MAE 322 Team BREACH Final Design Report

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1. Executive Summary

Our team was tasked with designing, fabricating, and testing a Search and Rescue Robot (SaRR) that will simulate real-life search and rescue operations by performing the following tasks:

1. Retrieve a simulated medical kit weighing 2.5 lbs
2. Quickly drive to and around a pylon placed about 50' away
3. Autonomously breach a 12" tall stair-step obstacle
4. Autonomously navigate a twisting chute without contacting walls
5. Autonomously sense and drive toward a light source
6. Autonomously place the simulated medical kit into a basket at the light source

In addition to these performance requirements, the SaRR was speed-tested against other groups in this course, placing third out of four robots.. It was also drop-tested from a height of 12" and maintained structural integrity and full functionality.

Our SaRR, delivered the simulated medical kit through the 100 foot course and past the wall obstacle to the simulated victim in approximately 90 seconds. The SaRR was created with simplicity of design in mind, using an adapted drivetrain from a previously made robot and two axle-driven "breach wheels" connected to a DC drill motor through a custom gearbox. Our SaRR was able to achieve the course goals individually; however, our testing never combined all autonomous functions in one script. In the testing phase, our SaRR easily drove, picked up the simulated medkit, breached the stair wall, navigated the chute, and located the simulated victim, demonstrating all basic functionalities in their proper manual/autonomous mode.

2. Introduction

The SaRR is designed upon a simple rectangular chassis. The chassis will be fabricated from aluminum angle beam mounted atop a rectangular acrylic plate. All operational systems will be mounted to this chassis. During the process of building the SaRR, we will arrange some of the non-load bearing components to achieve symmetric weight distribution along the chassis' two axes, with modifications made to ensure the weight distribution is ideal for breaching the wall obstacle. For movement and steering, the SaRR will operate using two independent DC motors to drive its front wheels, each being individually controllable to enable steering. The SaRR will use a rotating beam with forked prong for retrieving, retracting, and placing the medical kit. This arm will be driven by an identical DC motor to those use in the drivetrain in order to maximize simplicity via modular design. For breaching the wall obstacle, the SaRR will use specially crafted cross-shaped wheels. These wheels will be drive the SaRR up the stair-like obstacle while the drive wheels push. The breaching wheels will be driven together, linked by an axle, by yet another identical DC motor. Additional hook-like structures may be added to increase the climbing ability of the breach wheels, and the corners that slide against the ground may be rounded for improved driving performance. For autonomous navigation of the chute and autonomous seeking of the simulated victim, we will implement both light and proximity sensors at the front of the SaRR. The autonomous control code will take data from all three sensors to relate the SaRR's position to the chute and light source. A preliminary model of the SaRR is shown in Figure 1. The drive wheels are seen on the left hand side of the notional model, which is considered the front of the SaRR. The breach wheels are positioned at the rear of the SaRR. The med kit retrieval arm is positioned at the front of the SaRR to minimize arm length required to pick up and deploy the med kit. Additional systems such as motor controllers, sensors, batteries, wiring, and the motor that operates the retrieval arm are mounted atop the chassis, and will be distributed to ensure symmetric weight distribution.

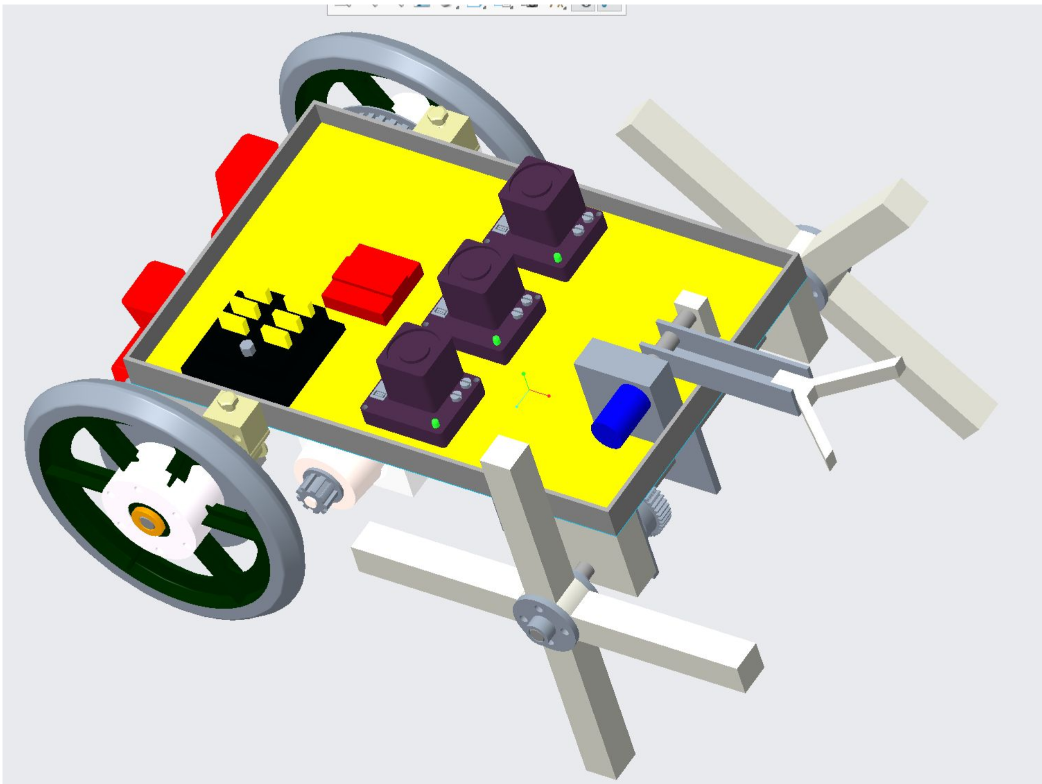


Figure 1: CAD Model of the SaRR

The principles guiding our design were 1) simplicity and 2) robustness in form and function. True simplicity involves being able to physically build the SaRR very quickly without wasting time on unnecessary complexities. Robustness in form and function involves being able to survive drop tests and complete the necessary tasks with a very high success rate. These principles are related such that a truly simple robot design allows us the freedom to dedicate more time to important tasks like refining the performance of the SaRR, and the way the software and hardware integrate. The primary goal of our SaRR was to complete all course challenges consistently, with speed and other refinements secondary.

