Autonomous Robotic Metallic Debris Collector

ECE4012 Senior Design Project

"The Rambler"

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Executive Summary

The Robotic Metallic Debris Collector (RMDC) is a mobile robotic platform for autonomously collecting metallic debris from the ground at various construction worksites. The operational environment of the robot will be an unbounded indoor area within the construction site. The robot will consist of a pre-packaged robotics platform with microcontroller and a device mounted on the chassis to collect the debris. The microcontroller will act as a hub to control the numerous I/O devices that perform the required functionality of the robot.

The microcontroller will ensure the basic tasks of detecting and magnetically collecting debris from the ground (including screws, nails, bolts, and scrap metal), then delivering it to a designated drop zone. It will also guide the robot through the construction site to avoid static and dynamic objects in its path which could ultimately prevent it from completing its main objective.

The robot will provide benefits to many construction sites by saving time and money during post-construction clean up. In fact, the average national (US) cost of third-party cleanup crews is about $442; thus, after just sixteen jobsite cleanup operations the robot will be paid for and the company using it will be saving an upwards of $400 per cleanup. It will also help with the safety of the workers during peak construction hours. Implementation of this robot at numerous construction sites will save the construction company a great deal of labor hours and costs per site over several years.

In order to completely develop the Robotic Metallic Debris Collector, the total development cost will be approximately $85,000. Therefore, that amount would need to be raised before the development process could begin on the Robotic Metallic Debris Collector.

Autonomous Robotic Metallic Debris Collector

1. Introduction

The Robotic Metallic Debris Collector (hereafter referred to as RMDC) is an affordable, semi-autonomous robotic system that is based on the cleanup requirements of construction sites. The system consists of a robotic platform with multiple I/O devices and a microcontroller. The team requests $800 for parts in addition to the supplies provided by Stanley Black & Decker to fund the build of a functional prototype of the robot.

The RMDC will have no direct competition as it will be the first robot on the market to perform this task. That being said, the main competition for the RMDC will come from third-party cleanup crews that are often hired to clean up after a construction crew.

1.1 Objective

The objective of the RMDC is to create a mobile robot to autonomously collect metallic debris from the ground at various construction sites. The robot will be controlled autonomously by an on-board microcontroller to roam an unbounded worksite and collect metallic debris while avoiding any static or dynamic obstacles. Although there are numerous types of debris at construction sites, this robot will concentrate primarily on the metallic objects dropped by workers; this includes screws, nails, bolts, and scrap metal. **Figure 1** (next page) shows the type of debris targeted for collection (left) and the notional depiction of the RMDC prototype (right).

Figure 1

1.2 Motivation

Debris naturally coalesces on the ground during construction. Nails get dropped, bins of nuts and bolts get toppled, and scrap metals fall from the cutting boards. People working at these construction sites are at risk for injuries due to all of the debris that falls to the ground. The standard procedure at most worksites is to, at the end of the day, conduct a manual sweep of the site for these debris, which is very time consuming and not very cost effective. Therefore, the main motivation of this project is to assist construction companies with such clean-up to ensure a safe working environment and improve worker efficiency.

1.3 Background

The world of automation through robotic systems includes both commercial and mainstream residential applications. However, the RMDC prototype will be the first of its kind to be used on construction sites. Stanley Black & Decker, Inc. (SBD) is a world-renowned manufacturer of industrial tools and hardware, providing solutions for construction sites worldwide. SBD is looking for a specific autonomous solution that is not necessarily a large factor in the construction of a building overall, but plays a large role in worksite safety while saving time and money.

Construction sites, especially those in developing countries, are a treasure trove of hazards such as dangerous equipment, immensely heavy materials, and more. One of these hazards is the metallic debris that is accidentally dropped during work (e.g. bolts, nails) or pieces of scrap metal left behind from adjustments made to larger pieces. Though workers are, for the most part, protected from such ground-based hazards by their heavy-duty work boots, at the end of a work day they must spend anywhere between one to three hours cleaning the worksite of such debris before they can go home. The RMDC prototype could make a difference in construction sites worldwide. Not only would this robotic system reduce the time allotted to cleaning at the end of a work day, but if used during the workers' break periods it could lighten the overall cleanup responsibilities of the workers.

