the main guidance and control algorithm governing the movement of the UGV. The thesis then considers the use of feature recognition method of image processing to form the basis of the target identification and tracking algorithm.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
AGVT	Advanced Ground Vehicle Technology
AHP	analytic hierarchy process
AI	artificial intelligence
ALV	autonomous land vehicle
AO	area of operations
BCT	Brigade Combat Team
BDAR	battlefield damage assessment and repair
BIT	built-in test
CCD	charge-coupled device
C-IED	Counter-Improvised Explosive Device
CPU	central processing unit
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DSTA	Defence Science and Technology Agency
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EOD	explosive ordinance disposal
FEBA	forward edge of battle area
FOV	field of view
GPS	Global Positioning System
HNA	hybrid navigation algorithm
HRI	human-robot interface
IED	Improvised Explosive Device
IMU	inertial measurement unit
INS	inertial navigation system
LIDAR	light detecting and ranging
LOAC	Laws of Armed Conflict
MEMS	microelectromechanical system
NIST	National Institute of Standards and Technology

OEF	Operations Enduring Freedom
OIF	Operations Iraqi Freedom
OPSIT	operational situations
OS	operating system
PFM	Potential Field Method
R&D	research and development
RDT&E	Research, development, test and evaluation
RF	radiofrequency
RGB	red, green and blue
ROE	rules of engagement
ROS	Robot Operating System
SE	systems engineering
SEA	Southeast Asia
SLAM	simultaneous localization and mapping
SRI	Stanford Research Institute
TACOM	Tank Automotive Command
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicles
U.S.	United States
VBM	vision-based method
VFH	vector field histogram

EXECUTIVE SUMMARY

The development of unmanned systems as a force multiplier in the armed forces has been gaining traction in recent years. This is largely attributed to the urgent need for reducing the operational risks faced by troops in a multitude of situations located within the various theaters of war. The pace for the development and deployment of unmanned ground vehicles (UGV) was, however, not keeping with that of the other assets deployed in the aerial and naval realms of the military. This thesis focuses on implementing a systems engineering approach for the rapid development of UGVs by exploring the requirements, available technologies and the salient points on the development and tuning of the algorithm parameters that govern the guidance, navigation, control and target identification efficacy of the system.

Though platform specific, the author observed the significance of adjusting tuning parameters such as the linear velocity, angular velocity and look-ahead distance within the pure pursuit method, which was implemented for the UGV's path following the algorithm. These parameters had an immediate effect on the UGV to accurately maneuver through a user-designated route. Any inaccurate tuning of the parameters resulted in the UGV exhibiting instability in its maneuver, often causing the system to veer off course or even failing to reach its designated position.

As part of its autonomous capabilities, the development designed the UGV to possess obstacle avoidance capabilities with the use of the vector field histogram algorithm. Parameters governing the detection and avoidance of obstacles were tuned in order for the system to perform adequately through the designated test route. These parameters included the detection limits of its sensor suite and the certainty thresholds of the algorithm to properly perceive the presence or discard the possibility of an obstacle within its path.

The implementation of the two algorithms, the pure pursuit method and the vector field histogram algorithm, allowed the system to maneuver efficiently through the user defined test route.

The last algorithm employed in this research was the use of feature recognition through image processing, which gave the UGV the capabilities to identify potential targets in its operational environment. Similarly, the author also noted parameters requiring adjustment for the system to recognize the designated targets under varying light conditions and target profile exposure.

The development in this research was based on a Pioneer 3AT robot platform equipped with light detecting and ranging (LIDAR) sensor, orientation sensor, image camera and an onboard mainframe computer as its primary hardware to detect, process and execute the autonomous behavior of the UGV. The author employed the use of software programs such as Ubuntu, MATLAB and Robotic Operating System (ROS) in support of the system architecture to compute all variables for UGV's operations. The author conducted the development and testing of the UGV prototype within a lab environment, but took note of the projected operational environment expected for the UGV. This resulted with a verification set up where the efficacy of the system was tested through varying light conditions and obstacle positioning to understand the performance and limitations associated with the respective methodologies applied in the system comprehensively.

The author documented the pertinent behavior change of the system associated with the adjustments of the respective tuning parameters. This will allow for future iterations and development of the system to be carried out with relative ease and to allow future developments using similar methodologies to be developed. The author recommended future developments of the prototype to expand on its sensor suite to include the use of a three-dimensional LIDAR and other sensors for the system to perceive its vicinity with higher certainty values, and thus provide a better more robust obstacle-free trajectory for the UGV to maneuver through its required path. Other features such as the employment of thermal imaging in lieu of the current image camera was also recommended as part of the future works to add versatility to the target identification and tracking subsystem by allowing the UGV to discern its intended target even through obscured environmental conditions such as airborne particulates.

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I. INTRODUCTION

The use of unmanned ground vehicles (UGV) in combat roles has gained momentum in recent conflicts due to their ability to perform tasks that ground troops deemed too risky or mundane for manned operations. These included operations involving reconnaissance, surveillance or explosive ordinance disposal (EOD), where the deployment of unmanned systems would minimize the exposure of danger to soldiers by transferring the operational risks to the battlefield robots. This trend has been widely apparent in the war against terrorism, during which fielding unmanned counter-improvised explosive device (C-IED) systems was necessary to support troop movements and operations in deployments such as Operation Enduring Freedom (OEF) and Operations Iraqi Freedom (OIF). The urgent fielding of such systems was imperative as ground forces were transiting into counter-insurgency operations in Afghanistan and Iraq, leading to troops' significant susceptibility to enemy IEDs (Eisler 2012).

Along with the growing global trend of downsizing or streamlining military forces, the impetus for developing a credible force multiplier is steadily gaining significant attention to maintain the operational capabilities of our future force structure. The emergence of such trends led to extensive research and development (R&D) in the evolution of UGVs together with its technologies, to augment force restructuring and maintain force potency. Currently fielded UGVs are, however, largely limited in its autonomous capabilities for navigation, and they are not specifically designed or developed for use in tropical operational environments (Gonzales and Harting 2014).

A. DEVELOPMENT OF UNMANNED GROUND VEHICLES

The development and fielding of UGVs in an operational role are not a new concept in the battlefield. In tracing the developments and deployment of such systems from the 1930s, the evolution of UGVs has shown marked improvements since the technology's tele-operated days.

1. 1930s–1940s

According to a study conducted by Gage (1995), early adoption of unmanned systems can be traced back to the combat deployment of remotely operated tanks fielded by the Soviet Union against Finland during the Winter Wars in the late 1930s. These rudimentary tanks were radiofrequency (RF) controlled and pneumatically actuated upon receiving the wireless commands from the radio operator. The pairing of such an unmanned system together with a manned tank allowed the Soviet forces to double their available firepower without the need to increase its manpower requirements. The commands executed by the unmanned tanks included directional movement across the battlefield and pre-assigned commands for offensive or evasive actions, such as the firing of its main armament or creating a smokescreen.

Gage (1995) also notes that similar employments of early unmanned vehicles included the Goliath tracked mines fielded by Nazi Germany against the Allied Forces in World War II. The Goliath mine was a remotely controlled demolition vehicle that had been laden with large amounts of explosives. The Nazis deployed the Goliath vehicles to breach enemy strongholds, and to creep up toward and destroy enemy armored formations. Gage highlights that the primary objective for deploying such an unmanned vehicle was to achieve the tactical advantages of overcoming significant enemy resistance without the associated operational risks of fielding conventional manned systems.

Such early systems were largely limited to the human controller’s field of view (FOV) to maneuver and engage their targets. The systems could only receive remote commands that executed limited instructions, hence, they were able to behave in a linear fashion for the execution of only one command before the commencement of follow-on instructions. The remote vehicle was akin to an extended arm of its human controller, and lacked the capability of being cognizant of its surroundings to react adequately to the environment. This severely limited the abilities of the platform to perform autonomously as a credible force multiplier.

2. 1960s–1970s

The development of modern UGVs found its origins among early research efforts in the field of artificial intelligence (AI), which focused primarily on sensor-based data collection, and control algorithms for path planning and obstacle avoidance. An early version of modern mobile robot development effort appears in the Defense Advanced Research Projects Agency (DARPA) funded robot, Shakey (Gage 1995). The development of the robot originated from Stanford Research Institute (SRI) to serve as a test-bed for AI advancement. It included the fusion of image cameras, acoustic range finders, and touch sensors mounted onboard a wheeled platform. The system had the sensor information processed through its mainframe computer, which subsequently executed the navigation, exploration and kinematic instructions to maneuver the robot. Though Shakey was equipped with various sensors to gain some consciousness of its surrounding, it failed to achieve autonomy in its operations. It often required human intervention to assist in its tasks and failed to navigate independently (Gage 1995). Nonetheless, the creation of Shakey laid the foundation of establishing functional and performance requirements for the modern-day mobile robots. Gage adds that the study also helped identify technological limitations as well as the subsequent expansion and definition of present-day research fields of vision processing and planning.

The same research facility conducted further studies later a few years later that yielded limited success with autonomous navigation and obstacle avoidance. The upgraded system utilized a stereo vision system, where three-dimensional (3D) information can be extracted from digital images of the same scene taken by two cameras at separate vantage points. By comparing the two simultaneously captured images from the cameras, the onboard mainframe of the robot performed feature extraction by examining the relative positions of objects within the two images to analyze for range and position information of any obstacles. This information would then be further computed to obtain a feasible obstacle-free path for the system to maneuver to its designated endpoint. However, this was too computationally intensive resulting in the system performing at a significantly slow rate of about 15 minutes to capture, process and maneuver in a one-meter space (Gage 1995). During this timeframe, other international facilities also undertook research efforts in the field of mobile robotics, which included the French HILARE project that served as a test-bed to perform general research on robotics and robot perception and planning in Europe (Gage 1995).

3. 1980s–Present

Gage (1995) highlights that DARPA became more directly involved in the research fields of robotics during this period apart from sponsoring research efforts such as that of Shakey. Deriving from DARPA's Strategic Computing Program, the organization developed the Autonomous Land Vehicle (ALV) to further research efforts in higher level autonomy reasoning for the robots. Initially, the ALV was equipped with a sensor suite consisting of a color video camera together with a laser scanner that would provide path recognition and navigation capabilities. Processing power of the mainframe was significantly more powerful compared to the Shakey allowing for higher resolving performance in its obstacle avoidance abilities. DARPA conducted a successful demonstration of the robot in 1987. The robot traversed over rolling terrain while avoiding ditches and other small obstacles at a top speed of up to 3 km/h. Gage added that the success found in the ALV program led to the expansive propagation into specialized research by academic institutions and defense partners. The downstream research efforts were in support of specific fields for off-road navigation and sensor fusion. The success of the ALV also gave rise to other specialized programs such as the U.S. Army Tank Automotive Command (TACOM) and DARPA Advanced Ground Vehicle Technology (AGVT) where the focus of the research was to develop applications suited for military operations.

4. Current Developments

The armed forces' growing interest in deploying unmanned systems for defense related operations fueled current R&D efforts into robot autonomy in numerous organizations. The United States (U.S.) Army led initial large-scale efforts with initiatives such as the Future Combat Systems program to spur modernization. The Brigade Combat Team (BCT) modernization program subsequently succeeded the prior program. Stemming from the unabated demands from warfighter in various theaters of operations, other initiatives such as that outlined in the U.S. Department of Defense (DOD) Unmanned Systems Integrated Roadmap had also placed a clear emphasis on further development of unmanned systems. Despite the increased demands, the role for UGVs hardly expanded beyond the conventional operations for C-IED activities (Gage 1995). Gage also notes of the limited efforts to develop technologies for incorporating the use of UGVs in a wider spectrum of operations such as in logistic carriers, mine-clearing, medical evacuations or armed roles.

B. MODES OF OPERATION

In conjunction with the National Institute of Standards and Technology (NIST), the DOD had defined an unmanned system as one that "receives its mission from a human and accomplishes that mission with or without further Human-Robot Interaction" (HRI). The DOD further classified this definition into the following three main categories (Department of Defense 2013), according to their modes of operation:

1. Tele-Remote Operations

This mode of operation involves a human operator in direct control of the unmanned system on a continuous basis. The connection from a stand-off distance is either achieved with a tether or linked by radio-control. The system takes limited to no initiative in achieving the required mission and can only operate if the communication lines are established.

2. Semi-Autonomous

A semi-autonomous system can execute its mission after a human operator plans the mission outline and directs the system to execute it. The system achieves only limited autonomy through its onboard sensors for purposes such as independent waypoint navigation through an open terrain.

3. Fully Autonomous

The DOD defines a fully autonomous system as one that would be able to wholly plan, execute and adapt its execution to accomplish the given mission within a defined scope without any human intervention or interaction. Such tasks include the capabilities of obstacle avoidance during maneuvers.

C. NAVIGATION TECHNIQUES

In order for the UGV to perform autonomous navigation, the system would be required to move through a series of designated waypoints from an initial coordinate to its terminal coordinate. Therefore, it is imperative for the UGV to first determine its own position and continuously update its most current state through the computation of its movements. Supporting this computation was the information gathered by the UGV's onboard sensors to monitor its movement and to derive an optimal trajectory plan for the system to maneuver successfully. As defined by Borenstein (1996), the two main classifications of localizations utilized in autonomous navigation are as follows:

1. Local Localization

This method of localization evaluates the UGV's position and orientation using only the information obtained from the various sensors found onboard the system. The UGV takes its starting position as the initial reference point and continues to compute its relative distance and bearing from this initial point. The system continues to do so throughout the entire navigation process to estimate its position.

2. Absolute Localization

Absolute localization utilizes an external reference to determine the UGV's position. External references can be in the form of satellite signals, such as those from the Global Positioning System (GPS), or through terrestrial recognition of landmarks or signal beacons. The UGV identifies itself in a global reference frame and determines its relative position within this frame by measuring the offset from the various signal sources.

D. PROBLEM FORMULATION AND THESIS OBJECTIVE

The remarkable achievements by numerous research organizations in their prototype demonstrations have marked a significant improvement in the field of autonomous robotics. These developments were mainly developed and demonstrated under continental environment where vegetation is relatively light and uniform. By contrast, the conditions one expects from a tropical jungle environment differs significantly, and so, poses a unique challenge with the development of the robot.

1. Problem Formulation

So far, large-scale research efforts have yielded very limited work with developing a suitable system for use in a jungle-like environment where the density of vegetation is thicker. Harsher environmental conditions could significantly affect the performance and efficiency offered by current developments. Such environmental conditions include the presence of dense overhead tree canopies, which attenuates GPS signals resulting in the failure of the system to monitor its movement and navigation accurately.

2. Objective

The objective of this thesis is to explore the main functional subsystems required to perform autonomous navigation by a UGV in a cluttered terrain. The author investigates the use of various sensors in the field of robotics to understand their capabilities and limitations when fielding in a tropical jungle environment to achieve autonomous navigation, obstacle avoidance and target detection.

After ascertaining the optimal suite of sensors, this research encompasses the UGV’s navigation from a known position to a terminal location in a controlled environment after ascertaining the optimal suite of sensors. It sought to achieve the following:

- perform autonomous movement through a series of waypoints
- perform dynamic obstacle detection and avoidance
- perform target detection and tracking

E. ORGANIZATION OF THESIS

The organization of this thesis holistically explores and matches the effective system requirements expected from various stakeholders against available technologies to deliver a suitable solution. The organization was laid out in the following manner to guide the author through the various stages of development.

Chapter II of the report explains the established and successfully fielded technologies that are available for our prototype development. Chapter III summarizes the systems engineering approach adopted by the author to combine the stakeholders' requirements and operational concepts expected of the UGV. The establishment of an effective functional mapping also allowed the conduct of component evaluation. Successful candidates from the evaluation then constituted the eventual construct of the prototype in which the system will be adequately equipped to fulfill its intended mission.

Chapters IV and V present the detailed design architecture and implementation of the various hardware and software for the construct of the UGV. They also cover the key parameters governing the behavior of the system so that developers can calibrate the pertinent parameters on future iterations of the platform to suit or adapt to a change in the operating environment.

F. BENEFITS OF STUDY

This research explores the pertinent points associated with the projected deployment of the UGV in a cluttered environment with the employment of established techniques and hardware for its construct. Specifically, understanding the various parameters of the algorithm that require fine-tuning during the course of the study will greatly aid future iterations of similar developments.

II. BACKGROUND

A. RELATED RESEARCH

Research efforts in robotics had been extensive since the field's inception. As described in Chapter I, the focus on design and development of the UGV has mostly been for deployment in continental environments. A purpose-built system capable of operating in the cluttered terrain expected of a tropical jungle had been limited. This section discusses several core concepts that the author referenced to while developing the UGV prototype in this study.

1. Simultaneous Localization and Mapping

A considerable amount of research had been devoted to the field of simultaneous localization and mapping (SLAM) in recent years. The technique has allowed the placement of an unmanned system in a foreign environment with minimal user input programmed into the system. The UGV abilities of sensing, learning and remaining cognizant of the environment have garnered immense interest due to the higher level of self-awareness demonstrated by the system, and have formed the baseline for future AI works. The SLAM algorithms call for continuous processing and analysis of the unknown surrounding to construct a virtual map through fusion of data extracted from the various onboard sensors. The system utilizes the constructed map as a means for navigating toward its designated position. Consisting of multiple layers of software and computations, SLAM utilizes methods such as the continuous fusion of landmark recognition and information extraction, information correlation as well as state estimation and update to interpret its environment (Riisgaard and Blas 2004). Riisgaard and Blas note, however, that the high latency resulting from the computationally intensive process leads to the system not performing with the fidelity expected of a combat system.

Though the advancement of SLAM in the field of robotics has been making significant headway in recent experimentation for the various algorithms used, the computational complexity associated with them are still significantly limited to solve large-area SLAM computation (Dissanayake et al. 2011).

2. Unmanned Vehicles for Natural Environment

As highlighted earlier, there have been limited research efforts in the field of UGV sensor system operating in a cluttered terrain. According to Ibanez-Guzman, Jian and Gong (2004) who co-conducted their developmental efforts in conjunction with the Defence Science and Technology Agency (DSTA) of Singapore, the difficulties faced with navigating in such proximities includes the rapidly changing ground conditions and resolving obstacles presence and distance. They attributed both conditions to the extreme environmental conditions expected of a tropical jungle. They propose the installation of a navigation suite that is adaptable for use on the existing stockpile of vehicles, and note that the stark contrast in their research and engineering efforts from other developments were largely due to the operating environment. Ibanez-Guzman et al. (2004) added that even though the challenges faced by their team were unique to their research, the development and implementation of their system architecture following the principles of multiple data fusion allowed them to circumvent the situation. Overlapping of navigational data with feedback information from several sensors allowed the team to mitigate the identified challenges. Together with the use of GPS-aided guidance, the system managed to complement the individual limitations of the various sensors in terms of their range, certainty and response.

However, due to the limitations on hardware capabilities and high latency in processing the sensor information to compute a feasible path-finding solution, the team highlights that the maximum attainable speed documented in the development was 18 km/h (Ibanez-Guzman et al. 2004). This research conducted further illustrated the computational and engineering strain that one could face with operating an unmanned system in a tropical environment, as well as the need for a properly integrated suite of sensors to overcome the associated navigation challenges (Ibanez-Guzman et al. 2004).

3. Joint UAV-UGV Operations in Cluttered Environments

Research by Carnegie Mellon University extended research efforts in the field of robot autonomy and localization with the use of overhead high-resolution data to enhance the navigation capabilities of the UGV in an environment with dense vegetation. The study utilized an airborne laser to collect ground information in an attempt to aid with the UGV's localization and path planning (Vandapel, Donamukkala, and Hebert 2006). The author demonstrated the use of registering local three-dimensional (3D) ground laser data with the global 3D aerial data to ascertain impassable areas for the UGV as a tool for subsequent path planning. This method computes its feasible paths by filtering the vegetation and terrain information of both the ground and aerial data to interlace a traversable map. Similar to the SLAM technique, the UGV is able to use the map as a navigational tool. While the research successfully demonstrated the potential capabilities of having such joint unmanned operations, the aerial data collected only allowed the UGV to traverse through areas where vegetation was sparse. This operational limitation could severely impact the strategic significance of a military UGV in achieving tactical surprise by maneuvering through a heavily vegetated terrain.

B. LOCAL LOCALIZATION TECHNIQUES

The computation and analysis of various sensors mounted onboard the UGV allowed the employment of local localization technique. This thesis has adopted the local localization method as it displays lower susceptibility of GPS signal errors or failures compared to absolute localization.

The capability of allowing the robot to recognize and update its position continuously is pivotal for a system to maintain autonomous operations in an environment where attenuation or denial of GPS signals might occur. Ilyas, Cho, Park and Baeg (2013) identified in their works that odometry and inertial navigation methods allowed the system to employ local localization as its primary technique for navigating. The following section describes the main working principle behind the two methods.

1. Odometry

Odometry, or dead-reckoning method, is a position estimation technique used for navigation. The method estimates the position of the system after a period of time relative to its initial position by measuring distance and orientation of movement (Ilyas et al. 2013). The use of motion encoders found in the wheels of the UGV measure the traveled distance based on the number of wheel rotations during motion. Additional information from the bearing of wheel orientation, along with the information of the traversed distance allows the estimation of the system's final position.

This system can be fully self-contained within the UGV and is not susceptible to external interruption such as signal interference or jamming. The relative ease of implementing this localization method within any system also provides an easily accessible capability of position estimation. Coupled with its high sampling rate and inexpensive implementation, odometry has been widely adopted in the field of robotics navigation (Demetriou 2005).