Research on existing robots that meet similar design expectations was performed to ensure all relevant options were considered and that an optimal tradeoff between simplicity and functionality could be achieved. In MAE 322 lecture, we were shown SaRRs from previous semesters, and from those designs we judged what worked most effectively. Our team ultimately chose the cross-shaped climbing breach-wheel method for passing the wall obstacle because many previous groups were able to achieve success with similar designs, with what we project to be relatively low labor and cost inputs. Additionally, our team researched methods of autonomous navigation online by researching open-source Arduino code. We implemented a modified version of the light sensing and navigation code written in lab. Additional preliminary research involved comparing the geometry of designs being considered, such as drawing force diagrams for elements such as wheels, breach wheels, and grabber arms. These drawings also informed decisions about chassis length, as we initially considered a shorter chassis design, as well as the size of breach wheels.

Figure 2 shows a simplified diagram of the course that the SaRR will need to run. The purpose of the Search and Rescue Robot (SaRR) is to carry a medical kit through multiple obstacles to a patient in a disaster zone. It completes the following tasks: 1) picks up a 2.5 lb simulated medical kit under manual remote control, 2) drives to and around a pole under remote control, 3) autonomously breaches a 12” wall with a 6” step in front of it, 4) autonomously navigates a chute with unknown turns, 5) autonomously navigates to a simulated victim holding a flashlight, and 6) deposits the medical kit at the light.

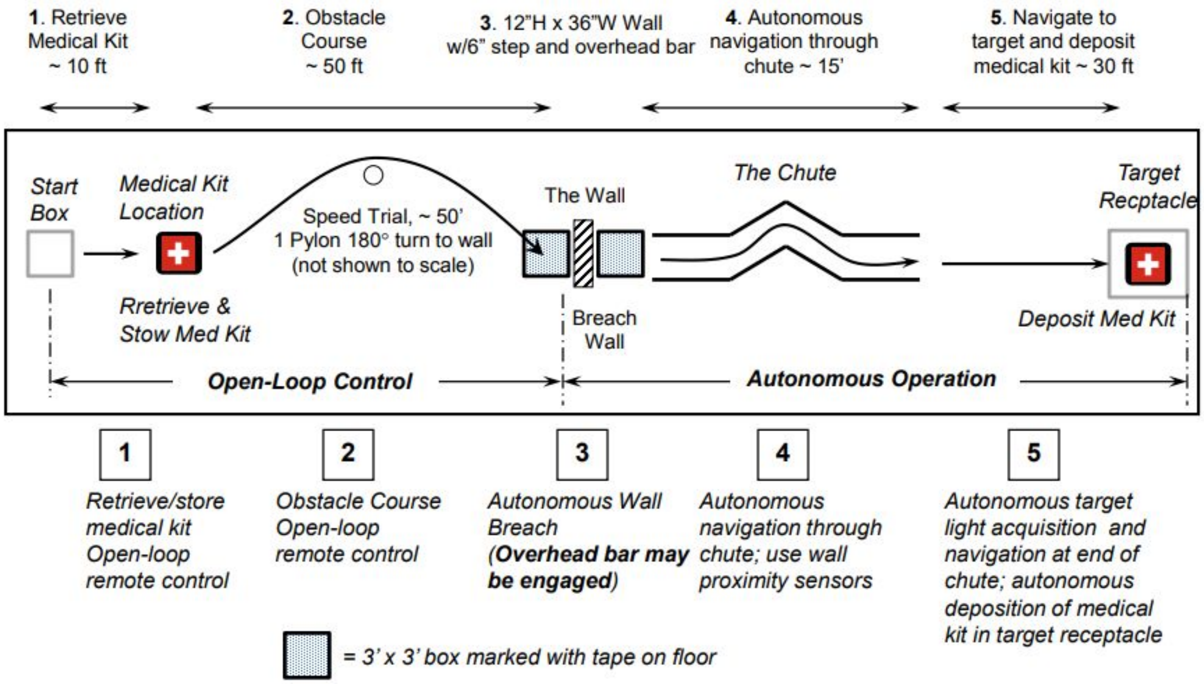


Figure 2: Simplified Diagram of the Course the SaRR will Run

3. Project Management

The team consists of five members. The team leader is William Kelly. Caleb Owens, Tanner Kliewer, David Wu, and Connor Roettig make up the rest of the team. The general work breakdown that we implemented is shown in Figure 3.

