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I, Adithya Kaushik, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

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Development of Cleaning Robot for Trench Drains

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Development of Cleaning Robot for Trench Drains

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by

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Abstract

The purpose of this thesis is to discuss the development of a novel method for the cleaning of trench drains. It deals with the design, conceptualization, analysis and testing of a device which fits into the drain and cleans it without needing to interfere with the surrounding traffic or the drain itself. The project was an effort to shift the cleaning process for the trench drains from manual to either semi-automated or automated methods. Due to the previous methods like manual cleaning and cleaning through water jets being slow and highly inefficient processes respectively, there was a need for an automated mechanism which was fast, reliable and did not waste resources. The transition was intended to ensure a safer process with lesser manpower required in addition to being easier to implement.

Over the course of developing this mechanism, two complete prototypes were designed and implemented in the drains. The performance of both the models has been discussed in detail.

The prototype developed has three main sections to implement these functionalities:

1. A drive system to make it move forwards and backwards in the drain. This system controls the overall feed of the robot and the suction hose inside the drain.

2. A suction hose with a hose attachment and a shovel. This is the main section involved with the cleaning inside the drain.
3. A cutting mechanism with rotating brushes due to which all the clogged and hardened dirt is loosened and falls to the drain bottom from where it can be sucked into the hose efficiently. This ensures easy removal of the dirt from the drain.

Overall, the various tests were conducted on the prototypes at different stages of their development which proved the working concept of the design and their functions. The new cleaning mechanism was found to work and operate smoothly for a little more than four total sections (14.2 ft) of the drain with it being entirely inside the drain throughout the operation time. Ideally, the second prototype was found to work most efficiently when the average depth of sedimentation inside the drain was 2.5 inches. Also, as observed from various tests, the robot works best with twin vacuum system with a total power of 3.2 HP.

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Table of Contents

Chapter 1 Introduction.....	1
1.1 Background.....	1
1.2 Review of Existing Methods.....	3
1.2.1 Current Cleaning Methods.....	4
1.2.2 Existing Cleaning Robots.....	6
1.2.2.1 Inspection Robots.....	7
1.2.2.2 Sewer Cleaning Robots.....	11
1.3 Need for A Novel Mechanism.....	18
Chapter 2 Robot Design and Analysis – Prototype 1.....	21
2.1 Design Concept.....	21
2.2 Robot Components.....	23
2.2.1 Drive System.....	23
2.2.2 Suction System.....	35
2.2.3 Cutting System.....	39
2.3 Component Stress Analysis.....	46
2.4 Proposed Assembly Sequence.....	50

Chapter 3 Robot Fabrication – Prototype 1.....	54
3.1 Drive System.....	54
3.2 Suction Hose.....	57
3.3 Cutting Assembly.....	58
3.3.1 Cutting Arms And Metal Brushes.....	61
Chapter 4 Robot Testing – Prototype 1.....	64
4.1 Setup.....	64
4.2 Observations.....	65
4.3 Test Summary.....	67
4.4 Modifications.....	67
Chapter 5 Robot Design- Prototype 2.....	69
5.1 Design Concept.....	69
5.1.1. Drive System.....	72
5.1.2 Suction System.....	75
5.1.3 Cutting System.....	79
5.2 Component Stress Analysis.....	82
5.3 Proposed Assembly Sequence.....	86

Chapter 6 Robot Fabrication – Prototype 2.....	88
6.1 Drive System.....	88
6.2 Suction System.....	91
6.3 Cutting System.....	94
Chapter 7 Robot Testing.....	98
7.1 Setup.....	98
7.2 Observations.....	98
7.3 Test Summary.....	99
Chapter 8 Refined Prototype 2.....	100
8.1 Modifications.....	101
8.2 Final Testing.....	102
8.3 Test Results.....	104
Chapter 9 Conclusions And Recommendations.....	114
9.1 Conclusions.....	114
9.2 Recommendations.....	116
Bibliography And References.....	124
Appendix.....	127

List Of Figures

Chapter 1

1.1 Trench Drains.....	2
1.2 Slotted Drains.....	2
1.3 Complete Manual Cleaning Procedure.....	5
1.4 Sewer Cleaning Process.....	6
1.5 GECKO Inspection Robot.....	8
1.6 STORMER S3000 Inspection Robot.....	9
1.7 STORMER S3000 Inspection Robot with mounted camera	10
1.8 IRIS Crawler Robot.....	11
1.9 LOMBRICO Robot Mini Excavator.....	12
1.10 LOMBRICO Robot Mini Excavator in action.....	13
1.11 LOMBRICO Robot Mini Excavator connected to sewer truck.....	14
1.12 Schwalm Talpa Robot System.....	15
1.13 Schwalm Talpa Robot System with wheel widening feature	15
1.14 Bandicoot Manhole Cleaner.....	16
1.15 Bandicoot Manhole Cleaner in action.....	17

Chapter 2

2.1 Complete Model of First Prototype with all components...	23
2.2 Drive System with pulleys.....	24
2.3 Drive System with all components.....	25
2.4 Remote Control for Drive System and Cutting System.....	34
2.5 Suction Hose (In Green) with cross section 1.5 inches x 1.5 inches.....	34
2.6 Cutting Assembly with electronics.....	40
2.7 Cutting Arms with 6-inch Metal Brushes.....	41
2.8 Stress Analysis on Drive Frame of Prototype 1.....	46
2.9 Displacement Analysis on Drive Frame of Prototype 1.....	47
2.10 Stress Analysis on Cutting Arms of Prototype 1.....	48
2.11 Displacement Analysis on Cutting Arms of Prototype 1...	49
2.12 Complete Model of first Prototype.....	51

Chapter 3

3.1 Drive System of Prototype 1.....	54
3.2 Suction Hose after Fabrication.....	57
3.3 Cutting Assembly after Fabrication.....	59
3.4 Cutting Arms with Metal Brushes after Fabrication.....	61
3.5 Complete Prototype Assembled.....	63

Chapter 4

4.1 Prototype 1 in operation in Cardboard Drain.....	64
4.2 Prototype 1 in operation in Concrete Drain.....	65

Chapter 5

5.1 Second Model complete assembly with 6-inch metal brushes	70
5.2 Drive System without wheels attached.....	72
5.3 Drive System with wheels attached.....	73
5.4 Suction Hose with Hose Connector and Shovel.....	77
5.5 Shovel Design	78
5.6 Connector Design.....	79
5.7 Metal Brushes with Cutting Arms attached to Cutting Assembly.....	80
5.8 Cutting Arms holding 8-inch metal brushes.....	81
5.9 Stress Analysis of Drive Frame for Prototype 2.....	82
5.10 Displacement Analysis of Drive Frame for Prototype 2...	83
5.11 Stress Analysis of Cutting Arms for Prototype 2.....	84
5.12 Displacement Analysis of Cutting Arms for Prototype 2....	85
5.13 Second Model complete assembly with 8inch metal brushes.....	87

Chapter 6

6.1 Complete drive frame assembly with all components.....	89
6.2 Fabricated Pieces for Shovel.....	91
6.3 Fabricated Suction Hose welded with Hose Inlet.....	92
6.4 Fabricated Suction hose welded with Connector.....	92
6.5 Connection between Robot and Circular Vacuum Hose.....	93
6.6 Fabricated Cutting Assembly with Cutting Arms and Brushes.....	94
6.7 Segmented View of Second Prototype after Fabrication.....	96
Chapter 8	
8.1 Complete Assembly of final model with Drive System, Hose, Cutting Assembly and 8-inch Arms.....	100
8.2 On Board Electronics for Cutting System for Second Prototype.....	102
Chapter 9	
9.1 Auger Flights found on “Israeli Mole Robot” which drives the robot forward.....	117
9.2 Ditch Witch FX30.....	119
9.3 Hurricane 300.....	120
9.4 Hurricane 500.....	120

9.5 Tenergy 7.2V Nimh Battery Pack.....	121
9.6 12V 5000mah Nimh Battery Pack.....	122

List of Tables

7.1	Observations with Dry and Wet Debris.....	98
8.1	First Robot Trial with 3.5 inches of Dirt.....	105
8.2	Second Robot Trial with 3.0 inches of Dirt.....	106
8.3	Third Robot Trial with 2.5 inches of Dirt.....	107

List of Plots

8.1	Plot Showing Robot Performance For 3.5 Inches Of Debris On Average	105
8.2	Plot Showing Robot Performance For 3.0 Inches Of Debris On Average	106
8.3	Plot Showing Robot Performance For 2.5 Inches Of Debris On Average	107
8.4	Plot Of Average Robot Speed Vs Debris Collected For 3.5 Inches Of Debris On Average	110
8.5	Plot Of Average Robot Speed Vs Debris Collected For 3.0 Inches Of Debris On Average	111
8.6	Plot Of Average Robot Speed Vs Debris Collected For 2.5 Inches Of Debris On Average	112

Chapter 1

Introduction

1.1 Background

Throughout the state of Ohio, there are several drain systems to direct the flow of rainwater and other wastes outside the major cities. These drain systems run through various terrains and environments including running near large roadways and freeways. There are two major drain systems running through most of Ohio currently, namely the Trench Drains and the Slotted Drains.

The Trench Drains consists of successive drain sections, each of length 1 meter, which run in roadway depressions along the shoulder to remove storm water from the roadways. They are 4 inches in width, 10 inches deep, with the bottom of the drain curved with a radius of 2 inches.

The slotted drains are circular drains with a diameter of 12 inches. These drains run slightly below the surface with narrows slits providing the entry of storm water coming from the roads.

Both the drains are quite efficient in carrying out sewage and water out of the roadway depressions. They are found to take very large amounts of water at a very rapid rate, which ensures faster removal of water and wastes products. This,

however, means that due to the large amounts of substance being carried regularly, the drains become clogged more often. If the clogging and dirt accumulation can last over a period, the resulting blockage needs to be cleaned with more expensive methods. Sometimes, the drain sections must be replaced entirely, which can lead to significant cost for ODOT.

Due to this, the drains must be thoroughly and regularly cleaned to ensure smooth operation throughout the year. This project discusses the entire cleaning process along with all the mechanisms involved for only the trench drains.

Fig 1.1. Trench Drains

Fig 1.2. Slotted Drains

1.2 Review of Existing Methods

As already mentioned, there is an urgent need for a thorough process to clean trench and slotted drains. Currently, with the ever-increasing use of these drains along highway depressions due to their efficiency and the reduction of availability man hours for maintenance, the drains are greatly left unchecked. Due to this, the blocked drain sections can obstruct the flow of water away from the roadways, causing a concern of water and ice on highways, thereby leading to a greater risk of accidents.

It has also been found that the cleaning of these drains become more difficult over time. If left unchecked for a long period of time, the dirt and debris accumulated in the bottom of the drain sections quickly get bound by weeds and other vegetation flowing in along with the storm water. Once this happens, it becomes extremely difficult to clean the drains, with many sections having to be replaced to resume the desired water flow.

Hence, due to these reasons there is an ever-growing need for newer and more innovative cleaning methods that are efficient enough to help keep the water flow in the drains checked.

For this purpose, there are a couple of methods already in place. These methods include manual cleaning and cleaning using a sewer jet. Manual cleaning for the trench drain involves unscrewing the grates, removing the debris and loading it in

buckets, cleaning around the drain with a blower and re-installing the grates. The process needed 3 man-hours to clean 30 ft of debris inside the drain, resulting in a production rate of 10ft per man-hour. This made the method slow and labor intensive. The sewer jet method, although faster, also ends up using a lot of water which leads to wastage of the resource. This prohibits waterjet cleaning for longer distances in the drain due to environmental hazards. Hence, both these methods are quite slow and often impractical for a sustained cleaning process inside the drain.