The main drawback to the technique is that it provides only good short-term accuracy due to the accumulative nature of error over a period. The fundamental concept of odometry integrates incremental motion information over time, but leads to calculation errors amplified over larger distances and longer durations. The rudimentary nature of odometry also fails to capture external influences that might affect the motion of UGVs such as wheel slippage or undulating terrain whereby the ground distance traveled by the system does not accurately represent the map distance traveled (Borenstein, Everett, and Feng 1996).

2. Inertial Navigation

The main working principle of an inertial navigation system (INS) is similar to that of the odometry method. Employed in the INS method, however, was the computation of the UGV's motion state evaluation, in which its velocity and acceleration form the metric for determining its position(Johann Borenstein, Everett, and Feng 1996). Instead of using encoders to record movement data like in odometry, the INS method uses devices such as the gyroscopes and accelerometers to measure the UGV's rate of rotation and acceleration, respectively. Such devices offer far superior accuracy and precision compared to encoders. The eventual processing and integration of these measurements allows the estimation of the UGV's relative position from its originating point. Similar to odometry, the devices that make up the INS technique can also be self-contained to reduce the dependencies of external signals or references.

The similarities of both techniques extend to their drawbacks as well, in that an error associated with the inertial sensor drifting over longer periods due to the need to integrate rate data to yield a position, though not as pronounced as odometry. This disadvantage is slowly being displaced with the introduction of low-cost, highly accurate microelectromechanical systems (MEMS) units that are capable of providing gyroscopic, acceleration and directional data. The accuracy and affordability of MEMS has gained increasing attention as an attractive solution for robotic navigation.

C. SENSORS REVIEW

Supporting the fundamental concept of localization, navigation and detection, sensors form the key interface that allows the UGV to be cognizant of its surroundings, allowing it to traverse across mixed terrain, avoid obstacles and perform its designated tasks. The effects of a dynamically changing environment in the real world can undermine the ability of the UGV to identify, determine and understand the state of its surroundings. An UGV typically uses a mix of sensor readings to discern its surroundings to circumvent the information feedback limitations posed by the individual sensors. Demetriou (2005) describes the advantages in fielding various sensor suites to synthesize the information from the various sources as follows:

a. Redundancy

An overlap of information from different sensor sources yields not only a higher rate of reliability for observing a sector of interest, but also extends deployment periods even if one sensor type fails or registers an error. Redundancy in available information also allows the system to have more metadata to choose from and minimizes uncertainty, hence creating a more accurate perception of the environmental features for the UGV to achieve its mission.

b. Complementary

Complementary information from different sensor sources can be fused together to allow for a clearer perception of features that may not be possible from a single sensor source. The combination of data from a mixed configuration can help resolve any incompleteness of information, unlike the performance from a single sensor. An example of this would be the detection of an obstacle from an image, but the failure to determine its distance from the UGV, thus, not providing an adequate maneuver path to avoid it.

c. Timeliness

The combination of sensors might be able to provide more timely information when compared to a single sensor source due to the increased speed of an individual hardware operation. The timeliness for the information feedback can also be attributed to the possible parallelism in processing as part of the data fusion that results in a higher overall success rate.

1. Sensor Classification

Demetriou (2005) highlights that the classification of sensor types can be broadly categorized based on the characteristics of their performance or purpose. The purpose of understanding and classifying the sensor types is to better comprehend the data flow requirements for the collection and subsequent fusion of information. Due consideration should be given to properly evaluate the nature of the UGVs likely operating environment and operational scenarios. This must be done to ensure that environmental conditions neither obstructs data processing among suitable sensors nor jeopardizes the UGV’s functions or operational efficiency.

Other than the considerations of the environmental conditions, the characteristics of the sensors would also play a part in determining its location on the UGV, and power requirements drawn from the UGV’s powertrain. This would be critical to manage any electromagnetic interference/electromagnetic compatibility (EMI/EMC) associated with the positioning of such devices to ensure that noise levels between the electronics are minimized, and thus, the data received from the sensors do not result in false readings.

The function of classifying the sensor types is also critical in conducting Built-In Tests (BIT) and aiding the UGV or the UGV operator in maintenance and health status updates during the course of operations.

a. Sensor Type Classification

The first method for categorizing robotic sensors can be based on whether the information of interest originates internally or externally from the UGV. Sensors that collect information from within the UGV's state of motion are considered a proprioceptive sensor, while sensors collecting information that are influenced externally from the UGV were classified as exteroceptive sensors (Borenstein, Everett, and Feng 1996).

Proprioceptive sensors measure information originating from the UGV such as information regarding its wheel directions and speed, electrical loading, internal temperature or other aspects regarding its status. This information is critical not only in aiding navigational algorithms, but will also be critical in monitoring self-maintenance and internal conditions of the UGV. The latter is key to ensuring that the operations of the UGV fall within its prescribed limitations so as not to overstrain the system to a stage of premature failure. Exteroceptive sensors, on the other hand, acquire information originating from the environment around the UGV and determine the measurements of objects relative to the UGV's frame of reference. Such sensors are useful in extracting meaningful environmental features such as light intensity or range. This perceptivity aids the UGV in comprehending its surroundings to execute the correct navigational maneuver or to detect anomalies from its environment such as the presence of a potential target or obstacle.

Borenstein et al. (1996) also highlight an alternate method of classifying the sensor types by distinguishing their information collection technique as active or passive. An active sensor works by probing the environment with self-generated energy beams and collecting the reflected energy pattern after it bounces off the surfaces in the surroundings. Processing and analyzing the returned energy path offers meaningful information such as bearing, distance or dimensions of the surroundings. Active sensors include devices such as sound navigation and ranging (SONAR) and light detecting and ranging (LIDAR) sensor, which utilize acoustic waves and laser energy, respectively. A passive sensor is a device designed only to receive and measure natural emissions produced by the environment; they do not emit any energy. A military UGV could gain an operational advantage by reducing its signature or detectability with this feature of passive sensors. Passive sensors include digital imaging cameras, thermal imagers and contact sensors.

2. Available Sensor Technology

This section discusses on sensor types that are commercially available for use in the various fields of robotics navigation and target detection. Such devices form the core suite of cognitive sensors that allow the UGV to gain valuable perception of its surrounding to navigate, maneuver and perform in designated areas of operation. Categorized as either proprioceptive or exteroceptive, the sensors are described in the following paragraphs.

a. Proprioceptive Sensors

These sensors measure intrinsic changes to the UGV and take readings either as inputs into their algorithm computations or for monitoring the status of the system.

(1) Encoders

A common encoder type used in wheeled UGVs is the incremental rotary encoder. This device senses the mechanical motion of the rotating wheel and triggers digital pulses in response to the motion. The incremental rotary encoder utilizes an opaque rotating disk with equally spaced transparent sections that spins in tandem with the rotating wheel to determine movement. Shining a light source through the rotating disk, a photo detector on the opposite side detects the intermittent pulses of light through the voids in the disk. The effects of the intermittent light pulses cause the encoder to generate a series of equally spaced pulses when the UGV is in motion, thus estimating the approximate velocity and distance traveled by the UGV to keep track of its position. Besides the use of a light source in optical sensing, the use of magnetic, inductive, capacitive or mechanical means can also achieve similar results as long as the employment of an appropriate sensor is in place.

(2) Potentiometers

A potentiometer measures variable voltages resulting from the varying power input into an electrical component. By measuring the different voltages delivered to power the motor and individual wheels, the system resolves the distance traveled and uses the wheel's rate of turn to measure the angle of movement. Both factors are critical in position estimation for the local localization technique. Apart from using a potentiometer in the UGV's drivetrain system, the use of this device in other components to measure voltage differences yields invaluable information about the system's performance. Potentiometers can also be found as a component in other devices such as motion sensors.

(3) Gyroscopes

The use of gyroscopes in robotics has enabled stabilization in many applications through the measurement of angular velocity through motion as an effect of Coriolis force. This capability allows the sensing of rotational motion of the UGV and, thus, the ability to compute the directional heading with reference to its initial position accurately when in motion. In recent years, the introduction of mass produced microelectronics provides affordable MEMS gyroscopes, essentially miniaturized vibrating structure gyroscopes (Demetriou 2005).

Most of such sensors use a tuning fork configuration with at least two masses oscillating and moving constantly in opposite directions. When the UGV is in motion, the Coriolis force created from the two masses moving in different direction results in a capacitance change. The detection and processing of this differential charge between the axes allows the mainframe computer to perform calculations in order to understand the movement of the UGV. The significant effects from the high accuracy available from this hardware would be essential to compensate for the fundamental weakness and errors associated with the simpler odometry method. Despite the accuracy and precision made available with the use MEMS gyroscopes, the compounding nature of the navigation errors with time must be noted with the use of these devices.

b. Exteroceptive Sensors

These sensors measure external variables from the system and can be used by the system to understand its surroundings.

(1) Digital Compass/ Magnetometer

Digital compasses utilize a magnetometer to measure the direction of the Earth's magnetic field to determine the geographic poles which is akin to a conventional compass. The use of magnetoresistive alloys, which are sensitive to magnetic fields, enable the device to discern the direction of movement with a high degree of accuracy. Unlike gyroscopes that provide directional headings only when the UGV is in motion, digital compass, which depend on Earth's natural magnetic fields, can still provide heading information even when the UGV is stationary. Thus, digital compasses reinforce navigational precision alongside the use of other sensors. This requires proper design of the UGV to position the digital compass in a way that avoids interference from any surrounding ferrous material that might otherwise give inaccurate readings.

(2) Accelerometers

Accelerometers are MEMS devices that measure values of acceleration. Developers install them in specific orientations within a robotic platform to measure the change in acceleration of the respective axis. The use of accelerometers can derive useful metrics such as velocity, by measuring any changes in movements whereby a sudden change from the UGV's stationary position results in a measurable difference in the acceleration forces applied to the device. Demitriou (2005) highlights that accelerometers possess a very poor signal-to-noise ratio at lower speeds, when executing low speed turns and are susceptible to significant drift errors over further distances

(3) Ranging Sensors

Ranging sensors are devices that can determine distances of objects in its FOV without physical contact. This allows the UGV to determine whether an obstacle is within its path and to plan its maneuver accordingly to avoid it. Such sensors are vital in the

UGV’s obstacle avoidance capabilities that contributes to the quality of autonomous operations. The most commonly used range sensors employ the time-of-flight ranging method for detection, identification and collision avoidance.

The working principle behind such a sensor is the active generation and emission of energy pulses, reflecting the energy beams off any objects within its FOV back to the emitting source. The calculation of time required to detect the pulses of reflected energy back to the sensor produces an accurate solution to the direction and distance of the object. These predominant sources of energy generation are from an ultrasonic or electromagnetic source. Therefore, the pertinent parameters involved in the range calculation are the speed of the pulses for sound or light traveling in space. Such sensors possess the edge of straight-line active sensing and swift responses to its generated pulses, the observable distance to any object can thus be computed quickly without the need for complicated analysis for the calculations.

Despite the high rate of accuracy with such sensors, they are also susceptible to errors associated with ascertaining the exact time difference between the generated and returned pulses, and the variation in speed of pulse propagation through the environment. The latter is evident with the adversely affected range computation using acoustic means, especially during deployments in harsher environmental conditions in which fluctuating temperatures and humidity are present (Demetriou 2005). Examples of other ranging sensor includes LIDAR, light-based sensors and ultrasonic sensors.

(4) Vision-Based Sensors

Vision-based sensors are capable of yielding tremendous amounts of information for use in the UGV’s recognition of terrain, features or position. Similar to the workings of biological eyes, the ability of vision-based sensors to capture an image provides many features that aid the UGV in understanding the environment and planning its next course of action. The challenges with vision-based sensors are to process the image adequately and to draw meaningful information such as landmark or feature recognition. Also, vision-based sensors must be able to draw a reasonable conclusion regarding its position, by mapping the captured image to an internally stored image or map bank. The wealth of information made available in any captured image, therefore, poses difficulty in extracting such visual features. This challenge is further aggravated when environmental conditions, such as particulates in the air or variations in lighting conditions, warrant additional analysis to discern the required features from the raw metadata.

The capabilities of a vision-based sensor can be further harnessed to include target recognition and tracking capabilities. Pixel resolution performance of the image-capturing device can hence form a critical performance specification in processing detection and tracking of targets.

Examples of vision-based sensors include digital cameras using charge-coupled device (CCD) sensors for day use, or the use of infrared imagers in obscured environmental conditions or night use.

D. OBSTACLE AVOIDANCE ALGORITHM

The UGV’s ability to conduct autonomous navigation hinges largely on its ability to process and integrate the input from various sensors to discern a probable path in the presence of an obstacle. This section discusses the various methodologies that have been widely adopted in the field of robotics for the purpose of obstacle avoidance during movement.

1. Bug Algorithm

The initial proposal and development of the Bug algorithm method was for the algorithm to perform as a reactive avoidance method using contact sensors. The implementation of this algorithm on a UGV results in it traversing the designated path as an “obstacle-hugger.” This is due to the nature of the algorithm that dictates a straight-line maneuver from its initial position to its objective position, and directs an alternate path only when it contacts an obstacle. This avoidance method forces the UGV to circumnavigate an obstacle by skirting around it until an obstacle-free path toward its intended goal is possible. Despite further work on the algorithm to accept range sensor data for it to be aware of the presence of obstacle at a greater distance, the steering principle for this method remains largely similar to prior versions. Although the simplicity in this algorithm results in significantly lower computational requirements, the failure to take into account the dimensions of the UGV and the reactive nature of the algorithm results in significant drawbacks (Susnea, Minzu, and Vasiliu 2009). This can be in the form of relatively high inefficiency for the planned trajectory and requiring significantly more time to circumnavigate the obstacles to reach its goal.

2. Potential Field Method

This algorithm idealizes the robot and its environment as charged particles by applying an artificial potential field with the two entities. Akin to how fields of the same magnetic poles oppose each other while opposite poles attract, the potential field method (PFM) adopted a similar relationship between the UGV and its objective position. By allocating the UGV and its goal differing poles, it creates a suitable attractive force between them; it draws the UGV toward its intended path by calculating the path of highest attractive force. Similarly, by applying a similar field toward all obstacles along the environment as the UGV, this creates a repulsive field between the UGV and the obstacle that “pushes” the UGV away from it. The combination of these two behaviors results in an optimal potential field that would control the acceleration of the robot toward its goal and away from obstacles. Classical methods of PFM requires the location of the obstacles to be known beforehand so that a repulsive force can be implemented, this algorithm has been further developed in recent years so that a dynamic potential field can be constantly updated when the robot is in motion.

3. Vector Field Histogram

Developed by Borenstein and Koren (1991), the vector field histogram (VFH) method for collision avoidance is a real time obstacle avoidance algorithm based on the feedback of the changing environment. An onboard mainframe conducted analysis on the returned energy pulses from the ranging sensors as described in the prior section. These energy pulses provide range information of the physical environment and processed the information to illustrate the likelihood of the presence of obstacles as a statistical representation within the UGV’s environment. The returned pulses are first processed and represented within a two-dimensional Cartesian histogram grid to represent the confidence of the algorithm in the presence of an object in that cell location by allocating a certainty value within each grid. Further reduction of this information formed a binary histogram that when compared against a prescribed threshold, represented a potential candidate direction for the UGV to steer toward an obstacle-free path. Such a method thus allowed the UGV to visualize its surroundings and obstacles to shortlist its probable paths and select the one that most closely matches the direction toward the objective. The VFH method also takes into account the dimensions of the UGV and its kinematic behavior such as its turning radius to provide a valid steering direction.

The VFH algorithm has also been further enhanced by its developers into the VFH+ algorithm (Ulrich and Borenstein. 1998). The enhanced method was developed to better account for the UGV's trajectory motion by using threshold hysteresis where it accounts for the upper and lower bounds of obstacle detection. Deliberate considerations on the UGV's trajectory to mask obstacles-blocked sectors also enhanced the smoothness of its eventual steering direction. As noted by the developers, incorporation of a cost-based direction selection for its steering direction greatly enhanced the efficiency and reliability of the algorithm. The marked improvement was due to its commitment effect of candidate path selection by selecting those most optimal.

Despite its dynamic nature of computing an obstacle-free path, the performance of the VFH and VFH+ algorithms are still limited to the capabilities of its sensors. This might result in highly localized navigation solution leading the UGV into dead-ends that could have been avoided. Also, the ability for this algorithm to resolve a probable path depends highly on the resolution of the sensor used. This is evident with the poor angular resolution suffered by ultrasonic sensors.

4. Vision-Based Method

As described in the prior section, the use of an image-capturing device offers tremendous amount of useful information for the system. Contributing to the powerful and versatile approach with navigation is the sensors' potential in providing extremely detailed information that might not be available with the other sensor combinations, such as visually differentiating between varying ground conditions. Vision-based method

(VBM) can be broadly categorized by two different working principles (Demetriou 2005). The first method is to compute apparent motion by discerning stationary objects against moving ones when the UGV is in motion, commonly known as optical flow. By comparing the difference between two consecutive images obtained at a set time interval, the algorithm allows the analysis and detection of salient information regarding the surroundings. One can conduct the analysis on the presence of optical flow with multiple analysis techniques such as the differential method, phase correlation method or general variation of methods to estimate flow vectors in order to direct the UGV. The second method employed for VBM is to rely on image processing techniques to detect pixels that differ in appearance to recognize and classify objects deemed as obstacles, and to chart a probable path to steer the UGV.

Demetriou (2005) notes that though both methods were well established techniques in the field of vision-based algorithms, their efficiency remained highly susceptible to varying environmental conditions. The change in the direction or levels of illumination can cause a false recognition of obstacles thus impeding movement. The potential problem of motion discontinuity induced by objects moving with respect to other objects or its background will also cause an incorrect selection for the UGV's required steering direction. He further noted that the use of vision-based algorithms can also be significantly more computational intensive when compared to other navigational techniques.

5. Hybrid Navigation Algorithm

Working around the drawbacks from the various principles in the prior described navigational methods, further research efforts seek to develop a hybrid navigational algorithm (HNA). A common method employed with HNA is the mix of a layered PFM to represent the global environmental conditions from the UGV to its designated objective. Accompanying the layered PFM are subsequent reactive layers to represent the dynamic changes to the localized environment in the UGV's immediate surroundings during movement, and to represent the navigational path for the vehicle.

E. PATH PLANNING ALGORITHM

Forming one of the core functions for autonomous operations of the UGV is the capability of being able to execute maneuvers through the designated waypoints by steering correctly. There are numerous alternatives for each of the algorithms presented, but these were mainly derivations of its original forms. Some iterations of the methods may be platform specific as conducted by the respective studies. Such iterations under various research will still follow the main working principles governing each method described in the following section.

1. Follow-the-Carrot

This algorithm represents the simplest form of path planning and following algorithms. Described by Lundgren (2003), the main working principle behind this algorithm is for the system to lay an imaginary line connecting its current position to the intended goal, and to measure the direct angle lying between the two points. Implementation of a look-ahead distance within the algorithm allowed the UGV to perceive intermediate waypoints along this imaginary line at the prescribed distance. The resultant angles between such intermediate points and the objective position provide steering direction to the system to follow that imaginary line at a constant speed. The main drawback associated with an UGV utilizing this relatively simple algorithm is the tendency of the system to oscillate along its intended path. An inadequate tuning for the look-ahead distance can contribute to the UGV's instability in its maneuver, causing it to steer away from the line and requiring counter steering to bring it back on the correct course.

2. Pure Pursuit

The use of pure pursuit control to steer autonomous systems is widely adopted in many UGV developments. The principle of this control algorithm took into account the curvature required for the UGV to steer from its current position to its intended position (Lundgren 2003). This algorithm first defines an imaginary circle whose lines passes through both positions and calculates the shortest distance between the two points. By specifying a look-ahead distance within the algorithm, it defines the radius of the imaginary circle. This then allows the algorithm to iteratively construct the intermediate arcs between itself and its goal position as it moved, thus, obtaining the required trajectory for it to reach its objective position. Though similar to Follow-the-Carrot algorithm, a pure pursuit control significantly reduced its heading errors, resulting in a smoother trajectory with minimal oscillations along its path.

3. Vector Pursuit

The vector pursuit algorithm is a path following method utilizing theory of screws(Wit 2000). While similar to the abovementioned two algorithms in utilizing a look-ahead distance to define the intermediate waypoints between the UGV's current position and intended goal position, vector pursuit method incorporates the orientation of the two points in its calculations. Wit (2000) highlighted that in this method, characterizing the rotation of UGV along a center line in space offers the instantaneous motion of the system and thus allowing the calculation of the angular velocity about the line. Further extrapolation of this motion can resolve the position and orientation of the UGV's position to its look-ahead distance, hence allowing the calculation of the desired instantaneous motion and direction of the UGV. Wit (2000) also added that though vector pursuit method allows the UGV to arrive at its intended position and heading, there are substantial amount of complexity and computation requirements in order to implement.

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III. SYSTEMS ENGINEERING APPROACH TO PROBLEM

Imperative to comprehensively understanding the operational demands, stakeholders' expectations and technology readiness associated with the unmanned ground vehicle (UGV) development for it to achieve its intended purpose, the systems engineering (SE) process provided a formal methodology to approach the given problem. Identification of the UGV's critical requirements such as its functions, architectures, and potential interactions with its environment or own subsystems aids in applying the correct technologies and implementation plan.

This section explores potential characteristics for the development of the UGV, which would influence the design for the proof of concept prototype. In particular, the focus of the research revolved around the selection and evaluation of a suitable sensor suite together with an optimal technique for the conduct of autonomous operations such as navigation and target identification.

A. NEEDS STATEMENT

There is a need to develop a rapid prototype of an autonomous ground platform capable of navigating through designated waypoints while detecting and avoiding obstacles during maneuver. The platform will also be capable of identifying potential targets at its designated terminal waypoint. Operational environment for the vehicle will be in a cluttered terrain with varying light and environmental conditions.