	Caleb	Connor	Tanner	Will	David
Primary:	Electrical	Fabrication	CAD/Design	Team Leader	Programming
Secondary:	Machining	Ordering	Electrical	Ordering	Machining
Tertiary:	Writing	Writing	Writing	Machining	Writing

Figure 3: General Breakdown of Roles

Milestones and Time Committed:

- Order all supplies.
  - By Mar 25, 2018.
  - Achieved: Week-to-week
  - Hours: 5
- Build the chassis and set up the drivetrain to get a drivable robot.
  - Milestone Date: April 6
  - Achieved: April 5
  - Hours: 80
- Make the plastic cross-shaped wheels and get manual wall climbing working.
  - Milestone Date: April 13
  - Achieved: May 7
  - Hours: 120
- Finish Med Kit Retrieval Arm.
  - Milestone Date: April 27
  - Achieved: May 14
  - Hours: 80
- Chute navigation autonomous.
  - Milestone Date: April 27
  - Achieved: May 13
  - Hours: 30
- Light tracking autonomous.
  - Milestone Date: April 27
  - Achieved: May 13
  - Hours: 10
- Writing Presentations, Reports, and other Miscellaneous Tasks.
  - Hours: 25

Our project management revolved around clear goal setting and division of labor such that every member is contributing at the same time. This way, we aimed to not waste precious time in design bottlenecks, where the ability of the group to work is dependent on the work of a minority of members being completed. However, this was an issue throughout the project, as often times our programming would need to wait for fabrication/mounting to be complete, or testing of designs was delayed by programming. This group had meetings as necessary but found that remote communication and organizing with GroupMe, Trello, and Google Team Drive worked well for coordinating tasks. We sought to have all group members present and working whenever we are in the machine shop. However, with varying schedules and unforeseen events, this equilibrium was achieved mostly in the first three weeks and last three weeks of the project. As some of our team members were away from campus at times, we will distributed tasks that could be done remotely, such as CAD design. Additionally, we kept a tracker for the number of hours worked to keep each other accountable and motivated, and for informing course instructors. Team BREACH contributed a cumulative 350 hours of labor of design, fabrication, testing, and evaluating our SaRR. Our initial time estimate was 380 hours. Although we ran up against the final testing deadline, if we had more time to refine our autonomous code, we likely would have approached the initial estimate.

As we have projected the most critical issue to our team's success being its small size relative to the other groups, our approach at every turn was to emphasize simplicity and employ labor and time saving measures wherever possible. Due to our small size, we had to individually make larger efforts to ensure that we met the required goals of the SaRR and would be able to show progress to course instructors. With repeated emphasis on completing this task with simple mechanical design, we were able to achieve many of the primary goals with reasonable labor usage.

Finally, to evaluate our performance in project management, we rated ourselves on a 1 - 5 scale on the nine knowledge areas of project management, as presented by Frank Ryle in lecture. As shown in Figure 4, several key knowledge areas are evaluated lower than others.

Knowledge Area	Score (1 - 5)
Cost	4
Scope	5
Quality	2
Risk	3
Integration	1
Stakeholders	3
Communication	3
Schedule	2
Resources	4
Procurement	3
Total (out of 50 possible)	30

Figure 4: Knowledge Areas

We have identified the areas of quality, integration, and schedule as the primary areas that contributed to our inability to demonstrate a single autonomous script that contained wall breaching, chute navigation, and light tracking on testing day. By falling behind schedule, build quality declined on several of the last areas of the SaRR that were implemented, particularly mounting the proximity sensors. Our largest issue on testing day was integration of each autonomous code element with the array of sensors, the drivetrain, breach mechanism, and medkit arm. With more time, better integrated code would likely have been implemented. However, the goals left unachieved on testing day indicate suboptimal integration as a result of poor scheduling, brought on by quality issues after significant rework was done in the final weeks of this project.

4. Design and Analysis

To determine the acceleration of the SaRR, we need to account for the static friction coefficient between the rubber wheels and vinyl floor, as well as the sliding friction coefficient between the HDPE breach wheels and the floor. We estimate these to be 0.70 and 0.30, respectively.

This yields the equation to solve for maximum acceleration, again assuming a symmetric weight distribution. The motor, rated at approximately 13Nm, can provide 128N of force at a displacement of 4 inches, the radius of our drive wheels. However, the acceleration is limited in this case by the grip of the drive wheels, rather than motor torque.

$$\Sigma Fx = ma = mg/2(0.70 - 0.30) \quad .$$

With our values of m = 20lbs, maximum acceleration is found to be 1.96 m/s2.

The torque required to lift the SaRR over the obstacle, using nothing but the breach wheels, can be estimated at mg(6.5in) = 14.675 Nm for a vertical ascent. This exceeds the torque rating of 13Nm that the single motor running the breach wheels has. However, the approach angle is much smaller and the drive wheels will be assisting, so this motor is adequate for the breach wheel application as well. We introduced a gearbox for the breach mechanism that contained a 7:1 reduction, thus increasing torque from the Black and Decker drill motor's 115in-lbs to 805 in-lbs, before losses. Assuming a 30% loss in the geartrain, our SaRR has 563 in-lb of torque.

Our SaRR will be designed and fabricated to achieve a symmetric weight distribution about both the longitudinal and latitudinal axes of the SaRR while the med kit is in fully retracted position. Major components such as the motors that power the drivetrain will be fixed to the chassis first. The actual weight distribution is as follows for both the loaded and unloaded SaRR. All units are in inches and are measured from our coordinate system at the back right wheel.

Center of Mass							
Component	Mass (kg)	x-Location	y-Location	z-Location	x-center	y-center	z-center
Chassis	1.25	11	7	7.5	13.75	8.75	9.375
Drive Train	7.5	7.3125	7	5	54.84375	52.5	37.5
Electronics	1.25	9	7	8.5	11.25	8.75	10.625
Lifting Arm	1	18	7	9	18	7	9
Arm with Block	3.5	18	7	12	63	24.5	42
Total	11				8.894886364	7	6.045454545
Total with Block	13.5				10.58101852	7	7.37037037

Assuming symmetric weight distribution about the longitudinal and latitudinal axes, the reaction force on each wheel mount will be equal, as calculated here:

$$FLR = FRR = FLF = FRF = mg/4 = (11.0kg)(9.8m/s2)/4 = 26.95\ N$$

The SaRR wheel mounts are the likeliest point of structural failure in the drop test, and need to survive high impact forces. As such, they were designed to be robustly mounted to the aluminum frame, and easily survived the drop test. We estimate the latitudinal/longitudinal center of mass of the SaRR to decelerate over a displacement of one-quarter inch, due to flexure in the chassis when dropped. Using this half-inch estimate, we then determine the reaction on the whole system as: $F = mgh/d$ which using m = 20lb, h = 12in, d = 0.25 in, the reaction force on the whole system equals 108.4 N. Assuming equal impact, each wheel mount will need to withstand one quarter of the overall reaction, or 27.1 N each.

The placement of the last load-bearing member, the med kit retrieval arm, is close to the front axle of the SaRR. The weight distribution of the SaRR with no med kit will skew towards the front, but with medical kit retracted, we are likely to achieve symmetric weight distribution. The maximum moment acting on themed kit retrieval arm (and thus the necessary torque needed by the motor) is:

$$8\ in\ *\ 2.5 lbf\ =\ 20\ in\ lbf\ torque$$

The motor and gearbox assembly used was rated at 40 in-lb of torque, so we achieved a safety factor of 2 for the medkit retrieval arm. Originally, we planned on using two 20 kg-cm servo motors, combining to make 40kg-cm of torque. As we were planning to use a 6 inch long arm, this would yield a required torque of about 18kg-cm. However, the ratings were stall torque, and dynamic torque for the servo motors was too small to achieve the task.

The med kit retrieval arm is another component where simplicity is emphasized. We have decided to retrieve the med kit in open-loop manual control, as programming any autonomous feature would require excess time commitment for an optional objective. Our approach is to fabricate a beam that is rotated by a DC motor. This retrieval arm will be rotated down when approaching the medical kit. The bent shape of the beam, shown in Figure 2, allows the forked structure at the end of the retrieval arm to be at the proper height for picking up the medical kit. Once the SaRR is driven to the appropriate location and the handle of the medical kit is within the retrieval arm fork, the arm will be rotated upwards. The rotation mechanism we have chosen is using another DC motor, identical to the ones in the drivetrain and breach mechanism, to rotate the arm about a pin.

Additional considerations include choosing a wall breach approach position. For our SaRR, this was with both breach wheels touching the first step. This way, the wheels climbed at the same rate and maintained stability about the SaRR's x-axis.

We calculated required torques and energies needed to traverse the obstacle course.

Required Torques (m_medkit=2.5kg,m_robot=11kg,g=10m/s/s)					
Task	Driving	Lifting	# of accelerations		
Medkit Pickup	51.096672	3.072	5	255.48336	3.072
Drive Loop	255.48336	N/A	2	510.96672	
Wall Breach	30.6580032	67.056	8	245.2640256	67.056
Chute	76.645008	N/A	10	766.45008	
Light	153.290016	3.072	10	1532.90016	3.072
				3311.064346	73.2

Another factor governing the success of our SaRR is its ability to efficiently use the energy available. Provided 100 kJ from the drill battery, our estimates for energy usage were calculated as approximately 24.3kJ per course run. If we assume 100kJ available, we predict we will be able to complete the course four times under one charge. This idealization relies on the ability to limit slip on the wheels and breach mechanism to prevent excess energy loss.

	all values in J
5076.396518	Total Power Required
6076.396518	plus1000 for thermal losses
12152.79304	50% motor efficiency
16203.72405	75% drive train efficiency
24305.58607	with design factor

Code:

- Simple logic used for autonomous control system due to time constraints
- Wall breaching involves driving breach wheels and both back wheels forward almost max power for a designated period of time 3-4 seconds

- Chute navigation uses the left and right proximity sensors. It takes the difference between the two. If that difference is not sufficiently near 0, the bot turns in the appropriate direction to normalize it. It drives forward if the difference is within the threshold.
- Light navigation uses the left and right photosensors and the front proximity sensor. If the light sensors don't read a strong light signal, the bot turns until it finds one. It then takes the difference between the two photosensors and tries to get that sufficiently near 0 by turning, as in chute navigation. It drives forward if the difference is within the threshold. If the front proximity sensor reads an object, the basket, close to it, the bot stops.
- Placing the med kit involves lowering the arm for a designated period of time and then driving back a short period of time.