To overcome this, various ways have been proposed which are more efficient than the current methods and conserve resources while cleaning. Some of these methods are given below:

1. Horizontal Directional Drilling
2. Horizontal Auger Boring
3. Cleaning Robots
4. Innovative Hydro Jetting Nozzles

1.2.1 Current Cleaning Methods

There were two main methods which were observed during repeated site visits.

These are listed in detail below.

1. Manual Cleaning

As shown in Fig 1.3, a total of three crew members were required for this process. The process consisted of unscrewing the grates, removing the debris and loading it in buckets, cleaning around the drain with a blower and re-installing the grates. The crew was able to clean 30 linear feet of drain in 1 hour, resulting in a cleaning speed of 10 lf/man-hour.

Fig 1.3. Complete Manual Cleaning Procedure

2. Sewer Cleaners

In this process, a water jet nozzle was placed in the drain along with a suction tube placed behind it, also in the drain. The main cleaning is done by propelling the nozzle inside the drain using pressurized water jets as shown in Fig 1.4. The suction tube behind the nozzle sucks out the loosened debris and transports it to another location away from the drains.

Fig 1.4. Sewer Cleaning Process

Apart from these methods, two other methods were tried out, namely compressed air and the use of a drain snake. These involved compressed air to blow the debris out of the drain and using a cable to clear up clogging of dirt inside the drain respectively. However, both these methods were found to work only for short distance and failed for longer drain distances.

1.2.2 Existing Cleaning Robots

Out of the proposed methods, the use of cleaning robots had a few advantages.

1. These did not need to use water in the cleaning process, which led to conservation of the resource.
2. Being largely automated, the robots did not tire over the course of cleaning and could be used as per convenience for however long the cleaning was to be done.

1.2.2.1 Inspection Robots

These robots are typically only used for pipe and drain inspections. Hence, they are designed to operate entirely within the drains.

1. Steerable Pipe Inspection Robot GECKO 9060

The Gecko 9060 steerable pipe inspection robot is a sturdy compact device designed and manufactured in Germany to be versatile and productive. It can be used to inspect a wide range of pipes, duct work, and industrial sites. These units are mainly used for inspecting shorter length pipes from 4 – 12 inches.

This robot has a specially designed 6 wheels drive system that can be driven out to a maximum length of 250 meters (820 ft.) with an optional length cable along with variable speed settings up to 33 meters/minute. With a weight of 9.5 pounds, it is designed to run in 4” or larger pipes and can navigate 45-degree arcs in an 8” pipe.

The live image from the mounted camera is displayed on an 8.4” color LCD monitor, which is protected by a metal case with a sun shield for daytime viewing. The camera head is composed of high-grade aluminum stainless steel which is very durable. An optional Sonde can be added to this set to locate the camera head behind walls or underground.

Fig 1.5. GECKO Inspection Robot

2. Pipe Crawler STORMER S3000

The STORMER S3000 Pipe Crawler is a portable all-in-one device for inspecting pipelines with diameters from 150 to 1000 mm (5.9"-40"). It is manufactured in England and features a dependable, sturdy and highly adjustable design. The pipe

inspection robot includes several modules that are easy to transport and assemble: pan-and-tilt camera, insertion cable, CCU, cable reel and crawler.

The tear and wear-resistant, multi-core, Kevlar braided insertion probe is designed to undergo multiple inspections in abrasive environments. The crawler features an extremely adjustable design that can be modified within seconds depending on the pipeline diameter or other inspection requirements.

It has a front camera mount for inspecting pipes of narrow diameter, and a top camera mount for pipes of bigger diameters. It is a powerful 5 speed 15 Nm 4-wheel drive with chain transmission running on 48 V DC motor. The live feed from the camera is connected to an LCD monitor for viewing.

Fig 1.6. STORMER S3000 Inspection Robot

Fig 1.7. STORMER S3000 Inspection Robot with mounted camera

3. IRIS Crawler Package A

This robot is an inspection robot for use in drains having a diameter between 6” and 12”. It is an all in one pan-tilt crawler along with being light weight and portable. This makes it convenient for use in a variety of drain environments. It consists of 600’ of premium Kevlar mini-coax cable with forward and rewind cable assist to facilitate both forward and reverse direction of the robot when it is in operation inside the drain.

Fig 1.8. IRIS Crawler Robot

1.2.2.2 Sewer Cleaning Robots

All the above-mentioned robots, though small enough to enter the drains being dealt with here, they are only used for inspection and perception purposes. Since they do not possess enough power and torque for manipulating heavy debris inside the drains, such robot can rarely be transformed into cleaning robots.

After researching for existing robot solely used for the purpose of drain and pipe cleaning, the following were found to be the most robust mechanisms.

1. LOMBRICO OF VENICE from Gerotto.it

This robot is a Tracked Mini Robot Excavator activated by an external hydraulic system and controlled with a manual manifold. It is a remote controlled ROV equipped with a suction hose that is connected to the suction unit. It is composed of:

- complete stainless-steel structure;
- two hydraulic driven rubber tracks;
- hydraulic manual manifold to control the movements of the robot;
- quick connection system to the external hydraulic source;
- video inspection system (optional).

The Lombrico was designed and created to aspirate every type of material obstructing sewer pipes, tunnels, tanks of different dimensions, mines and spaces under conveyor belts, together with Suction Excavators, Vacuum Trucks and Industrial Aspirators, with a suction diameter from 80 mm [3"] to 250 mm [10"].

Fig 1.9. LOMBRICO Robot Mini Excavator

Some of the advantages of this robot over the current methods are given below:

- safe position of the operators, thanks to remote control;
- reduction of manual labor, resulting in a limitation of possible human mistakes;
- perfect maneuverability of the robot, to reach even the most inaccessible places;
- reduction of the time of aspiration and of the costs, because shutdown of the plants is no longer necessary.

Due to these aspects of functionality, this robot was one of the main starting points for the creation of the final prototype.

Fig 1.10. LOMBRICO Robot Mini Excavator in action

Fig 1.11. LOMBRICO Robot Mini Excavator connected to sewer truck

2. Schwalm Talpa Robot systems

These robots are specially designed for heavy duty sewer main and lateral repairs. They are designed to be customizable according to customer needs by having a host of attachments ranging from inspection cameras to robotic cutters. They can perform a wide range of functions which include Sewer rehabilitation, Pipe and asset inspection and Pipe cleaning.

Fig 1.12. Schwalm Talpa Robot System

Due to their versatility and small size, they are ideal for use in pipes with diameters ranging from 5.5” to 12”. These robots can be further modified with various wheel widening attachments to fit precisely in the concerned pipe and operate with more stability.

Fig 1.13. Schwalm Talpa Robot System with wheel widening feature

3. Bandicoot Robot

This robot is designed for cleaning sewer lines and manhole networks. The robot has four limbs and a bucket system attached to a spider web looking extension, which can go inside the manhole. After shoveling the heap of garbage at the bottom of the manhole, it will be collected by using the bucket system before lifting it upward. It also has Wi-Fi and Bluetooth modules for controlling the robot remotely.

Fig 1.14. Bandicoot Manhole Cleaner

Fig 1.15. Bandicoot Manhole Cleaner in action

All these methods, though used for cleaning purposes for different types of drains, are of little use when it comes to cleaning trench drains. This is because the necessary conditions for cleaning, the size limitations and the nature of the dirt present in these drains are different than any of the situations previously seen. For instance, the Lombrico, though using suction to collect debris, is still quite large and requires a longer time to connect to a sewer truck. This involves the use of more manpower, which eventually decreases efficiency. The Schwalm Talpa robots, though having a wide variety of attachments, are currently used for minor cleaning and sewer repairs and thus are not robust enough to continuously handle the trench drains for a long period of time.

The trench drains are mostly near roadway depressions and thus, any cleaning that is to be done also has to involve the transportation of the dirt away from the roadway in an efficient manner. Also, the entire operation of cleaning the dirt as well as

transporting it should be accomplished entirely within the drain in order to ensure maximum safety to all personnel from the oncoming traffic. Moreover, the resulting mechanism should also be designed for heavy duty usage as the debris and vegetation are quite hard to remove using modifications of the robots existing in the market currently.

Therefore, there needed to exist a robotic mechanism which moved inside the drain freely, breaking the dirt down and transporting it to a collection unit simultaneously. Furthermore, all these functionalities had to be accomplished at a rate faster than the existing cleaning methods for trench drains.

Since no mechanism was found to satisfy these requirements, it was decided that a novel mechanism was to be designed and fabricated drawing inspiration from the current robots in the market.

1.3 Need for A Novel Mechanism

Due to the limitations of the methods and robots already in use, there is a need for the development of a mechanism with an entirely new concept in order to achieve the required task. This section discusses the requirements that need to be met by the robot in order to achieve satisfactory performance.

1. The robot needs to clean the drains by operating entirely inside them. This is necessary as this is one of the few ways to ensure minimum hindrance to traffic. Moreover, since the drains are cleaned from the inside, the resulting cleaning process is not messy and reduced time that would otherwise be taken to clean the surface around the drains.
2. The robot needs to be remotely controlled and operated. This is necessary in order to ensure minimum manpower, thereby, ensuring safety to all personnel involved. Another worker could be involved in supervising the robot and instructing the remote operator according to the robot operation.
3. The robot needs to be heavy duty for long term use. This means that the robot requires mechanisms powerful enough to deal with hardened debris and even vegetation. This is accomplished by combining a cutting mechanism to break down the dirt as well as a suction mechanism to transport the debris to a collection unit nearby.
4. The robot needs to be faster and more efficient than the existing methods used by ODOT for drain cleaning. The speed at which manual cleaning is done is at a rate of 10 feet per hour. The sewer cleaner, although 6 times faster than manual cleaning, leads to wastage of water, which eventually flows into the same drain with storm water. The resulting robot needs to accomplish decent cleaning at a

faster rate than both these methods in addition to not using water or other resources during the cleaning process.

5. As the robot would need a complete drive system for driving it inside the drains along with the suction and the cutting mechanisms, the entire robot was decided to be made modular in design. Essentially each of these subsystems will be designed and fabricated separately so that each system can be replaced with a different one without losing any of the robot functionalities. This ensures that the design is highly customizable and can be used for trench drains of different widths and curvatures.

Chapter 2

Robot Design and Analysis – Prototype 1

2.1 Design Concept

After the conceptualization stage, the first model for the device was ready to be designed. For this, all dimensions of the model were verified, and adequate tolerances were given to prevent the robot from touching any of the drain surfaces. To accommodate all the functionalities of the robot within this highly confined space, it was decided that no screws or nuts would be used and the construction for all the frames would be done solely through welding.

For this purpose, a combination of software like SOLIDWORKS, AutoCAD Mechanical and Google SketchUp were used for the complete 3D modelling of all the robot components and the overall assembly.

Keeping the trench drain dimensions in mind, the entire model was constructed giving adequate tolerances for each surface to prevent the robot from getting stuck inside the drain at any point.

For the initial designing, all the systems needed for achieving the functions discussed in the conceptualization stage were listed. These are again mentioned below:

1. Drive System – To Drive the robot forward and backward in the drain. This system was to be remotely operated.
2. Suction System – To suck, collect and transport all the debris from the drain out and away from the roadway to a collection unit.
3. Cutting Assembly – To break down hard debris and vegetation to be suctioned out with ease.

Moreover, as the entire robot was to be constructed with a modular framework, each of these systems were to be independently functioning to remove and replace them according to constraints for different drains and dirt types. For instance, a larger drain would require a wider cutting mechanism to efficiently break down debris. Similarly, a drain with different dirt type may affect the suction system. For example, wet sand or clay would require a larger suction area to avoid the suction hose inlet from clogging.