B. STAKEHOLDER ANALYSIS

Understanding the expectations of the various stakeholders allowed proper addressing and management of their concerns and expectations. This process helped with incorporating their respective requirements into the design of the UGV for it to achieve its required goals. The following section presents the categorization of the stakeholders into four primary categories, based on their influence and interest.

1. Regulators

The regulators allude to the administration of the entire project that included the administrative and strategic bodies such as the government or the DOD respectively. They are in charge of the endorsement of projected expenditure, schedule and general wellbeing of the whole project. Tasked as the executive body for the project, the regulators are empowered with veto rights.

2. Developers

The developers of the program consist of various R&D agencies such as DARPA, academic institutions and defense contractors themselves. This classification of stakeholders refer to various organizations that have a strong interest in the development of the UGV and will ensure that the required technologies are developed, evaluated and implemented in the overall system. They are concerned with the developmental efforts, progress and allocated resources for the system to reach the required level of technology and program maturity.

3. Users

Users of the UGV would primarily reside in the services of the armed forces. This will include the combatants who would be deploying such systems in the frontlines, having a vested interest in its operational efficiency and suitability. Their requirements involve technical reliability for the UGV to operate autonomously with minimal human intervention and to achieve operational efficiency by having its signature kept minimal to avoid premature detection or engagement with an adversarial force.

Other users include the maintenance crew that would be required to perform maintenance and troubleshooting the systems to ensure that they remain available and operational at the prescribed levels. They would be concerned with the ease of maintenance and the availability of spares for rapid equipment turnover on the frontlines.

4. Opponents

Opponents of the program are those who might be against the development of the UGV due to their security interest or beliefs opposing the deployment of an unmanned system in an armed conflict. Security concerns would be primarily from adversarial nations or organizations who might feel that the force multiplying effect of the UGV might skew the any technological advantages in the current battlefield. Other opponents of unmanned system might also include human rights group that opposed the deployment of unmanned system as a combat platform in the theater of war.

Table 1 summarizes the key stakeholders' concerns and their potential impact on the design.

Table 1. Summary of Stakeholders' Analysis.

Stakeholder	Goals	Concerns	Impact on design
Regulators			
Government	To demonstrate technological advantage in war-fighting capabilities. To act as deterrence to potential adversaries.	Budget and time overrun resulting in future budget being cut and credibility reduced. Failure resulting in loss of credibility, governance and public confidence.	Administrators will influence timeline and available budget for the R&D efforts.
Department of Defense	To possess technological, strategic and tactical advantage over adversaries by upgrading current fleet or stockpile of vehicles. To maintain force credibility and readiness even with shrinking manpower.	Budget and time scheduling Technology feasibility and maturity Doctrinal integration with current force structure.	Doctrines would dictate the requirement and performance of UGV.
Developers			
Government linked R&D facilities	To achieve technological maturity for UGV system.	Safe and efficient deployment of UGV with frontline units. Meeting budget and time schedule.	Utilizing tested hardware and software to achieve high technology readiness level.
Defense Contractors	To be awarded development contract for company profit, recognition or innovation.	Market competition. Failure to meet budget and time schedule resulting in financial losses and loss of credibility.	Applicability of system to fit current fleet of vehicles while still maintaining technological superiority.

Stakeholder	Goals	Concerns	Impact on design
Academic Institution	To further R&D funding and accomplishment for improved standing.	Unable to secure research grants Unable to deliver on research objectives resulting in loss of credibility.	
Users			
Combatants	To maintain tactical superiority against adversaries. Ease of integrating UGV into current structure, doctrines and practices.	Efficiency and reliability of UGV as a credible force multiplier.	Usability for operators would influence design and interfacing. Employment of system will be influenced by war-fighting methods.
Maintenance crew	High rate of reliability and ease of maintenance. Availability of spares for maintenance and overhaul.	High complexity of system might impede Battlefield Damage Assessment and Repair (BDAR).	Complexity on the system should be minimized to facilitate the maintenance and turnover.
Opponents			
Adversaries	To maintain own technological edge and ensure that security and sovereignty not compromised.	National security breached due to inferior technology or failure to achieve credibility against UGV.	---
Human Rights Groups	Ensure that conventional rules of engagement (ROE) for warfare not contravened. Continuity and abidance to Laws of Armed Conflict (LOAC) for wartime accountability.	Blurring of accountability and responsibility during armed conflicts. Unnecessary collateral damage/ fatalities during conflict.	Developers and Users might not be able to fully address autonomous operations for the UGV in a full combat engagement role, so as to remain an accountable and responsible global citizen.

C. LIMITATIONS AND BOUNDARIES

In order to determine the systems requirements for the UGV, it is important first to distinguish and describe the system's boundaries and any potential interactions with other external systems such as the operators and the operating environment.

Understanding the boundaries of the system will assist in the recognition of the potential inputs, outputs, interactions and the required interfaces for the system to function adequately. Of particular interest are external systems from the UGV that had been classified as either natural or human systems. Natural systems possessed significant influence on the functional baseline of the UGV due to them being beyond any practical human control, such as the environmental conditions. The uncontrollable nature of such systems requires the development of the UGV to include technologies capable of mitigating such limitations in order to achieve the desired performance. Human systems on the other hand are manageable entities, such as the operators, developers or sponsors. Human systems must therefore be accorded with adequate management to ensure success of the overall system development.

1. Natural Systems

These entities are systems present in the natural world and are beyond any practical controls of the system developer.

a. Illumination Condition

The operational environment consisting of the day and night operations together with the surrounding vegetation and overhead canopies will result in varying levels of illumination that can reach the UGV. This variation in luminance requires the sensors onboard the UGV to discern such feedback noise in its detection and be resilient to the variables in order for it to function efficiently.

b. Surrounding Vegetation

Density of vegetation surrounding the UGV might hinder the propagation of energy beams from active sensors, thus having an effect on the performance of the system to discern between a path and a potential obstacle, or its ability to detect a potential target. The density of vegetation in a tropical environment is significantly thicker than that found in a continental climate. The abundance of tall, broad leave trees form the dominant plant type in such a climate hence might attenuate external communication means such as GPS signals. This can render the use of such technologies infeasible for the development.

c. Ground Conditions

Similarly, for ground conditions, the tropical climate can rapidly transform relatively dry ground conditions into a muddy terrain. This will require the vehicle to account for the necessary compensatory maneuvers in order for it to maintain the correct trajectory during movement and for accurate position estimation. The rapid downwash of rain in such an environment might also affect the appearance of natural dirt paths to look similar to a muddy ground, which may cause the system perceive it as an obstacle and being impassable.

d. Atmospheric Conditions

The high humidity levels and density of particulates in the air can affect the performance and reliability of the UGV and its subsystem. This might be especially apparent with active sensors where the attenuation or losses from the emitted energy beams will cause distortion in the sensor readings. The atmospheric conditions can also affect the signal refraction on the surface of the target, aggravating the attenuation effect. All of these will have a consequence on the sensor's performance, thus affecting the overall accuracy and efficiency of the autonomous navigation capability.

2. Human Systems

Human systems are generally able to be adjusted and influenced according to the requirements and needs expected of the project. This section discusses the expected human systems that the UGV would interact with through its development and deployment.

a. Operator's Input

Human operators will be required to input the necessary waypoint and mission information required for the UGV to perform its navigation task autonomously. The UGV will also be able to perform as a remotely controlled vehicle by an operator through a wireless connection. The wireless connection will transmit the commands and instructions as instructed by the human operator while also providing status and environmental feedbacks back to its controller.

b. Developers

The engineers and contractors who will design and build the UGV are required to provide technical support during maintenance and troubleshooting, and to provide training to the users prior to product delivery. The developers will need to analyze, troubleshoot and rectify any issues encountered by the UGV during its course of deployment.

c. Sponsors

The sponsoring stakeholder is the ultimate approving authority for allocating the budget for the project development. As such, this party can dictate the direction and scope of the project or terminate it altogether as deemed fit. The sponsors are also responsible for providing national and strategic level oversight for the development of the system to ensure that it fulfills the required missions and achieves its intended goals and outcomes.

D. CONCEPT OF OPERATIONS

Having analyzed the needs statement, stakeholder analysis and the boundaries of the system, there is a need to establish the concept of operations, operational scenarios and its various vignettes. This will allow for the continuous identification of the system's operational and functional requirements, as well as to better understand any mission limitations or to plan for contingencies. It should be noted that the operational scenario and associated vignettes are meant to facilitate strategic level discussions on what we expect the system to do and not how the system is going to execute its intended functions.

1. Projected Operational Environment

Large-scale developers conducting research efforts and design for military UGVs have focused their attention for the development of vehicles deployed in continental climates such as that in central parts of Asia and North America. The focus of this research will however look at operations in jungle environment where it comprises largely of densely forested areas, farmlands, plantations and grasslands such as that found in Southeast Asia (Department of the Army 1982).

a. Environmental Conditions

One could classify the environmental conditions in Southeast Asia (SEA) to be of a typical tropical climate with frequent rainfalls averaging 178 days in a year and approximately 200mm of rainfall. The environment is also expected to have high and uniform temperatures (74°F to 93°F) and relative humidity (>75%) all year round, with wind speeds averaging 35kts. Developers can expect maneuvers to take place in both day and night conditions under the abovementioned weather conditions.

b. Ground Conditions

The UGV deployed in this region would expect ground conditions to be of non-tarmac surfaced or dirt track that traverse the Area of Operations (AO). The system will also expect other kinds of route conditions such as light gravel or light clay-type sand surfaces. Due to the high level of precipitation expected in the region and presence of irrigation canals in cultivated area, ground conditions are generally damp with an occasional down wash that transforms such access to turn muddy.

c. Terrain and Vegetation

Owing to the tropical weather in the locality, the UGV would expect vegetation to be significantly dense, consisting of tall trees with interlocking canopies from as low as 10 m from the ground upwards. Apart from an occasional fallen tree or construction of manmade routes, the trees would form a contiguous canopy that severely attenuate any aerial wireless transmission from reaching ground level. Due to the thick overhead canopies resulting in the lack of sunlight reaching the ground, there is a lack of any thick vegetation at the lower heights, thus permitting maneuver. The only major impediment in movement might be caused by the extensive above-ground root systems or the occasional hanging vines, both of which are commonly found in such regions.

The UGV will also expect occasional movement through plantations and farmland types of agricultural land found in the AO. Such regions will find trees such as rubber or coconut crops planted in an organized and properly spaced out manner to aid with the implementation of proper irrigation canals. Though dense overhead canopies are still present in such estates, they are usually free of undergrowth and root formations that greatly facilitates movement. The relatively open space between the trees also allows wireless transmission from ground means.

2. Operational Scenario

The design of the UGV expected three modes of performance with varying degrees of autonomy: 1) tracking and trailing behind a manned vehicle, 2) operating remotely through wireless means, and 3) navigating autonomously to an objective point while avoiding obstacles. As described in the following section are details of the implementation and context for each deployment.

a. Tracking and Trailing Behind Manned Vehicle

In order to reduce manpower overheads when deploying in the frontlines while also maintaining superiority in firepower and maneuverability, the UGV can perform a role as an armed escort or wingman, or as a logistic transporter to haul supplies alongside its manned vehicle, or its master. Programming of the UGV in the initial stages of the mission allows the operators to activate its tracking system and register its intended target for the UGV to follow, in this case, its master vehicle. When required, the operator in the master vehicle can also activate the UGV to adopt an offensive stance by coming abreast its manned vehicle as a fire support vehicle, though the final fire command and control would still reside with operator.

b. Wireless and Remotely Operated

As part of its intended mission to reduce operational risks exposed to the warfighters, the deployment of the UGV serves this purpose. This will include missions as a force vanguard to the main body of the vehicle fleet by performing reconnaissance roles. The remote deployment of the UGVs to probe unknown territories will detect any adversary presence without the need to commit troops upfront. The purpose of deploying an UGV can be extended to missions where there is a need investigate any potential obstacles or traps during the force's advance along its main supply route. Used in an ad-hoc nature, activation of the UGV in these scenarios occurs when the ground commanders deem it as necessary to reduce risk exposure to their troops or assets.

c. Autonomous Navigation and Operation

Similar to the operations as described for the armed wingman and remote operations scenarios, a fully autonomous operation provides a more deliberate tactical option for ground commanders to deploy at the frontlines. This can serve a strategic purpose of probing and investigating potential breakout points for one's own forces as it advances beyond the Forward Edge of Battle Area (FEBA). There is a need for more deliberate planning to navigate through passable terrain for the UGV and to allocate sectors that might be pertinent to intelligence gathering. The UGV will be able to maneuver through the prescribed area of interest without any subsequent human intervention. Further use of such autonomous behavior might also include perimeter defense or patrol missions where the UGV will maneuver through a designated route, and wirelessly transmit any findings back to its control station. The system will also be able to recognize and track any designated target types as required during the mission with its image-capturing capabilities.

d. Commonality in Mission Scenarios

This section describes the common operational activities that occur within each operational scenario. Such activities include the pre-mission preparation, execution and post-mission maintenance.

(1) Mission Pre-deployment Phase

The UGV will first conduct its start-up BIT prior to programming of the required mission profiles described in the prior section. The conduct of the test ensures that all critical features such as its drivetrain system, navigation system, and communication system together with the sensor suite are all in fully functional conditions. The inclusion of a user interface or a control station allows the user to access the BIT information and feedback and provide an avenue for programming user inputs or receiving subsequent mission feedbacks. The user interface also allows the monitoring of the system status by its operators.

(2) Mission Execution Phase

There is also a requirement for the UGV to be able to communicate to its control base or master vehicle during the deployment phase for subsequent commands or to transmit information from the UGV back to the operator for further analysis when required. The operational context envisaged in the prior sections also includes deployment of the UGV in terrains where the limitations for aerial RF transmission severely restricts the GPS signal propagation due to its intermittent connections. The UGV should also be able to perform and monitor its own statuses to ensure that it is performing within its prescribed limits and not suffer from any premature failures.

(3) Mission Recovery Phase

Having achieved the key objectives of the mission, the UGV vehicles would be required to navigate its way back to a prescribed location or back to its base station. The operator can conduct further analysis and extract the recorded mission information from its deployment. The conduct of preventive and corrective maintenance of the UGV also ensures that all mechanical issues are resolved and sensors are still operational.

3. Stressor Vignettes

Shown in Table 2 are vignettes that describe specific operational scenarios that might occur during the course of operation or maneuvering that could affect the operational efficiency of the UGV. This process of stressor identification would further augment the postulated operating conditions and allow the design of a robust architecture capable of handling a wider range of operations.

Table 2. Identification of Likely Stressor Vignettes Used in Study.

Scenario	**Description**
Scenario A UGV Communication Failure	This scenario depicts the loss or degraded performance of the communication/ navigation system onboard the UGV with external RF signals from the base station. This will result in failure to transmit data wirelessly for data communication or navigation.
Scenario B UGV Encountered Adverse Environmental Conditions	This scenario depicts the encounter with adverse weather that might be triggered by the monsoon season where unusually high rainfall or strong winds might cause performance degradation. This might result in a higher susceptibility to position misrepresentation.

a. Scenario A—Communication Failure

Following the conduct of the various start-up BIT on the UGV, it will seek to establish a wireless connection to the ground control station or master control via its various frequencies. The operator would access all feedback results highlighted from the conduct of the BIT through the user interface, and remain informed of the status for the various subsystems and strength of the communication network.

Wireless networks might be able to cross various RF bands depending on the communication suite installed. Any further failures to connect to the network might trigger a prompt to the operator for the option to connect the UGV's communication network via a separate proxy such as other portable radio systems.

The UGV will register continuous network connection failures as an error message on the operator's user interface, before switching the system into a standby mode. The UGV will then record this error within the system's mainframe computer as an error log for further diagnostics during its servicing or its next successful connectivity.

Should communication failure occur midway of an operation, the UGV will remain stationary with all mechanical device shutdown to reduce its signature and susceptibility to enemy's detection. Its last known position would, however, continues to be broadcasted wirelessly to its master node for recovery.

b. Scenario B—Adverse Environmental Conditions

With the seasonal monsoon season occurring twice annually in the region, there might be occurrences of peculiarly high rainfalls that result in inundated stretches on the routes. Though the higher level of surface water might not severally affect the performance of the UGV, the secondary effects from excessive erosion of the soil might cause a potential slipping effect when maneuvering, and affect any motion readings used to track direction or distance. This will eventually have an effect on the accuracy of the position estimation for the vehicle.

The higher rainfall might also obscure the FOV or performance of the sensors found onboard the UGV. The developers will include specific design considerations to protect the sensors' surface from the effects of the rainfall or splashes. Such design considerations will also include accessories such as rain shields to divert rainfall quickly away from the sensors' operational FOV.

E. FUNCTIONAL IDENTIFICATION AND ANALYSIS

Functional analysis is a method of gaining insight into the purpose of a system by breaking it down and analyzing each component it incorporates. Through functional analysis, the system requirements for the UGV can be determined to allow for subsequent design of the system. A key step in functional analysis is to perform functional decomposition, whose purpose is to identify and decompose the critical functions of the system, as shown in Figure 1. One should note that functional decomposition focuses primarily on what the UGV must do and not how the UGV will go about doing it.

1. Functional Decomposition

From the analysis done on the operational scenarios and stressor vignettes, it was determined that the UGV would be required to perform six primary functions to conduct autonomous navigation adequately. Described in the following section is the functional decomposition where the core functions of the system are broken down into their sub-requirements for greater clarity.

a. Function 1: To Maneuver

To allow the UGV to traverse through the designated AO, and move to intended mission. The platform shall be capable of by providing mechanical means of power and directional steering for it to maneuver its required path and to also negotiate or overcome the projected operational terrain.

(1) Function 1.1: To Provide Propulsion

The UGV shall be able to generate sufficient energy to sustain its movement across the surface and be able to overcome various obstacles expected in its AO. The propulsion shall also be able to control torque generation for it to move at different speeds and terrain, or to generate sufficient power for maneuvering at different mission profiles. The propulsion shall also be able to provide sufficient power in order to accommodate the required operational loads expected of the UGV during its mission.

(2) Function 1.2: To Provide Steering Kinematics

The UGV shall be able to change its directional heading in order to maneuver around or over obstacles. It shall also possess a full range of forward and backward steering motion with a drivetrain capable of delivering power and control to all wheels.

(3) Function 1.3: To Provide Braking Power

The UGV shall be able to control power delivered to the drivetrain and control its speed by being able to apply sufficient braking power to the wheels. This will enable proper control of the system and prevent collisions.

b. Function 2: To Monitor Self Status

In order to increase autonomy for the system, it must be able to monitor its own status and troubleshoot where possible. The system should be designed with redundancy functions for critical functionalities and be able to switch to the alternatives if required.

(1) Function 2.1: To Conduct Built-In Tests

The system shall be able to conduct periodic BITs in order to ensure functionalities are operational. The platform shall be able to communicate information derived from the BITs to operator's control interface and archived for further monitoring or any required intervention during its mission.

(2) Function 2.2: To Monitor Internal Temperature

The system shall be able to monitor critical internal statuses such as its internal temperature to ensure that performance of the electronics are within the prescribed operational conditions. This forms a critical function due to the UGV operating in a tropical region where the higher ambient temperature might have an impact on the sensitivity and accuracy of the equipment, in particular on its electronics and sensor suite.

(3) Function 2.3: To Monitor Encoder Readings

As part of its proprioceptive sensors, the encoder readings would allow the tracking of the UGV's movement by processing the readings through the platform's mainframe computer to obtain its estimated position.

c. Function 3: To Communicate Externally

The system shall be equipped with appropriate communication suite for it to maintain contact with other nodes or operational equipment efficiently. It shall be able to communicate over the required frequencies and data-links for it to maintain the constant status update status with its master control or operator's control located in the master vehicle or the operational headquarters (HQ).

(1) Function 3.1: To Receive Wireless Transmission

The UGV shall be able to receive commands transmitted from its master control to receive remotely sent commands or to receive revised mission profiles. The platform must have the capabilities to receive such wireless transmissions within the required frequency ranges.

(2) Function 3.2: To Process Wireless Transmission

The UGV shall be able to demodulate received wireless transmission in order to decrypt and process such instructions into a recognizable form, which are identifiable by the various subsystems. These coherent instructions will enable the execution of specific commands as directed by the transmitting source.

(3) Function 3.3: To Transmit Wireless Transmission

The system must be able to transmit data (telemetry, status, images, information etc.) back to its master node so that operators can monitor, analyze and decide on the required course of actions.

(4) Function 3.4: To Provide Onboard User Interface

An onboard panel to display BIT and connectivity status would aid the operator or maintenance crew to conduct diagnosis in the field and to understand the operational status of the UGV. The user interface shall be able to display basic information during the start-up procedure or to display more details during the conduct of BDAR. The user interface shall also be able to provide means of connection with external peripherals for the extraction of information from the UGV.

d. Function 4: To Sense Environment

The UGV shall be equipped with capabilities for it to determine surrounding environmental conditions for it to understand its surroundings and avoid impassable terrain. Detection of external factors will also add robustness to the conduct of localization by the UGV by being able to have more accurate position estimation.

(1) Function 4.1: To Measure Bearing Traveled

Apart from the encoder readings, the use of an additional exteroceptive sensor can perform tracking of any changes in the bearing that the UGV's maneuver. The extracted and processed information offers higher resolution for the position estimation and tracking.

(2) Function 4.2: To Measure Distance Traveled

Similar to the prior function, the use of exteroceptive sensor can also sense the change in distance moved in order to get better resolution in position estimation and tracking.

