DEBSA Limited Şirketi
Critical Design Report

**Doğa Veske, Baran Bodur, Serhan Yılmaz,
Arda Efe Okay, Alper Özkan**

Customer: Assist. Prof. Elif Vural

Project Name: Robot taking part in a Pistol Duel

Project Initialization Date: 21.09.2015

Project Duration: 8 Months

Electrical and Electronics Engineering Department
Room C-208
Middle East Technical University
Ankara, Turkey
November, 2015

Contents

1 Introduction

As we progress further along the project timeline, we get closer to completing our project. While the design and implementation of the critical modules are completed, there is still room for modification and improvement. There is also work to be done concerning some of our non-critical modules and overall integration of the system.

In this report we will provide a system description which gives information about the systems involved in our project and how they interact. We will also evaluate our current design and implementation of systems in a critical manner. We will determine the advantages and disadvantages of our systems and our approach of design. The report will also include insight to the overall integration of the systems in addition to their individual design. We will also look into the testing methods used in the process and outcomes of the tests. The report will also include our additions to the conceptual design and our analysis for monetary and power budgets, timelines, safety and error.

2 System Description

Our robot is designed to take part in a pistol duel. This means identifying turns, readying the shooting subsystem, detecting the opponent, shooting at the opponent, evading enemy fire by both randomly moving and by identifying enemy projectiles. This is achieved by several interconnected systems. These systems being

- Decision Subsystem
- Evasion Subsystem
- Detection Subsystem
- Shooting Subsystem

Each system has its own designated task which will be covered on further topics and these systems are managed by the decision subsystem which in turn takes the necessary actions. The subsystem interactions can be seen in the block diagram below.

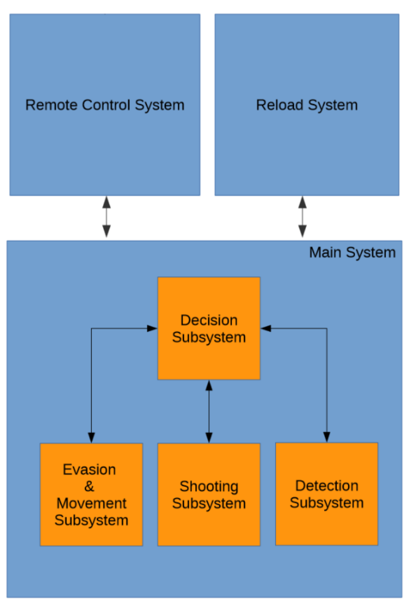

Figure 1: Block Diagram showing the subsystem interactions

2.1 Decision Subsystem

The decision system is basically the system that governs the other ones. It collects raw data from the other subsystems such as the Detection Subsystem and the related sensors from the Evasion Subsystem, then it determines the right course of action and sends the related subsystems such as the Shooting Subsystem the appropriate signal(Such as detecting an opponent with the Detection Subsystem and Shooting them with the Shooting Subsystem). The decision subsystem acts as a hub for all the signals within the system. The diagram below shows the signal flow going in and out of the decision subsystem and within the entire system.