Keeping all these factors in mind, the components for each subsystem were then identified and selected based on mainly their size to power ratio. This was done as the robot needed to be heavy duty despite its small size and hence needed components capable of transmitting higher power and torques in a constrained space.

Fig 2.1. Complete Model of First Prototype with all components

2.2 Robot Components

2.2.1 Drive System

Keeping in mind all the components selected for the drive system, the initial frame for the drive system was designed. This design involved constructing the frame in such a way that all the electronic components were housed inside it while the pulley were attached on the outside with the rubber belts riding over them. Also, the height of the walls of the frame were kept shorter than the diameter of the pulleys so that the frame itself would not interfere with the motion of the belts riding over the pulleys.

Fig 2.2. Drive System with pulleys. Drive Frame (In Grey) and Robot Wheels (In Black)

Figure 2.2 shows the Drive Frame for housing drive components with wheels. The drive system with all the electronic components and the pulleys is shown in the Fig 2.3 below. All the components are modelled to scale with respect to the drive frame. A cover plate comes on top of the drive system which completes the housing and makes the entire system compact. Since the components are housed inside, there is very little chance of the debris in the drain interfering with the electronics on board.

Fig 2.3. Drive System with all components. 12V Batteries (In red), DC 12V Motor (In Green), Shaft Coupler (In White), Bevel Gears (In Dark Red), Shafts (In Grey) and Wheels (In Black)

Figure 2.3 depicts the Drive System top view showing all the components. To make each component stable, bearings have been added in each side of the frame through which the driver and driven shafts protrude. Bearing caps have also been added on the outside of the frames over these bearings to keep them in place. Shaft spacers

have been inserted to keep the lateral movement of the shaft in check. The pulleys are installed after the bearings and spacers.

The system is constructed in such a way that the bearings, caps, pulleys and spacers must be installed only once. Once these are installed, the drive cover plate is screwed on top of the drive frame for a compact system. The belts are then installed over the pulleys to complete the driving system subassembly.

The first subsystem was mainly responsible for driving the robot inside the drain. The driving was to be multidirectional and needed to be controlled remotely. Also, the frame for this system was to be strong and stable enough to house the other two subsystems on it.

The components needed to accomplish this were then listed. They are as follows:

1. Drive Frame

For the drive frame, there was a need of a material strong enough to withstand the weight of the suction and cutting mechanisms while at the same time being light enough to facilitate smooth robot movement inside the drain.

Aluminum sheet metal was chosen for this purpose due to the following reasons:

- A known lightweight metal, it has a specific weight of approximately 2.71 g/cm³ and is about a third of the weight of steel.

- It is a corrosion resistant metal that naturally generates a protective coating. The coating formed is extremely thin and is generated when aluminum encounters an oxidizing environment. This makes it perfect for any device constructed for long term use in trench drains.
- Aluminum is impermeable even at very low thicknesses and is also 100% recyclable which further make it more environment friendly than other metals.

2. Drive Belts and Pulleys

For efficient performance of the suction and cutting subsystems inside the drain, the robot needed to be very stable and smooth while in operation. This is very difficult as once the robot is inside the drain; it essentially rides on unknown and rough terrain. The best chance for stability in such environments is through using robotic tank treads for mobility. These treads provide enough friction to push the robot forward with a high torque and are also continuous, thereby ensuring greater stability of the overall mechanism.

However, there were not many robotic tank treads available in the market which met both the size and the stability requirements. They were also not designed to be heavy duty enough to sustain the mechanism.

Thus, it was proposed that a pulley and belt mechanism be used instead with the pulleys acting as the axles and the belts acting as the treads. This essentially served as an alternative to the tank tread problem and provided similar drive transmission.

A set of cast iron pulleys and rubber belts were chosen as these pulleys were readily available in the required sizes and were also strong enough to withstand the robot weight.

3. DC Motor

To provide the driving force to the drive system, a DC motor had to be selected which was small enough to fit inside the drive frame mount and transmitted enough torque to move the robot in either direction with ease. In order to fit such a powerful motor inside the limited space, it was essential to have a motor gearbox with an adequate torque-speed ratio. Since the torque required was high, the speed would automatically be low.

To choose the motor having the optimal values of torque and speed, calculations are first done to estimate the power needed for the whole mechanism. Hence, torque is calculated for the robot to move forward with 4-inch diameter wheels.

Total torque required = torque to overcome friction + torque to accelerate forward

As it is desired for the robot to move with a constant velocity, it is assumed that torque to accelerate forward = 0

The friction force is calculated as a product of Coefficient of Friction and the Normal Reaction on the mechanism. The coefficient of Friction depends on the two surfaces in contact. Here, the two surfaces are rubber and dry concrete. For this, the value is assumed to be 0.6. The normal reaction is the weight of the robot, which was measured to be 40lbs. Calculating the frictional force for a horizontal plane:

$$F_f = \text{coefficient of friction}(\mu) \times \text{Normal Reaction} (= \text{mass} \times g) = 0.6 \times 40\text{lbs} = 24\text{lbs}$$

This is the frictional force acting on the robot. To make the robot move, a force greater than this will have to be applied in the opposite direction. Therefore, calculating the minimum torque required to overcome frictional force,

$$\text{Torque}(\tau) = \text{Force} \times \text{Wheel radius} = 24\text{lbs} \times 2 \text{ inches} = 48 \text{ in.lbs} = 5.423 \text{ Nm}$$

However, most motors do not function at 100% due to power losses and losses from heat, etc. This needs to be accounted for in the calculations. For a motor efficiency of 65%, torque required = $5.423 / 0.65 = 8.343 \text{ Nm}$

Now, calculating the power required:

$$\text{Power} = \text{Torque} \times \text{Angular Speed} = (\text{Torque} \times 2\pi \times \text{Motor rpm}) / 60 = 8.343 \times 6.28 \times 37 / 60 = 32.31 \text{ W}$$

The DC motor selected was a 12V motor capable of transmitting 98 kg.cm of torque with a speed of 37 RPM. Moreover, it had a single shaft of diameter 60mm which was to be connected to the drive pulleys for the transmission to work.

4. Bevel Gear

To achieve the connection between the motor and the pulleys, an arrangement with bevel gears was decided upon. Bevel gears are gears where the axes of the two shafts intersect and the tooth-bearing faces of the gears themselves are conically shaped. Bevel gears are most often mounted on shafts that are 90 degrees apart but can be designed to work at other angles as well.

A set of bevel gears with a shaft hole of 8mm were chosen along with an 8mm-12mm coupler to exactly fit the motor shaft. The second gear was then paired with an 8 mm shaft which was connected to the two pulleys at the front end of the robot. The assembly was further bolstered with shaft spacers, bearings and shaft tighteners to secure the bevel gears, pulleys and the motor in place.

In this way, connection was established between the DC motor and the set of pulleys at the front end of the robot, which made the robot front wheel drive.

5. Coupler

The motor shaft of the drive motor selected was 12mm in diameter while the bevel gears had space for fitting a shaft only 8mm in diameter. Due to this dissimilarity, there was a need for an additional mechanism to establish the connection between the drive motor and the bevel gears. This led to the fabrication of a coupler mechanism which had an opening on either side, one for 8mm shaft and the other for the 12mm shaft. This mechanism, even though establishing connection, faced a problem in transmission of power to the wheels due to rotation of the drive motor. Due to the component being freely rotating, there was instability in its rotation which led to a wobbling effect. This effect caused periodic disengagement between the bevel gears, which led to vibrations in the drive system and caused damaged to the bevel gears and the shafts. To overcome this, a bearing and a bushing assembly was constructed wherein the coupler was inserted through the bearing, which was clamped to the drive frame. This kept the coupler firmly in place when the robot was in operation.

6. Batteries

12V NiMH batteries were used to drive the DC motor for driving the drive system. NiMH batteries were chosen because of their high energy density, which is about

50% better than NiCd batteries and 60% better than Li ion batteries. They are also Robust and can tolerate over charge and over discharge conditions which simplifies the battery management requirements. They can also charge very quickly when compared to other batteries and are environment friendly and much safer than Lithium based batteries.

To calculate battery power, the power required to run the motor needs to be computed.

Motor power = torque x angular speed = voltage x current

$$\text{Power} = 8.343 \times 3.872 = 12 \times I$$

$$\text{Thus, } I = 2.854 \text{ A}$$

This will be the current draw for the DC motor. For a 12V DC motor requiring 8.343 Nm of Torque, a current of 2.854 A needs to be supplied constantly.

Another important metric is the duration of time that the batteries are intended to run between successive charges. Therefore, to estimate the runtime of the batteries, the batteries are rated at 3000mAh which means that the batteries will discharge completely if a 3000mA current is drawn for 1 hour. Therefore, for a draw of 2.854A or 2854mA

Runtime of the batteries = Discharge rating/ (motor current draw/60) = 3000/
(2854/60) = 63.078 minutes

The batteries would run for an average of 63.078 minutes before discharging once completely.

7. Microcontroller

There is need for a basic control system for the drive system which decides the amount of current being delivered, the amount of battery discharge for the operation and the reversal of shaft rotation which enables a multidirectional drive in the robot.

A Sabertooth 2x12V microcontroller is used for this purpose. This device works well with 12V batteries and motor on board and has RC capabilities. This feature allows the drive to be controlled remotely.

8. RC Receiver and Transmitter

The receiver component is connected to the microcontroller to enable the RC capabilities for the Drive system. An operator instructs the drive system through a Transmitter. This transmitter sends a command signal to the receiver which in turn controls the microcontroller and subsequently the motors and pulleys. For this

purpose, the remote transmitter and controller used here is the SPEKTRUM DX6e Drone controller, which is shown in Fig 2.4.

The RC transmitter is connected and paired with both the receivers in the drive and the cutting system. The Remote Controller controls the whole robot motion through the help of these receivers. The transmitter is shown in the image attached.

The components of the transmitter are listed below:

1. Lever to control cutting speed
2. Display Screen
3. ON/OFF switch
4. Lever to control motion of robot (Forward and Backward)

Fig 2.4. Remote Control for Drive System and Cutting System

2.2.2 Suction System

The suction system is designed keeping in mind the debris type and nature. The space constraint prohibits the use of hoses with larger diameters which are ideally the most suitable for sucking up greater volumes of debris. Also, the smaller hose sizes limit the suction power of the vacuum system to be used as a higher rated system can make the hose collapse on itself. Based on the sizing requirements, the suction hose chosen was of a diameter of 3 inches externally which gave a reasonable suction area while not sacrificing too much of the suction power.

After deciding on the circular hose of diameter 3 inches, the section to be attached to the prototype was designed to be of square cross section with a side of 1.5 inches. This side length was chosen based on the assembly constraints of the model which have been discussed later in this section. Fig 2.5 below shows the scaled model of the hose section attached onto the prototype.

Fig 2.5. Suction Hose (In Green) with cross section 1.5 inches x 1.5 inches.

The hose is attached to the cover of the drive system (In Grey) as shown.

As this system essentially consists of a single square section which transports dirt from the drain to a circular hose, there needed to be attachments in the front and rear ends of the section to facilitate a smooth movement of debris.

Temporarily, a bent cylindrical cardboard section is used at the front to efficiently suck the dirt from the drain bottom while duct tape is used to attach the circular hose from the vacuum system to the square section of the robot.

Holes are drilled on top of the suction tube to enable attachment to the cutting system. Holes are also drilled onto the sides towards the bottom on either side enabling connection to the cover plate.

The suction system was decided to be the second subsystem in the prototype design. This system was responsible for sucking in the dirt and debris through the hose inlet and transporting it from the drain to a nearby collection unit. For this purpose, the following components were selected in the design of the suction system.

