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Cross Disciplinary Project Management in the Design and Construction of a Firefighting Robot

A Major Qualifying Project

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By

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Abstract

The objective of this project was to understand how to manage a cross-disciplinary team of engineers focusing on team dynamics, engineering design and subsequent construction of a Firefighting Robot. The rationale for completing this project was to utilize management techniques and strategies to help a team of cross-disciplinary engineers complete their work efficiently. The State-of-the-Art of managing a cross-disciplinary team of engineers draws from Project Management in Civil Engineering. The methods used include SMART project management methods, Axiomatic Design, Gantt and PERT charts, a Critical Path Analysis, and a Risk Analysis. The results indicated that the methods increased the efficiency of a cross-disciplinary team of engineers, by providing the guidance and leadership needed to complete the product. The conclusion illustrates that the addition of an MGE to an engineering design team provided support and management in areas of project strategy, engineering design, timelines, budget, and overall project completion. Working together, the ability to achieve the operational goal for the Firefighting Robot (FRED2) met the goals set at the onset of the project.

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Objective/Rationale

The objective of this project was to manage a cross-disciplinary team of engineers focusing on team dynamics, engineering design and subsequent construction of a Firefighting Robot. The rationale for completing this project was to utilize management techniques and strategies to help a team of cross-disciplinary engineers complete their work efficiently. The strategies and methods included delivering designs on a schedule while maintaining progress that was both achievable and reasonable. As the project manager of the project it was my duty to help define the project goals and assist in the communication within the team itself as well as the advisors of the project. To help achieve the project goals as a team, management had to continue to manage scope creep as it became evident, while keeping the financials and costs of the project on budget.

By incorporating various managerial approaches in the project, The Firefighting Robot (FRED2), management techniques and strategies can be utilized to facilitate and create a more efficient team dynamic and a functional robot. The project team of civil, mechanical, computer science, electrical, robotic, and management engineering majors created a structured timeline which allowed for all the different attributes of the robot to be delivered and aligned with the development and design of the robot. Management of the project utilized the strategies and methods needed to keep deliverables on a timeline, manage scope creep, staying in communication with both the team members and it's advisors, and keeping a record of cost and evaluating progress that would benefit the MQP team.

According to Management: Tasks, Responsibilities, Practices, a book about management and its effectiveness of teamwork, author Peter Drucker states:

"Similarly, the team is the preferred design principal for innovative work. But for most operating work the team is not appropriate by *itself and alone* as the design principle of organization. It is a compliment- though a badly needed one. It may well be that it is team organization that will make the functional principle fully effective and will enable it to do what its designers had hoped for. (Drucker, 1974)"

The purpose of the robot was to assist firefighters fighting an indoor fireground, as they are put at risk by the constantly changing environment. A fireground is an area in which firefighters carry out operations and complete tasks in the event of a fire. Since they are often unaware of the structural layout of the building, firefighters can become disoriented and easily lost. In addition, the temperatures create an unsafe and unpredictable environment. The use of robotics cannot only assist firefighters, but can identify some unsafe aspects of the fireground, as well as weaknesses in the structural layout. The goal of the robotics project verses the management MQP, was to create a robot that could survive the high temperatures of the fireground, navigate to avoid obstacles autonomously while locating trapped humans, and return real time data to help assist the firefighters outside the fire ground. The goal of the management MQP was to manage the cost, time, and quality of the final prototype for possible consumer use.

The State of the Art

The state-of-the-art in managing a cross-disciplinary team of engineers demonstrates project management methods drawn from Project Management in Civil Engineering. Civil engineering construction projects are often constrained due to time and budget. Some projects, when reported, can exceed the time and budget due to the complexities that revolve around the design and quality. This can be difficult to forecast or predict as many changes during the construction process may occur. In civil engineering, most difficulties occur from details with the ground conditions, what materials the structures are assembled of, and the forces imposed on that structure (Salathia, 2004). The construction of roads, railways, tunnels, bridges, pipelines, and dams must all be designed and built according to the field conditions found on the site. Knowing these conditions and being able to foresee the complications that occur beforehand can be difficult. In order, to achieve the successful management of the project at hand, depend on the appropriate course of action, the judgment of the engineer in charge as well as their team of engineers and contractors. The importance of establishing appropriate supervision of the construction work, as it proceeds, is what leads to completion of the project (Salathia, 2004)

Working on a project, team members must accomplish the work necessary to complete the project. The FRED2 team had various members that were vital to the success of the project. A project manager connects the team. Team members may have the expertise to do the work required independently but may lack the ability to work as a cohesive group. A project manager would assist in answering questions, keep communication flowing between team members, making sure team understands what the desired outcomes are, staying on course with scheduled milestones, focusing on and evaluating project goals (Drucker, 1974). For the FRED2 team, each member of the team brought a specific strength that helped reach the overall goals of the project. The project team included mechanical engineer, computer science engineers, a civil engineer, a robotics engineer, and a management engineer. The role of management engineer was to make sure that team members stayed connected and were focused on their component of FRED2 to complete the project. Although there were no direct conflicts between team members about the project, there were obstacles and setbacks that required communication for resolution and performance of the prototype.

Including a project management on the team, made communicate easier between the team members, assisted in coordinating effective interaction to achieve the shared objective of completing the time, budget, and quality constraints of the prototype. Managing a team during a complex project requires some fundamental skills of basic human interaction.

The Project Management Institute defines human resource management as:

"The art and science of directing and coordinating human resources throughout the life of a project, by using administrative and behavioral knowledge to achieve predetermined projects objectives of scope, cost, time, quality, and participant satisfaction (Salathia, 2004)

The importance of understanding this definition is a key element in management, because throughout the progress of an engineering project, with numerous contractors and outside consultants, communication and project planning become the focal point for project completion by a deadline. Another way of understanding this definition is to perhaps measure success of the projects by analyzing the cost, time, and quality. Cost, time, and quality create the project management tool known as the Iron Triangle, which helps deliver projects on time, within the budget while meeting the quality specifications (Shenhar Dvir, 2007). The Iron Triangle (Figure 1) was originally conceived as a framework to enable project managers to evaluate and balance the competing demands of cost, time, and quality within their projects (Atkinson, 1999). As the project manager, the utilization of the Iron Triangle was an excellent tool to manage and evaluate the project. By understanding the mutual dependency between the three constraints, the FRED2 team was able to build the highest quality robot, while keeping to the time restrictions and budget that restricted the team from developing the perfect robot. In engineering and construction, the ability to build a quality product can vary between the amount of time allotted to construct as well as the resources and monetary support. By understanding the Iron Triangle and it's framework, the ability to realize that having certain constraints can have an impact on the quality of any potential product, allowed the team to make certain decisions and compromises throughout the design, build, and eventual testing of The Firefighting Robot.

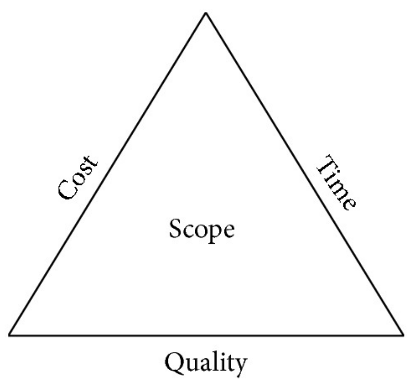


Figure 1 – Iron Triangle

When changes occur, it was important as the project manager to assess the impact of that given event or decision and create a range of options. In addition, show how the impact on these three constraints and thereafter create unnecessary balance between them (Sember, 2008). As project manager, the Iron Triangle further assisted in discovering the priorities, motivation for the team members, and how well the goal of the project was understood. This tool enabled the ability to assess the productivity and overall execution of the FRED2 team designs that had been laid out by the team in the SMART goals. The team was able to build a level of communication and focus on productivity that helped create an effective team. As Patrick Lenciono states in his book,

“The kind of trust that is necessary to build a great team is what I call *vulnerability-based trust*. This is what happens when members get to a point where they are completely comfortable being transparent, honest, and naked with one another, where they can genuinely mean things like “I screwed up,” “I need help,” “Your idea is better than mine,” “I wish I could learn to do that as well as you do,” and even, “I’m sorry.”

When everyone on a team knows that everyone else is vulnerable enough to say and mean those things, and that no one is going to hide his or her weakness or mistakes, they develop a deep and uncommon sense of trust. They speak more freely and fearlessly with one another and do not waste time or energy putting on airs or pretending to be someone they are not. (Lencioni,2012)”

A successful project manager must be able to build and lead an effective team by managing a group of diverse individuals each with their own skill set and goals to work cohesively and effectively to accomplish the goals set for the project.