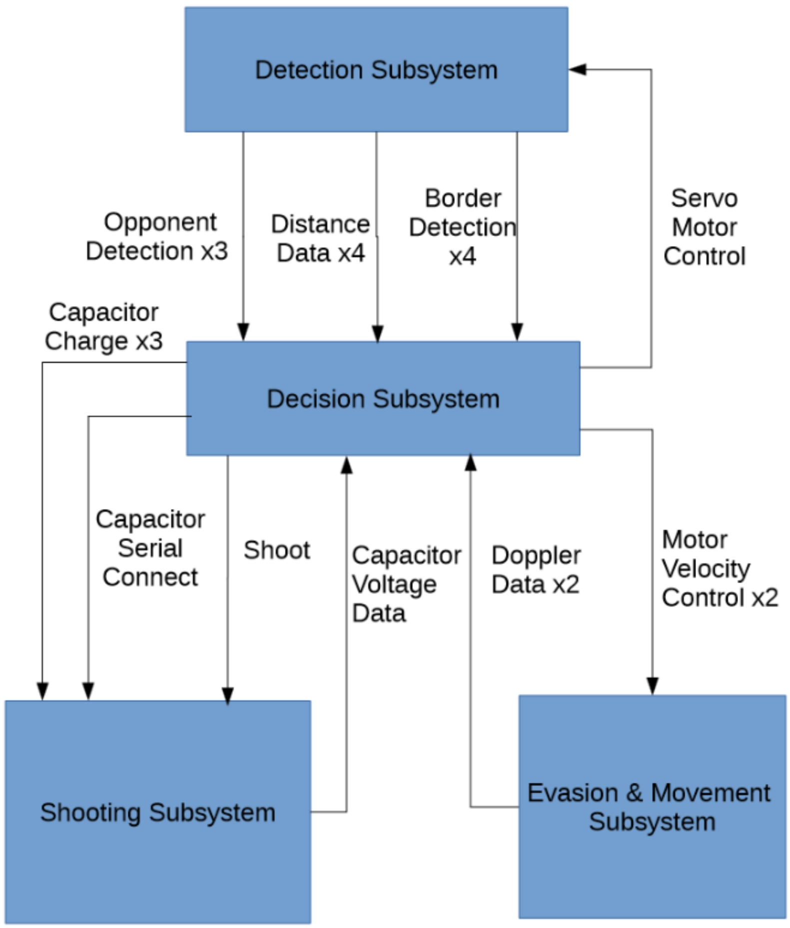

Figure 2: Signal Flow Diagram showing Decision Subsystem Functions

2.2 Evasion Subsystem

ARMUT will have two HB100 doppler sensors, which can detect the speed of incoming (or outgoing) objects via doppler effect. By using two of these sensors, ARMUT can also determine approximate direction of the projectile, and perform an evasive maneuver to the opposite side.

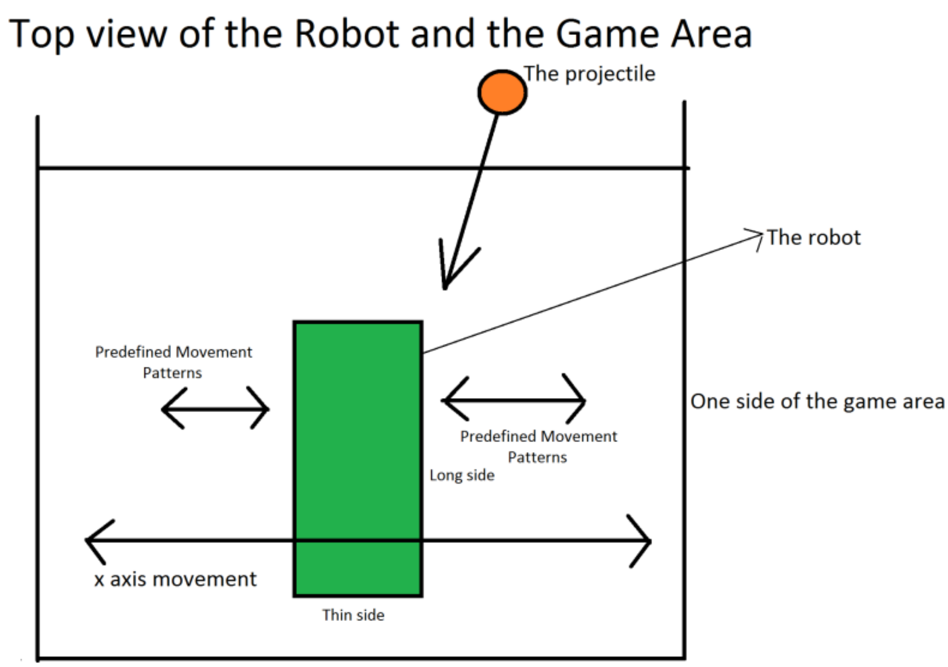

Figure 3: Diagram showing the Doppler-Guided Evasion

The use of two Doppler sensors can be seen in the previous figure. The doppler sensors will detect frequency shifts caused by the projection of relative velocity (u') on the axis between sensor itself and the projectile. Therefore if the projection of u' on the second sensor axis is larger (angle b is greater), it will detect a greater frequency shift when compared to the first one.

In order to make such decisions, we need to know

These HB100 sensors will give the frequency of the doppler shift (not the shifted frequency but how much shifted it is), however there are multiple ways to process these signals. Before sampling the signal with ADC, it is first amplified, shifted by 2.5 V (to make it compatible with 0-5 scale), and filtered by a low pass filter (to prevent aliasing and reducing noise).