1. Suction Hose Inlet and Rectangular hose section

Aluminum sheet metal was selected as the material for machining both the suction hose inlet and the rectangular hose section. This was decided based on the material for the drive frame and in order to make the whole prototype frame consistent. The advantages of aluminum sheet metal in machining the suction hose section was the same as those for the drive system.

2. Circular Suction Hose section

As most collection units have a circular cross-sectional hole to fit the vacuum hose, there was a need for a circular hose section which gradually transformed the cross-sectional area through which dirt was being sucked from a rectangular shape to a circular shape. Many materials were considered including rubber and certain types of plastic. However, the material that was selected was a tube made of a resin-based polymer composite. This was done keeping in mind the abrasive nature of the dirt

being sucked while also maintaining a light-weight material which could be dragged inside the drain easily.

For the suction hose, it was decided that rectangular hose be selected for installing on the prototype which would transition to a circular cross section to be connected to the hose from the vacuum system. This was done to ensure that the cutting system sits perfectly on top of the suction system and the whole robot is stable in operation. Also, based on the design, the connections on the prototype with a square suction hose were more rigid. Moreover, since the connector was welded to the suction hose, it avoided any leakage happening due to the transition from the circular to the square hose.

3. Vacuum Unit

The vacuum collection unit was to be decided later according to the initial results obtained from the trial run of the prototype inside the drain.

2.2.3 Cutting System

This subsystem was solely responsible for breaking the dirt down and decomposing hard debris into smaller coarser particles which could be suctioned away with ease. The added advantage of this subsystem was that when working efficiently, most of the dirt entering the suction hose would be soft and coarse which would mean that lesser power would be required for the suction mechanism. Thus, the lesser power required would compensate for the small diameter hose being used for the prototype.

The entire cutting system has been modeled in two parts, namely the cutting assembly housing the drive motor and batteries and the cutting arms housing the metal brushes. The idea is that the cutting arms be hooked on to the cutting assembly to form a single compact system.

The cutting system section consists of the electronic components required for the cutting system along with their mounts. However, this assembly sits at the top of the prototype and needs to transmit power to the metal brushes. This is problematic as the metal brushes need to be centered height wise inside the drain to ensure optimal cleaning, which leads to the cutting assembly being at a higher level than the metal brushes.

To counter this, the arms have been designed with a welded cover and holes for the shaft. They also have a notch which enables them to be hooked on to the cutting

assembly for operation. Fig 2.6 below shows both the cutting assembly separately along with the assembled cutting system.

Fig 2.6. Cutting Assembly with electronics. Shafts (In White), Bevel Gears (In Dark Red), Bearings (In White), DC Motor (In Green) and Battery (In Brown)

Figure 2.6 shows the Cutting Assembly containing all the components which are listed below:

Fig 2.7. Cutting Arms with 6 inch Metal Brushes. Cutting Frame (In Grey), Cutting Arms (In Grey next to brushes) and Six Inch Metal Brushes (In Pink)

Cutting System with 6-inch metal brushes. The arms are hooked onto the cutting assembly using two screws.

Moreover, the arms were constructed by using sheet metal welded together. This was done because Aluminum is a very light metal, with a high strength to weight ratio, which can be used to support heavier components while keeping the entire weight of the prototype low. It also has high corrosion resistance, which is useful while the robot is in operation inside different drains with different debris types and amounts.

In the cutting assembly, the shaft containing the driver sprocket is secured on to the frame through the means of bearings and spacers the same way as used in the drive system. However, as there was no space to fit bearing caps to keep the bearings and shafts in place, shaft collars have been inserted to tighten the shaft and all the parts from the inside which prevents it from moving laterally. A shaft coupler is used to establish connection between the cutting motor and the bevel gears, similar in functionality to that installed in the drive system.

Once the driver transmission components are secured, the motor is then fitted at a measured distance so that it can adequately transmit power to the shaft. The motor is then attached to battery, microcontroller and other electronics which are housed towards the rear end of the cutting assembly.

The arm assembly is fitted with the shaft bearings and spacers too. Additionally, the arms are also joined at the top through a cover plate. This plate also acts as the cover plate for the cutting system so that the debris does not interfere with the on-board electronics.

Holes are drilled through the bottom of the frame for the cutting assembly for attachment to the suction tube.

1. Cutting Systems Frame and Cutting Arms

Once again, aluminum sheet metal was used to machine the frames and the arms due to the afore mentioned advantages.

2. NiMH Batteries

The batteries used here were NiMH due to the same reasons as those mentioned for the drive system. The only difference is that due to the cutting mechanism requiring more power to break down the debris, a 24V 5Ah (20xC, 120Wh) NiMH adaptive battery pack is used.

3. DC Motor

A 24V DC motor is used which has a maximum speed of 285RPM and a torque of 39 kg.cm. This is done to make the metal brushes rotate at a similar speed so that their momentum helps in breaking the dirt down.

4. Microcontroller

There is need for a basic control system for the cutting system which decides the amount of current being delivered, the amount of battery discharge for the operation

and to regulate the speed of shaft rotation so that the metal brushes can be adequately controlled.

A Sabertooth 2x25A regenerative dual motor driver is used for this purpose. This device works well with 24V batteries and motor on board and has RC capabilities. This feature allows the drive to be controlled remotely.

5. RC Transmitter and Receiver

The receiver component is connected to the microcontroller to enable the RC capabilities for the cutting system. An operator instructs the cutting system through a Transmitter. This transmitter sends a command signal to the receiver which in turn controls the microcontroller and subsequently the motors and the brushes. In this prototype, a single transmitter controls both the microcontrollers in the drive as well as the cutting system.

6. Bevel Gears

To achieve the connection between the motor and the brushes, an arrangement with bevel gears was decided upon. Bevel gears are gears where the axes of the two shafts intersect and the tooth-bearing faces of the gears themselves are conically shaped.

Bevel gears are most often mounted on shafts that are 90 degrees apart but can be designed to work at other angles as well.

A set of bevel gears with a shaft hole of 8mm were chosen along with an 8mm-12mm coupler to exactly fit the motor shaft. The second gear was then paired with an 8 mm shaft which was connected to the sprocket at the front end of the robot. The assembly was further bolstered with shaft spacers, bearings and shaft tighteners to secure the bevel gears, sprocket and the motor in place.

7. Chain and Sprockets

The second part of the transmission involves the use of a sprocket and a metal chain. The bevel gears transmit power from the motor to the drive socket. This drive socket rotates and in turn transmits power to the driven sprocket through the help of a chain. The sprocket and chain chosen were made of stainless steel due to it being corrosion resistant which enables long term use without repeated maintenance.

8. Metal Brushes

The metal brushes chosen were three circular discs made of steel with 6” outside diameter initially with an arbor hole. The metal brushes are attached to the same

shaft as the driven sprocket. This ensures that the torque from the Motor is completely transmitted to the metal brushes. The design and motion of the metal brushes further ensure that the debris is both broken down and guided towards the suction hose inlet.

2.3 Component Stress Analysis

1. Drive Frame

A detailed stress analysis was conducted on the drive frame to make sure that it could hold all the components. The results for this analysis are explained in the images below.

Fig 2.8. Stress analysis for Drive Frame of Prototype 1

Fig 2.9. Displacement analysis for Drive Frame of Prototype 1

The rates of both stress and displacement of material for the drive frame is shown in the Fig 2.8 and Fig 2.9 respectively. It can be seen from the stress analysis that the material has a yield strength of $5.15 \times 10^7 \text{ N/m}^2$. Due to this, the material would not deform significantly under the stress that is applied by the other systems in the prototype. Also, even at the worst conditions, the displacement is shown to be less than $6.06 \times 10^{-3} \text{ mm}$ which further proves the robustness of the design for the prototype. Clearly, as the weight on the drive frame increases, there is an increased chance of the plates buckling under load (as shown in the green regions). Due to this, the sides of the drive frame were decided to be welded on top of the drive frame bottom plate so that the buckling effect does not place additional stress on the welds in the frame. Also, it was found that the drive frame also bent at the center when the weight was drastically increased. It was decided that the load from the suction hose

and the cutting system would be distributed throughout the entire length of the prototype so that the drive frame remains stable during operation.

2. Cutting Arms

The stress and displacement analysis on the cutting arms were conducted separately to determine the angle of depression through which they were to be lowered.

Fig 2.10. Stress Analysis on Cutting Arms of Prototype 1

Fig 2.11. Displacement Analysis on Cutting Arms of Prototype 1

It can be seen from the stress analysis that the material has a yield strength of $5.15 \times 10^7 \text{ N/m}^2$. Due to this, the material would not deform significantly under the stress that is applied by the other systems in the prototype. Also, even at the worst conditions, the displacement is shown to be less than $2.407 \times 10^{-2} \text{ mm}$ which further proves the robustness of the design for the prototype. As seen from Fig 2.10 and Fig 2.11, it is observed that the lower the arms are inside the drain, more the stress on the junction between the arms and cover plate (as shown in green in Fig 2.10). Also, the longer the arms are, the greater they bend under the load of the brushes due to decrease in stability. However, the arms needed to be lowered enough to lower the brushes adequately inside the drain and they had to long enough to contain the brushes but give the suction enough clearance to operate for maximum cleaning

efficiency. Based on this, an optimal angle of depression and an optimal arm length was decided to accomplish both factors.

2.4 Proposed Assembly Sequence

All the individual subsystems are taken and lined up. The drive system is first taken, and a cover plate is screwed on to it. The connection is established through hinges on the sides for ease in accessing the components inside.

The suction system is then attached on top of this cover plate with the help of screws and angle plates. A total of six angle plates are used to secure the connection.

The cutting system is then screwed on top of the suction tube with the help of three threaded screws.

The chain is then installed which connect the driver and the driven sprocket and enable power transmission to the metal brushes.

The rubber belts are then secured over the pulleys to complete the assembly.

The figure below shows the completed model of the first prototype. All the subsystems are to scale with respect to one another. The assembly is 9.75 inches in height and 4 inches in width and designed to fit entirely in the drain space.

Fig 2.12. Complete Model of first Prototype. Metal Brushes (In Gold), Cutting Arms (In Pink), Drive Frame (In Blue), Robot Wheels (In Black), Suction hose (In Green), Top Cover (In Grey) and Cutting Assembly (In Brown)

The entire prototype is designed to be highly modular, meaning that any of the subsystems can be replaced with another one with different characteristics and the robot would still be able to operate with ease. This ensures that the robot is highly customizable based on the user's needs and can be used in different drains with different dimensions, shape and dirt types.

Once the robot was entirely modelled in three dimensions, it was checked for final dimensions. This was done by modelling a drain to scale and checking its fit inside

the drain. The clearances on the sides and the top of the robot were adjusted according to the observations made by this check.

The cutting system and drive system had their walls filed and machined to further reduce the overall robot frame width. The height of the metal brushes was also checked, and it was decided to construct two separate arms with 6-inch and 8-inch metal brushes respectively. This was done to increase the area on which the cutting system would act depending on the amount of sedimentation.

The three-dimensional model also helped in deciding the dimensions and tolerances for constructing many auxiliary parts. For instance, seeing the assembled drive system helped in modelling a motor mount for the drive motor as all the tolerances and dimensions were easily verified. This helped in furthering bolstering the overall design by enabling accurate design for motor mounts, connection screws, etc.

The model also helped visualize the actual operation of the robot inside the drain. This brought up few new concerns which were promptly addressed. For instance, it is assumed that the suction system would be efficient enough to suction out all the debris out of the robot's path. However, if the suction system did not work according to plan, the debris would collect at the drain bottom. This would hinder the pulleys from moving forward and the drive system to stop functioning efficiently. To counter this, a shovel was designed and modelled which would further aid the

scooping of debris into the suction hose inlet. Similarly, a hose connector was also decided to be designed for enabling transition of the square suction tube to a circular hose going to the vacuum collection unit. However, this was to be designed after observing the performance of the robot.

