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Executive Summary

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1 Introduction

The ongoing war between Russia and Ukraine caused extensive amounts of antipersonnel mines to be scattered across many Ukrainian cities, particularly threatening Ukrainian civilians. The antipersonnel mines come in two variants being PFM-1 and PFM-1S [1]. The mines could be easily deployed from various aircrafts which can glide to the ground without exploding. Both of the variants were designed to explode upon contact which is dangerously effective towards the civilians who are unaware of the possible threat the mines carry.

The scattered mines bring a clear need to the deployed areas which requires a mine clearance robot to destroy the PFM-1's to protect and help the civilians. The possible MCR design must fulfill the required design objectives and the surrounding terrain conditions. Considering various created designs the most feasible and practical design that met all the required objectives was determined as ESDC (Extended Spring Drop Cart).

2 Background

As wars in the 1990s became more prominent in many parts of the world, landmines were spread all over the world and over time was declared a global crisis. The U.S Department of State released an article in 1998 [4], this article using two different resources of data estimates the amount of landmine injury and mortality rate over 12 different countries. The National Defence University published an article outlining the average mine distribution by country. The findings of each article are shown below in Figure 1.

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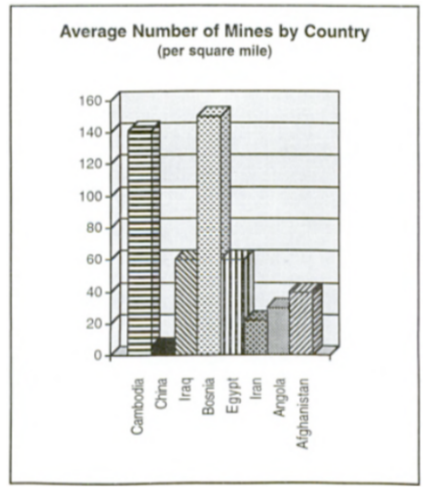
Country	UNLDB	HK98 Case Study		Difference Between UNLDB and HK 98		Average Difference (%)**
		Low	High	Low	High	
Angola*	15,000,000	6,000,000	15,000,000	9,000,000	0	.300
Eritrea*	1,000,000	500,000	1,000,000	500,000	0	.250
Mozambique*	3,000,000	1,000,000	1,000,000	2,000,000	2,000,000	.667
Namibia	50,000	50,000	50,000	0	0	.0
Somalia	1,000,000	1,000,000	1,000,000	0	0	.0
Sudan	1,000,000	1,000,00	1,000,000	0	0	.0
Afghanistan*	10,000,000	5,000,000	7,000,000	5,000,000	3,000,000	.400
Cambodia*	6,000,000	4,000,000	6,000,000	2,000,000	0	.167
Bosnia-Herzegovina*	3,000,000	600,000	1,000,000	2,400,000	2,000,000	.733
Croatia*	3,000,000	400,000	400,000	2,600,000	2,600,000	.867
Nicaragua	108,297	85,000	85,000	23,297	23,297	.215
Iraq (Kurdistan)	10,000,000	10,000,000	10,000,000	0	0	.0
TOTAL	**53,158,297**	**29,635,000**	**43,535,000**	**23,523,297**	**9,623,297**	**.300**

(a) Analysis of case study data



(b) Mine deployment data by country

Figure 1: Pre-existing estimates of mine deployment numbers, by country

3 Review of Literature

Before generating concepts, a survey of existing solutions to mine detection and disposal, along with other relevant technologies, was conducted.

3.1 Similar Design Case: DR-20 Mine Clearance Robot

Several small robot designs that seek to handle explosives (mines and others) already exist. Multinational defense company QinetiQ, for example, produces the Dragon Runner 20 (DR-20) [12]. The DR-20 is a small wirelessly controlled robot used for reconnaissance and explosive ordnance disposal (EOD), among other tasks. Figure 2. shows the DR-20 handling a mock explosive device during testing.

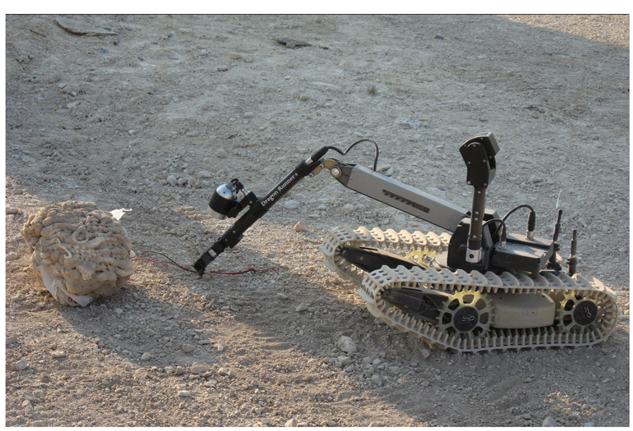


Figure 2: Dragon Runner 20 unmanned robot [13]

The DR-20 weighs between 20-26 lbs and measures 35 x 16 x 21.3 inches in its base configuration [12]. The robot moves up to 6 km/h using rubber tracks on each side [12]. QinetiQ offers separate track configurations which feature extra sprockets at the front or rear of the robot to angle the tracks upwards, providing additional mobility [13]. The DR-20 holds a small robotic arm which can grab and lift objects up to 10 lbs. Operators direct the robot through four onboard cameras – two with night capabilities [12].

3.2 Similar Design Case: TrackReitar CleanField

Compared to the QinetiQ, the TrackReitar CleanField is rather sizable. While outside the size envelope relating to this project, there are strong takeaways that could be employed from researching the TrackReitar CleanField. Figure 3 depicts the TrackReitar CleanField clearing a mine.

Figure 3: TrackReitar CleanField [14]

The TrackReitar CleanField mine clearing robot is made by a slovakian company that specializes in autonomous, tracked vehicles [14]. This 100kg robot is a large mine clearing robot designed to be used during combat or afterwards, during humanitarian mine clearing. Specifications suggest that it can travel up to 10km/h, and up inclines of 36º [14]. It uses differential steering, a method in which one side of the vehicle is driven with more torque than the other to execute a turn [15]. Differential steering allows TrackReitar to boast a minimum turning radius of zero, implying the ability to pivot directions. TrackReitar does not seem to publish information about the method in which the robot clears mines, but does suggest the ability to defuse multiple variants of APL. Drawbacks of this vehicle include its 6-7 hour charging time [14], and the sheer weight, which does not allow single person deployment without mechanical assistance. While no cost figures are published online regarding the cost of the TrackReitar robots, due to its size and complexity, it would be reasonable to assume a relatively large cost when compared to some other mine clearing robots that are on the market. Thus, complexity should be minimized in a project where cost is a design consideration.

3.3 Similar Design Case: SHRED

The Standoff Robotic Explosive Hazard Detection-Neutralization System (SREHD) robot was created by Carnegie Robotics and is currently being used by the U.S. Army. The robot has the capability to detect and neutralize mines semi-automotically. Figure 4 shows a SHRED robot collecting a mine.

Figure 4: SHRED in Operation [17]

The robot uses TALON IV robotic platforms designed with a track driven system allowing the robot to maneuver in over numerous varieties of terrain without fail. The robot is also lightweight stripped of any unneeded components while still maintaining its durability. The robot uses a strong arm to pick up, move or open objects in order to find the mines. Once a mine is found it sprays an x on its target with UV sensitive dye and a IR night additive allowing soldiers to see the mark even at night. The robot has five cameras providing the users with an overview of the situation, giving them the opportunity to decide if they want to dedicate the mine, take it or leave it. If they choose to detonate it an explosive payload will be deployed on the target, using Multi-Array Charge (MAC) for buried threats and 2 C4 blocks for surface-laid threats or other missions as stated in the product overview [16]. With all the components integrated into one robot the still maintains its simplicity with its design and use.

The project development breakdown in 2018 projected a cost of 2019 was $8.022 million with now cost analysis provided [18]. The SREHD as an army based machine it's no surprise at the cost being put into it and unfortunately limits us to make something of the capability, but it sparks inspiration in terms of esthetic and integration of parts.

3.4 Similar Design Case: Mars Perseverance/Curiosity Rovers

While not a mine clearing robot, the Mars Rover programmes are an example of robots built to withstand the most inclement and demanding of environments. Certain attributes of these robots could be applied to the design of a MCR, particularly the manner in which the rover interfaces with the ground. Figure 5 shows the "Bogie" on the Mars Perseverance rover

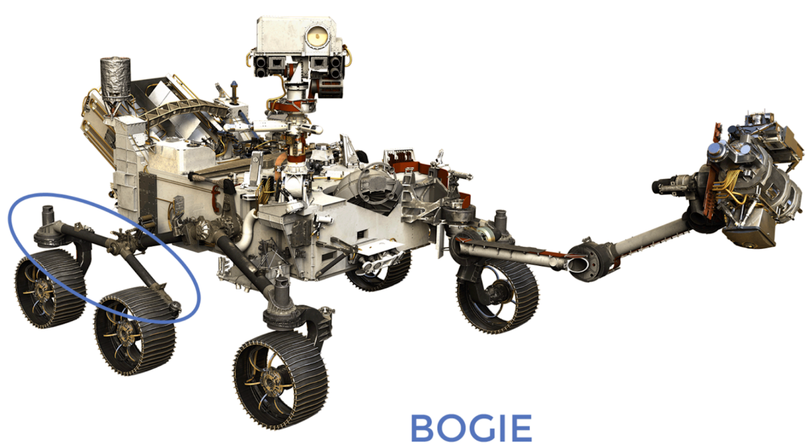


Figure 5: The 'Bogie' used on the Mars Rover [citation]

The mars rover is based on a 6-wheel drive system, with a suspension system that consists of a ”bogie,” to which two wheels are attached [19]. This bogie allows for increased ground contact over rough terrain, including allowing the rover to travel “through depressions that are as large as the rover’s wheel” [19]. The steering front wheels are attached to the chassis via a rocker arm. This unique design is a simple yet effective system that could be an influence to smaller MCRs.

4 Market Survey

Customers could include the likes of various militaries around the world, the countries affected by the current Ukraine/Russia war are the most likely to be in an upcoming need for mine clearing methods such as the MCR developed by this team. Furthermore, there are numerous organizations worldwide that specialize in ridding the world of landmines.The HALO Trust is an organization that has been operating since 1988 and has cleared over 1.7M landmines worldwide. In 2021, their fiscal income was £94.92 million [20], indicating that the worldwide amount of capital spent to remove these harmful mines is unreasonably high. While cost is a crucial design objective to optimize, it is also of reasonable importance to consider that military budgets allow for the prioritization of functional devices and rapid deployment over cost saving concerns. This consideration has been reflected in the design objectives laid out by the team.

These considerations are further supported by statements made by the White House regarding the United States’ policy on Anti-Personnel Landmines (APLs). In the most recent amendment, it is stated that “Since the United States Humanitarian Mine Action Program was established in 1993, the United States has provided over $4.2 billion in aid in over 100 countries for conventional weapons destruction programs.” [21] This makes the U.S a large potential client of the project, as the source also states that they are the largest financial supporter of consequence mitigation related to landmines and explosive remnants of war. While budgets for mine clearance programs are seemingly rather large, there is still a valid rationale to reduce the cost of mine clearing programs as much as possible. The continued danger imposed by APLs from long resolved conflicts suggests that existing mine clearance methods are not accessible enough. The UN suggests that landmines from decades ago are still a threat to new victims. The implementation of more rapid, cost effective mine clearing methods is likely to help NGO’s such as the UN to achieve the goal of zero future landmine victims [22].

5 Problem Statements

This report outlines the need and goal statement used to direct concept generation, evaluate the concept designs, and test the final prototype. The following statements were created based on the information outlined in the background, literature review, and market survey:

Need Statement

> Current methods of clearing surface level anti-personnel mines are dangerous or expensive, leading to high casualty rates among personnel or prohibitively high costs.

Goal Statement

> Design a remotely operated vehicle to effectively clear surface level anti-personnel mines in a safe and economical manner. Ensure the vehicle can be deployed efficiently.

6 Design Objectives

This report outlines 9 relevant design objectives for the mine clearing robot's design. Table 1 lists each design objective with a short description and target range or value. Brief justifications for each objective follow the objectives table.

Table 1: Design objectives for mine clearing robot, descending order of perceived importance

No.	Design Objective	Description	Units	Target Value/Range
1	Safe Operation	Mitigate risk of injury caused by rover. Hazards that cannot be mitigated must be marked with warnings or instructions.	Level of concern	No safety concerns in normal operation
2	Adequate Impact Force	The impact mechanism must generate enough force to trigger the mine.	Newtons	>150
3	Low Cost	Robots are single use, so cost per robot significantly impacts overall budget.	$CAD	<100
4	Dimensions Within Envelope	Project should follow given dimension constraints, and minimize volume	Inches (w x h x l)	12x12(36)x20
5	Minimize Component Count	Fewer parts means lower complexity, cost, and higher reliability.	No. of Parts	<75
6	Accommodate Induction Coil	Leaving room for an induction coil allows for integration of mine detecting mechanism.	Level of Acommodation	Excellent
7	Low Assembly Complexity	Low assembly complexity (simple parts, few tools) increases deployment efficiency.	Assembly Complexity	Good
8	Maximize Mobility	Project must handle 15 degree incline, sine wave dirt track, and leafy paths. Additional mobility is good.	Speed, Traction, Stability	Good
9	Minimize Shipping Volume	Parts should pack together neatly with minimal empty space to minimize shipping costs	Part Sizes	Few Large Parts

Safe Operation: Safety is of utmost importance in any engineering project, especially when the project centers around a public safety issue as is the case here. The robot should not create any unnecessary hazards to the operators or those nearby, or else it fails to meet the outlined goals.

Adequate Impact Force: In order for the mines to be detonated they must be struck with an impact force of 150N. If the force needed is not achieved, attempting to retrieve the robot could pose a great risk to the operator. Thus, designing a solution that ensures this force is attained is crucial.

Low Cost: According to the project description and literature review, cost reduction of the robot is critical in its effectiveness in decreasing the fatality and injury rate of mine detonation. A low cost would allow for widespread adoption of the design. The target cost of $100 means was chosen to be roughly equivalent to the cost of an individual mine [**CITE HANDOUT**].

Dimension Constraints: The design should fit within the client-specified dimension constraints of 12"x12(36)"x20" (l x w x h), where (36)" represents the maximum impactor height. Beyond this, designs should seek to minimize their overall volume for additional mobility.

Minimize Component Count: Minimizing the number of parts in the robot is an easy method of bringing down the robot's overall complexity and cost. Fewer parts also generally allows for simpler assembly, which reduces the risk of improperly assembling the robot. The goal of 75 parts was set based on the groups initial expectations of how many parts would be required to complete the robot.

Accommodates Induction Coil: Being able to accommodate the induction coil allows for future integration of a mine detecting device. If implemented, this would allow customers to buy a single device for mine detection and clearing and lower their overall project costs. An excellent level of accommodation, meaning the induction coil fits in the chassis without modification to the original design, would simplify this process in the future.

Low Assembly Complexity: Minimizing the number of parts alone was deemed insufficient to ensure the robot could be assembled quickly and easily. When parts are shipped into the field for assembly, efficient assembly and deployment is essential given each robot only clears a single mine out of the thousands in scattered across various minefields. We aimed for good assembly complexity, meaning the robot could be assembled quickly with few specialized tools and fasteners.

Maximize Mobility The robot will be expected to traverse several types of terrain. If the robot gets stuck in an minefield, attempting to retrieve poses a safety concern for the operations. At a minimum, the robot should fulfil the client-specified mobility constraints, including the ability to drive: on a 15 degree incline, over a sine wave dirt track, and across leafy lawns. Beyond these constraints, we aim for a good level of mobility with reasonable speed, traction, and stability.

Shipping Volume: As this product will be deployed to various destinations it is important to have something that does not take a lot of time or space to package. Efficient packaging also lowers the overall shipping costs. The goal of few large parts was set to limit the package volume of a single robot.

7 Concept Alternatives

This section outlines three potential concepts which seek to fulfill the design objectives. Proceeding sections will rank the effectiveness of each concept against our design criteria to decide which concept we will move forward with . Note the concepts here are just that, concepts, and certain parameters are subject to change in future prototypes as we proceed with more in depth design validation and testing. Expect the general chassis envelope and key functions of each robot to remain as presented in this report, but details like the shape of specific components, the number or size of supports, and other minor features will depend on this future work.

7.1 Extension Spring Drop Cart

The first concept introduced in this report is the Extension Spring Drop Cart (ESDC). Figure 6 shows a simplified full view of the cart, with drive components, some supports, and the trigger mechanism not shown for clarity.

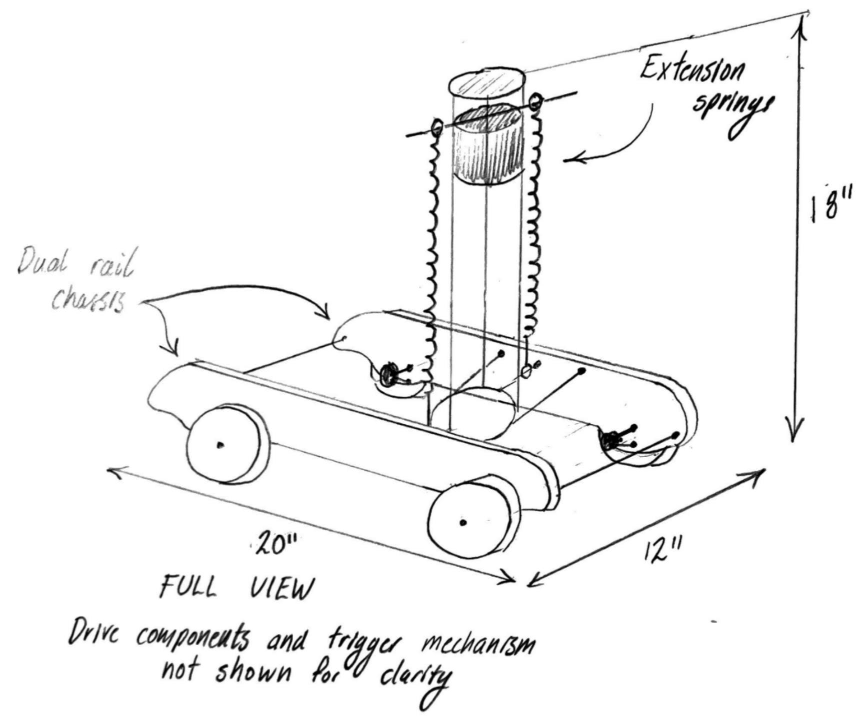


Figure 6: ESDC illustration

The ESDC is a four-wheeled robot with a vertical "sprung drop tower." The chassis fills the maximum allowable outer dimensions for this project at 20 inches long and 12 inches wide, but the overall height is only half the allowable max at 18 inches. The chassis consists of two plywood frame rails which support the drivetrain components. Static rails connect both framerails together and provide the robots overall structure. The rails are shaped such that the wheels sit lower than most of the chassis, which allows the required 3.5 inches of ground clearance without needing 7-inch diameter wheels. The wheel size will range from 4-6 inches depending on the geometry of the rails and results of testing.

The ESDC features one 12V gear motor mounted to the center of each chassis rail (two motors total). Each motor transfers power from its shaft to both wheels on the frame rail using a series of gears. Gearing allows for increased torque to the wheels at the cost of speed – likely needed given the relatively low power of the motors and several kilogram mass of the robot. Figure 7 shows a side view of the concept motor and gearing system on one of the frame rails. Note the gearing shown in this sketch is for demonstration only. The exact gear sizes and ratios will depend on more detailed analysis of the prototype. The given design could implement a suspension system to stabilize the robot. A simplification of the bogie employed by the Mars Rovers is a candidate, if suspension is deemed required by prototype testing.

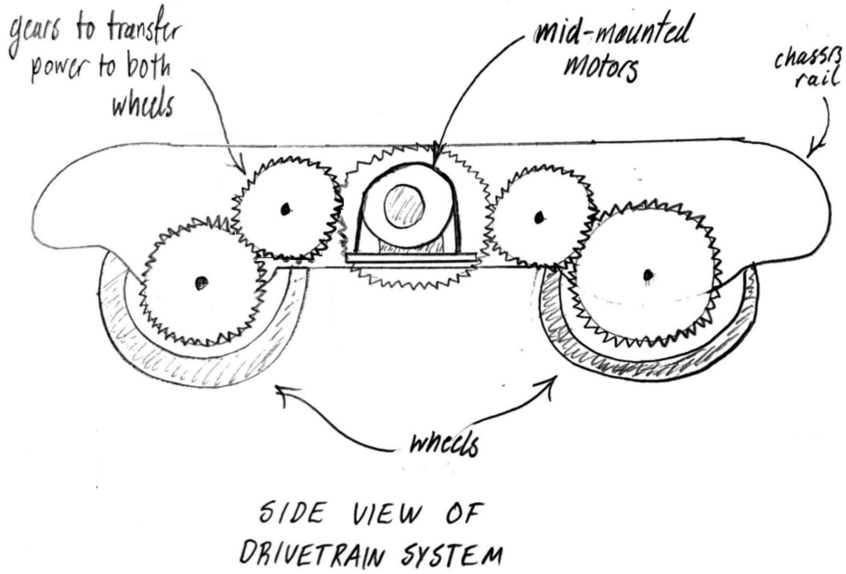


Figure 7: Side view of ESDC drivetrain

The impactor is the last major component in the ESDC design. It sits between the frame rails roughly in the middle of the chassis. Three 15-inch uprights form the impactor's main structure and serve as a track for a cylindrical mass. In its "loaded" position, the mass sits on a pin-trigger atop the impactor. Two extension springs run from the chassis to the top of the impactor and connect to the spring "arm" which sits on – but is not connected to – the top of the mass. Figure 8 shows a simplified side view of the impactor mechanism.

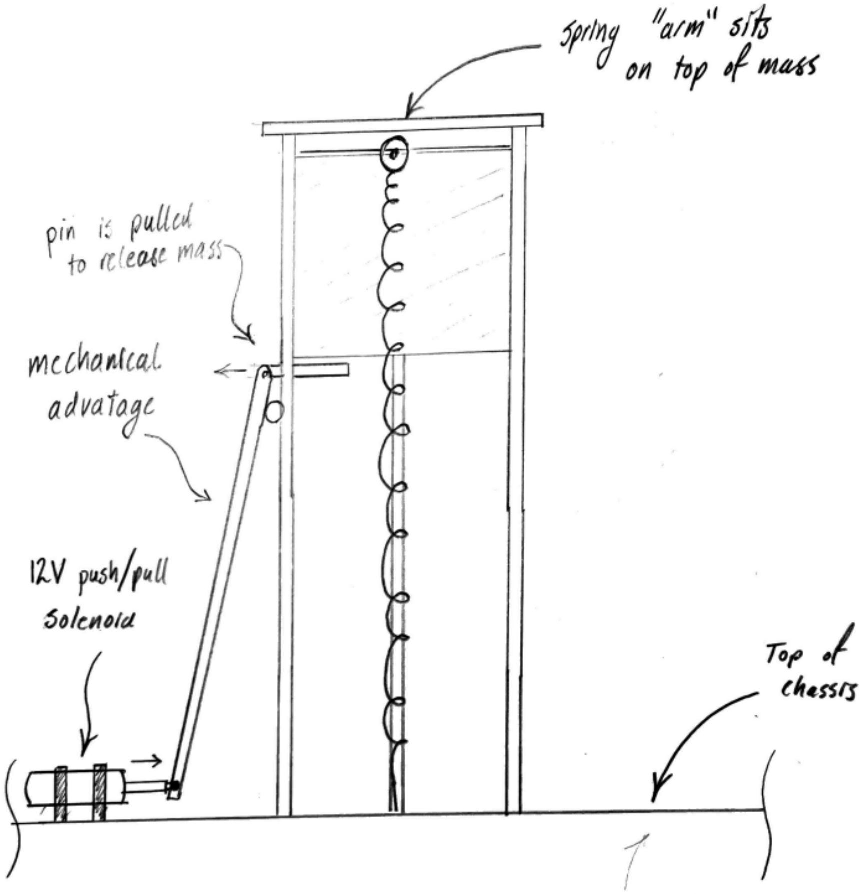


Figure 8: Side view of ESDC impactor mechanism

A small push/pull solenoid mounted to the chassis drives the trigger release mechanism. To overcome the force of friction on the trigger pin, the solenoid uses a lever system to gain significant mechanical advantage over the pulling motion. Pulling the pin releases the mass which accelerates downwards under the force of both springs, and the force of gravity. Since the spring arm is not fixed to the mass, the extension springs "let go" of the mass as they retract to their unstretched length. The impactor's design was primarily driven by the springs required to generate the impact force. Preliminary calculations showed the force generated from this impactor design is highly-sensitive to spring characteristics, especially spring deflection. The work each spring applies to the mass is proportional to the deflection squared but only linearly proportional to the spring rate (the spring's stiffness). This relationship encourages the use of long springs with large deflections under max load. To generate the 150N impact force required over 0.2s, calculations suggest two springs of 8-inch deflection and 1200 N/m spring rate could be used with a 6 kg mass dropped from 18 inches above the ground. Appendix A contains a more detailed explanation of the calculations. The ESDC's primary design principle was simplicity, which offers several intrinsic benefits. First, the ESDC uses very few major parts; only 34 major parts makeup most of the concept's construction. The ESDC is also relatively cheap, with an estimated prototype cost of only $247. While this value surpasses the initial goal of $100, it is valid only for a single prototype. Full scale production of the concept would significantly reduce the cost per unit due to bulk discounts on the electrical components and springs, which could be purchased directly from the manufacturer and not second-hand suppliers.

The ESDC excels in the following design objectives, too:

- The concept can generate the full 150N over 0.2s, as supported by calculations.
- The concept fully encapsulates the moving mass eliminating the risk of the user being struck and increasing safety.
- The concept leaves significant room in-and-around the chassis for future integration of a 20-cm induction coil.

Despite excelling in several design objectives, the ESDC performs poorly in others. Notably, the shipping volume. The ESDC features two large rails and at least three 15-inch uprights that cannot be disassembled for shipping. These components may increase shipping costs significantly. The concept's mobility is also sub-par. Its use of wheels instead of tracks limits traction and the vertical impactor shifts the center-of-gravity upwards which risks tipping unless properly balanced.

7.2 Mouse Trap

This specific design was inspired and conceptualized from a mouse trap. One of the main advantages of this design is its simplicity and flexibility. The torsion springs connected to the rotational arm will store enough energy to create the rotational speed required to generate the impact force that will trigger the mine. The dimensioning of the concept design can be found in Figure 9. The dimensions are precisely calculated to create the most efficient rotation and build enough force to destroy the mine. Small changes can be considered throughout the mechanism to ensure the application of the required impact force.

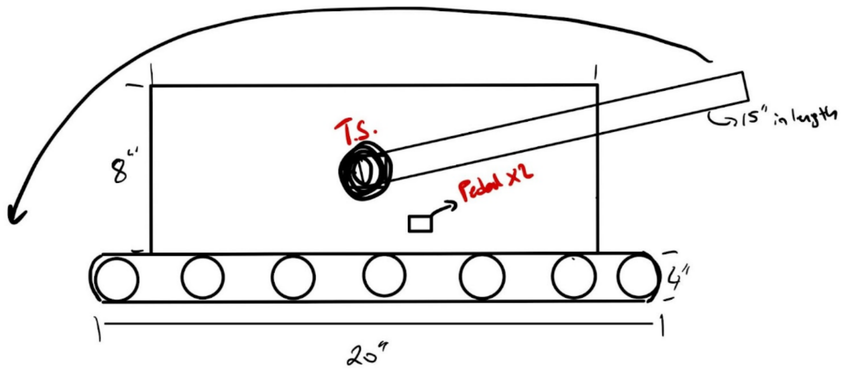


Figure 9: Mousetrap concept design sketch

The impact mechanism consists of three significant parts. Firstly, the rotating arm. The rotating arm's concept will be similar to a mouse trap. The arm will rotate in between 180-270 degrees to impact the mine while the second significant part, a torsional spring, will change the potential energy stored within itself into kinetic energy of the rotating arm . Lastly, a mechanical lock will be implemented into the back section of the robot to hold the stored energy in the torsion spring before releasing it to strike the mine. The size and the dimensions of the parts can be adjusted depending on the design and condition flexibility. The mechanism can be observed in Figure 10.

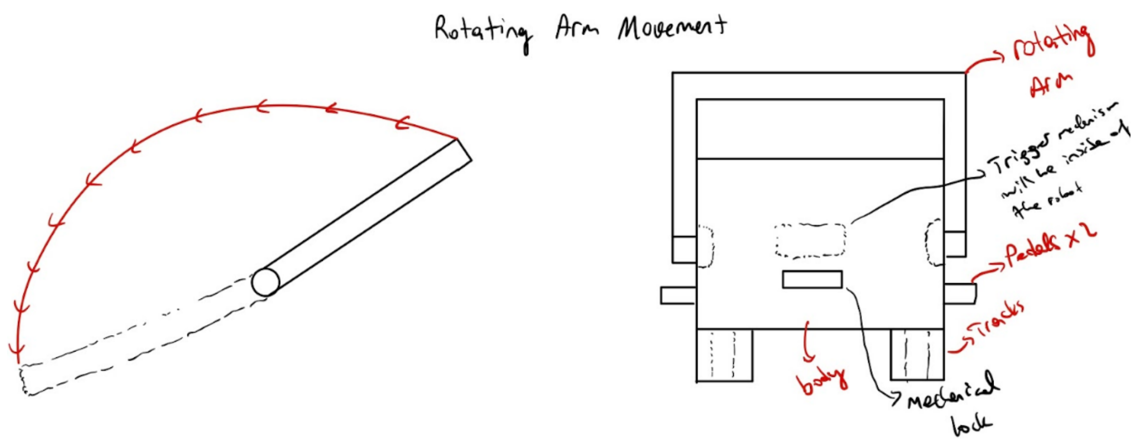


Figure 10: Rotating arm movement sketch

The wheel mechanism consists of 3D printed track parts and gears in order to create the track mechanism. The tracks can provide significantly better mobility than other methods across different types of terrain. However, the manufacturing and the assembly of the parts can be more involved and complex compared to other mechanisms, such as wheels. Nonetheless, for this specific design the track system was determined to be implemented to the robot in order to ensure greater traction and mobility. The size of the tracks can be adjusted depending on the design validations and testing results. The following Figure 11 shows the track mechanism.

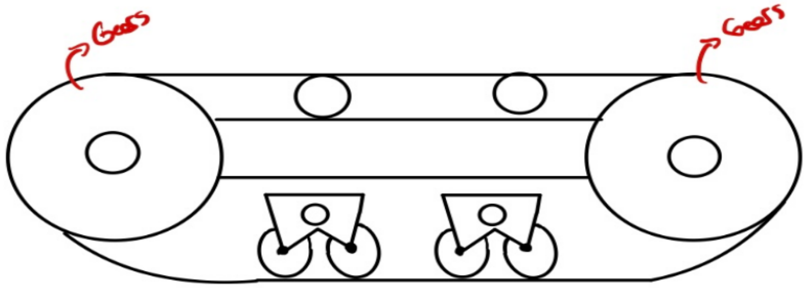


Figure 11: Mousetrap track sketch

Overall, the concept design has some disadvantages and advantages. To begin with, this design's advantages can be listed as; the simplicity of the design makes it easy to design and use, the low center of gravity improves stability and allows flexibility within the design. Last but not least, less moving parts compared to the trebuchet style concept means less complexity in this concept. One of the top disadvantages of the robot is safety. The main reason for the safety concerns stem from the possible injuries that loading the swinging bar could cause. As a protection, two sets of plastic pedals will be inserted to the chassis for the safety of the users feet and it will highly be recommended that the user uses both of the hands while loading the rotating arm to try and prevent any possible injuries that might occur. Another disadvantage of the design concept is due to the complexity of the tracks. Since the tracks will be 3D printed, the design and assembly will be time consuming and tedious to connect all of the individual track pieces together.

7.3 Trebuchet

The trebuchet style impactor and tracked chassis design was conceptualized from the idea of medieval style trebuchet. The addition of a flexible link between the projectile and swingarm allows for more energy to be transferred into the launch, sending the projectile further. In our case, the projectile won't actually be launched, it will stay fixed to the end of the flexible link and strike the mine at full extension from the swing arm. The approximate dimensions of this concept design can be seen in Figure 12 and occupy the maximum possible volume envelope. This could indeed be revised smaller, but there are certain considerations such as stability, control system layout, swing arm mounting, etc. which, for the sake of design flexibility, benefit from starting at the maximum dimensional allowances and revising smaller versus having to revise larger.

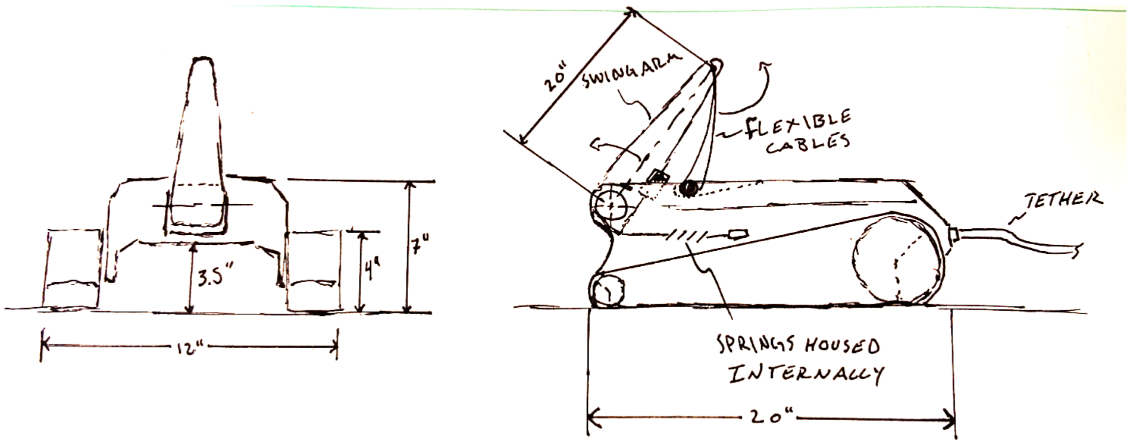


Figure 12: Trebuchet concept sketch

A number of extension springs will be attached to the swing arm after wrapping around a cammed lobe (Figure 13) to increase the initial torque on the swing arm at the beginning of the throw and increase the velocity as the load strikes the mine. The number of springs is still to be determined and is based on the exact lengths of the swing arm and flexible link. The springs will be anchored inside the chassis.

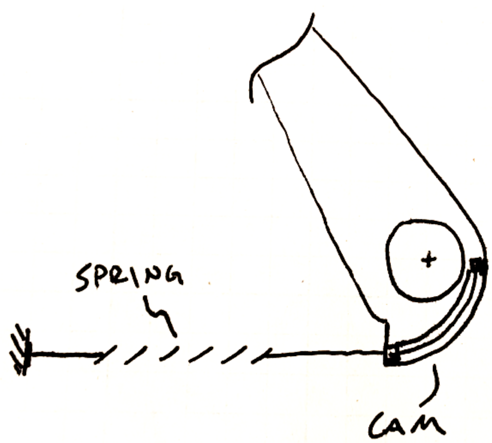


Figure 13: Illustration of cammed lobe on trebuchet concept

The trigger mechanism concept (Figure 14) would be actuated by some sort of linear actuator or a small motor to remove the firing block and release the two arms that capture a reverse chamfered extrusion fixed to the swing arm.

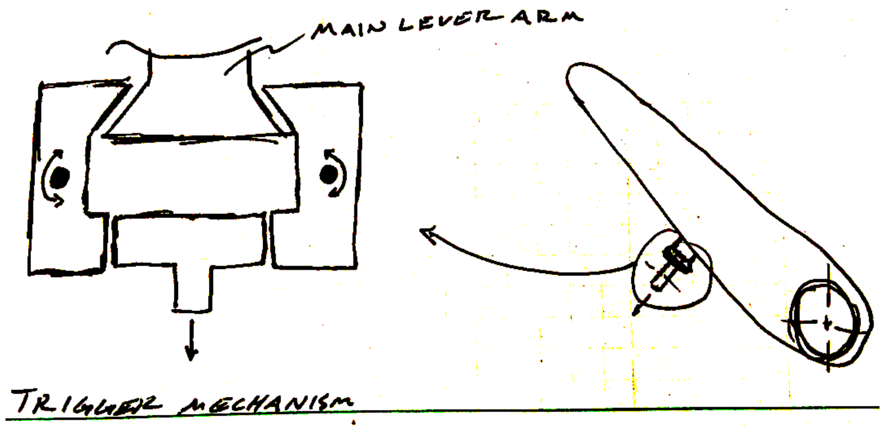


Figure 14: Trebuchet trigger mechanism

This concept was designed with tracks in mind as the method of locomotion. Tracks provide unparalleled traction and maneuverability if they can be independently driven. They can also be designed in quite a simple manner, although no matter what they will always be, at a minimum, slightly more complex than wheels. That being said, a modular design (an impact module, chassis module, locomotion module) would provide sufficient design flexibility to accommodate wheels instead of track if we so choose. It's considered acceptable to leave this option open as the mechanism of locomotion, whatever it may be, will be designed in a way that meets or exceeds all of the performance requirements of the robot traversing to the mine.

The advantage of a trebuchet style design is that you can generate more impact force from the same torque applied to the swing arm, this is due to the position of the load and flexible link being close to the swing arm pivot at the start of the throw and as the swing arm travels through its path, the flexible link rotates such that the effective swing arm length is at a maximum, maximizing the force imparted on the mine. This comes at the cost of increased complexity. Complexity is the antithesis of our design philosophy as it drives costs up (low cost is a high priority design objective) and typically requires more testing. The other drawback to this design, which affects another high priority design objective, is the safety aspect. Having a swing arm with a swinging mass on the end of it, all containing a lot of kinetic energy, would prove difficult to test as well as demo in a safe manner. At first glance, this design seems like it should lose out to the other two concepts purely from a safety and complexity standpoint.

8 Concept Selection Method

To evaluate designs objectively, a set of evaluation scales were created based on the objectives outlined earlier in the report. Each objective is qualified or quantified to a scale, and certain levels on that scale are assigned a numeric score. Table 2 lists each of these scales and their scoring. Not every objective was mapped to five separate numerical scoring levels. The impact force, for example, uses only two scoring levels.