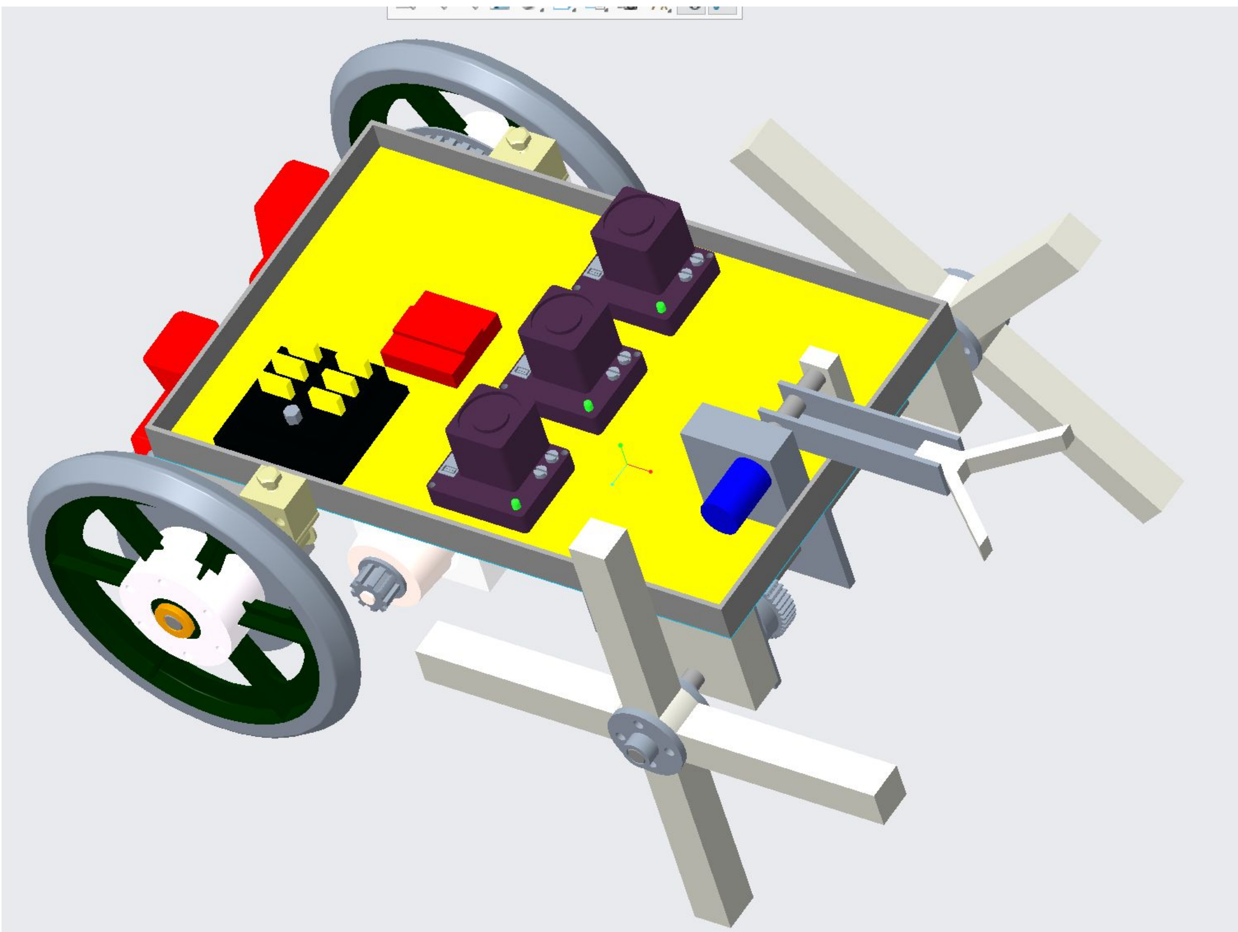
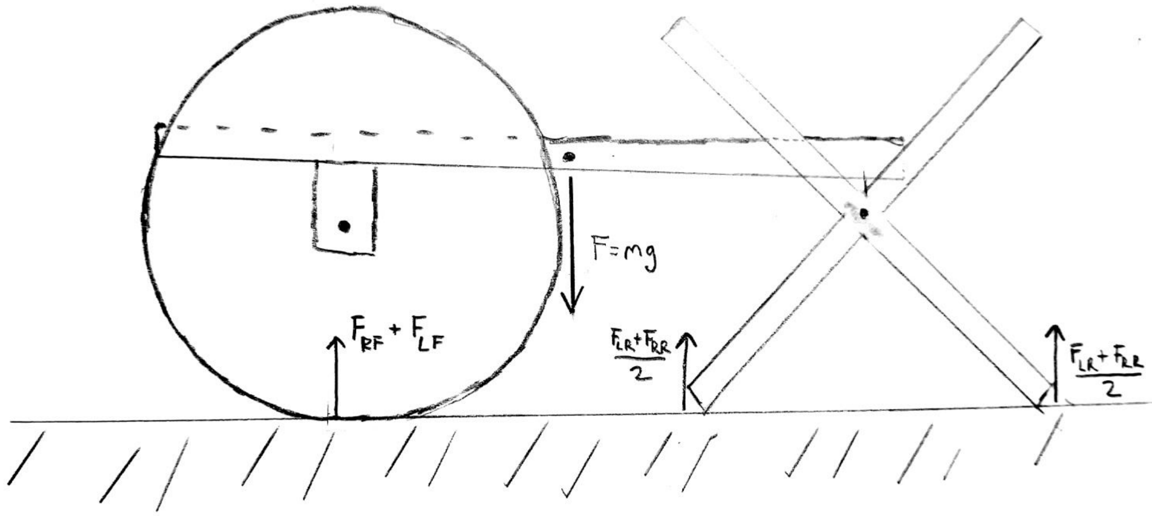
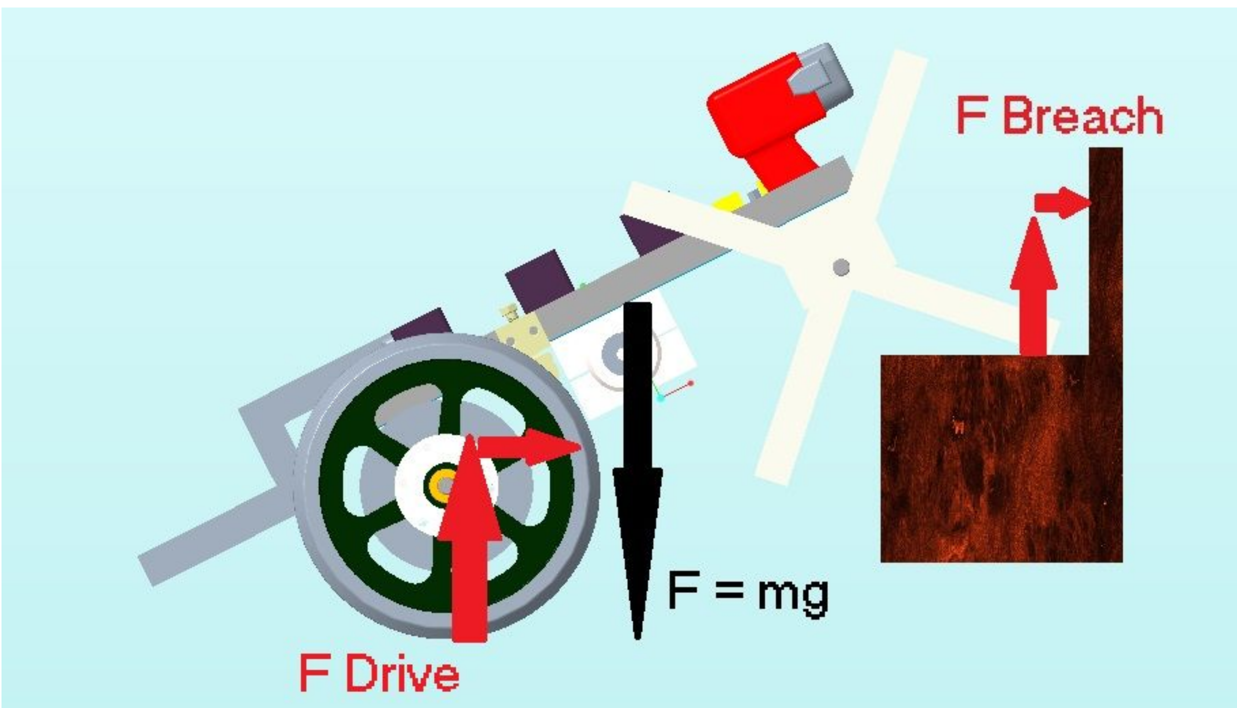


Figure 5: Final Design

Figure 6: Underside of Chassis showing Gearbox (below)





Figures 7 & 8: Free Body Diagrams

5. Specifications

The final specifications for our SaRR are as follow:

- Weight: 11.0kg, / 25lb 4 oz

- Time to run course: 90 seconds
- Maximum Speed: 2.5 feet per second / 0.76 meters per second
- Turning Radius: 18 inches
- Maximum Range: 4 Full course runs (400 feet plus obstacles)
- Dimensions:
  - Length: 21.5”
  - Width: 14.5”
  - Height: 10”

The following tasks were done with manual control:

- Driving
- Medkit Retrieval
- Wall Approach

The following tasks were performed under autonomous control:

- Wall Breach
- Chute Navigation
- Light Detection and Navigation
- Medkit placement (not achieved in testing, can be done under manual control)

6. Drawings

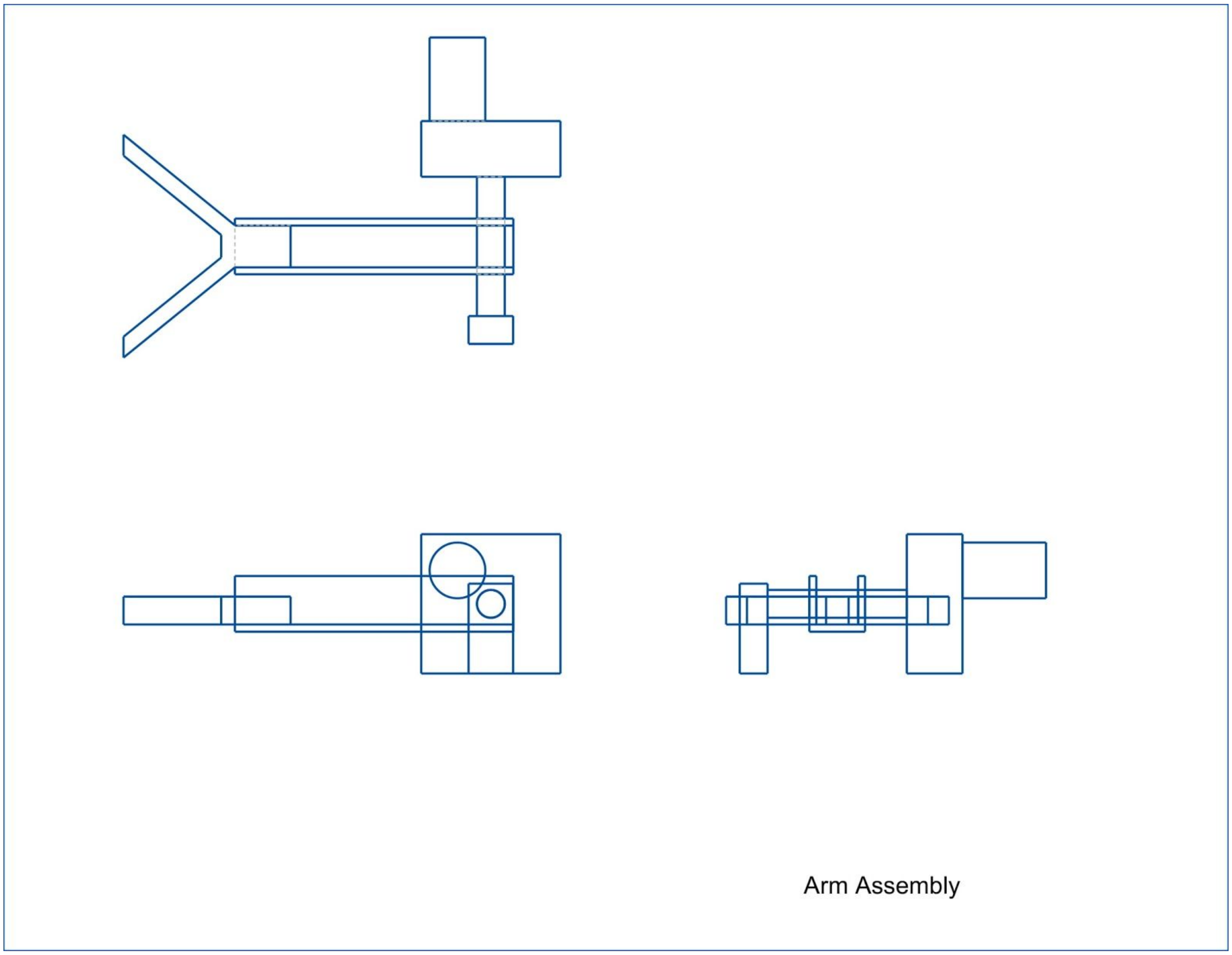


Figure 9: Arm Assembly

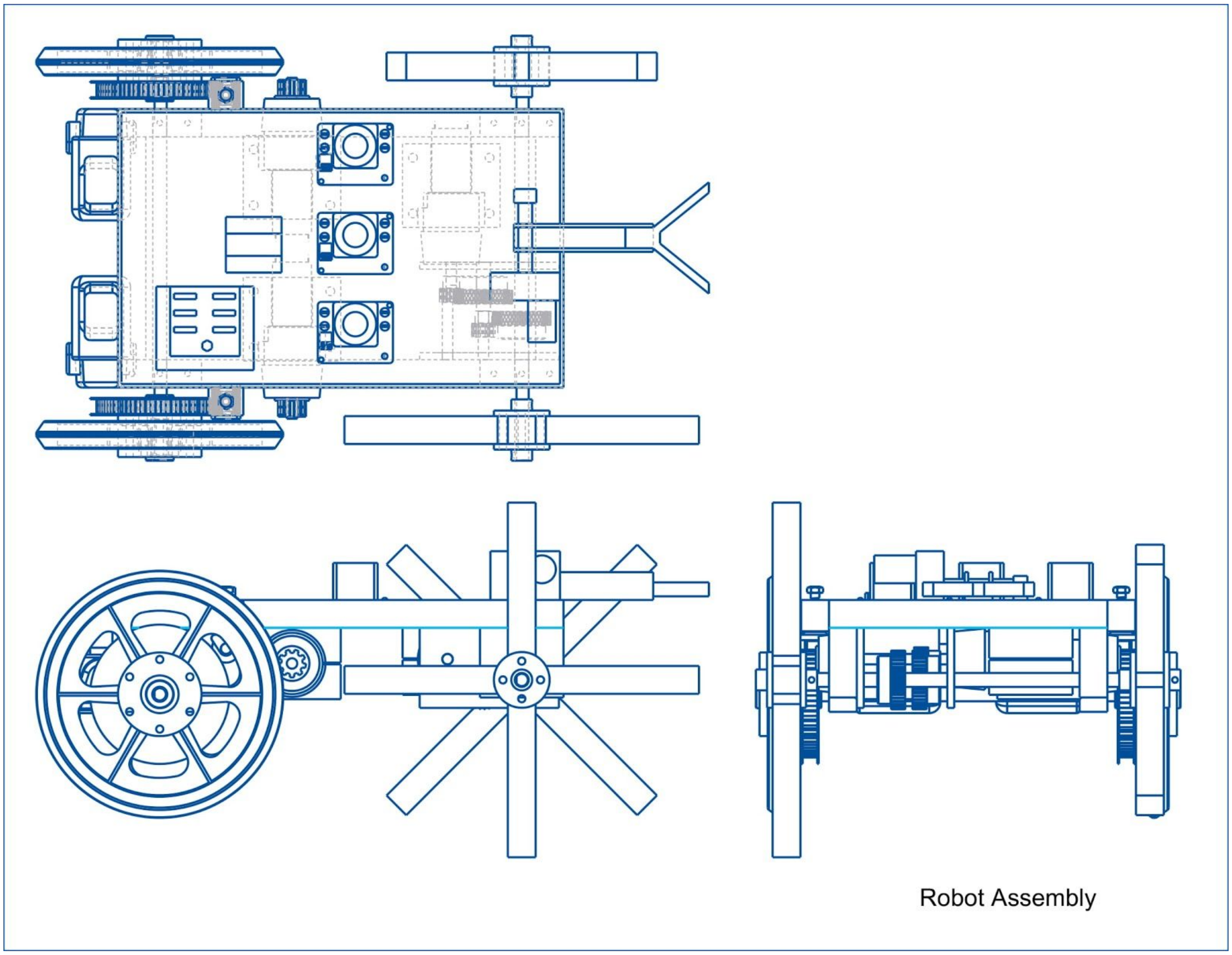


Figure 10: SaRR Assembly

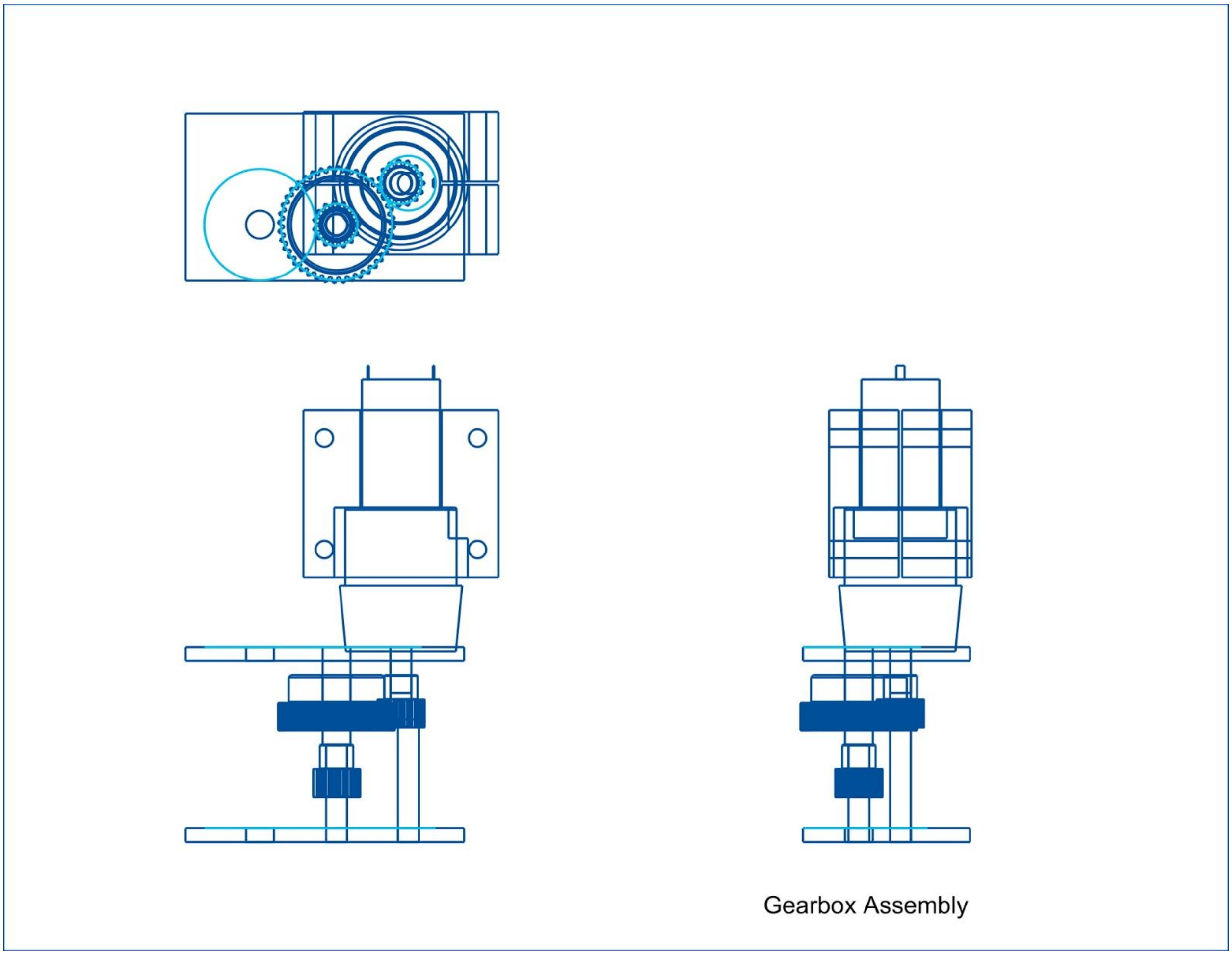


Figure 11: 7:1 Gearbox

7. Test Results

Team BREACH's SaRR ran the course on average 90 seconds. We were able to successfully drive, retrieve the medkit, autonomously breach, and autonomously navigate the chute. We failed to autonomously navigate to the light source and deposit the med kit, although the autonomous light detection capability was demonstrated by running a separate program. We were able to lower the medkit using manual control, but not autonomous.

The following value represent approximate average time to complete each task:

- Med Kit retrieval: 10 seconds

- Driving around pylon to wall: 30 seconds
- Autonomous Breach: 5 seconds
- Autonomous Chute Navigation: 20 seconds
- Autonomous Light Detection: 20 seconds
- Pauses: 5 seconds
- Total: 90 seconds

On testing day our SaRR was unable to complete all autonomous tasks running the same script. We demonstrated each designated autonomous task independently, with the exception of lowering the medkit into the basket, which could only be done manually.

We assessed the reasons why some autonomous tasks were unable to be fully integrated. Foremost, our autonomous script was heavily modified shortly before testing and bugs were present during testing, leading to some functions happening properly but not others. Additionally, the left front proximity sensor was broken off during one wall breach attempt, and our inability to quickly diagnose whether the replacement sensor was functioning properly took precious time away from debugging elsewhere.

While we were able to show each functionality, minus autonomous deposition of the medical kit, we achieved the goals stated. For future revisions, further debugging of the control script is necessary to sequentially breach the wall.

The autonomous wall breach was successful. Autonomous wall breach involved running both the breach wheels and rear drive wheels forward. However, in all but one attempt the medical kit became unstowed and fell out of the retrieval arm. In further iterations, this flaw could be remedied by introducing a bar that restrains the medical kit handle in the grabber when stowed.

The autonomous chute navigation was also successfully demonstrated. Using the two corner proximity sensors, our SaRR was able to quickly navigate the chute. Further revision includes better integrating this code into the master autonomous control script.

Autonomous light detection and navigation was also successfully demonstrated, but not while using the master autonomous control program that we breached the wall obstacle with. Additionally, we were unable to correctly program the retrieval arm depositing the med kit when arriving at the simulated victim. Further revision includes refining intensity thresholds used in the script and adding a command to rotate the arm downwards when the front-facing proximity sensor detects the basket.

8. Further Work & Conclusions

Further work primarily involves revision of the autonomous script and implementing a system to prevent the medical kit from becoming unstowed during the autonomous wall breach. Additionally, creating more sturdy mounts for the proximity sensors would serve to increase the reliability of the SaRR, as we experienced a failure of one of these mounts during testing, resulting in the destruction of a sensor.

Team BREACH was able to demonstrate the required objectives and has assessed the reasons why our autonomous script failed to integrate each independent autonomous subroutine. Overall, we are satisfied with the construction of a SaRR that was able to achieve all the mechanical challenges: driving, medkit retrieval, wall breaching, and sensor-based navigation. We recognize our testing inadequacies stem primarily from bugs in our code. Team BREACH performed a significant amount of rework on systems such as the drivetrain for the breach wheels and the medkit retrieval arm. Our SaRR proved robust enough to pass the drop test with no detectable change in construction or performance. If we were to build a second prototype, we would be able to use the lessons we learned to avoid spending time on rework and dedicate more time to refinement, particularly in build quality and implementation of autonomous control code.