For the RMDC prototype to operate successfully, both the hardware and the software must integrate and function seamlessly. The I/O devices – which includes distance sensors, metal detectors, motors, rechargeable batteries, a robotic forklift, and solenoid-mounted magnets – must be designed to work efficiently together through the use of a microcontroller. The microcontroller will have to communicate with and send commands to these devices extremely quickly for everything to function properly as a collective, robotic unit. Because this is a unique device, a custom mobile base will be assembled with the goal of containing all of the required components.

2. Project Description and Goals

2.1 Hardware

SBD provided the team with an all-purpose robotic platform manufactured by Ubiquity Robotic named Magni Silver. The Magni Silver is a fully realized robotic platform that has the capability to be reprogrammed and repurposed to fit any high-level robotics project. This platform comes with much-needed payload support, navigational tools, heavy-duty mobility, processing power, and feedback control so the team can focus more time on building and implementing a robust, reliable manipulator for debris collection. Since most of the metallic debris around a worksite usually involves small shrapnel such as nails, staples, screws, nuts and bolts, a typical robotic manipulator like a robotic arm is not an ideal choice for this project because it will have a hard time gripping small debris. The team opted to use an array of ceramic magnets as the main device to collect the small debris. The ceramic magnets will be aligned on a rectangular metallic sheet which will be mounted on a forklift that is attached to the front of the robot. Collection and delivery of the metallic debris is the most essential part of this project so most of the time spent on hardware will be designing, building, and testing the forklift.

2.2 Software

The Magni Silver runs on an open-source middleware called Robot Operating System (ROS) – more specifically Kinetic ROS – which supports a multitude of publicly-available third-party APIs. There are two primary aspects in developing the software for the robot: navigation and debris collection and delivery. The navigation aspect includes programming the robot to autonomously patrol an unbounded area of a worksite without collision for a specified amount of time. The robot will utilize a random pathing algorithm much like the iRobot "Roomba" to collect metallic debris within a 10-meter radius centered at its starting position. When the timer runs out a software interrupt will trigger, sending the robot to deposit the collected debris back at its starting location. If, at any point throughout its operation, the robot detects a ceiling-mounted fiducial marker, it will reset its position to the known position of the aforementioned marker to account for errors in motor-mounted odometry.

2.3 Goals and Add-Ons

Final Product Goals

- Patrol the unbounded area of a worksite autonomously.
- Detect and collect small metallic debris on the ground.
- Deliver the debris to a designated, static drop zone.
- Must be able to navigate around static obstacles in the environment.

Extra Features

- Detection and collection of non-ferrous metallic debris.
- Integration of robotic arm and on-board container for collection of larger debris.
- Deliver the debris to a dynamic drop zone without assistance from fiducial markers.
- More robust collection pathfinding routine.

2.4 Targeted User and Price

This robot is intended to be operated on a construction or industrial worksite where metallic debris might be a common work hazard. The robot must be user friendly, such that a person with no prior knowledge in the field of robotics or electronics can operate it. Since the Magni Silver robot is built and manufactured by Ubiquity Robotics, much of the base robotic platform is already operational and fully tested. The team can focus on implementing and integrating the manipulator for the robot as well as development of custom software algorithms. The team is aiming to meet a market price of $7000 for the whole robotic platform.

3. Technical Specifications

Table 1 specifies the features of the robotic platform.

Table 1. Magni Silver Platform

Feature	Specification
Payload	100kg
Odometry	Hall sensor odometry (accurate to 2mm)
Software	Ubuntu 16.04, ROS Kinetic + Core Magni Packages
Computer	Raspberry Pi 3A+
Camera	Upward-facing Pi Camera Module
Navigation	Ceiling fiducial-based navigation
Included Sensor Package	HC-SR04 Sonar (x5) array
Dimensions	490 x 310 x 750 mm

Table 2 displays the specifications for the custom forklift mechanism to be built.