(3) Function 4.3: To Sense for Presence of Objects

The UGV shall be equipped with additional sensors for it to understand its surroundings in order to recognize the presence of objects around it. This metadata of objects in the UGV's vicinity can be processed and analyzed so that it can calculate a feasible path while discerning any obstacles within its trajectory.

(4) Function 4.4: To Determine Range of Detected Objects

Knowing the presence of any obstacles will require the UGV to understand their range from itself. The range information is to allow calculation and application of proper kinematic response to avoid obstacles along its maneuver path.

e. Function 5: To Analyze Sensor Information

The ability for the UGV to conduct autonomous navigation across its AO depends largely on its ability to receive, analyze and subsequently fuse information from various sensors in a timely manner. The accurate response from the integration of information collected will then allow the execution of a calibrated response so that the UGV can traverse without any obstacles collision.

(1) Function 5.1: To Transfer All Sensor Information

There is a need to transmit all sensor information to a central processor to achieve coherent data fusion for the purpose of downstream computation and analysis. This will require a low latency and error transfer rate of information.

(2) Function 5.2: To Process and Fuse Sensor Information

In order to enable coherency in the data collected from the environment, there is a need for a centralized processing of all the metadata. The UGV will have its sensors placed at different heights and positions across its chassis; there is a need for the processor to fuse this information into a common reference frame so that the information would remain logical and consistent for the system to comprehend. This function shall also be able to process the information for the applied algorithms to function adequately.

(3) Function 5.3: To Calculate Trajectory

With the availability of coherent information of its surrounding after the fusion of the metadata, it will thus be possible for the UGV to calculate an available trajectory for it to reach its intended objective position. The processing of the path will require the processor to be powerful enough to fuse the collected real time sensor information, and to calculate the required trajectory based on the dynamic environment simultaneously.

(4) Function 5.4: To Determine Current Position

In order for the system to achieve the required fidelity of localization, there will be a need for the UGV continuously to keep track of its estimated position from the start. This function will thus require the system to monitor its bearing and distance traveled to watch its movement and position accurately. This function works with information obtained from both its onboard encoders and/or other sensors such as the gyroscopes and digital compass.

(5) Function 5.5: To Archive Data

Processed data can be archived for future reference should there be a need for the UGV to revisit its traversed route. The operators shall be able to reconstruct the archived information of the AO into an updated operational map. The metadata archival could also provide as an invaluable intelligence source for analysis by higher commands. The UGV's maintenance crew can track the platform's usage, project its maintenance requirements or to inspect any potential system failures from the archived information as well.

(6) Function 5.6: To Execute Navigational Instructions

Upon the computation of a feasible trajectory, there is a need to transfer and translate the required kinematic movements to the drivetrain of the UGV for it to execute the maneuver. This will require the subsystem to take into account the current movement of the UGV and to adjust its steering to achieve the calculated trajectory path.

f. Function 6: To Provide Electrical Power

Electrical power is required to power the various systems and subsystems throughout the mission such as its sensor and communication suites.

(1) Function 6.1: To Store Power

The system will be able to efficiently charge and store any harnessed electrical energy generated from its movement. The UGV shall also be able to tap and utilize its stored power to sustain its operations.

(2) Function 6.2: To Distribute Power

Different subsystems onboard the UGV would require different operational voltages. The power distribution is to ensure a steady stream of power channeled to such devices to allow fully operational capabilities without any interruption.

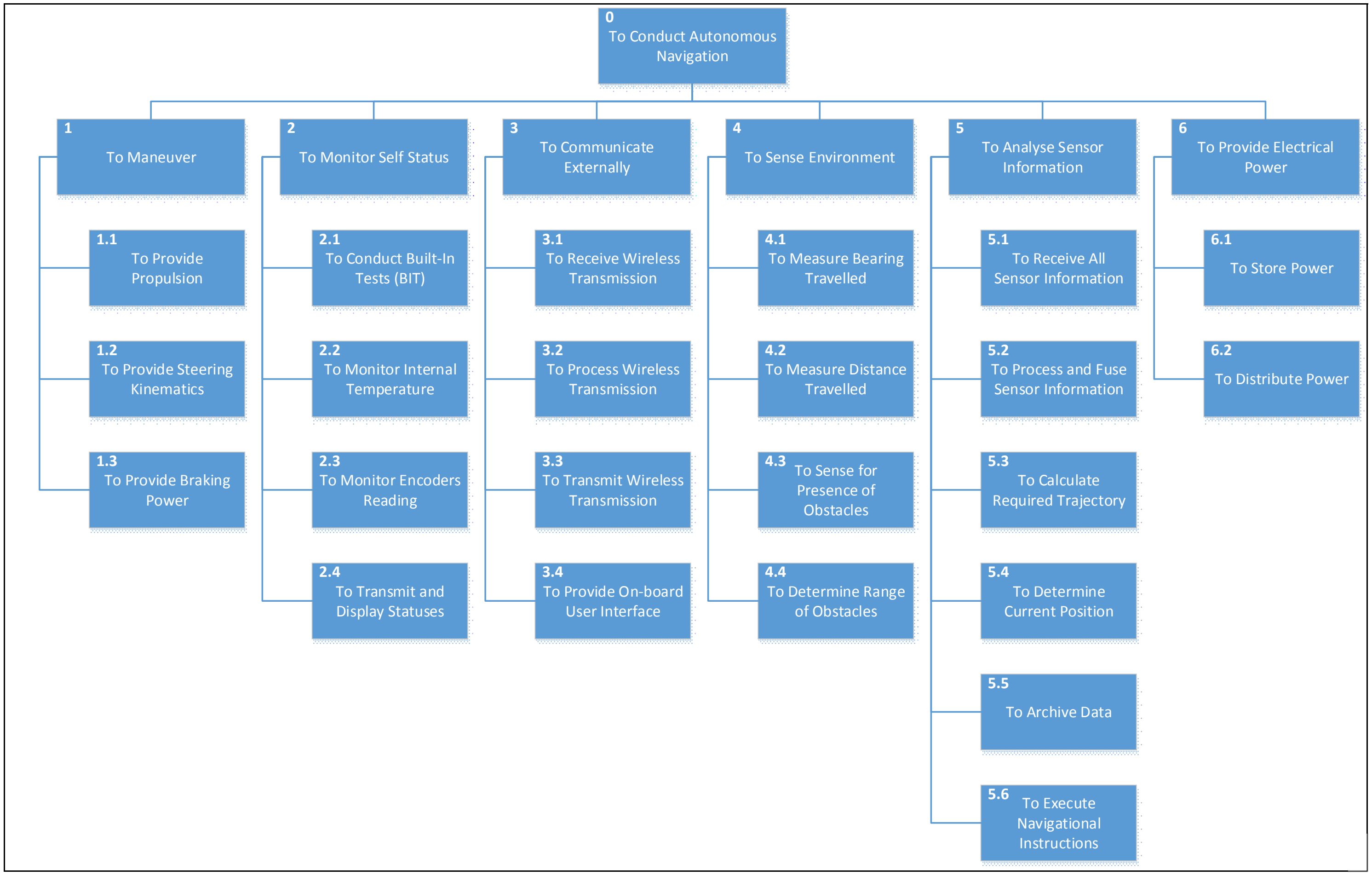

Figure 1. Functional Decomposition to Perform Autonomous Navigation.

2. Functional Flow Block Diagram

Using the operational scenario and functional decomposition as described in the prior sections, the next step is to understand the system's functional flow at various phases of the mission. The identified profile allowed further exploration of the various trigger points that might be required to initiate any follow-on functions. This profile also offered an opportunity to understand the requirements for information flow through the system to ensure the accommodation of the required data and control triggers. The use of the following two operational situations (OPSIT) illustrates the developer's key considerations during the design of the UGV.

a. OPSIT 1—General Deployment of UGV

Figure 2 illustrates the high level functions required for the use of the UGV in a scenario where autonomous navigation would be required. The primary focus for this OPSIT is to explore the key communication interfaces and information flow required between the UGV and its operator through its deployment.

Upon the conclusion of mission planning and pre-operations check of the UGV, there is a need for a user interface for the operator to input key operational and navigation data into the UGV system. This information includes required navigational waypoints and contingency plans for extraction of system should any failure occur.

With the deployment of the UGV for its mission, continuous communication between the system and the operator will be necessary in ensuring the transmission of up-to-date operational information back to the operator for further analysis or intervention. There are concurrent activities required from the sensor suite to detect its surroundings while monitoring its position before it can calculate the required obstacle-free trajectory to reach its goal.

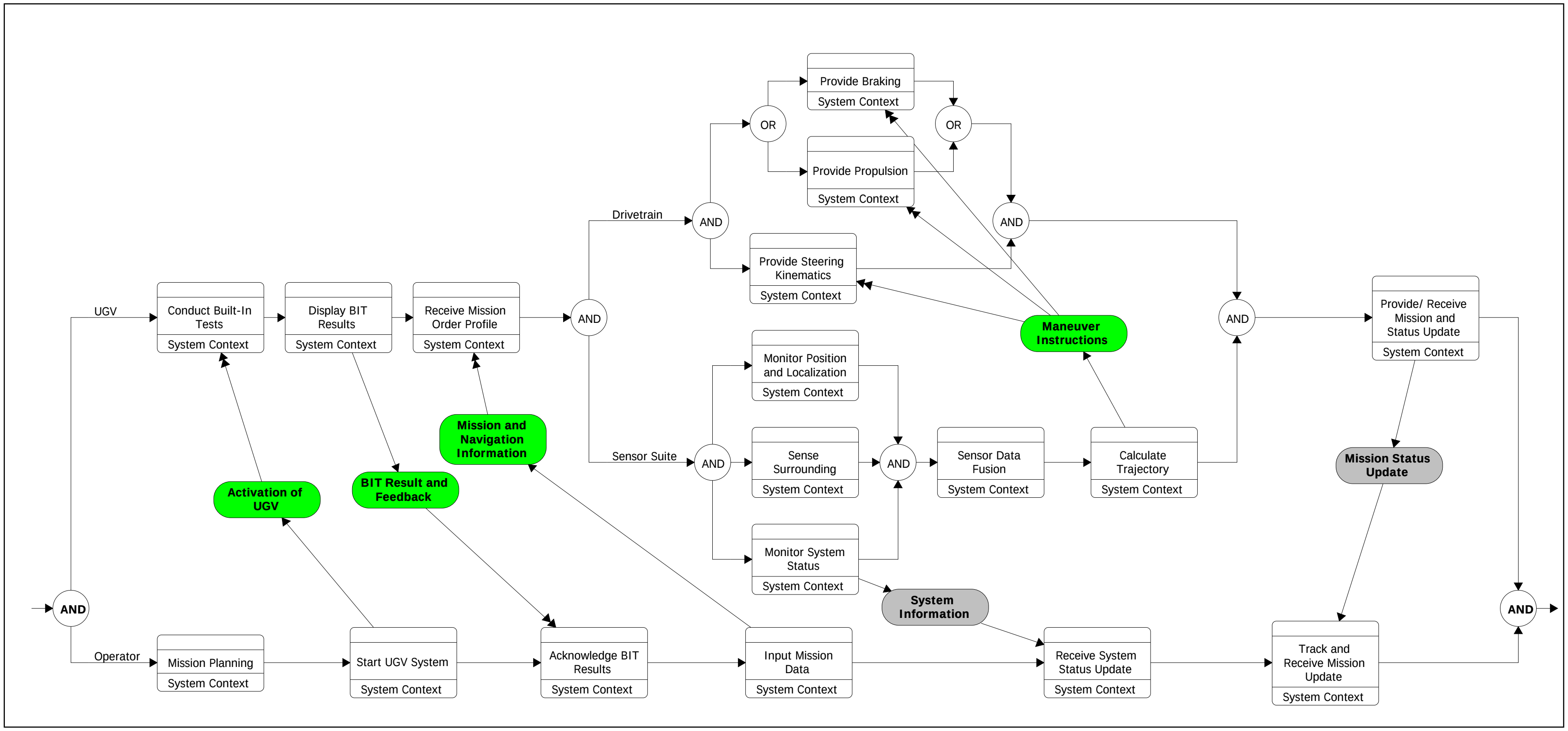

Figure 2. Operational Situation for the Proposed General Deployment of the UGV.

b. OPSIT 2—Communications Failure

This OPSIT describes one of the stressor vignettes highlighted in the prior section where communication failure occurs and is illustrated in Figure 3. The occurrence of such a situation happening might be very likely due to the close terrain nature of the operating environment where wireless signals can suffer high loss rates or be attenuated to the point of communications failure. Therefore, there is a need to explore the required operational protocol or actions to reestablish communications. Such procedures might include the need to plan for mission contingencies such as a tactical rendezvous point for the system's extraction should it fail to maintain a strong communication link with its operator.

The operator must be able keep an effective oversight over the unmanned system through the deployment to not only receive and monitor its status, communicate updated positions and battlefield information, but also to transmit any ad-hoc mission essential updates to the UGV. Therefore, it requires a robust communication suite onboard the UGV to detect any loss of connection and automatically attempt to reestablish the data link. Any subsequent failure will also prompt the system to switch the transmission of information over a different radiofrequency band automatically. Should the attempt at reestablishing the network fail, it will also be necessary for the system to record the data for future extraction.

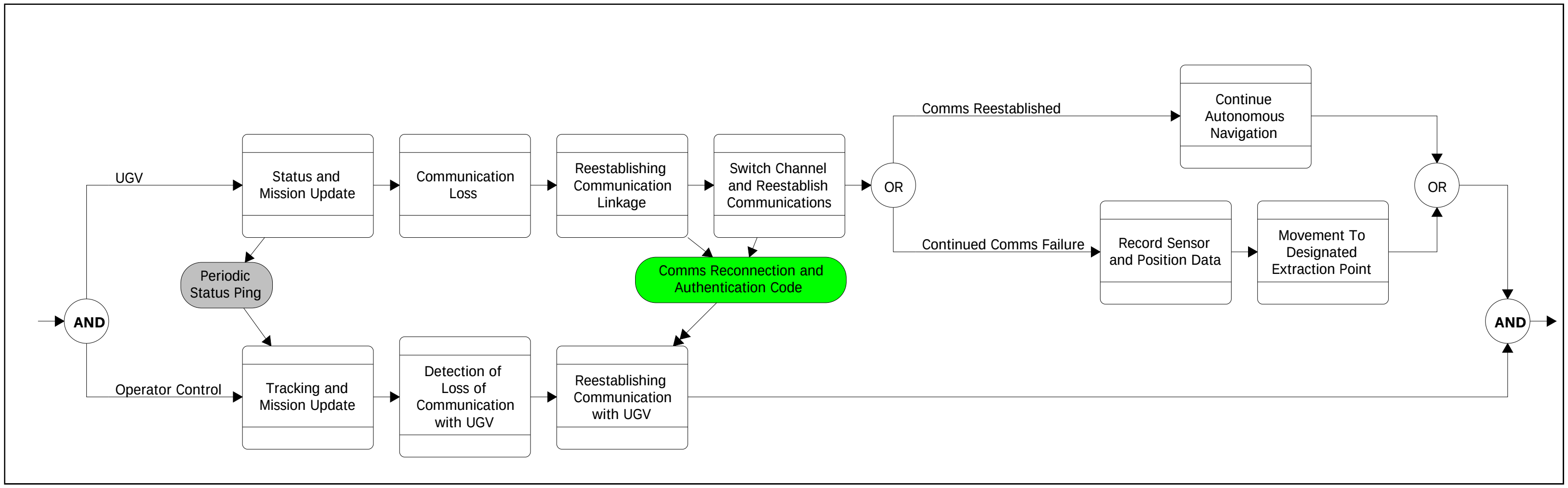

Figure 3. Operational Situation of UGV Experiencing Communications Failure.

F. COMPONENT EVALUATION

Based on the requirements identified from the prior systems engineering approach, the author conducted an evaluation to ascertain and implement the optimal hardware and algorithm for the prototype development. The selection done at this stage is only for the construct of the prototype.

1. Evaluation Methodology and Criteria

The author adopted the Analytic Hierarchy Process (AHP) to evaluate the various candidates proposed in Chapter II to fulfill functions required in the development of the UGV. AHP conducts a pairwise comparison between the candidates and weighs their relative strength of one system to another. The selection was to derive the optimal candidates that would fulfill the purpose of developing our prototype. Three evaluation criteria formed the principle considerations in this evaluation to ascertain the suitability and optimality of the technology to this study. The rationale for the three considerations is as follows:

a. Ease of Implementation

In order to provide rapid development of the prototype, due considerations had been made to minimize unnecessary system complexity. This criterion described the ease of implementing any given hardware without any requirements of proprietary connections or associated devices, and the ease of integrating them in a suite where required.

The author applied similar considerations for the evaluation of the algorithms. Forming the considerations were the need for easily tunable parameters and its complementary effects with the prescribed hardware.

b. Accuracy

Designed for use in a cluttered environment, the accuracy of the hardware and algorithm plays a key role in the success of the prototype navigating autonomously. This would be in the form of accurate feedback for the algorithm to function. Therefore, it was given due considerations to be encompassed in our evaluation criteria.

c. Availability

Another criterion key to the possibility of rapid prototyping is the availability of the given hardware and tools to implement the algorithms. This criterion determines the availability and reliability of the equipment that is in possession of the facility to aid in the development.

2. Evaluation Results

Utilizing AHP as an evaluation tool along with the three mentioned criteria that were weighted equally, the following section presents the summarized scores for the hardware and algorithm selection.

a. Sensor Suite Selection

The comparison of sensors for the development of the prototype was to ascertain the optimal sensor requirements for the system to detect the presence and range of obstacles, with the evaluation results summarized in Table 3. The candidates for this category are the range sensors described in Chapter II. From the evaluation conducted, the LIDAR sensor achieved the highest score among the other candidates. The ease of integrating and processing LIDAR scan information for subsequent data fusion was relatively undemanding as the returned pulse of emitted energy can be clearly resolved with minimal post-processing. The high score achieved by the LIDAR sensor was also largely due to its offering of superior angular resolution, allowing it to resolve the range and presence of obstacles with appreciably better accuracy than the rest. The ready availability of the LIDAR in the facilities also allowed it to score higher than others did.

Table 3. Summarized Scores of Sensor Evaluation for UGV Prototype.

	Local Score			**Global Score**
	Ease	**Accuracy**	**Availability**	
Acoustic Sensor	0.07	0.05	0.26	0.130
LIDAR	0.36	0.37	0.29	0.340
Light Sensor	0.05	0.10	0.07	0.071
Camera	0.29	0.17	0.26	0.241
Radiofrequency	0.23	0.31	0.11	0.217

The evaluation in this study also resulted in including the image camera to complement the use of the LIDAR as the system's sensor. The rationale to install an image camera is to allow the UGV to have the capability of identifying and tracking a potential target, but also to incorporate the growth potential for the UGV to expand on its detection capabilities through image processing with future developments of the vehicle.

The additional inclusion for the use of an inertial measurement unit (IMU), despite it not being part of the evaluation, was to provide higher accuracy displacement tracking in lieu of encoders. The IMU performed the tasks of measuring acceleration, bearing and displacement of the system during movement.

b. Obstacle Avoidance Algorithm Selection

The conduct of the evaluation for the identified algorithms followed the use of AHP, with the results summarized in Table 4. The evaluation results displayed superior resolving capabilities for the VFH method when compared to the other algorithms. The primary factor attributing to this result was the algorithm's capability to react to any detected obstacles dynamically from the sensors' feedback; thus allowing the system to remain proactive in a foreign environment. This capability would be significant advantage for VFH when compared to the other algorithms as it significantly minimizes the amount of pre-planning required to identify obstacles prior to the commencement of the mission. Hence, the implementation of this technique would provide higher fidelity and efficacy for the development of the UGV. From the evaluation, the author observed that the VFH method offered a better balanced algorithm with its ease of implementation and accuracy required for the identified purpose.

Table 4. Summarized Scores of Obstacle Avoidance Algorithm for UGV Prototype.

	Local Score			Global Score
	Ease	Accuracy	Availability	
Bug Algorithm	0.41	0.04	0.29	0.247
PFM	0.22	0.10	0.29	0.205
VFH	0.22	0.29	0.29	0.267
HNA	0.08	0.29	0.06	0.140
Vision-Based	0.08	0.29	0.06	0.140

c. Path Following Algorithm Selection

It is critical for the UGV to track its movement via designated waypoints, so the final evaluation component was for the path following algorithm. As shown in Table 5, pure pursuit method scored the highest in the evaluation due to its well-balanced abilities to conduct relatively accurate tracking while also being suitable for the rapid prototyping, with its complexity significantly easier than vector pursuit. The system mobility can easily be characterized in a two-dimensional space, not requiring the added features offered from the vector pursuit method. Pure pursuit algorithm would also offer significantly better control and accuracy when compared to Follow-the-Carrot algorithm, despite the latter being easier to implement.

Table 5. Summarized Scores of Path Planning Algorithm for UGV Prototype.

	Local Score			Global Score
	Ease	Accuracy	Availability	
Follow-the-Carrot	0.48	0.14	0.43	0.350
Pure Pursuit	0.41	0.43	0.43	0.421
Vector Pursuit	0.11	0.43	0.14	0.229

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IV. UGV PROTOTYPE DESIGN

A. HARDWARE DESCRIPTION

This section outlines the hardware utilized in the development of the UGV prototype. The chosen hardware includes those from the prior evaluation and formed the basis of the various subsystems that made up the eventual prototype.

1. UGV Platform—Pioneer 3AT Robot

The UGV platform used for the prototype development is a Pioneer 3AT robot from Adept Technologies, Inc. This platform has the capability of powering various sensors from its powertrain and is equipped with its own wheel encoders to monitor its position and orientation during movement. Powering the platform are three 7.2Ah batteries that provide approximately two hours of operations. Spliced onboard are also two 5V and two 12V connectors to connect devices such as the installed computer and sensors. The key performance specifications of the platform are shown in Table 6.