Then the signal is processed digitally, with the aim is to find the dominant frequency of the spectrum. The most powerful way is to use Fourier Transform in the form of STFT. The maximum binsize of FFT in Arduino is 256, which will result in very low resolution over our 5 kHz band. To further enhance this resolution, a digital low pass filter was used so that same bins will be shared over 1.25 kHz, which means ARMUT can detect projectiles up to 17 m/s speed, with a velocity resolution of 0.14 . Since Arduino samples 9615 times per second and needs 1024 (256 * 4) to obtain an FFT and decide on action, our time resolution is 9 Hz (we look for incoming projectiles 9 times per second).

Currently, we suffer from some errorous FFT results at high frequency bins, possibly due to some computational glitch or spectral leakage of the default window type. These errorous bins and its values are generally constant, therefore it is possible to ignore them. If they cause more problems, there are always time domain frequency detection methods such as zero crossing detection or autocorrelation, that are better suited for microprocessor implementations but gives us less information.

2.3 Detection Subsystem

In the project we are designing an autonomous robot which interacts with another robot inside an arena. Therefore perceiving the environment is crucial in the design of our robot. There are two main parts of this perception, one is to detect the location of the robot inside the arena, the other is detecting the opponent robot. For the detection of the opponent robot we are going to use 3 ultrasonic sensors, for locating ourselves we decided to use 4 ultrasonic sensors and 4 contrast sensors.

2.3.1 Auto-navigation

During the duel, we should stay inside our 1m x 1m battle arena. For this purpose it is decided to use CNY70 contrast sensors. Our battle arena base colour and its borders will be in different colours such as black and white. Therefore 4 contrast sensors placed at the corners of our robot can easily detect the borders whenever we come next to one, especially to the centre line.

Second, we need to know our orientation and position in order to reload, to position ourselves ready for shooting and to run during our opponents turn. For this purpose we are planning to place 2 walls to the 2 neighbour sides of the arena and 4 ultrasonic sensors to the 2 neighbour sides of our robot, 2 in each side. With this configuration we can position ourselves by measuring the distance between us and the walls. Furthermore we can find our orientation angle by comparing the outputs from the sensors which are on the same side.

2.3.2 Opponent detection

Opponent detection is a must subsystem due to the aim of project. We are planning to use 3 ultrasonic sensors placed side by side for this purpose. There will be a platform where the coilgun and these sensors will be mounted. The platform will be rotated by a servo motor according to the algorithm and the received signals from the sensors. The system will work basically as follows, the servo motor will start to rotate the motor from one side to another and during this process we will look to the differences between the distance signals from the sensors. A significant amount of distance, such as 20cm, will mean there is an obstacle which is seen some sensors but not all of them. According to which sensor sees the obstacle the servo will rotate to that side in try to lock to the obstacle.

2.4 Shooting Subsystem

The shooting subsystem utilizes a coil-gun structure to accelerate the projectile in order to hit the opponent. The coil-gun accelerates ferromagnetic metals by applying strong magnetic field which can basically be obtained by providing high currents (several Amps) to an inductor for a short amount of time. The major problem with this structure is that providing high currents with low voltage being a near impossible task as each component has a small but non-zero resistance. In order to overcome this problem, the basic structure is modified such that voltage source is replaced by a initially charged capacitor. In order to charge the capacitor, a DC-DC boost converter circuitry is used. However, as charging a single capacitor to high voltages (200-300V) is a slow process, the design is modified further to use 3 capacitors which are charged separately to a lower voltage (70-80 V) and then are serially connected with the use of relays to provide the high voltage requirement. This is illustrated in figure 2.