Chapter 3

Robot Fabrication – Prototype 1

Based on the final model, the first prototype was fabricated with all its subsystems. The fabrication process is discussed in detail in this section along with the components, fitting and overall assembly.

3.1 Drive System

Fig 3.1. Drive System of Prototype 1

The components included in the drive system are listed below along with their order of assembly after fabrication.

- Drive Frame
- Pulleys
- Shafts

- Shovel
- Dc Motor (With Motor Holder)
- Spacers
- Coupler (With 8mm Extension Shaft)
- Bevel Gears
- Batteries
- Microcontroller
- Rc Receiver
- Switch
- Wires
- Hinges

The order of assembly for the complete drive system is mentioned below.

- The shovel is screwed to the front of the drive frame.
- The 8mm shafts are inserted into the bearings, which are already pressed on to the drive frame.
- While inserting the drive shaft, the bevel gear is already inserted and placed accurately where needed. The shaft is then pressed through the other bearing. This ensures that the first bevel gear is in place before all other components are assembled.

- The pulleys (acting as wheels) are then hammered on to the 8mm shafts. This ensures a tight fit and prevents the shaft or the pulleys from sliding laterally. After this is done, it is recommended to keep the assembled components as one single piece for ease of successive assemblies.
- The DC motor is then screwed onto the motor holder. The coupler is attached to the motor shaft through a key and the second bevel gear is attached to the coupler by an 8mm extension shaft.
- The motor and the motor holder are then placed onto the drive frame such that both bevel gears have an optimal engagement. After deciding the position of the holder, spacers are then added behind the motor holder to keep it fixed in place. This ensures the transmission is uniform with the bevel gears fixed in place.
- The batteries are then connected to the microcontroller, switch and receiver and are placed behind the holder. The wires coming from the DC motor are then screwed into the microcontroller. While disassembling the robot, it is recommended to just unscrew the motor wires from the microcontroller and keep all other electronics intact.
- Hinges are attached to the sides of the drive frame with the help of screws.

Switch the circuit on and install the cover plate on top of the drive frame using hinges.

3.2 Suction Hose

Fig 3.2. Suction Hose after Fabrication. Vacuum Hose from Pump, Square Suction Tube (1.5 Inch Width), Cover Plate for Drive Frame and Hinges to Connect to Drive System and Cutting Assembly

The order of assembly for the suction system is given as follows.

- Cover plate is attached to the bottom of the square suction tube. The connection is currently made using duct tape and treating the cover plate and the suction tube as a single piece.
- Hinges at the top of the square suction tube are installed for connecting to the cutting assembly.
- The hose attachment is then attached to the front of the suction tube. The vacuum hose coming from the pump is then attached to the rear end of the suction tube. Both these connections are also made using duct tape.

3.3 Cutting Assembly

The components for the entire cutting assembly are shown are listed and shown in the Fig 3.3 below.

1. Cutting Frame (With Motor Holder)
2. Stationery 8mm Shaft
3. Rotating 8mm Shaft
4. Dc Motor
5. Bevel Gears (With Extension Shaft)
6. Coupler
7. Sprocket

8. Shaft Collar

9. Bearings

Other parts (those not shown in the figure) include

10. Shaft Spacers

11. Battery

12. Microcontroller

13. Rc Receiver

14. Switch

15. Wires

Fig 3.3. Cutting Assembly after Fabrication

The order of assembly is given as follows.

- The cutting frame has the motor holder already attached with the help of an epoxy. There is also a stationary rod this is pressed onto the cutting frame.
- The dc motor is screwed on to the motor holder. The coupler, extension shaft and the bevel gear are then connected to the motor with the help of keys and set screws respectively.
- The rotating shaft is then pressed to the first bearing in the cutting assembly. Two shaft spacers are inserted onto the shaft. The second bevel gear is then inserted and the alignment of the two bevel gears are checked.
- After this the sprocket and the shaft collar are inserted on to the shaft and it is then pressed on to the second bearing of the frame.
- The position of the spacers, bevel gears, sprocket and the collar is finalized and everything is screwed in place using set screws.
- The battery is then connected to the microcontroller, switch and the RC receiver and the arrangement is place inside the cutter frame. The wires from the motor are then screwed on to the microcontroller. It is recommended to keep all electronics apart from the motor already connected for ease of assembly.

3.3.1 Cutting Arms And Metal Brushes

Fig 3.4. Cutting Arms with Metal Brushes after Fabrication

The components for the cutting arm assembly are listed below.

1. Cutting Arms (With Cover)
2. 0.625 Inch Shaft
3. Metal Brushes
4. Spacers
5. Sprocket
6. Chain

The order of assembly for the cutting arm is given below.

- The cutting arms are welded on to the cutting cover and they are treated as a single piece. The arms are placed on to the cutting assembly in such a way that one of the grooves in the arms hooks on to the stationary shaft in the cutting assembly. In addition to that, the arm has been designed to allow some space for the bearing to be accommodated.
- Once the arms are installed, the 0.625-inch shaft is pressed on to the first bearing in the arm.
- The first two metal brushes are then placed on the shaft and fixed by use of a key.
- A spacer is added after this to position the brushes and the sprocket properly.
- The sprocket is then inserted on to the shaft such that it aligns perfectly with the sprocket in the cutting assembly.
- The second spacer is then installed, after which the two remaining metal brushes are inserted with keys.
- The shaft is then pressed on to the second bearing and the alignment of all the components is verified and screwed in place.

The overall prototype is finally machined and ready for the first phase of testing.

The entire mechanism is shown in Fig 3.5 below. Duct tape is used at various parts as observed from the figure. This is done as the robot is not quite stable and needs further bolstering before running it for longer durations.

Fig 3.5. Complete Prototype Assembled

Chapter 4

Robot Testing – Prototype 1

4.1 Setup

A set of initial tests were setup to see the prototype in operation for the first time. For this purpose, the robot was operated with just a 5HP temporary vacuum cleaner unit.

There were two tests carried out on this version of the robot, one on flat cardboard surface and the other inside the drain. For each test, the robot was made to move once without any dirt present and a second time with dirt.

The tests were carried out once with belts installed on the wheels and a second time with just the wheels. Fig 4.1 and Fig 4.2 below show the robot inside the cardboard drain and the real drain respectively.

Fig 4.1. Prototype 1 in operation in Cardboard Drain

Fig 4.2. Prototype 1 in operation in Concrete Drain

4.2 Observations

In the cardboard drain, the robot was found to move satisfactorily, both with and without debris. Some of the debris was not able to be broken down efficiently which made the robot ride over the debris and lowered its performance.

In the real drain, several problems were seen both with and without the presence of debris. These have been discussed below.

1. During the test, the bevel gears in the drive systems were found to disengage repeatedly. This disengagement was observed when there was some resistance

(presence of dirt) to the robot movement. It was also observed when the belts were installed temporarily.

2. The suction at the front end of the square tube was found to be too low due to which the dirt was not sucked in efficiently. The vacuum power in itself was found to be too low in addition to some leakage being caused though the hose length. This might be occurring due to the holes drilled in the suction tube for the screws as well as the regions at the front and the back of the tube being attached through duct tape. Due to the leakage caused, the suction pressure at the end of the tube may not be enough.
3. The robot could not move at all inside the drain with or without the belts. The wheels, being flat widthwise, did not have enough contact with the drain surface, which was curved. Additionally, when the belts were put on, they did not meet the drain surface either. This resulted in very less traction produced for the robot to move forward.

These observations were used to decide the next steps in rectifying the design. These steps have been listed as conclusions below. Modifications were also recommended afterwards.

4.3 Test Summary

The drive motor needed to be changed due to the continuous disengagement of the bevel gear. The whole arrangement needed to be replaced with just DC motor to drive the wheels. All the remaining parts such as couplers and bevel gears needed to be eliminated to ensure better transmission.

The suction hose connections at the front and the back to be secured with rigid structures instead of duct tape.

The wheels will have to be redesigned to provide more contact area between them and the drain surface. To do this, the wheels should have a curved profile widthwise matching the curvature of the drain surface to better suit the movement of the robot inside the drain.

4.4 Modifications

Based on the conclusions from the previous test, it was decided that the whole drive system was to be changed.

The robot needed to be four-wheel drive for better control of wheels with two DC Dual Shaft Motors, one each for the front and rear set of wheels. The power of these DC motors will have to be enough to pull the robot forward. This is checked in the calculations mentioned later.

Furthermore, it was decided that due to the limited space available, it would be better to use 3 metal brushes instead of 4. This would provide more space for the sprocket and the chain to function. It would also prevent the chain from encountering the rotating brushes while in operation.

The wheels have been redesigned and now have a curved profile suiting that of the drain surface.

Due to the considerable modifications that needed to be made, it was decided that a second prototype be designed which took the best features of the first prototype while also overcoming the limitations observed during the initial test. The second prototype has been discussed along with all its aspects in the next section.

Chapter 5

Robot Design- Prototype 2

5.1 Design Concept

Based on the modification from the first prototype, several changes were made to the design in order to develop a more robust prototype. Firstly, the drive motor and the entire bevel gear arrangement needed to be replaced with a more compact and stable mechanism for torque transmission. Also, the robot was to be made four-wheel drive for better traction during operation. To do this, the current drive motor was to be replaced with two motors. These two motors were to be double shaft as well to avoid using other gears for transmission.

To ensure that these two motors combined transmit the same power and torque as the previous motor, certain calculations had to be carried out regarding the torque, power and speed of the robot. These calculations would be the basis of choosing the DC motors for the drive.

Fig 5.1 Second Model complete assembly with 6-inch metal brushes

Parameters for Torque Required are given below.

- Weight of robot – 40lbs
- Friction coefficient between rubber and concrete – 0.6
- Wheel radius – 2 inches
- Formulas used:
- Force – Weight x Coefficient of friction
- Torque – Force x Wheel radius

Weight (lbs)	Friction Coefficient	Frictional Force(lb-f)	Wheel Radius(in)	Torque Required(in- lbs)	Torque (Nm)
40	0.6	24	2	48	5.424

Thus, the robot needs at least 5.424 Nm of torque to run smoothly inside the drain with all its weight.

For the next step, the torque provided by the motor is calculated:

Parameters for Torque Provided are given below.

- Motor Speed – 37 RPM
- Angular Speed – 3.872 rad/sec
- Motor Efficiency – 0.7
- Formulas used:
- Angular Speed – $(2 \cdot \pi \cdot \text{Motor rpm})/60$
- Linear Speed – Angular Speed x Wheel Radius

Motor Speed (rpm)	Angular Speed(rad/sec)	Linear Speed(in/sec)	Linear Speed (ft/min)	Motor Efficiency	Motor Torque Rating (Nm)
37	3.872666667	7.745333333	38.72666667	0.7	7.748571429

Hence, it is found that combining two motors will transmit 7.75 Nm of torque in total which is greater than the torque required.

The next section discusses the components that were that were chosen with different specification and dimensions when compared to the first prototype.

5.1.1. Drive System

The drive system frame was redesigned in order to make it of lesser width. Fig 5.2 below shows the newly modelled drive frame. As seen from the figure, the frame contains four notches, two on either side for the protrusion of the motor shafts. The wheels are then screwed on the outside of the frame on to these shafts.

Fig 5.2. Drive System without wheels attached

**Fig 5.3. Drive System with wheels attached. Curved Wheels (In Black),12V
DC Drive Motor (In Blue) and 12V CD Battery (In Green)**

Wheels are curved towards the outside to increase contact area with the curved drain surface.