Table 6. Key Performance Parameters of Pioneer 3AT Robot.

Parameter	Specification
Maximum Speed	0.7 m/s
Turn Radius	0 cm
Swing Radius	34 cm
Weight (Platform)	12 kg
Dimensions (LxWxH)	508mm x 497mm x 277mm
Nominal Radius	344mm

2. Mainframe Computer

The main controller fusing and performing all calculation is the central processing unit (CPU). This component runs on Ubuntu 14.04 OS with software suites utilized in the construct of the UGV installed on its hard drive. The CPU is the mainframe that accepts all information from the various sensors, fuses the information together and computes all algorithms to find a feasible solution for executing all autonomous tasks. The powertrain found onboard the Pioneer 3AT robot will provide electrical power to the computer, and requires a DC-AC inverter to bridge the power interface for converting the onboard 12V power to the computer's requirement of 110V. Summarized in Table 7 are the key performance parameters of the mainframe computer.

Table 7. Key Performance Parameters of Onboard Mainframe Computer.

Parameter	Specification
Processor	Intel i7-3770
RAM Capacity	16 GB
Storage Capacity	120 GB
Graphics Processor	Intel Ivy Bridge Graphics
Interface (Power)	110V, bridged using a DC-AC inverter

3. LIDAR—Hokuyo URG-04LX

The purpose of the LIDAR used in this development is to sense and determine ranges of any obstacles found along the designated path of the UGV during autonomous movement. Feeding the readings obtained from this sensor into the VFH algorithm computes a feasible path. Summarized in Table 8 are the key performance specifications of the Hokuyo LIDAR.

Table 8. Key Performance Parameters of Hokuyo URG-04LX LIDAR.

Parameter	Specification
Detection Range	60—4095 mm
Scan Angle	240°
Angular Resolution	0.36°
Interface (Data)	USB 2.0 Full Speed
Interface (Power)	Dedicated 5V DC

4. Image Capture—Logitech Pro 9000

The employment of an image camera allowed the system to fulfill the function of identifying and tracking a potential target, and offered downstream capability-growth potential for future iterations of the UGV. The key specifications of the Logitech camera used in the prototype are described in Table 9.

Table 9. Key Performance Parameters of Logitech Pro9000 Webcam.

Parameter	Specification
Focus Type	Auto
Image Resolution	1600 x 1200 pixels
Field of View	150°
Interface (Data)	USB 2.0 Full Speed
Interface (Power)	Dedicated 5V DC

5. Orientation Sensor—Redshift Labs UM7-LT

The use of the UM7-LT orientation sensor within the development of the UGV allowed highly accurate tracking of the system displacement and attitude during maneuver. It offers the capabilities of a digital compass, accelerometer and gyroscopes to monitor the vehicle’s movement in various axes. The key specifications of the Redshift Labs orientation sensor used in the prototype are as described in Table 10.

Table 10. Key Performance Parameters of Redshift Labs UM7-LT Orientation Sensor.

Parameter	Specification
Output Data	Attitude, Magnetometer, Accelerometer
Roll/ Pitch Accuracy	± 4°
Angular Resolution	0.01°
Interface (Data)	USB 2.0 Full Speed
Interface (Power)	Dedicated 5V DC

6. Wireless Communication—Linksys WUSB54G

In bridging a wireless network between the master computer and the UGV, the inclusion of a Linksys wireless dongle allowed for wireless transmission and reception while providing high data transfer rates. However, one must note that the use of Wi-Fi might only provide an approximate proxy for the actual communication suite installed on military vehicles. The key specifications of the Linksys wireless dongle installed on the UGV's mainframe are described in Table 11.

Table 11. Key Performance Parameters of Linksys WUSB54GC Wireless Dongle.

Parameter	Specification
Network Protocol	802.11g
Max. throughput	54Mbps
Connection Interface	USB 2.0

B. SOFTWARE DESCRIPTION

The development of the UGV prototype required various software programs for the UGV to communicate and process the various information made available during its mission. The correct interfacing of the software would thus allow the system to leverage on the various layers of software capabilities to execute proper control of the UGV. The UGV development included the use of three primary software programs. These software programs not only perform the role of providing a suitable software environment for communications between the various subsystems of the UGV and the subsequent computation of information, but also perform the role as a controller to execute required maneuver instructions. The software programs used in the development are as described in the following section.

1. Robot Operating System—"Indigo" Build

The low-level software architecture employed between the robot and its sensor hardware is utilizing the Robot Operating System (ROS). The use of ROS facilitates the process of hardware abstraction, installation of device drivers and packages management required for executing terminal control of the system. This software also acts as a bridge between the various hardware items to communicate and to publish their respective information, to facilitate downstream data processing, computation of guidance commands and execution of navigation instructions.

2. MATLAB—Version 2016a

MATLAB forms the high level software architecture for extracting the information from various sensors and processing them into coherent instructions. The selection of this software was due to its processing capabilities for managing and computing metadata and its capability in seamlessly interfacing with all identified hardware. Inherent within the MATLAB software, the various algorithms and toolboxes installed allowed rapid development and testing of the prototype. Used in the development are toolboxes such as the image processing and robotics toolbox to aid in the buildup of the system. MATLAB forms the core fusion interface of the sensor information and calculates the required obstacle-free path trajectory to direct the UGV on its required route.

3. Ubuntu 14.04

Ubuntu forms the overarching operating system (OS) to access both ROS and MATLAB. Both of the latter systems depend on the Linux-based Ubuntu OS for installation and launching into its own respective software environment for them to receive user commands. The Ubuntu OS using an easily accessible user interface also provides the means for accessing the wireless network, so that the master node can remotely command the UGV and monitor the status of the system.

C. INTERFACE DESIGN

Due to the utilization of several hardware and software in the proposed construct of the UGV prototype, there was a need to ensure that the interface between them would be able to transmit, receive and interpret the information exchanged properly. The following section describes the software and hardware used in the various subsystems with the proposed interface architecture to connect them together within the development of the prototype.

The identification of four primary subsystems in the construct of the prototype allowed the inspection of the required physical architecture and interfacing to enable communications between the various modules and subsystem. The detailed description for the four identified subsystems are as follows:

1. Sensor Subsystem

This subsystem consisted of all the chosen sensors used in the collection of environmental information of the UGV's surrounding for it to perform autonomously. It included the use of LIDAR, image camera and orientation sensor. Bridging the devices that formed the core of this subsystem was ROS that provided the main software layer to load drivers, communicate information and execute low-level operations.

2. Guidance and Control Subsystem

The guidance and control subsystem formed the "brains" of the UGV. This is where initial assembly of data fusion from sensor information for coherency occurred, before processing them through the onboard computer to derive a feasible navigation path. All computation on the obstacle avoidance and path planning algorithms formed part of this system. This subsystem was also responsible for tracking the UGV's estimated position and providing the vehicle's kinematics for passing the speed and heading instructions onto the mechanical controls of the UGV.

The main hardware for this subsystem is the CPU, whose functions included parsing and processing of the collected information using the prescribed algorithms. All conduct of data processing and maneuver computation was using MATLAB as its primary processing software. The MATLAB software that also acted as the master controller, together with the computation scripts calculated the required trajectory based on the mission parameters and sensors feedback. The software then converted the required MATLAB kinematics output into ROS instructions, which was a coherent format recognizable by the vehicle control subsystem. As described earlier, the Ubuntu

OS installed in the mainframe computer formed the overarching software environment for the management of the entire software architecture.

3. Vehicle Control Subsystem

The vehicle control subsystem represented the components that executed the terminal instructions given to the UGV to direct its movement through the designated path. It controls the speed of the UGV through the manipulation of the electric motors, and steers the UGV to its required direction by adjusting the skid-control of the wheels.

The vehicle control subsystem consisted of the drivetrain and powertrain that received its kinematic instructions from the master controller and executed them accordingly. This subsystem worked with ROS as its main execution software that converted any received instructions from the master controller into a suitable format before it was recognizable and executable.

4. Communications and Tele-Operation Subsystem

This subsystem connected the UGV to its remote operator wirelessly to allow the transmission of commands and data. It provides the means of transferring location and operational statuses of the UGV periodically back to the master node for monitoring and tracking. The wireless network used in the prototype design is utilizing standard 2.4 GHz Wi-Fi for this purpose.

With the master node located remotely, it can wirelessly promulgate commands to the UGV for updates on coordinates or mission profile. The master node was equipped similarly with a computer loaded running both Ubuntu as the main operating system and MATLAB as the execution software for mission control.

D. PHYSICAL ARCHITECTURE

The author proposed for the overall architecture of the prototype development to follow the layout as illustrated in Figure 4. Due to the sensitivity and performance parameters of the various sensors, it was imperative to identify suitable physical placement and data links between the devices to the mainframe computer that would parse and process the information before executing the required maneuvers. This was evident with the LIDAR that has a forward field of view (FOV) of 240°, and would require sufficient clearance in its FOV to prevent any false positive feedback on the presence of obstacles. Also applicable to the orientation sensor, its positioning onboard the UGV would affect the results of its detection due to potential magnetic interferences from any metal bodies that may cause incorrect readings.

The segregation according to its various subsystems also allowed the developers to clearly define and understand the various subsystem boundaries and perform troubleshooting when or wherever required.

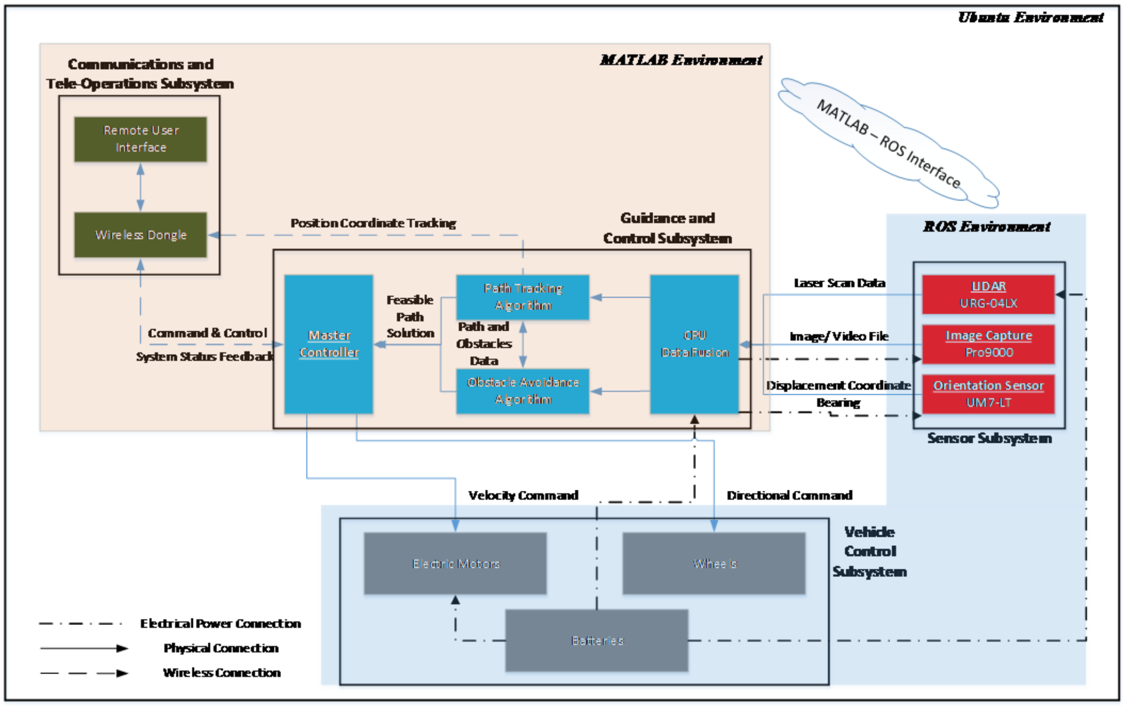


Figure 4. Proposed Architecture for The Development of UGV Prototype.

E. COMPONENT-TO-FUNCTION MAPPING

In order to have comprehensive oversight for the fulfillment of the identified functions, the study included the conduct of component-to-function mapping. This process was not only to ensure that the construct of the prototype was adequately equipped to perform its roles, it also served to identify unnecessary redundancy that had been factored in the development as well as to identify any critical component that may constitute singular failure points of the system. The results presented in Table 12 summarize the findings from the functional mapping.

Table 12. Component-to-Function Matching to Ensure Fulfillment of Identified Functionalities.

		Components											
S/N	**Function**	Remote User Interface	Wireless Dongle	Master Controller	Path Tracking Algorithm	Obstacle Avoidance Algorithm	CPU Data Fusion	LIDAR	Image Capture	Orientation Sensor	Electric Motor	Wheels	Batteries
Func 1.1	To Provide Propulsion										x		
Func 1.2	To Provide Steering Kinematics											x	
Func 1.3	To Provide Braking Power										x		
Func 2.1	To conduct Built-In Tests	x					x						
Func 2.2	To Monitor Internal Temperature												
Func 2.3	To Monitor Encoder Readings						x					x	
Func 2.4	To Transmit and Display Statuses	x	x	x			x						
Func 3.1	To Receive Wireless Transmission		x				x						
Func 3.2	To Process Wireless Transmission		x				x						
Func 3.3	To Transmit Wireless Transmission		x				x						
Func 3.4	To Provide On-Board User Interface	x											
Func 4.1	To Measure Bearing Travelled									x			
Func 4.2	To Measure Distance Travelled									x			
Func 4.3	To Sense for Presence of Objects							x	x				
Func 4.4	To Determine Range of Detected Objects							x					
Func 5.1	To Transfer All Sensor Information						x						
Func 5.2	To Process and Fuse Sensor Information			x	x	x	x						
Func 5.3	To Calculate Trajectory			x	x	x	x						
Func 5.4	To Determine Current Position				x					x			
Func 5.5	To Archive Data						x						
Func 5.6	To Execute Navigational Instructions			x							x	x	
Func 6.1	To Store Power												x
Func 6.2	To Distribute Power												x

F. TEST DESIGN

With the required hardware for the construction of the prototype determined, the study proceeded with the design of the required test scenarios to investigate the performance and feasibility of the system. The design of the test scenarios aimed to replicate various conditions expected from its operating environment.

1. Development Limitations

Accompanying the development of the test scenarios were limitations associated with the prototype development. It would be noteworthy to understand that though the identified limitations might somewhat restrict the realism of the system's behavior; the navigation algorithms are largely independent of conditions such as the luminance or environmental conditions. The implementation of measures to emulate other environmental conditions aimed to mitigate limitations such as variable lighting conditions, which may affect the visual acuity of the imaging device and subsequently the target recognition algorithm. Summarized in Table 13 are the identified limitations for the experiment.

Table 13. Identified Limitations Associated With Prototype Development.

Limitation	**Mitigating Measure**
Navigation and Obstacle Avoidance	
Lack of outdoor capable hardware such as a suitable laser range sensor.	Development has been done in lab conditions, but efforts are in place to replicate a cluttered environment through the designated waypoints.
Lack of terrain features represented in test conditions.	The inclusion of the IMU accounts for, and compensate for any drift errors associated with traveling on cross-country terrain and slippages due to loose top-soil.
Target Recognition	
Illumination may not fully represent the rapidly changing light conditions found in the jungle environment.	Course of evaluation has been done in varying degrees of illumination within the lab to represent the different illumination conditions expected.
Absence of vegetation that obscures line of sight to target.	Tests have been conducted with a partially concealed target and from different perspectives to represent vegetation blocking the line of sight.

2. Assumptions

The author had implemented the following assumptions for the various algorithms during the development of the prototype for the course of testing:

- constant linear velocity of 0.4 m/s employed for UGV's maneuver
- target representation by a red-filled circle
- communication loss between system and controller was negligible
- UGV assumed to reach its intended objective waypoint, as long as it reaches within the 0.2 m radius from the terminal waypoint.

3. Route Design

The test route had its waypoints designed in the manner that allowed the UGV to maneuver through a series of motions ranging from a straight-line to various degrees of curvature. The route was initially set without obstacles to ensure that the algorithm governing its path following was functional. Subsequent placement of obstacles along the routes allowed the tests to evaluate its avoidance algorithm. In order to replicate a cluttered environment within the test setting, clusters of boxes were set up at random positions along the intended route with no more than two meter distance from one obstacle to another. The proposed test route is illustrated in Figure 5.

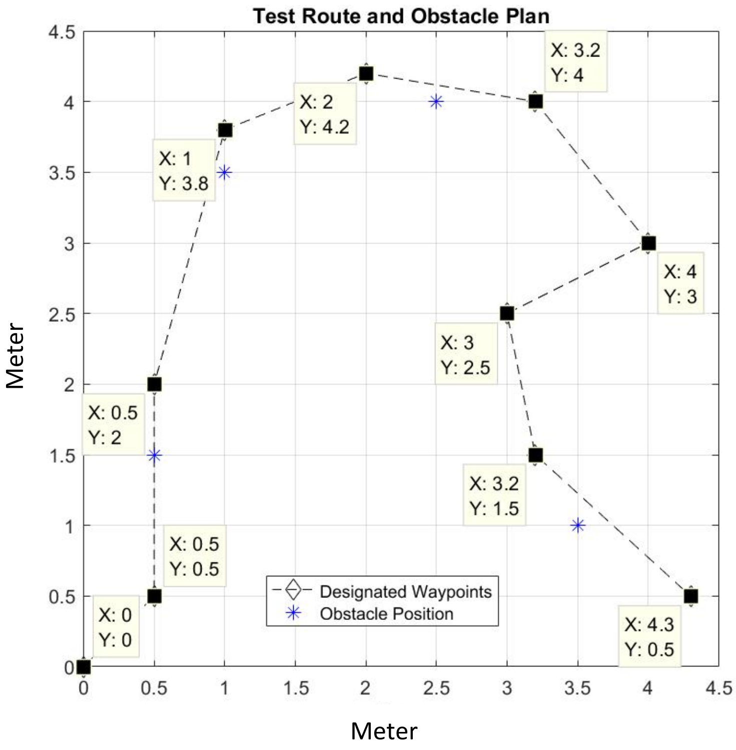


Figure 5. Proposed Test Route for UGV Prototype Evaluation.

4. Test Procedure and Exit Criteria

The categorization of the test procedure for the evaluation of the prototype was according to the required functions that the UGV had to perform. The specific functional tests allowed the understanding of the respective functions' behavior and fine-tuning of the associated parameters for it to behave and react as required. It would be necessary for the functions to achieve the required exit criteria first, before the development matured into an integrated effort with the full assembly of the subsystems forming into the final prototype.

Prior to an actual maneuver test for the UGV, the conduct of parameter fine-tuning was necessary using simulations and static tests. This allowed the developer to safely ascertain the behavior and reaction of the platform under various conditions before the conduct of the actual test.

Upon maturing from the subsystem tests, the procedure also called for a final integrated test after the full assembly of subsystems formed the final prototype. This test aimed to understand any unidentified interactions or characteristics arising from the integration of the various subsystems and functions.

a. Functional Tests

Three primary functions would require testing before the full assembly of the prototype into an integrated system. The following section outlined the high level test procedures and the required exit criteria that each function is required to achieve.

(1) Path Following

The objective for this test is to evaluate the efficacy of the path following algorithm by observing the movement of the UGV through the open test route. The first conduct of the test was a static test with the robot supported from the bottom of its chassis, restricting its wheel movement to determine the required tuning parameters for it to function properly during the live maneuver test.

Upon deriving the adequate system parameters, the UGV would be required to traverse through the prescribed waypoints with an average missed distance from each waypoint of no more than 17 cm, as summarized in Table 14. This criterion was set as half the width of the UGV platform that the author had deemed a sufficient error of margin to accommodate any random errors arising from the hardware. The test procedure proposed for 10 runs.

Table 14. Proposed Test Criteria for Path Following Algorithm.

Test Criteria	Pass Requirement
Missed distance from waypoint	≤ 17 cm average

(2) Obstacle Detection and Avoidance

Derivation of the required obstacle detection and avoidance parameters form the core of this test. The system was meant to detect and discern the obstacle layout as illustrated in Figure 5 from a stationary position, with varying obstacles cross-sectional areas exposed to the sensor. Upon successful detection of the obstacles, the algorithm shall also identify a feasible steering direction for its maneuver. The test procedure proposed for 10 runs with the exit criteria summarized in Table 15.

Table 15. Proposed Test Criteria for Obstacle Identification Algorithm.

Test Criteria	Pass Requirement
Obstacle 1 Identification	95% detection
Obstacle 2 Identification	95% detection
Obstacle 3 Identification	95% detection
Obstacle 4 Identification	95% detection

(3) Target Identification and Tracking

This test would seek to evaluate the capabilities of the target identification algorithm in identifying a stationary target from various distances. The target is a red circle whose true diameter measured 10 cm. Placement of the obstacles was at the one-, three- and four-meter mark, with the targets placed at various points along the respective distances and perpendicular to the UGV's line of sight. Visibility of the target will also be varied between full exposures and exposing only a semi-circle at the respective test point. The test procedure proposed for each test distance to have 30 target exposures, with the exit criteria summarized in Table 16.

Table 16. Proposed Test Criteria for Target Identification.

Test Criteria	Pass Requirement
2 m (Full Exposure)	100%
2 m (Half Exposure)	95%
3 m (Full Exposure)	90%
3 m (Half Exposure)	85%
4.5 m (Full Exposure)	80%
4.5 m (Half Exposure)	75%
4.5 m (Full Exposure, Night)	75%

V. PROTOTYPE VERIFICATION AND FINDINGS

Even though the design and development of the prototype followed established methodologies and algorithms for its path following and obstacle avoidance capabilities, the author observed multiple factors that had required tuning in order to achieve credible autonomous operations. This chapter highlighted the author's pertinent insights during the development of the prototype for the various operations.

The areas of interest observed in this study included the findings with the application of the various sensors and algorithms. Also included were the applicability of these technologies to address the concerns of the stakeholders and achievability of its mission scenarios identified in the prior chapters.

A. TEST VERIFICATION

This section discusses the results obtained from the conduct of the various tests together with the obtained tuning parameters for the algorithms. The parameters found in this section formed the allocated baseline for future developments of the UGV.

1. Path Following Results

During the course of prototype development, the author observed that three main algorithm inputs for the pure pursuit algorithm played a critical role in governing the kinematic behavior of the UGV. These factors determined the feasibility and efficacy of the system during movement and regulated the eventual movement stability of the system. The three factors are its linear velocity, angular velocity and its look-ahead distance. These input variables for the algorithm also allowed the UGV to traverse adequately through the designated waypoints, while also fulfilling the test criteria. From the fine-tuning process conducted in a simulated environment, an optimal set of values for the three factors were as follow in Table 17.

Table 17. Optimal Path Following Algorithm Parameter.

Factor	Value
Linear Velocity	0.4 m/s
Angular Velocity	0.8 rad/s
Look-ahead Distance	0.9 m

As part of the test criteria, the author tested the UGV's maneuver with the tuned algorithm in the designated test route that was obstacle-free. This test was meant to evaluate the efficiency of the kinematic instructions executed by platform after MATLAB processing with the average deviation from the designated waypoints measured. The summarized test results are shown in Table 18.

Table 18. Path Following Algorithm Test Results for Maximum Deviation.

	Run									
	1	2	3	4	5	6	7	8	9	10
Max Dev. (cm)	6	5	5	6	4	5	4	5	5	4
Pass/ Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

2. Obstacle Detection and Avoidance Results

Apart from the intrinsic characteristics of the LIDAR such as its detection range and angular resolution, the author observed that several parameters governing the efficiency of the VFH algorithm contributed significantly to how the UGV would react in the presence of obstacles. These parameters included the number of angular sectors that computed free space proximity, and the histogram thresholds that performed the role of retaining or discarding a probable obstacle presence during maneuver planning. The following parameters, shown in Table 19, displayed the optimal behavior required from the UGV in the given scenario.

Table 19. Optimal Obstacle Detection Algorithm Parameter.

Factor	Value
LIDAR Detection Range	0.06—4m
No. of Angular Sectors	660
Histogram Threshold Value	3 - 8

The test conducted on the detection capabilities of the LIDAR and its subsequent mapping of the obstacles for its polar density histogram plot was recorded as summarized in Table 20.

Table 20. Obstacle Detection and Avoidance Algorithm Test Results for Identifying Obstacles.

	Run									
	1	2	3	4	5	6	7	8	9	10
Obstacle 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obstacle 2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obstacle 3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obstacle 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Percentage Detected	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Pass/ Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

3. Target Identification

The final components verified for the UGV were its target identification and tracking capabilities. The principle utilized in this method employed was for the extraction of selected colors and probable shapes that represented the target. The simulated target in the course of this study was a red circle measuring 10 cm in diameter.

Similarly, the author also observed multiple factors that required adjustments for the system to perform at the required fidelity. Such tuning factors included the adjustments for color and lumens tolerance levels from the target and environment respectively. These were key for the algorithm to recognize the required targets under varying environmental conditions such as lighting and visibility of the target. The results from the test conducted have been summarized in Table 21.

Table 21. Evaluation Results from Target Identification Test.

Test Criteria	Requirement	Test Result
2 m (Full Exposure)	100%	100%
2 m (Half Exposure)	95%	100%
3 m (Full Exposure)	90%	100%
3 m (Half Exposure)	85%	100%
4.5 m (Full Exposure)	80%	100%
4.5 m (Half Exposure)	75%	96%
4.5 m (Full Exposure, Night)	75%	93%

B. FINDINGS AND DISCUSSION

Covering the insights and observations obtained from the conduct of the various tests in this section, it served as a reference for any system modifications required in future iterations of the UGV.

1. Path Following

The findings observed from the tuning of parameters are described in the following section. The author noted on the effects that resulted from specific changes to the parameters and recorded the corresponding behavior that the UGV exhibited.

a. Linear Velocity

This parameter governed the forward and backward motion of the UGV and determined its achievable velocity during its movement. The maximum velocity achievable by the system was 0.7 m/s due to the hardware limitation of the Pioneer 3AT robot. The author noted that even though a higher value resulted with the system being able to complete the designated path faster, the UGV tended to significantly cross its intended waypoints when negotiating a bend. The author highlighted that these observations were more apparent when the UGV was trying to overcome a sharper bend. This was due to the added forward momentum of the system, which caused significant slippage when performing such sharp maneuvers. The plotted paths illustrated in Figure 6 compared the performance of the UGV with a linear velocity of 0.2 m/s and 0.4 m/s. Both systems had their angular velocity and look-ahead distance programmed to 0.5 rad/s and 0.6 m respectively.

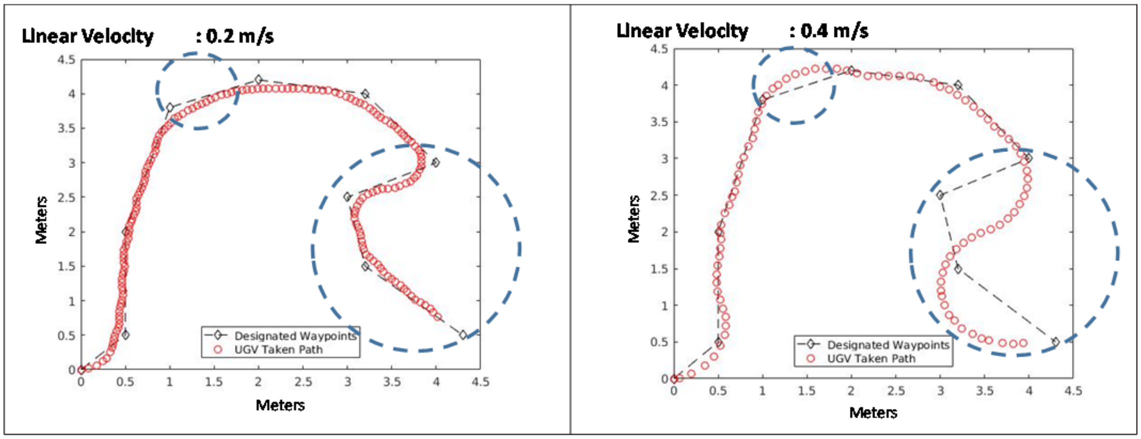


Figure 6. Effects of Linear Velocity on Maneuver Efficiency.

As concluded from the tests, a lower linear velocity offered the system more response time to react to any changes in its maneuver direction. The option of a lower velocity might not be a feasible manipulation factor due to the nature of military UGVs requiring swift reactions in the theater of operations. Exploration of the other factors would be required to understand the necessary tuning within the pure pursuit algorithm for the UGV to function adequately.

b. Angular Velocity

The angular velocity of the system determined the rate of turn achievable by the UGV in its maneuver. A higher angular velocity allowed the system to maneuver through a curvature in the route or turn about a sharp bend with higher efficiency than that of a lower angular velocity. This characteristic thus allowed the system to reach all its intended waypoints as directed.

The author observed during the tests that a lower angular velocity of 0.3 rad/s caused the system to veer significantly off its intended path and away from its designated waypoint. The author also highlighted the tendency for the UGV to display sluggish counter steer reactions for it to recover its maneuver back on to the designated route. This sluggishness often drove the system further away from its intended maneuver path when passing through sharp bends.

The application of a higher angular velocity of 0.4 rad/s during the conduct of follow-on tests yielded a much faster reaction time and better stability for the system to recover back to its intended path and waypoints. Despite the quicker recovery of the system to its intended path, the author noted that the UGV was still displaying wide turning radius when negotiating a sharp bend, possibly attributing to incorrect settings of the other tuning variables. Illustrated in Figure 7, the blue circles highlighted the comparison of the mentioned anomalies along the path taken by the UGV with different angular velocity.

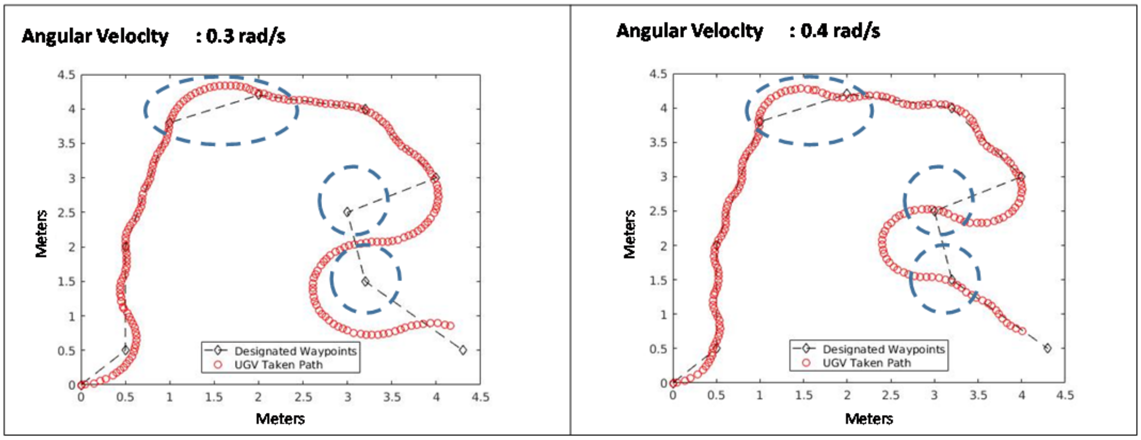


Figure 7. Effects of Angular Velocity on Maneuver Efficiency.

As illustrated in Figure 8, the author also observed that the application of a higher angular velocity to the UGV caused the system to oscillate along its maneuver path in the earlier portion of its designated route, even though the route was in relatively straight-line. The author opined that the observed phenomenon was due to the algorithm producing rapid counter steer maneuvers for the control of the system to overcompensate the faster rate of orientation change in order to steer the UGV back onto its calculated path.

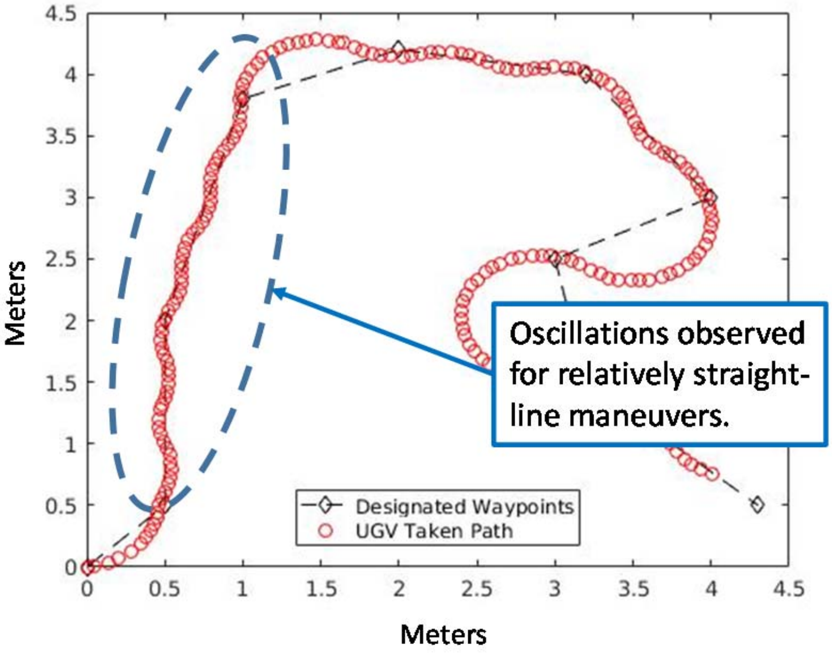


Figure 8. Oscillations Observed With Inadequate Angular Velocity.

This series of tests conducted for the manipulation of the angular velocity thus concluded that the application of a higher parameter value was required for the UGV to negotiate bends and sharp corners. The nature of skid steered vehicles such as that of the prototype platform, and many tracked vehicles in the armed forces inventory that is able to pivot about a stationary point with a minimal turn radius would hence allow a higher angular velocity to be implemented without sacrificing its accuracy to follow its intended route.

c. Look-Ahead Distance

The look-ahead distance as previously described, was an algorithm input that allowed the system to project an imaginary arc for the computation of intermediate waypoints to guide the vehicle from its current position to the next intended position. The size of this arc, or also known as its look-ahead distance, would govern the movement characteristic of the UGV to its next intermediate position.

The author tested the UGV by programming the look-ahead distance at 0.1 m increment understand the effects on its behavior, while holding the other parameters constant. The author observed from the various tests conducted at a lower look-ahead distance that the actual path taken by the UGV was closer to its intended route, and noted the behavior of rapid corrections to the steering direction should the UGV veer off course. Such rapid succession of correcting its steering direction however resulted in frequent oscillations in its forward movement along the intended path, similar to that of a high angular velocity. The author suggested that the main contributor to this effect was due to the shorter look-ahead distance; where the algorithm projected an almost instantaneous intermediate waypoint ahead of the robot, thus requiring constant counter steering motion to compensate for and correct any offsets in its maneuver.

The author also noted that the converse when implementing a further look-ahead distance yielded a significant effect on the behavior and performance of the robot as well. A larger look-ahead distance displayed much better system stability during movement, resulting in no observable oscillations during its maneuver. The larger distance allowed the UGV to project its look-ahead points further forward, for it to better anticipate and plan its required trajectory. The plot in Figure 9 represented the UGV route when the linear and angular velocity was held constant at 0.2 m/s and 0.5 rad/s respectively, with varying look-ahead distance.

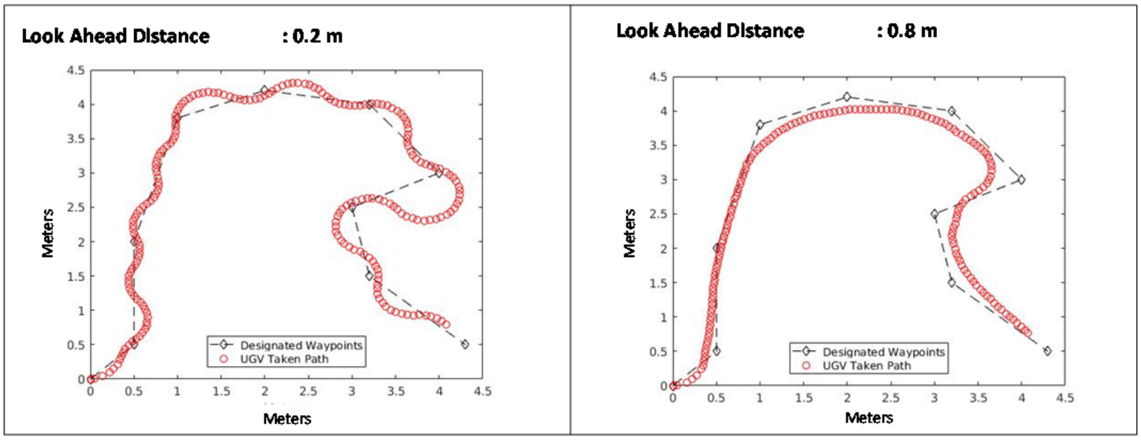


Figure 9. Effects of Look-Ahead Distance on Maneuver Efficiency.

The observations from subsequent tests with an even larger look-ahead distance resulted in the systems cutting corners and moving away from its intended path when negotiating a curved route. The effect of cutting corners caused the system to maneuver past, instead of crossing the designated waypoints. This observation was more apparent with the implementation of a larger look-ahead as illustrated in Figure 10.

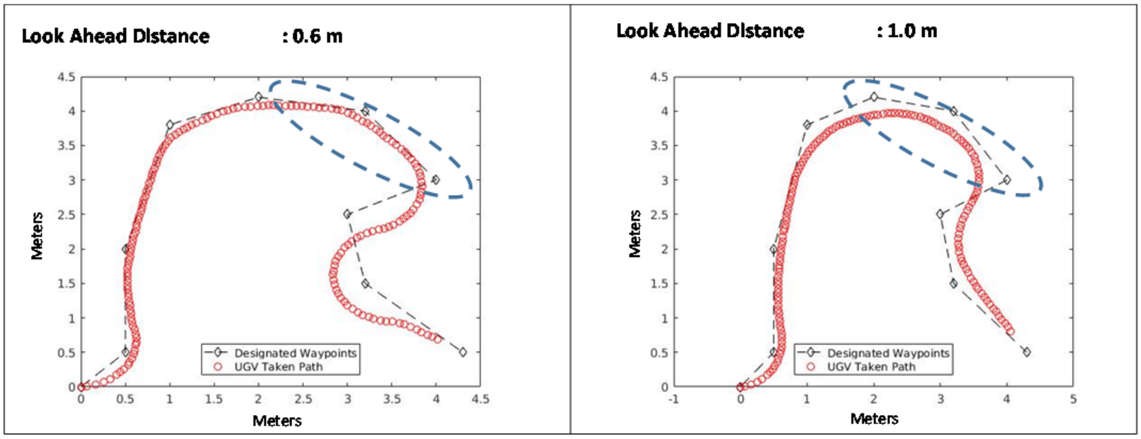


Figure 10. Observation on UGV Cutting Along Bends with High Look-Ahead Distance Parameter.

2. Obstacle Detection and Avoidance

Of three primary parameters that governed the efficiency with the implementation of the VFH method in the prototype development. These parameters affect the real time detection and eventual processing of the dynamic environmental conditions for the UGV to discern an optimal obstacle-free steering direction. Discussions on the results and accompanying findings for the implementation of this method are as follow.

a. LIDAR Detection Range

The Hokuyo LIDAR was the primary sensor to emit laser pulses to determine the presence and range of any obstacles along the path of the UGV. The course of development yielded an optimal detection range for the LIDAR to be at a range of 0.1 m to 4 m in order for the sensor to detect and ascertain obstacles. The sensor would discard any detection beyond the prescribed ranges as false positive. The lower bound for the range allowed the elimination of any false positive arising from the structural interference mounted on the robot, as such the instrument frame located within the FOV of the sensor. The selection of the upper detection range was due to the limited size of the lab area that would reflect the walls and other furniture as obstacles and have a potential effect on its obstacle-free steering. The programming of the algorithm bin size, or also known as the angular resolution of the sensor into 660 bins, allowed the UGV to leverage on the actual angular resolution of 0.36° that the LIDAR was capable of fully.

Subsequent conduct of the required tests allowed the verification of the subsystem's performance to ascertain the performance level with the respective parameter inputs. Three boxes with its side profile of approximately 15 cm width were set up at a distance of 1.2 m, 2.7 m and 4.5 m away from the LIDAR to verify its prescribed performance. The author designed the conduct with the side profiles of the boxes to emulate the tree trunks expected in the projected operating environment.

As illustrated in Figure 11, one could observe the division of the negative and positive x-axis within the feedback plot from the laser scan data. Taking reference from the LIDAR's position as the center of origin, all detection on the right of the system were considered in its negative range of plots, with the converse being true for any detection on the left of the LIDAR. The Y-axis reflects the detected displacement away from the sensor. On the detection of all objects within the prescribed detection range, with all the objects within the range 4 m clearly sensed and reflected on the plot. The obstacle located the 4.5 m range had been discarded from the processing. An accompanying color image seen in the same figure showed a similar viewpoint from the LIDAR's perspective of the obstacle set up.

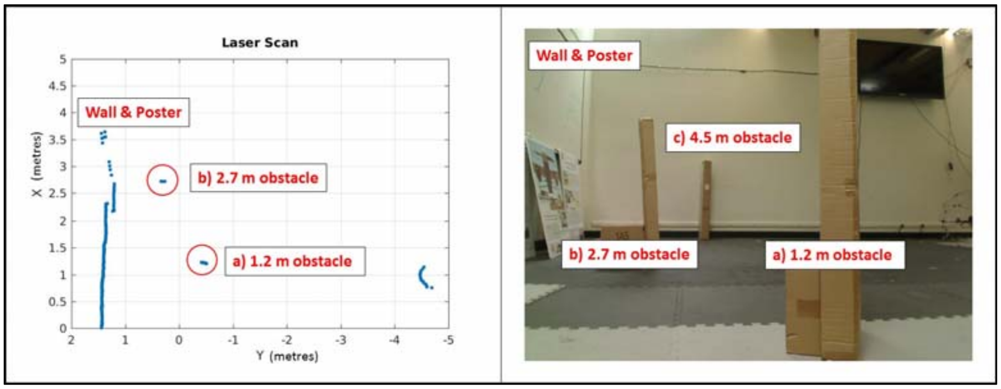


Figure 11. Laser Scan Plot Marks Detection of Obstacles within Prescribed Detection Range.

b. VFH Implementation

Subsequent from the sensing phase of the sensor, the algorithm reduced the information of the laser scan feedback into a polar obstacle density histogram. All detections were gridded in its X-Y coordinates by the VFH algorithm, and allocated a magnitude score for confidence level, representing the confidence of the actual presence of an obstacle in the particular grid. Further reduction of the certainty values in the grid gave rise to a polar density histogram around the UGV for the system to discern the location and presence of any objects surrounding it. As illustrated in Figure 12, the blue histograms plotted within the polar obstacle density plot asserted the presence of the wall with reference to the position of the UGV, while the cleared spaces represented the unobstructed space within the detection ranges. With the introduction of an obstacle as seen in Figure 13, the corresponding histogram verified the presence, magnitude and location of the object with respect to the UGV.

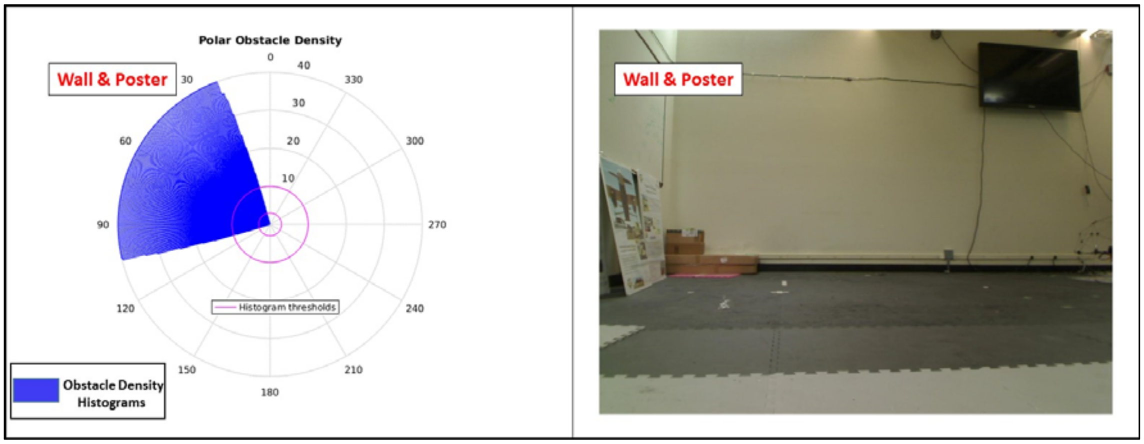


Figure 12. Polar Obstacle Density Plot of an Open Space Detecting Only the Wall Located Left of System.

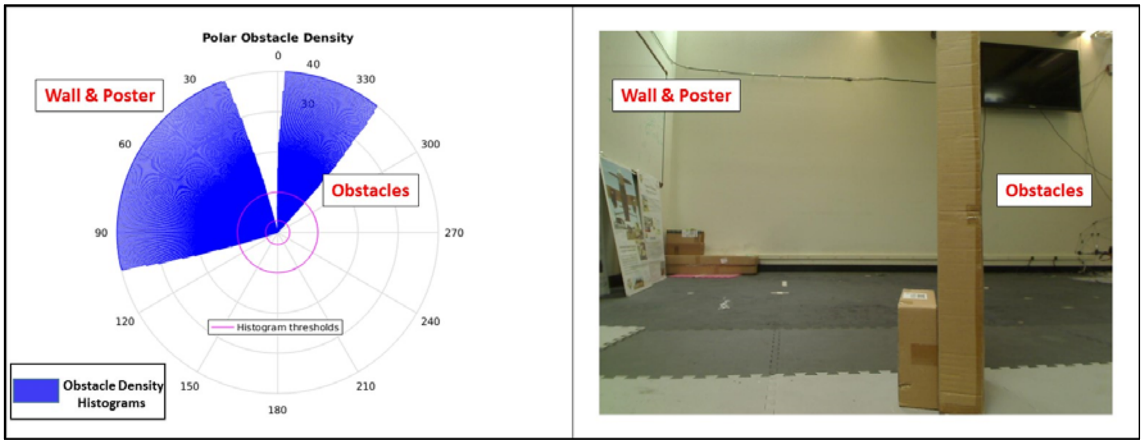


Figure 13. Polar Obstacle Density Plot with the Detection of Obstacles.

c. Histogram Threshold

Allowing the system to identify both the location and magnitude on the state of space in its vicinity, it further allowed the algorithm to compute a corresponding steering direction for the UGV to maneuver. The research included the considerations on multiple factors for the computation of a feasible steering direction executed by the UGV to avoid obstacles. These considerations included intrinsic characteristics of the UGV such as its dimensions, turning radius and safety distances. It also included extrinsic factors such as the UGV's intended heading at that moment of time. Such factors formed the thresholds from which the algorithm selects the feasible candidate directions within its unobstructed vicinity. The eventual steering direction chosen by the VFH algorithm took into account the intended heading direction of the UGV in order for it to achieve the correct trajectory to reach the designated position. Figure 14 shows the display of polar histogram with the free space representation and required steering direction.

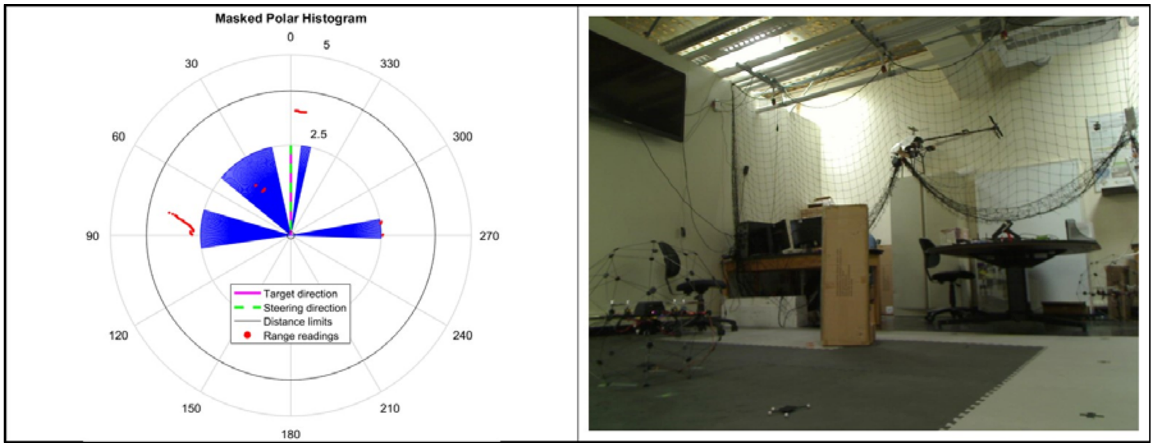


Figure 14. Masked Polar Histogram Highlighting Range Obstacles Detection and Proposed Free Space Steering Direction.

Observed during the course of the test was that the histogram threshold value as one of the significant parameters. The author noted that this parameter played a significant role in the UGV’s computation for a feasible path, especially through a more convoluted area. As previously described, the allocated threshold values represented the certainty values of an obstructed space and hence affecting the algorithm’s interpretation of its proximity. Any certainty values derived from the sensor feedback that is higher than the prescribed thresholds would constitute an obstacle, while certainty values below the thresholds constituted free space.

Shown in Figure 15, a larger certainty value threshold of between 20 and 30 precluded the potential collision risk with an obstacle further away, as the system perceived it as an open space as circled. This might result with the UGV having insufficient reaction time during maneuver to classify the presence of that obstacle as a true obstruction in order to compute an alternate free route, evidently so when high speed maneuvers are necessary. This was due to the algorithm sensing and reacting only when certain of an obstacle presence at a closer range.

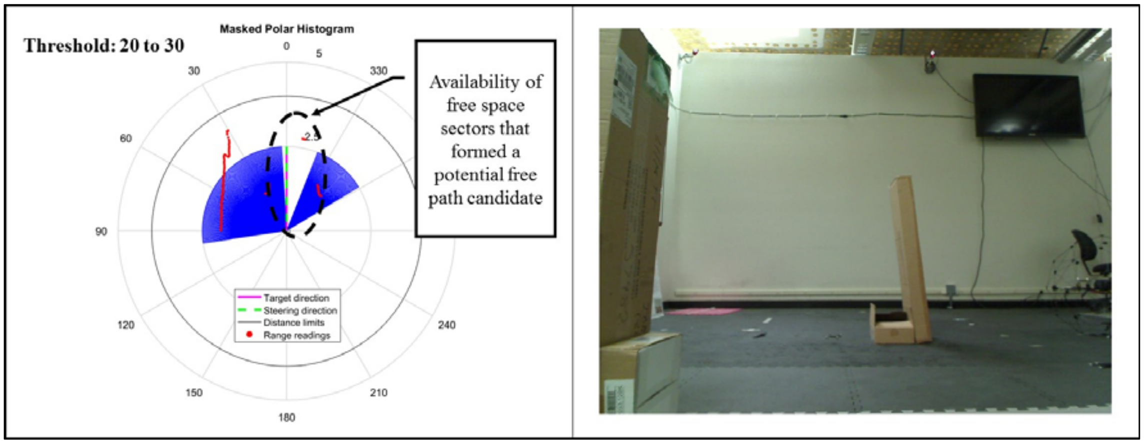


Figure 15. Polar Histogram with a Relaxed Threshold Precluded Potential Obstacle Presence.

The observations from a more restrictive threshold of between one and five using an identical obstacle set up displayed the converse results. The application of a lower threshold prohibited the movement along potentially passable paths and significantly impeded the freedom of maneuver for the UGV as illustrated in Figure 16. This restriction resulted with the algorithm projecting only a very narrow sector that it perceived as open space for steering the vehicle through.

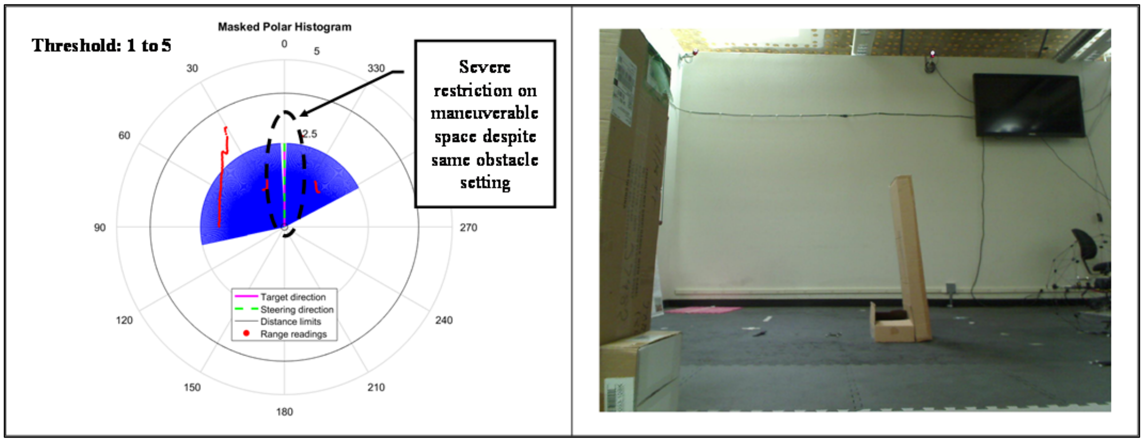


Figure 16. Polar Histogram with a Restrictive Threshold Severely Limits Selection of the Potential Paths.

C. TARGET IDENTIFICATION

The use of the Logitech Pro9000 webcam enabled image recording capabilities onboard the UGV, with the camera offering a maximum resolution of 1600 pixels by 1200 pixels. Processing the captured images within a MATLAB environment utilized of the Image Processing Toolbox to analyze and extract information from the images. The main working principle for the image processing was for the system to first recognize and isolate a designated color for it to distill the image down into its binary form, showing only the selected color. The next step was for the algorithm to recognize shape factors within the binary image to hone in onto the target. Similar to the other presented algorithm used in this study, application of extensive tuning was necessary for the system to operating adequately.

Two primary factors had the most significant impact on the efficacy of the target identification algorithm. The two factors are its color deviation threshold and darkness threshold, which described the color intensity and luminance level respectively. Both factors not only affected the efficiency of the algorithm, but also remained highly susceptible to changing ambient light conditions if not properly tuned.

1. Deviation Thresholds

During the initial conduct of the tests, the author noted that the target identification algorithm failed to identify the entire target surface accurately. Instead, the algorithm picked up only a few key aspects of potential targets and selected the one with the largest signature. As illustrated in Figure 17, the parameters set for the red, green and blue (RGB) palette and darkness threshold failed to converge on the proper recognition of the red circle held directly in front of the camera. Instead, the recognition was detecting a bright object located behind the subject, as demarcated by the green crosshair.

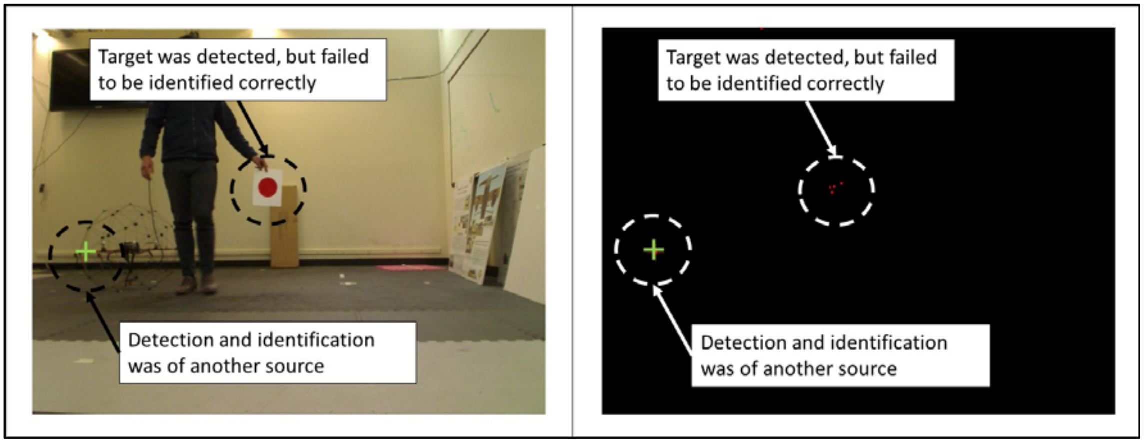


Figure 17. Misinterpretation of Target Prior to Finalized Parameters Tuning.

The development further led to subsequent experimentations to understand the corresponding RGB thresholds and luminance thresholds by analyzing a series of images of the red circle held at different distances and orientation from the camera. Figure 18 illustrates the after effects of tuning the parameters to suit the condition in normal daylight condition. One could observe that the algorithm managed to accurately isolate and identify the full target profile in the binary image. The figure showed the raw image captured from the webcam on the left, with its corresponding binary image that had isolated the required colored element shown on the right. The white shades within the binary image showed the actual shape profile of the intended target, and outlined in red with a green crosshair placed in the center of the target to draw user's attention to the identified target.

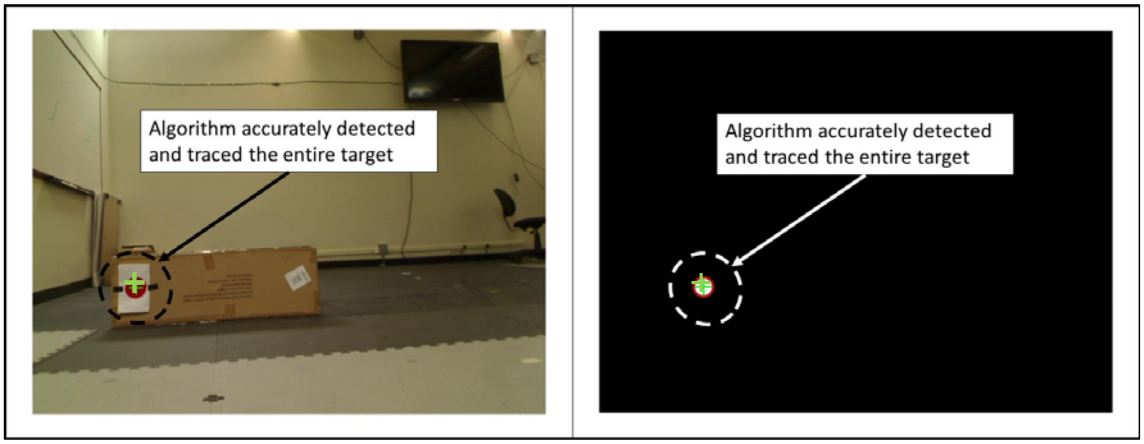


Figure 18. Detection of Target in Daylight Conditions at Range of 3 m.

Follow-on tests conducted in low light condition also yielded similar results for the algorithm displaying high fidelity levels of target identification, as shown in Figure 19.

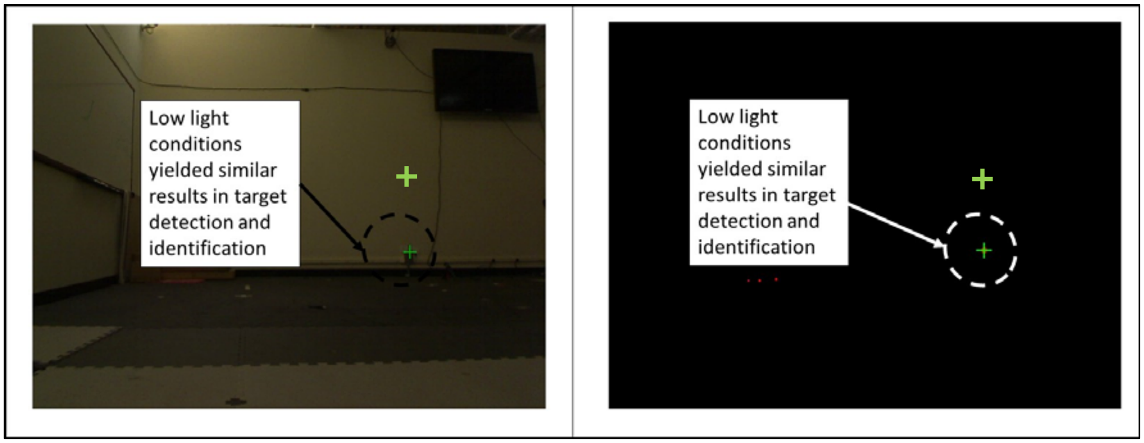
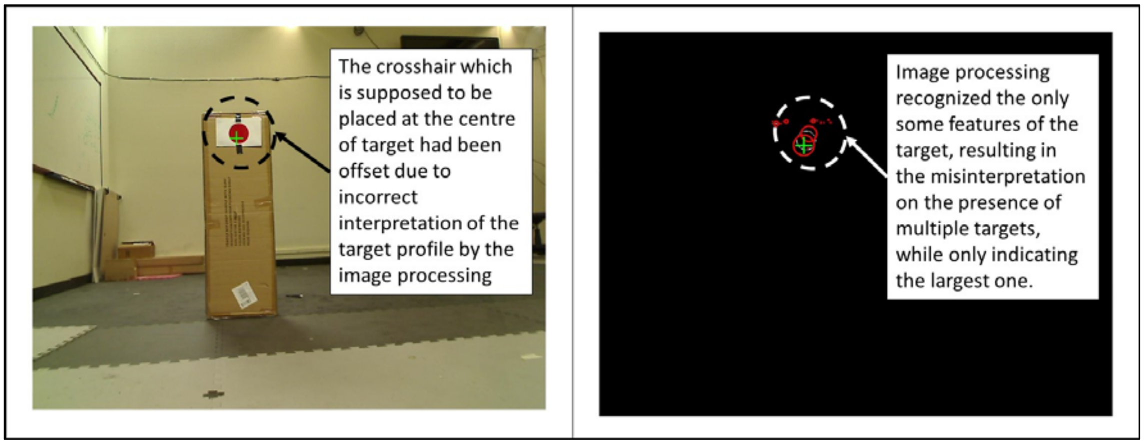


Figure 19. Detection of Target in Low Light Conditions at Range of 4.5 m.

2. Precision in Target Identification

Although the results from the test showed promising performance of the target identification, the author noted from several of the binary images that the performance of the algorithm lacked the expected precision.

The binary images on approximately 15% of the total captured images showed that the algorithm managed to capture only some key features of the true target despite having its full profile exposed to the camera. This resulted with the algorithm highlighting and processing these specific areas and recognizing it as several smaller targets instead of a continuous one. Figure 20 exhibited this effect where the representation in the binary image showed that the algorithm interpreted the true target as two smaller separate targets, resulting in an incorrect identification and representation of the intended objective. The author opined that this anomaly could lead to a false positive recognition of targets, and recommended further tuning of the parameters to ensure that performance of the algorithm reached an acceptable level of precision.



The crosshair which is supposed to be placed at the centre of target had been offset due to incorrect interpretation of the target profile by the image processing

Image processing recognized the only some features of the target, resulting in the misinterpretation on the presence of multiple targets, while only indicating the largest one.

Figure 20. Algorithm Incorrectly Interpreting a Single Target as Multiple Targets.

VI. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

The system engineering approach adopted in this research offered a structured and systematic way to identify the needs, objectives, functional requirements for the construct of an UGV demonstration prototype. The proposed development of the UGV included the capabilities of path following and navigating through designated geographical waypoints while avoiding obstacles in a dynamic environment. The development also included the ability of the UGV to identify and track targets of interest within its AO.

In order to allow an expeditious approach for rapid prototyping of the UGV for autonomous operations, the author embarked on studying and reviewing established technologies, methodologies and algorithms capable of performing the required tasks. The objective for this particular exercise was to gain understanding in the efficacies and relevancy of the respective methods for the development of our prototype.

The author conducted in-depth exploration of the system requirements, stakeholders' expectations and needs analysis. This allowed the development to distill expectations of the stakeholders into effective requirements for the proper evaluation and selection of techniques employed in the final UGV prototype. Proposal on the boundaries of the system and likely operational scenarios added robustness to the identification of required performance criteria and specifications. The study eventually conducted an evaluation using the Analytical Hierarchy Process to compare and select the various potential technology candidates suitable for employment in the prototype. The evaluation concluded that the UGV would be equipped with LIDAR as its range sensor, IMU for its displacement sensing, and being equipped with an image camera for the purpose of target identification. The thesis proceeded with selection for the key guidance and control algorithms governing the behavior for the system's autonomous capabilities. The algorithms employed in our development included pure pursuit method for path following, VFH method for obstacle avoidance and feature recognition for target tracking.

