Path-Planning Software for Mobile Robotic Systems

ECE4011 Senior Design Project

Team NavX

Project Advisor: Professor Erik Verriest

Project Sponsor: Harris Corporation

Alvin O'Garro, aogarro3@gatech.edu

Jacob Jeong, jacobsh.jeong@gmail.com

Antony Samuel, antonysam2000@gmail.com

Kartik Sastry, ksastry3@gatech.edu

Submitted

August 22, 2018

Table of Contents

Executive Summary

A major challenge for mobile robotic systems is path planning. Harris Corporation, an American technology company and defense contractor, is sponsoring the development of a 3D path planning tool for quick and efficient routing towards a static or potentially dynamic target using airborne LiDAR/Hi-Res 3D point cloud data. Harris is interested in mission planning, Intelligence, Surveillance and Reconnaissance (ISR), area scanning, emergency situation response, and warehouse/material handling applications of this technology. A $15,809.30 cost-estimate is determined based on entry-level software engineering salary.

NavX's objective is to develop software that computes the shortest navigable path through austere terrain for an existing robot, the Tactical Unmanned Ground Vehicle (TUGV). Whether or not a specific region is navigable is determined based on the physical constraints of the TUGV. The software will translate pre-processed LiDAR data into a usable set of waypoints for a mobile robot to navigate on a given terrain (urban, suburban, and back country environments). The software will collect data from an airborne LiDAR system, generate a discretized representation of its environment, and implement a path-planning algorithm that operates on the selected representation to determine waypoints for the robot. Options for path-planning algorithms include Dijkstra's Algorithm, A* and Dynamic A*.

NavX's final product will be software that computes an optimal global path for a mobile robotic system using airborne LiDAR data, and, potentially, static terrain/elevation data in addition. This global path will be transferred in the form of waypoints to a robot on the surface. Another Harris-sponsored design team will use this global path as guidance for local motion planning. In real-time, the TUGV will deviate from and rejoin the global path as necessary to account for unforeseen circumstances.

Path-Planning Software for Mobile Robotic Systems

1. Introduction

NavX's objective is to develop software that computes the shortest navigable path through austere terrain for an existing robot, the Tactical Unmanned Ground Vehicle (TUGV). Whether or not a specific region is navigable is determined based on the physical constraints of the TUGV. The team requests $26,348.80 to fund the development of this software.

1.1 Objective

Robotic path planning is a broad and well-studied problem. NavX will focus on the specific aspects of map development and shortest path routing under vehicle performance limitations. For context, NavX's sponsor, Harris Corporation, will acquire, pre-process, and supply high-resolution LiDAR point cloud data with point classification (which determines whether a surface point is water, foliage, or ground). Using this data, NavX's software will build a discretized representation of the environment within a host computer called the base station. Following the construction of the map, the software will create a graph representation of the environment, and assign edge weights as functions of point-to-point distance, terrain classification, and physical limitations of the TUGV robot. Finally, the software will employ graph search algorithms such as Dijkstra's Algorithm or A* to compute the minimum-cost path through the terrain, and translate the path into a set of coordinates, called waypoints. Additionally, NavX will collaborate with another design team, Harris Team B, to develop a transfer mechanism to load the produced waypoints onto the TUGV vehicle. Harris Team B's work focuses on real-time considerations when following the produced waypoints.

1.2 Motivation

One of the major challenges for mobile robotic systems is path planning. Harris Corporation, an American technology company and defense contractor, is sponsoring NavX's development of a 3D path planning tool for navigating towards a potentially moving target. The planning software will take airborne LiDAR point cloud data with point classification as an input, along with desired start and end locations, and produce a set of navigable waypoints that the TUGV robot can follow. Harris Corporation is interested in mission planning, intelligence, surveillance, and reconnaissance (ISR), area scanning, emergency situation response, and warehousing/material handling applications of this path planning technology [1]. The use of airborne LiDAR to map environments is not new work. Some recent examples can be found in [2], [3], and [4]. However, as advances in sensor technology increase the information content and resolution of LiDAR point cloud data, path planning based on this data is still a desirable venture.

1.3 Background

Motion planning has been a long-standing area of research in the robotics and control communities, with seminal work beginning perhaps as early as 1957 [5], [6], [7]. The fundamental building blocks utilized in NavX's project can be categorized as mapping/representation techniques and planning algorithms. A wide variety of mapping/representation and planning techniques have been established over time. [6] provides an exhaustive classification of mapping schemes, as well as associated algorithms. After conducting initial research, NavX has decided that a discrete-space representation of the TUGV robot's environment is most appropriate for this project due to the discrete nature of LiDAR data. Discretized representations lend themselves to graph-based models, which in turn allow for the use of graph algorithms for planning [8], [9]. For contrast, [10] takes an analytic approach to path planning based on a continuous-space model of the environment. A final building block in NavX's work is the existing Tactical Unmanned Ground Vehicle (TUGV) robot that was produced by a previous ECE 4011/4012 team [11]. The limitations imposed by the construction of this robot (such as maximum incline) will be taken into account when planning suitable paths.

2. Project Description and Goals

NavX's objective is to develop software that computes the shortest navigable path through austere terrain for an existing robot, the Tactical Unmanned Ground Vehicle (TUGV). Whether or not a specific region is navigable is determined based on the physical constraints of the TUGV. The path will be computed between a specified starting and ending point, where the latter may also be moving. NavX's sponsor, Harris Corporation, anticipates deployment of this technology in austere terrain conditions. A list of the expected capabilities of NavX's software, in order of interdependence, is provided below:

- Interpret and extract information from LiDAR data with point classifications per the LAS standard [12].
- Build a graph model of a geographic area and assign edge weights per information extracted from LiDAR data and fundamental vehicle limitations.
- Employ a graph search algorithm to compute the single-source, least-cost path to a specified destination.
- Translate the result of the graph search into a sequence of waypoints.
- Prepare the waypoints for transmission to the TUGV robotic vehicle.

3. Technical Specifications

NavX's directives are to develop a path planning tool that can be deployed on a typical laptop. Table 1 contains specifications for a typical laptop base station. NavX plans to use a similar laptop for testing.

Table 1: Summary of Base Station Computing Specifications

Base Station Parameter	Minimum Requirements
Clock Speed	2.0 GHz
RAM	8 GB
Disk/Flash Memory	256 GB
I/O Capability	• 802.11n compliant Wireless LAN (Wi-Fi) • USB Interface for Serial Communication

4. Design Approach and Details

4.1 Design Approach

NavX's design is comprised of two main units: the base station and the TUGV. The base station, running NavX's path planning software, converts input LiDAR data into waypoints that the TUGV can use to navigate its environment. The raw LiDAR data is processed with Geographic Information System (GIS) software, and subsequently used to populate a discrete-space map representation of the TUGV's environment. This map representation is then used to compute a shortest-distance path and produce waypoints to send to the TUGV robot.

4.1.1 The Base Station

The base station will be a laptop computer that hosts and runs the software needed to generate the waypoints to be sent to the TUGV robot. This software will contain two main components. If preprocessed point cloud data can be obtained, then the main two components of the software architecture at the base station will be the map generation software and the path planning software. The map generation software will transform the point data into a discretized representation of the TUGV robot's environment. The path planning software will compute a path through that map representation, as shown in Figure 1.