As already discussed, the drive frame has been simplified to a great extent with all auxiliary transmission components such as the bevel gears, couplers, etc removed. The frame now houses just the motors and the electronics for control. The width of

the robot has been reduced and the frame sides themselves have been used as motor mounts to keep both motors stable.

Currently, the motors are first screwed on to the drive frame through the help of threaded screws on the sides. The wheels are then installed on the shafts with the help of set screws. The cover plate is attached to the top of the drive frame using hinges and an additional locking mechanism to keep the drive frame secure.

The drive system had a considerable number of components that were to be replaced after the first test. These components, be it in design changes or part replacements, are all listed below.

1. Drive Frame

Aluminum sheet metal is used again for the purpose of housing the drive system components. However, the design of the frame is different. Instead of being 4 inches wide at the center and 2 inches wide at the ends, the new frame had a uniform width of 2.375 throughout. This was done to ensure that the sides of the frame do not get stuck inside the drain.

2. Customized wheels

Instead of using drive belts and pulleys, customized wheels were used to better acclimatize to the drain. These wheels had a curved profile widthwise which matched the curved drain bottom. This would enable the robot to move smoothly inside the drain. Moreover, the rubber chosen for the wheels were chosen such that they were hard enough to withstand the weight of the robot while being flexible enough to allow dirt to slip under them.

3. DC motors

The two DC motors used for this purpose were DC 12V motors running at 31RPM with 3A current and transmitting 50 kg.cm of torque. Due to them being double shaft, the motors could be easily installed at either ends of the drive system to provide torque to both sets of wheels.

All the other parts and components of the drive system were kept the same.

5.1.2 Suction System

The dimensions of the hose have been changed as the new drive frame was designed to be lower than the previous one. The new suction hose contains a rectangular cross section with a height of 2.5 inches. This ensures that the debris sucked in is more in quantity.

Generally, a circular hose was ideally to be used for fabricating the suction hose of the prototype. However, it was decided that the suction hose be kept rectangular instead of changing to a circular shape. This was done because even though debris particles spread out symmetrically in a hose of circular profile (resulting in a smoother and more efficient flow), it was found that a rectangular cross-sectional hose with approximately a 2 to 1 width-to-height ratio reproduces the symmetrical behavior of a circular pipe. Moreover, a rectangular cross-sectional hose had the added advantage of a stable base for the cutting system to be mounted on (as the surface for the connection was flat). Due to these reasons, the suction hose was made of a rectangular cross section with the height slightly larger than the width. A ratio of 2 to 1 was not possible as the overall robot needed to be under 10 inches to fit inside the drain. This results in an optimal design of the hose fulfilling all space and functionality constraints.

A shovel is then modelled which is curved and has the same profile as the bottom surface of the drain. This acts a scoop in front of the suction hose inlet and helps in collecting all the dirt broken down in front of the hose inlet from where it is sucked out.

Also, a suction hose inlet was further modelled with the same dimensions with the intention of being bent at an angle to help concentrate the suction towards the bottom of the drain. This is done to increase efficiency as the debris would directly be sucked

out after being broken down and would clear the area in front of the robot at a faster rate.

Additionally, a hose connector is modelled to be attached at the rear end of the hose section to facilitate the transition from a rectangular to a circular cross section.

These additionally components would prevent debris from clogging inside the drain and would enable the drive system to move smoothly while in operation. The new suction hose along with the hose inlet, connector and the shovel are shown in Fig 5.4 below.

Fig 5.4. Suction Hose with Hose Connector and Shovel

Fig 5.5 and Fig 5.6 below show the hose connector and the shovel respectively modelled to scale with respect to the prototype.

Instead of using angle plates for connection, the entire hose section has been drilled at various positions for threaded holes. These holes enable the hose section to relate to both the drive and the cutting mechanisms efficiently without taking much time. Also, the hose connector, hose inlet and the shovel have been welded to this section to make the entire system as one piece. The lesser number of holes along with the welded components further prevent leakage of air through the hose channel. This in turn prevents loss in suction power.

Fig 5.5. Shovel Design

Fig 5.6. Connector Design

1. Suction Hose Inlet and Rectangular hose section

A rectangular suction tube of width 2.25 inches and height 2.5 inches was decided upon in order to increase the cross-sectional area for transportation of the dirt. For the hose inlet, another tube of length 3.5 inches with a rectangular cross section with the same dimensions was made. However, this section was bent at an angle of 17 degrees from the center and was welded to the rectangular hose section. This ensured that the dirt sucked was from the drain bottom.

5.1.3 Cutting System

The cutting system is kept the same as the metal brushes were seemed to be working fine. However, a new design for the cutting arms was to be constructed for 8-inch diameter metal brushes. This new set of arms would be assembled and kept as a

separate module. This would be beneficial when there is a need for larger areas to be cleaned and the debris is clogged to a higher level inside the drain. The new set of arms along with the brushes can be readily installed and the robot would be able to handle a different condition of drain within minutes.

Fig 5.7. Metal Brushes with Cutting Arms attached to Cutting Assembly

The cutting mechanism is kept the same as the arrangement is satisfactorily stable given the space constraints. A second set of arms have been designed for larger metal brushes. The assembly sequence for these arms is also kept the same.

Fig 5.8. Cutting Arms holding 8-inch metal brushes.

All the components of the cutting system were kept the same as this system was found to be working as planned. Another set of arms were designed for 8-inch metal brushes in case the robot needed to break down more dirt during operation. Moreover, it was decided to replace the four metal brushes with just three to provide more space for the driven sprocket and the chain to rotate.

5.2 Component Stress Analysis

1. Drive Frame

A detailed stress analysis was conducted on the drive frame to make sure that it could hold all the components. The results for this analysis are explained in the images below.

Fig 5.9. Stress Analysis of Drive Frame for Prototype 2

Fig 5.10. Displacement Analysis of Drive Frame for Prototype 2.

For the second prototype, the rates of both stress and displacement of material for the drive frame is shown in the Fig 5.9 and Fig 5.10 respectively. It can be seen from the stress analysis that the material has a yield strength of $5.15\text{e}+07 \text{ N/m}^2$. However, due to the change in design of the drive frame with respect to the first prototype and the replacement of the DC motor, the overall load on the frame is much less than that in the first prototype. This led to the new drive frame being subjected to a stress significantly lesser than that in the first drive frame. Also, even at the worst conditions, the displacement is shown to be $2.384\text{e}-03 \text{ mm}$, which is

lesser than that observed in the previous prototype, which further proves the robustness of the design for the prototype.

2. Cutting Arms

As it was decided that the new prototype would have bigger brushes to increase the cleaning area inside the drain, the stress and displacement analysis on the newly designed set of cutting arms were conducted separately to make sure that they could hold the bigger brushes.

Fig 5.11. Stress Analysis of Cutting Arms for Prototype 2.

Fig 5.12. Displacement Analysis of Cutting Arms for Prototype 2.

It can be seen from the stress analysis that the material has a yield strength of $5.15 \times 10^7 \text{ N/m}^2$. Due to this, the material would not deform significantly under the stress that is applied by the other systems in the prototype. Also, even at the worst conditions, the displacement is shown to be less than $2.974 \times 10^{-2} \text{ mm}$ which further proves the robustness of the design for the prototype. Understandably, due to the bigger brushes being used, there is more stress on the newly designed arms than the arms used in the first prototype. However, it is observed the arms are able to withstand this increased stress with ease. As seen from Fig 5.11 and Fig 5.12, it is observed that the lower the arms are inside the drain, more the stress on the junction between the arms and cover plate (as shown in green in Fig 5.11). Also, the longer

the arms are, the greater they bend under the load of the brushes due to decrease in stability.

5.3 Proposed Assembly Sequence

All the individual subsystems are taken and lined up.

The drive system is first taken, and a cover plate is screwed on to it. The connection is established through hinges on the side for ease in accessing the components inside.

A locking mechanism is installed which keeps the components secure and helps in maintaining the structure of the robot inside the drain.

The suction system is then attached on top of this cover plate with the help of threaded screws on both ends. A total of six screws are used to secure the connection.

The cutting system is then screwed on top of the suction tube with the help of three threaded screws.

The chain is then installed which connect the driver and the driven sprocket and enable power transmission to the metal brushes.

Fig 5.13 below shows the completed model of the second prototype. All the subsystems are to scale with respect to one another. The assembly is 9.75 inches in height and 3.5 inches in width and designed to fit entirely in the drain space.

Fig 5.13. Second Model complete assembly with 8 inch metal brushes

The cutting system is installed on top of the suction hose with an offset of 7 inches from its position in the first prototype. This is done to provide enough time for the suction hose to suck all the broken-down debris once the metal brushes have acted on them.

Chapter 6

Robot Fabrication – Prototype 2

Based on the lessons learnt from the first prototype, the second prototype was fabricated with all its subsystems. The fabrication process is discussed in detail in this section along with the components, fitting and overall assembly.

6.1 Drive System

The complete fabricated drive system is shown in Fig 6.1 along with all the electronic components.

Fig 6.1. Complete drive frame assembly with all components

The components included in the drive system are listed below along with their order of assembly after fabrication.

1. Sabertooth Motor Driver
2. Nimh Batteries
3. Drive Frame
4. Welded Cover Plate
5. Dc Dual Shaft Motors

The order of assembly for the complete drive system is mentioned below.

- The DC dual shaft motors are inserted into the drive frame which already have threaded holes drilled to attached and fix the motors on to.
- Customized wheels are then taken and screwed on to the motor shafts on both sides. The tightening is done with the help of set screws.
- The batteries are then connected to the microcontroller, switch and receiver and are placed behind the holder. The wires coming from the DC motor are then screwed into the microcontroller. While disassembling the robot, it is recommended to just unscrew the motor wires from the microcontroller and keep all other electronics intact.
- Hinges are attached to the sides of the drive frame with the help of screws.
- The cover plate on top of the drive frame is then fixed using these hinges.

6.2 Suction System

The suction system is one piece which includes the rectangular hose section, hose connector, hose shovel and suction hose inlet. The piece is connected to the drive system through the help of three threaded screws which hold the system in place during operation.

Fig 6.2 shows the individual components used to make the system. The parts shown are the shovel, suction hose with welded hose inlet and the welded hose connector respectively.

Fig 6.2. Fabricated Pieces for Shovel

Also, the suction hose of the robot is welded directly to the suction hose inlet and to the connector for circular hose as shown in Fig 6.3 and Fig 6.4 respectively.

Fig 6.3. Fabricated Suction Hose welded with Hose Inlet

Fig 6.4. Fabricated Suction hose welded with Connector

The connection between the welded connector of the robot and the circular suction hose is reinforced through duct tape as shown in Fig 6.5. This is done as previous tests showed a leakage of air when the connection was done by merely inserting the circular hose into the connector. Once duct tape was used, there was an instant increase in cleaning efficiency of the robot which was visible through the naked eye. This method is found to work on the current prototype. However, the strength of the

duct tape is found to decrease significantly when it encounters dirt and debris directly, rendering it useless when the drain contains heavy debris or wet debris. Hence, to avoid this limitation, the connection needs to be further reinforced through machined fixtures to make it more robust in order to make the robot more heavy duty.

Fig 6.5. Connection between robot and circular vacuum hose

6.3 Cutting System

As the cutting system was kept the same, the only fabricated components were the set of arms for the larger metal brushes. Fig 6.6 below shows the fabricated arms attached to the cutting assembly through the help of black threaded screws on the sides.

Fig 6.6. Fabricated Cutting Assembly with Cutting Arms and Brushes

The order of assembly for both the cutting assembly as well as the cutting arms are the same as that in the first prototype.