Table 2. Forklift Mechanism

Feature	Specification
Payload	At least 20 kg
Optimum Height for Debris Collection	2 cm minimum off the ground
Servo	12V power rating

Table 3 displays the specifications of the RMDC's operational environment.

Table 3. Operational Specifications

Feature	Specification
Bounded Area	10-meter radius
Metallic Debris	< 5 inches in length, < 200 grams in weight

Table 4 displays the specifications of the microcontroller, a major component of the robot.

Table 4. Raspberry Pi 3A+ Microcontroller

Feature	Specification
Processor	Broadcom BCM2837B0, Quad Core ARM A9
Flash Storage	32 GB (Micro SD)
RAM	512 MB
GPIO	40-pin header
Wireless Connectivity	2.4GHz/5GHz Wi-Fi, Bluetooth 4.2/BLE
Interfaces	USB 2.0 (x1), Full-size HDMI (x1), CSI camera (RasPi module), DSI display (RasPi module), Micro SD
Power Input	5V/2.5A DC

Table 5 displays the specifications for the ultrasonic sensors used for obstacle detection and avoidance.

Table 5. HC-SR04 Ultrasonic Sensor

Feature	Specification
Working Frequency	40 Hz
Operational Range	5-400 cm
Field of View	15°
Dimensions	45 x 20 x 15 mm
Power Requirements	5V/15mA DC

Table 6 displays the specifications for the spinning lidar sensor used for 360-degree sensing capabilities.

Table 6. Sweep V1 Lidar

Feature	Specification
Rotation Frequency	2-10 Hz
Sample Rate	1000 samples/sec
Operational Range	4000 cm
Field of View	360°
Power Requirements	5V/400mA DC

Table 7 displays the specifications for the camera that will allow for computer vision.

Table 7. Pi Camera Module

Feature	Specification
Sensor	CMOS sensor technology
Interface	USB 2.0
Framerate	30 fps
Field of View	180º Fisheye Lens

4. Design Approach and Details

4.1 Design Approach

The RMDC will be built upon the existing Magni Silver from Ubiquity Robotics. This has been chosen as the development platform because it is a pre-packaged robotics testing and development suite; it combines reliable mobility, advanced navigation, internal power source, and a powerful computing unit. The Magni Silver is controlled via a Raspberry Pi 3A+ (RasPi) running Kinetic ROS on Ubuntu. There are a wide variety of packages available for ROS, ranging from mathematical simulations to SLAM pathfinding and navigation [1]. The RasPi will be responsible for controlling two 200W hub motors – each equipped with Hall sensors for odometry – collision-detection via five peripheral ultrasonic sensors (a spinning lidar system will also be trialed), navigation using ceiling-mounted fiducial markers, and collection of metallic debris using a custom forklift-mounted natural magnet on the front of the platform. The Magni Silver can output both 7A 5V and 7A 12V DC power with which it powers the RasPi and all peripherals. The platform can carry a payload of up to 100kg.

Implementation of a GUI has not been considered due to the planned level of operational autonomy of the robot, but could be developed as an add-on to remotely display battery life and coverage of cleanup area.

4.2 Codes and Standards

The RasPi's Linux-based Ubuntu OS operates on the C++ and Python programming standards as set by [2] and [3], respectively. Note that the Robot Operating System (ROS), while having "Operating System" in its name, is actually middleware and does not have any standards associated with it. The RasPi's computing power comes from its ARM A9 core, which conforms to the 1.2.ARMv7-A microarchitecture [4].

A USB 2.0 port that conforms to the USB Implementers Forum, Inc.'s standards is used to interface with and program the RasPi [5].

The on-board Wi-Fi chip conforms to IEEE 802.11 b/g/n/ac standard. This means that it supports both the 2.4GHz and 5GHz bands. It supports a bandwidth of up to 54 Mbps and is backwards compatible with 802.11b while being faster and having better signal range [6]. In addition to Wi-Fi, the RasPi has Bluetooth 4.2/BLE capabilities which meets the standards set by the Bluetooth Special Interest Group (previously standardized by IEEE 802.15.1) [7].

4.3 Constraints, Alternatives, and Tradeoffs

The constraint of the RMDC's design lies with using a pre-packaged robotics platform; a custom, efficiently-designed robot will not be built from scratch with the precise purpose of collection metallic debris. However, the Magni Silver platform is more than capable of prototyping such a concept, thus it is not a constraint within the scope of this project.

Additionally, there are two major design alternatives that have been identified which affect the pathfinding and obstacle-avoidance capabilities of the robot.

4.3.1 Navigation Alternatives:

Navigation could be conducted through Hall sensor odometry or ceiling fiducial markers. Using Hall sensors allows for accurate plotting of the robot's path since the start of a run, however they are only accurate up to 2mm (inaccurate compared to other odometry, such as magnetic encoders) and are affected by motor slip. On the other hand, the Magni Silver's built-in ceiling-oriented RasPi camera can be used to detect fiducial markers. Such marker recognition algorithms are widely available (including ROS packages), however many markers are needed for accuracy in tracking the RMDC's position.

- **Decision:** both Hall sensor odometry and ceiling fiducial markers will be implemented in the RMDC's navigation algorithm. Odometry will be used to keep precise track of the RMDC's current location and traversed path, and markers will be placed in a grid (locations known to the robot) on the ceiling in order to correct errors in odometry when the RMDC passes under one.

4.3.2 Obstacle Detection Alternatives:

It has been determined, based on low cost and complexity, that obstacle avoidance data can be best collected through either ultrasonic or spinning lidar sensors. A spinning lidar would provide the RMDC with a high-accuracy 360-degree field-of-view whereas the Magni Silver's five-sensor ultrasonic suite only detects objects up to 4m in front of each sensor. However, while lidar uses the speed of light to calculate distance, and is thus faster than sonar's speed-of-sound calculations, it does not work as well in non-ideal conditions (i.e. dusty areas); sound waves are very minimally affected by dusty conditions.

- **Decision:** the spinning lidar unit will be tested, but a Stanley Black & Decker advisor has warned the RMDC Team that the provided unit is very buggy and there might be problems using it to map the surrounding area. Thus, the backbone of obstacle-detection development will be the ultrasonic sensor suite, however it will be supported or replaced by the spinning lidar depending on its usefulness/usability.

5. Schedule, Tasks, and Milestones

The RMDC Team is split up into two sub-teams:

1. **Hardware Team:** Yee Aung (YA) *[Lead]*, Christian Brice (CB), Nam Igwe (NI)

2. **Software Team:** Tyler Brown (TB) *[Lead]*, Ying Ying Choi (YC), Mohammad Karim (MK).

The Hardware Team is responsible for designing and implementing all of the custom hardware that will be mounted on the Magni Silver, such as the Ultrasonic sensors and magnetic forklift mechanism. The Software Team is responsible for programming and debugging the custom software that will allow the RMDC to successfully carry out pathfinding, debris detection and collection, and drop-off. **Appendix A** contains a list of all of the tasks as well as the task leader, other responsible members, and the level of importance of each task. **Appendix B** contains a timeline (in tabular form) of the major tasks, delineating the start date, end date, and duration for each. The goal of this project is to finish the design and assembly portion by April 2, 2019 and conduct hardware tests and software debugging until April 22, 2019.

6. Project Demonstration

The RMDC will be designed to be tested indoors on smooth, level terrain. The operational area will be populated by a number of small metallic debris (such as screws and nails) as well as static obstacles of different sizes. A grid of fiducial markers will be placed on the ceiling to act as a passive localization system for the robot. The formal demonstration will consist of the following tasks:

1) The robot will randomly patrol the area around its starting position within a 10-meter radius.
2) The robot will automatically pick up debris along its path by utilizing a magnetic forklift attached to the front of the chassis.
3) Upon detection of an obstacle, or in the case where the robot perceives that it traveled beyond the 10-meter radius, it will deviate away from the obstacle/bound and continue on its path.
4) When the robot's demonstration timer runs out it will navigate to the drop off location.
5) When the robot arrives at the drop off location, it will use its forklift to raise the metallic debris over a collection bin, and retract the solenoid connected to the magnets in order to drop the debris (there will be a thin plastic sheet between the debris and the magnet).

7. Marketing and Cost Analysis

7.1 Marketing Analysis

An autonomous robot with a metal-detecting function is not a new concept; however, no autonomous robot that both detects small metallic objects and collects them for drop-off currently exists in the consumer market. The closest competitor to the RMDC exists in the form of cleaning companies available for hire to clean up construction sites. **Table 8** (next page) shows the costs of hiring a cleaning company.

Table 8. Robot Vacuum Costs

Item	POWERbot R7040 Robot Vacuum	iRobot Roomba 675 Robot Vacuum	ILIFE V3s Pro Robotic Vacuum
Cost	$499.00 [8]	$299.99 [9]	$159.99 [10]

The RMDC benefits mainly from its reusability after the initial purchase. Compared the hiring of a cleaning company, which incurs a cost every time a construction site needs to be cleaned, the RMDC can easily be cheaper in cost after multiple uses. The RMDC also benefits from having no other robots occupying a similar function within the market, allowing it to be sold at a higher price.

7.2 Cost Analysis

The development cost for a prototype is approximately $85,000. **Table 9** shows a breakdown of the material costs involved.

Table 9. Material Costs

Product Name	Quantity	Unit Price	Total Price
Magni Silver	1	$1900.00 [11]	$1900.00
Spinning Lidar	1	$349.00 [12]	$349.00
Ceramic Magnet	20	$5.95 [13]	$119.00
12” x 12” Metal Sheet	2	$4.13 [14]	$8.26
12V 3000rpm Motor	2	$21.59 [15]	$43.18
Solenoid	2	$13.37 [16]	$26.74
Adafruit BNO055 IMU	1	$34.95 [17]	$34.95
		Combined Cost	**$2481.13**

Six engineers will be working together for the development of the RMDC. **Table 10** shows the projected total labor hours for one engineer.

Table 10. Projected Labor Hours per Engineer

Task	Hours
Class	20
Weekly Meetings	22
Reports	8
Research	15
Presentation	5
Fabrication	6
Assembly	10
Testing	30
Total	**116**

The development costs were calculated with an assumed salary of $40 per hour. Assuming 30% of the total labor as fringe benefit as well as 120% of material and labor as overhead, the projected total development cost is $85,082.09. The calculations are shown in in **Table 11** (next page).

Table 11. Projected Total Development Costs

Component	Cost
Parts	$2,481.13
Labor	$27,840.00
Fringe Benefits, % of Labor	$8,352.00
Subtotal	**$38,674.13**
Overhead, % of Material, Labor, & Fringe Benefits	$46,408.96
Total Development Cost	**$85,082.09**

The production will consist of 3,000 units sold at a price of $7,000.00 per unit over 5 years. The profit over five years of production is given in **Table 12** with the following assumptions: (1) there is an approximately 10% discount to the total parts cost for purchasing all components in bulk and (2) there is an approximately 10% sales expense calculated from the input cost. If the RMDC was sold for $7,000 per unit, a profit of around $1,450 would be made. The $7,000 price of the product is rather high, but this is a product that does not exist in the current consumer market, allowing the product to be priced higher without competition from the market.

Table 12. Selling Price and Profit Per Unit (based on 5000 Unit Production)

Expense of Income Component	Amount
Parts Cost	$2,233.92
Assembly Cost	$20.00
Testing Labor	$10.00
Fringe Benefits	$9.00
Subtotal	**$2,272.92**

Overhead	$2,727.50
Input Costs Subtotal	**$5,000.42**
Sales Expense	$500.04
Amortized Development Costs	$50.00
Subtotal, All Costs	**$5,550.46**
Profit	$1,449.54
Selling Price	**$7,000.00**

8. Current Status

Every aspect of development for the RMDC has been identified and discussed in this project proposal. Currently the development team in is possession of the Magni Silver platform and a spinning lidar, and will begin researching relevant ROS packages and ordering parts the week of January 21st, 2019. The main goal by the end of the Spring 2019 semester is to have an autonomous, obstacle-avoiding robot that successfully collects a percentage of all debris within a specified area and deposits it at a specified drop zone.

9. References

[1] https://index.ros.org/packages/#kinetic

[2] http://www.open-std.org/jtc1/sc22/wg21/docs/standards#14882

[3] https://www.python.org/dev/peps/pep-0008/

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[5] https://www.usb.org/document-library/usb-20-specification

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[8] https://www.samsung.com/us/home-appliances/vacuums/powerbot-robot/powerbot--r7040-robot-vacuum-vr1am7040wg-aa/

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[11] https://ubiquityrobotics.com/magni.html

[12] https://www.robotshop.com/en/sweep-v1-360-laser-scanner.html

[13] http://www.magnet4less.com/product_info.php?cPath=2_6&products_id=256

[14] https://www.onlinemetals.com/merchant.cfm?pid=12780&step=4&id=944&CAWELAID=120293320000037830&CATARGETID=120293320000073197&cadevice=c&gclid=CjwKCAiA4OvhBRAjEiwAU2FoJeZX0D49cU38XqeX_lBbrG2kioJclwDC1dpPsybqzNShmD3-AZu6NxoCJIgQAvD_BwE

[15] https://www.amzn.com/B078F7M8R8/

[16] https://www.amzn.com/B01NCVIH80

[17] https://www.adafruit.com/product/2472

Appendix A: Task Distribution and Level of Importance

Task Name	Task Leader	Other Members	Importance
Deciding on Hardware	NI	[Hardware]	*low*
Research RasPi 3	CB	[Hardware]	*low*
Research Sensors, Motors	NI	MK	*low*
Research Forklift	YA	---	*low*
Configuring Platform	YA	CB, NI, MK	*medium*
Secure Hardware Funding	YA	CB, YC, MK	*high*
Ordering Parts	YA	[All]	*medium*
Testing Ordered Parts	CB	[All]	*medium*
Building the Platform	CB	[All]	*medium*
3D Printing Peripheral Mounts	YA	[Hardware]	*medium*
Integrating Peripherals	NI	[Hardware]	*medium*
Prototype Pathfinding Algorithm	TB	[Software]	*medium*
Configuring Hardware APIs	MK	YA, CB, NI	*low*
Refining Pathfinding Algorithm	TB	[Software]	*medium*
Debris Detection and Collection Algorithm Development	YC	[Software]	*medium*
Delivery Algorithm Development	TB	CB, YC, MK	*high*
Project Proposal Paper	CB	[All]	*medium*
Demo/Experiment/Debugging	CB	[All]	*high*

Appendix B: Timeline Table of Major Tasks

Task Name	Start Date	End Date	Duration (days)
Decide on Hardware	11/15/18	11/19/18	11
Research RasPi 3A+ API	11/05/18	11/19/18	11
Research Sensors, Motors	11/05/18	11/19/18	11
Research Forklift Mechanism	11/5/18	11/19/18	11
Initial Project Proposal	11/20/18	12/05/18	12
Secure Hardware Funding	1/07/19	1/11/19	5
Revised Project Proposal	1/14/19	1/18/19	5
Order Parts	1/21/18	1/25/18	5
Configure Hardware APIs	1/21/19	2/04/19	11
Refine Pathfinding Algorithm	1/14/19	1/28/19	11
Develop Debris Detection and Collection Algorithm	2/19/19	3/05/19	11
Develop Delivery Algorithm	1/29/19	2/11/19	14
Trials/Experiments	3/06/19	3/13/19	9
Pathfinding/Navigation Debugging	3/06/19	3/13/19	6
Metallic Debris Detection Debugging and Testing	3/12/19	3/19/19	6
Pick-Up/Drop-Off Debugging	3/20/19	4/01/19	9