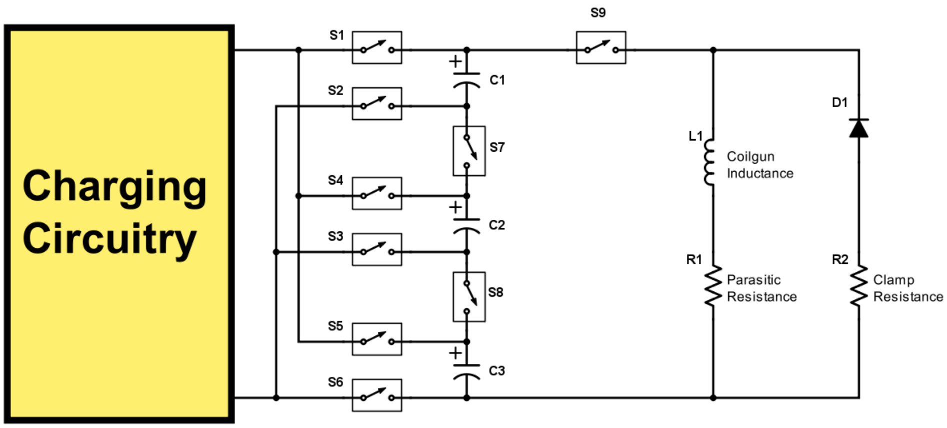

Figure 4: Schematic of the Capacitor Switching Circuit

In order to protect the circuitry from very high voltage spikes due to inductive behavior, the inductors are wrapped with reverse clamping diodes to provide a discharge path. The charging circuitry which is shown in figure XX2, requires a high inductance for fast charging. In order to provide the high current and high inductance requirements, a home-made 3 mH inductor is made from 300-turns 5cm long 3cm radius solenoid shaped 1mm diameter copper wire with iron core. The transistor used is a high power IGBT with 600 V, 50 A, 400 W ratings which are more than enough for the system requirements.

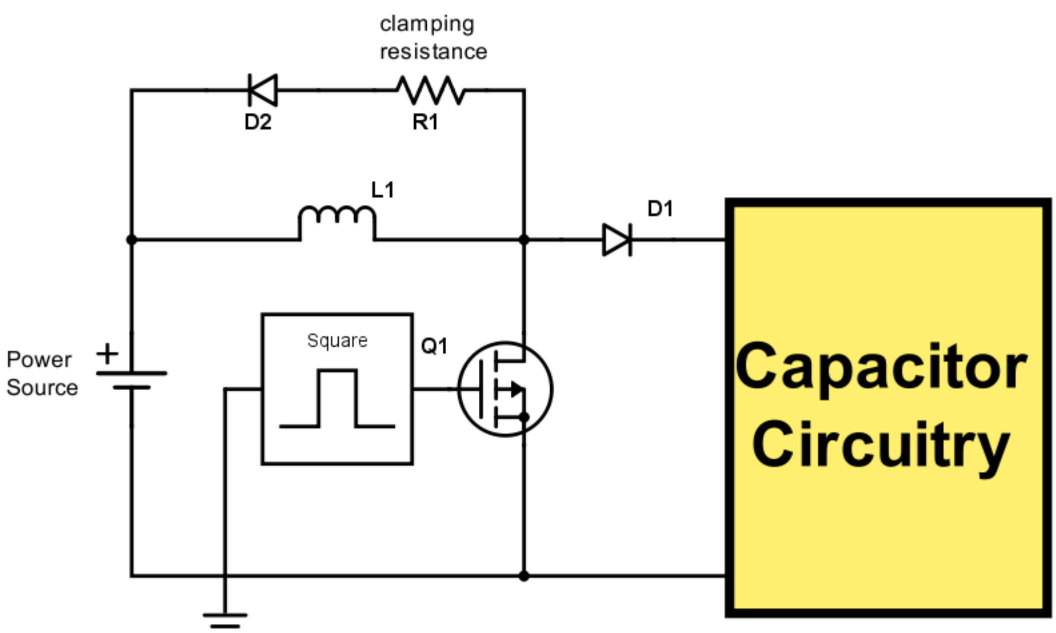

Figure 5: Schematic of the Charging Circuit

For reaching high magnetic force hence high projectile velocity, the radius of the solenoid which creates the magnetic field (evidently the projectile radius as well) should be as small as possible. For this reason, the projectile is designed in such a way that its perpendicular area to its moving direction is $1cm^2$ which is the minimum amount in accordance with the standards. The minimum volume regulation is hence fulfilled by making the remaining dimension of the projectile 5 cm long.

2.4.1 Reloading System

For this project, the robot will have internal magazine and a reloading. Our robot will carry 7 projectiles at the same time. It will reload the projectile from magazine when attack turn starts. If magazine is empty, it will reload from external reload system. There will be a magazine on the shooting module. Using a servo motor system, the robot will reload bullet from magazine. Also, there will be a magazine-pipe on the reload unit. The bullets will placed as horizontally in a vertical pipe. With gravity and a servo-reload design, the next projectile will flow into loading chamber. This chamber has 2 gates. One takes projectile from pipe and the other send the projectile to the shooting module. This mechanism will be placed outside of the game field.

3 Integration Analysis

All of ARMUT's subsystems are controlled by the decision subsystem, which is an Arduino Mega. Data from ultrasound and doppler sensors can be read respectively from digital and analog pins of the Arduino. Servo motor, high torque motors, and relays can be controlled via Arduino. This covers all major input and output parts of the subsystem, therefore there will not be any electronic inter-operability problems. Possible interoperability problems may be caused by mechanical implementations, mainly due to the high weight of the coil gun. This problem should be resolved by adding mechanical supports to the coil gun rotation mechanism.

4 Test Results

4.1 Detection

4.1.1 Opponent detection

Currently we implemented the servo motor with a platform carrying 3 sensors. However we have not finalized the system. Our system can realize obstacles in front of it but it is not able to lock to them yet. Nevertheless with further improvements to our algorithm we believe that such a configuration will be sufficient for detection.

4.1.2 Auto-navigation

Up to now we implemented the ultrasonic sensors to our robot . We successfully acquired the distance and orientation information. Furthermore our robot can track a flat wall while maintaining its orientation angle and the distance between itself and the wall. This is actually what we are planning to do while the turn is at the opponent robot.

4.2 Shooting

The following tests for the Shooting Subsystem were performed with

- 12 V voltage source
- 6800 uF capacitor x3
- 3 mH charging inductor

- 0.8 mH coil-gun inductor
- 20 ms response time high current mechanical relays.

4.2.1 Results for Charging

- For total 180 V (60 V each) $\longrightarrow$ 12 s (4 s each) is required
- For total 225 V (75 V each) $\longrightarrow$ 24 s (8 s each) is required
- For total 285 V (95 V each) $\longrightarrow$ 54 s (18 s each) is required

4.2.2 Results for Shooting

The projectile velocity is obtained by measuring the vertical slip due to gravity for a constant distance to a target with horizontal aiming.

- For total 180 V $\longrightarrow$ 25 A average inductor current for 10 ms, 5 m/s projectile velocity
- For total 225 V $\longrightarrow$ 35 A average inductor current for 10 ms, 8 m/s projectile velocity
- For total 285 V $\longrightarrow$ 45 A average inductor current for 10 ms, 13.5 m/s projectile velocity

4.3 Decision

The decision subsystem did not go under a testing period similar to the other modules as it is an Arduino microcontroller. We know the capabilities of this product and it was utilized during the testing periods of other modules which show that it can utilize the control and data signals for modules appropriately.

4.4 Evasion

Data is obtained from two ADC channels without any problem, with a sampling frequency of 9.6 kHz. Since it is very critical in our operations, we tested this even with a stopwatch.

FFT of current and previous data can be stored using 3 kB of RAM. Fortunately, we have chosen our Arduino board carefully as Arduino Mega which has 8 kB of RAM, so that these kind of operations can be done.

Speed of larger(hand sized) objects can be determined from the peaks at the FFT bins.

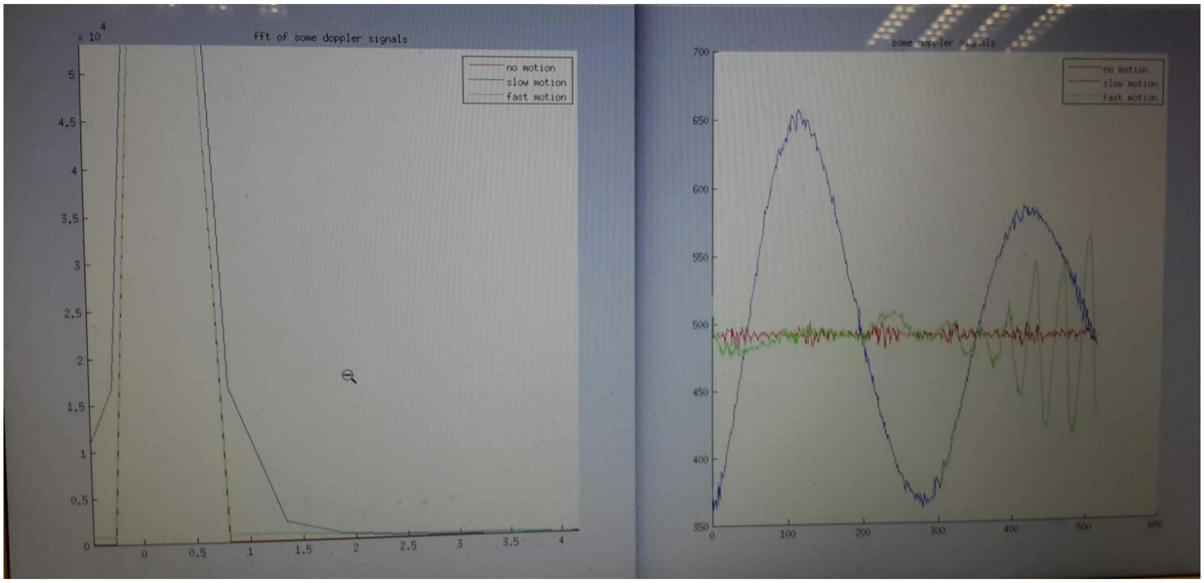

Figure 6: Detection of different objects with different speeds.

$$\Delta f = 2vf/c$$

Movement of smaller objects from half a meter can be detected, but we did not attempt to extract velocity data of these objects. Their movement can be found by subtracting current and previous FFT data.

5 Additions to the Conceptual Design

Shooting Subsystem: The weeks following the CDR, methods for fast high power switching instead of mechanical relays are analyzed and tested. Unfortunately, after thorough studies it turned out that there isn't any applicable fast switching mechanisms within the price range. Therefore, the plan for turning off the magnetic field when the projectile reached the center to achieve higher velocities is aborted. Instead the time, money and energy allocated for it are transferred to the other parts of the system.

Reloading Subsystem: On the previous design, there were not any internal magazine on the robot. It had only one bullet and it should reload for all shootings. Now, using a small magazine will decrease the power consumption and possible errors. In best case, the robot will not make any reload from external system.

Evasion Subsystem: There are no major changes in the working principle of the evasion subsystem. However, the method of frequency extraction from the data coming to Arduino is not yet determined. Our initital idea was to use FHT (basically gives same magnitute as FFT) library of Arduino, and therefore extracting all frequency data and consider the ones we are interested in.

6 Requirement Analysis

As previously mentioned in both our presentations and the conceptual design reports, we have set some requirements for our robot. Some of these requirements are due to the standards given by the standards committee, some are determined as minimum requirements by the project definition and rules. The others are determined by us to make our robot as effective as possible. These requirements can also be seen as project deliverables as they include the robots capabilities and limits.

6.1 Requirements due to Standards and Project Definition

Game Field awareness: Due to the Project definition, both sides have to share the game field. They both own 1 meter x 1 meter portion of the game field and crossing its boundary would result in disqualification. To satisfy this requirement, we fitted our robot with ultrasonic sensors, keeping track of the distance with the side and back walls. It can utilize this data to make sure it stays on its own side.

Projectile Dimensions: The standards committee ruled certain projectile specifications regarding dimensions and weight. The ferromagnetic projectiles we designated fit the required dimensions(maximum dimension = 1 cm, minimum dimension = 4 cm, minimum volume: 4 cm^3)

Projectile Safety: As this project is a shooting competition, shooting is bound to be an issue. Due to this we are taking some precautions such as covering our projectile with another material. Currently our projectile meets the safety standards. More information on this can be found at Safety and Error Analysis section.

Turn Passing: As mentioned in the conceptual design report, our robot will be able to pass turns with a simple bluetooth signal. This won't contain any control data.

Shooting Charge Time: Each turn has a 45 second limit. If a the robot who has the turn fails to shoot in this time, then the turn is passed to the opponent. To preserve our turn, we need to make sure our shooting subsystem is ready to shoot under 90 seconds regarding the defensive turn. The test results indicate that our capacitors can be charged to 225 V at 24 seconds, well under the limit. To charge them to 285 V takes 54 seconds, still under the limit.

6.2 Requirements for Effectiveness

Independence: As we mentioned in our conceptual design report, we want our robot to be independent. We don't want to use an external PC as assistance. This makes our robot more robust and reduces possible errors. Our tests show that our robot is capable of autonomous behaviour independent from a PC.

Projectile Speed: Due to our intuition and some observations, we want to be prepared to the possibility of the opposing robots being short. As our gun barrel does not move vertically, we can not adjust our shooting for opponent size. We don't want a curved path for our so we keep the barrel with a low angle to the ground. This requires a high projectile speed to reach the other side. Our tests show a 13.5 m/s for 285 V charge and 8 m/s for 225 V charge which we think

Robot Speed and Acceleration: To successfully evade our opponents shots, we need to be able to make sudden movements, as otherwise our robot will be too predictable. Our tests showed that our robot can speed up to 75 cm/s very quickly so this requirement is satisfied.

Opponent Detection Range: As we have a relatively large game field, our detection should be able to work for long ranges. Our sensors can acquire objects up to 2 meters which is a satisfactory distance. The range can be optimized adjusting the sensor array. Our robot satisfies this requirement too.

7 Safety and Error Analysis

Safety is a critical issue and it should be well-defined especially in a project involving shooting. We understand, its importance and we will arrange mechanical properties of the robot accordingly. All moving parts and electrical contacts (especially the ones carrying high voltage) will be sealed.

Our product will be completely safe for the user, as long as he/she operates the product within the limits and follows the instructions which will be specified in the user manual.

Possible safety issues and their respective solutions include:

Projectile shooting: User should initialize the robot according to the defined conditions in the user manual. Prior to the initialization, the robot should be on the test field and only moving object in front of it within a radius of 1.5 meter should be the target robot. If these conditions are satisfied the robot will never shoot to a human being. However, just in case our iron projectiles will be covered with cotton/styrofoam type of shell, and will be lighter than a table tennis ball. It is tested that, such a projectile will not cause any significant damage to the defined styrofoam by the standards committee. However, we cannot guarantee this safety if the user exceeds maximum voltages defined in the user manual.

High voltage: Our design depends on generating high voltages (up to 1 kV), and instantaneous high currents generated by these voltages. User access to these areas will be prevented, by sealing these high voltage areas with insulator materials.

Impact: According to our design there should not be any objects within its operation area of 1x1 m. If such objects are present, robot will ignore them and cause harm to these objects. The user should respect instructions in the field and prevent any such situation.

7.1 Mechanical Robustness

Until now the lower floor of our robot is completed, and the implementation can be safely called as robust since all sensors, microprocessor, motors, and battery are either screwed or clamped tightly. However, we need to be very carfeul with our final mechanical implementation since there will be moving parts and upper floors will be less stable in general.

7.2 Possible Shooting Subsystem Errors

A significant failure we might observe with the shooting system is caused by the projectile being in the wrong position. Although the centrifugal force of rotation of ARMUT should be enough to push the projectile to its desired place, in the case of error the force acting on our projectile while shooting will be greatly reduced. This will cause lower projectile speed.

7.3 Possible Evasion Subsystem Errors

Evasion subsystems basically look for fast objects incoming towards our robot, and determine which side of the robot it is directed to. Therefore, any extra object moving close to the expected opponent projectile will cause problems. However, these effects are completely random and taking an action according to them will be very similar to our original random evasion mechanism.

Another possible failure is being unable to detect the projectile, either due to frequency cut off we use or because it is out of our antenna span. I that case, evasion mechanism of ARMUT depends entirely on random movement.

7.4 Possible Reloading Subsystem Errors

The robot may not approach to reloading area properly. It causes reloading problems and the robot may not shoot anything as it is not loaded. Reloading system may also reload 2 bullets at the same time. It causes an error on shooting, either causing our weapon to jam, or 2 bullets being shot with low speed.

8 Environmental Impact Analysis

ARMUT only uses eletrical energy, stored in the form of chemical energy in our accumulator battery. It can be recharged easily by a simple adaptor connected to a regular AC plug. Since it is reusable, it will not cause any enviromental damage. However, when the accumulators safe operation time ends it should be replaced, and the accumulator should not be thrown away to a regular trash bin. In order to simply this process and prevent environmental harm our company will replace the accumulator after its life time, only with the expense of the accumulator.