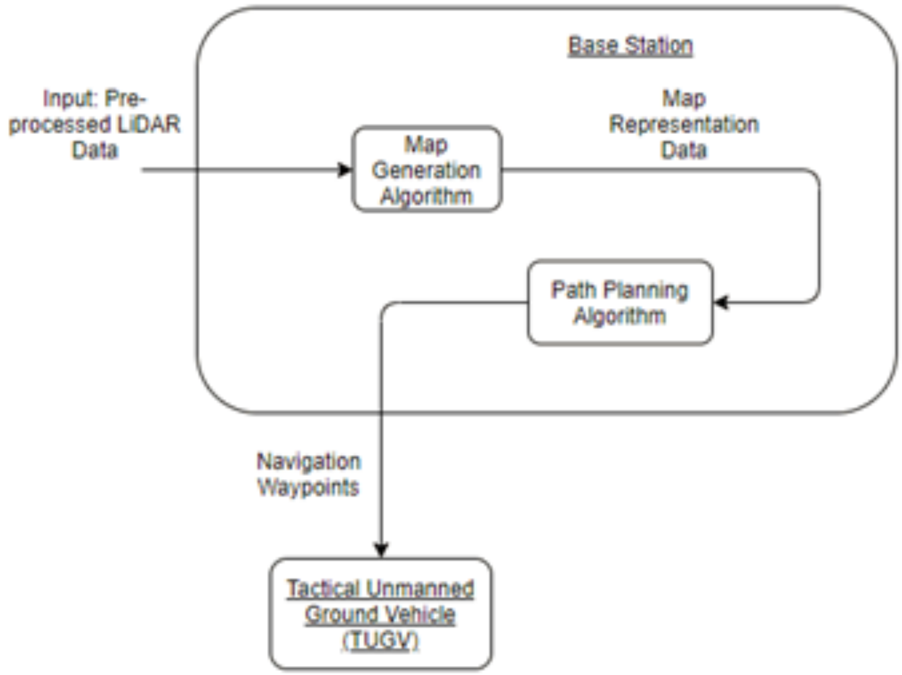


Figure 1. Software architecture for the Base Station.

At this point, NavX has decided that a discrete-space representation of the TUGV robot's environment is most appropriate for this project due to the discrete nature of LiDAR data. Additionally, an established history in the robotics literature and ease of implementation make the pairing of a discrete-space map representation and a graph-based planning algorithm an attractive option. Discretized representations lend themselves to graph-based models, which in turn allow for the use of graph algorithms for planning [8]. When a usable test data set is obtained, the team will begin testing the map representation that works best with the terrain in which the robot could be placed. NavX will remain open to the possibility of changing the nature of the map representation as a contingency. Possible alternative map representations available to NavX are the occupancy grid maps, geometric maps, and landmark based maps [13]. Each representation has associated benefits and weaknesses, and tradeoffs between navigation effectiveness and constraints on computation time and space will be considered.

The path planning algorithm used will be entirely dependent on the map representation, as the data in the map will be used to decide what path through the map will have the lowest cost to traverse by the robot. For instance, a discrete-space map may better facilitate a graph-based search approach such as A* or Dynamic A* [14]. However, if a landmark based map representation is used instead, the method of the Generalized Root Locus may be better for computing a low-cost path [10].

Once the path waypoints are generated, the data will be transferred to the TUGV to be used as a global path for the robot's navigation. Data will likely be transferred over a persistent 2.4 GHz Wi-Fi connection to the TUGV robot, as the networking hardware already exists onboard the TUGV robot. In the case of a moving endpoint, it may be desirable to maintain such a persistent connection. This imposes clear restrictions on the control radius however, as the base station must remain within wireless range of the TUGV robot, which may be affected by the geography of the deployment region. Additionally, a nearly real-time constraint will need to be introduced on the run-time of the path updating algorithm (which will not necessarily re-compute the entire path). In the case of a static endpoint, transferring the waypoint data one time over a serial connection would suffice. This transfer can be done prior to deployment of the TUGV robot, and as a result, there are no limitations on the control radius of the TUGV robot, barring the potential need for a persistent connection for other purposes such as monitoring or emergency notification.

4.1.2 The Tactical Unmanned Ground Vehicle

As the TUGV has already been designed and constructed by a previous team, the scope of NavX's design is not concerned with making modifications to the robot itself. The robot's architecture was designed for manual, rather than autonomous, navigation through movement commands sent from the base station over a Wi-Fi channel (2.4/5GHz), as shown in Figure 2.

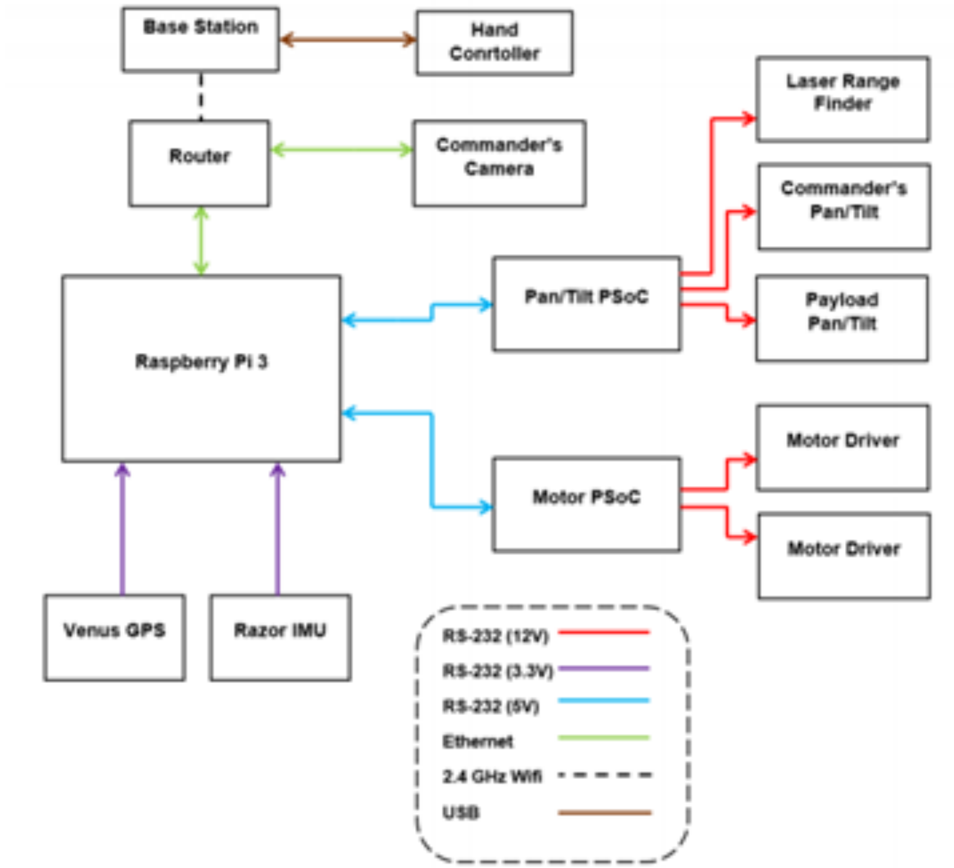


Figure 2. System block diagram of the TUGV robot [11].

Waypoint data can be sent from the base station to the robot using the same communications system without any modifications to the robot's hardware. Harris Team B will be responsible for modifying the software on the TUGV robot to be able to receive and interpret waypoint data.

4.2 Codes and Standards

A significant standard for NavX's design is the LAS Standard, which defines the format for LiDAR data. The LAS standard is a public, binary file format for storage and exchange of 3D point cloud data [12]. LiDAR LAS files contain a variety of data including (terrain) point classification, pulse intensity, GPS time stamp, number of return pulses. These data are used to determine whether or not the robot can physically pass through points in its environment.

For wireless communication between the TUGV and base station, 2.4 GHz and 5 GHz bands will be used in accordance with the IEEE 802.11 Standard [15]. If wireless capabilities are deemed unnecessary, then data should be transferred to the TUGV over a serial connection, as defined by the RS-232 standard [16].

4.3 Constraints, Alternatives, and Tradeoffs

Constraints on this design include the computational limits of the base station and the resolution of LiDAR data that is obtainable. Both constraints will limit the optimality of the path we can generate. Further constraints that must be considered are the physical capabilities of the TUGV robot. The path taken will be restricted by the maximum slope the robot can ascend or descend, both in the direction of travel and laterally. Additionally, information on slippage in varying terrain conditions (water, snow, mud) will be useful.

A possible alternative to NavX's present approach is to obtain and process raw LiDAR data instead of simply using pre-processed data. This would require a LiDAR processing unit on the base station. Figure 3 shows an alternative software architecture that includes the LiDAR processing unit. This would increase the range of the environments in which the TUGV robot could be deployed. However, such an addition would impart a large time cost for deploying the design, so this task is left out of the scope of the design.

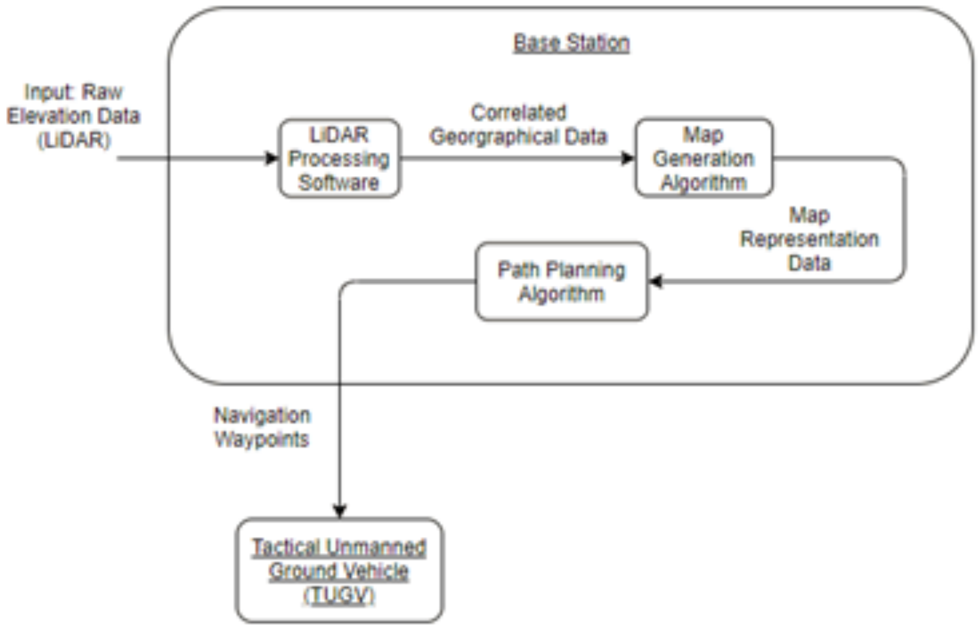


Figure 3. Alternative architecture for the base station including LiDAR data pre-processing.

5. Schedule, Tasks, and Milestones

The Gantt chart provided in Appendix A lists all major tasks that NavX anticipates as part of this project, the person(s) assigned to the tasks, and their respective (estimated) completion times in number of days. The estimated completion time of each task is proportional to its estimated difficulty. The tasks that are on the critical path of this project in red, and tasks off the critical path are indicated in blue. Orange bars are also shown to visualize the effect of uncertainty in task completion times. The PERT chart provided in Appendix B shows a task-flow diagram with all tasks and their estimated completion times, and accounts for uncertainty in task completion times.

The tasks on the critical path, namely developing a map representation and implementing the path planning algorithm, were estimated to require the most effort and time due to lack of prior experience by team members, as well as time required for testing and documentation. Additionally, for tasks that involve a refinement phase, a buffer period of one week has been allocated to cope with uncertainty.

6. Project Demonstration

The project demonstration will present the entire process of determining the shortest-distance path, constrained by navigability of the terrain. The presentation will begin with the input of pre-processed LiDAR data. A live demonstration will be most effective in presenting each key component of the path-planning software listed in Section 2, as well as for showcasing overall computation time.

The demonstration will begin with presenting a 3D colormap of the LiDAR data to be used by the program to provide a visual representation of the terrain environment. The same LiDAR data will then be processed by NavX's software. Additional visualization scripts may be created for the purpose of demonstration in order to better visualize the internal map representation and waypoints generated. The demonstration will thus validate the capability of NavX's software to compute a shortest path.

Prototype testing will be done in a similar manner by testing with several sets of LiDAR data provided by Harris Corporation, into the path planning program to compute a shortest path between two points. The potential case of a moving endpoint will be simulated with time-periodic updates to the endpoint coordinates provided as input to NavX's program.

7. Marketing and Cost Analysis

7.1 Marketing Analysis

The project's corporate sponsor, Harris Corporation, has defined the system requirements and specifications; therefore, Harris Corporation is the sole customer for this project. While other LiDAR based navigational systems already exist, this project has the marketing advantage of being designed solely to Harris Corporation's design criteria [2], [3], [4].

7.2 Cost Analysis

NavX's product is purely software-based. As such, there are no physical parts to purchase. Furthermore, Harris Corporation will provide test LiDAR data processed using their proprietary GIS software, so there is no need for NavX to purchase any software. Thus, prototyping and project costs will consist solely of a (hypothetical) software engineering salary for each of NavX's four members. Assuming a $41.17/hour software engineering salary and an average of ten working hours per week for 16 weeks, each of NavX's four members will require $6587.20 in compensation, yielding a total cost estimate of $26,348.80 [17].

8. Current Status

Currently, the project is in its preliminary design phase: integrating advisor and sponsor feedback and review into the project proposal, and conducting initial research of existing path-planning algorithms and systems. Based on this research, NavX has made a preliminary decision to adopt a discrete-space representation of the TUGV robot's environment, given the spatially discrete nature of LiDAR data. As a consequence of the discretized environment representation, NavX has also made a preliminary decision to compute shortest paths using graph algorithms like Dijkstra's Algorithm or A*.

9. Leadership Roles

Leadership roles are defined by the requirements of ECE 4011 and 4012 as well as the design requirements. Alvin O'Garro will oversee web page development for the design project and lead the research and development of the path planning algorithm. Jacob (Shin Hyun) Jeong will lead data preprocessing and oversee task scheduling and design expo coordination. Antony Samuel is the liaison to the team's corporate sponsor, Harris Corporation, and will oversee data acquisition. Kartik Sastry will lead map development efforts, as well as serve as the team documentation coordinator and the liaison to the team's project advisor, Professor Erik Verriest.

10. References

[1] McGonagle, M. (2014). University Capstone: Research robotic path planning with moving end point or target.

[2] Y. Egi, C. Otero, M. Ridley and E. Eyceyurt, "An Efficient Architecture for Modeling Path Loss on Forest Canopy Using LiDAR and Wireless Sensor Networks Fusion," *European Wireless 2017; 23th European Wireless Conference*, Dresden, Germany, 2017, pp. 1-6.

[3] C. Zhang, J. Wang, J. Li and M. Yan, "2D Map Building and Path Planning Based on LiDAR," *2017 4th International Conference on Information Science and Control Engineering (ICISCE)*, Changsha, 2017, pp. 783-787.

[4] L. Wang, J. Wang, X. Wang and Y. Zhang, "3D-LIDAR based branch estimation and intersection location for autonomous vehicles," *2017 IEEE Intelligent Vehicles Symposium (IV)*, Los Angeles, CA, 2017, pp. 1440-1445.

[5] J. C. Latombe. *Robot Motion Planning*. Kluwer Academic Publishers, 1991

[6] S. M. LaValle. *Planning Algorithms*. Cambridge University Press, 2006

[7] L. E. Dubins, On curves of minimal length with a constraint on average curvature, and with prescribed initial and terminal positions and tangents, *Amer. J. Math*., vol. 79, no. 3, pp. 497-516, 1957

[8] A. V. Aho and J. D. Ullman, Foundations of Computer Science: C Edition. New York, NY: W. H. Freeman, 1994.

[9] L. Yang, J. Qi, D. Song, J. Xiao, J. Han, Y. Xia, “Survey of Robot 3D Path Planning Algorithms,” Journal of Control Science and Engineering, vol. 2016, April, 2016. [Online serial]. Available: https://www.hindawi.com/journals/jcse/2016/7426913/. [Accessed Mar. 4, 2018].

[10] N. s. P. Hyun, E. I. Verriest and P. A. Vela, "Optimal obstacle avoidance trajectory generation using the root locus principle," In Proc. 2015 54th IEEE Conference on Decision and Control (CDC), 2015, pp. 626-631.

[11] A. Beaty, J. Freeman, R. Jones, “Tactical Unmanned Ground Vehicle,” Georgia Tech School of Electrical and Computer Engineering, Atlanta, Georgia. Tech. Report. 16 Dec. 2016.

[12] The American Society for Photogrammetry & Remote Sensing. (2011). LAS SPECIFICATION VERSION 1.4 – R13.

[13] J. O. Wallgrun, "Robot Mapping," in Hierarchical Voronoi Graphs: Spatial Representation and Reasoning for Mobile Robots, Heidelberg, Springer-Verlag, 2010, pp. 11-43.

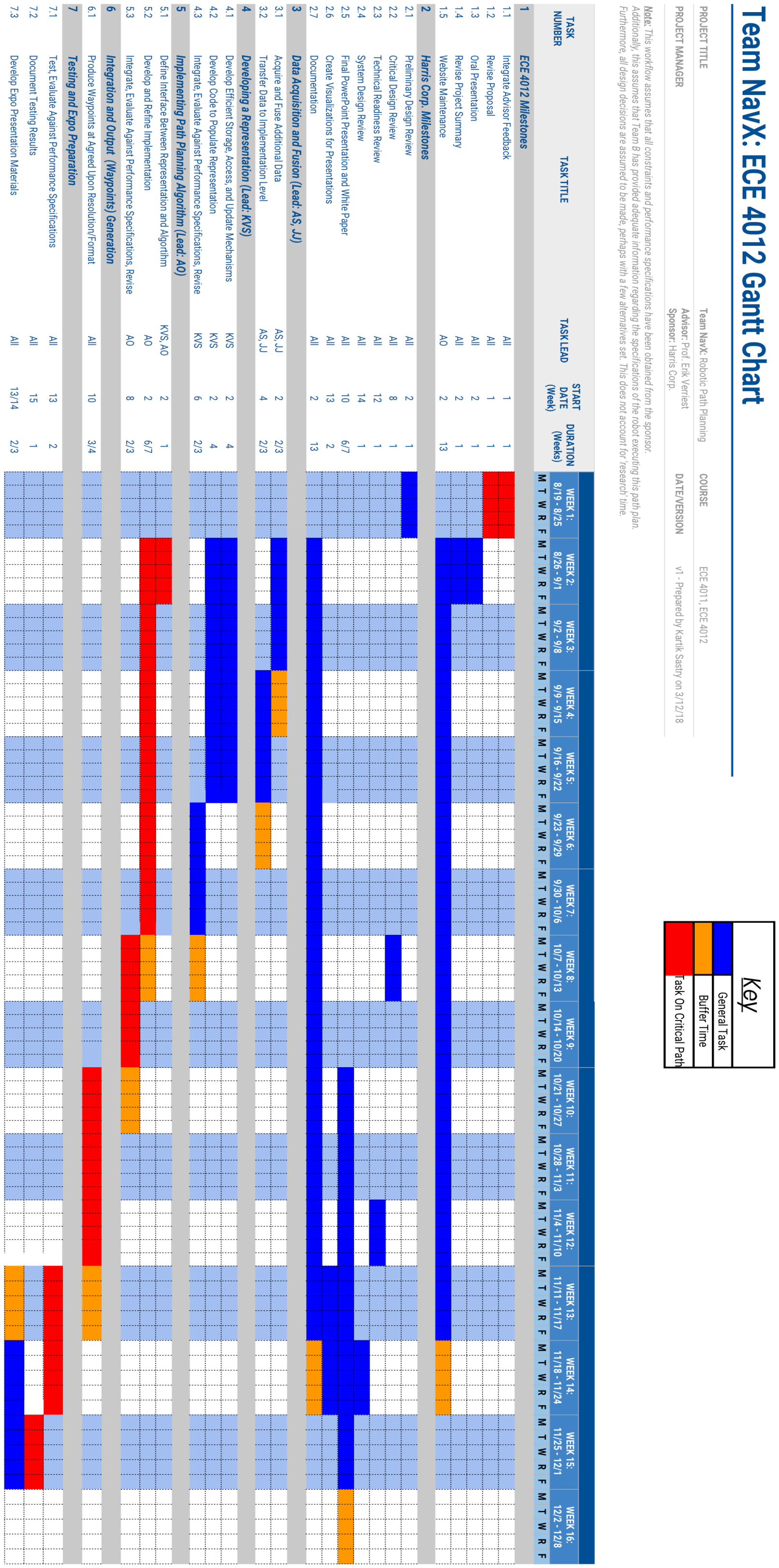
[14] M. Čikeš, M. Đakulović and I. Petrović, "The path planning algorithms for a mobile robot based on the occupancy grid map of the environment — A comparative study," *2011 XXIII International Symposium on Information, Communication and Automation Technologies*, Sarajevo, 2011, pp. 1-8.

[15] IEEE802.org. (2018). IEEE 802.11, The Working Group Setting the Standards for Wireless LANs.

[16] Omega, “The RS232 Standard” (2018). OMEGA Web Technical Reference

[17] Glassdoor.com. (2018). Salary: Entry Level Software Engineer | Glassdoor.co.uk.

Appendix A (Gantt Chart)



Appendix B (PERT Chart)