Working within several software layers such as ROS, MATLAB and Ubuntu, the system architecture conducted at this stage segregated the UGV prototype into four primary subsystems for control. The four subsystems are to fulfill the tasks of sensing, data fusion and computing, vehicle control and communications. The establishment of the interface design and physical architecture for the UGV aided the understanding of the required layout and linkages required to connect the components so that the exchange of energy and information would be seamless. Test criterion were also established as exit criteria to fine tune the various algorithms and evaluate the subsystems behavior and performance before system integration was conducted for the final UGV prototype.

During the course of system development and integration, the observations for requiring extensive parameter tuning were apparent within each algorithm. The author observed highly dependent relationships between the parameters within each algorithm, and suggested that one would expect a cascading effect on the overall behavior of the UGV should one parameter be suboptimal. Examples of these tightly correlated parameters was evident with the pure pursuit algorithm where though a high angular velocity was desired for the system to execute sharp maneuvers, a mismatch of the other accompanying parameters such as the linear velocity and look-ahead distance resulted in an overall system instability. The author also proposed similar relationships with the implementation of the VFH algorithm where the threshold values for the polar histogram was highly dependent on the accuracy of the sensor employed.

B. RECOMMENDATIONS

The author wishes to highlight on the following recommendations for the conduct of future works.

1. Obstacle Avoidance

One must note of the limitations on the capabilities and quantity of the sensors employed in this development. The stability of the system can be further improved with the use of a 3D LIDAR with longer range resolution for the UGV to perceive its surrounding better, and was recommended for further developments to incorporate this a more powerful LIDAR system.

The use of several layers of different sensor feedback by employing the use of multiple sensors onboard the UGV would also allow the VFH algorithm to gain better perception of any obstacles within its back by allowing a more robust certainty value to be input within the computation. This implementation will also enable the system to understand the environment better. The author however cautioned on the necessary trade-offs that must be properly studied on as the addition of sensors would not only add a strain to the power requirements drawn from the UGV, it could also possibly reduce other operational loads such as weaponries and ammunition that could be carried on board the vehicle.

2. Target Identification

Alternate hardware types for the target recognition algorithm should also be explored. Different kind of hardware such as a thermal imaging camera could be utilized in the development that could add robustness to the target identification. The use of such an imager not only allows the system to be more resilient to environmental obscurities such as airborne particulates or moisture in the air, it also allows the system to be independent on the illumination conditions in its operating environment.

The author also recommended the exploration of alternate algorithms in the image processing that could yield more robust image analysis for the function of target identification. This included the use of artificial neural network algorithms for the system to identify specified regions of interest after training the network. This method would allow the system to be readily employed in any foreign environment and be set up for operational use with minimal adjustments to its parameters.

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APPENDIX A. ANALYTIC HIERARCHY PROCESS FOR SYSTEM EVALUATION

Step 1: Setting Global Criteria Importance and Weight

Criteria	**Acoustic Sensor**	**LIDAR**	**Light Sensor**	**Camera**	**Radiofrequency**
Acoustic Sensor	1.00	0.20	2.00	0.20	0.33
LIDAR	5.00	1.00	5.00	1.00	3.00
Light Sensor	0.50	0.20	1.00	0.20	0.14
Camera	5.00	1.00	5.00	1.00	1.00
Radiofrequency	3.00	0.33	7.00	1.00	1.00
Column Sum	**14.50**	**2.73**	**20.00**	**3.40**	**5.48**

Step 2: Normalizing Criteria

	Acoustic Sensor	**LIDAR**	**Light Sensor**	**Camera**	**Radiofrequency**
Acoustic Sensor	0.069	0.073	0.100	0.059	0.061
LIDAR	0.345	0.366	0.250	0.294	0.548
Light Sensor	0.034	0.073	0.050	0.059	0.026
Camera	0.345	0.366	0.250	0.294	0.183
Radiofrequency	0.207	0.122	0.350	0.294	0.183

Step 3: Scores and Consistency

	Acoustic Sensor	**LIDAR**	**Light Sensor**	**Camera**	**Radiofrequency**	**Score**	**Consistency**
Acoustic Sensor	0.069	0.073	0.100	0.059	0.061	**0.072**	5.196
LIDAR	0.345	0.366	0.250	0.294	0.548	**0.361**	5.397
Light Sensor	0.034	0.073	0.050	0.059	0.026	**0.049**	5.098
Camera	0.345	0.366	0.250	0.294	0.183	**0.287**	5.160
Radiofrequency	0.207	0.122	0.350	0.294	0.183	**0.231**	5.173
						Const. Index	0.051
						Const. Ratio	0.046

Step 1: Setting Global Criteria Importance and Weight

Criteria	Acoustic Sensor	LIDAR	Light Sensor	Camera	Radiofrequency
Acoustic Sensor	1.00	0.20	0.33	0.33	0.20
LIDAR	5.00	1.00	5.00	3.00	1.00
Light Sensor	3.00	0.20	1.00	0.33	0.33
Camera	3.00	0.33	3.00	1.00	0.50
Radiofrequency	5.00	1.00	3.00	2.00	1.00
Column Sum	**17.00**	**2.73**	**12.33**	**6.67**	**3.03**

Step 2: Normalizing Criteria

	Acoustic Sensor	LIDAR	Light Sensor	Camera	Radiofrequency
Acoustic Sensor	0.059	0.073	0.027	0.050	0.066
LIDAR	0.294	0.366	0.405	0.450	0.330
Light Sensor	0.176	0.073	0.081	0.050	0.110
Camera	0.176	0.122	0.243	0.150	0.165
Radiofrequency	0.294	0.366	0.243	0.300	0.330

Step 3: Scores and Consistency

	Acoustic Sensor	LIDAR	Light Sensor	Camera	Radiofrequency	Score	Consistency
Acoustic Sensor	0.059	0.073	0.027	0.050	0.066	**0.055**	5.090
LIDAR	0.294	0.366	0.405	0.450	0.330	**0.369**	5.298
Light Sensor	0.176	0.073	0.081	0.050	0.110	**0.098**	5.057
Camera	0.176	0.122	0.243	0.150	0.165	**0.171**	5.294
Radiofrequency	0.294	0.366	0.243	0.300	0.330	**0.307**	5.178

Const. Index	0.046
Const. Ratio	0.041

Step 1: Setting Global Criteria Importance and Weight

Criteria	Acoustic Sensor	LIDAR	Light Sensor	Camera	Radiofrequency
Acoustic Sensor	1.00	1.00	3.00	1.00	3.00
LIDAR	1.00	1.00	5.00	1.00	3.00
Light Sensor	0.33	0.20	1.00	0.33	0.33
Camera	1.00	1.00	3.00	1.00	3.00
Radiofrequency	0.33	0.33	3.00	0.33	1.00
Column Sum	**3.67**	**3.53**	**15.00**	**3.67**	**10.33**

Step 2: Normalizing Criteria

	Acoustic Sensor	LIDAR	Light Sensor	Camera	Radiofrequency
Acoustic Sensor	0.273	0.283	0.200	0.273	0.290
LIDAR	0.273	0.283	0.333	0.273	0.290
Light Sensor	0.091	0.057	0.067	0.091	0.032
Camera	0.273	0.283	0.200	0.273	0.290
Radiofrequency	0.091	0.094	0.200	0.091	0.097

Step 3: Scores and Consistency

	Acoustic Sensor	LIDAR	Light Sensor	Camera	Radiofrequency	Score	Consistency
Acoustic Sensor	0.273	0.283	0.200	0.273	0.290	**0.264**	5.172
LIDAR	0.273	0.283	0.333	0.273	0.290	**0.290**	5.162
Light Sensor	0.091	0.057	0.067	0.091	0.032	**0.067**	5.033
Camera	0.273	0.283	0.200	0.273	0.290	**0.264**	5.172
Radiofrequency	0.091	0.094	0.200	0.091	0.097	**0.115**	5.146

Const. Index	0.034
Const. Ratio	0.031

Step 1: Setting Sub-Criteria Importance and Weight

	Bug Algorithm	PFM	VFH	HNA	Vision-Based
Bug Algorithm	1	2.00	2.00	5.00	5.00
PFM	0.5	1	1.00	3.00	3.00
VFH	0.5	1	1	3.00	3.00
HNA	0.2	0.333333333	0.333333333	1	1.00
Vision-Based	0.2	0.333333333	0.333333333	1	1
Column Sum	2.4	4.666666667	4.666666667	13	13

Step 2: Normalizing Sub-Criteria

	Bug Algorithm	PFM	VFH	HNA	Vision-Based
Bug Algorithm	0.417	0.429	0.429	0.385	0.385
PFM	0.208	0.214	0.214	0.231	0.231
VFH	0.208	0.214	0.214	0.231	0.231
HNA	0.083	0.071	0.071	0.077	0.077
Vision-Based	0.083	0.071	0.071	0.077	0.077

Step 3: Scores and Consistency

	Bug Algorithm	PFM	VFH	HNA	Vision-Based	Score	Consistency
Bug Algorithm	0.417	0.429	0.429	0.385	0.385	0.409	5.011
PFM	0.208	0.214	0.214	0.231	0.231	0.220	5.006
VFH	0.208	0.214	0.214	0.231	0.231	0.220	5.006
HNA	0.083	0.071	0.071	0.077	0.077	0.076	5.002
Vision-Based	0.083	0.071	0.071	0.077	0.077	0.076	5.002

Const. Index	0.001
Const. Ratio	0.001

Step 1: Setting Sub-Criteria Importance and Weight

	Bug Algorithm	PFM	VFH	HNA	Vision-Based
Bug Algorithm	1	0.33	0.14	0.14	0.14
PFM	3	1	0.33	0.33	0.33
VFH	7	3	1	1.00	1.00
HNA	7	3	1	1	1.00
Vision-Based	7	3	1	1	1
Column Sum	25	10.33333	3.476190	3.476190	3.476190

Step 2: Normalizing Sub-Criteria

	Bug Algorithm	PFM	VFH	HNA	Vision-Based
Bug Algorithm	0.040	0.032	0.041	0.041	0.041
PFM	0.120	0.097	0.096	0.096	0.096
VFH	0.280	0.290	0.288	0.288	0.288
HNA	0.280	0.290	0.288	0.288	0.288
Vision-Based	0.280	0.290	0.288	0.288	0.288

Step 3: Scores and Consistency

	Bug Algorithm	PFM	VFH	HNA	Vision-Based	Score	Consistency
Bug Algorithm	0.040	0.032	0.041	0.041	0.041	0.039	5.001
PFM	0.120	0.097	0.096	0.096	0.096	0.101	5.004
VFH	0.280	0.290	0.288	0.288	0.288	0.287	5.011
HNA	0.280	0.290	0.288	0.288	0.288	0.287	5.011
Vision-Based	0.280	0.290	0.288	0.288	0.288	0.287	5.011

Const. Index	0.002
Const. Ratio	0.002

Step 1: Setting Sub-Criteria Importance and Weight

	Bug Algorithm	PFM	VFH	HNA	Vision-Based
Bug Algorithm	1	1.00	1.00	5.00	5.00
PFM	1	1	1.00	5.00	5.00
VFH	1	1	1	5.00	5.00
HNA	0.2	0.2	0.2	1	1.00
Vision-Based	0.2	0.2	0.2	1	1
Column Sum	3.4	3.4	3.4	17	17

Step 2: Normalizing Sub-Criteria

	Bug Algorithm	PFM	VFH	HNA	Vision-Based
Bug Algorithm	0.294	0.294	0.294	0.294	0.294
PFM	0.294	0.294	0.294	0.294	0.294
VFH	0.294	0.294	0.294	0.294	0.294
HNA	0.059	0.059	0.059	0.059	0.059
Vision-Based	0.059	0.059	0.059	0.059	0.059

Step 3: Scores and Consistency

	Bug Algorithm	PFM	VFH	HNA	Vision-Based	Score	Consistency
Bug Algorithm	0.294	0.294	0.294	0.294	0.294	0.294	5.000
PFM	0.294	0.294	0.294	0.294	0.294	0.294	5.000
VFH	0.294	0.294	0.294	0.294	0.294	0.294	5.000
HNA	0.059	0.059	0.059	0.059	0.059	0.059	5.000
Vision-Based	0.059	0.059	0.059	0.059	0.059	0.059	5.000

Const. Index	0
Const. Ratio	0

Step 1: Setting Sub-Criteria Importance and Weight

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit
Follow-the-Carrot	1	1.00	5.00
Pure Pursuit	1	1	3.00
Vector Pursuit	0.2	0.333333333	1
Column Sum	2.2	2.33333333	9

Step 2: Normalizing Sub-Criteria

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit
Follow-the-Carrot	0.455	0.429	0.556
Pure Pursuit	0.455	0.429	0.333
Vector Pursuit	0.091	0.143	0.111

Step 3: Scores and Consistency

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit	Score	Consistency
Follow-the-Carrot	0.455	0.429	0.556	0.480	3.044
Pure Pursuit	0.455	0.429	0.333	0.405	3.033
Vector Pursuit	0.091	0.143	0.111	0.115	3.010

Const. Index	0.015
Const. Ratio	0.025

Step 1: Setting Sub-Criteria Importance and Weight

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit
Follow-the-Carrot	1	0.33	0.33
Pure Pursuit	3	1	1.00
Vector Pursuit	3	1	1
Column Sum	7	2.33333333	2.333333333

Step 2: Normalizing Sub-Criteria

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit
Follow-the-Carrot	0.143	0.143	0.143
Pure Pursuit	0.429	0.429	0.429
Vector Pursuit	0.429	0.429	0.429

Step 3: Scores and Consistency

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit	Score	Consistency
Follow-the-Carrot	0.143	0.143	0.143	0.143	3.000
Pure Pursuit	0.429	0.429	0.429	0.429	3.000
Vector Pursuit	0.429	0.429	0.429	0.429	3.000

Const. Index	0.000
Const. Ratio	0.000

Step 1: Setting Sub-Criteria Importance and Weight

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit
Follow-the-Carrot	1	1.00	3.00
Pure Pursuit	1	1	3.00
Vector Pursuit	0.333333333	0.333333333	1
Column Sum	2.333333333	2.33333333	7

Step 2: Normalizing Sub-Criteria

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit
Follow-the-Carrot	0.429	0.429	0.429
Pure Pursuit	0.429	0.429	0.429
Vector Pursuit	0.143	0.143	0.143

Step 3: Scores and Consistency

	Follow-the-Carrot	Pure Pursuit	Vector Pursuit	Score	Consistency
Follow-the-Carrot	0.429	0.429	0.429	0.429	3.000
Pure Pursuit	0.429	0.429	0.429	0.429	3.000
Vector Pursuit	0.143	0.143	0.143	0.143	3.000

Const. Index	0.000
Const. Ratio	0.000

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APPENDIX B. MATLAB CODE FOR PATH FOLLOWING

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                          %
% This code incorporated the use of pure pursuit algorithm%
% for path following and also vector field histogram      %
% obstacle avoidance algorithm.                            %
% They have been nested into a loop to guide the system   %
% through the designated waypoints from its start position%
% at (0,0) to its terminal waypoint.                       %
% The code required the initialization of ROS to be done  %
% and the start-up of drivers for the system to be done   %
% prior to running this MATLAB script.                     %
%                                                          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


close all, clear all, clc

posesub = rossubscriber(‘/my_p3at/pose’);
posepub = rospublisher(‘/my_p3at/pose’);
lasersub = rossubscriber(‘/scan’);

% Creation of Area of Operations
map = robotics.BinaryOccupancyGrid(5,5);

% Designating required waypoints for patrol
path = [0.00 0.00;
0.50 2.00;
1.00 3.80;
2.00 4.20;
3.20 4.00;
4.00 3.00;
3.70 1.50;
3.00 0.50];

% Defining UGV’s start and goal position for operations

CurrentLocation = path(1,:);
```

```
Goal = path(end,:);
initialOrientation = 0;
robotCurrentPose = [CurrentLocation initialOrientation];

% Displaying the intended route

plot(path(:,1), path(:,2),'k--d')
hold

% Defining parameters for Pure Pursuit Controller

controller = robotics.PurePursuit;
controller.Waypoints = path;
controller.DesiredLinearVelocity = 0.3;
controller.MaxAngularVelocity = 0.5;
controller.LookaheadDistance = 0.5;
Threshold = 0.2;
distance = norm(CurrentLocation - Goal);

% Defining parameters for Vector Field Histogram Algorithm

vfh = robotics.VectorFieldHistogram;
vfh.NumAngularSectors = 240;
vfh.DistanceLimits = [0.2 4];
vfh.RobotRadius = 0.344;
vfh.MinTurningRadius = 0.2;
vfh.SafetyDistance = 0.1;

controlRate = robotics.Rate(10);

while distance > Threshold

% Obtain Inputs for VFH
laserscan = receive(lasersub);
ranges = double(laserscan.Ranges);
angles = double(laserscan.readScanAngles);

% Calculating updated Position and Orientation
PosX = posesub.LatestMessage.Pose.Pose.Position.X;
PosY = posesub.LatestMessage.Pose.Pose.Position.Y;
```

```
CurrentLocation = [PosX PosY];

% Converting Current Orientation from Quaternion to Euler
Angles
Orient = posesub.LatestMessage.Pose.Pose.Orientation;
Euler = quat2eul([Orient.W Orient.X Orient.Y Orient.Z]);
Theta = Euler(1);

% Defining the updated Coordinates and Orientation
Pose = [PosX PosY Theta];
targetDir = -atan2(CurrentLocation(2) - Goal(2),
CurrentLocation(1));


% Application of VFH Algorithm
Steering = vfh.step(ranges, angles, targetDir)

if ~isnan(Steering)
% Application of Pure Pursuit Control
[v, omega] = step(controller, Pose);

else
% Stop the UGV and search for a valid direction
v = 0.00;
omega = 0.3;
end

% Publish robot kinematics into UGV using the controller
outputs.
linepub = rospublisher('/my_p3at/cmd_vel');
linemsg = rosmessage(linepub);
linemsg.Linear.X = v;
linemsg.Angular.Z = omega;
send(linepub,linemsg);

% Obtaining updated position of UGV along the route of
maneuver
robotCurrentPose = Pose;

% Re-compute the distance to the goal
```

```
distance = norm(Pose(1:2) - Goal);

% Conduct the loop at prescribed rate
waitfor(controlRate);

% Track and plot UGV movement
plot(PosX, PosY, ‘or’)

end

% Upon reaching intended goal, stop UGV
v = 0;
omega = 0;
linepub = rospublisher(‘/my_p3at/cmd_vel’);
linemsg = rosmessage(linepub);
linemsg.Linear.X = v;
linemsg.Angular.Z = omega;
send(linepub,linemsg);
```

APPENDIX C. MATLAB CODE FOR TARGET RECOGNITION

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                         %
% This code illustrates the target recognition algorithm  %
% employed in this study. The main target reference used  %
% is a red circle.                                        %
% The algorithm first isolates the designated color for   %
% recognition and takes into consideration the darkness of%
% the captured image, before a binary image is produced.  %
% The algorithm further proceeds to detect the the given  %
% shape parameter “Centroid” as its target within the     %
% binary image.                                           %
%                                                         %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



imaqreset, clc, clear all

% Establishing connection with camera and setting frame
parameters
vid=videoinput(‘winvideo’); % Defining the video input
set(vid,’FramesPerTrigger’,1); % Setting frames per trigger
vid.FrameGrabInterval = 1;

% Main loop for when the connection is active
while (1)

% Obtaining snapshot of videoframe.
% Transforming image into true frame by flipping LR to
obtain view from UGV perspective
image = getsnapshot(vid);
image_true = fliplr(image);

% Isolating just the red components within frame
% imshow(image);
% redimage = -image_true(:,:,1)/2 + image_true(:,:,2)/2 +
image_true(:,:,3)/2;
redimage = imsubtract(image_true(:,:,1),
rgb2gray(image_true));

% Establishing thresholds for deviation and luminence
```

```
% Used subsequently for meshing of images to filter and
process
redBallParams.redMax = 255;
redBallParams.darkMin = 30;

% Processing of image files to extract desired
characteristics
redthresh = redimage < redBallParams.redMax;
luminence = 3*image_true(:,:,1)/2 - image_true(:,:,2)/2 -
2*rgb2gray(image_true);
darkThresh = luminence > redBallParams.darkMin;

% Binary image which is a combination of isolated red
components and at
% required luminance level
target = redthresh & darkThresh;

% Setting target parameters for recognition
% In this case, identifying and tracking a filled circular
object

s = regionprops(target,
{‘Centroid’,’Area’,’EquivDiameter’});

if isempty(s)

Centre = [];
Dia = [];

else

[~, id] = max([s.Area]);
Center = s(id).Centroid;
Dia = s(id).EquivDiameter/2;

end

% Identifying processed image for designated target shape
% Identifying associated dimensions of target from UGV
point of view
Identified_Tgts =
regionprops(‘table’,target,’Centroid’,’MajorAxisLength’,’Mi
norAxisLength’);
centers = Identified_Tgts.Centroid;
diameters = mean([Identified_Tgts.MajorAxisLength
Identified_Tgts.MinorAxisLength],2);
```

```
radii = diameters/2;

% Graphically represent true image (RGB) and also binary
image.
% All potential targets are marked out, with main target
represented with a
% red crosshair in centre

figure;
subplot(2,1,1);
hold;
imshow(image_true);
plot(Center(1),Center(2),'+','Color','r','MarkerSize',20)


subplot(2,1,2);
hold;
imshow(target); viscircles(centers,radii);
plot(Center(1),Center(2),'+','Color','r','MarkerSize',20)

pause(3)
end
```

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