“A good way to understand a working group is to think of it like a golf team, where players golf and play on their own and then get together and add up their scores at the end of the day. A real team is more like a basketball team, one that plays together simultaneously, in an interactive, mutual dependent, and often interchangeable way. (Lencioni, 2012)”

Methods

The methods implemented for management of the FRED2 team during this project included SMART, Axiomatic Design, Gantt and PERT charts, a Critical Path Analysis, and a Risk Analysis. The utilization of the Iron Triangle guided the management of the project throughout its development.

SMART

SMART goals focus on the key elements surrounding the designs of the project. Those goals are intended to focus attention and resources on what is most important for the team in accomplishing and achieving the set priorities for building FRED2. SMART is an acronym for specific, measurable, attainable, relevant, and time bound. The criteria of SMART are designed to foster a clear and mutual understanding of the expected levels of performance in developing an effective design or completing a project (UCal, 2017).

Since this is a cross-disciplinary team, it was important to meet the needs of the team's MQP engineering requirement. It also needs to be stated, that FRED2 is the second attempt at building a Firefighting Robot, this project is working on improving the previous iteration of the prototype robot FRED. A decision matrix (Appendix A) was created and criteria was established that would meet MQP requirements. The criteria targeted durability, ease of use, heat resistance, time to implement, cost and the team's prior experience. The criteria were scaled by scoring criteria from one to five, one being the lowest and five being the highest in priority. Criteria that received a score of 35 or higher signified a main component of FRED2 that needed to be addressed and focused on to complete the project. From the decision matrix, there were a few areas that met the criteria and could be assessed from a managerial perspective as potential SMART goals (Figure 2). The application of SMART would determine and identify the criteria most needed to build FRED2, because it will affect the robot's functionality, how the robot will meet key customer needs, and the team's ability to complete those goals. SMART goals were selected from the criteria goals (Figure 2) that achieved a score of 35 or higher on the decision matrix, qualified as attainable and realistic goals for the project. The goal was to complete the designs and systems by C-term and be able to construct a functioning robot at the beginning of D-term. As a team these goals where created for the development of the robot, as the project manager the responsibility of delivering these goals on schedule was important for completion.

Goal Criteria: FRED2

- Whegs (Wheels)
- Temperature: Internal
- Temperature: External
- Heat Shields
- Waterproofing
- Battery Management
- Automation
- Long Range Communication

Figure 2 – Goal Criteria:FRED2

The goals that were selected for SMART were: whegs (wheels), temperature, heat shields, automation, and long-range communication. As a management tool, SMART established clear steps that were necessary to direct team members toward completion of project, an example is illustrated in Figure 3. Management of the SMART goals involved weekly meetings with individual members, whole team meetings, and team meetings with advisors to assess progress for FRED2. SMART goals would be evaluated and re-set if needed based on progress of the team.

In the construction and design of the heat resistant whegs, the whegs were a priority because without the ability for the whegs to withstand high temperatures and uneven surfaces in the fireground, the robot would not be able to move. To measure the reliability of the design for the whegs, the robot had to be tested in a simulated fireground, to assess the whegs resistance to heat exposure. Throughout the design and construction of the robot, the whegs were a topic of discussion during team meetings, as well as meetings with the cross-disciplinary engineer's advisors. The goal was to have the a wheel design completed by the end of C-term, after a few failed designs that caused wiring to be exposed, exposure to a wet environment, overheating, and electrical malfunction , the team decided to complete the robot and continue working on designing a better solution for the wheels. Working with the mechanical engineer, utilizing AutoCAD a commercial computer-aided design and drafting software application (Autodesk, 2020), the team was able to create a transformable wheg wheel design that would work in a fireground during D-term.

SPECIFIC	Heat resistant whegs.
MEASURABLE	Can withstand temperature of 215℃
ATTAINABLE	Construct whegs using heat resistant materials
RELEVANT	Ability for movement in a fireground
TIME-BOUND	By end of C-Term

Figure 3 – SMART Criteria for Whegs

Temperature for SMART focused on the internal and external environment for the robot. Keeping the internal temperature below 60℃ but enabling the robot to withstand an external temperature of 215℃. The heat shielding was designed to reflect and repel as much heat as possible to allow the robot to continue exploring the fireground. The first of the measurable data for SMART was to keep the internal temperature below 60℃ for 15 minutes. The 15 minutes target was chosen because the previous design and tests of the Firefighting Robot were only 11 minutes 36 seconds and the team wanted to surpass the 11-minute mark. As the project manager, upon reviewing past data from the previous project, suggested the possibility of a more rigorous test of the external heat shielding. After meeting and discussing past results, compared with the improvements of the robot, the team decided to add a test where the external temperature was set at 215℃. SMART goals were re-evaluated and adjusted to meet the new goals for the robot. It was decided to do a 3-minute test at 215℃, since the previous team did not do an extreme heat test for their robot. By including this test, it would allow for a more realistic test of the functionality and reliability of the Firefighting Robot.

. The SMART goal for automation was for FRED2 to be able to perform basic navigation through an environment with limited sight that would be able to detect obstacles and avoid collisions. The team added a stretch goal to the FRED2 design, the ability to use sensors to help firefighters ascertain the whereabouts of trapped humans inside the fireground. The automation of the robot and its exploratory function were addressed during weekly meetings with the team and advisors. The ability to detect obstacles and avoid collisions was accomplished, unfortunately the stretch goal was not attainable. It became evident that a search feature via sensors was going to be difficult to accomplish, the team along with the advisors decided to not pursue the sensor capability. As project manager, the SMART goals were reviewed frequently with the team during B-term and throughout C-term until its completion at the end of C-term. Even though work on the robot was continuous and progress was being made in improving the capabilities of FRED2, it was evident that FRED2 would not be completed until D-term. The team came to the realization that more time was necessary for the design specifications needed for automation.

The final SMART goal was the possibility of long-range communication between the robot inside the fireground and with a Fire Chief at the scene. Due to the complexities of creating a long-range signal in a burning building, after multiple weeks of discussion and deliberation it was decided that this goal was not attainable. Instead, the team decided that communication would focus on a wireless signal available to the operator outside the fireground. The electrical engineer of the group suggested that it was possible for the signal to show firefighters a live visual feed as well as thermal video feeds from the robot in a display. The robot would be able to have a switch that allowed the user to change the controls from manual to autonomous depending on the readouts and data that the robot is giving live. Although this seemed complex, it was decided that there was enough research on the long range communication signal prior to the change in design that it would be possible to alter it into a wireless signal via Wi-Fi and come out with similar results. The decision did not create any slack time in the development of the design even though design was altered.

SMART as a management tool, defined goals and established the criteria, it permitted team meetings to have set topics for discussion, it gave team members opportunity to share and discuss roadblocks that were encountered during development, it created a schedule to complete specific goals, and it also gave the opportunity to celebrate completion of a goal. Occasionally, the progress and completion of a goal were underestimated, but team members were forthcoming with delay of their tasks whether it was needing an additional day or two or even a week. Team meetings were an important time to reassess the stage of development of FRED2, it became apparent toward the end of C-term that the whegs design as well as construction of the chassis would not be completed and the team would need D-Term to construct FRED2. Unfortunately, with the start of D-Term came the beginning of the COVID-19 pandemic. The final construction of FRED2 was in question, as the team would not be able to meet on campus to complete the construction of the Firefighting Robot. The FRED2 team petitioned to remain on campus but was denied approval to continue working on the robot. The team, along with the advisors made the decision to utilize COMSOL, a simulation software (COMSOL, 2020). This software program was utilized to test the chassis design of the robot, because it would be the only way to observe if FRED2 worked in a fireground. The robot chassis was tested in a simulated fireground that conducted the necessary tests to produce results that the team needed for their MQP requirements.

Axiomatic Design

Axiomatic Design is management technique that was utilized to assist and provide guidance in building FRED2 by adding a systematic approach to the design process and the design solution, as well as variables that may influence the final product (Albano Suh, 1992)

In today's highly competitive manufacturing world, companies are forced to develop and deliver high-quality products manufactured at low costs and with quicker ability to sell product to consumers. Since unsatisfactory design results in a great number of process iterations, the effectiveness of design can be of great value for improving performance and quality of manufacturing and of service to customers (Botsaris, 2008). Developed by N.P. Suh a professor at MIT, axiomatic design offers a systematic approach to manage interactions between elements of the design and functions the design must fulfil (Figure 4). As stated by Professor Suh, "all of these are design activities, although the contents of these activities and the knowledge required to achieve the design goal are field specific. While these fields appear to be distinct since each field utilizes different databases and different design practices, they share many design characteristics. What is common in all these activities is that they must do the following" to produce a final product (Botsaris, 2008). Based on two axioms, the independent Axiom 1 and information Axiom 2, which provide a solid scientific foundation for design, axiomatic design theory helps to overcome the shortcomings of trial-and-error approach to product design and development. These axioms convey the basic idea why some designs fail, is because the specification of more functional requirements than necessary can lead to over-design and additional costs, while specification of fewer functional requirements than necessary to achieve design objectives can lead to unacceptable solutions (Botsaris, 2008).

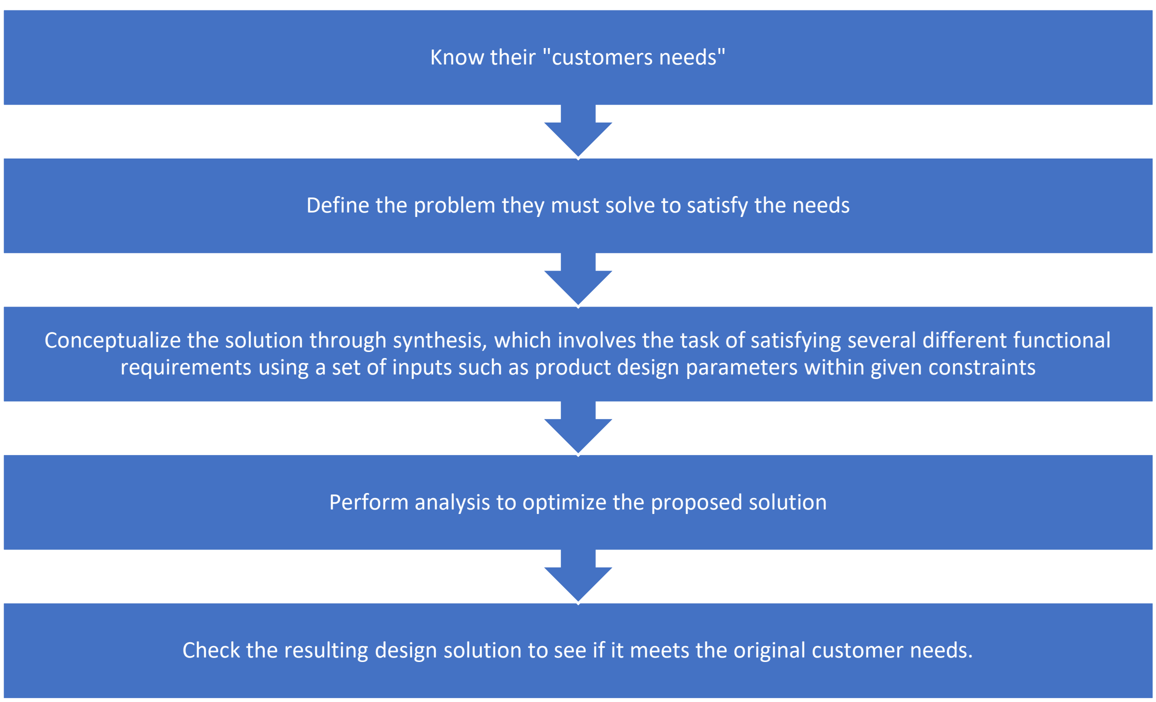


Figure 4 – Axiomatic Systematic Approach

Axiomatic design is a framework and its applications are being applied in process and product development, manufacturing systems, and in structural design for civil engineering structures (Albano Suh, 1992). The design process takes place in four domains: customer, functional, physical and process. The number of domains always remains at four, but the nature of the design elements in each domain changes depending on the product and the needs of a consumer (Figure 5).

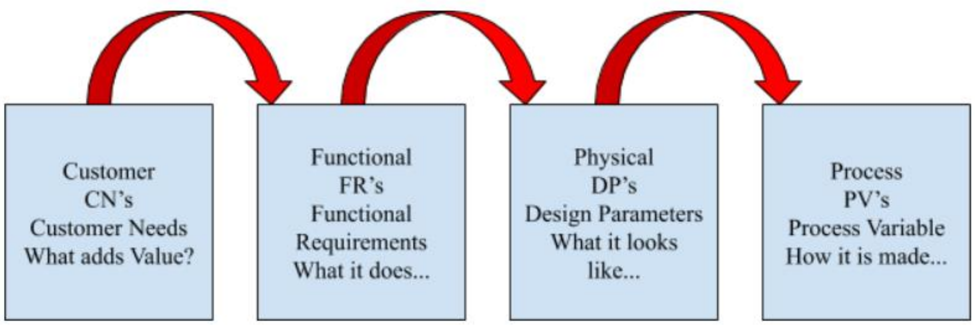


Figure 5 – Axiomatic Design's Four Domains

The axiomatic design framework provided the team the ability to determine the customer requirements for a final product., creating a robot that would be able to assist firefighters in a fireground. Once the customer needs were established, the appropriate functional requirements of the product for the functional domain and the constraints of the system were determined. The functional requirements must be determined in a solution neutral environment, meaning without known understanding of the solution, therefore creative ideas were introduced to meet customer needs. The constraints were stated in the customer domain, but they are evident throughout the whole design process. The next task was the physical domain with specific design parameters which are the physical variables in the physical domain that distinguish the design that specifies and satisfy the functional requirements. This mapping from the functional requirements to the design parameters create the product design.. Lastly, the team began the process domain by focusing on the manufacturing process for the product design by following the two axioms that illustrate the basic postulate of the axiomatic design approach (Figure 6).

Axiom 1	**The independence axiom:**	
		Maintain the independence of Functional Requirements
Axiom 2	**The information axiom:**	
		Minimize the information content of the design

Figure 6 – Two Axioms used in Axiomatic Design

The purpose of the two axioms was to create a design that is as uncomplicated as possible while being able to create functions that are independent to one another, but still meet the needs of the customer. Axiomatic design is built from a divide-and-conquer logic, where the decomposition process begins with the decomposition of the overall functional requirement into sub-requirements. As the product is decomposed it is necessary to specify a set of functional requirements that can progress to the physical domain by the formation of a design solution and specification of the design parameters for the same hierarchical level. This creates a cycle between the functional and physical domains called zigzagging. By the continuous back and forth between the Functional and Physical domains, the product design can be modified to suit the requirements specified for the final design of the product. Zigzagging can also involve the other domains and is repeated until it is possible to construct the product from the information contained in the product architecture (Botsaris, 2008).

Since FR0's purpose is to deliver a functioning prototype, that is both on time with all the deliverables, while keeping under budget, the priorities focused on those three different requirements determined before the build (Figure 7). Since the purpose of FRED2 is to function in a fireground, FR2 was that FRED2 could be tested in an actual simulation of a fireground. Without a fully functioning robot, there would be no results for the group to present and illustrate why and how FRED2 is an essential device to fight fires. As the project manager, the concern of FR1 and FR3 were pivotal during discussions, due to the realization that the more time that was spent on redesigning FRED2, meant more money and time would be required to achieve the robots functionality. Also, it became more evident as cost for parts and software increased, the more expensive FRED2 would become. Although the goal of the project was not marketability, ensuring a low-cost build to construct the robot would enable it to be marketable to customers in need of this type of equipment. Due to the limited budget that the group was given, as project manager keeping the design under budget was difficult. Throughout the design and building phase, decisions were made carefully as to where money was spent. FR3 was the amount of time that was needed to complete the construction of the prototype. Since we had what was considered ample time to complete the prototype, especially since we were improving upon a past firefighting robot design, a total of eight months from the end of August to the beginning of April seemed sufficient time to complete the project.

	DP0 – Construct necessary budget and schedule	DP1 – Adhere to Proposed Budget	DP1.1 – Develop system to manage financial risk	DP2 – Outline deliverable and testing schedule	DP2.1 – Supply schedule to assemble technologies	DP2.2 – Outline Testing Schedule	DP3 – Assemble a timeline	DP3.1 – Create a system to manage risk
FR0 – Deliver Function Prototype on time and Budget	X							
FR1 – Maintain project below budget		X		0	0	0	0	0
FR1.1 – Manage Financial Risk			X	0	0	0	0	0
FR2 – Prototype functions properly		0	0	X			0	0
FR2.1 – Integrate Design		0	0		X	0	0	0
FR2.2 – Test Prototype Functionality		0	0		0	X	0	0
FR3 – Project is on time		0	0	X	X	X	X	
FR3.1 – Manage the risks in schedule		0	0	0	X	0		X

Figure 7 – Axiomatic Design Decomposition

The axiomatic design was a great management tool for keeping FRED2 on track toward completion, because of the clear guidance that it provides, however time was a constant issue that had to be navigate. To effectively manage the amount of time allocated to the project; the group decided to establish project milestones. By incorporating a timetable, as the project manager, it was of great assistance in determining whether the project was progressing, or if there was a need for more resources to overcome potential roadblocks that might occur during the project's development. One of the biggest roadblocks was the unexpected supplier constraints. While constructing the robot, several of the deliverables that had been established as milestones were delayed. Although these constraints did not hold up any of the initial phases of FRED2's design development, as the project progressed it became evident that without some of the materials and required designs the team could not proceed in the prototype's development and needed to re-evaluate how to accomplish building a functional FRED2.

When deciding how to best manage and create the timeline for the FRED2 team, it was clear that restrictive timelines where counterproductive to the team's success. A timeline that is constructed by a manager alone, without the consensus of the entire team, also creates dysfunction to the group dynamic. Important to create a feasible timeline with set goals as a whole group (Lencioni, 2002). As project manager, it was key to communicate continuously with team members, share information with team members and advisors, ask questions about the design progress, and maintain progress relating to the timeline specifications that the team had set for FRED2..

Gantt Chart

A Gantt chart is a project management tool assisting in the planning and scheduling of projects of all sizes, although they are particularly useful for simplifying complex projects. For the FRED2 MQP team, a Gantt chart (Figure 8)was used to create timelines and tasks that displayed a horizontal bar chart, showing start and end dates, as well as dependencies, scheduling and deadlines, including how much of the task is completed per stage and who was responsible for the task at hand. This helped the team keep on task and complete all the necessary designs and parameters (APM, 2020)

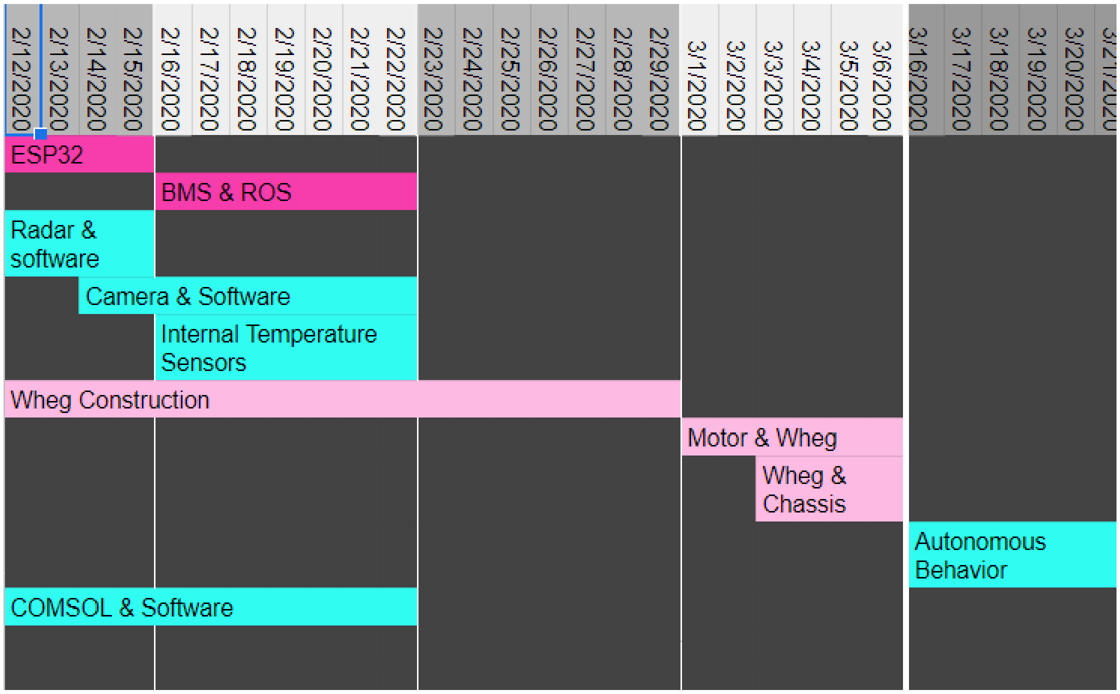


Figure 8 – Integration Gantt Chart for Project Completion C-Term

As a result of a bar chart format, it was possible to check on progress with a quick glance. One can easily see a visual display of the final assembly and integration of the robot, the timelines, and deadlines of all tasks, as well as the relationships and dependencies between the various activities. Project management solutions that integrate Gantt charts give managers visibility into team workloads, as well as current and future availability, which allows for more accurate scheduling (APM, 2020). Appendix B references the Gantt charts used in the beginning terms of the project and what needed to be completed by then end of each term.

PERT Chart/Critical Path/ Risk Analysis

Along with Gantt charts the use of a PERT chart can also be beneficial to a project team. The analysis and construction of a final PERT chart enabled the FRED2 team to visualize the projects milestones as individual tasks to help identify the critical path of the project.

The creation of a "critical path" allows project managers to expand the flow of materials from the beginning of design process to the construction of the final product. To visualize this, a PERT chart can be created charting and noting the time each step will take. This will enable the project manager as well as team members to see how long it will take to reach each milestone.

The first step to any managerial problem is to develop a comprehensive plan that encapsulates all potential problems and how to minimize them. After brainstorming as a team, the entire project process had to be examined to find a possible obstacle as well as the critical path. Along with the axiomatic design process, a PERT chart was used to find the critical path from which a timeline was then developed with the help of the FRED2 team. About halfway through developing the project timeline, it was determined that the risk of project completion time was high and the likelihood that the project would need an additional term to complete seemed inevitable.

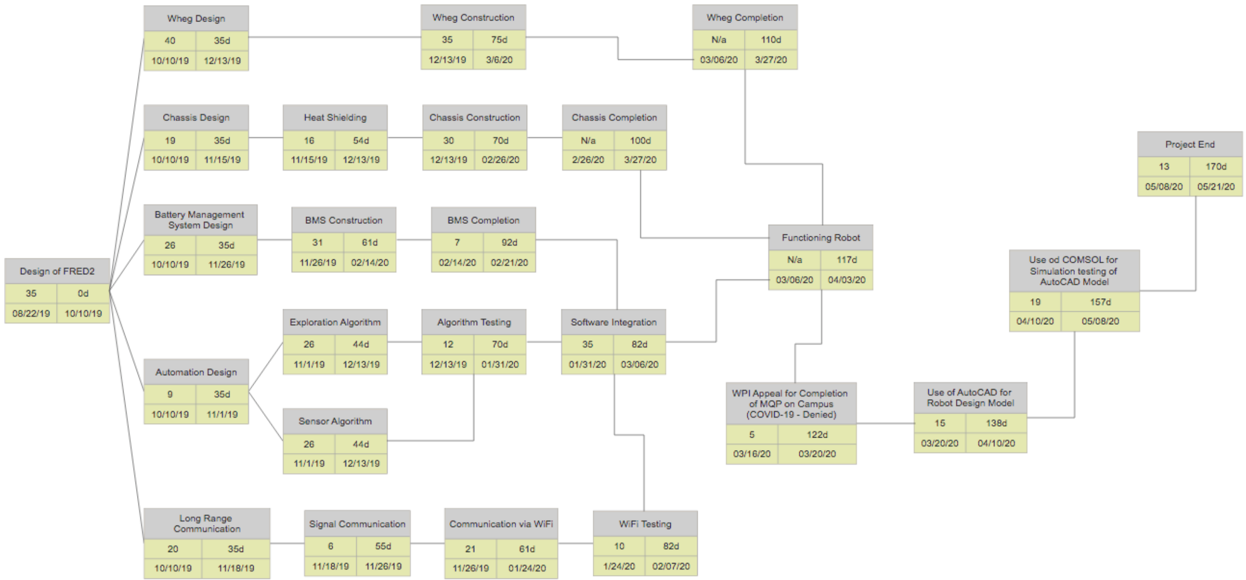


Figure 9 - PERT Chart with critical path

Due to COVID-19 Wheg Completion and Chassis Completion never finished. A functioning prototype was never built or tested. Used software to generate model and results.

For potential project failures to be discovered it was important to have a background on ongoing team prototype problems. After surveying and identifying possible problems the results were put in a risk management table (Figure 10). As project manager, maintaining progress for project was important to reach completion goal. Therefore, as project manager it was important to figure out how to prevent the problems that could arise, how to address those problems immediately without causing a disturbance in the timeline, the importance of incorporating team discussions when problems came along and stressing to the team how important it is to communicate with entire team if a problem exists. Management of the team utilized information, strategies, and techniques from previous classes on management, personal work experiences in management, and seeking advice from advisors to solve problems a team may be dealing with.

Management tools were shared and discussed with the FRED2 team to ensure that project management was utilized properly and how it can benefit the overall outcome of the project.

Item	Risk	Risk Description	Mitigation	Mit. Risk
1	Med	Development and Construct of Whegs	- Construct Whegs with 3d printer to visualize design concept and construct heat resistant material to match said design	Low
2	Med	Sustainability of Battery Management System	- Utilization of BMS professors on WPI campus to help design and create reliable and dependent BMS system	Low
3	Med	Sensor fusion software design and Autonomous Exploration	- Integrate software over scheduled time - Analyze and refer to previous FRED designs to maximize productivity and sensor integration	Low
4	Med	Test time may be to be limited and cost of fire tests are too high	- Follow previous live fire testing simulations to help maximize results at minimum cost	Low
5	Med	Development of Completed Prototype for testing	- Plan development for majority of project - Total project was 8 months leaving 5 months for construction with 1 month of available slack for testing	Low

Figure 10 - Table of Anticipated Risks for the FRED2 MQP

With the completion of the risk analysis the robot design was analyzed by isolating project variables. The variables with the help of the FRED2 team were organized into a PERT chart, this provided the necessary information to calculate possible obstacles through the critical path. The critical path is important because it allows for the identification of obstacles as well as the amount of time spent on each variable. This time also known as “slack time” is the amount of extra time spent on any given variable on the critical path that will not affect the projects total time. Slack time is what clearly defines what variables can be extended without affecting the project.

The benefits of the critical path method include the promotion of proactive planning, allocating resources such as time, and continuously monitoring progress in comparison to timelines. Using the Critical Path Method sponsors more efficiency and productivity, reduces uncertainty, and increases the chances that tasks will be completed on time (Critical Path Method, 2015). A disadvantage of using the Critical Path Method is that it requires an estimate of how long each activity should take, which can be very difficult to accurately determine. The critical path method also does not necessarily fix problems; it is merely used to inform project members of primary tasks with no slack time (Critical Path Method, 2015).

It was critical that the FRED2 team did not over schedule tasks that needed to be performed by specific team members. This caution came from the Queuing Theory (Figure 11), which is a mathematical study of waiting lines and clearly shows how important it is to think about the cause and effect if a task is not completed in time for another to begin. Queuing theory provides the design engineer with a traffic flow model that can be used in the design of signalized intersections (Papacostas, 1993). As a management tool, the Queuing theory permitted team members to visualize the cause and effect if a task was not completed. As project manager, having a team member wait to complete their task because another team member did not complete a task wastes time and delays the completion of the prototype. According to the Harvard business review:

> [The graph] shows that with variable processes, the amount of time projects spend on hold, waiting to be worked on, rises steeply as utilization of resources increases. Though the curve changes slightly depending on the project work, it always turns sharply upward as utilization nears 100%. (Stefan Thomke, 2012)

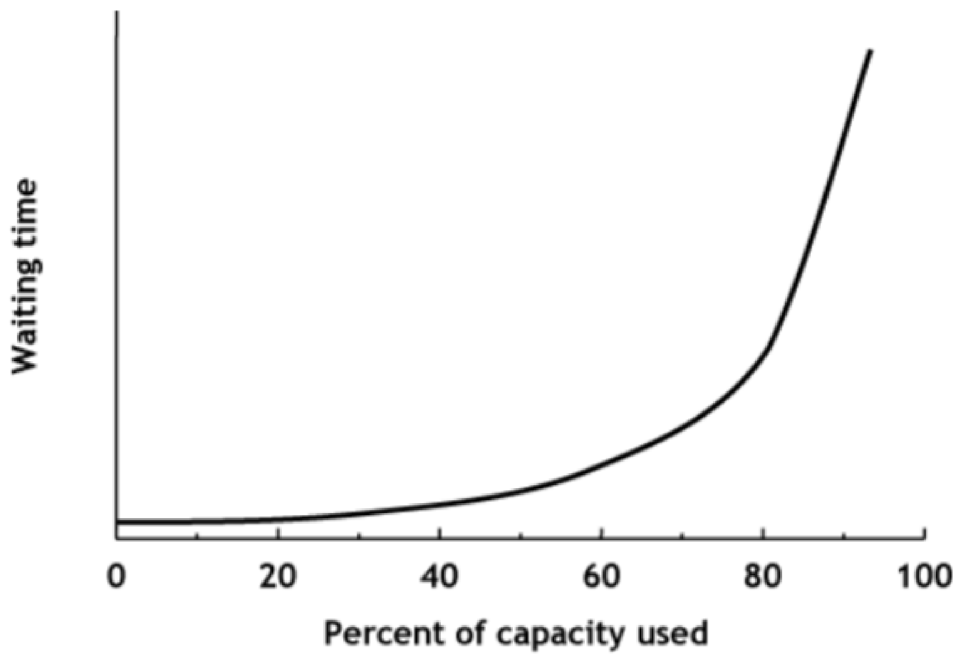


Figure 11 – Queuing Theory Graph

When incorporating multiple phases into a single product it will inevitably result in at least one stage of development waiting for another member's completion of work, information, or actual piece of the product to proceed to the next step of building FRED2. This leads to increased wait times which in turn results in missed milestones. When a new task becomes possible, based on the timeline of the proposed project, the FRED2 team must make sure the prerequisites for each task are completed before moving on to the next task. By continuing to check in with team members, following the timeline schedule, checking on status of material availability, and being in constant communication will allow the FRED2 team to ensure that all design aspects that involved various majors would remain on target for the set production and testing schedule. In doing this, it provided the assurance and to alleviate potential obstacles that could arise from team members falling behind. One could relate this to a checks and balances amongst all members of the team, to make sure components, time, and budget are kept on track.

Other Methods

Multiple communication tools in addition to the above-mentioned methods were utilized to manage the team in having a better chance of a successful build of FRED2. The additional management communication tools used were Slack, Outlook, and Google Drive and Docs. Slack became the team's main form of communication. Slack replaced emails and enabled one to create various team channels that can be used to discuss specific topics. For the team, two channels were created (Figure 12). The first channel was to communicate with everyone including the advisors, where discussion occurred on anything relating to the design of the project as well as progress of the project for each design. The relay of communication between team members and the advisors allowed for transparent communication, including the asking and answering of questions, any concerns, and immediate information updates from anyone who may have missed a prior meeting. The second channel became the team channel, where communication between team member permitted the ability to plan meetings, update each other on individual progress, and if necessary, keep each other accountable. Slack allowed for private conversations between team members, permitting team members to quickly receive information or feedback on the robot's progress.

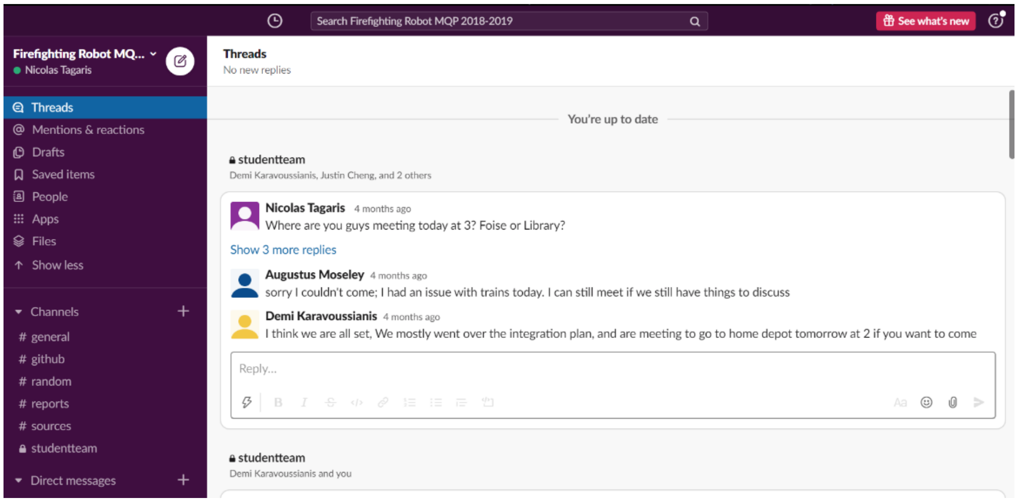


Figure 12 – Slack Feed for Communication

Since this MQP focused on project management, the ability to stay connected with team members one on one after specific tasks or actions was beneficial in keeping the progress of the development of the robot on track. Slack permitted the ability to upload videos, pictures, and documents with ease for everyone to view and give feedback, it also allowed team members to pin specific items that may be useful later, therefore minimizing search time in the future. Google Drive and Docs encouraged sharing and writing collectively, therefore expediting the research and writing process for the MQP. Outlook was used as a calendar to set up meeting agendas, reminders of upcoming meeting, the ability to schedule a meeting, and gave the option to rsvp if they would be attending scheduled meetings. Meetings were frequent, two to three times per week, focusing on what was worked on, what needed to still be completed, and anything else that was pertinent to the topic on the agenda. The weekly meetings created a constructive narrative to continue improving the prototype robot design and function.

Results

The MQP for management engineering utilized numerous methods to manage the team in building the prototype FRED2. Many obstacles did appear during the development of the FRED2 prototype. All manufacturing needed to be done on campus because using off campus vendors was too expensive. This further became an issue when it was discovered that WPI did not own the required equipment to construct the whegs out of the heat resistant material that had been decided on. By adhering to the management methods selected which included SMART techniques, axiomatic design, the use of Gantt and PERT charts as well as critical path and risk analysis the remaining aspects of the design required minimal re-organization. The software integration, the battery management system, heat shields, and completion of the prototype parts were on target and completed by the end of C-term, the only thing left to complete in D-term were the whegs and the chassis, followed by the actual build of FRED2 and testing phase in D-term. Not only were the key aspects of the project completed, the team stayed within budget with the capability of live fire testing.

Regardless of the completion of the robot on time, nobody expected the unprecedented event of the COVID-19 pandemic. This resulted in the team unfortunately not having the opportunity to complete the final construction of the prototype and test the prototype properly in a live fireground and fire test. Although, with the inability to complete the test live, the team was able to overcome this obstacle by using computer software COMSOL. The COMSOL simulation software provided the ability to create a completed and constructed design concept of the robot to be placed in a simulated fireground. Even though the team were not able to test a tangible prototype, the ability to overcome and create a solution that was applicable shows the dedication of all team members to produce a viable product for utilization in a fireground and have the ability to support firefighters during a fire. The approach to this MQP for management engineering focused on being part of the team, not only as a manger but someone who also participated and contributed in the construction of FRED2. Research on current management strategies, problems, design, or method of management are plenty. Lencioni states,

> "When it comes to building a cohesive team, leaders must drive the process even when their direct reports are less than excited about it initially. And they must be the first to do the hardest things, like demonstrating vulnerability, provoking conflict, confronting people about their behavior, or calling their direct reports out when they are putting themselves ahead of the team. The leader must also be the driving force behind demanding clear answers to the six big questions, even when everyone else wants to end the discussion and just agree to disagree. They must be constant, insistent reminders to the leadership team about those answers, challenging them about everything from their behavior in relation to the organization's values to their commitment to the team's rally cry." (Lencioni, 2012)

Management style can be broken down and analyzed in many forms, based on the survey results (Appendix D) team members agreed that having an MGE on the team assisted in keeping project on track and allowed the team the ability to focus on the build of the prototype and not have to worry about the administrative aspect of the project. Reflecting on the management style utilized as the project manager of the team, management was one of trust, perceptiveness, and persistence. However, communication skills, creating a more balanced work environment with more integration of team members working together, and grasping a better understanding of strengths and weaknesses of a team member are areas that still need to be worked on as a project manager. The ability to have an MGE as part of an MQP project team was beneficial to the members of the FRED2 team. The opportunity for the MGE team member allowed for real life application of management techniques and strategies, and the ability to facilitate the role of a project manager. The MGE's ability to take over responsibility for planning and overseeing a specific project ensures that the team can focus on the development of the product and their designs without having to worry about the administrative aspect of a project (Appendix E). The lessons learned from being part of the team as the project manager included the importance of communication for clarity, time-management, project planning/schedules, staying on budget, and utilizing the strengths of your team. Another experience of management was the ability to observe the team members. Observation not only permitted but became a learning experience to see how "things" were resolved in a team setting, how the team solved obstacles and setbacks during the project, how they communicated with each other, and even how they dealt with disappointment. By observing the team, the management strategies and techniques could be adjusted to further assist the team in completing the goal. The takeaway from the experience working as a project manager with the FRED2 team was one of learning and grasping a better understanding of project management.

Conclusion

The purpose of the MQP was to manage a cross-disciplinary team of engineers and to aid them in accomplishing their design of a Firefighting Robot FRED2 by utilizing many management techniques and methods such as SMART and Axiomatic Design. After the initial meetings, it was evident that meeting goals was going to be a greater challenge due to constraints of the design specification for FRED2. As the project manager, for the team to reach set goals and to fulfill the MQP experience, it was necessary to review and analyze past design ideas, discuss and promote team growth, settle team setbacks as they arose and eventually lead the team by including many managerial strategies and techniques to facilitate the progress in the completion of the Firefighting Robot FRED2. The FRED2 team was not able to complete the final build of the prototype robot due to the Covid-19 pandemic, however a simulation was performed, and results showed that FRED2 met the MQP goals set by the team.

Appendix A

Decisions Matrix for SMART Goals

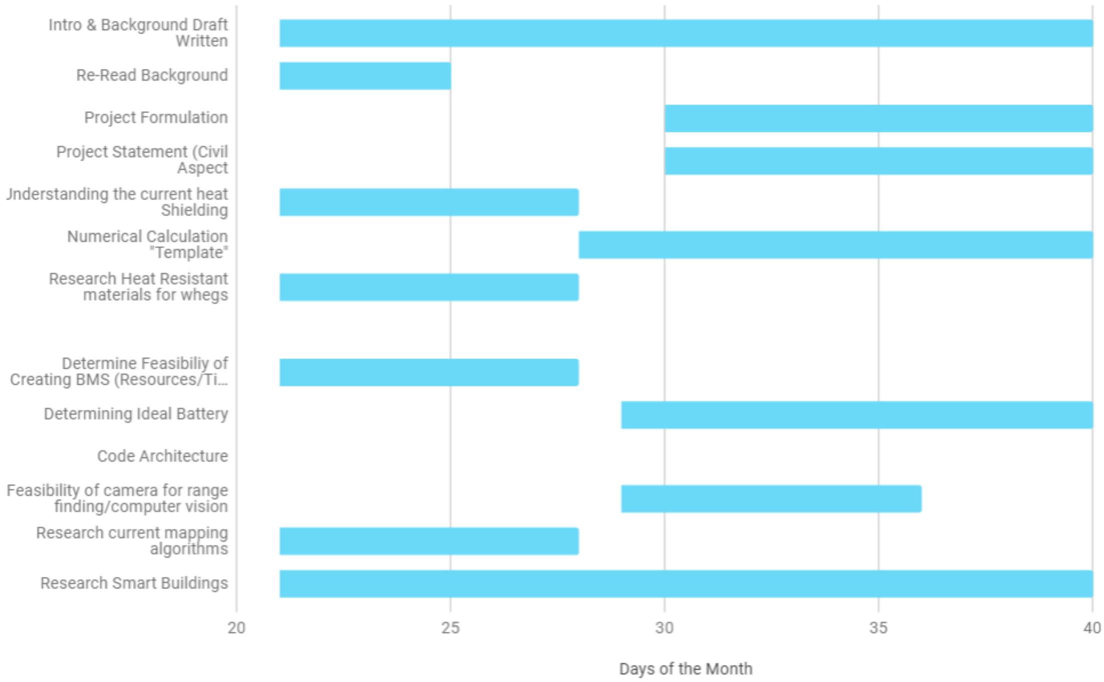
Rank	3	1	2	2	2	1	
Criteria:	Durability	Ease of Use	Heat Resistance	Time to implement	cost	Prior experience	**Total**
Weight	1 - no impact 5 - vital impact	1 - more difficult to use 5 - only usability improvement	1 - adds another component to make heat resistant 5 - significantly improves heat resistance	1 - impossible/all year 5 - 1-3 days to implement	1 - out of budget ($2500) 5 - free	1 - no one has ever worked on anything similar 5 - 1 person has relevant, extensive experience	
Optimize Heat shielding to maintain internal temperature of less than 60c for 15 minutes	4	3	5	2	3	3	38
Whegs that reliably and automatically deploy	3	2	1	3	3	2	27
Heat Resistant Whegs	4	3	5	3	2	3	38
Waterproofing all sides/angles	5	3	3	2	3	2	36
Physical Mapping w/ no initial assumptions	1	4	2	3	5	4	31
Heatproof Shell 215 °C for 3 minutes w/ Internal Temp < 60 °C	4	3	5	2	3	3	38
Battery management system	4	4	3	3	3	2	36
Extended long-range communication	1	4	3	2	3	2	25

Range Finding/3D imaging	1	4	2	1	2	2	19
Heat and Pressure mapping	1	4	2	2	2	2	21
Refine User Interface	1	5	2	4	5	4	34
Autonomous exit prior to critical internal temperature	2	4	3	2	4	4	32
Add an interior time algorithm that estimates and displays the time before internal temperature reaches 60 °C	1	4	3	3	5	3	32
Autonomous exploration of the fireground, moving toward hot zones and avoiding collisions	1	3	2	2	5	5	29
Automatically launch scripts on robot boot	1	5	2	5	5	4	36
Metal whegs (or other heat-resistant material)	5	3	4	2	3	2	38
Automatic wheg deployment	5	4	2	3	4	4	41
Waterproofing different angles/sides of the robot to account for any splashing/ non-vertical water flow	3	5	5	2	3	2	36
Body/shell of FRED can survive 215 °C for 3 minutes, with an internal temperature of 60 °C	5	5	5	1	3	4	42

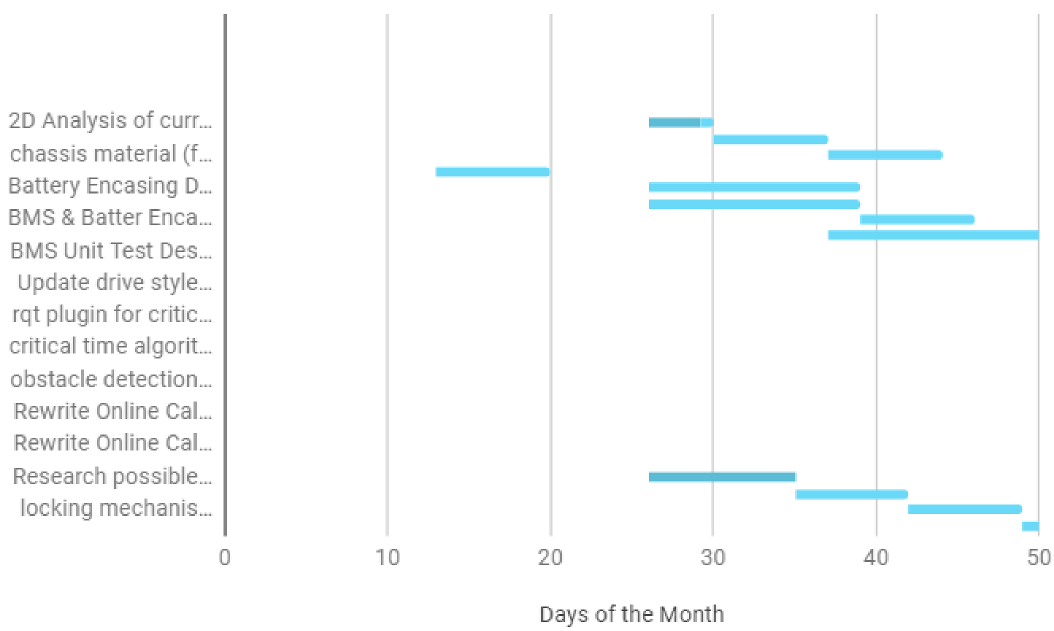
Compensate for ZnSe lens distortion, especially for IR rangefinders	1	3	3	3	2	2	24
Deployment Time of less than 2 minutes	1	5	3	2	3	2	26
Move at 0.5 m/s with heat and impact shielding on	1	3	3	3	3	3	27

Appendix B

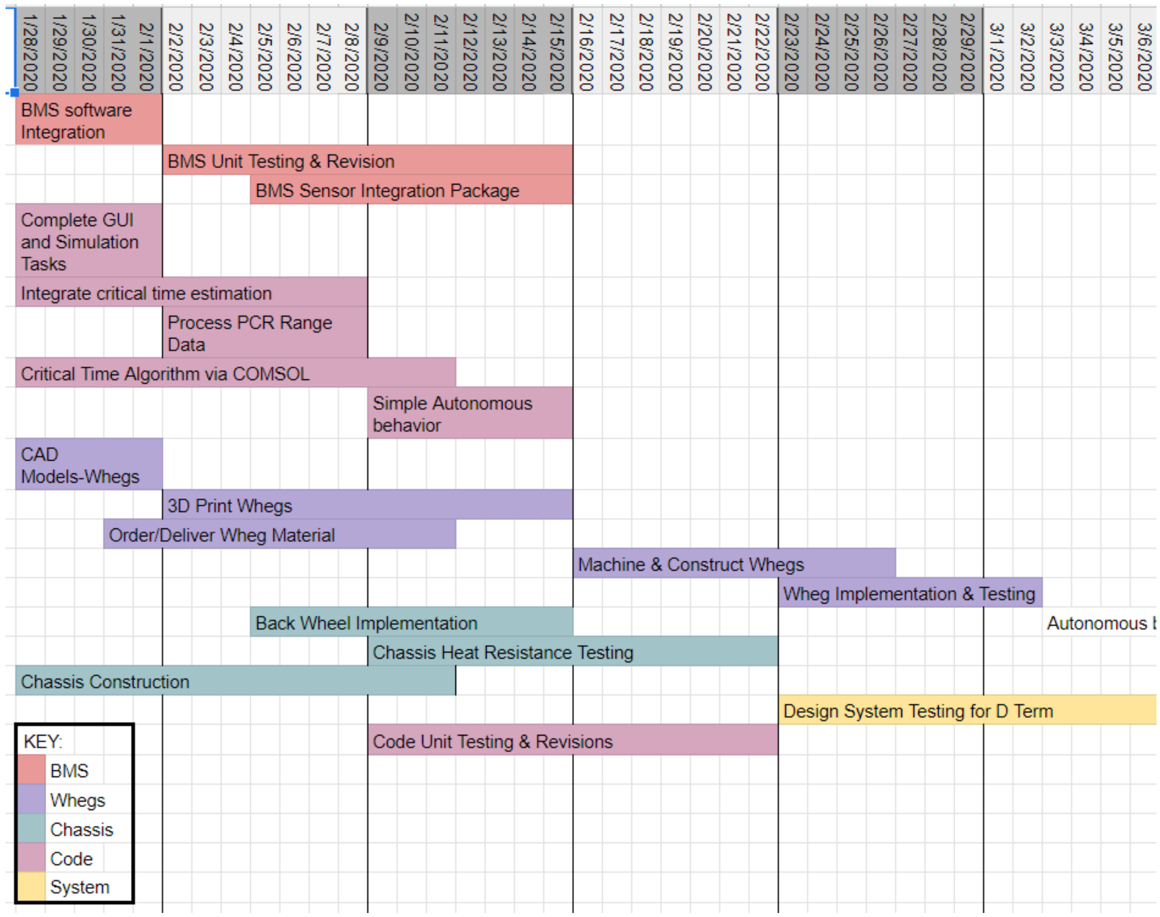
Gantt Chart A Term



Gantt Chart B Term



Gantt Chart C Term



Appendix C

Management Survey with FRED2 Team Responses

1. What degree are you currently pursuing? (any minors or double majors please include)

4 responses

- Computer Science & Mechanical Engineering Double major
- ECE/CS
- Civil Engineering
- Computer Science, Robotics Engineering

2. Which/how many clubs have you been involved in during your WPI career?

4 responses

- Concert Band, Greek life, Hellenic Student Association, Saxophone Ensemble, Rugby
- Beta Theta Pi, Engineering Ambassadors, Alpha Phi Omega, French Circle, German Club, SocComm, Student Government Association
- Radio club
- Science Fiction Society, Masque

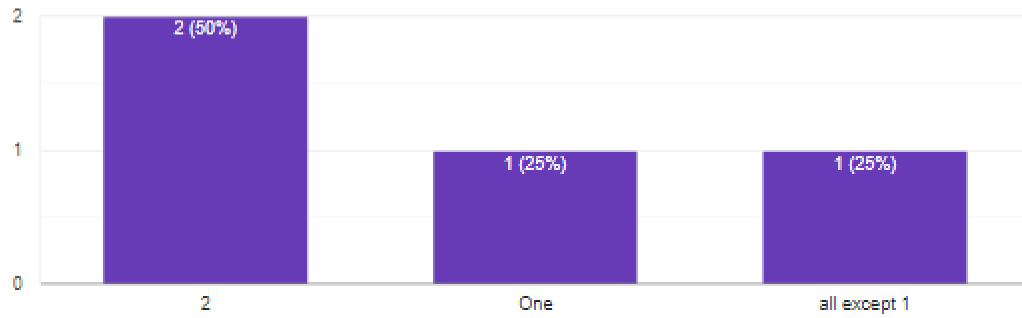
3. How many classes were you taking at the same time as this MQP?

4 responses

- two other classes each term (full course load)
- 2.5
- Two
- 1 regular undergraduate course and 1 graduate course during A and C terms; 1 graduate course during B term; 1 PE course and 1 graduate course during D term

4. How many of those classes were required for graduation?

4 responses



5. Where do you hope to be next year?

4 responses

I've accepted a job as a software engineer in Boston

I hope to be part of the workforce, doing something I enjoy, though I do not have any concrete plans.

California

Working

What was your project and goal for the MQP?

4 responses

Our project is to design and prototype a Firefighting remote exploration device, capable of autonomously navigating a fire ground and returning relevant information to the Incident Commander. Our project goals include creating a prototype of a heat, water, and impact resistant robot capable of simple autonomous navigation.

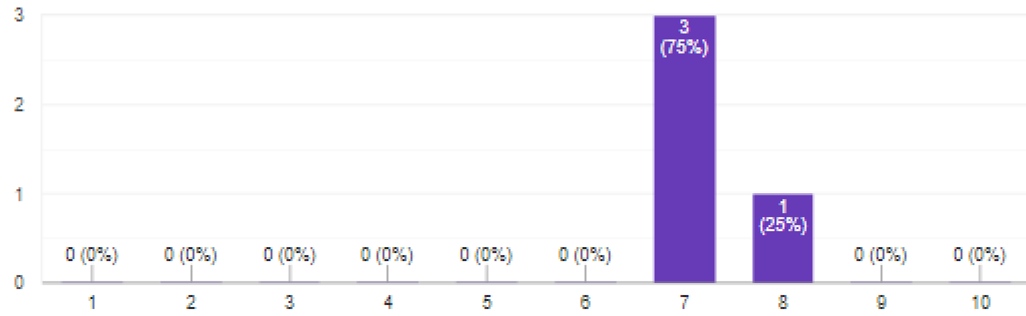
The project was to prototype a robot to withstand the conditions of a fire environment and relay video and other useful data to the incident commander. The goals for this year was to construct a prototype that would be able to last in a fire environment, move around autonomously while collecting data, and have means to monitor the state of the internal components to help determine the remaining time left for the robot to operate.

To create a robot that explores a fireground to provide supplemental information to firefighters on-duty.

To design and prototype a firefighting remote exploration device

6. Rank the overall Management of your Project?

4 responses



7. Do you feel that the goals of the project where satisfied?

4 responses

We are currently working hard to achieve the goals for the project, and I feel most of them will be satisfied.

Given the circumstances, I was satisfied with our results, even though we did not meet all of our initial goals.

No, the robot was not able to be fully constructed based on the current circumstances.

No

8. Are you satisfied with the amount of work produced by the project?

4 responses

This project produced a significant amount of challenging work for our team. At first the project felt very daunting, but now that we have solidified design decisions, the upcoming work feels more straightforward.

I believe our team tried our best to make the most out of the circumstance.

Initially, though there were less technical aspects of civil engineering that could be contributed as the project transitioned to simulations,

Yes

9. Do you believe that the work was fairly distributed across group members?

4 responses

This project is very multi-disciplinary by nature, which allowed the team to distribute the work fairly evenly by major and interest.

The work done to construct the robot was broken down based on tasks related to specific majors. As such, there was definitely a discrepancy overall between what needed to be done and how much needed to be done between the majors.

Mostly; I felt that there was not much that I could add to the projected (see previous answer).

Yes

10. How close to the timeline originally set did the project stay on schedule?

4 responses

Our project fell behind the original timeline by about 4 weeks. We had originally intended to have completed the construction by now, but are still in the building stage.

We were a bit behind schedule and were projected to complete the body of the robot in D-term before we knew the change in operation that would occur for this time.

When we were on the physical construction of the robot, production was only shortly behind schedule.

No more than two weeks behind at any point in time

11. How many hours do you think you respectively spent in A, B and C-term?

4 responses

A term: 25 hrs/week B term: 35 hrs/week C term: 30 hrs/ week

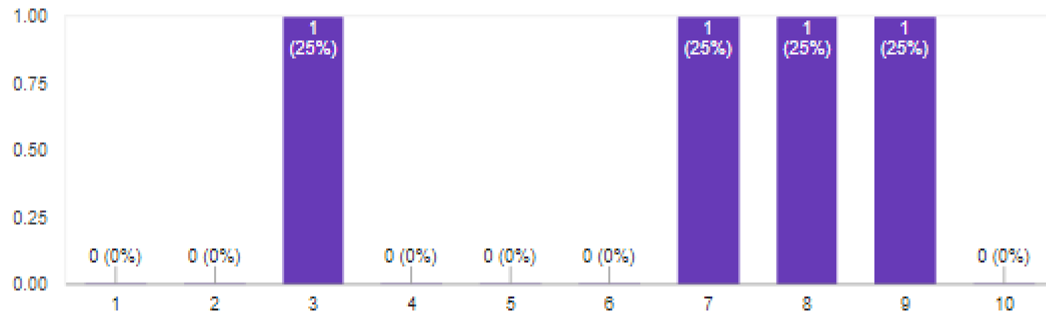
30, 50, 80

65,70,40, respectively

About 100 hours each term

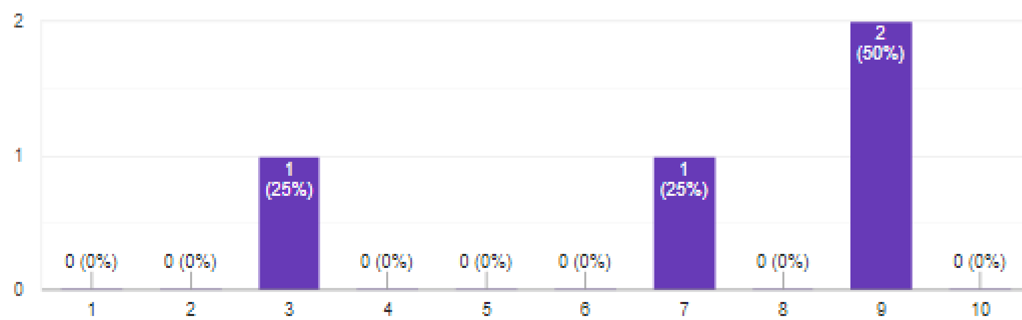
12-14. Do you think having a Management Engineering Major can help other MQP projects in the future?

4 responses



13. Would having an MGE major to manage all group coordination and meetings be beneficial to MQP projects?

4 responses



14. Briefly, why your response to the answers above? (12-13)

4 responses

Planning meetings, communication with advisers, delegating tasks, and overall being a "group leader" is a large added responsibility to any single team member, so having someone that could take on all of that with relevant experience would be beneficial to the project.

I believe the project was sufficiently well managed even with an MGE major

Maintaining designated roles and adhering to a detailed schedule can make a project much more efficient.

I think having an MGE major as part of any project team could have the potential to be beneficial. Though I do not know what the major entails in its entirety, I do understand that the focus is on management and having a designated person to do that is helpful. For the most part, however, our team has been self-driven and self-managed in terms of our individual responsibilities pertaining to our majors. However, as a collective, we are able to take on non-major-specific tasks as we saw fit.

15. What is one thing you would have changed about the project?

4 responses

I would have had another team member with mechanical engineering experience. designing both the chassis and wheels are two large tasks that could have easily been enough work for two people

Ideally, we would have been able to build a physical robot, if not for COVID-19

Work more closely with FPE

Other than the COVID-19 issue, I would try to find a way to better balance the amount of work/be more integrated. This is generally my preference for the kind of team dynamic I want to be in.

16. Did you feel that the grouped worked well together with zero dysfunction or conflict at all? If so please respond as to why you think the group dynamic worked so well; if not skip this question.

3 responses

Our team was very open with communication and listening to each other. I think it actually helped that none of us really knew each other before the project started, because there was no bias.

Yes; we had three team members with clearly delineated areas of focus in ME, ECE, and CS

Each member for the most part was able to identify the tasks they need to accomplish. Most of these tasks were major specific and we had enough foresight and enough of a shared vision to understand how our individual tasks would contribute to the over all project and goals we set out to accomplish.

17. What where the conflicts or problems that occurred that created dysfunction and delayed the project.

1 response

There were no internal conflicts. There would be the occasional delay in accomplishing tasks but nothing significant to greatly hinder overall progress.

18. Do you feel that when problems occurred other group mates where easily accessible to talk?

2 responses

We did not have many social/dynamic problems, but when there were problems relating the the project content, the team was very willing to meet extra/at a different time and accessible.

Yes, though we rarely had these kinds of issues if at all, so it is hard to say.

19. How where these conflicts resolved?

1 response

All of our minor issues to my understanding were easily resolved and without trouble.

20. Do you have any other feedback for Management Engineering majors as to how we can use management to help other MQP projects?

4 responses

Management Engineering for delegation and deadlines! holding yourself accountable to do a certain amount of work or finish something before the next meeting gets difficult as the year progresses, so having a member helping with the delegation and accountability would be helpful!

Not really

Constant communication should be practiced

Understanding group dynamic, the needs of the group and individual, as well as the strengths and weakness of the team and individuals is important. When everyone understands each other, has a shared vision of what outcome they would like to reach, and is able to communicate their ideas effectively, the team as a whole will avoid many pitfalls related in internal organization and management.

21. Is there anything that the readers of MQP should know about you or the project itself?

4 responses

Everyone on the team worked really hard to complete this project, we all stepped out of our comfort zones and learned a lot doing so!

I worked on the software component of the robot

The project changed drastically from what was initially proposed, but I am still glad that I was able to work on this project.

Nothing in particular comes to mind. I think it is understood that though our accomplishments were limited by the outbreak, we did our best to work remotely and make much out of what we could do.

Appendix D

Responsibilities for Project Manager

- Determine and define project scope and objectives
- Predict resources needed to reach objectives and manage resources in an effective and efficient manner
- Prepare budget based on scope of work and resource requirements
- Track project costs to meet budget
- Develop and manage a detailed project schedule and work plan
- Provide project updates on a consistent basis to various stakeholders about strategy, adjustments, and progress
- Manage contracts with vendors and suppliers by assigning tasks and communicating expected deliverables
- Utilize industry best practices, techniques, and standards throughout entire project execution
- Monitor progress and adjust as needed
- Measure project performance to identify areas for improvement

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