ARMUT's bullets will be reusable, therefore if the user does not leave them on the ground they will not cause environmental damage.

9 Revised Timeline

Our Project is progressing smoothly and we expect it to meet the deadlines for the integration. Our updated timeline showing our future work can be seen below.

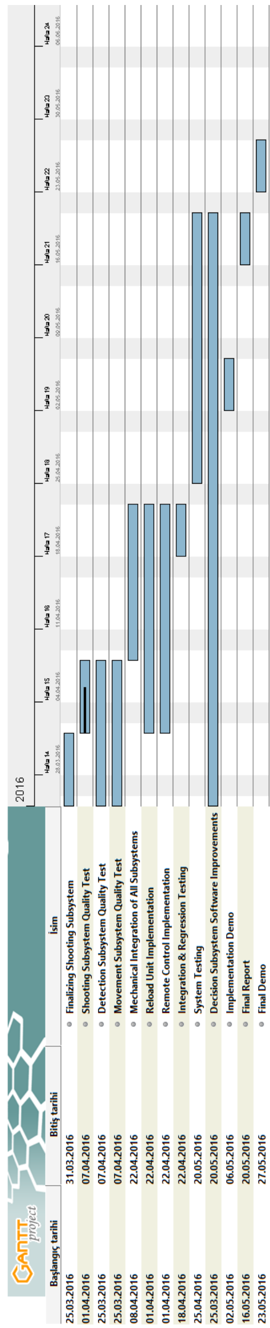

Figure 7: Our Revised Timeline.

10 Cost Budget

Our additions to the Conceptual Design did not change our budget much, the most significant addition was to the Detection System which resulted in us adding more ultrasonic sensors. The updated budget is as follows

- Arduino Mega Microcontroller Board : 7 $
- 1 kg Enamelled Copper Wire: 15 $
- High Voltage ($\approx$ 100V) Capacitors: 3x5 $
- Relays/Power Transistors: 5 $
- Power Supply: 10 $
- Optical Sensor: 2 $
- High Torque DC Motors: 2x10 $
- Motor Driver Circuitry: 5 $
- Wheels: 2x5 $
- Gun Barrel: 1 $
- Colour Sensors: 4x0.5 $
- Ultrasonic Sensors: 7x3 $
- Iron Powder: 2 $
- Servo Motors: 2 $
- Common Electronic Components: 15 $
- PCB Costs: 3 $
- Mechanical Parts: 15 $
- Grand Total: 150 $ $\pm$ 14

11 Power Budget

12 Possible Applications

As the nature of this project category is an aggressive one, this project seems a likely fit for military purposes. As this project touches a lot of unmanned warfare concepts, the entire system could be implemented as a soldier-robot to minimize casualties. The robots can be equipped for special operations or general usage. Even though the robot seems like a fit for military usage, it doesn't mean there are other uses for it. The points for military usage also apply for civil security, but the decision making is far more complicated as we want the AI to avoid aggression towards civilians.

Another field our robot can find its place is entertainment. Robo Olympics already has a solid audience. Also the average viewer enjoys watching destructive competitions so we think our robot will find a good niche to fit in. Our concern with this usage is that it might be a bad influence for younger viewers but we don't think it will be that effective.

If we consider the uses for separate subsystems we can find a wider variety of fields. Our shooting system, electromechanical systems, can be used in complete vacuum, as opposed to conventional firearms which require oxygen in the air. While using weapons in the outer space is in a very far future, it is something to consider.

Another subsystem that shows similar versatility is our evasion subsystem. The usage of Doppler sensors allows us to detect incoming debris and could be used by aircraft to detect and evade debris which can damage it severely. Outer space usage seems to be a common use with the shooting module as our evasion subsystem can also be used in spacecraft, making passage through asteroid belts or other zones with debris safer. As outer space expeditions become more and more common, this usage will also be more significant.

13 Conclusion

Seeing the results from our testing and integration period, our design is holding up. Testing shows promising results and we are confident in the ability of our individual modules. However the integration period is not finalized and unforeseen errors might come up. As future engineers, we are confident we will be able to deal with these problems when they show themselves. For now, we will continue testing and optimization for individual modules while also moving the integration process. In conclusion, we are confident in our design and our implementation.