The overall prototype is now completely fabricated and is ready for the next set of tests. The entire mechanism is shown in the Fig 6.7 below. The first segment in the figure shows the entire prototype while the second segment shows the front end of

the robot. The third segment shows the rear end of the robot. All the parts are labelled in the figure.

As seen from the figures, the second prototype is much more robust in design. Little to no duct tape is used and all the connections made are either through screws or through welding. Moreover, the cutting mechanism is also moved to the front by a total of 7 inches. This is done to provide enough space to the shovel and hose inlet mechanism to work on the broken-down debris which eventually could improve the efficiency of the robot.

Fig 6.7. Segmented View of Second Prototype after Fabrication

The fabrication had to be done very accurately for certain parts with very little room for error due to the extremely confined space. For instance, the shovel had to be

machined exactly as in the model due to its position in the robot, A shovel too high would result in not scooping debris from the bottom of the drain efficiently while a shovel too low would scratch the drain surface and slow the robot down. Also, throughout the fabrication procedures of both prototypes, the welding had to be done very precisely so that the frame is both narrow enough to work inside the drain smoothly and wide enough to house all the electronic components inside.

However, despite the mentioned challenges, the second prototype was fabricated and was finalized to be tested on a sample drain channel.

Chapter 7

Robot Testing

7.1 Setup

- Suction used was GUARDAIR cannister vacuum with 15HP.
- The test was carried out for three different inlet sizes, namely 1.5”, 2.5” and 3.5”.
- The test was carried out for both dry and wet debris.

7.2 Observations

A total of six combinations were tested where the performance of robot for dry and wet debris was observed for each of the inlet sizes. The results observed are shown in table 7.1 below.

	1.5 in inlet	2.5 in inlet	3.5 in inlet
Dry Debris	Picked up most Debris, but hose can be easily stuck	Picked up some at least half of the debris. The chance of getting stuck was reduced	Couldn't pick up any debris. The hose can hardly be stuck
Wet Debris	Picked up most Debris, but hose can be easily stuck	Picked up some less debris than dry debris. The chance of getting stuck was reduced	Couldn't pick up any debris. The hose can hardly be stuck

Table 7.1. Observations with Dry and Wet Debris

7.3 Test Summary

Based on the results, the following conclusions were obtained:

- The robot performs better when the clearance between the cutter and the hose is larger. The cutter can be extended to allow more time for the suction to act on the loosened debris particles.
- A more powerful vacuum force is needed at the source.
- Based on the inlet sizes tested, it is observed that the larger the size, less the chance of debris getting stuck. However, larger the size, more the suction power needed.
- The clearance between the suction hose inlet and the metal brushes was observed to be too small, especially when working with wet soil. Also, small rocks got stuck in the hose inlet opening which led to blockage of the hose. The clearance had to be increased.
- Some of the dirt was found to slip off from the shovel surface back into the drain while the robot was in operation.
- The cutting system stopped working after a while due to the metal brushes not being able to handle the rough nature of hardened dirt. The electronics needed to be inspected again.

Chapter 8

Refined Prototype 2

The second model was revised after the above-mentioned set of tests to come up with the final prototype.

Figure 8.1 shows the final prototype developed before the final set of tests were performed. Also, for better performance inside the drain, the cutting arms with the 8-inch metal brushes are used for all remaining tests.

Fig 8.1. Complete Assembly of final model with Drive System, Hose, Cutting Assembly and 8-inch Arms.

8.1 Modifications

The screw positions on the cutting assembly is adjusted and another hole is drilled in the front end of the assembly. The cutting arms are then screwed onto the cutting assembly through the newly drilled screw hole to push the metal brushes 7 inches in front of the suction hose inlet. This is done so that there is more clearance available when the cutting assembly is attached to the suction system.

A more powerful vacuum machine was used for the subsequent testing. Several machines were identified, and one was chosen with almost double the power with 3.2HP.

More work needed to be done on the suction system of the prototype as only few amounts of debris were found to be suctioned away when the debris was wet or filled with stones and pebbles. Due to this reason, it was decided that all subsequent testing be done using debris which was dry, granular and did not consist large pebbles or vegetation to make it easier for the robot to be operated in its current state.

The electronics was inspected and rectified. The microcontroller was replaced along with stronger wires and more robust connections. Figure 8.2 shows the changed electronic system for the second prototype.

Fig 8.2. On Board Electronics for Cutting System for Second Prototype

8.2 Final Testing

The final tests were conducted on the second prototype with a dual cortex vacuum machine attached to the device.

There was a total of three trials conducted for different depth of sedimentation in the drains (3.5, 3.0 and 2.5 inches respectively). The parameters that were observed for evaluation were the Robot stopping and starting times, the robot speed and distance covered in the drain.

Moreover, there are certain parameters which are kept constant throughout the trials in order to better evaluate the prototype. These include the dirt type and nature, average suction speed and power, average speed of the metal brushes, etc.

Parameters:

Since there were too many parameters, it was decided that the amount of dirt cleaned would be the focus. This meant that all other parameters would be kept constant and the robot would be checked for its average speed and the distance it covers inside the drains with respect to the debris that it removes during its operation.

To accomplish this, the robot had a total of 3 runs (cycles) where it was inserted into the drain at a single starting point and made to operate until complete battery discharge. For each of the first, second and third cycles, the drains were filled with debris up to 3.5 inches, 3.0 inches and 2.5 inches from the bottom respectively. As established from the previous test, it was decided that the dirt type be kept constant with the dirt being dry, coarse and granular.

During each cycle, the robot performance is judged based on two separate aspects. The first aspect is the time it takes to clean the drain during operation. This includes all the times it stops inside and resumes working. All the start and stop times during each run are recorded along with the reason for the robot stopping mid operation. The second aspect is the cleaning rate of the robot, which is the average speed of the

robot traversing the drain while removing the debris. This aspect measures how fast and efficient the robot is inside the drain for each cycle.

During the cycles, the suction parameters are mostly kept constant (constant cfm, suction HP and suction speed) while only the rate of transferring the debris is checked. The robot performance in all three cycles has been discussed below.

8.3 Test Results

For each cycle, the robot is operated inside the drain till its batteries completely discharges. During this run, the robot was found to start and stop many times due to debris clogging either the suction hose or the inlet above the drive system. Each of these starts and stop times along with the distances covered by the robot inside the drain before stopping each time have been noted. Once this is done, the total time of the robot operation is recorded and compared against the volume of dirt removed through the suction to evaluate the performance of the robot for each cycle.

Table 8.1 shows the values obtained for the first cycle by running the robot in a drain with 3.5 inches of dirt.

		Time		Length of drain completed (ft)	Avg Robot Speed (in ft/min)	Avg Cutting Speed (RPM)	Avg Suction Power (cfm)	Reasons for stopping
		Hours	Min					
	Time project started	0 hr	0 min	2.9	1.45	285	3.2	Buildup of debris inhibiting forward robot motion
	1st Stop time	0 hr	2 min					
	Resume time	0 hr	2 min	5	0.7	285	3.2	Debris accumulated in Suction Hose preventing further flow
	2nd Stop time	0 hr	5 min					
	Resume time	0 hr	5 min	7.1	1.05	285	3.2	Debris accumulated in Suction Hose preventing further flow
	3rd Stop time	0 hr	7 min					
	Resume time	0 hr	7 min	8.5	0.7	285	3.2	Buildup of debris in suction hose and in front of the robot
	4th Stop time	0 hr	9 min					
	Resume time	0 hr	9 min	9.7	1.2	285	3.2	Robot Battery discharged fully
	Time project finished	0 hr	10 min					

Table 8.1. First Robot Trial with 3.5 inches of Dirt

Plot 8.1 shows a plot depicting the robot performance for an average depth of sedimentation of 3.5 inches. The horizontal axis depicts the time taken during the run while the vertical axis depicts the volume of dirt removed from the drain during the corresponding time interval.

Plot 8.1. Plot Showing Robot Performance For 3.5 Inches Of Debris On Average

Table 8.2 shows the values obtained for the second cycle by running the robot in a drain with 3 inches of dirt.

		Time		Length of drain completed (ft)	Avg Robot Speed (in ft/min)	Avg Cutting Speed (RPM)	Avg Suction Power (cfm)	Reasons for stopping
		Hours	Min					
	Time project started	0 hr	0 min	4.2	0.84	285	3.2	Buildup of debris inhibiting forward robot motion
	1st Stop time	0 hr	5 min					
	Resume time	0 hr	5 min	7.7	0.875	285	3.2	Debris accumulated in Suction Hose preventing further flow
	2nd Stop time	0 hr	9 min					
	Resume time	0 hr	9 min	10.5	0.7	285	3.2	Debris accumulated in Suction Hose preventing further flow
	3rd Stop time	0 hr	13 min					
	Resume time	0 hr	13 min	12.9	0.8	285	3.2	Buildup of debris in suction hose and in front of the robot
	4th Stop time	0 hr	16 min					
	Resume time	0 hr	16 min	14.2	0.85	285	3.2	Robot Battery discharged fully
	Time project finished	0 hr	18 min					

Table 8.2. Trial with 3 inches of sedimentation

Plot 8.2 shows a plot depicting the robot performance for an average depth of sedimentation of 3.0 inches.

Plot 8.2. Plot Showing Robot Performance For 3.0 Inches Of Debris On Average

Table 8.3 shows the values obtained for the third cycle by running the robot in a drain with 2.5 inches of dirt.

		Time		Length of drain completed (ft)	Avg Robot Speed (in ft/min)	Avg Cutting Speed (RPM)	Avg Suction Power (cfm)	Reasons for stopping
		Hours	Min					
	Time project started	0 hr	0 min	3.25	0.8125	285	3.2	Buildup of debris inhibiting forward robot motion
	1st Stop time	0 hr	4 min					
	Resume time	0 hr	4 min	5.25	0.667	285	3.2	Buildup of debris inhibiting forward robot motion
	2nd Stop time	0 hr	7 min					
	Resume time	0 hr	7 min	8.15	0.725	285	3.2	Debris accumulated in Suction Hose preventing further flow
	3rd Stop time	0 hr	11 min					
	Resume time	0 hr	11 min	10.75	0.65	285	3.2	Buildup of debris in suction hose and in front of the robot
	4th Stop time	0 hr	15 min					
	Resume time	0 hr	15 min	12.45	0.85	285	3.2	Robot Battery discharged fully
	Time project finished	0 hr	17 min					

Table 8.3. Third Robot Trial with 2.5 inches of Sedimentation

Plot 8.3 shows a plot depicting the robot performance for an average depth of sedimentation of 2.5 inches.

Plot 8.3. Plot Showing Robot Performance For 2.5 Inches Of Debris On Average

Inferences:

Over the course of the three cycles, the prototype proved the working concept proposed at the beginning of the project. It demonstrated the possibility of a novel drain cleaning mechanism entirely within the confines of the drain which transported debris out of the drain with reduced manpower and traffic interaction in comparison to the previous methods. However, the prototype encountered few problems which stopped it from working effectively in the long term.

1. The robot kept getting stuck repeatedly between two consecutive drain sections, which interrupted its smooth operation within the drain. This was later rectified by carefully placing the drains one after the other. However, the robot width needs to be further reduced for increased clearances for successful runs in real scenarios.
2. The buildup of debris at the hose inlet was still found to be an issue for the robot. However, the clearance between the inlet and the metal brushes allowed more time for the suction to operate and this enabled the robot to traverse a greater distance before the dirt got accumulated. This issue was further rectified by the new shovel design which scooped more dirt from the bottom.
3. One of the main observations from the three cycles was the inability of the robot to operate once the debris accumulated in the suction hose behind it. This can be seen especially in all three plots which show the sharp decrease in volume of dirt

removed toward the later stages of the operation. When the robot is stopped and the suction hose is completely cleaned, there is a sharp increase in the volume removed from the drain again which can be seen in the cycle with 3.0 inches depth of sedimentation. This showed that the increased weight of the suction hose was putting significantly more load on the batteries, which were discharging at a quicker rate. This can be solved by coupling the robot with more powerful vacuum systems which sucked the debris more efficiently and had more capacity for collection for longer runtimes. The batteries could be replaced with an additional AC supply coming from a source at the same location.