Table 2: Full evaluation scale table for all design objectives

		Numeric Rating				
Objective Name	Units	0	2	5	7	10
Impact Force	N	<150				>150
Cost	$CAD	>$325	$250-$325	$175-250	$100-175	<$100
Number of Components	Quantity	>200	100-200	75-100	50-75	<50
Shipping Volume	N/A	Many large individual parts which cannot be disassembled for shipping		Large individual parts which cannot be disassembled for shipping		No or very few large individual parts that cannot be disassembled for shipping
Accommodates Induction Coil	N/A	No space in or around chassis for induction coil			Space in or around chasses for induction coil, but would require significant modifications to fit	Space in or around chassis for induction coil without significant modifications to design concept
Dimension Constraints	in	Dimensions outside (12x12(36)x12)			All dimensions within (12x12(36)x12)	All dimensions significantly below (12x12(36)x12)
Safety	N/A	Safety concerns with potential to cause serious bodily injury or death	Safety concerns with possibility for bodily harm (e.g., broken bones)		Safety concerns with potential for minor injury (e.g., cuts, minor pinches, bruises)	No safety concerns in normal operation
Assembly Complexity	N/A	Assembly is not fast, and requires many specialized tools or fasteners (poor)	Assembly is not fast, but requires some specialized tools or fasteners (okay)	Assembly is not fast, but requires no specialized tools or fasteners (adequate)	Assembly is fast, but requires some specialized tools or fasteners (good)	Assembly is fast, requires no specialized tools or fasteners (excellent)
Mobility (Speed, Traction, Stability)	N/A	Poor	Okay	Adequate	Good	Excellent

8.1 Hierarchical Weighting Factors

Some objectives are more critical to the design goal than others. To account for this in the evaluation, objectives are weighted depending on their perceived importance. This analysis applies hierarchically weighting factors. Figure 15 is a chart showing the hierarchy of weighting factors.

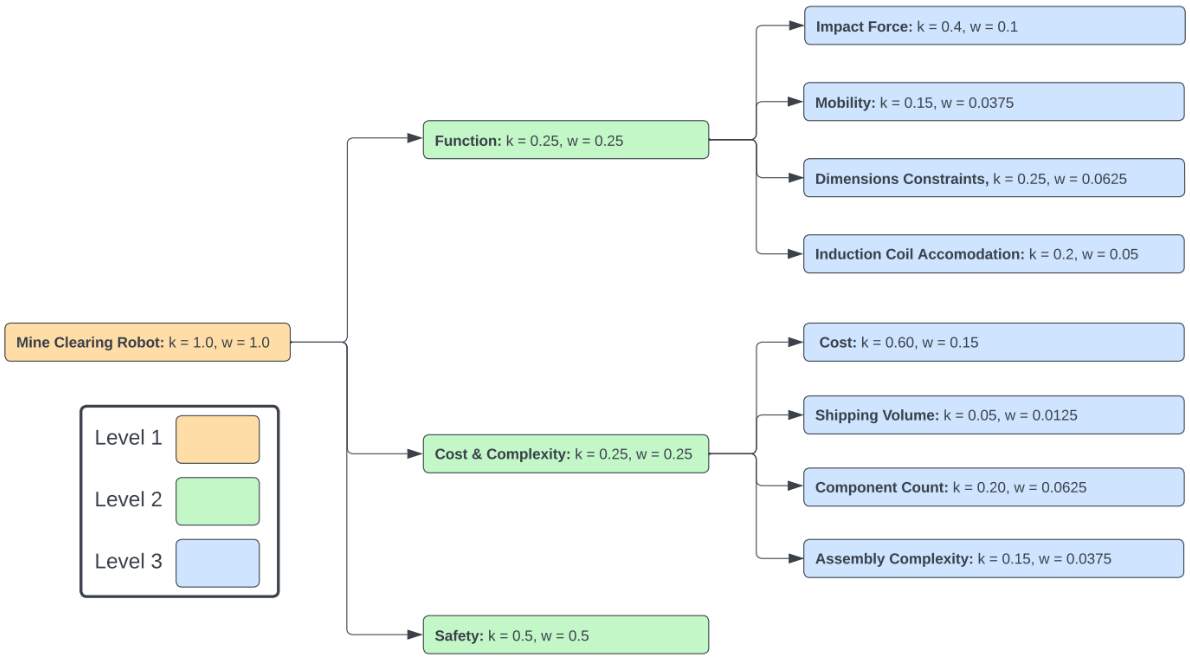


Figure 15: Hierachal weighting factors

Starting at level 2, the objectives were divided into three primary groups: function, cost and complexity, and safety. Safety was deemed the most important of all factors and assigned the greatest value (k = 0.5). An unsafe concept fundamentally fails the goal of this project. Function, and cost/complexity – while both important objectives – do not endanger humans when they are not met. These two objectives are weighted equally (k = 0.25) because each robot must function, but a functioning robot that is too expensive is impractical.

The function objective contains four sub-objectives. The impact force receives the highest weighting (k = 0.4) because it is crucial to the function of the robot; with enough impact force the robot cannot clear mines. Dimension constraints are ranked second (k = 0.25), followed by accommodating an induction coil (k = 0.2). Both objectives come as a direct request from the client and therefore take precedence over mobility (k = 0.15). The chart ranks dimensional constraints slightly higher than accommodating and induction coil since completing a viable concept solution to the currently-outlined problem is more important than accounting for other problems, which are not yet fully defined.

The cost complexity objective contains three sub-objectives. Material costs have the greatest effect on the total cost of the robot and significantly affect the viability of the design so they receive the highest value (k = 0.6). Next to the material costs, component count (k = 0.20) was considered to have the greatest overall effect on the robot's cost and complexity. Assembly complexity (k = 0.15) has less overlap with the complexity of the robot itself, but is still important for efficient deployment, which is a large objective in the project. Shipping volume (k = 0.05) was deemed the least significant objective because shipping costs would likely represent only a small fraction of the overall project budget if the robot saw mass adoption.

8.2 Weighted Selection Table

Combining the weighting factors with the evaluation scales provides the overall scoring system used to rank each design. Table 3 shows the full weighted selection table.

Table 3: Weighted Selection Table

		Trebuchet		Mousetrap		ESDC	
Design Objective	Rel. Weight	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Safety	0.5000	5	2.5	5	2.5	7	3.5
Costs	0.1500	0	0	0	0	5	0.75
Impact Force	0.1000	10	1	10	1	10	1
Dimension Constraints	0.0625	5	0.3125	7	0.4375	7	0.4375
Component Count	0.0625	10	0.625	7	0.4375	7	0.4375
Ind. Coil Accommodation	0.0500	10	0.5	10	0.5	10	0.5
Assembly Complexity	0.0375	2	0.075	5	0.1875	7	0.2625
Mobility	0.0375	10	0.375	10	0.375	2	0.075
Shipping Volume	0.0125	10	0.125	5	0.0625	5	0.0625
		Total:	**5.5125**	**Total:**	**5.5**	**Total:**	**7.025**

Based on the results of table 3, this report selections Concept 1, the Extension Spring Drop Cart, for further development and prototyping.

While the ESDC did not outperform the other concepts in every objective, its performance was highest in the highly weighted categories. Its enclosed impactor design resulted in a much higher safety score versus the other designs with swinging arms that are more likely to strike the operator. The simple design also resulted in the lowest material costs, another highly weighted factor. The ESDC, being the only design with concrete calculations to support its impact force, gained significant points over the other concepts for the impact force calculation.

9 Final Design

The rest of the formal design process was undertaken using the ESDC as the base concept. The final prototype features a similar design, with minor changes to the overall structure and powertrain – and a finalized name: the Minefield Assessment and Removal Vehicle - Number 1 (MARV-1N). Figure 16 shows a full view of MARV-1N.

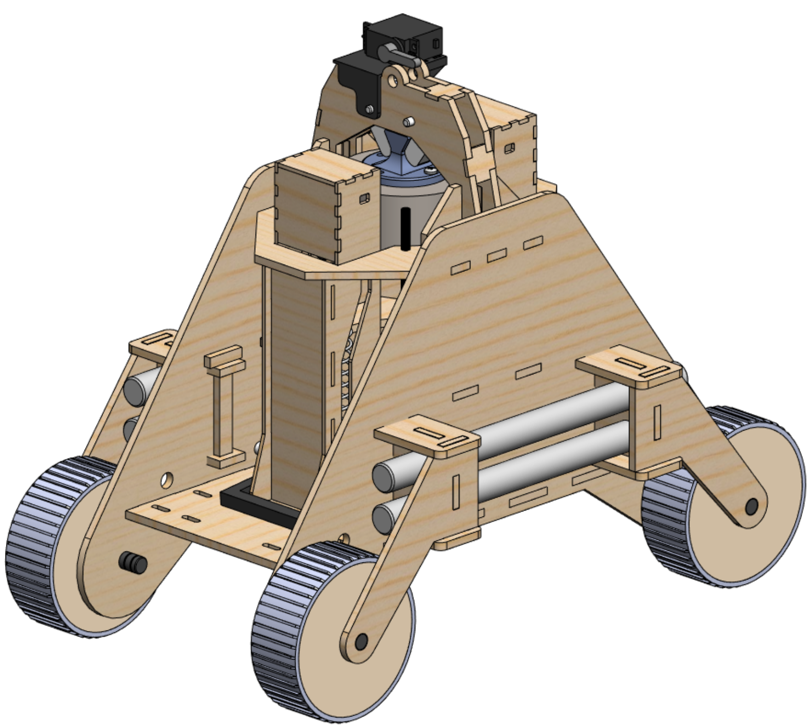


Figure 16: Full view of MARV-1N

9.1 MARV-1N

MARV-1N is a 4-wheeled robot with two driven wheels at the rear, each powered by a 12VDC gearmotor. The robot features a tower-style impactor at the center which drops a 3 kg projectile through a hole in the chassis onto the mine. Two vertically-mounted extension springs accelerate the projectile downwards as it drops. Operation follows a simple 4-step process:

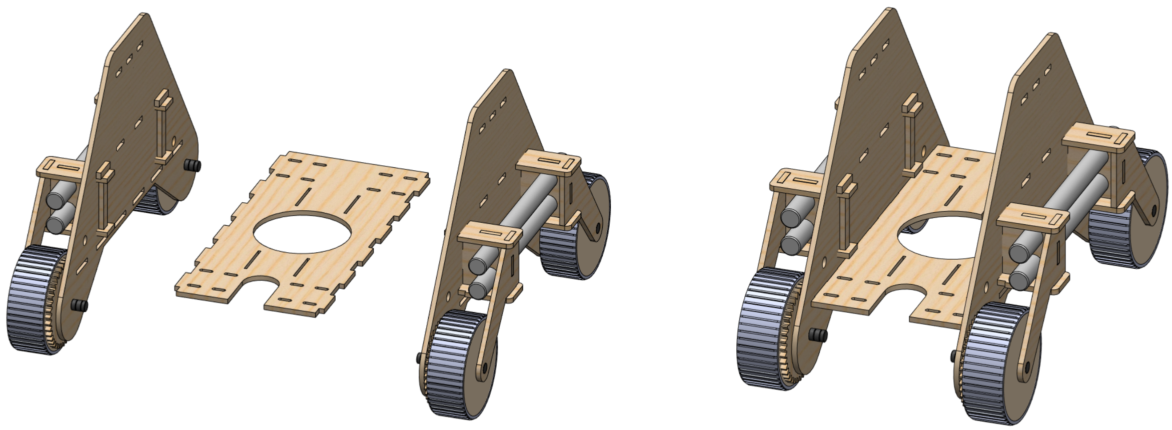
1. Load the projectile into the impactor
2. Set the trigger
3. Drive MARV-1N over the mine
4. Activate the trigger to drop the projectile and detonate the mine

MARV-1N employs a 2-wheel skid steer system allowing for some maneuverability in the field. To turn, the driven wheels spin in opposite directions – rotating the robot about the rear.

MARV-1N's design focuses on modularity and simplicity. The impactor, chassis, and wheel "modules" function independently of each other. The modular design also allows MARV-1N to be assembled quickly without fasteners or special tools.

9.1.1 Chassis Design

The main chassis structure comprises (3) laser-cut plywood plates: an identical set of side plates and a base plate that connects them. All chassis components are assembled with press fit tabs, allowing for fast, tool-free assembly. Figure 17 shows these plates, with the wheels and wheel supports attached to the side plates.



(a) Exploded View

(b) Assembled View

Figure 17: Exploded and assembled views of MARV-1N's chassis, including wheels and wheel supports

The chassis plates create a strong base on which other sub-assemblies are installed. The side plates contain several cut-outs that hold press-fit tabs from the impactor and wheel supports. The base plate also features cut-outs to hold the impactor in-place, and a large circular clearance hole in the middle for the impactor's projectile.

Notice each wheel support shown in Figure 17 contains (2) circular cut-outs that house steel rods. These rods are not critical to the robot's operation, but they can be used to add additional weight to the chassis. Weight adjustment allows operators to tune MARV-1N's performance based on the terrain and the mine's activation force. Weight can be removed to improve mobility and efficiency with the tradeoff of lower impact force due to a less efficient projectile release. In most cases, we expect operators to use no additional weights since MARV-1N still achieves well above 150 N of impact force without them.

Both motors seat into 3D printed housings which are cable-tied to the base plate. While the motors have a set of threaded mounting holes, avoiding the use of several small fasteners to mount the motor allows for significantly faster installation. Testing showed this mounting adequately supports the motors during normal operation. Figure 18 shows the motor mounting on the chassis.

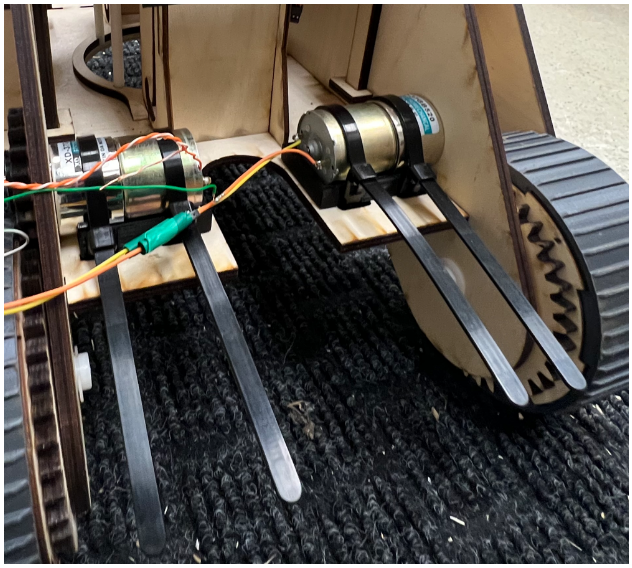


Figure 18: MARV-1N's fastener-less motor mounting system

9.1.2 Trigger Design

The trigger is critical to the functionality of the impactor mechanism. It must withstand the static forces of the impactor and projectile when loaded and must not activate when exposed to vibrations caused by the robot driving over rough terrain. Once actuated, the trigger must provide a clean, co-axial release of the mass to maximize the transfer of stored energy into the mass that impacts the mine. Figure 19 shows the trigger solution designed to meet these requirements. This trigger is cheap to manufacture, quick to assemble, and simple to operate.

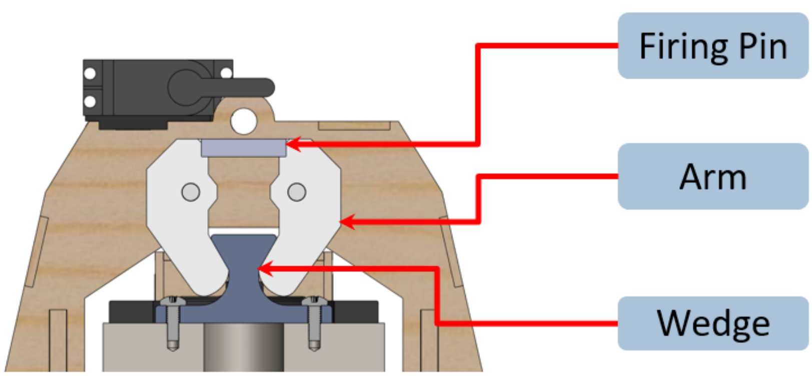


Figure 19: Cross section of the trigger with key components labelled

The trigger assembly is sandwiched between two 6mm pieces of laser cut plywood which make up the frame of the trigger. The frame mounts on top of the impactor with press-fit tabs. Between the frame pieces, two 3D printed arms are mounted on ¼" Delrin shafts opposite each other. At the top of the arms, in semi-circular cutouts, sits the firing pin. The firing pin is a ¼" Delrin shaft which has been cut to length with roughly chamfered edges. The firing pin keeps the wedge – a 3D printed flange bolted to the mass – locked in place until the servo receives the signal to fire. Note these bolts are the only (4) fasteners in the design, and they are not considered a part of assembly since the wedge and mass can be shipped pre-assembled. Figure 20 shows a full view of the impactor.

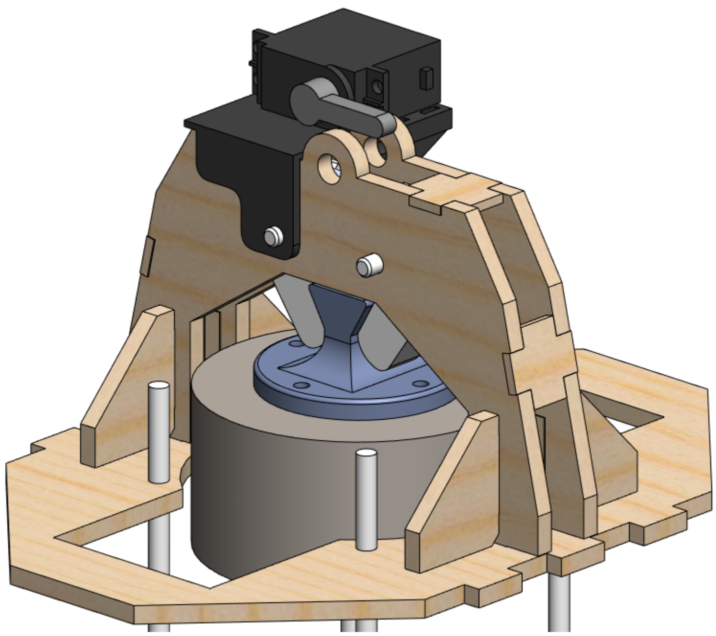


Figure 20: Full view of the trigger mechanism (servo cable not shown)

A servo sits on top of the trigger to pull and release the firing pin once activated. The servo is mounted to a 3D printed bracket with cable-ties. A small cable connects the servo arm to the firing pin.

Before firing, the trigger arms hold the wedge in place and the firing pin prevents these arms from rotating. Once the servo pulls the pin out of the trigger, the arms are free to rotate about the Delrin shaft at their center. This allows the wedge and mass to force the trigger arms out of the way, and accelerate through the impactor towards the mine.

9.1.3 Impactor Design

After the trigger releases the projectile, the impactor is responsible for directing it towards the target (a mine) with enough energy to detonate it. This is accomplished by using two extension springs to accelerate the projectile downward, through the “barrel” of the impactor, and out the bottom of the chassis base plate. During its fall, potential energy stored in the springs and the gravitational potential energy of the projectile are both converted into kinetic energy of the projectile. Figure 21 shows a full view of the impactor assembly.

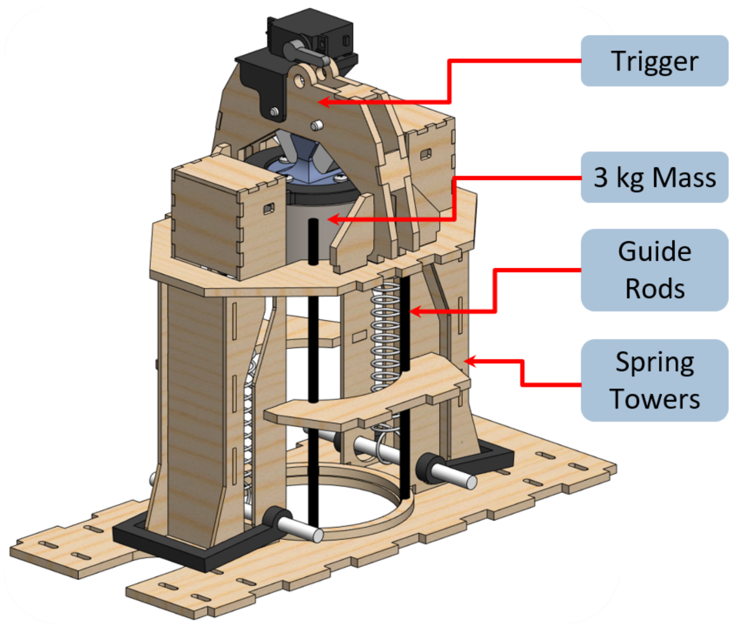


Figure 21: Cross section of the trigger with key components labelled (servo cable not shown)

The spring bar (3D printed) is the black part in Figure 21 that sits on the projectile and connects to each spring. The springs pull down on each end of the spring bar, which in turn pushes the projectile downwards. The impactor also holds (4) Delrin guide rods which keep the projectile centered as it travels down through the impactor and prevent the projectile from striking any part of the chassis. Delrin provides a low-friction surface so the projectile loses little energy when gliding along the guide rods. Figure 22 shows a cross-section through the impactor.

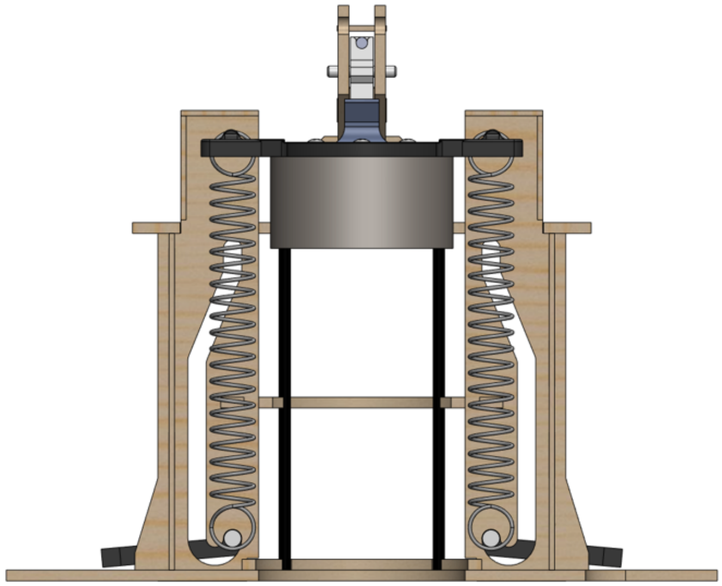


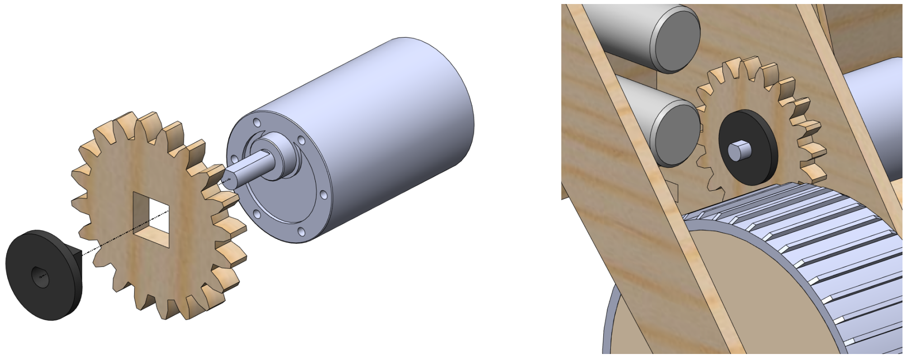
Figure 22: Cross section of the impactor in its loaded position

9.1.4 Wheel and Powertrain Design

The wheel consists of four main components: the 3D printed tread, the plywood wheel centers, the Delrin shaft, and the plywood drive gear. The assembly is secured on the shaft by use of c-clips (final spec used being 0.75 OD, 0.5 ID delrin c-clip). The design of the 3d printed wheel tread was influenced by the mars curiosity rover ***refbogie*** and implemented to cater to the design criteria of the project. To achieve a large contact patch, while not exceeding the width requirements of the design envelope, a tread width of 1.8in was chosen. This allowed for the gear assembly and outer axle supports to be implemented without being outside the desired width.

The wheel tread features 50 ridges with a square profile of 0.06in. With a 4.8in diameter, the axle is dropped 1.25in below the lowest point of the chassis, allowing for a ground clearance of greater than 3.5in to be achieved.

Each wheel is driven by the rotation of the motor gear which mounts directly to the motor. The motor gear features a square cut-out that houses a 3D-printed shaft collar. The shaft collar press-fits over the gear motor's D-shaft, and transfers rotation from the shaft into the gear, as shown in Figure 23. This fastener-less collar was tested extensively and retained the gears on the shaft in all operating conditions.

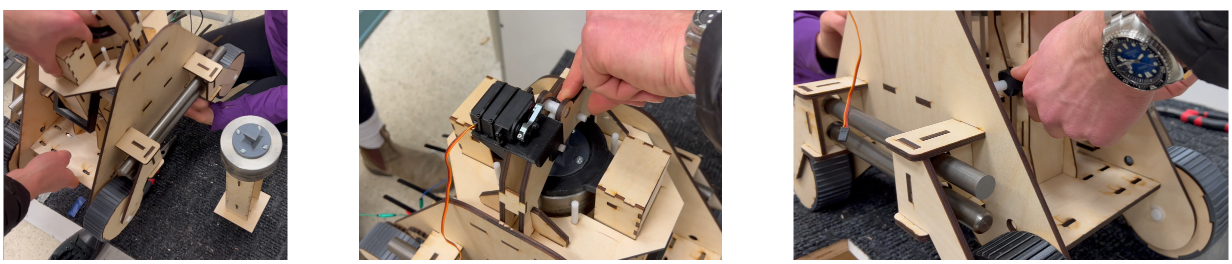


(a) Exploded View (b) Assembled View on Robot

Figure 23: Exploded and assembled views of the motor gear

9.1.5 Loading

Loading MARV-1N is a simple and safe process, as depicted in Figure 24. First, one or two operators lower the robot over the projectile, which rests on a small stand to hold it at the correct height for loading. Next, one operator inserts the firing pin into the trigger, causing the trigger arms to clamp the wedge. Finally, operators can lift the robot off the loading stand, and pull down the spring handles to engage the springs. These handles lock in slots at the bottom of the impactor, as shown in Figure 25.



(1) Lower robot over projectile (2) Place firing pin in trigger (3) Engage extention springs

Figure 24: Three step process to load MARV-1N

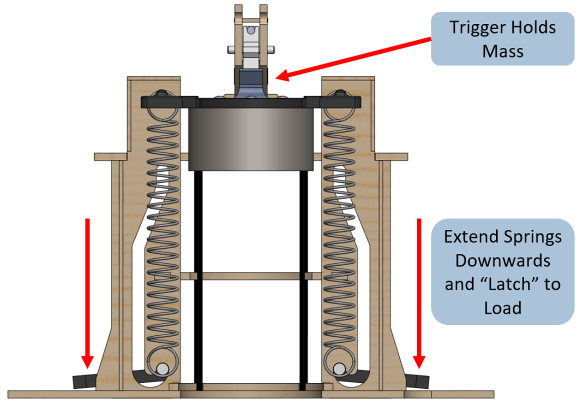


Figure 25: Cross section of impactor showing spring locking mechanism

[THIS NEEDS REVIEW, SOME REPETITION WITH ABOVE] With the projectile retained in the trigger (projectile is retained once the firing pin has been placed in the trigger), the field operators can load the robot by pulling down on the handles attached to the bottom end of each spring and locking them in place at the bottom of the spring towers (shown in figure [X]). This puts MARV-1N in a "ready-to-fire" state and it can then be driven to the mine. Once it has been aligned properly with the mine, the operator presses a button on the controller which prompts the Arduino Nano to send a signal to servo, which causes the servo arm to rotate upward and pull the firing pin, releasing the projectile. MARV-1N is designed to be loaded by one or two people, albeit it is easier to load with two people. The impactor and trigger were designed such that pinch points were minimized during the loading procedure. Since the projectile gets seated in the trigger prior to the springs being tensioned, there are no safety concerns related to any issues that might arise from incorrect or improper loading. The most dangerous phase of the loading procedure is the tensioning of the extension springs and the load handles have been designed so that the operators can keep their hands and fingers out of any potential pinch points.

9.1.6 Controller Design

The design of the controller was based around the use of an Arduino Nano to control a servo motor and two DC motors through a L298N bridge. The two DC motors were controlled through the mapping of a joystick and the servo through a push button. Figure 26 shows the electrical configuration of the controller.

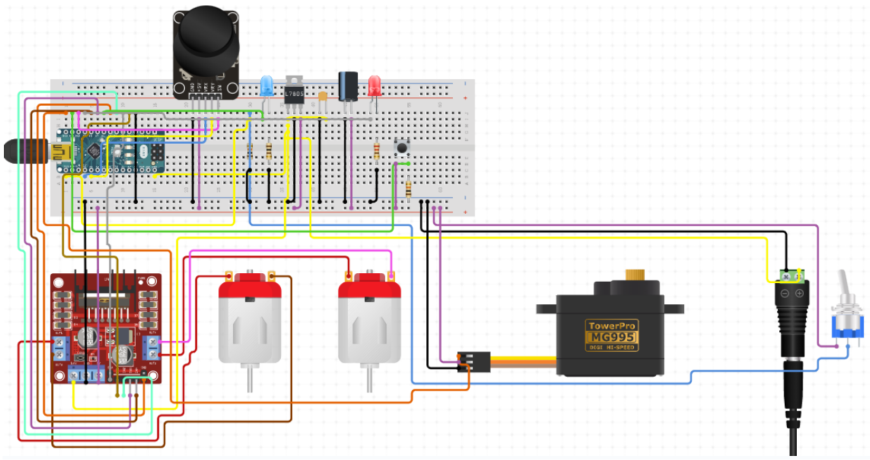


Figure 26: Electrical configuration of the prototype controller

To minimize the number of electronic parts that are destroyed during mine detonation, only the servo and gear motors are located on the robot, while the rest of the electronics are placed on the controller. This allowed for the inclusion of added safety features on the controller at little cost to consumer. These features include the use of a switch to change from driving/assessment mode to detonation mode. An LED light on the controller indicates the current mode during operation. This prevents operators from accidentally triggering MARV-1N, and it allows for easier integration of a mine detecting mechanism. The controller can be cased inside a protective housing to prevent damage to the electrical components, or short inadvertent short circuits.

9.2 Prototype Construction Process

The construction process started with brainstorming possible designs for the features of the MCR. After all the members of the group agreed upon the designs the prototyping process began. The main goal of this design process was to build the MCR around the impactor which means that rest of the determined features to be placed according to the impactor. However, in order to determine the placement around the impactor a chassis design was a must. So a prototype was created by using material on behalf of what was provided to the group by the machine shop. The purpose of the design was to observe and determine how the subparts and chassis were going to be

The very first design was the chassis. The chassis was completed using material on behalf of what was provided to the group by the machine shop. The purpose of the prototype design was to observe and determine how the chassis was going to be shaped.

9.3 Engineering Analysis

Many of the design choices in the MARV-1N prototype are supported by theoretical calculations. Generally, analysis fell into one of two categories: impactor or powertrain. Impactor analysis centered around determining the type and number of springs required to detonate a mine. Powertrain analysis looked into the gearing, wheels, and shafts required to drive the robot in its predicted operating conditions.

While the mechanical strength of the chassis was also considered during design, little analysis was devoted to predicting the overall robot's strength for several reasons. Notably, a stress analysis of the robot would be very sensitive to several undefined parameters, like the cleanliness of the trigger release, and the exact material properties of the chassis. Furthermore, impactor calculations roughly predicted that forces generated in the robot were relatively low. When comparing these forces to preliminary chassis designs, we found that stress was not a critical factor. Subsequent testing of the robot (described in later sections) confirmed this assumption was valid.

9.3.1 Impactor Analysis

Impactor analysis first aimed to determine the spring required to generate 150 N of impact force. Impact time was assumed at 0.05s, while the projectile mass (3 kg) and its starting height (9 in above the ground) were dictated by the design. Analysis combined these predefined parameters with data from a given spring to predict the amount of force generated by the impactor. Figure 27 shows a simplified version of this analysis with spring parameters used in the final prototype.

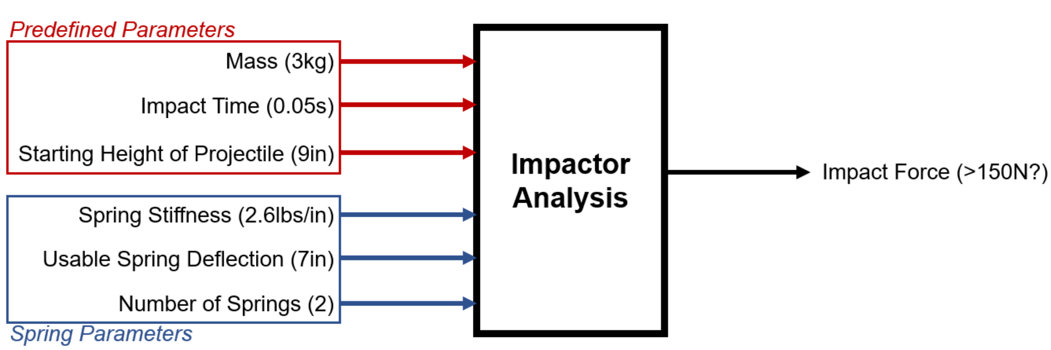


Figure 27: Simplified depiction of impactor spring analysis

We surveyed springs available for purchase online and tested the parameters of any relevant springs in the impactor analysis formulae. During this survey, long and relatively flexible extension springs stood out as offering the optimal parameters for two important reasons. First, the work a spring exerts when moving an object is quadratically proportional to its deflection, but only linearly proportional to the spring constant. In simple terms, a small change in spring deflection alters the resulting impact force more than a similar small change in the spring constant. Secondly, while short and stiff springs are often capable of storing more potential energy than their flexible counterparts, they require significantly more applied force to deflect. Overly-stiff springs were therefore disregarded to maximize safety and minimize the required strength of impactor supports.

The survey selected two identical extension springs with parameters as listed in Table 4. Impactor analysis calculations are presented below the table.

Table 4: Data of extension spring used in final prototype

Length	3.5”
Extended Length	8.99”
Spring Rate	2.6 lbs/in
Outer Diameter	1”
Maximum Load	15.7 lbs.

[INSERT RECOIL ANALYSIS CALCS]

Recoil during the projectile release was another important consideration in the impactor analysis. Recoil refers to the upwards force applied on the robot by the springs as they pull the projectile downwards. Any work the springs exert lifting the robot upwards corresponds to less work they can spend accelerating the projectile downwards. Recoil was roughly estimated using SolidWorks motion analysis tools.

A simplified simulation environment was created with two masses connected by a linear spring. The first mass starts on the “ground,” and the second mass starts 9 inches above the first. The linear spring was modeled to have the same spring constant and free length as two of the springs used in the prototype, in parallel. At the start of the simulation, both masses are released from rest. The simulation ends when the masses are separated by the free length of the spring (3.5 inches). Figure 28 depicts the simulation setup.

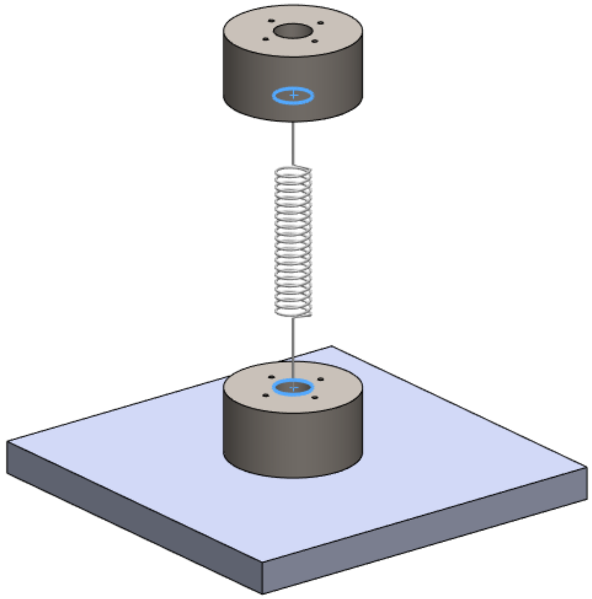


Figure 28: Recoil simulation setup

The simulation was repeated twice with different masses to measure the impact of robot weight on recoil. Table 5 lists the results of both simulations and estimates the amount of energy lost due to recoil. Note the dropped mass is 3kg in both cases. This simulation was not intended to provide a very accurate prediction of recoil. To account for inaccuracies in this analysis, slots for up to 4kg of additional mass were added to the robot's wheel supports, allowing for minor adjustments to the robot's recoil.

Table 5: Results of recoil simulations

Robot Mass	Simulated Recoil	Work Loss	% of Total Projectile Energy Lost
3 kg	3.0 inches	2.2 J	19%
6 kg	1.8 inches	1.3 J	11%

The analysis of impactor force fails to consider recoil or friction between the projectile and guide rods. In regular circumstances, well-defined calculations to estimate the known losses are preferred. Nevertheless, real-world impact testing that was conducted early in the design process found the impact requirements were greatly overestimated, and that mines could be triggered with a significantly slower-moving projectile than what was initially predicted. In some cases, measured impact force data was over 150N greater than what analysis suggested. Since friction along the Delrin rods would be low, and recoil could be adjusted with weight, both sources of loss were assumed to be insignificant. Subsequent testing of the robot confirmed this assumption was valid.

9.3.2 Gear Analysis

Based on the motor specifications of the gear motors provided by UVIC, the goal was to lower the torque required to be produced by the motor so as to use more of the motors power to produce rpm. This needs to be balanced with the fact that as the gear ratio is increased, the wheel spins increasingly slower relative to the motor shaft. Since the gear motors have a maximum rpm of 50 rpm, that left a fairly narrow range of acceptable gear ratios if we wanted to maintain a reasonable driving speed. The rolling resistance and friction between the gears, as well as between the wheel centers and axles, would affect the torque significantly. Since trying to estimate these friction coefficients would've been quite error prone without significant research, a decision was made to get a 2:1 gear set laser cut right away so we could test that ratio out immediately. Ultimately this proved to be a good route as the 2:1 gear ratio ended up working perfectly and no changes had to be made.

Table 6: Motor Specifications

Voltage	12	VDC
Current	0.68	A
Power	5	W
Torque	9.6	kgcm
Speed	45	rpm
Stall Torque	26	kgcm
Stall Current	2.19	A

The gear ratio and the distance between the motor and wheel axle determined the pitch circle of the motor and wheel gear. A diametral pitch of 10 was selected for both gears, leading to the following gearing configuration, as summarized in Table 7.

Table 7: Gear Specifications

Gear Name	**Diametral Pitch (DP)**	**Pitch Circle**	**# of teeth**
Motor Gear	10	2	20
Wheel Gear	10	4	40

9.3.3 Wheel Analysis

The design of the wheels was driven by two main requirements. Firstly the requirement to traverse over a 3 inch sine wave pattern, this required the use of wheels with a diameter of larger than 3 inches, to avoid becoming stuck in the troughs of the wave. Another constraint was the ground clearance required to drive over the mine. Originally, it was thought by the team that to achieve a ground clearance of 3.5 inches, the radius of the wheel must be larger than 3.5 inches. The alternative solution devised by the team was to use an axle mounting point that is below the “floor” of the chassis, allowing for the final utilization of a 4.5 inch wheel diameter. This small diameter reduces the weight of the rotating assembly that is required to be driven, while also allowing for the 3d printing of a wheel tread which remains near the 125mL print volume guideline.

The wheel axles were designed to allow for the wheel to rotate on the axle, while having the axle fixed in the chassis side of the axle mount. This means the axle is press fit into the chassis, and secured with c-clips. The tolerance devised for the axle fits on both the wheel centers and the chassis attachments can be observed in the drawings for the respective parts. A diametric clearance of 0.01 inch was decided to be an optimal clearance for the laser cut centers to run freely on the 0.5 inch nominal dimension shafts. These fits were based on selections from tabulated data for close running shaft fits, which allowed for the first iteration of fits to come out adequately to serve the purpose of the design.

The design of the tread itself was based loosely on the mars curiosity rover, with a straight “spline” style tread. While no challenges were faced with the testing of the wheels, reducing material use is advisable. Additionally the flexibility gained from 3D printed treads allow for further optimization as more field testing is conducted to improve traction in various terrain conditions.

10 Testing

Several tests were carried out to prove the MARV-1N prototype’s functionality in comparison to the original design objectives. This section summarizes and discusses the results of each test. The full test reports can be found in Appendix [X].

Table 8 lists the test results for all (8) tests conducted. Certain objectives are omitted from the test report because they are impractical to test formally. MARV-1N's performance against these objectives is evaluated qualitatively instead. The "dimensions within envelope" objective was tested by trivial measurements, and no formal report is included.

Table 8: Summary of test results

Objective (Target)	Test Result	Objective Met?
Assembly Complexity (Low)	Low	Yes
Dimensions within Envelope (12x12(36)x20)	12x(16)x20	Yes
Impact Force (150N)	240N Min 363N Avg 500N Max	Yes
Mobility (Traverse Dirt Sine Wave)	Pass	Yes
Mobility (Climb 15° Incline)	Pass	Yes
Mobility (Traverse leafy paths and lawns)	Pass	Yes
Mobility (Good Speed and Maneuverability)	Adequate	No

10.1 Tested Objectives

Assembly complexity was the first objective testing. Results showed MARV-1N could be assembled in 5:32, with no fasteners and with only (1) tool: a mallet to help press shafts into tight fitting holes. In a pinch, the mallet could be substituted by many objects which operators would have available in the field, such as rocks, sticks, or bottles. MARV-1N low assembly complexity can be attributed to the repeated use of press-fit tabs rather than fasteners, which often require specialized tools and more time to install. Overall, MARV-1N's assembly complexity met the outlined objective.

Impact force, one of the most important objectives, was also tested. Results showed MARV-1N greatly surpassed the 150N requirement, reaching an average impact force of 363N. While this meets the design objective, it also suggests MARV-1N's design could be further optimized. For example, the design could implement cheaper and weaker springs that fulfill the objective at a lower cost. Another method of optimizing the design would be decreasing the robot's overall height, since results indicate the robot could still achieve 150N with less help from gravity.

Mobility was another important area of testing. Testing first had to prove MARV-1N could fulfill all of the client-defined mobility constraints, including overcoming a dirt sine wave obstacle, traversing leafy fields with long grass, and climbing or descending inclines. Testing results showed MARV-1N succeeded in all of these constraints. Its excellent performance is mostly attributable to the wheel design. MARV-1N uses large, wide, rover-inspired wheels that are designed to provide a large contact patch with the ground. The wheels also feature a sharp tread pattern, which digs into softer surfaces like the grass and dirt. Combined, these features allow MARV-1N's wheels to display excellent traction over a wide variety of surfaces.

Despite its excellent traction performance, MARV-1N did not meet the overall mobility objective due to its slow speed and limited maneuverability. Tests showed MARV-1N can travel at a maximum of 0.16 m/s in a straight line. The gearing and motor system implemented in MARV-1N was designed primarily to provide enough torque to overcome obstacles it may encounter during operation. As such, the 2:1 gearing from an already slow motor means MARV-1N has enough torque to traverse most terrain without getting stuck, but not quickly. The 2-wheel skid-steering system also severely limited maneuverability. A typical skid-steering implementation uses (4) driven wheels which allows the robot to rotate about its center. MARV-1N, on the other hand, rotates about the rear, meaning its front wheels will drag during turning. Since maneuverability was not a priority for the client, this system was deemed an acceptable compromise for simplicity during the design phase.

The robot's dimensions were the final tested objective. Measurements showed MARV-1N meets the envelope requirements.

10.2 Qualitatively Evaluated Objectives

MARV-1N was deemed to display a very low level of safety concern. The prototype features several safety-related features which help minimize the risk of injury. First, the large chassis and spring guards isolate any moving components from the operators. The impactor design also allows the trigger to be "primed" before the impactor springs are engaged. This means operators can touch, set, and adjust the trigger without risking the springs releasing. MARV-1N was also tested extensively, with no injuries or injury concerns recorded during any test.

MARV-1N did not achieve the ¡75 part objective, with the final prototype using 112 parts. The original goal of 75 parts was set as an arbitrary limit to guide the design process towards simple solutions. In the end, MARV-1N required more parts than what was originally expected. The number of parts was increased due to several sub-assemblies containing several parts which could realistically be consolidated into single pieces. The trigger is a notable example, with several supports and gussets which could be better-integrated into the chassis.

MARV-1N also failed to accommodate the induction coil to the excellent degree that was originally intended. This is due to the larger-than-planned impactor and chassis designs which take up a large percent of the bounding box. Both assemblies are significantly larger than the original concept sketch, and leave little room for the induction coil as a result. Still, reducing the size of both items would be relatively easy. The spring guards, for example, are oversized versus the springs they hold. The angles sections of each chassis side plate could also be cut closer to the center of the robot to accommodate the induction coil.

MARV-1N achieved the original shipping volume goal of containing few large parts. The largest parts are the chassis side plates, of which the design uses only 2. Also, since the majority of the robot is made of laser-cut plywood, even large pieces like the side plates could be packed tightly in a flat box.

MARV-1N narrowly surpassed the original cost objective with a total cost of $132.28.However, whenthecontroller$
This represents a more realistic unit cost since, unlike the robot itself, the controller is not destroyed during operation, and can be reused multiple times. The cost breakdown by part in table **??** indicates pre-purchased parts, like the motors and servo were the largest part of the budget. If these parts could be purchased at bulk prices, MARV-1N this report speculates MARV-1N cost could drop to within the original objective range.

In order to prove the functionality of MARV-1N, testing was carried out over 2 tests. Firstly the robot was tested for impact force where a number of trials were conducted to get an idea of the maximum, minimum, and average impact force it is able to produce, as well as the reliability of being able to produce sufficient impact force. Test 2 was concerned with the driveability requirements of MARV-1N, these being: 15 degree climb angle 3” pk-pk sine-wave terrain (dirt with leaf coverage) Drive forward and in reverse Small degree of turning

The full test plans can be found in appendix [X], but are summarized here along with the results.

10.3 Cost Analysis

11 Future Work

To improve the steering characteristics of MARV-1N, multiple solutions are presented and worthy of prototyping and further development. These solutions include the use of caster wheels on the non driven wheels. This would allow for the pivoting of the vehicle in tight turning scenarios, and would serve to improve the results of the driveability test explained in *section 10*. One downfall of caster wheels is a lack of stability; this could be combatted with the implementation of a system that employs a tie rod that creates a parallel linkage between the two pivoting wheels, ensuring the wheels point in the same direction when turning. The steering could also be improved through the implementation of a four wheel drive system. This would more closely emulate the commonly used applications of skid steer, such as track driven vehicles. A four wheel drive architecture would allow for the benefits of wheels to be maintained, with steering characteristics of tracks also gained. Both of these solutions offer promise in the improvement of the steering capability and maneuverability of MARV-1N.

Another future objective of the project is to address material usage as a whole. This manifests in several manners, which include addressing the amount of material used, number of parts and reducing manufacturing time, as well as considering the environmental effects of materials used in the production of MARV-1N. This effort would serve to improve the satisfaction of design objectives mentioned in *section 10*, such as improving on **objective 3** and **objective 5**. To reduce the amount of material usage, the plywood cut parts can be optimized by utilizing simulation tools to remove material from non essential sections of each part. For example, the side plates utilize an excess amount of material that is not conducive to reducing waste, therefore, this would be a part that is well suited to reduce material usage. There are parts that exist in the first iteration of the design that could be consolidated with others to not only reduce manufacturing time, but also assembly complexity. For example, the servo mount was manufactured as a standalone part, but is likely well suited to be integrated into the impactor design. In doing this, the trigger uprights could be made able to receive the servo directly, eliminating the need for a platform and cable ties. Foreseeably this could be achieved with a slot and a press fit to slide the servo into, eliminating complexity while achieving the same, or improved functionality. This is just one of multiple components that could benefit from the sort of optimization that is carried out in later product development stages. Lastly, by maximizing the use of biodegradable materials, the environmental impact of using the MARV-1N would be largely reduced, allowing for a smaller impact on the areas in which the robot is intended to be improving for human habitation. This is believed to be an important criteria for the prolonged and widespread use of a product such as MARV-1N, as the intention is to improve the areas in which it will operate, not to create further issues that require attention, where possible.

A further point of optimization which was raised based on the impact test results was the potential for eliminating springs altogether. The impact test conducted with no springs yielded an impact force of 140N. While it's desirable to far exceed the detonation requirement of 150N, being so close without the use of springs is evidence that further work on the impactor, primarily increasing the drop height, would allow MARV-1N to achieve and likely exceed this 150N requirement using gravitational potential energy alone. This would serve to reduce the overall cost, part count, as well as assembly complexity.

12 Conclusion

Overall, MARV-1N is a fully functional prototype of a mine clearance robot that is able to effectively detonate and clear several types of anti-personnel mines. The prototype design fully met the performance requirements of the client and met the majority of the design objectives outlined in the initial concept report. The fact that the impactor design was able to reliably achieve more than the required 150N of impact force and met nearly all of the design objectives shows that the concept evaluation methodology chosen did indeed select the best concept design. The design objectives that were not met have no effect on the functionality or performance of MARV-1N, although they would impact future commercialization. During the design and build of this first iteration, many lessons were learned that can be applied to future iterations in further refining the design. Improvements and optimizations around impactor design, cost, and material usage would help MARV-1N to meet every single design objective and make it a very attractive product in the line up of mine detection and clearance robots worldwide.

References

Appendix A: Concept

Appendix B: Test Reports

Assembly Complexity Testing

Scope, Administrative Details and Test Design

This test seeks to quantify and qualify the complexity of MARV-1N's assembly process. Relevant parameters are the time of assembly, tools required for assembly, and number of fasteners needed during assembly. These three parameters are chosen to summarize the overall complexity of the robot. A complex design will generally take more time to complete, require more specialized tools, and use several fasteners.

Table 9: Administrative Details of Assembly Complexity Testing

Test Date	March 30, 2023
Test Location	Residence of Group Member
Conducted By	Members of Group 15

Design of Test

The test consists of two main parts: a measurement of assembly time, and a count of the quantity of tools and fasteners used. The independent variable can be thought of as the assembly complexity. The dependent variable is time or the number of tools and fasteners used.

The measurement of assembly times requires only (1) tool, a stopwatch. This test requires at least (2) people to conduct.

Procedure

The assembly process requires an "assembler" and a "timekeeper:"

1. Place all of the robot's parts on a flat surface.
2. Assemble any parts that will be pre-assembled for shipping. Do not start the stopwatch yet.
3. Next, the timekeeper starts the stopwatch while the assembler begins assembling the robot. During the assembly, the timekeeper should also record the number of tools and fasteners used.
4. The assembler should indicate to the timekeeper when they are finished assembling.

5. The timekeeper records the assembly time.
6. Both the timekeeper and assembler should inspect the final robot, ensuring it is assembled correctly. If the robot is not assembled correctly, disregard the assembly time and restart.

There are no notable safety concerns in this test.

Results, Analysis, Interpretation

The assembly testing of MARV-1N generated the following data, summarized in Table 10.

Table 10: Results of Assembly Complexity Testing

Assembly Time	5:32
Number of Tools Used	1
Number of Fasteners Used	0

This test generates simple results, and requires no additional analysis.

Discussion of Results

See the testing section in the body of this report for a discussion of results.

Summary/Conclusion

MARV-1N achieved a relatively low assembly time of 5:32. MARV-1N also required no fasteners, and only 1 tool (a mallet) to assemble. Overall, MARV-1N simple design made of mostly press-fit connections allowed the robot to achieve a very low level of assembly complexity, which met the design objective.

Future tests of assembly complexity could employ a standardized set of instructions that contained "checkpoints" at which the timekeeper could record a split time. Breaking assembling into timed sections would help to indicate which parts of the assembly require the most time, and which parts require less time. Assemblies that require the most time to assemble may need design changes to reduce the assembly complexity.

Mobility Complexity Testing

Scope, Administrative Details and Test Design

This report describes the formal mobility testing performed on the MARV-1N prototype. Specifically, the following tests were performed:

1. Dirt sine wave test: measure the robot's ability to pass over a 3" peak-to-peak sine wave dirt obstacle at any angle of incidence.
2. Incline climb test: measure the robot's ability to drive up a leaf-covered walking path with an incline of up to 15 degrees (straight up, down, or side to side)
3. Leafy lawn test: measure the robot's ability to drive over a leaf-covered lawn with 3" grass
4. Speed and maneuverability test: measure the robot's speed and qualitatively evaluate its general maneuverability

MARV-1N was designed to fulfill all the client-defined mobility constraints, which are represented by tests 1-3. The fourth test measures the robot's maneuverability beyond these constraints. MARV-1N was designed to have excellent general mobility.

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Table 11: Administrative Details of Mobility Testing

Test Date	April 8, 2023
Test Location	UVic Campus, ELW Design Lab
Conducted By	Members of Group 15

Design of Test

The first three tests in this section require no special tools and can be completed by a single person. In these cases, the robot is placed next to the given obstacle or terrain before the operator attempts to drive over it. For mobility tests 1 and 2, the angle of incidence is varied slightly in-between trials.

The first three tests, however, will require a location that contains the obstacles the robot is required to overcome. For this test, all three testing scenarios were conducted on paths, lawns, and dirt around UVic's Engineering Lab Wing building. A ruler (or tape measure) and level can be used to determine the length of grass, and slope of the incline.

Determining the robot's speed, part of the fourth test, is achieved by measuring the time it takes the robot to pass between two points that are a known distance apart. Then, the speed is a simple time-displacement-velocity calculation. This test requires a stopwatch and some method of measuring a reasonably long distance, like a tape measure. A tool to mark the measured points may also be convenient, such as a marker or tape.

Procedure

Procedure for tests 1, 2, and 3:

1. Place the robot directly in front of the obstacle
2. Step back from the robot, and use the controller to drive the robot over the obstacle
3. Record the robot's ability to overcome the obstacle (a simple pass or fail)
4. Stop here for test 3. Continue to step 5 if completing tests 1 or 2.
5. Bring the robot back in front of the obstacle.
6. Rotate the robot approximately 30 degrees relative to the obstacle.
7. Repeat steps 2-6 until the robot has rotated 180 degrees relative to its starting position in step 1. For test 1, angles above 90 degrees will involve driving the robot backwards over the sine wave track. For test 2, angles above 90 degree will involve driving the robot down the incline.

Procedure for tests 1, 2, and 3:

1. Mark two parallel lines on a large, flat surface without obstructions approximately 1 meter apart. If a full meter of space is not available, use the longest straight line of space instead.
2. Place the robot behind the first line with its wheels aimed at the second line.
3. Use the controller to drive the robot at full speed between the lines.
4. Start a stopwatch as a given point on the robot (i.e., the front of a wheel) passes the first line.
5. Stop the stopwatch as the same point passes the second line.
6. Record the time taken and distance between lines.

There are no notable safety concerns any of these tests

Results, Analysis, Interpretation

The mobility testing of MARV-1N generated the following data, summarized in Table 12.

Table 12: Summary of mobility test results

Dirt Sine Wave	Pass
Leafy Incline	Pass
Leafy Lawn, 3" Blades	Pass
Line Separation	60cm
Time Between Lines	3.7s
Maneuverability	Adequate

Interpreting the robot's speed requires one simple calculation, as follows:

$$V = \frac{d}{t} = \frac{0.6m}{3.7s} = 0.16m/s \tag{1}$$

This indicates the robot max speed is approximately 0.16 m/s. The measured speed can be compared to the theoretical speed. With a motor shaft speed of 45 rpm, a 2:1 ratio between the motor and wheel, and a wheel diameter of 4.8 inches, the theoretical speed is as follows:

$$V = \left[2\pi\left(\frac{D}{2}\right)\right] \cdot \left[\frac{RPM}{60}\right] = \left[2\pi\left(\frac{4.8inches}{2}\right)\right] \cdot \left[\frac{45RPM}{2 \cdot 60}\right] = 0.14m/s \tag{2}$$

Discussion of Results

See the testing section in the body of this report for a discussion of results.

Summary/Conclusion

MARV-1N passes all client-specified mobility constraints, including the dirt sine wave, incline, and leafy lawn obstacles. The robot's measured speed was close to the designed value, but at 0.16 m/s, MARV-1N is not very fast. Furthermore, MARV-1N two-wheel skid-steering system limited its maneuverability.

Impact Testing

Scope, Administrative Details and Test Design

This report describes the impact force testing of the MARV-1N prototype. The test involves only a single parameter: the measured impactor force. To trigger a mine, research has shown approximately 150N of impact force is required, as measured by the client-provided testing apparatus. MARV-1N was expected to generate well above 150N of impact force, as is discussed in the engineering analysis section of this report.

Table 13: Administrative Details of Impact Testing

Test Date	April 8, 2023
Test Location	ELW Design Lab
Conducted By	Members of Group 15

Design of Test

The impact test is relatively simple and requires (2) people. Impact force is measured impacting a piston with the projectile, and measuring the resulting deflection. The measured deflection is then checked against an experimental curve that models the piston deflection at various magnitudes of impact force. If the deflection is above a certain value (in this case, approximately 21mm), the robot has passed its test.

Performing this test requires an experimental impact force measuring device, and platform to support the robot, and a ruler to measure the resulting deflection. Three impact force tests were performed to measure the dispersion and repeatability of the impactor.

Procedure

Procedure for tests 1, 2, and 3:

1. Load the projectile in the robot and engage the springs.
2. Place the robot on top of the test platform and align it with the piston below.
3. Step back from the testing apparatus
4. Trigger the impactor to release the projectile with the controller
5. After the impact test, measure the piston deflection.

6. Repeat for however many trials are required

Unlike the previous tests, impact tests introduce a few notable safety concerns. First, when the projectile impacts the piston, it can bounce upwards and outside of the immediate testing area and potentially strike a nearby observer. Test operators should be careful to stand well clear of the piston, preferably with a solid object separating them and the piston. Also, while MARV-1N was designed with safety in mind, the design is still a prototype. Test operators should exercise caution around the loaded robot at all times. This includes never placing hands or feet beneath the impactor.

Results, Analysis, Interpretation

The impact testing of MARV-1N generated the following data, summarized in Table 15.

Table 14: Summary of impact test results

Impact Trial 1	500N
Impact Trial 2	240N
Impact Trial 3	350N

Results clearly show MARV-1N fulfills the 150N force requirement. For a better idea of MARV-1N's typical performance, the results of three trials can be averaged. Table **??** summarizes analysis of these trials:

Table 15: Summary of impact result analysis

Average Impact Force	363N
Maximum Impact Force	500N
Minimum Impact Force	240N

Discussion of Results

See the testing section in the body of this report for a discussion of results.

Summary/Conclusion

Results of the impact tests indicate MARV-1N achieves the 150N impact force required to detonate a mine, with an average impact force of 363N, and no measurements below 240N. The maximum impact force was significantly higher than the average at 500N. The large range of impact values may suggest MARV-1N's trigger may not release the projectile in a consistent manner.

Only three trials were performed to prevent damage to the prototype, but further testing may seek to increase the number of trials, possibly until the robot breaks. This could provide insight into which components in the impactor are the weakest links. Future revisions of the robot could then increase the strength or performance of these parts to increase MARV-1N's reliability.

Appendix C: Bill of Materials and Cost Breakdown

Refer to the following tables for a full bill of material, with each part assigned a unit and total price.

Table 16: Cost Estimates of 6mm (1/4”) Plywood Parts

No.	Part Name	Quantity	Length (in)	Width (in)	Plywood Area (ft^2)	Unit Price	Total Price
1	Impactor Top Plate	1	8.6	8.4	0.502	$2.26	$2.26
2	Impactor Mid Plate	2	6.2	2.5	0.108	$0.48	$0.97
3	Trigger Plate	2	6.8	4.7	0.222	$1.00	$2.00
4	Trigger Gusset	4	2.2	1.3	0.020	$0.09	$0.36
5	Trigger Lateral Support Plate	4	1.1	1.0	0.008	$0.03	$0.14
6	Chassis Side Plate	2	18.9	11.9	1.562	$7.03	$14.06
7	Chassis Base Plate	1	15.5	7.3	0.786	$3.54	$3.54
8	Wheel Gear	2	4.2	4.2	0.123	$0.55	$1.10
9	Axel Support Vertical Plate	4	3.0	2.6	0.054	$0.24	$0.98
10	Axel Support Flat Plate - Bottom	4	3.4	1.8	0.043	$0.19	$0.77
11	Axel Support Flat Plate	4	3.4	1.8	0.043	$0.19	$0.77
12	Axel Support Retaining Plate	4	3.3	1.3	0.030	$0.13	$0.54
13	Axel Support Angle Plate	4	7.2	2.9	0.145	$0.65	$2.61
14	Impactor Guide Rod Support Bottom	1	5.2	5.2	0.188	$0.85	$0.85
15	Motor Gear	2	2.2	2.2	0.034	$0.15	$0.30
						Total:	$31.21

Table 17: Cost Estimates of 3mm (1/8”) Plywood Parts

No.	Part Name	Quantity	Length (in)	Width (in)	Plywood Area (ft^2)	Unit Price	Total Price
1	Impactor Spring Guard Side Plate	2	7.3	2.5	0.127	$0.42	$0.84
2	Impactor Spring Guard Cam Plate	4	10.2	2.7	0.191	$0.63	$2.52
3	Impactor Spring Guard Top Plate	2	2.5	1.7	0.030	$0.10	$0.19
4	Impactor Spring Guard Top-Side Plate	2	2.5	2.3	0.040	$0.13	$0.26
5	Wheel Center	8	4.5	4.5	0.141	$0.46	$3.71
						Total:	$7.53

Table 18: Cost Estimates of 3D Printed Parts

No.	Part Name	Quantity	Filament Length (m)	Volume Used (cm^3)	Unit Price	Total Price
1	Flywheel Trigger Flange	1	2.33	14.9	$0.55	$0.55
2	Impactor Pull Handle	1	2.38	15.2	$0.56	$0.56
3	Trigger Arm Long	2	1.10	7.02	$0.26	$0.52
4	Servo Holder	1	2.53	16.1	$0.60	$0.60
5	Wheel Tread	4	9.48	60.5	$2.25	$9.00
6	Impactor Spring Bar	1	4.46	28.452	$1.06	$1.06
7	Motor Mount	2	0.85	5.42	$0.20	$0.40
8	Hub Collar	2	0.30	1.91	$0.07	$0.14
					Total:	$12.84

Table 19: Cost Estimates of Delrin Shafts

No.	Part Name	Quantity	Nom. Diameter (in)	Length (in)	Unit Price	Total Price
1	Firing Cable Roller	1	3/8”	0.86	$0.12	$0.12
2	Axle	4	1/2”	2.94	$0.68	$2.70
3	Spring Pull Down Rod	2	3/8”	6.00	$0.87	$1.74
4	Trigger Arm Shaft	2	1/4”	1.50	$0.13	$0.26
5	Guide Rod	4	1/4”	8.76	$0.74	$2.98
6	Firing Pin	1	1/4”	1.20	$0.10	$0.10
					Total:	$7.90

Table 20: Cost Estimates of Pre-Purchased Parts

No.	Part Name	Quantity	Notes	Supporting Reference	Unit Price	Total Price
1	Gear Motor	2		[website]	$12.99	$25.98
2	MG996R Servo	1			$7.39	$7.39
3	Mass (Flywheel)	1	Bulk Steel, 374.21cc		$5.44	$5.44
4	Extension Spring	2		mcmaster	$6.10	$12.20
5	Weight Rod (Not Included)	4	Bulk Steel, 115.67cc		$1.68	$6.73
					Total:	$51.01

Table 21: Cost Estimates of Controller Parts

No.	Part Name	Quantity	Notes	Supporting Reference	Unit Price	Total Price
1	Side Plate	2	6mm Plywood (7.1” x 1.2”)	–	$0.27	$0.53
2	Bottom Plate	1	6mm Plywood (7.3” x 3.7”)	–	$0.84	$0.84
3	Arduino Nano	1			$11.33	$11.33
4	2-Pos Slide Switch	1			$0.52	$0.52
5	10k Ohm Resistor	2			$0.01	$0.02
6	LED	2			$0.03	$0.07
7	100 Ohm Resistor	1			$0.04	$0.04
8	5 V Regulator	1			$0.90	$0.90
9	100 nf Ceramic Capacitor	1			$0.02	$0.02
10	Electrolytic capacitor 1uF/50V	1			$0.11	$0.11
11	220 Ohm Resitor	1			$0.01	$0.01
12	Mini Push Button	1			$0.08	$0.08
13	T0-220 Heat Sink	1			$0.34	$0.34
14	PS2 X Y Axis Joysrick Module	1			$2.00	$2.00
15	L298N Motor Driver	1			$3.50	$3.50
16	Solerable Breadboard	1			$0.99	$0.99
					Total:	$21.30