4. The other main shortcoming of the prototype was discovered to be its inability to clean drains with over 3.5 inches of sedimentation. It was seen that the robot performed best when the depth was 2.5 inches and its performance decreased during the trials with 3 and 3.5 inches of dirt. However, this can be rectified with a more powerful suction with a larger inlet area.

Results:

The plots for the average speeds of the robot with respect to the distance traversed inside the drains for each of the trials have also been shown in Plots 8.4, 8.5 and 8.6.

Plot 8.4. Plot Of Robot Speed Vs Drain Distance traversed For 3.5 Inches Of Debris On Average

As expected, the robot started out at a speed of 1.45 ft/min for the first cycle. However, the speed exponentially reduced when the debris started accumulating in the suction hose. The speed was halved to 0.7 ft/min eventually and the robot found the hose to be too heavy. Thus, the hose had to be removed and cleaned after 5 minutes of operation. Once the operation resumes, the robot moves faster once again till the suction hose starts collecting debris. It was also observed that as more time passed, the suction hose started accumulating debris at a faster rate. This could be because of the reduction in battery power as the cycle time progressed which led to the robot torque decreasing, resulting in less debris being scooped into the hose inlet.

Plot 8.5. Plot Of Robot Speed Vs Drain Distance traversed For 3.0 Inches Of Debris On Average

For the second cycle with 3.0 inches of sedimentation inside the drain, the robot showed a trend like the first cycle. However, the robot performed much better than the previous cycle. Even though the debris accumulated both at the suction hose inlet as well as the suction hose behind the robot, the decline in speed was not sharp and the robot was able to traverse longer distances in the drain between successive stoppages to clean the hose. This can be seen from Plot 8.5 where the speed of the robot does not vary much throughout the cycle. Since the robot has letter volume of debris to remove, the suction works more effectively, and the robot drive moves through the drain at a faster pace.

Plot 8.6. Plot of Robot Speed Vs Drain Distance traversed for 2.5 Inches of Debris On Average

It was found that 2.5 inches of depth of sedimentation ensured the most optimal speed of the robot throughout the three cycles. Due to significantly less volume of dirt to be removed as compared to the first cycle, the robot performs much better in almost all the aspects. The operation runtime is almost doubled, with the robot now running for about 17 minutes. Also, the distance traversed inside the drain is significantly more along with a higher average robot speed.

Clearly, it is inferred from the plot that as the depth of sedimentation inside the drain is increased, the robot performance would eventually decrease. This is mainly because the debris starts clogging at the hose inlet and the suction hose which puts more load on the drive motor. This discharges the battery at quicker rates which

eventually leads to lower volumes of dirt being sucked out in the long run. This proves that higher volumes of dirt inside the drain lead to lesser runtimes of the batteries, which eventually decreases the average speed. Hence, an inverse relationship exists between the two. To improve these aspects and make the robot more robust and capable of running in the drain for longer durations, various mechanisms and improvements are discussed in the next section.

Chapter 9

Conclusions And Recommendations

9.1 Conclusions

The various field tests conducted on the final prototype have proved that the concept of the robot works. Through the project, it was established that a robotic mechanism could be modelled specifically to clean trench drains such that it would operate entirely within the drain, be remotely operated and clean the drain through a combination of suction and rotation. This would further ensure safety of all personnel during operation along with minimum traffic interaction. Additionally, there would also be little to no wastage of surplus resources since the robot works without water.

For the final set of tests, a total of five trench drain sections were connected and laid out, with each section having a length of 1 meter (3.28 ft). Thus, the entire drain channel was 16.4 feet long. The final prototype of the robot was tested in these trench drains and was found to run for a total distance of 14.2 feet inside a drain with an average depth of sedimentation of 3.0 inches during its best performance. It was also found that the prototype worked best with an average depth of sedimentation of 2.5 inches inside the drain, operating for the longest duration and obtaining the most optimal cleaning.

The optimum suction power was found to be 3.2HP with the robot running at a speed of 0.9 feet per minute (maximum speed of drive motor).

Based on the claims made at the start of the project, the robot fulfilled the following functions;

1. The robot proved the concept of a mechanism cleaning the trench drains entirely from the inside of the drains. This enabled the robot to function in high traffic areas without causing much hindrance to the traffic. Moreover, as the entry and exit point of the robot was at a single location, the entire process could be handled without blocking any traffic at all. This made the robot have minimum traffic interaction.
2. As the robot was bidirectional and remote controlled, the manual labor involved could be greatly reduced. At this time, a total of two people involved in the entire process would be enough, with one carrying the suction hose and the second supervising the robot operation inside the drain in addition to controlling it remotely.
3. As claimed earlier, the robot operates without using any additional resources like water as used during the waterjet cleaning. Also, the mechanism is designed to collect the debris and transport it to a single vacuum collection unit. This causes minimum amount of debris being sprayed on to the drain surface which could eventually result in a relatively more efficient process.

4. Although the robot batteries were found to run out completely within an average duration of 20 minutes, the robot was found to be faster than manual cleaning in this interval. At the best conditions (2.5 inches of sedimentation), the robot was found to run 12.45 feet in 17 minutes. This is equivalent to 37.35 feet in an hour, which was faster than the 30ft of drain cleaned manually in an hour by three people.

Although the robot fulfilled all the criteria it set out to accomplish, more work needs to be done on the suction hose, the vacuum collection unit as well as the motors to improve the robot performance and make it run for longer times. Now that the concept of the robot was proved to be working, more research needs to be conducted on the different vacuum systems and suction hoses it could be coupled with in order to make the entire process more robust.

The next section discusses the various future steps that could be taken to better the robot and its long-term performance.

9.2 Recommendations

One of the concerns during the development of the robot was that the overall power of the robot could be insufficient while traversing the drain. This could become a concern especially when the dirt is in hard granular or wet sludge form, with the

robot unable to suck the dirt efficiently. To overcome this, three areas were investigated, namely a different robot design, a powerful suction system and different battery types for longer runtimes. Implementing a combination of these three could result in much better results while enabling the robot to operate for longer.

Two Directional Augers:

One recommendation could be the use of augers instead of the current cutting assembly. The Augers would be attached on both sides of the robot with all the electronic components housed in between. The robot would then agitate the dirt by the successive motion of both the augers.

Fig 9.1. Auger Flights found on “Israeli Mole Robot” which drives the robot forward.

The angle of inclination of the augers would have to be kept in mind while designing to drive the robot forward during operation. Incorrect inclination would result in improper speed of the robot. The direction of the robot inside the drain would have to be controlled. Due to the absence of wheels or tracks, the motion of the robot would be completely determined by the rotation of the augers.

Suction Systems:

Another potential problem could be the insufficient suction power provided by the existing vacuum system. To rectify this, various suction systems were considered that could be coupled with the robot to increase the suction power. These machines, being much more powerful than the existing suction system, would enable the robot to suck more debris for longer durations. Three suction systems are discussed in this section.

1. Ditch Witch FX30

Fig 9.2. Ditch Witch FX30

As shown in figure 9.2, the Ditch Witch FX30 is 200 inches in length, 86 inches in height and 96 inches in height. It has an airflow rating of 500 cfm with an 800-gal capacity and a vacuum of 15mm in Hg.

2. Hurricane 300

Fig 9.3. Hurricane 300

As shown in figure 9.3, the Hurricane 300 is 146 inches in length, 115 inches in height and width 80 inches. It has an airflow rating of 850 cfm at 15mm Hg vacuum.

3. Hurricane 500

Fig 9.4. Hurricane 500

As shown in figure 9.4, the Hurricane 500 is 204 inches in length, 133 inches in height and 99 inches in width. It has an airflow rating of 2350 cfm at 27mm Hg.

All the three afore mentioned suction systems have a much greater capacity than the existing suction system and can be coupled with the robot through a 3 inch suction hose to improve the overall suction performance.

Alternate Battery Systems:

1. Nimh Tenergy Battery pack:

The Tenergy 7.2V NiMH battery pack has a high capacity rating of 3000mAh. It has standard dimensions of 5.39" (Length), 1.87" (Width) and 0.95" (Height) and can fit into the given space. These batteries can run the overall robot drive system at 14.4V if two or more are connected in series. However, this would result in decreased runtime of the batteries and excessive wiring leading to lesser space.

Fig 9.5. Tenergy 7.2V Nimh Battery Pack

2. 12V 5000mah Nimh Battery Pack:

This battery pack has a capacity of 5000 mA and a discharge Rate of 30 Amps. Moreover, it has standard dimensions with a height of 0.88", width of 1.68" and Length of 4.50". Due to its high discharge rate, it is more suitable for the drive motors and would give the robot more driving torque. However, in situations where the robot gets stuck inside the drain, these batteries would damage the circuits by providing sudden and discontinuous currents.

Fig 9.6. 12V 5000mah Nimh Battery Pack

Apart from these changes, the robot can be further automated through actuators and sensors in order to reduce manual involvement. For instance, a sensor could be used to decide the drive velocity of the robot by sensing the level of debris present in front of the robot. By adjusting the speed based on the dirt continuously, the robot can control the speed of linear motion on its own.

Another option could be introducing artificial intelligence to make the robot more autonomous and to enable decision making.

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Appendix

Cad Drawings:

Over the course of developing the first prototype, detailed drawings were developed to machine the robot frame and to fit all the components in the given space. These drawings are shown below:

1. Drive Frame:

Consists of 14 plates in total to make the housing for the drive motor and batteries. Also contains the shaft insert holes for robot wheels.

1A and 1B – These plates are used to make up the wall supports next to the wheels. Two of each of these plates are required for support on each side.

1C – Two of these plates are used to make up the wall support of the drive frame housing compartment.

1D – 14

2. Motor Holders:

Drive Motor Holder – Consists of 3 sections with motor
screwed to the front plate

Cutter Motor Holder – Consists of 3 sections with motor
screwed to the front plate

3. Cutter Frame and Arms:

Cutting Assembly –

Consists of the following components listed in order from top to bottom.

1. Shaft
2. Sprocket
3. Bevel gears
4. Bearings
5. Shaft coupler
6. DC cutter motor
7. Cutter Battery
8. Cutter frame

This section of the frame consists of 3 plates, one for the base to house the components and one on either side for support.

Cutting arms – Consists of three plates, with two for the arms and one for the top cover. The drawing shows the cutting arms with the 3 inch

Cutting arms without the 3 inch metal brushes

4. Overall Model:

CAD DRAWINGS:

Over the course of developing the second prototype, detailed drawings were developed to machine the robot frame and to fit all the components in the given space. These drawings are shown below:

1. Drive Frame:

As shown in the figure, two of each of these plates are used for machining the drive frame for the second model.

The plates on the left of the figure are used to make the walls of the drive frame and have notches to fit the motor shafts.

The plates on the right make up the top and bottom of the frame.

The bottom and the walls are welded together to make the housing compartment while the top plate is attached to the frame with the help of welded hinges.

2. Suction Hose and attachment:

As shown in the figure, the tube on the left is used to make up the main body of the suction hose attached to the robot. This tube has the hose attachment attached on the front and the hose connector attached to the rear to connect to the circular tube from the vacuum system.

The tube on the right is the hose

3. Shovel:

4. Hose Connector:

5. Cutting Assembly with Arms: