ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA

(ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

ESPECIALIDAD MECÁNICA

APPLICATION OF MECHANICAL ENGINEERING DESIGN METHODOLOGY TO REVERSE ENGINEER AND RE-DESIGN A GRILL CLEANING ROBOT

Author: María Reina Gómez-Acebo

Director: Christopher G Rylander (University of Texas at Austin)

Madrid

May 2015

AUTORIZACIÓN PARA LA DIGITALIZACIÓN, DEPÓSITO Y DIVULGACIÓN EN ACCESO *ABIERTO* (*RESTRINGIDO*) DE DOCUMENTACIÓN

1º. Declaración de la autoría y acreditación de la misma.

El autor D. María Reina Gómez-Acebo , como Estudiante de la UNIVERSIDAD PONTIFICIA COMILLAS (COMILLAS), **DECLARA**

que es el titular de los derechos de propiedad intelectual, objeto de la presente cesión, en relación con la obra PROYECTO FIN DE GRADO DE APPLICATION OF MECHANICAL ENGINEERING DESIGN METHODOLOGY TO REVERSE ENGINEER AND RE-DESIGN A GRILL CLEANING ROBOT [1], que ésta es una obra original, y que ostenta la condición de autor en el sentido que otorga la Ley de Propiedad Intelectual como titular único o cotitular de la obra.

En caso de ser cotitular, el autor (firmante) declara asimismo que cuenta con el consentimiento de los restantes titulares para hacer la presente cesión. En caso de previa cesión a terceros de derechos de explotación de la obra, el autor declara que tiene la oportuna autorización de dichos titulares de derechos a los fines de esta cesión o bien que retiene la facultad de ceder estos derechos en la forma prevista en la presente cesión y así lo acredita.

2º. Objeto y fines de la cesión.

Con el fin de dar la máxima difusión a la obra citada a través del Repositorio institucional de la Universidad y hacer posible su utilización de *forma libre y gratuita* (*con las limitaciones que más adelante se detallan*) por todos los usuarios del repositorio y del portal e-ciencia, el autor **CEDE** a la Universidad Pontificia Comillas de forma gratuita y no exclusiva, por el máximo plazo legal y con ámbito universal, los derechos de digitalización, de archivo, de reproducción, de distribución, de comunicación pública, incluido el derecho de puesta a disposición electrónica, tal y como se describen en la Ley de Propiedad Intelectual. El derecho de transformación se cede a los únicos efectos de lo dispuesto en la letra (a) del apartado siguiente.

3º. Condiciones de la cesión.

Sin perjuicio de la titularidad de la obra, que sigue correspondiendo a su autor, la cesión de derechos contemplada en esta licencia, el repositorio institucional podrá:

(a) Transformarla para adaptarla a cualquier tecnología susceptible de incorporarla a internet; realizar adaptaciones para hacer posible la utilización de la obra en formatos electrónicos, así como incorporar metadatos para realizar el registro de la obra e incorporar "marcas de agua" o cualquier otro sistema de seguridad o de protección.

(b) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en

[1] Especificar si es una tesis doctoral, proyecto fin de carrera, proyecto fin de Máster o cualquier otro trabajo que deba ser objeto de evaluación académica

servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato. .

(c) Comunicarla y ponerla a disposición del público a través de un archivo abierto institucional, accesible de modo libre y gratuito a través de internet.[2]

(d) Distribuir copias electrónicas de la obra a los usuarios en un soporte digital. [3]

4º. Derechos del autor.

El autor, en tanto que titular de una obra que cede con carácter no exclusivo a la Universidad por medio de su registro en el Repositorio Institucional tiene derecho a:

a) A que la Universidad identifique claramente su nombre como el autor o propietario de los derechos del documento.

b) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.

c) Solicitar la retirada de la obra del repositorio por causa justificada. A tal fin deberá ponerse en contacto con el vicerrector/a de investigación (curiarte@rec.upcomillas.es).

d) Autorizar expresamente a COMILLAS para, en su caso, realizar los trámites necesarios para la obtención del ISBN.

d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

5º. Deberes del autor.

El autor se compromete a:

---

[2] En el supuesto de que el autor opte por el acceso restringido, este apartado quedaría redactado en los siguientes términos:

(c) Comunicarla y ponerla a disposición del público a través de un archivo institucional, accesible de modo restringido, en los términos previstos en el Reglamento del Repositorio Institucional

[3] En el supuesto de que el autor opte por el acceso restringido, este apartado quedaría eliminado.

a) Garantizar que el compromiso que adquiere mediante el presente escrito no infringe ningún derecho de terceros, ya sean de propiedad industrial, intelectual o cualquier otro.

b) Garantizar que el contenido de las obras no atenta contra los derechos al honor, a la intimidad y a la imagen de terceros.

c) Asumir toda reclamación o responsabilidad, incluyendo las indemnizaciones por daños, que pudieran ejercitarse contra la Universidad por terceros que vieran infringidos sus derechos e intereses a causa de la cesión.

d) Asumir la responsabilidad en el caso de que las instituciones fueran condenadas por infracción de derechos derivada de las obras objeto de la cesión.

6º. Fines y funcionamiento del Repositorio Institucional.

La obra se pondrá a disposición de los usuarios para que hagan de ella un uso justo y respetuoso con los derechos del autor, según lo permitido por la legislación aplicable, y con fines de estudio, investigación, o cualquier otro fin lícito. Con dicha finalidad, la Universidad asume los siguientes deberes y se reserva las siguientes facultades:

a) Deberes del repositorio Institucional:

- La Universidad informará a los usuarios del archivo sobre los usos permitidos, y no garantiza ni asume responsabilidad alguna por otras formas en que los usuarios hagan un uso posterior de las obras no conforme con la legislación vigente. El uso posterior, más allá de la copia privada, requerirá que se cite la fuente y se reconozca la autoría, que no se obtenga beneficio comercial, y que no se realicen obras derivadas.

- La Universidad no revisará el contenido de las obras, que en todo caso permanecerá bajo la responsabilidad exclusiva del autor y no estará obligada a ejercitar acciones legales en nombre del autor en el supuesto de infracciones a derechos de propiedad intelectual derivados del depósito y archivo de las obras. El autor renuncia a cualquier reclamación frente a la Universidad por las formas no ajustadas a la legislación vigente en que los usuarios hagan uso de las obras.

- La Universidad adoptará las medidas necesarias para la preservación de la obra en un futuro.

b) Derechos que se reserva el Repositorio institucional respecto de las obras en él registradas:

- retirar la obra, previa notificación al autor, en supuestos suficientemente justificados, o en caso de reclamaciones de terceros.

Madrid, a 1 de Junio de 2015

ACEPTA

Fdo. María Reina Gómez-Acebo

Proyecto realizado por la alumna:

María Reina Gómez-Acebo

Fdo.: MaríaReinaGA Fecha: ....../ ....../ ......

Autorizada la entrega del proyecto cuya información no es de carácter confidencial

EL DIRECTOR DEL PROYECTO

Christopher G Rylander

Fdo.: Fecha: 6 / 30 / 2015

Vº Bº del Coordinador de Proyectos

Jesús Jiménez Octavio

Fdo.: .... Fecha: ....../ ....../ ......

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA

(ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

ESPECIALIDAD MECÁNICA

APPLICATION OF MECHANICAL ENGINEERING DESIGN METHODOLOGY TO REVERSE ENGINEER AND RE-DESIGN A GRILL CLEANING ROBOT

Author: María Reina Gómez-Acebo

Director: Christopher G Rylander (University of Texas at Austin)

Madrid

May 2015

APPLICATION OF MECHANICAL ENGINEERING DESIGN METHODOLOGY TO REVERSE ENGINEER AND RE-DESIGN A GRILL CLEANING ROBOT

Author: Reina Gómez-Acebo, María.

Director: Rylander, Christopher.

Collaborating Institution: The University of Texas at Austin.

ABSTRACT

If any gastronomic treat could give the proverbially American apple pie a run for its money, it might just be barbecue. Barbecue has been a staple of American culture since colonial times, especially Southern American culture. The state of Texas offers one of the four barbecue traditions that belong to the "barbecue belt" of the United States.
80% of American households own a grill or a smoker, and it is estimated that they are used, on average, at least three times a week.

Design Management from the department of Mechanical Engineering at the University of Texas at Austin asks undergraduate students in their senior year to reverse engineer and redesign a new consumer product that has been recently placed on the market. Due to the large demand for barbecue and grilling in Texas, one of the most recent inventions has been a grill-cleaning robot called "Grillbot".

This product is an automated outdoor grill-cleaning device. It has more than 20 parts, contains electro-mechanical elements, deals with thermal heat transfer, and it has a large user demographic. The electro-mechanical system, as well as the thermal dissipation methods embedded in the Grillbot provides ample opportunities to perform analytical and experimental modeling on the product. Additionally, because the product was only released in January of 2014, it is only about a

year old. The immaturity of the product is advantageous to find critical design issues that were overlooked during development.

The purpose of the Grillbot is to remove the particle buildup from a heated grill without the need for user effort. The machine does work by means of three separate electric induction motors that impart torque to shafts with embedded wire bristles. The motors rotate based on an algorithm programmed into the controller that randomizes alternating motion. The rotating brushes are removable and available for purchase with either steel or copper bristles. The Grillbot works on three timed settings: 10 minutes, 20 minutes, and 30 minutes. These three settings are intended to accommodate all levels of grime removal. The power from the Grillbot comes from an internal battery source so that it can function portably. The Grillbot can nominally run for five 30-minute cycles on one battery charge. The battery is then recharged from an AC power adapter that is plugged into a female port on the Grillbot.

One of the primary reasons the Grillbot was a good selection for preliminary market analysis is that the customer reviews from several sources loved the idea, but had complaints on its operation. It was believed that many improvements could be made that would allow the Grillbot to endure hotter environments, be more user-ergonomic, and remove more sediment.

Therefore, this project focused on engineering solutions that would make the Grillbot a better machine. It was divided in three different phases: task clarification and reverse engineering, conceptual re-design and parametric re-design.

During Phase I, we interviewed customers about their experiences with the Grillbot and analyzed their responses. We conducted reverse engineering of the product following three basic steps: prediction, teardown, and analysis. In the prediction step, we created a black-box model, a hypothesized functional structure, and a predictive cross-sectional sketch. This is to expand our thoughts and imagination of the product so that it increases the possibilities of redesigning it. The teardown step consists of the product-disassembly plan, the bill of materials, and the exploded view. In this step we got to see the actual inside of the product and learn how it works. Finally, the analysis step is composed of the actual function structure and the function component matrix.

For Phase II, we were requested to explore adaptive redesigns of the Grillbot. One adaptive redesign should significantly alter the functionality of the product, and one adaptive redesign should incorporate a major industrial design change to the product. The industrial design change should address an aesthetic, ergonomic, or style aspect of the product. In phase I, we formulated five redesign avenues: noise reducing material, improved brush bristle material, increased motor power, improved handle and addition of weight. House of Quality, customer needs analysis, and feasibility, were considered to finalize redesign avenues for the functional shift and the industrial shift.

Functional Shift

Based on the House of Quality from Phase I, effectiveness of cleaning rated high in the relative importance column. During the interview, one of the customers commented that if the Grillbot were heavier, it would clean better. This tells us the customer wants the grill to perform cleaner. Even after the Grillbot's long cleaning process, dirt still remained on the edges of the grills because the brushes are not designed to clean them. Thoroughly cleaning the grill is important because when food residue is not cleaned well and remains on the grill, the food residue will burn when the customers use it again later. When food is burnt, carcinogenic substances called polycyclic aromatic hydrocarbons (PAHs) are produced. As a result, we decided on "improve cleaning" as our functional redesign avenue.

Industrial Shift

Based on customer interviews, customers gave a low rating for "quiet noise level" and "pleasing noise." Many customers said the product is too loud to talk comfortably near the grill. Therefore, we decided the industrial redesign should be noise reduction. There are two factors that make noise: collision between the device and the wall of grill, and the operation of the device's motors. Since the noise coming out from collision was louder than from the device itself, we mainly focused on reducing noise from collisions.

For Phase III, we determined our parametric interests and experiment responses based on our concept variants and Pugh chart. We built prototypes and conducted experiments with the prototypes. Then we analyzed data in order to figure out the best prototype. Also, we worked on a Design Failure Modes and Effects Analysis, Design for Assembly, Design for Manufacturing, and Design for Environment.

Through all of the experimentation, analysis, design, and prototyping, we have made a Grillbot that cleans better than before. During experimentation and the subsequent parametric analysis, we proved that both longer bristles and increased weight improved the cleaning function. We used statistical analysis to plot the correlations between performance increase and concept variance change. With this data, we can conclusively recommend the implementation of bristle lengthening and down-force increase for a simple, inexpensive, and efficacious redesign. After performing FMEA, we found the various modes of failure and ways to lessen the chances of them happening. By considering DFM, DFA, and DFE, we identified other ways to improve the Grillbot such as better manufacturing, assembly, and use. Finally based on our experimental results, we built a final prototype. This functional Alpha prototype represents the semester-long body of work we put towards the Grillbot.

APLICACIÓN DE LA METODOLOGÍA DE DISEÑO MECÁNICO PARA LA INGENIERIA INVERSA Y RE-DISEÑO DE UN ROBOT DE LIMPIEZA DE LA PARRILLA

Autor: Reina Gómez-Acebo, María.

Director: Rylander, Christopher.

Institución Colaboradora: The University of Texas at Austin.

RESUMEN DEL PROYECTO

Si alguna delicia gastronómica podría ser competencia a la tarta de manzana Americana, sólo podría ser la barbacoa. Barbacoa ha sido un elemento básico de la cultura americana desde la época colonial, especialmente de la cultura estadounidense del sur. El estado de Texas ofrece una de las cuatro tradiciones de barbacoa que pertenecen al "cinturón de la barbacoa" de los Estados Unidos. 80% de los hogares estadounidenses posee una parrilla o un fumador, y se estima que se utilizan, en promedio, al menos tres veces a la semana.

El departamento de Ingeniería Mecánica de la Universidad de Texas en Austin pide a los estudiantes de último año de grado realizar ingeniería inversa y rediseñar un nuevo producto de consumo que ha salido recientemente al mercado. Debido a la gran demanda de barbacoa y asar a la parrilla en Texas, uno de los inventos más recientes ha sido un robot de limpieza de parrilla llamado "Grillbot".

Este producto es un dispositivo de limpieza de la parrilla automatizado. Cuenta con más de 20 piezas, contiene elementos electromecánicos, se ocupa de la transferencia de calor térmico, y tiene un amplio campo demográfico de usuarios. El sistema electro-mecánico, así como los métodos de disipación térmica implementados en el Grillbot ofrece amplias oportunidades para llevar a cabo la modelización analítica y experimental en el producto. Además, dado que el producto fue

lanzado en enero de 2014, sólo tiene alrededor de un año de edad. La inmadurez del producto es ventajosa para encontrar problemas de diseño críticos que se pasaron por alto durante el desarrollo del mismo.

El propósito del Grillbot es eliminar la acumulación de partículas de una parrilla calentada sin la necesidad de esfuerzo del usuario. La máquina hace el trabajo por medio de tres motores eléctricos de inducción separados. Éstos imparten un par a los ejes que tienen cerdas de alambre incrustados. Los motores giran según un algoritmo programado en el controlador que general movimiento alterna de forma aleatoria. Los cepillos giratorios son desmontables y están disponibles para su compra con cerdas de acero o de cobre. El Grillbot trabaja en tres configuraciones programadas: 10 minutos, 20 minutos y 30 minutos. Estos tres valores pretenden ofrecer todos los niveles de extracción de mugre. La alimentación de la Grillbot proviene de una fuente de batería interna de manera que pueda ser portable. El Grillbot nominalmente puede funcionar durante cinco ciclos de 30 minutos con una sola carga de la batería. La batería se recarga después con un adaptador de alimentación de CA que está conectado a un puerto hembra en el Grillbot.

Una de las principales razones por las que el Grillbot era una buena opción para el análisis preliminar de mercado es que varias fuentes contaban con opiniones de los clientes que decían que les gustaba la idea, pero tenían quejas sobre su funcionamiento. Por ello, se creía que se podrían hacer muchas mejoras que permitiría al Grillbot soportar ambientes más cálidos, ser más fácil ergonómicamente, y ser capaz de quitar y despegar más sedimento de la parrilla.

Por lo tanto, este proyecto se centró en buscar soluciones ingenieriles que harían del Grillbot una máquina mejor. Está dividido en tres fases diferentes: clarificación de tareas e ingeniería inversa, rediseño conceptual y rediseño paramétrico.

Durante la Fase I, entrevistamos a los clientes acerca de sus experiencias con el Grillbot y analizamos sus respuestas. Se llevó a cabo la ingeniería inversa del producto siguiendo tres pasos básicos: predicción, desmontaje y análisis. En la etapa de predicción, creamos un modelo de recuadro negro, una hipótesis de la estructura funcional, y un boceto de predicción de la sección transversal. Esto era para ampliar nuestros pensamientos e imaginación del producto y así aumentar las posibilidades de rediseñarlo. En el paso de desmontaje llegamos a ver el interior real del producto y aprender cómo funciona. Se realizó entre otras cosas, el informe de datos de los materiales y la vista de despiece. Por último, la etapa de análisis se compone de la estructura funcional real y la matriz función de componentes.

Para la Fase II, se nos pidió explorar posibles rediseños aplicables al Grillbot. Un rediseño de adaptación debía alterar significativamente la funcionalidad del producto, y otro rediseño adaptativo debía incorporar un importante cambio de diseño industrial al producto. El cambio de diseño industrial debía influir en la estética, aspecto ergonómico, o en el estilo del producto. En la fase I, se formularon cinco avenidas de rediseño: incorporar materiales de reducción de ruido, mejorar el material de las cerdas del cepillo, aumentar la potencia del motor, mejorar el mango y añadir peso. La Casa de Calidad, el análisis de las necesidades de los clientes, y la viabilidad fueron considerados para finalizar las avenidas de rediseño para el cambio funcional y el cambio industrial.

Cambio funcional

Centrándonos en la Casa de Calidad de la Fase I, la eficacia de la limpieza obtuvo una calificación alta en la columna de la importancia relativa. Durante la entrevista, uno de los clientes comentaron que si el Grillbot pesara mas, limpiaría mejor. Esto nos dice que el cliente quiere que el Grillbot limpie mejor. Incluso después del proceso largo de limpieza del Grillbot, la suciedad aún permanecía en los bordes de las rejillas, porque los cepillos no están diseñados para limpiarlos. Limpiar la parrilla minuciosamente es extremadamente importante porque cuando los residuos de comida no se limpian bien y se mantienen en la parrilla, se quemarán cuando los clientes vuelvan a utilizar la parrilla de nuevo más tarde. Cuando se quema la comida se producen sustancias cancerígenas llamadas hidrocarburos aromáticos policíclicos (HAP). Como resultado, decidimos "mejorar la limpieza" como nuestro avenida de rediseño funcional.

Cambio Industrial

Basándonos en las entrevistas, los clientes dieron una puntuación baja a "nivel de ruido tranquilo" y "ruido agradable." Muchos clientes dijeron que el producto es demasiado ruidoso como para hablar cómodamente cerca de la parrilla. Por lo tanto, decidimos que el rediseño industrial fuera la reducción de ruido. Hay dos factores que causan ruido: colisión entre el dispositivo y la pared de la parrilla, y el funcionamiento de los motores del dispositivo. Como el ruido debido a la colisión es más fuerte que el que produce el propio dispositivo, nos hemos centrado principalmente en la reducción de ruido de las colisiones.

Para la Fase III, determinamos nuestros intereses paramétricos y respuestas experimentales basándonos en las variantes conceptuales y en la tabla Pugh. Construimos prototipos y realizamos experimentos con ellos. Luego analizamos los datos con el fin de averiguar el mejor prototipo. Además, también trabajamos en un Análisis de los modos y efectos del fallo de Diseño, Diseño de la Asamblea, Diseño para la Fabricación y Diseño para el Medio Ambiente.

A través de toda la experimentación, análisis, diseño y creación de prototipos, hemos hecho un Grillbot que limpia mejor que antes. Durante la experimentación y el análisis paramétrico posterior, hemos demostrado que las cerdas más largas y un mayor peso mejoraron la función de limpieza. Se utilizó el análisis estadístico para representar gráficamente la correlación entre aumento de rendimiento y el cambio de concepto de varianza. Con estos datos, podemos recomendar de forma concluyente la implementación de alargamiento de cerdas y el aumento de peso para un rediseño sencillo, barato y eficaz. Después de realizar AMFE, encontramos los distintos modos de fracaso y maneras de disminuir las posibilidades de que suceda. Al considerar DFM, DFA, y DFE, se identificaron otras formas de mejorar el Grillbot tales como una mejor fabricación, montaje y uso. Por último sobre la base de nuestros resultados experimentales, se construyó un prototipo final. Este prototipo Alfa funcional representa el cuerpo de un semestre de trabajo que pusimos en el Grillbot.

INDEX

PHASE I: TASK CLARIFICATION AND REVERSE ENGINEERING

Introduction

The product offered to redesign and develop is called “Grillbot,” which is an automated outdoor grill-cleaning device. It has more than 20 parts, contains electro-mechanical elements, deals with thermal heat transfer, and it has a large user demographic. The electro-mechanical system, as well as the thermal dissipation methods embedded in the Grillbot provides us ample opportunity to perform analytical and experimental modeling on the product. Additionally, because the product was only released in January of 2014, it is only about a year old. The immaturity of the product is advantageous for us to find critical design issues that were overlooked during development. Finally, I have a genuine interest in learning how this product functions and engineering solutions that will make it a better machine.

The purpose of the Grillbot is to remove the particle buildup from a heated grill without the need for user effort. The machine does work by means of three separate electric induction motors that impart torque to shafts with embedded wire bristles. The motors rotate based on an algorithm programmed into the controller that randomizes alternating motion. The rotating brushes are removable and available for purchase with either steel or copper bristles. The Grillbot works on three timed settings: 10 minutes, 20 minutes, and 30 minutes. These three settings are intended to accommodate all levels of grime removal. The power from the Grillbot comes from an internal battery source so that it can function portably. The Grillbot can nominally run for five 30-minute cycles on one battery charge. The battery is then recharged from an AC power adapter that is plugged into a female port on the Grillbot.

One of the primary reasons the Grillbot was a good selection for preliminary market analysis is that the customer reviews from several sources loved the idea, but had complaints on its operation. We believe we can make improvements that will allow the Grillbot to endure hotter environments, be more user-ergonomic, and remove more sediment.

Gantt Chart and To-Do List

In order to organize the task distribution and effectively monitor the progress, I utilized the Gantt chart tool based on a detailed to-do list (Appx. A). Tasks were distributed in sequential order of project progression. To track our progress, we had structured meetings on Tuesday and Thursday afternoon where we discussed our individual progression and updated the Gantt chart accordingly. At these meetings, we would also talk about the next stages of the project and construct a timeline for the completion of those tasks as well.

Literature Review

The appeal of grilling is simple: grilling ads flavor, takes a relatively short amount of time to cook large amounts of meat, is simple to use, and can be a social bonding opportunity. The ease of grilling has led to a huge market for grill-related products (Consumer Reports, 2014). Despite the positive attributes that using outdoor grill devices for cooking can provide, there is also a negative side of using grills to consider. The cleaning process is meticulous and strenuous. Over 70% of users complain that cleaning the grill after use is the worst aspect of the grill process (Grilling Product Reviews, 2014). Hence, grill cleaning is the complaint that the Grillbot aims to address.

Based on studies conducted by the Hearth, Patio & Barbeque Association (HPBA), over 80% of American households own a grill or a smoker. Each household is estimated to use their grilling product on average 45 times per year. In addition, it is reported that the main consumer group of grills and grilling supplies is male (70%) and because larger families of more than three members tend to grill more often than individuals, the male consumer is most likely the head of the household (HPBA, 2014). The price point is also a contributing factor into who will buy the product. The Grillbot is significantly more expensive at a cost of $130 than the standard wire-cleaning brush at approximately $10-20 (Grilling Product Reviews, 2014). This information indicated that the consumer of our product will have a disposable income. Because this product is non-essential and leads to satisfaction with only marginal gains, it is considered a “delight” based on the Kano Model.

Therefore, based on statistics provided from our research, we know that our consumer base predominately consists of middle-aged males 30 – 70 years in age who have the financial ability to indulge in “delight” commodities. By knowing this, we are able to factor in the target market when conducting our customer interviews. This information will also help us understand the customer needs by understanding the primary customer.

From our research we have found the main competitor of the Grillbot to be the manual wire brush (Consumer Reports, 2014). The Grillbot contrasts with the wire brush in that it requires very little manual effort from the consumer. The inventor of the product wanted to make cleaning the grill automatic so that users never felt burdened by the cleaning process. However, from consumer reviews, we have discovered that by automating the scrubbing process, you sacrifice in other areas of enjoyment. For example, many Amazon reviews have described the sound the Grillbot makes as “releasing a wild animal (inside)” (Customer Reviews.. Amazon, 2015). Many complaints have emerged from this loud banging sound coming from the grill. Another complaint concerns the efficacy of the product itself. In fact, many people note that no matter how long they run the Grillbot for, there is still a need to use the manual brush after the timed cleaning cycle. Finally, the reviews from Amazon also point to a decay in the brush integrity after a short period of use. Namely, reviews comment on the loss of wire bundles from the rotator brush and of rapid decline in battery performance (Customer Reviews.. Amazon, 2015). By having an idea of the main product defects, we will be able to address complaints through our interview selection and design process.

One of the patents found that help us to understand the Grillbot more thoroughly is of a battery-operated motor in a work apparatus (U.S. Patent No. 8,947,024). We know that the Grillbot contains three individual direct current motors that power the rotating brush arms from the description on Amazon.com, so this patent is related because it describes a product embedded in the Grillbot. It will help us model the system to address the main complaints of our interview subjects. Another patent we found useful for our product is the ceramic coating patent, which is used on the wire brushes (U.S. Patent No, 7462375). This patent is crucial for our product because, if not used, the food particles will stick to the wire brushes and prevent motion. We could use this patent in the Grillbot on other surfaces other than the wire brushes. It could greatly assist in expediting the product cleaning process if we could further reject sediment. Another patent related to the Grillbot is from The Sherwin- Williams Company, (*U.S. Patent No.8844087)* and this patent involves the wire spindles attached to the rotating brushes. The patent describes the structural reasons for selecting the number of wires to embed in a bristle. Because we have found many complaints already with the work done by these bristles, we can use this patent to test different parameters for more effective grime dispersal. Lastly, we have found a patent for an automatic detergent dispenser (*U.S. Patent No. 5839454).* We believe this product will be useful for designing additional methods to increase the effectiveness of the Grillbot. The patent describes the useful hydrophobic properties of soap and methods for dispersing the cleaning fluid. For a future design we are interested in finding methods other than manual work to assist in deep cleaning the grill surface. The patent covers are shown in Appendix B.

To summarize our findings, we have discovered that our target demographic is middle-aged, head of household males with disposable incomes. The product aims to make grill cleaning easier and more effective. The main features of the product that detract from customer satisfaction are its loudness, ineffectiveness, and short life span. Using this information we have constructed our customer interviews to address these points as well as provide an open forum for new criticism.

The Grillbot is one-of-a-kind when it comes to robotic grill cleaners. Therefore, there are no direct competitors, but there are other options when it comes to cleaning a grill. In the end, cleaning a grill is a relatively easy task and most people would opt to simply use a brush. For the few who find it too strenuous to manually clean a grill with an ordinary grill brush, the only other option is the Grillbot or a better, more innovative grill cleaning brush. The Grillbot's competitor comes in the form of "the most innovative and toughest grill brush in the world"- the Rugged Grill Brush, seen in Appendix C. This industrial strength brush has a 6" x 3" stainless steel bristled cleaning surface and a long, angled handle for maximum leverage and reduced work. The brush's durable, twisted wire surface makes it the most effective grill-cleaning brush on the market. Its stainless steel frame makes it dishwasher friendly for easy cleaning. Perhaps the biggest threat that this brush poses to the Grillbot's success is its ability to clean deeper and between the grill gratings.

The Rugged Grill Brush offers grill-masters everywhere a quicker, easier, and more efficient way to clean their grill. The Grillbot offers the same service, making this brush its number one competitor.

Customer Needs Analysis

Mind Map

To begin the customer needs analysis we first drew up a basic mind map to understand how the product was being used, where it was being used, and who it was being used by. In addition, an activity diagram was formulated that addresses in detail the "How?" of the mind map.

Based on the demographic and market research we conducted on our product, we surmised that it would be consumed as a "delight" for the purchaser or as a gift. People who use this product generally see it as a novelty item. This is because the item is not essential for grill cleaning at this point in time. Also, because of the $130 cost of this item, consumers who see the efficiency of a competitor's $10 manual wire scrubbing brush are unlikely to buy this product. It is inefficient from a time and cost perspective. So the amount of physical work it takes to scrub a grill with a normal brush is worth it to some consumers.

Activity Diagram

To understand how the customer uses the product, we had to record the procedural steps. First, the product has to be fully charged to be useful. If it is not fully charged, the machine has a beeping mechanism to let the consumer know that it needs to be charged. Next the device is set on the main grill and the time setting button is pressed once for 10 minutes, twice for 20 minutes, or three times for thirty minutes. The lid is then closed so that the Grillbot does not fall off. If the lid were to be left open, the Grillbot would roll off the side. After the cycle has been run, the user then removes the Grillbot either to clean it or to store it. If the user were to clean the Grillbot they would need to remove the brushes by pressing the release button, and wash them in a washing machine, ideally. If a washing machine is not available, it will be difficult to clean the tightly spaced metal bristles.

This activity analysis is helpful for several reasons. First, we know that the grill must have a lid. Therefore, any permanent set grills (i.e. campground grill, park grill, or neighborhood grill) are excluded from product use. This narrows our market down to personal grill users. In addition, we discovered that the consumer would be unsatisfied if they did not have a dishwasher. The metal bristles gather significant debris, and if the consumer were required to clean them by hand, it would take more effort than using a standard wire brush. Overall, we have determined based on the cost of the product, the applicability of the product, and the requirements of operation, that our consumers would need to possess a disposable income to consider this product. The activity diagram can be found in Appendix D.

Customer Interview Planning Process

When planning the customer interviews we knew we needed to keep in mind who the ideal customer of our product would be. We considered the target demographic as well as how much grilling experience each reviewer had. We opted to interview college-aged people with varying degrees of grilling experience and desire. On each survey we asked them to rate their grilling experience level from 1 to 5. We will use that information when analyzing their responses and weighing customer needs.

To best record all of the customer responses, we decided to give out customer interview sheets that each customer could fill out himself or herself. Each person recorded their name, grilling experience, and opinions on several different criteria. We kept each question open ended, without steering their opinions one way or the other. The interview sheet, as found in Appendix E, starts with a series of questions that ask the reviewer to rate the Grillbot from 1 to 5 on various aspects. For each of those ratings the customer adds additional comments. Below that, are a few more questions that ask what they liked, disliked, and what they would change. Finally we asked how much they would pay for the Grillbot. The last question will come into use when we decide how much less expensive we should make the Grillbot, as we believe cost savings would be a good thing to improve. The interview responses are also shown in Appendix E.

We set up three grills: one charcoal, one propane gas, and one charcoal that had not been cleaned in about a year. The very dirty grill was not lit up, but we did light and cook hamburger patties on the other charcoal and gas grills. The three types of grill surfaces would allow the customers to imagine how the Grillbot would clean their own grill, no matter the type. Additionally the customers could see the effects of cleaning both hot and cold grills. Before cleaning we asked each customer to hold, take apart, and reassemble the product. They were given only basic instructions like how to turn it on and off. After cooking the burgers and dirtying the grill surfaces, we waited until each grill was under 250 degrees F (as instructed in the manual). Then each customer placed the Grillbot on the grill, noting the ease or difficulty with holding and placing the Grillbot and selecting a cleaning time. We had about three customers interact with it on each grill. After cleaning for 10 minutes the customers took note of how clean the grill became and turned the Grillbot back on for an additional 10 minutes if it needed more cleaning. Throughout this process, the customers talked amongst themselves discussing some of the positives and negatives about the product.

Customer Interview Results

The general consensus was that it was too expensive and noisy but did clean better than expected. For many the Grillbot seemed like an unnecessary expense because with a $10 or less brush and a few minutes a person could accomplish the same level of cleanliness. The sounds the machine made while working underneath the grill covers inspired what became a running joke: that it sounded like a Tasmanian devil or like we were grilling a live squirrel. We did conduct the customer interviews in the evening and at night, so some of the customers could have interpreted the higher noise level as more bothersome because of the surrounding neighbors.

Though all of the customers would not have paid the $130 manufacturer's suggested retail price, those who rated their grilling experience higher also rated their suggested price higher. We show this in Appendix F. This might mean that more experienced grillers appreciate the product more and therefore give it a higher value. After all, most people found that it did do an acceptable job of cleaning the grill, though a few were tempted to do a once-over cleaning with a hand brush to finish off the job.

Looking at the summary of the ratings each customer gave for the first part of the interview, we noticed that noise was the biggest problem while appearance and ease of use were very good. The full report of the customer interview sheets as well as the customer interview summary data is located in Appendix G. In the customer needs analysis, we recorded each comment the customer made as well as some of the non-verbal actions we witnessed. For each of those customer "voices" we interpreted the actual need. For each of the customer needs we ranked the importance of that need. We based this importance ranking (from 1 to 4) on both the customer interviews as well as our own judgment. Then we compressed the many voices they expressed into the core customer needs, as seen in the customer interview summary. These core customer needs are then included in the House of Quality, which will be the next step.

The general conclusions we drew from the customer needs analysis were that the Grillbot generally worked well. The robot had an attractive appearance and was easy to disassemble. It cleaned the grills better than some expected, though it took a much longer time that a hand brush. Many customers really liked the automatic aspect to it—that it did all the work for you. Also the battery life was excellent, with over an hour and a half of cleaning, the battery was still half full. Unfortunately the noise, cost, and difficulty of cleaning the Grillbot led many customers to dislike it. They could not enjoy a relaxing meal eating their cheeseburgers while the robot bumped clumsily along inside the grill. Again, the cost was higher than many are willing to pay for a clean grill. One of the biggest issues we encountered was the difficulty with cleaning the Grillbot's own brushes and body. The body could be cleaned with soapy water and paper towels, but there was no easy way to clean the brushes by hand. Cleaning the brushes requires the use of a dishwasher, which could pose an inconvenience to many.

Though generally easy to use, a few people found the brush removal and re-assembly difficult or confusing. It takes significant force to press the button that releases the brush. When putting the brush back on, one must align it with the teeth on the rotating spindle or else it will not rotate and pop off when the motor starts, which happened a couple of times. One feature we did not test yet was the overheating alarm. According to the product manual, the Grillbot can clean in temperatures up to 250 degrees F. When it exceeds that temperature it turns off and sounds an alarm telling the user to take it off the grill.

Next we will take these results and implement them into the House of Quality to better understand them. The House of Quality analysis will help us to act on what to do next.

House of Quality (HOQ)

We used our customer interviews as a basis for developing and creating a House of Quality (shown in Appendix H). The purpose of the HOQ is to organize and assess the customer needs regarding the Grillbot. After we conducted customer interviews, the importance of the customers' responses was discussed. The customer interviews gave us a deeper insight into the biggest issues with the Grillbot and allowed us to determine the first room of the House of Quality: Customer Needs.

We determined all of our customer needs and then placed them into one of the following five categories: User Interactions, Aesthetics, Portability, Effectiveness, and Value. Then, using the customer ratings from our customer interview results, we found an average rating of relative importance for each of the customer needs.

Similarly, we used our customer interviews to determine the next section in the HOQ: Customer Perceptions. Normally, the customer perceptions section would evaluate customers' perceptions of our product in comparison to their perceptions of our competitors' product. However, since there are no other grill-cleaning robots, we were unable to do so.

The customer needs section is directly related to the next section of the HOQ: Metrics. We put the measurable characteristics of the product that are directly related to the specified customer needs in the metrics section. We also labeled each metric with a direction of improvement. For example, since we want to increase the mass of the Grillbot, we put an arrow pointing upward. Likewise, since we want to decrease operating noise level, we put an arrow pointing downward. Finally, we added the units associated with each metric under the direction of improvement row.

The next section of the HOQ is arguably the most important: the interrelationships section. The purpose of this section is to analyze the relationships between the customers' needs and the metrics in order to easily identify how we can manipulate certain aspects of the product in order to meet customers' needs. We represented connections between certain metrics and customer needs through marking their intersection with either a check mark or an "X." For example, 'Easy to hold and place on grill' and 'Mass of Grillbot' have a strong negative relationship (the greater the mass of the Grillbot, the harder it is for the user to hold and place it on the grill.) Therefore, we placed a **bold "X"** in the cell of intersection. The rating system we used involved four options: strong positive, medium positive, medium negative, and strong negative, signified by a **bold check-mark,** a regular check-mark, a regular "X", and a **bold "X"**, respectively. Once again, this section provides an easy analysis of how we can manipulate certain metrics to meet desired customer needs.

The next section lies directly beneath the interrelationships section and is titled the "Targets Section." In this section, we listed our current metric values as well as our desired, "target values." We decided to increase the mass of Grillbot because customers want it to be heavier so that it can clean more effectively. Likewise, our team wants the strength of the wire brushes to increase so it can get rid of the heavier grime left on the grill grating. We would also like to increase the rotational velocity of the brushes: the faster the rotation, the more strokes made by the brush. On the customers' interviews, they complained about the Grillbot's price, so we set the target value of cost to $60, which is a half of its current price. For ‘operating noise level’ and ‘beeping after shut down,” we searched the desirable noise level for ‘operating noise of computer.’ We think this noise level is comparable to the noise level we wish to achieve for the Grillbot. We did not find a large amount of complaints on the color and volume of the Grillbot, so we decided the target values can remain the same as the current values.

In the final section, we demonstrated how the alteration of one metric might affect the value of another metric. In order to determine this, we used the same method we used for the interrelationships section. For positive relationships, we used check marks, and for negative relationships, we used “X” marks. Once again, the boldness of the marks indicates how strong the relationships are. As previously mentioned, this section of the HOQ helps us to see how one metric affects another. For example, we want to increase the rotational rate of the wheels, but this would increase the operating noise level. We then must decide which metric is the most important to alter, which is made easy by the “Relative Importance” column in the customer needs section.

Overall, the House of Quality provides for a simpler, visual analysis of how to improve the quality of our product.

Specification Sheet

After completing the House of Quality report, we created a specification sheet, shown in Appendix I, which summarizes the performance and other technical characteristics of the Grillbot. We assigned each one of our metrics a physical value such as mass, torque, or decibel level to establish a baseline target during the redesign processes. Additionally a notation of “Demand” or “Wish” was assigned to establish each metric’s priority if they ever are to come into question.

We chose the Grillbot for improvement based upon its availability for simple improvements in areas of customer usability and functionality.

Based on our requirements and the House of Quality, our specification sheet also takes into account our concerns about the operation (noise levels and effectiveness) and time constraints. We will use the verification methods mentioned to verify and test our design specifications in order to redesign the Grillbot.

Using the information from our background research, House of Quality, and specification sheet we have identified three key problem areas associated with the product. The first problem area is the loud sound produced in the grill during a Grillbot cycle. We intend to address this problem through design inclusion in the area of vibration dampening. Another main problem area we found was the effectiveness in food particle removal. We intend to address this problem by redesign in the area of torque applied, as well as design implementation of some additional fluid cleaning aid. Finally, we identified customer dissatisfaction with the general accessibility of the product. Because some grills have low clearance sections and small surface areas, we are interested in redesigning the critical geometries of the outer shell. Also a problem associated with accessibility was directed towards the main carrying handle, which can be resolved with a more ergonomic design.

We then started conducting reverse engineering of the Grillbot. Reverse engineering helps you learn about a product and it follows three basic steps: prediction, teardown, and analysis. In the prediction step, we created a black-box model, a hypothesized functional structure, and a predictive cross-sectional sketch. This is to expand our thoughts and imagination of our product so that it increases the possibilities of redesigning it. The teardown step consists of the product-disassembly plan, the bill of materials, and the exploded view. In this step we got to see the actual inside of the product and learn how it works. Finally, the analysis step is composed of the actual function structure and the function component matrix. Further design techniques will be provided in Phase II: Conceptual Engineering Design.

Black Box Model

Our black box model of the Grillbot represents the overall function of the device using energy, material, and information as categorical inputs and outputs (Appx. J). The primary system function of our black box is to remove sediment from a dirty grill. The boundary of the black box, or primary function of the Grillbot, is defined to divide the action of the Grillbot during cyclic operation and the beginning and finishing processes that directly involve the user.

The energy inputs supplied to the machine are electrical energy through the lithium-ion battery pack and thermal energy of the warm grill. One of the material inputs to the black box is the hand that positions and selects the running cycle. Another material input is the grilling unit to be cleaned. The informational inputs to the system are the run-time setting fed by a control button actuated by the user, the battery sensor which indicates with LED lighting the percentage of power left in the battery, and the temperature monitor that alerts the user if the heat from the grill exceeds the material capabilities.

During use of the primary function, the Grillbot outputs thermal energy expended by the friction between the brush wheels and the grill, acoustic energy by operational noise and collisions with the top grill lid, rotational kinetic energy through the rotating wire spindles, vibrational energy of the clattering grill lid, and optical energy of the LED display. The Grillbot operation also outputs material flow by means of the clean grill, removed food particles, and the hand to remove the Grillbot. Lastly, the information output of the Grillbot consists of a completion "Beeping" sound, and the display of the remaining charge.

The sum of the energy input flows is equivalent to the sum of the energy output flows indicating that the energy of the system is conserved by means of the primary operating function. Additionally, the material flows are conserved because the dirty grill and the hand that places the Grillbot for use are also output flows. The informational flows, however, do not follow conservational laws because the required information is not equivalent for input and output flows.

Predictive Cross-Sectional Sketch

A predictive cross-sectional view that details the internal components of our device was sketched. Based on our brainstorming ideas (Appx. K), we finalized our sketch (Appx. L). We know this device operates on electrical power, which is obtained by a power outlet and stored in the battery. Also, we assumed there is an AC/DC converter, which converts AC electrical energy from the wall to DC electrical energy for the motors. In our predictive cross-sectional sketch, the power would be delivered to the controller when the switch is pushed, and the controller would send a signal to its motors. In addition, we assumed there are three independent motors that rotate each brush wheel. Shafts that translate rotational mechanical energy connect the motors to the brush wheels. The controller also sends a signal to the Liquid Crystal Display (LCD) and the speaker. When the LCD gets a signal, it would light up and give users information such as the remaining battery life and cycle time. The speaker would also do that same action. It would make acoustic sound that gives us information. The controller also includes the thermocouple, which detects the temperature of the inside of our device. The predictive cross-sectional sketch expands our thoughts and imagination of the inside of our device and visualizes the enclosure. It helps us in redesign because our prediction could contain a better or cheaper processing idea.

Hypothesized Functional Structure

The functional diagram is an expansion of the black box diagram and is based on our predictive cross-sectional sketch. It takes the same kinds of energy, material, and information inputs and outputs and separates them into the individual parts and processes of the product. The functional diagram allows us to see the inside of the product and recognize energy flows and information transfer. It also shows each point of energy conversion. These points are important in recognizing where potential energy losses from friction and noise can occur.

The hypothesized functional structure (Appx. M) begins with the material input of hand and the information signal to turn it on and set the time. From there, the information is coupled with an electrical energy source inside the circuit board, and that energy is sent forward to the motors, LCD, or speaker. On the way to the motors, the electrical energy is transmitted through the motor wires. Next, the motors convert the electrical energy to rotational mechanical energy. During the conversion process, some energy is lost as waste heat and waste acoustic energy. Next, the rotational mechanical energy is sent to the brush wheels, which convert the rotational mechanical energy to translational mechanical energy to clean the grill. The brush wheels take a dirty grill as a material input and send a cleaner grill and food crumbles as the material output. That process results in acoustic, heat, and translational energy losses. The electrical energy and information that goes to the LCD shows the time left as well as battery life as information outputs. By showing that information the LCD releases optical energy. A temperature-sensing device, likely a thermocouple, converts heat into electrical energy, which gives the controller a temperature reading. This temperature signal turns off the device when it is over 250 degrees F (the melting temperature of standard plastics). Finally, the speaker produces acoustic energy in order to indicate excessive environmental temperatures, as well as when the Grillbot is powered on or off.

Product Disassembly Plan

After completing all of our predictive models, we began to disassemble our product following a systematic procedure. First, we produced the disassembly plan for the Grillbot by documenting the steps we followed during the teardown (Appx. N). Then, we laid out all the different components and parts with their corresponding screws beside them and carried out the exploded-view. Last of all, we used all the information gathered to create the bill of materials (Appx. O).

We used a few tools that were easily available to us in the J lab and were all reversible processes. Those tools are mentioned in the disassembly plan as well as the direction of disassembly, where “i” is the vector for the x direction and “j” for the y direction. Unfortunately, we broke an unessential doghouse clip from the top shell because the plastic was not flexible.

First, we removed the top and bottom screws to get the two main body shells apart. Once the base assembly was separated, the internal structure was revealed. The inside of our product was similar to what we had expected in our predictive cross-sectional sketch (Appx. L). Components that attach to the bottom shell are the three motors, the battery pack, the thermocouple, and the main circuit. Components that were attached to the top shell are the LCD sub-circuit and the power cord. Also, they were both connected to the main circuit.

Next, we removed the handle from the top shell and detached the LCD and the power button. We pulled out the power cord from the main circuit and unscrewed it from the top shell. It was easy to take out the battery and the battery cushion pads from the device. We unscrewed the shafts from the lower shell in order to separate the motors. After we removed the motors, we unscrewed the bottom pads from the lower shell and the label from the handle. We used our hands and screwdrivers to detach the thermocouple from the lower shell, which was mounted with epoxy.

Bill of Materials

The purpose of the bill of materials (Appx. O) is to analyze the internal components of the product. It is a complete catalog of each individual part of the product. It provides a wide range of information for each part, including its function, dimensions, material, manufacturing process, mass, and quantity. Understanding each part helps us gain a thorough understanding of the product as a whole. It also provides for organization and consistency in our analysis of the Grillbot throughout the reverse engineering process.

In order to determine names of each part, we considered their location and function in the Grillbot. For example, the pieces that connect the brush wheels to the motor were named brush-motor shaft. We used an electronic scale to measure the mass. We briefly described the function of each part. The battery function, for example, was described as "Import stored EE to the Main Circuit." In order to obtain robust and precise dimensions, we used a ruler and calipers. We assumed depth (y-axis), width (x-axis), height (z-axis), and inner and outer diameters as the basic dimensions. For the screws, we measured the nominal diameter, the body diameter, the total length, and the length of the head.

We used our prior knowledge of materials manufacturing to assume the most probable form of manufacturing for each part. For example, the top shell is plastic and has a parting line. Therefore we assumed it was injection molded. For bulk orders of screws, it is better to outsource Original Equipment Manufacturer (OEM) screws rather than make them in-house. For the same reason, we assume other parts such as the battery charger, the rubber power button cover, the circuits, the LCD display, motors, and the battery are all OEM products.

In addition to prior knowledge, we used the patent of our product to discern materials. From the patent we learned that the top shell, the lower shell, the pads, the brush-motor shafts, and the brush wheels are made out of TC-895 A/B BLACK. This material has a low thermal conductivity, and is manufactured by BJB Enterprises (Woods, 2012).

Performing a deep analysis of each component of the Grillbot, we understood why the engineers chose to use certain materials and processes for specific component. Based on our bill of materials, we were able to discuss possible redesign avenues.

Exploded-View

The exploded view is a very helpful tool for visualizing the physical arrangements of interior and exterior parts (Appx. P). Understanding a product solely based on its drawing views can be very confusing, especially when the product has over 20 parts. The other purpose of the exploded view is to use it as a guide for reassembly.

The many radial components as well as the linear components made our product challenging to present in an exploded view. For example, screws attach the shell body assembly in the "z" direction, but a 180-degree radial distance separates them. To show the locations of parts, we found it best to show the main axes on a 3-D image of the Grillbot instead of in the exploded views.

To elucidate the part alignment, we included a subassembly of the electronics unit. The subassembly includes the main circuit board and the sub-circuit, which are connected by an 8-pin cable. It was easier to show the internal circuitry as a subassembly because in the main assembly we wanted to highlight the position of the motors. However, the motors are soldered directly to the main circuit board and not removable. Therefore, the position of the electronics was necessarily in the middle of the lower shell, making the components difficult to see. The exploded view, the subassembly of the sub-circuit, and the axial denotations are located in Appendix P.

Actual Function Structure

In the actual function structure, we recreated the functional model (Appx. Q) using the real-life components and design of the Grillbot. The diagram works in a similar fashion to the hypothesized version and is as follows. First, the hand comes in and out as a material input to operate the power button. Those power on/off and time setting signals move through a sub-circuit located near the power button before arriving at the main circuit. The main circuit sends electrical energy and information signals to either the motors or the sub-circuit. From the sub-circuit, electrical energy powers the speaker, which beeps and sends the power on/off status and temperature overheating alarm as information outputs. Alternately from the sub-circuit, electrical energy powers the LCD, which displays the signals of battery and cleaning time remaining as information to the user. From the main circuit, electrical energy flows through motor wires, which transmit the energy to each motor. The motors convert electrical energy into rotational mechanical energy, albeit with waste thermal and acoustic energy. The brushes take the rotational mechanical energy and convert it to translational mechanical energy, moving the Grillbot over the grill surface and cleaning it. The brush wheels take a dirty grill as material input and send out a cleaner grill and food matter as the material output.

Comparison

The hypothesized and actual functional structures are very similar, meaning that our prediction was accurate. The main difference between the two structures was the inclusion of a sub-circuit that controls the power button and the LCD. This secondary circuit board is located underneath the LCD and the power button. This circuit board produces the information on the LCD.

Function-component matrix

The function-component matrix (Appx. R) shows the components of the product and their corresponding functions. A cross ("x") marks components with that function. The matrix shows, for example, how the battery cushion pads stabilize the battery by helping the battery to stay in place and protecting it. At the same time, the bottom pads stabilize the product, supporting it when the brush wheels are not in place. They help the Grillbot to stand still, and they make it sturdier. The Grillbot should not get too hot, so the thermocouple detects the temperature of the inside of the Grillbot. The main function of the motor wires is to transmit electrical energy from the main circuit to the motors. We used the function-component matrix to build our actual functional structure.

Summarization of Reverse Engineering

We use reverse engineering to know a product inside and out. Knowing a product on this level reveals flaws or weak points in its structure, leading one to determine and act on opportunities for redesign. This project is no different. We performed thorough reverse engineering on our product, ultimately to determine potential avenues for redesign.

The first part of the reverse engineering procedure was the prediction step, which consists of deduction and inference to hypothesize the product design. We performed this analysis through predictive modeling, which includes the black box model (Appx. J), the predictive cross-sectional sketch (Appx. L) and the hypothesized functional structure (Appx. M).

The next part of the reverse engineering is the teardown, which involves taking apart the product to determine its internal structure and how it actually functions. While performing the teardown, we recorded the steps of disassembly and named each of our parts based on their function (Appx. N). Once disassembled, we took pictures of all of the parts for the exploded view. We created a bill of materials table (Appx. O) to list the characteristics of each part. After teardown, we constructed the actual functional structure, and our team compared it to the hypothesized functional structure. The purpose of this analysis is to support the next stage of the reverse engineering process, and, eventually, the conceptual design phase of this project.

Throughout the prediction and teardown steps, we were consciously looking for potential avenues for redesign. We used customer needs analysis to narrow our scope to specific redesign avenues. For example, most of the customers listed noise level of the product as an issue for the product. In response, we discussed noise reduction as one of our redesign avenues. We concluded that the sound is not a result of a specific part or function of the product, but simply an unavoidable outcome of the product producing adequate force for cleaning. Therefore, in order to reduce sound, we decided our only option for redesign was to add noise-absorbing material to the product. In doing so, we could also add weight to the Grillbot, which leads us to our next redesign avenue. Some possible noise absorbing materials that we researched are listed in Appendix S.

One issue we noticed with the Grillbot during the performing stages of the product was that for certain grills, it did not have enough force to clean the grooves and sides of the grill rack. In order to increase the cleaning power of the brushes, we would need to add weight to the Grillbot. Adding weight would create a greater downward force of the brushes, but also creates greater resistance against the lateral motion of the brushes. Therefore, in order to avoid the possibility of the brushes locking up, we also need to increase the motors' output power, which would also increase its cleaning power.

Along the same lines, we also noticed how quickly the brushes became dirty and how difficult it was to clean them. In order to eliminate this issue, we simply proposed a different material for the brush bristles. By using a more durable and stick-resistant material, we could increase the lifetime of the brushes and reduce the amount of cleaning necessary.

The last avenue for redesign is based on our customers' complaints about the handle for the product (Appx. G). The current handle design has small-lipped edges that make the Grillbot difficult to grasp. We aim to provide a more efficient handle while still maintaining the low height clearance of the product. A simple way to do this is to smooth out the edges to be more comfortable for the user. However, if possible, the ideal redesign would be to create a novel arched handle that allows the user to grasp it fully. In the next phase of this project, we will explore whether or not this type of handle is feasible for compliance with our design specifications.

When it comes to importance of each proposed redesign, we considered the most important aspect to be the key functionality of the product: how well it cleans the grill. Therefore, the most important redesign avenues are to increase weight and motor power. We considered the customer's needs to be second highest in importance, so we placed the noise reducing material and the better handle next in importance. Finally, we consider the new brush bristles to be least important since it is simply a redesign based on our opinion and experience with the product.

The redesign avenues listed in order of greatest amount of innovation to least amount of innovation are as follows: noise reducing material, improved brush bristle material, increased motor power, improved handle, addition of weight. The redesign avenues listed in order of attainability (from least attainable to greatest) are as follows: noise reducing material, improved brush bristle material, improved handle, increased motor power, addition of weight.

Update Specification Sheet

After going through the redesign process, we evaluated the previously completed specification sheet (Appx. I) to see if there were any necessary updates to be made. The first change we made was the mass section. After weighing the components and getting a combined weight of 3.35lbs, we decided to lower our minimum allowable weight to 3.5lbs. After disassembling our product, we know the exact number of parts of the Grillbot. Therefore, we changed the maximum allowable number of components. We used a phone application called "dB" to measure the noise rather than using a sound level meter. We also compared the result we got from the phone application to the noise made by similar products to verify the values we got. Lastly, we used the motor torque and power to calculate the rotation rate of the wheels with the following equation:

$$speed(rpm) = 63{,}025\,\frac{Power(Hp)}{Torque(lb \cdot in)}$$

It is important to update the specification sheet, because we know the true values and can work on the redesign avenues better. The updated specification sheet is located in Appendix T.

Problem Statement

After going through the reverse engineering process, we came up with several redesign avenues. The most significant of the redesign solutions is noise level reduction. All of the customers during the interview process marked the noise as a problem. In response to these critiques, we considered avenues to decrease rattle. We are considering attaching noise-absorbing materials around the shell of our product. In addition to reducing noise, adding material to the product will also increase overall mass. Since one of our redesign avenues is to create more down force, adding noise-absorbing material will target multiple customer complaints.

PHASE II: CONCEPTUAL RE-DESIGN

In order to maximize organization and efficiency for Phase II, we developed an updated Gantt chart and To-Do List. In the Gantt chart, the greatest amount of time was allotted for the brainstorming section of this phase. Both of these can be shown in Appendix U.

Redesign Avenues

Considering customer needs analysis (Appx. G), the House of Quality (Appx. H), and feasibility we finalized the redesign avenues for the functional shift and the industrial shift.

Functional Shift

Based on the House of Quality from Phase I, effectiveness of cleaning rated high in the relative importance column. During the interview, one of the customers commented that if the Grillbot was heavier, it would clean better. This tells us the customer wants the grill to perform cleaner. Even after the Grillbot's long cleaning process, dirt still remained on the edges of the grills, because the brushes are not designed to clean them. Thoroughly cleaning the grill is important because when food residue is not cleaned well and remains on the grill, the food residue will burn when the customers use it again later. When food is burnt, carcinogenic substances called polycyclic aromatic hydrocarbons (PAHs) are produced ("Cancer," 2014). As a result, our team decided on "improve cleaning" as our functional redesign avenue.

Industrial Shift

Based on the customer interviews, customers gave a low rating for "quiet noise level" and "pleasing noise." Many customers said the product is too loud to talk comfortably near the grill. Therefore, we decided the industrial redesign should be noise reduction. There are two factors that make noise: collision between the device and the wall of grill (Appx. V), and the operation of the device's motors. We measured noise for both. Since the noise coming out from collision was louder than from the device itself, our team mainly focused on reducing noise from collisions.

Mind Maps

After redesign avenues were finalized, we moved on to brainstorming. The brainstorming methods we used were mind-mapping (Appx. W) and 6-3-5 (Appx. X).

Industrial Redesign Avenue

We began with our industrial redesign avenue: noise reduction. The first six concept ideas that branched out from the center were the following: “the grill,” the body of the Grillbot, the motor, the brush, avoiding collision, and external factors. We considered changing the grill itself so it reduces collision noise. We thought of adding pads around the inside perimeter. For the body of the Grillbot, we considered changing its material or adding a soft bumper to reduce the collision noise. We could also change the original motor and decrease its speed or we could simply add sound-absorbing material around the motor. The brushes could be modified in two ways: by adding bristles over the ends of the brush, or making the brushes longer so that it reduces the sound of the collision. Since most of the noise is produced due to collisions, we could install radars, IR sensors, and probes to avoid them.

Functional Redesign Avenue

Similarly, the functional shift mind map branched out from “Improve Cleaning.” The concepts that branched out from the center of the map were increasing friction, cleaning dispenser, changing brushes, increasing cleaning duration, and adding mini robot and ultrasonic cleaning. Cleaning has to do with friction. If there is more friction, the device can remove the dirt attached to the grill more effectively. If our device had a cleaning fluid dispenser, fluid could soften the grime by decreasing surface tension and “wetting” the dirt, which helps to clean it better. Naturally, we would use a cleaning fluid dispenser; however, the fluid would decrease the friction between grill and the device. Therefore, we need to experiment the effectiveness of both ideas. We could also redesign the brushes to have different materials, different patterns (geometry), or larger cleaning area. Other ideas are incorporating a mini robot to help clean or using an ultrasonic cleaning bath.

6-3-5

With four senior mechanical engineering students (including myself) and two other undergraduate students, we conducted two 6-3-5 (Appx. X) exercises. By using this intuitive rapid-fire brainstorming technique, we came up with various new solutions.

Functional Design Change

After reviewing our idea, we noticed that many people drew brushes with different patterns. Therefore, our redesign prospects focused on the bristle material, length, and geometry. Other ideas were using cleaning fluid, increasing force, using ultrasonic vibration, and increasing number of passes. From these concepts, we generated numerous ways of accomplishing these functions.

Industrial Design Change

One of the best ideas was to attach a shock-absorbing material that acts as a micro-pneumatic damper. In addition to cushioning the body, it would include springs that absorb the force. An analog to reduction of force is a mass-spring-damper system. This is a proven method of absorbing force and energy. For our product, dissipation and redistribution of collision energy is the best way to dynamically attenuate the acoustic energy of the lid. We considered adding sensors to avoid the device to collide. The sensor can tell the motor circuit to change direction and avoid collision.

Functional Background Information

Our team researched five analogies (Appx. Y) that gave us ideas to redesign our product. The five analogies are car wash, toothbrush, ultrasonic glasses cleaner, dental floss, and water jet.

The first analogy is car wash. A car wash is a facility that cleans the exterior of automobiles. One of the common cleaning methods is using giant brushes with cleaning fluid dispensers. Because our product also uses brushes adding at least one cleaning fluid will make it clean thoroughly like in a car wash. Cleaning fluid, such as soap, is made up of molecules with two very different ends. One end of soap molecules is hydrophilic. The other end of soap molecules is hydrophobic. Hydrophobic ends of soap molecules attach to the oil. This will make a drop of oil attached to the grill to be pulled off easily from the surface (“Soap,” n.d.). We could design our product to have a soap dispenser. We could implement this idea by having a nozzle stick out of the Grillbot, having a dispenser at the end of the brush, or having a dispenser on the radial part of the brush.

We gained an idea from toothbrush bristles. A toothbrush is a stick with tiny bristles mounted at the tip. One uses this to clean one’s teeth. Some toothbrushes have bristles of various lengths. This pattern helps to clean one’s teeth more effectively, especially given the spaces between teeth. The bristles of varying lengths reach the parts of one’s mouth where even-length bristles cannot reach. For example, the short bristles reach areas towards the top of your tooth while the longer bristles reach to the crevices between teeth. Because the bristles have different lengths, they reach various areas without interfering with each other. When the Grillbot moves across the grill with single-length bristles, it does not clean the edges of grill grates. However, if the brush bristles of Grillbot had different lengths, the longer one will clean the edges while the short bristles would simultaneously clean the grill surface.

The third analogy is dental floss, a cord of thin filaments used to remove dental plaque from between teeth where toothbrushes cannot reach. Dental floss and Grillbot are similar because they both are trying to get rid of food residue, and the objects that they clean have uneven surfaces. The principle of dental floss is sliding the floss between the teeth in a reciprocating motion. We can adopt it to our Grillbot by having a conveyor belt inside our product and make it move translationally. The friction caused by the belt will push off the food residue and will clean the edges of the grill.

Water jet cleaning also inspired the team. Water jet cleaning is a method that shoots water at a very high-pressure. The principle of it is to spit out high-pressured water, which pushes off the dirt on the grill. We could adopt this idea by having a nozzle that swings slowly. This method can be useful if we can have a small high-pressure pump inside of our device, as the water jet will lift up food particles. Also, this method just needs water; therefore the customer does not need to buy detergent.

The fifth analogy is ultrasonic glasses cleaner. Ultrasonic glasses cleaner uses high-frequency sound waves to remove many types of contaminants from parts immersed in aqueous media. If our device has a big bath that could immerse grills in, high-frequency sound waves between 20-80 kHz (“Ultrasonic,” n.d.) will remove dirt on the grill.

Morphological Matrix

The morphological matrix (Appx. Z) helps to organize and categorize many different ways of performing specific functions. First, we came up with sub-functions that affect cleaning quality from our actual functional diagram from Phase I. The components that have to do with cleaning are the motor, the brush-motor shaft, and the brush wheel. We first listed their sub-functions: converting electrical energy (EE) to mechanical energy (ME), converting rotational mechanical energy (RME) to translational mechanical energy (TME), transmitting rotational mechanical energy, and regulating friction. In order to advance the cleaning process, we considered adding other components to complete extra tasks such as converting EE to thermal energy (ThE) and importing fluid. We investigated these functions in terms of EE, ME, ThE, acoustic energy, and fluid principles.

To convert EE to ME, we came up with using an AC motor and a DC motor with different speeds or durations to improve cleaning. Furthermore, if we have more motors, it could increase the cleaning effectiveness. Though, in order to have an AC motor, we need to have a current inverter inside of the device or a cord needs to be plugged into the wall. We think it is not feasible, because people usually grill outside and it is hard to find an outlet outside. Additionally, if we use an AC motor, we will need a converter for the battery that would convert AC to DC, which is an extra component. From the 6-3-5, we came up with the sub-function idea that converts directly from EE to TME, which increases the efficiency. We could use linear motors, a technology HIWIN Corporation invented (Linear, 2013). If we had linear motors, our device could clean more thoroughly, because it would not skip any area. Our current device moves randomly; therefore, it could miss some spots. However, the spaces between grill gratings are small. Therefore, we think a DC motor would be the best choice.

To convert RME to TME, we considered using three-wheeled or multi-wheeled omnidirectional robots, Chebyshev linkage, Hoekens linkage, and a slider. The Grillbot currently uses a three-wheeled robot, which allows it to move in various directions. We came up with a multi-wheeled robot, but this design would make it hard for the device to change direction in a small space. We considered those linkages, because part of their motion contains linear motion. We can utilize Chebyshev linkage and Hoekens linkage to convert rotational motion to approximate straight-line motion of a point with a four-bar linkage (Appx. AA). We think using a slider could be good for our product because it will clean the same surface repeatedly, which could get rid of residue on the grill better. Due to the small space between the gratings of the grill, using a slider is not a good idea. Linkages are hard to adopt, because they need a larger area. Our target volume is 241 cubic inches (Appx. H), and we want to maintain it. As a result, a three-wheeled robot is the most feasible idea.

To regulate friction, we considered using electric sensitive material, adding a potentiometer, using different types of brush materials or brush patterns, and increasing the weight of device. If we use electric sensitive material, it would adjust how hard the bristle works depending on the amount of voltage. As the bristle gets stiffer, the friction caused by the brush will get larger, thereby cleaning better. There are many types of grills. For a coated grill, it needs to be cleaned carefully; otherwise the bristles will peel the coating of grill. For an uncoated grill, we can use sturdy bristles. Therefore, depending on the type of grill, the users can adjust the hardness of the bristle. It has a potential for many users to clean different types of grills. We could use a potentiometer to change the angle of various parts. For instance, our team could use it to change the angle of the bristles or even the water jet nozzles (we will discuss the benefits of adding a water jet later in this section). Then, the water jet nozzles will swing (changing angles over time), shoot water at a larger area, and clean the edges of the grill. Different types of brush materials would have different friction coefficients, and we could use copper, steel, and rubber. More friction will result in better cleaning. If the device were to have different brush patterns (different geometry or alignment of the brushes), it would be able to remove food residue on the edges of the grill due to new reachable contact areas and contact angles. Since electric sensitive material can generate and also adjust friction force, we decided it is the best idea.

To import fluid, we found several ideas such as the following: adding different types of pumps and flammable chemicals, dispensing soap or water radially and axially on wheels, adding a dispense nozzle, and incorporating a water jet. Flammable chemicals can be used to melt dirt stuck onto the grill. However, using a flammable chemical is not very feasible, because it might heat up the device too much and burn it (“Common,” 1991). We could have an electrical pump to dispense fluid, but it would be hard to manufacture it so it is small enough to fit inside the device

("Electric," 2015). A component that dispenses fluid would soften the food particles. Once they are moisturized, the device could remove them more easily. We considered using water or cleaning fluid. The team decided that cleaning fluid is more beneficial, because the dirt attached to the grill is mostly oily residue. The cleaning fluid can reduce the surface tension between the grill and the dirt making it easier to remove. Having fluid dispensers is a feasible idea; we could have the fluid dispenser on a radial or axial position (Appx. AB). Adding a water jet is another good idea. Shooting water at a high-pressure will easily remove dirt on the grill, but the cost to implement this method would be expensive.

To convert EE to ThE, we imagined using induction heating, resistance heating, laser, steams, or radio waves. Induction heating and resistance heating could be used to soften food particles. Another idea is that we could shoot lasers and burn down the dirt on the grill instead of using brushes. Using steam is similar to using dispensing fluid. It will soften dirt, and it will come off easily. Steam is the most feasible idea, because implementing laser equipment would cost too much and using a heating element might cause the device to melt or even burn the grill.

To convert EE to vibrational energy, we considered having an ultrasonic bath on our device. It will use sound waves of frequencies 20-80 kHz ("Ultrasonic," n.d.). However, the bath should be big enough for the grill to be immersed in, which is impossible. That would change the Grillbot into a completely different device. Additionally, it costs too much and requires a complicated system to generate the sound waves. Therefore it is not a good idea.

To transmit RME to a large area, we considered longer bristles, hinged legs, and a bear trap. Longer bristles have a larger area to sweep off the dirt. Hinged legs are another way to transmit RME, but it will not be feasible to redesign, because we want to keep the same volume (Appx. H). Therefore, we cannot adopt this idea. We could have a brush that clamps to the grill. The clamp will grip the grill and rotate around it. It would increase the friction while it is transmitting RME. However, the spaces between the grill bars are small and there are different types of grills, which limit its function; therefore it is not feasible. Lengthening the brushes is the most feasible idea, because it will increase the cleaning area and is easy to manufacture. It will also reduce collision noise.

Theory of Inventive Problem Solving (TIPS)

Based on our House of Quality, we picked the feature we want to improve: the length of the brush. Increasing the radial length of the brush (#3) affects the rotational speed (#9), because it would have a larger circumference, which could decrease the rotational speed. Three principles we got are the other way around (#13), asymmetry (#4), and counter-weight (#8). The most feasible idea we would like to implement is principle #8. If we could adopt the aerodynamic lifting force, it will have the same rotational speed with the various bristle lengths. TIPS result can be found in Appendix AC.

Concept Variants

We selected the five concept variants (Appx. AD) for the functional redesign avenue based on mind maps, 6-3-5 sessions, the morphological matrix, the TIPS, and background analogies. We selected the five concepts for industrial redesign avenue based on mind maps and 6-3-5s. We also considered general physical limitations, cost, complexity, performance, and how much each design meets customer needs to narrow our focus and eliminate unrealistic avenues.

Concept Variants for Functional Redesign

The particular customer complains about the cleaning performance of the product concerned the lack of penetration ability to remove grime from the spaces in between the parallel grill bars and the inability to remove hardened oils that have large intermolecular forces binding them to the surface. The first functional redesign concept variant is to increase the weight of the Grillbot. We considered this equation: $F_{friction}=\mu_k*(mass*gravity)$. As you increase the mass of the device, the friction will get larger. Increasing friction between the grill and the device will pull off more dirt from the grill. Therefore, it will clean better. Additionally, we reasoned that by increasing the down force, we would also increase the depth of penetration, which would increase customer satisfaction. To increase the mass, we could make the device body thicker, add additional material to the empty space inside, or add magnets to the bottom surface, which would pull the Grillbot to the steel grill.

The second concept variant is modifying the bristles. By lengthening the bristles, we would increase the probability of removing lodged matter from between the bars as well as increasing the surface area of affectation for the top planar surface. This design would be easy to implement with manufacturing, because there are no extra parts to source.

The third concept is using cleaning fluid. Because the grill becomes oily after grilling, we think using cleaning fluid would get rid of oily dirt easier. The dispenser could be gravity-fed, using the fluid pressure to "push" the fluid out, similar to a generic squirt bottle.

The next concept variant is increasing cleaning time. Increasing the running time of the Grillbot allows more passes over the surface. As the number of passes increases, the probability of having an untouched area decreases. We can find motors that allow the device to run longer.

The last concept variant is using a water jet. If high-pressurized water were shot towards the grill, the force of water jet would act on the food particle, which would create a shear force. This would strip off the food residue. Also, it can reach the spaces between the bars. In order to adopt it to our device, we need a portable air compressor that could pressurize a container of water so that the output of the nozzle would be sufficient for removing organic matter.

Concept Variant for Industrial Redesign

Though the motors do produce noise, most of the noise comes from the collision of the Grillbot against the sides of the grill. To address the collision noise, our first concept variant is a spring with shock absorbing material on the outer surface. The premise of this design is to simulate a mass-spring-damper system, which is commonly used for signal and vibration attenuation. The spring will store most of the energy of the impact, and the damper (cushion material) will absorb some of the energy and soften the impulse. We will implement this idea by bending a thin aluminum sheet with a carpet material attachment on the surface (damper) and attaching it to two soft springs that are connected to the edge of the shell. We will add three of these systems at 120 degrees radial separation to ensure all sides are protected from impact.

We could lengthen the shafts that connect the brushes to the motors to prevent the device body from colliding with the grill lid. Also, we could add a soft material or bristle over the end of the brush to reduce the collision sound. This concept is rather simple, because we only need to extend the length of the shafts or add materials over the end of brushes.

The next concept is decreasing the thickness of the device body. Decreasing the thickness of the device of the body would decrease the mass, which would decrease the impacting noise.

The fourth concept is using sensors so we completely avoid collision. One of the most inexpensive yet effective forms of sensor detection is an infrared sensor, which has emitting and receiving transmitters. If we applied three of these sensors, which would have a 120 degree field of view, and in a 120 degree radial orientation, we could have the motors change direction before impact, thereby eliminating sound generation altogether.

The last concept is adding sound absorbing materials around the motor to reduce the noise coming out of the motor. This would be inexpensive and, in coupling with one of the variants above, could reduce the majority of operation noise.

Low Resolution Prototype

There were many ideas of changing the shape of the bristles. As it has a crucial role in cleaning, because it directly cleans the grill, we decided to make low resolution prototypes on the brush. The construction process can be found in Appendix AE. Prototype 1 has even length bristles, aligned in a straight line. Prototype 2 has uneven lengths, aligned in a straight line as well. Both prototypes will be able to clean the edges of the grill. We designed uneven bristle lengths, because when the motor is running fast, the even length brushes might not clean the edges of the grill. After we finished building them, we showed our prototypes to potential customers and received feedbacks. Three of them liked prototype 2, because they think the longer bristles can clean the edges of grill. Customer 1 likes prototype 1, because he thinks it will clean the edges of the grill. Customer 4 mentioned that he does not like prototype 1, because he thinks it would not clean the top of the grill. As a result, we will try to manufacture the brushes in the future with our designs, and test to compare the results of the current brushes and prototypes.

Order-of-Magnitude

After we had generated concepts, we wanted to see how they would improve the cleaning process mathematically. The calculation allows us to see if our concepts would be feasible. Concept variant #1 will increase the friction force applied to grime by a factor of 2. The resulting impact velocity from bending will also double. Overall, we can expect more than double the effective forcing on debris by adding 5 kg. For concept variant #2, the total cleaning area of the current brush is 220mm^2 and the total cleaning area of the new one is 8400mm^2, which is 3.76 times larger. Concept variant #3 uses soapy water to cut the grease and food particles, making for easy removal. The soap contains detergent molecules that bind to both polar and non-polar molecules, allowing them to emulsify and wash away. For concept variant #4, the total grill area being cleaned with the current brush is 1.26m^2 and 2.51m^2 with the target motor. The target motor can clean an extra area of 1.25m^2 because the cleaning time generated by the target motor is two times longer than the current motor. Lastly, concept variant #5 details the design and results of including a high velocity water jet at the base of the Grillbot. This addition extends beyond the penetrability of the brushes to include the spaces between the grille bars. The force applied from a fluid jet at 10 m/s is about 22 N, more than 20 times the forces applied by friction. The calculations for Order-of Magnitude can be found in Appendix AF.

Specification Sheets

Industrial Redesign Avenue

After selecting our avenues for improving the Grillbot’s design, we could define more finite specifications to help reach our product’s requirements. For the industrial redesign avenues, many of the original specifications are still valid. We decided mostly on adding sound-absorbing materials on the outer surface of the Grillbot as well as around the motors to reduce the noise. Since the materials are new changes we are implementing on the product, they do not change any specific metric. The only major change is the length of the shafts. The specification sheet can be found in Appendix AG.

Functional Redesign Avenue

Selecting various functional improvements to the Grillbot allowed us to narrow down and add new specifications to the specification sheet (Appx. AG). The first change we want to make to improve cleaning is to increase the weight. Therefore, we chose a higher target value for the mass. We also increased the cleaning time from 30 minutes to 60 minutes, and we changed the dimensions of the brushes. We want to increase the length of half of the bristles from 9 mm to 12 mm, which will increase the cleaning area of the brushes and therefore, the total area of the grill being cleaned.

Pugh Chart

We used the Pugh chart (Appx. AH) to methodically compare the concept variants. We considered increasing the weight, modifying the brushes, adding a water dispenser, increasing the cleaning time, and adding a water jet. We evaluated each of these variants based on the following criteria: purchasing cost, cleaning time, development risk, durability, maintenance, ease of use, battery life, and, most importantly, cleaning ability. In deciding on those criteria, we consulted the House of Quality and customer needs interviews we performed in Phase 1, as well as our own engineering judgment. In rating the concept variants on each of those criteria, we used the scale of worse than (-), same as (0), or better than (+). Each concept variant acts as the datum in one of the five Pugh charts in order for each variant to be relatively compared to the others.

With increased weight as the datum, most other options will cost more because of their relative complexity with the exception of adding run time. Because adding weight increases the cleaning force, it cleans about as quickly as modifying the brush, quicker than the water dispenser and the adding of run time. The use of the water jet is the only option that cleans more quickly than increasing the weight. Generally, the development risk of sourcing parts is difficult, and the durability is closely tied, because more complex systems are usually harder to procure and less reliable. Because of its higher weight, modifying the brushes makes the product easier to use while having to add fluid for the water dispenser or water jet makes them less easy to use.

With modifying the brush in terms of datum, purchasing cost, development risk, and durability prove to be better than the other variants because of its simplicity. Though simple, the better brushes also reduce their relative cleaning time while increasing their cleaning ability and not affecting their ease of use compared with the stock design.

While looking at the water dispenser as the datum point, we found that it performed worse than all the other variants except the water jet. Dispensing water added cost, development risk, and unreliability compared with increasing the weight, modifying the brush, or increasing cleaning time.

The water jet proves to be more expensive and more unreliable relative to the other options. However, it is ranked by far the best cleaning performer, because it adds a high-pressure water jet to the existing Grillbot, easily blowing away stuck food particles. However, due to its complex setup, which involves filling the Grillbot with a cleaning fluid and then having to clean up wet coals and ashes beneath the grate, the water jet is less easy to use and requires much more maintenance. Simply increasing time is inexpensive and easy, but does not solve some of the biggest requirements. It does not clean better or faster than any of the other variants while using more battery life.

As a result, we found a few solutions that rise above the others. Adding all of the new totals together gives the rankings from best to worst variant: modifying the brush (17 points), increasing cleaning time (11 points), increasing weight (4 points), adding a water dispenser (-11 points) and adding a water jet (-12 points). Though some of the variants scored very poorly, combining multiple concepts into one can round out the negatives and provide very good cleaning power.

Problem Statement

Functional Shift

Based on our House of Quality, we will improve cleaning of the Grillbot. The five concepts are increasing weight, modifying the brush, using a water dispenser, increasing cleaning time, and adding a water jet. Based on our order-of-magnitude and Pugh chart, we decided modifying the brush is the best idea to improve cleaning.

Industrial Shift

Based on customer needs analysis, we will work on noise reduction. Five concepts we have came up for this are adding soft bumpers, modifying the brush, adding sensor, decreasing the mass, adding sound absorbing shell around the motor. Decreasing the mass is conflicting with improve cleaning; therefore we want to avoid it. Finally, we want to try adding soft bumpers and sound absorbing shell around the motor, because it is cheaper than implementing sensors.

PHASE III: PARAMETRIC RE-DESIGN

In Phase II, we performed conceptual design for our product. As a result, we developed five concept variants for our functional redesign avenue. For Phase III, we determined our parametric interests and experiment responses based on our concept variants and Pugh chart. We built prototypes and conducted experiments with the prototypes. Then we analyzed data in order to figure out the best prototype. Also, we worked on a Design Failure Modes and Effects Analysis, Design for Assembly, Design for Manufacturing, and Design for Environment. We developed a Gantt chart and a to-do list (Appx. AI) to organize tasks.

Parametric Interests

In order to create a proper factorial experiment, we first needed to identify some factors and responses that best embodied our functional redesign avenue: improve cleaning. From our previous concept variants, we chose varying the length of the bristles as our first parametric interest, because it got the highest score on our Pugh chart (Appx. AH). Although increased cleaning time scored second on the Pugh chart, it does nothing to really improve cleaning. We are interested in better cleaning per unit time, so just adding more time is not a real solution. Additionally, no matter how much time the Grillbot had to clean, without changing the weight or bristles, it could never reach deep between the grates to thoroughly clean. Therefore we chose the third place finisher, increasing the weight, as our second parametric interest. This cleans better while also being low cost and simple to implement. Once we had those factors in mind, we had to think about the best responses and how to test them. Since we are trying to improve cleaning, our response variables are depth of penetration of the bristles and the amount of dye removed. These responses will tell us what features can clean the edges of the grill better and how much it can clean. The first one refers to how far the bristles reach on the grill grates while the second response measures how much food residue is actually removed. We thought that testing the response variable of depth of penetration on a real grill grate would be very difficult so we decided to simplify it by building a frame that would carry out this test.

Experimental Model

After some group brainstorming, we came up with the following experiment. We applied Prussian blue dye on a rod placed under the prototype brush and run it by attaching the brush to a motor. We chose Prussian blue dye, because it is a viscous pigment that resembles the actual grease on a grill. Also, as the dye is blue and we would be measuring the results optically, it would make it easier to see and compare.

We carried out four different trials as we had two factors: no weight and short bristles, no weight and variable bristles, weight and short bristles, weight and long bristles. We also decided to carry out the whole experiment twice for accuracy.

Building the Prototype

First we made the brushes out of PVC as we had easy access to it, and it would be easy to machine. We made two brushes, both the same length but a bit longer than the original brushes to be able to fit an aluminum adapter that would attach them to the motor. We drilled holes in them where we inserted the bristles, which were made of copper wire. We used copper wire as it has similar material properties to the original brass bristles. Lastly, we used hot glue to affix the bristles in place. While one of the brushes had constant bristle length (same length as the original ones), the half of the bristles of the other brush was longer than the other half. We had to make the brushes twice, because the first time, the bristles interfered in the center since the columns of holes were aligned. Therefore, when we made them again we had to make sure that the holes had a certain offset to prevent this problem from happening. These prototype brushes are shown in Appendix AJ.

The complete assembly of the experiment model can be seen in Appendix AK. We made the whole test stand out of wood, because it was easy to use and cut and strong enough to carry out the experiment. Most parts were glued together and some were reinforced with a few screws. We wanted the rod to be equivalent to a grill grate. We measured the diameters of about 20 grills to determine an average characteristic grate size. Based on those results, we turned down a steel rod to a diameter of 0.25 inches to act as the grill grate.

We made several parts out of aluminum in the machine shop including the sliding plate, which the motor and brushes mounted on, and the brush adapter, which uses a setscrew to connect the test brush to the motor shaft. The sliding plate rested in a channel in the brush mount, restricting the direction of the brush in only the z-direction. We made the aluminum adapter for the brushes 1.03 inches in diameter. It was slightly larger than the interior diameter of the PVC to be able to force this inside of the brush body. Nevertheless, after forcing in one of the brushes we realized that it was an extremely tight fit, and in order to switch the brushes we would have to saw the PVC to increase the allowance of the diameter. Therefore, we tested the first brush that has even length and sawed the second brush, which has various length of the bristles to put it in.
When we did the tests with the weight, we simply hung a 6.5oz mass on the plate.

To run the motor, we connected it to the DC power supply and fixed the voltage to around 12V. We measured the voltage provided by the Grillbot itself and it was approximately 7.62V, but we decided to increase this to 12V to make the motor go faster and increase the cleaning effectiveness.

Calculation

In order to predict what the results of our experiment would be as a result of changing the control variables, we ran some basic back-of-the-envelope (Appx. AL) calculations. Because the event of particle removal is so dynamic, it was difficult to create a model that could accurately represent the effect of our control variables. However, since we know that we can predict the static deflection of the brushes based on material and geometric properties, we can model the brush bending as a cantilever beam, in which the resulting equation is:

$$\delta = \frac{PL^3}{3EI} \qquad (1)$$

Therefore, what resulted were values corresponding to the proportionality of the control variables, δ of the displacement of the end of the beam, which we modeled as the depth of penetrating effect, and L^3, the length of the bristles. Therefore, we expect that our long bristle brush will have $2^3=8$ times as penetrating as the original brush. We also expect that our added mass will have an additional proportionality of double the depth without the weight attached. Altogether, we expect the depth to be affected by a factor of 16.

Of course, there are many assumptions made in this model that are not accurate. First, we assumed that the weight is applied that the end in the horizontal direction, which it is not. The actual force applied is equivalent to the Psin(θ), where θ is the angular displacement, which corresponds to the force and speed applied. This model is very nonlinear and would be very difficult to create. Additionally, we assume the displacement of the brush is equivalent to the depth of penetration. This static representation, again, is an oversimplification of the dynamics of the rotating brush. Because the depth also corresponds to the "falling distance," that is the amount the Grillbot falls to the grill as a result of the minimal contact with the bristles, which is affected by the rotational speed, stiffness of the brushes, and contingent on the contract from the other brushes, our model is incomplete.

The second response variable of surface area removed was predicted in the back-of-the-envelope calculations as an extension of depth of penetration. Using the geometries of the rod, we calculated the average arc length of affectation and then multiplied that by the length of the brush. The resulting surface area is, therefore proportional to the predicted depth that the brushes reach.

Because the surface area removed is a function of the depth multiplied by a constant, it is limited by the same assumptions as before in addition to others. First, we assume that the bristles reach every lengthwise point of the rod. However, because the clumps are spread over the length of the brush, there still will be "wet spots." We also assume that the bristles will cover the whole distance of the depth, which may not be the case due to jumping or sliding of the brush.

Results

Response Variable 1: Depth of Penetration. Once we ran the experiments, we had to process the gathered images. From our experiment we had set the camera so that it was parallel with the top section of the rod. From this knowledge, we could extract the depth of contact from the bristles on the rod, and the total surface area removed.

First, we measured the largest distance in the z-direction where the brush had removed oil from the rod in Microsoft paint by measuring the pixel counts. Because we knew that the rod diameter was ¼", we used a ratio of the pixel length of the displacement to the pixel length of the rod diameter. Using this ratio and the known diameter, we could gather an estimate for the depth that the bristles reached. The results from the experiment for the first response variable are shown in Appendix AM.

The results show that there is consistent improvement to the depth reached when at least one of the variables is increased. Surprisingly though, when both are increased, the brushes do not penetrate as far. In our back-of-the-envelope calculations, we predicted that the result from increasing both control variables would be compounding and show the greatest improvement, but our experimental results suggest a negative correlation between the two variables. On the other hand, we did expect the greatest improvement to come as a result of increasing the length variable, based on the prediction model that varies the response variable by a cubic transform of the change in length. Though the results do not demonstrate the proportionality expected, they do indicate that the length variable has more effect on the result than the mass variable.

Response Variable 2: Surface Area Contact. Our second response variable to measure is the total amount of surface area contact by the brush. We used the same images as the first response variable analysis, but used *Photoshop* to analyze the amount of pixel area removed. We first changed the color scheme so that the area of the oil removed was contrasting to the area that was not affected. We then selected that area and used the *analysis – count* tool to measure the amount of pixels in an area. Using that value, we found, as we did before, the ratio of the 2-D area removed to the 2-D total area. From that ratio, we used the geometry of the rod to project the 2-D ratio to an averaged arc length. The arc length times the length of the rod then gave us our total average surface area removed. The results from those calculations are shown in Appendix AM.

We found that the total surface area is simply half the circumference multiplied by the length, which is 9.42 in^2. Therefore, the surface area removed in each circumstance is less than ¼ of the total possible grime deposit. That being said, our results indicate much more consistent sensitivities to control variable changes than the depth responses. Similarly to the depth response, the lowest amount of oil removed occurred when the system was low weight, short brush. Unlike the depth variable, however, the surface area removed when the weight and length of the bristles were increased was greater than all of the other trials for both data values. This trend correlates to our hypothesis that increasing both of the variables will symbiotically improve performance. On the other hand, the length data does not support the cubic proportion we had assumed in our back-of-the-envelope calculations.

There are many reasons that our experimental results were not what we expected from the back-of-the-envelope results. First, the back-of-the-envelope calculations assumed that the depth would be solely a function of the displacement in the x-direction of the modeled rod. That assumption is entirely incorrect. There are many interacting phenomena as suggested earlier that demonstrate a much more weighted affect. That being said, these variables outside of our model are still functions of our control variables, just not in the proportions we assumed. In addition to the unaccounted factors, the number of data points we have are insufficient to draw any strong conclusive argument. We can analyze the data and point out the trends, but we cannot say with a degree of certainty that these trends will continue. Furthermore, if we were to collect more data, we believe that both response variables will align with our fundamental hypothesis: that increasing the control variables will improve depth and surface area contact.

Statistical Analysis

In order to better interpret the acquired data, we used statistical tools to acquire the mean response, main effect of each control, and control interactions, which we then used to plot regression models for the two responses.

What these 3-D plots demonstrate is that that maximum performance is predicted to occur when both concept variants are increased even though the results contest each other's main effect contribution from each variable. The depth plot demonstrates the Bristle length to be the most important variable to performance, whereas the surface area removal plot suggests weight to have the most effect. Regression Models are shown in Appx. AN.

Failure Modes and Effects Analysis

After conducting experiments and determining the design modification for the product, we built the Failure Modes and Effects Analysis (FMEA) for the original product and the redesigned product. It can be found in Appendix AO. We revisited the bill of materials (Appx. O) in order to think about the components that could fail. We wanted to focus on making adjustments to the components with Risk Priority Number (RPN) higher than 100. After we made adjustments, we input the data under improved situation columns in FMEA table. We will target specific areas of possible failure modes and evaluate their level of impact on the functionality of the product by doing this. Building FMEA will be beneficial for us to redesign our product to be more complete.

Original product. We listed some components that could fail throughout their lifetime and affect the functionality of the product. The components are the main circuit, the power button, the brush motor shaft, the battery, and the battery charger port. If one of the components fails, our device will not be able to function properly. We could have considered the screws, the casing, and the sub circuit; however, we determined that they are not crucial components to cause a disruption in the functioning of the machine if they failed individually.

Next, we identified the modes of failure for each of the components and the causes of failure. Also, we listed what will happen after failure. For the main circuit, the possible failure modes can be overheat and soldering failure. When there is a faulty electrical connection in the circuit, the circuit could burn. Also, when the solder gets weakened and it is not noticed in the earlier stage, the solder could fail. If the main circuit fails, then it will not be able to regulate electrical energy and work inefficiently. Furthermore, the device could fail to operate. For the power button, we thought of the modes of failure based on its material. The rubber can be easily torn and could be worn out after it is used many times or improperly. Then, the users will have trouble starting the device. It does not directly affect the functionality of the device, but it would not satisfy the users' expectations. For the motors, we stated four failure modes: stator, stall, come loose, and housing. The possible causes of a stator of a motor are physical damage, contamination, corrosion, high temperature, voltage imbalance, broken supports, and rewind. Stator failures often occur due to the rewind burnout of the windings. As a result, the motor could shut down or work inefficiently. Stall failure could happen due to fatigue, and this would reduce the motor's efficiency. The third failure, "come loose", can be caused by wear, tear, poor assembly, or faulty equipment. For example, if the motor's shaft were too small, then it would not fit in the brush motor shaft and would fail to connect the brush and the motor. Housing could be the last possible failure mode we came up with. It can be caused by improper installation, physical damage, corrosion, and material buildup, and the failure will result in motor shut down or inefficiencies. For example, a soft foot could lead to the motor shaft bending and broken. Material buildup can increase its operating temperature of the motor and lead to damage on other parts of the motor, such as bearings. Next, the failure modes of the brush motor shaft are wearing and fracture. Wear can occur when the product is overweight or when it is overused. Fracture can occur by abusing or misusing the component. Both failures would lead to failure to connect the brush and the motor. The brush wheel is the next component we will discuss, and its failure modes are wear and oxidation. Abusing the components or corrosion can cause them. Both failure modes will result in inefficiencies.

After we listed all the possible failure modes, effects, and causes, we moved on to assigning severity, occurrence, and detection ratings. We used "Severity of Effect Rating Scale," "Occurrence Likelihood Rating Scale," and "Detection Likelihood Rating Scale" as our reference when we are rating our own components. Then, we calculated the Risk Priority Number (RPN) for each of the failure modes. This number can be calculated by multiplying the three ratings: severity, occurrence, and detection. When we calculated the RPN, there were two components with an RPN higher than 100. They are the motor and the brush wheel. We also listed remedies for those components that fell under the critical RPN, but we mainly focused on those two components. We decided to replace the motor with a more efficient motor and use different materials for the brush wheel such as stainless steel 306 because it is sturdy and has fewer tendencies to get oxidized. We updated this information in the updated bill of materials (Appx. AP).

We calculated the new RPN for the components based on the remedies and listed them under the improved situation columns. None of the components had an RPN higher than 50. This way, the user could be satisfied with the product and also the failure can be minimized.

Redesigned Product. After we redesigned our product, we noticed a couple more failure modes that we could not detect prior to the experiments. We developed an FMEA for the redesigned product, and we primarily focused on the components we modified during the experiments. For the experiments, the two parametric interests were varying the brush length and adding weight. The FMEA for the redesigned product is shown in Appendix AO. The first component is the brush wheel. The potential failure modes are inefficiencies, misalignment, and bonding failure. Inefficiencies are caused when the hardware fails. When the brush pattern is too short, it does not penetrate much on the grill; therefore its cleaning area will be small.

Misalignment is a failure that can be caused by human error, and it will not clean the grill thoroughly.

Lastly, there could be bonding failure. If the bristles are not bonded properly, then the bristles will fall off. When the brushes miss some of the bristles, it will be inefficient. The next component we are going to analyze is the brush motor shaft. We added some weight during the experiments; in our product, if we were to add weight, then the brush motor shaft will be supporting the weight. The failure modes are fracture, instability, and loosening. Using an improper material could cause fracture failure. If the material is too brittle, then it cannot support the weight and will break. Instability and loosening failure modes could be caused by improper installation. When the brush motor shaft is not stable, it will not transmit enough rotational mechanical energy to the brush; therefore, it will be inefficient. Furthermore, if the connecting part is loose, then the brush will fall off, and it will not be able to clean the grill. The motor is not one of the parametric interests; however, we found that the solder is really weak and keeps breaking during the experiments. We need to solder with a stronger material, so that it does not fail.

Next, we calculated the RPN for each failure mode. Many of them were higher than 100 except for inefficiencies and misalignment failure of the brush wheel. As we did an FMEA for the original product, we focused on the failure modes with an RPN higher than 100. For bonding failure, we can use a stronger glue material or have a better attachment technique to attach the bristle to the brush. We can prevent fracture of brush motor shaft by using different materials that are less brittle but stronger. In order to prevent instability and loosening failure, we need to have a precise measurement prior to manufacture. Lastly, we need a stronger soldering material for the motor so the connection does not fail.

As a result, the RPN of all the failures is less than 100, and this will lower the chances of failure by making relevant adjustments for the product. The important modification of FMEA for the original product is changing the materials of bristle to SS 306, because when copper gets oxidized, it could leaves copper particles on the grill when the machine is cleaning; therefore the RPN reduced from 144 to 24. From FMEA for the redesigned product, the important modifications are mostly measuring accurately and precisely so that it decreases failure modes.

Design for Assembly

The design for assembly (DFA) guidelines allows us to come up with different ways to make our product easier to use. Using these guidelines, we found three ways that will help us to lower the total part counts, reduce assembly time, and decrease cost (Telenkom, Seepersad, & Webber, 2008).

Combining upper shell, handle, and label. We will reduce the total part count by combining the label, handle, and upper shell into one component. This is recommended in DFA guideline 1, shown in Appendix AQ, where it suggests minimizing part count by incorporating multiple functions into single parts. When our team was disassembling the part, we thought it was unnecessary to have different parts for the label, handle, and upper shell. If we combine them together, then the user will have less time to assemble the device. By doing this, the label, label screw, label washer, handle, screw that connects the handle and the upper shell, and upper shell can be reduced to one component (Telenkom et al., 2008).

Combining bottom shell with bottom pads. For the bottom pads, there are three pads that are screwed onto the bottom shell. Our team chose guideline 1, "minimize part count," by incorporating multiple functions into a single part to combine the bottom shell with the bottom pads. If they were mounted on the bottom shell, it would be easier for the users to assemble them. The bottom shell and the bottom pads are made out of the same material, and there is not a particular advantage the users get from having them separated (Telenkom et al., 2008).

Screws. Eight different screws are used for our product. Some of the components have the same number of screws and look similar; therefore, the users might get confused when trying to distinguish which screws to use. We can use DFA guideline 9, which is "color code parts" that are different but shaped similarly. If we use different colors or label them, then users would recognize them easily. The other method to reduce the types of screws could be using the same type of screws on the components. This is followed by guideline 5, "standardized to reduce part variety." For example, we could use the same type of screws for the sub circuit and the main circuit. Then, we can use the same screw for the lower shell and top shell screw, motor screws, and power cord screws. Since the shaft screws need to be smaller to connect the motor and the shaft, we want to keep that type of screw. It is shown in Appendix AQ-2 (Telenkom et al., 2008).

As a result, the number of components can be reduced from 56 to 42 components. Also, the types of screws can be reduced from 8 to 3 types. It will take less time to assemble or disassemble the product as well as decrease the manufacturing cost.

Design for Manufacturing

We applied design for manufacturing (DFM) principles to optimize cost reduction, efficiency, and ease of manufacturing. Additionally, we can improve quality control procedures. We can achieve these goals by using standard dimensional variable capabilities when determining the tolerance for our components (Telenkom et al., 2008).

Provide a draft angle. For the casing of our product, injection molding was used to manufacture them. The casings are the handle, the upper shell, and the bottom shell. The design guideline in Appendix AR, for injection-molded parts, suggested us to provide a draft angle for easier mold removal. If there is no thickness for draft, it might be hard to get the parts from the mold and parts will end up torn. There is some complicated shape on the back of the handle. Those shapes are also small and complicated; therefore, they might cause fracture when the manufacturer is removing the handle from the mold. Also, on the bottom shell, where we put in the bottom pads on, the angle is 90 degrees, which could cause fracture during removal from the mold. We will allow a minimum draft angle of two degrees to these features. The small draft angle of the handle will help facilitate its manufacturing while keeping its shape and the ability of the product (Telenkom et al., 2008).

Avoid sharp corners. In Appendix AT, the guideline recommends us to avoid having sharp corners, because this would cause a high stress concentration and significant obstruction of material flow. Our bottom shell, where the brush-wheels are placed under, has a sharp corner, which could cause a high stress concentration. We will apply the guideline when we are manufacturing the redesigned casing by replacing all the sharp corners with fillets that has minimum internal radius of 0.06 inches of the thickness and minimum outer radius of 1.06 inches of the thickness, based on the recommendations from the guidelines (Telenkom et al., 2008). This method will allow the bottom shell to flow consistently without clogging in a sharp corner.

Design for Environment

The design for environment (DFE) guidelines (Appx. AS) provide ways to reduce the environmental impact of our product. We have identified four guidelines that significantly reduce the Grillbot's environmental impact through increasing its sustainability.

Recycled materials. First, we will specify recycled materials for the plastic chassis. The plastics industry has a very large recycling program. Recycled plastic pulls plastic that may have otherwise been thrown away. The Grillbot would greatly benefit from sourcing recycled material by reducing its environmental impact while maintaining its function. This is according to DFE guideline 2.

Using the same materials. Along the same lines as the chassis plastic, we will specify that the upper and lower chassis parts are made of the same plastic material to improve the product's simplicity. The plastic will be recycled and made to be heat resistant. This is according to guideline 7.

Prevent hazardous material release. Following DFE guidelines 10 and 28, we will prevent release of hazardous substances and implement fail-safes against material loss. Our new brushes will retain their brass bristles much better than the original Grillbot. We will do this by threading the bristles all the way through the product, instead of press fitting a shallow section of bristle. During initial testing, several bristles fell out. These bristles, if ingested, could wreak havoc on the human digestive system, and in some cases lead to death. In addition to holding onto those bristles, we will add bright colors to the holes, so that the user will see if a bristle has been lost.

Maintaining part placement. Lastly, we will utilize the DFE guideline 53 by maintaining the placement of the electric motors during disassembly. Currently, the motors are free to fall out of the shell once unscrewed. We will add plastic retainers to the sides of the motor so that the user snaps them in and out of the chassis. Those plastic snaps will be molded in the same step as the bottom shell.

Revised Bill of Materials

After we redesigned our product, we made a change to the bill of materials that we created after disassembling the product. Since we concluded that using alternating lengths of bristles is more efficient in cleaning, we changed the diameter of brush wheel to 53.98 mm from 47.625 mm. The diameter is defined as the longest diameter for the brush wheel and the bristles combined. In addition, we changed the bristle material to SS 306. We also increased the mass by 6.5 oz (184 g). As a result, the top shell weighs 256.2g and lower shell weights 361.2 g. As we discussed in DFA, it is good to combine the handles with the upper shell because it will make disassembling and assembling the product easier and will prevent component loss. We named the combined component as upper shell. Also, we decided to combine bottom pads and the bottom shell together. This will also allow the users to assemble the product easily without changing the function. From these changes we reduced the total number of components from 57 to 44. The screws that will be used for the sub circuit and the main circuit are named circuit screws. The screws that are used for the lower shell and top shell, motor, and power cord are named regular screws. By doing this, the types of screws have been reduced from 8 types to 3 types. To determine the dimension and weight of particular types of screws, we averaged the values of combined screws. Since we are using circuit screws for the main circuit and the sub circuit, we wanted to create a screw that can be used for both places. We averaged the values of combined screws to resolve this problem. As we mentioned in DFA section, we added paint to the finish so that the users can distinguish each screws easily. Updated bill of materials can be found in Appendix AO.

Final prototype

For our final prototype, we embodied the optimal design variable values that we found from experimentation. From the experiment data, we found the brush that had various lengths bristles to have the best response. Although the results showed that the trial with increased bristle length and increased weight cleaned the grill more efficiently, we focused on making the brush for our prototype. If we were to increase the weight, however, we could make the casing thicker.

We 3D printed the body of the brush with holes of 0.25 inches. These are slightly larger than the previous prototype’s holes so that we could fit in more copper wire. Similar to the initial prototype, the bristles were secured with hot glue to prevent them from sliding or falling off. We then attached the brush directly to the motor shaft by installing a setscrew in a radial hole at the proximal location. Although we 3D printed this hole, it came out too small. We had to enlarge it by drilling it a bit so that the hole would fit the motor’s shaft. The final prototype is shown in Appendix AS.

CONCLUSION

Through all of the experimentation, analysis, design, and prototyping, we have made a Grillbot that cleans better than before. During experimentation and the subsequent parametric analysis, we proved that both longer bristles and increased weight improved the cleaning function. We used statistical analysis to plot the correlations between performance increase and concept variance change. With this data, we can conclusively recommend the implementation of bristle lengthening and down-force increase for a simple, inexpensive, and efficacious redesign. After performing FMEA, we found the various modes of failure and ways to lessen the chances of them happening. By considering DFM, DFA, and DFE, we identified other ways to improve the Grillbot such as better manufacturing, assembly, and use. Finally based on our experimental results, we built a final prototype. This functional Alpha prototype represents the semester-long body of work we put towards the Grillbot.

Finally, this class has been valuable to my future career in so many ways. First, I have learned the tools necessary to approach a design problem. By thoroughly understanding the customer needs and strategically selecting redesign avenues, I now have procedural direction when faced with a design challenge. By discovering the features of the Grillbot that the customers were dissatisfied with, I gained a methodology for clearly defining the problem without biasing the main goal with practical feasibility consideration. I also learned how important it is to fully understand a product through benchmarking and dissection. Understanding how the product works as well as how its competitor's product works is crucial to the preliminary stages of analysis. Finally, I learned methods of prototyping to successfully test redesign avenues and to construct simple models to simulate a much more complicated event. The Grillbot was a great product to redesign because it had many interacting features that involved electrical, translational, and rotational energy domains. In all, I am very pleased with the results of our redesign and would recommend the manufacturing implementation of our concept variants so that the product can better serve the needs of the customer.

ANNOTATED BIBLIOGRAPHY

Market Sources

1. [Customer reviews of grillbot GBU103 automatic grill cleaning robot]. Retrieved February 12, 2015, from Amazon website: http://www.amazon.com/Grillbot-GBU103-AutomaticCleaningOrange/productreviews/B00HVP1PII/ref=cm_cr_dp_see_all_btm?ie=UTF8&showViewpoints=1&sortBy=bySubmissionDateDescending

After reviewing the customer reviews on Amazon, we observed that most customers found that the product is too noisy, and some customers also mention that one of the brushes fell off (a few of them did so on the first use). One reviewer says that the screws were quite loose so they had to tighten them to prevent the brushes from falling off again. However, the brushes are hard to remove for cleaning, and they lose bristles constantly. A common theme in these reviews is that the lid of the grill must be closed, otherwise it falls off. As a result it bangs against the lid making a very disturbing noise.

The general consensus found on Amazon is that it cleans very well, as if someone had cleaned it himself or herself with a wire hand brush. Most customers say they were quite impressed although they also found a few drawbacks. The Grillbot is loud so it would not be appropriate to use late at night if you have neighbors nearby. It does not take long to clean up as the brushes can be put directly in the dishwasher, but they wear out with time and must be replaced. Overall customers seem to think it is a good product but wish it would be improved or available at a lower price.

The information in these reviews is useful because it gives us a good idea of what kind of questions to be asking our interviewees to get a better view of the key properties that require our attention. The information also gives us an idea of what to expect from long-term usage in a way that we may not have been able to witness or ask in our interviews. The customer comments provided us with useful information regarding the performance and durability of the Grillbot after extended use up to four or five months. With this data, we can redesign the Grillbot to improve on the points that have made these customers unhappy and increase customer satisfaction with the product.

2. Consumer Reports. (2014*) Grillbot – grill cleaner.* Retrieved from http://www.consumerreports.org/cro/news/2014/04/noisy-grillbot-could-be-better-at-fighting-grime/index.htm

Consumer Reports publishes reviews and comparisons of consumer products and services based on results and reporting from its survey research center and in-house testing laboratory. We found an article based on the Grillbot, where they talk about their personal experience with the product and give both positive and negative feedback. Because the reports are based on subjective experiences, this article is not entirely credible. The information gathered is qualitative and subject to interpretation. However, Consumer Reports is widely known among the market to test and report on new technology. Therefore, it is important to know what the report on our product contains and how it can be factored into our customer needs analysis.

This source provides customer opinions on the Grillbot from several perspectives and gives us ideas on what consumers want from the product. It is different from the customer reviews on Amazon.com because this is an article written by one person describing what they felt was good and bad about the product, which we feel adds perspective to the customer needs.

3. Grilling product reviews archives - GrillJunkie - Addiction to grilling. (2014, June 25). Retrieved February 16, 2015, from http://grilljunkieguy.com/category/grilling-product-reviews/grilling-product-reviews-grilling-product-reviews/page/2/

Grill Junkie's blog posts provide Grilling and BBQ product reviews through their Grilling Product Review (GPR) rating system. They review and rate grilling products by providing a 6 category written review and then assigning a 1 – 5 scaled FirePot rating to the product. In 2014, they posted a GPR for the Grillbot. Here, not only do they talk about the product itself, its features and pros and cons, but they also discuss all of the different grilling surfaces as well as traditional grill surface cleaning tools.

This source is useful to us because it informs us about the different grill cleaning methods there are already available in the market. It gives us an idea of what customers have and use at the moment and therefore what will be expected of the Grillbot if it is to replace all of these.

Although useful for reference, this source cannot be counted as entirely credible. For one, the article has no author other than “Grill Junkie Boy.” Additionally, the format of the website appears very unprofessional. There are pop up advertisements over a large portion of the screen and the information presented seems haphazardly strewn. However, because a part of our demographic will frequent this site to gather information, it is relevant to our research.

4. Member locator. (n.d.). Retrieved February 16, 2015, from

http://www.hpba.org/consumers/barbecue/grilling-facts-and-figures

This online article published by the “Hearth, Patio & Barbeque Association” highlights the results of a biennial study conducted by the organization. The study addresses the population demographics of grilling, population grill use, and other related facts concerning grill rates.

This article is relevant to our research because it helps to understand where, why, and how people are using grills. We are able to hone in on the product market for the Grillbot, which provides insight to answer the question, “Why is someone buying this product?”

The article does not mention the how the study was conducted, which immediately detracts from the credibility. It also does not have a published author, but rather is published by the organization itself, which removes responsibility from the author. In addition, the HPBA organization is an association that receives outside funding from individuals, which could bias the findings of the studies conducted.

Technical Sources

1. Bergman, T., Lavine, A., Incropera, F., & Dewitt, D. (2011). *Fundamentals of heat and mass transfer* (7th ed.). John Wiley & Sons.

In chapter 3 of this textbook, it covers the process of heat transfer via conduction. It shows how the temperature varies in solids depending on the types of materials, the size of surface area, and the shape of material. It also contains the material on heat transfer from extended surfaces. In chapter 7 and 8, it talks about the details of heat convection. In chapter 7, it mainly talks about the external flow of heat transfer on flat plates, cylinders, and spheres. Chapter 9 references techniques used to analyze radiant heat. Because radiation and conduction are the key elements of heat transfer to the Grillbot, we need methods to analyze the temperature gradients associated with the machine components.

This textbook is by Incropera, Bergman, and Lavine. The main author Incropera is currently the Clifford and Evelyn Brosey Professor of Mechanical Engineering at Notre Dame. The two other authors, Bergman and Lavine, also have degrees in engineering. This book is commonly used in academic institutions for classes such as Heat Transfer and Thermal Fluids Systems. This book did not target any particular private companies or institutions but to share information with colleagues in heat transfer community.

This source is relevant, because we are dealing with Grillbot, which cleans a hot grill. Our team is interested in increasing the thermal capacity of the Grillbot. In order to do that, we need to know the temperature distribution through different media, based on heat flux, to prevent melting or destroying the product due to radiation. In addition, the polymer wheels are in direct contact with the heating element, which is influenced by direct conduction. Finally, the internal electrical components are also of particular concern due to their vulnerability to excessive heating.

2. Karnopp, D., & Margolis, D. (2012). *System dynamics modeling, simulation, and control of mechatronic systems* (5th ed.). Hoboken: Wiley.

Because many of the embedded systems in the Grillbot are mechatronically controlled, the textbook by Karnopp and Margolis, *System dyananics modeling,* will prove a valuable resource in understanding current design so that we may produce a better redesign. This textbook is a very credible source because it was written by three mechanical engineering professors at the University of California. The credibility results from years of control system experience in industry as well as in academic pursuits.

The powertrain of the Grillbot is dependent on the transduction of electrical energy to mechanical energy. The battery recharges using 120V AC power from a standard wall outlet. By using the motor specs that deliver a specified power output and the battery life, we can calculate, using energy flow diagrams, the torque being applied to the grill surface and the transverse speed of the Grillbot.

By developing a dynamic model for the system, we can pinpoint negative parameters and vary them with our model to achieve a desired output. This is useful for our analysis because we know the product's limitations and we know how to change them for future design criteria. Therefore, this textbook is relevant to our analysis because it will assist us in analyzing the speed and direction of the motors once we are able to dissect the system and observe the controller unit.

Patents

1. Wichert et al. (2015) U.S. Patent No. 8,947,024. Washington, DC: U.S. Patent and Trademark Office.

The US patent issued to Rene Wichert in 2015 is for a battery operated motor in a work apparatus. Battery operated direct current motors are increasingly being used as a drive in handheld work apparatus, and in order to be able to use lightweight, high-powered electric motors, a substantial electronic outlay has to be implemented. It is an object of the invention to provide the operating signals, which are to be evaluated for the disruption-free operation of an electric motor to the control unit of the motor with little circuit complexity.

The electric motor of the invention includes an arrangement of field windings for driving the rotor with an electric motor, wherein the field windings are successively alternately connected to an energy source in such a manner that torque acts which drives the rotor.

The patent is of our concern because, even though we have not disassembled the Grillbot yet, we know it contains three motors so the electric motor will be a large part of it. Therefore, we can use this source to get an idea of what we might find once we take it apart. In addition, as the patent is extremely recent, it will probably be very useful to us further on, to compare with the motors in the Grillbot and it may even help us make improvements on it.

2. Ge, M. M. (2009) U.S. Patent No, 7462375. Elk Grove Village, IL: National Material L.P.

This patent for a ‘Method of Making a Stick Resistant Multi-layer Ceramic Coating’ talks about the detail of food ware articles such as a multilayer, stick resistant, and ceramic coating. This invention has a metal food ware article that has an inner food-contacting surface and an outer surface-bonding layer deposited on the food-contacting surface. It talks about how each stick-resistant layer is processed and what kinds of equipment are used in order to process it. This contains the kinds of materials that are used for each of the layers. They have done experiments on this invention to see if it resists food from sticking onto its surface. The experiments were an egg frying test and a rice-cooking test.

Molly Mo Hui Ge invented this stick resistant, multi-layer, ceramic coating. Since she is the only inventor and it is for her benefit, we would say it is a little bit biased.

This is a relevant source, because when Grillbot is cleaning the grill, the food will stick to the wire brush. We could use her idea of a stick resistant layer and process it, so that it minimizes the effort to wash the wire brush. The coating is not only stick resistant but scratch resistant, thermally stable, and corrosion resistant. Therefore it could apply to the bottom part of Grillbot. Scratch resistant and corrosion resistant functions could help maintain the Grillbot better and for a longer period of time. Also the corrosion resistant layer would prevent the wire brush from getting rusty and leaving particles on a grill, which could be hazardous to humans.

3. Woods, Ethan (2012). *U.S. Patent No. WO2013082046 A2*. Washington, DC: U.S. Patent and Trademark Office.

The International patent issued to Ethan Woods is for cleaning a surface, such as a barbeque grill. The hollow enclosure has a plurality of motors, where each has a rotational shaft selectively fixable with a rotatable brush. The author talks about the functions of each part and how this invention is working and changing direction of the grill cleaner. The enclosure of Grillbot contains a power source and a circuit. The circuit is used to change the direction of the cleaner. The circuit adapted for connecting power to each of the motors for a preset period of time upon actuation of an electrical switch connected thereto. As a result, the circuit runs each motor that moves Grillbot to a certain direction, and it eventually turns around due to the alternating directions of the motors.

This patent is written by Ethan Woods. He created a company called Grillbot LLC to sell and published this patent; therefore, this patent tends to be biased. He would write only good parts of Grillbot.

This patent is useful for our project because this is a patent of our product. It is a good source that explains the basic mechanisms of movement. Also, this talks about the details of each part such as brushes, battery, power source, and circuit. It thoroughly describes how each part is connected to motors. Customers complain that it makes too much noise, and this noise is coming from the motor. We can figure out causes of noise from reading this. In addition, it tells you the materials of each part, so it is easy to figure out what we need to change and improve. For example, many customers complained about how expansive it is. We could research costs of materials that were used and replace them to cheaper materials that have similar properties and functions.

4. Marsden, A. K., Lambertson, M. C., and Renzo, D.P. (2014) *U.S. Patent No.8844087*.

Cleveland, OH: The Sherwin-Williams Company.

The US patent issued to Marsden, Lambertson, and Renzo, is extremely specified with a "one finger separator." This invention can be used to clean variety of objects such as surface of desk, bath tub, and sink. This patent includes pictures of different point of views of this invention: top view, side views, bottom view, section view, perspective view, and assembly views. Each of part is labeled on the pictures and explained in detail in the patent. This invention is composed of a brush body having a proximal end, a distal end, and a handle on the proximal end of the brush body. The wire brush is detachable from the body.

The wire brush is a key feature of the design of the Grillbot. The condition of wire brush directly affects the effectiveness of our project. If the user did not clean the grill from last time use, crumbles would have been hardened and stick onto the grill, and it is harder to clean with the brush. This wire brush is detachable from the body and attaches the scraper to the body for use. We could use their idea that detaching brush and putting the scraper on it, so the Grillbot scrapes off foods' crumbles that are stick on to the grill pan.

5. Matz, W. W. (1998) *U.S. Patent No. 5839454*. Washington, DC: U.S. Patent and Trademark

Office.

The US patent issued to Matz is an automatic detergent dispenser for residential dishwashers, allowing transferring detergent from a container or an integrated storage receptacle to the dishwasher. The innovative part of this invention is that the user can adjust the amount of detergent to be dispensed. This patent includes pictures of how the container is attached to dishwasher and the connection of cords between containers to the dishwasher. This invention contains an electric pump, which operates on a timer used in conjunction with an existing dishwasher wherein the pump transfers liquid detergent from a container through the side wall of a dishwasher. The dispenser also contains a sensor, which determines whether the liquid level within the container has fallen to a point that requires replenishment and alerts the user to this condition by use of a light and of an alarm mechanism.

A grill is where food is roasted on. Hygiene is important because there could be bacteria that survive at high temperatures and oil that sticks to the grill pan can be hazardous to humans. It would be great if the Grillbot could inject soap while it is cleaning, so that it could get rid of all the dirt and oil. Also Grillbot could be used in a variety of ways, therefore, if it has this function, customers would be more satisfied to clean other surfaces.

REFERENCES

Plastics Processes. (2015). Retrieved March 6, 2015, from http://www.bpf.co.uk/plastipedia/processes/Default.aspx

Woods, Ethan (2012). *U.S. Patent No. WO2013082046 A2*. Washington, DC: U.S. Patent and rademark Office.

https://www.google.com/patents/WO2013082046A2?dq=ininventor:%22Ethan+WOODS%22&ei=AeXQVMW_DcKfgwS4roO4DQ&cl=en

Cancer and Food. (2014, March). Australia.

Common Laboratory Flammable and Combustible Chemicals. (1991). Retrieved from SAN DIEGO STATE UNIVERSITY: http://bfa.sdsu.edu/ehs/pdf/CommLabFlammable.pdf

Electric Motors (Pump Motors). (2015). Retrieved from WEG easy: http://www.weg.net/us/Products-Services/Electric-Motors/Pump-Motors

Factors to consider when choosing the best toothbrush. (n.d.). Retrieved April 5, 2015, from http://learn-medical.com/factors-to-consider-when-choosing-the-best-toothbrush/

Helmenstine, A. (2014, December 4). How Detergents Work. Retrieved April 4, 2015, from http://chemistry.about.com/od/howthingswork/f/detergentfaq.htm

Linear Guideways. (2013). Retrieved from HIWIN: http://hiwin.com/html/linear%20guideways/

Manual toothbrush. (n.d.). Retrieved April 5, 2015, from http://www.toothclub.gov.hk/en/en_adu_01_03_01_02.html

Panagakos, F. S., & Migliorati, C. A. (2014). Concepts of Oral Hygiene Maintenance that Would Apply for the Different Groups of Patients. In C. A. Migliorati, *Diagnosis and Management of Oral Lesions and Conditions: A Resource Handbook for the Clinician* (pp. 123-136). InTech.

Signature Series. (n.d.). Retrieved April 5, 2015, from http://www.belangerinc.com/signature

Soap - how does it get things clean? (n.d.). Retrieved April 6, 2015, from Planet-science: http://www.planet-science.com/categories/under-11s/chemistry-chaos/2011/06/soap---how-does-it-get-things-clean.aspx

Ultrasonic Cleaning 101. (n.d.). Retrieved from BLUE WAVE ULTRASONICS: http://bluewaveinc.com/ultrasonic-cleaning-101/

APPENDIX

Appendix A: To-do List and Gantt chart for Phase I

To-Do List Phase 1	
Task	**Completed?**
To-Do List	Complete
Gantt Chart	Complete
Product Brainstorming	Complete
Product Selection	Complete
Background Literature	Complete
Textbooks (2)	Complete
Patents (3)	Complete
Competitors' Product Information	Complete
Customer Reviews	Complete
General Sources	Complete
Put it all together	Complete
Customer Needs Analysis	Complete
Form Questions	Complete
Perform Interviews	Complete
Create Customer Interview Summary Sheet	Complete
Write-up	Complete
House of Quality	Complete
Specifications Sheet	Complete
Activity Diagram	Complete
Visual Diagram	Complete
Verbal Description	Complete
Black Box Model	
Brainstorming	Completed
Writing Up	Completed
Hypothesized/predicted Functional Model	Completed
Cross Sectional Sketch	
6.3.5	Completed
Final Copy of Cross Sectional Sketch	Completed
Result of Disassembly	
Disassembly (Unscrewing)	Completed
Writing Up	Completed
Bill of Materials	
Weighing Components	Completed
Dimensioning Components	Completed
Processes and Materials	Completed
Writing Up	Completed
Exploded View	Completed
Taking a Picture of the Exploded View	Completed
Writing Up	Completed
Actual Function Structure	
Constructing Actual Function Structure	Completed
Function Component Matrix	Completed

Writing Up	Completed
Summarization of Reverse-Engineering	
Brainstorming	Completed
Writing Up	Completed
Update Specification Sheet and Problem Statement	Completed

Gantt Chart

Week / Project Benchmark	Start Date	Target Date	Status (%)	3 02/02/15	4 09/02/15	5 16/02/15	6 23/02/15	7 02/03/15	8 09/03/15	9 16/03/15	10 23/03/15	11 30/03/15	12 06/04/15	13 13/04/15	14 20/04/15	15 27/04/15	04/
Phase 1																	
Product Introduction	02/02/15	09/02/15	100														
Background Literature	02/02/15	09/02/15	100														
Customer Needs Analysis	02/02/15	09/02/15	100														
Customer Interviews	09/02/15	16/02/15	100														
House of Quality	09/02/15	16/02/15	100														
Specifications Sheet	09/02/15	16/02/15	100														
Activity Diagram	09/02/15	16/02/15	100														
To-do List	2/16/15	2/16/15	100														
Gantt Chart	2/16/15	2/16/15	100														
Black Box Model	2/18/15	2/22/15	100														
Hypothesized Function Model	2/18/15	2/22/15	100														
Cross Sectional Sketches	2/18/15	2/22/15	100														
Product Disassembly	2/25/15	3/1/15	100														
Bill of Materials	2/25/15	3/1/15	100														
Exploded Views	3/2/15	3/6/15	100														
Actual Function Structure	3/2/15	3/6/15	100														
Comparison	3/2/15	3/6/15	100														
Function Structure	3/2/15	3/6/15	100														
Summarize Entire Reverse Engineering	3/2/15	3/6/15	100														
Update Specification Sheet and problem statement	3/2/15	3/6/15	100														
Phase 2																	
To-do List	3/9/15	3/9/15	0														
Gantt Chart	3/9/15	3/9/15	0														
Select Adaptive Avenues	3/11/15	3/15/15	0														
Brainstorming	3/11/15	3/15/15	0														
Mind Maps	3/16/15	3/20/15	0														
6-3-5	3/16/15	3/22/15	0														
Design Change Concept Generation	3/16/15	3/22/15	0														
Functional Re-design Concept Variants	3/23/15	3/28/15	0														
Industrial Design Shift Concept Variants	3/23/15	3/29/15	0														
Pugh Chart	3/30/15	4/2/15	0														
Order-of-Magnitude	3/30/15	4/2/15	0														
Phase 3																	
To-do List	4/6/15	4/6/15	0														
Gantt Chart	4/6/15	4/6/15	0														
Develop Experimental Model	4/6/15	4/11/15	0														
Experimentation	4/6/15	4/12/15	0														
Back-of-the-Envelope	4/13/15	4/16/15	0														
FMEA	4/15/15	4/19/15	0														
Design for Assembly	4/20/15	4/24/15	0														
Design for Environment	4/20/15	4/24/15	0														
Preliminary Drawings	4/20/15	4/24/15	0														

Appendix B: Patent cover pages

US005839454A

United States Patent [19]
Matz

[11] **Patent Number:** **5,839,454**
[45] **Date of Patent:** **Nov. 24, 1998**

[54] **AUTOMATIC DETERGENT DISPENSER**

[76] Inventor: **Warren W. Matz**, 13882 U.S. Hwy. 1, Juno Beach, Fla. 33408

[21] Appl. No.: **818,608**

[22] Filed: **Mar. 14, 1997**

[51] **Int. Cl.**[6] **A47L 15/44**
[52] **U.S. Cl.** .... **134/57 D**; 134/58 D; 134/99.2; 134/104.1; 134/113
[58] **Field of Search** .... 134/56 D, 57 D, 134/58 D, 99.2, 104.1, 113; 68/12.18, 17 R; 222/651, 652

[56] **References Cited**

U.S. PATENT DOCUMENTS

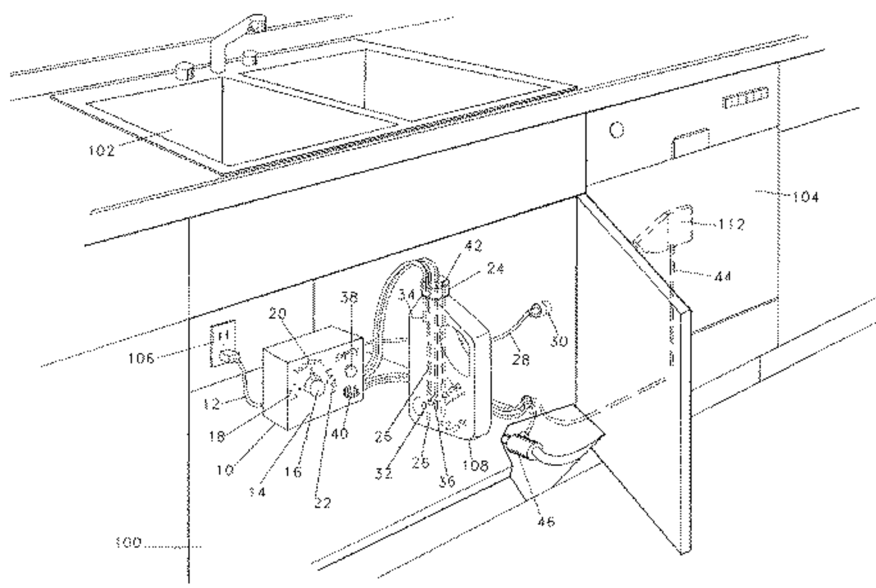
3,370,597	2/1968	Fox	134/58 R
3,749,288	7/1973	Wade	222/187
4,147,559	4/1979	Fraula et al.	134/99.2 X
4,218,264	8/1980	Federighi et al.	134/99.2 X
5,282,901	2/1994	Reinhard	134/57 D X

Primary Examiner—Philip R. Coe
Attorney, Agent, or Firm—McHale & Slavin

[57] **ABSTRACT**

The instant invention is an automatic detergent dispenser for residential dishwashers allowing transfer of liquid from a store purchased container or an integrated storage receptacle. The invention allows an individual to determine the amount of detergent to be transferred with provisions to operate the detergent transfer only upon demand preventing operation of the dishwasher if an insufficient amount of detergent is available. An alternative embodiment allows positioning of a storage container beneath the dishwasher chamber with provisions to fill the container.

19 Claims, 12 Drawing Sheets



US007462375B2

(12) United States Patent
Ge

(10) Patent No.: US 7,462,375 B2
(45) Date of Patent: Dec. 9, 2008

(54) **METHOD OF MAKING A STICK RESISTANT MULTI-LAYER CERAMIC COATING**

(75) Inventor: **Molly Mo Hui Ge**, Arlington Heights, IL (US)

(73) Assignee: **National Material L.P.**, Elk Grove Village, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 337 days.

(21) Appl. No.: **11/094,869**

(22) Filed: **Mar. 31, 2005**

(65) **Prior Publication Data**

US 2005/0186343 A1 Aug. 25, 2005

Related U.S. Application Data

(62) Division of application No. 10/371,198, filed on Feb. 20, 2003, now Pat. No. 6,906,295.

(51) **Int. Cl.**
C23C 16/00 (2006.01)

(52) **U.S. Cl.** **427/255.15**

(58) **Field of Classification Search** 427/250, 427/255.7, 248.1

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,436,830 A	3/1984	Andreev et al.
4,554,201 A	11/1985	Andreev et al.
5,262,241 A	11/1993	Huggins
5,403,882 A	4/1995	Huggins
5,447,803 A	9/1995	Nagaoka et al.
5,503,912 A	4/1996	Setoyama et al.
5,525,420 A	6/1996	Kaufmann
5,562,991 A	10/1996	Tannenbaum
5,700,551 A	12/1997	Kukino et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP 0872575 10/1998

(Continued)

OTHER PUBLICATIONS

Luo et al, Tribological investigation of TiAlCrN and TiAlN/CrN coatings grown by combined steered-arc/unbalanced magnetron deposition, Vacuum 53 (1999) p. 123-126.*

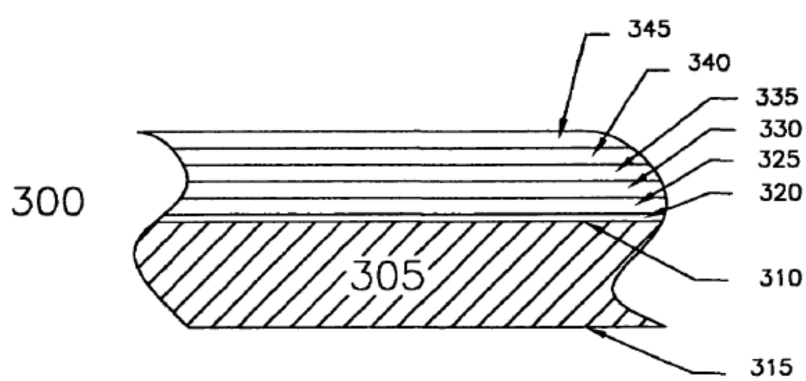
(Continued)

Primary Examiner—Timothy H Meeks
Assistant Examiner—Elizabeth A Burkhart
(74) *Attorney, Agent, or Firm*—Dinsmore & Shohl LLP

(57) **ABSTRACT**

A foodware article having a multilayer, stick resistant, ceramic coating. The foodware article of the present invention includes a metal foodware article having an inner food-contacting surface and an outer surface; a bonding layer deposited on the food-contacting surface; and a first layer of (Ti, Al, Cr)N deposited adjacent to the bonding layer. There is optionally a layer of chromium nitride deposited adjacent to the first (Ti, Al, Cr)N layer, and a second layer of (Ti, Al, Cr)N deposited on the chromium nitride layer. These layers can be repeated as many times as desired. The (Ti, Al, Cr)N layer is generally the top layer of the multiplayer coating. The coating is stick resistant, scratch resistant, thermally stable, corrosion resistant, and color stable. The foodware is suitable for use with both salty-based and acidic-based foods. A method of making such a foodware article is also disclosed.

21 Claims, 2 Drawing Sheets



US008844087B2

(12) **United States Patent**
Marsden et al.

(10) **Patent No.: US 8,844,087 B2**
(45) **Date of Patent: Sep. 30, 2014**

(54) **WIRE BRUSH**

(75) Inventors: **Andrew K. Marsden**, Avon, OH (US); **Michael C. Lambertson, Jr.**, Aurora, OH (US); **Dennis P. De Renzo, Jr.**, Concord Township, OH (US)

(73) Assignee: **The Sherwin-Williams Company**, Cleveland, OH (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 120 days.

(21) Appl. No.: **13/168,001**

(22) Filed: **Jun. 24, 2011**

(65) **Prior Publication Data**

US 2012/0096659 A1 Apr. 26, 2012

Related U.S. Application Data

(60) Provisional application No. 61/358,773, filed on Jun. 25, 2010.

(51) **Int. Cl.**

A47L 13/06	(2006.01)
A46B 5/02	(2006.01)
A46B 17/08	(2006.01)
A46B 15/00	(2006.01)
A46B 5/00	(2006.01)

(52) **U.S. Cl.**

CPC ***A46B 17/08*** (2013.01); *A46B 2200/3093* (2013.01); ***A46B 5/026*** (2013.01); ***A46B 5/02*** (2013.01); ***A46B 15/0081*** (2013.01); ***A46B 15/0055*** (2013.01); *A46B 5/0095* (2013.01)

USPC **15/111**; 15/236.01; 15/105

(58) **Field of Classification Search**

CPC A47L 13/34; A47L 13/06; A47L 13/12; A47L 13/022; A47L 17/06; A46B 2200/3093; A46B 5/026; A46B 15/0081

USPC 15/111, 236.01

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,091,579 A		5/1978	Giangiulio	
4,365,380 A		12/1982	Fassler	
5,643,403 A	*	7/1997	Poole et al.	156/762
6,966,094 B1		11/2005	Rigakos	
7,818,843 B2	*	10/2010	Kinskey et al.	7/105
8,225,451 B2	*	7/2012	Weinberger et al.	15/111
2002/0040686 A1		4/2002	Willinger et al.	

* cited by examiner

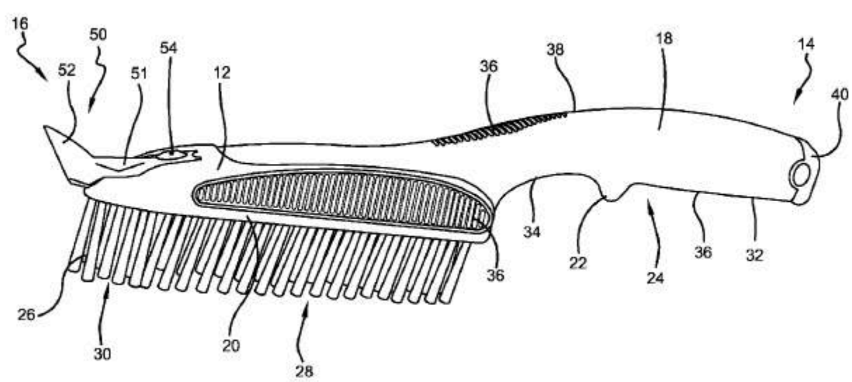
Primary Examiner — Shay Karls

(74) *Attorney, Agent, or Firm* — Deron A. Cook; Robert E. McDonald; Daniel A. Sherwin

(57) **ABSTRACT**

A wire brush may have wire type tufts extending from a head and may have a handle with only one finger separator. And/or a wire brush may have a manually detachable scraper that has a pair of tabs received in a pair of grooves formed on the brush body.

18 Claims, 9 Drawing Sheets



(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
6 June 2013 (06.06.2013)

WIPO | PCT

(10) International Publication Number
WO 2013/082046 A2

(51) **International Patent Classification:** Not classified

(21) **International Application Number:** PCT/US2012/066678

(22) **International Filing Date:** 27 November 2012 (27.11.2012)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
61/565,268 30 November 2011 (30.11.2011) US
13/671,125 7 November 2012 (07.11.2012) US

(72) **Inventor; and**
(71) **Applicant** : **WOODS, Ethan** [US/US]; 401 East 81st. Street, PHA, New York, New York 10028 (US).

(74) **Agent**: **PRINCE, Kevin**; 2580 Anthem Village Dr., Henderson, Nevada 80952 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title:** SURFACE-CLEANING DEVICE

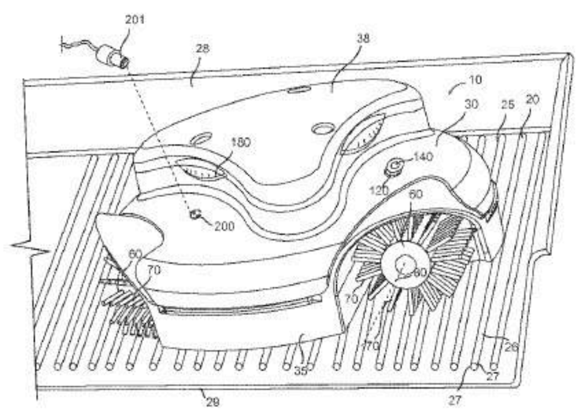


FIG. 1

(57) **Abstract**: A device for cleaning a surface, such as a barbeque grill, has a substantially hollow enclosure that has at least a lower side, an upper side, and a peripheral edge, and contains a plurality of motors that each has a rotational shaft selectively fixable with a rotatable brush. At least a portion of bristles of each brush projects below a plane of the lower side of the enclosure. The enclosure further contains a power source and a circuit adapted for connecting power to each of the motors for a preset period of time upon ac - tuation of an electrical switch connected thereto. The circuit is adapted to run each motor in a first direction and then an opposing direction, such that if the device becomes stuck at an obstruction, it will eventually turns around due to the alternating directions of the motors.

WO 2013/082046 A2

US008947024B2

(12) **United States Patent**
Wichert et al.

(10) **Patent No.: US 8,947,024 B2**

(45) **Date of Patent: Feb. 3, 2015**

(54) **BATTERY OPERATED ELECTRIC MOTOR IN A WORK APPARATUS**

(75) Inventors: **Rene Wichert**, Durlangen (DE); **Gernot Liebhard**, Waiblingen (DE); **Rudolf Saemann**, Balingen (DE)

(73) Assignee: **Andreas Stihl AG & Co. KG**, Waiblingen (DE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 150 days.

(21) Appl. No.: **13/523,701**

(22) Filed: **Jun. 14, 2012**

(65) **Prior Publication Data**

US 2012/0319626 A1 Dec. 20, 2012

(30) **Foreign Application Priority Data**

Jun. 16, 2011 (DE) 10 2011 106 578

(51) **Int. Cl.**

H02P 1/00	(2006.01)
H02P 6/00	(2006.01)
H02P 27/06	(2006.01)

(52) **U.S. Cl.**

CPC ***H02P 6/00*** (2013.01)

USPC **318/139**; 318/400.15; 318/144; 318/721; 318/823; 318/801

(58) **Field of Classification Search**

None

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,108,192 A *	10/1963	Reich	307/66
4,549,151 A *	10/1985	Kaneko	332/110
5,490,370 A *	2/1996	McNair et al.	56/11.9
5,744,921 A *	4/1998	Makaran	318/400.34
2002/0014870 A1*	2/2002	Krotsch et al.	318/254
2008/0136376 A1*	6/2008	Nebrigic et al.	320/136
2009/0302815 A1*	12/2009	Tanzawa	323/282
2010/0218385 A1*	9/2010	Mang et al.	30/216
2010/0283332 A1*	11/2010	Toukairin et al.	310/50
2010/0298983 A1*	11/2010	Beste et al.	700/276
2011/0068723 A1*	3/2011	Maiocchi	318/400.3
2011/0186318 A1*	8/2011	Ichikawa	173/176
2011/0227430 A1*	9/2011	Omori et al.	310/50
2012/0067608 A1*	3/2012	Heinzelmann et al.	173/217
2012/0191250 A1*	7/2012	Iwata et al.	700/275
2013/0069613 A1*	3/2013	Nakase et al.	323/284

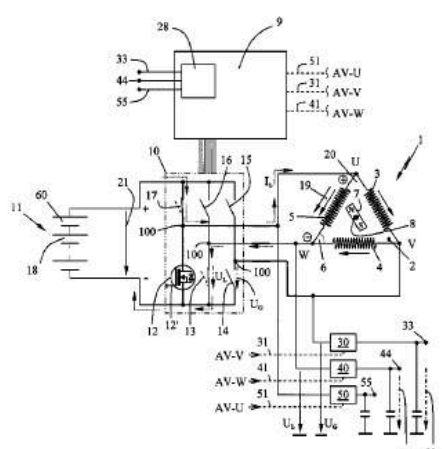
* cited by examiner

Primary Examiner — Eduardo Colon Santana
Assistant Examiner — Devon Joseph
(74) *Attorney, Agent, or Firm* — Walter Ottesen P.A.

(57) **ABSTRACT**

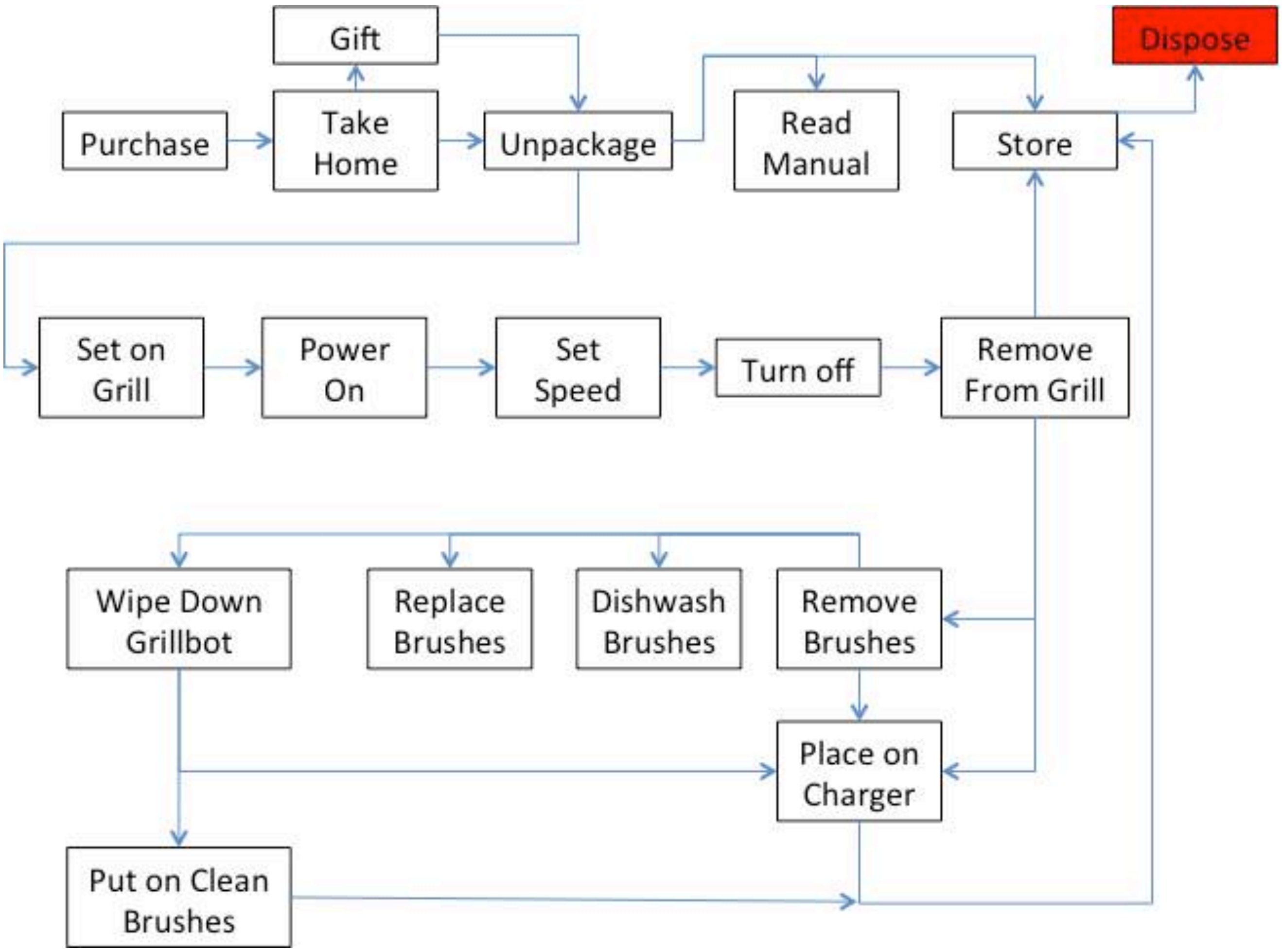
An electric motor includes an arrangement of windings provided for driving the rotor, with the windings being connected to an energy source to develop torque which drives the rotor. The electric circuits of corresponding ones of the windings each have a potential point, the voltage (U_L, U_G) of which is supplied to an evaluation unit via an adaptation device. The adaptation device can be operated in two switchable adaptation stages and is connected to a drive circuit that operates in dependence upon the rotational position of the rotor. The drive circuit switches the adaptation device into the first stage having a high sensitivity or into the second stage having a low sensitivity in dependence upon the rotational position of the rotor of the motor, such that the number of required analog inputs at a microprocessor in the evaluation unit can be kept low.

17 Claims, 4 Drawing Sheets



Appendix C: Rugged Grill Brush

Appendix D: Activity Diagram



Appendix E: Customer Interview Sheet

Name___________________________

	Bad				Good
Rate your grilling experience level	1	2	3	4	5
Appearance	1	2	3	4	5
Comments:					
Noise	1	2	3	4	5
Comments:					
Effectiveness	1	2	3	4	5
Comments:					
Easy to hold	1	2	3	4	5
Comments:					
Easy to clean the Grillbot	1	2	3	4	5
Comments:					
Easy to operate/figure out	1	2	3	4	5
Comments:					
Value ($130)	1	2	3	4	5
Comments:					
Overall rating	1	2	3	4	5

What do you like about the Grillbot?

What do you NOT like about the Grillbot?

What would you change?

Would you buy it? Why/why not?

If not, what would you pay for it?

Interview responses

Name BRETT

	Bad 1	2	3	4	Good 5
Rate your grilling experience level	1	2	3	~~4~~	5
Appearance	1	2	3	4	5

Comments:
ABOUT WHAT I EXPECTED

Noise 1 2 3 4 5
Comments:
VERY LOUD, HIT EDGES OF GRILL & SHOOK IT

Effectiveness 1 2 3 4 5
Comments:
LITTLE RESIDUE LEFT

Easy to hold 1 2 3 4 5
Comments:
COULD EASILY HAVE A HANDLE ON TOP

Easy to clean the GrillBot 1 2 3 4 5
Comments:
DIFFICULT TO TAKE OFF. BRISTLES HARD TO CLEAN

Easy to operate/figure out 1 2 3 4 5
Comments:
SINGLE BUTTON

Value ($130) 1 2 3 4 5
Comments:
WOULD NEVER BUY THIS, TOO EASY TO DO W/ A BRUSH

Overall rating 1 2 3 4 5

What do you like about the GrillBot?

EFFECTIVENESS

What do you NOT like about the GrillBot?

EXPENSE & NOISE

What would you change?

MAKE IT EASIER TO HOLD, CHEAPER

Would you buy it? Why/why not?

NO, TO EASY TO DO W/ A BRUSH

If not, what would you pay for it?

$30

Name Zac Haug

	Bad				Good
Rate your grilling experience level	1	2	3	4	5
Appearance	1	2	3	4	5

Comments

Noise	1	2	3	4	5

Comments:
Made a loud Noise when Cleaning

Effectiveness	1	2	3	4	5

Comments

Easy to hold	1	2	3	4	5

Comments:

Easy to clean the GrillBot	1	2	3	4	5

Comments
A little hard to get Brushes off and back on

Easy to operate/figure out	1	2	3	4	5

Comments:

Value ($130)	1	2	3	4	5

Comments
Too. Expensive, I wouldn't pay that much

Overall rating	1	2	3	4	5

What do you like about the GrillBot?
Cleaned the Grill well

What do you NOT like about the GrillBot?
The Price

What would you change?
I would Try and Make it a little Cheaper, and easier to take Brushes off.

Would you buy it? Why/why not?
No, Just because the price is so high.

If not, what would you pay for it?
$50

Name Sean C

	Bad 1	2	3	4	Good 5
Rate your grilling experience level	1	2	3	4	5

Appearance 1 2 3 4 5
Comments:

Noise 1 2 3 4 5
Comments:
Tazmanian devil in a box

Effectiveness 1 2 3 4 5
Comments:
everything but missed
the underlying cross bars needs more weight

Easy to hold 1 2 3 4 5
Comments:

Easy to clean the GrillBot 1 2 3 4 5
Comments:
cleaning bristles suck

Easy to operate/figure out 1 2 3 4 5
Comments:

Value ($130) 1 2 3 4 5
Comments:
worth $50

Overall rating 1 2 3 4 5

What do you like about the GrillBot?

It does an effective job of cleaning after I use

What do you NOT like about the GrillBot?

Noisy as all get out

What would you change?

rubber edges to minimize banging against sides

Would you buy it? Why/why not?

No too expensive for laziness

If not, what would you pay for it?

$40-50

Name Nick Burrin

	Bad				Good
Rate your grilling experience level	1	2	3	4	5
Appearance Comments	1	2	3	4	5
Noise Comments:	1	2	3	4	5
Effectiveness Comments	1	2	3	4	5
Easy to hold Comments:	1	2	3	4	5
Easy to clean the GrillBot Comments	1	2	3	4	5
Easy to operate/figure out Comments:	1	2	3	4	5
Value ($130) Comments	1	2	3	4	5
Overall rating	1	2	3	4	5

What do you like about the GrillBot?

Autonomous. Ease of use/disassembly.

What do you NOT like about the GrillBot?

Noise

What would you change?

Noise

Would you buy it? Why/why not?

No, too expensive for something I can do better/quicker.

If not, what would you pay for it?

$60

ame Hunter Johnson

	ad				Good
ate vour grilling experience level	1	2	3	4	5
Appearance Comments:	1	2	3	4	5
Noise Comments:	1	2	3	4	5
Effectiveness Comments:	1	2	3	4	5
Easy to hold Comments:	1	2	3	4	5
Easy to clean the GrillBot Comments:	1	2	3	4	5
Easy to operate/figure out Comments:	1	2	3	4	5
Value ($130) Comments:	1	2	3	4	5
Overall rating	1	2	3	4	5

hat do you like about the GrillBot?
The overall look is cool

What do you NOT like about the GrillBot?
I could do a better job at cleaning the grill in 2 minutes with a sponge

What would you change?
moves around too much

Would you buy it? Why/why not?
no, not effective

If not, what would you pay for it
10 $

Name Chase Alexander

	Bad				Good
Rate your grilling experience level	1	2	3	4	5
Appearance	1	2	3	4	5

Comments:

Noise	1	2	3	4	5

Comments: Too loud, sounds like trapped animal

Effectiveness	1	2	3	4	5

Comments:
Could be heavier, needs more weight to clean

Easy to hold	1	2	3	4	5

Comments:
Could use a handle

Easy to clean the GrillBot	1	2	3	4	5

Comments:

Easy to operate/figure out	1	2	3	4	5

Comments: 1 button => easy

Value ($130)	1	2	3	4	5

Comments: I would never buy this for that much
It only takes like 5 minutes to clean by hand

Overall rating	1	2	3	4	5

What do you like about the GrillBot?
Looks good, clean alright, easy to operate

What do you NOT like about the GrillBot?
Too loud, too expensive, doesn't clean completely

What would you change?
Make it heavier, cheaper

Would you buy it? Why/why not?

If not, what would you pay for it?
$20

ame Stephen R. Moreno

					Good
ate your grilling experience level	1	2	3	4	5
Appearance Comments:	1	2	3	4	5
Noise Comments:	1	2	3	4	5
Effectiveness Comments:	1	2	3	4	5
Easy to hold Comments:	1	2	3	4	5
Easy to clean the GrillBot Comments:	1	2	3	4	5
Easy to operate/figure out Comments:	1	2	3	4	5
Value ($130) Comments:	1	2	3	4	5
Overall rating	1	2	3	4	5

---

at do you like about the GrillBot?

~~Effortless~~ Effortless ; Effective

What do you NOT like about the GrillBot?

Loud ; Expensive AF

What would you change?

Cost ; Self-cleaning

Would you buy it? Why/why not?

No. Too much $ $

If not, what would you pay for it

$20

ame John LaMont

	Bad				Good
ate your grilling experience level	1	2	3	4	5
Appearance	1	2	3	4	5

Comments:

Noise	1	2	3	4	5

Comments:

Effectiveness	1	2	3	4	5

Comments:

Easy to hold	1	2	3	4	5

Comments:

Easy to clean the GrillBot	1	2	3	4	5

Comments:

Easy to operate/figure out	1	2	3	4	5

Comments:

Value ($130)	1	2	3	4	5

Comments:

Overall rating	1	2	3	4	5

---

hat do you like about the GrillBot?

Does my cleaning job for me

What do you NOT like about the GrillBot?

The price

What would you change?

Individual wire brushes need to be longer, strething towards Center.

Would you buy it? Why/why not?

No, Because it takes little time to clean my grill. ~~Not~~ worth $130.

If not, what would you pay for it?

$30.00

Name Connor Harness

	Bad				Good
Rate your grilling experience level	1	2	3	4	5
Appearance Comments:	1	2	3	4	5
Noise Comments:	1	2	3	4	5
Effectiveness Comments:	1	2	3	4	5
Easy to hold Comments:	1	2	3	4	5
Easy to clean the GrillBot Comments:	1	2	3	4	5
Easy to operate/figure out Comments:	1	2	3	4	5
Value ($130) Comments:	1	2	3	4	5
Overall rating	1	2	3	4	5

What do you like about the GrillBot?

How well it cleans the grill

What do you NOT like about the GrillBot?

Price

What would you change?

Lower price

Would you buy it? Why/why not?

No. Just don't grill enough

If not, what would you pay for it?

$50

Name John Douthit

	Bad				Good
Rate your grilling experience level	1	2	3	4	5
Appearance	1	2	3	4	5

Comments:

Noise	1	2	3	4	5

Comments:
Sounds like a tasmanian devil

Effectiveness	1	2	3	4	5

Comments:
would still rather use a brush

Easy to hold	1	2	3	4	5

Comments:
Definitely could be easier
A handle shouldn't effect performance

Easy to clean the GrillBot	1	2	3	4	5

Comments:

Easy to operate/figure out	1	2	3	4	5

Comments:

Value ($130)	1	2	3	4	5

Comments:
Way to expensive! $10 for a brush or $130 for this?

Overall rating	1	2	3	4	5

...t do you like about the GrillBot?
Creates less work for user

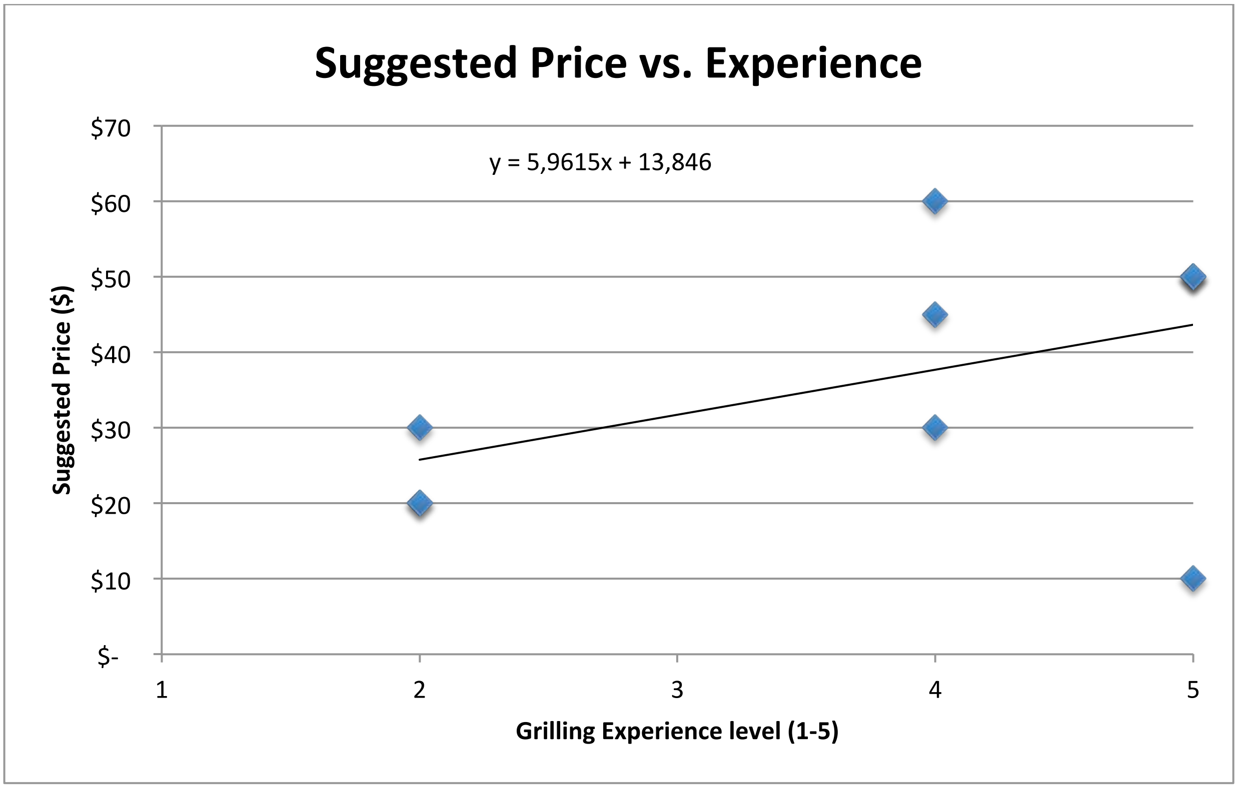
What do you NOT like about the GrillBot?
Way too loud and expensive.

What would you change?
Quieter and price decrease. Also needs more weight

Would you buy it? Why/why not?
No, way to pricey

If not, what would you pay for it?
$50

Appendix F: Suggested Price vs. Experience



Appendix G: Customer Interview Sheet Data

Customer Name	Customer #	Comment #	Voice of the customer	Customer Score	Interpreted Needs	Importance
Brett	1	1	*Grilling experience level*	*2*		n/a
		2	*Appearance*	*4*		3
		3	*Noise*	*1*		4
		4	*Effectiveness*	*5*		4
		5	*Easy to hold*	*2*		3
		6	*Easy to clean*	*3*		4
		7	*Easy to operate/figure out*	*4*		3
		8	*Value*	*1*		3
		9	*Overall rating*	*3*		n/a
		10	Appearance is about what I expected			2
		11	Noise is very loud, it hits the edges and shakes the grill		Make quieter	2
		12	Leaves little residue behind		Cleans thoroughly	4
		13	Could easily have handle on top		Easy to handle/grab	3
		14	Difficult to take off grill.		Make easier to grab	3
		15	Bristles are hard to clean		Easy way to clean brushes	4
		16	Single button is easy to use		Intuitive operation	2
		17	I would never buy this, it's too easy to clean grill with a simple brush		Lower price	3
		18	Too expensive and loud		Lower price, quieter operation	2
Zac	2	1	*Grilling experience level*	5		n/a
		2	*Appearance*	4		3
		3	*Noise*	3		4
		4	*Effectiveness*	4		4
		5	*Easy to hold*	3		3
		6	*Easy to clean*	2		4
		7	*Easy to operate/figure out*	4		3

		8	*Value*	2		3
		9	*Overall rating*	3		n/a
		10	Made a loud noise when cleaning		Make quieter	2
		11	A little hard to get brushes off and back on		Make easier to disassemble	2
		12	Too expensive, I wouldn't pay that much		Make less expensive	3
		13	Cleaned the grill well		Effective cleaning	4
		14	I would try and make it a little cheaper and easier to take brushes off		Make less expensive while also easier to clean/disassemble	3
Sean	3	1	*Grilling experience level*	4		n/a
		2	*Appearance*	4		3
		3	*Noise*	1		4
		4	*Effectiveness*	4		4
		5	*Easy to hold*	5		3
		6	*Easy to clean*	3		4
		7	*Easy to operate/figure out*	4		3
		8	*Value*	1		3
		9	*Overall rating*	3		n/a
		10	Tasmanian devil in a box		Make quieter	2
		11	Cleaned everything but missed the underlying crossbars		Better cleaning - maybe longer brushes	3
		12	Needs more weight		Needs to clean better or more with more force	3
		13	Cleaning bristles sucks		Make easier way to clean brushes	3
		14	Does an effective job cleaning after 10 minutes of use		Cleans thoroughly and quickly	4
		15	Noisy as all get out		Make quieter	2
		16	Rubber edges to minimize banging against sides		Make quieter, less banging	2
John	4	1	*Grilling experience level*	5		n/a
		2	*Appearance*	5		3
		3	*Noise*	1		4
		4	*Effectiveness*	3		4
		5	*Easy to hold*	3		3

		6	*Easy to clean*	4		4
		7	*Easy to operate/figure out*	5		3
		8	*Value*	1		3
		9	*Overall rating*	2		n/a
		10	Sounds like a Tasmanian devil		Make quieter	2
		11	Would rather use a hand brush		More effective at cleaning	3
		12	Could be easier to hold, adding a handle shouldn't affect performance		Easy to grasp	2
		13	Too expensive! $10 for a brush of $130 for this		More value for the money	3
		14	I like that it creates less work for the user		Automatic function	4
		15	Too loud and expensive		Make quieter and more affordable	2
		16	Needs more weight		High scrubbing force	3
Nick	5	1	*Grilling experience level*	4		n/a
		2	*Appearance*	4		3
		3	*Noise*	1		4
		4	*Effectiveness*	4		4
		5	*Easy to hold*	4		3
		6	*Easy to clean*	4		4
		7	*Easy to operate/figure out*	5		3
		8	*Value*	3		3
		9	*Overall rating*	4		n/a
		10	I like the autonomous aspect		Automatic function	4
		11	It cleans even on a hot grill. I didn't have to wait for it to cool		Temperature resistance	4
		12	Easy to use and disassemble		Intuitive operation	2
		13	Don't like the noise		Make quieter	2
		14	I could clean grill better for cheaper		Add value by increasing effectiveness	3
Hunter	6	1	*Grilling experience level*	5		n/a
		2	*Appearance*	4		3
		3	*Noise*	2		4
		4	*Effectiveness*	2		4

		5	*Easy to hold*	5		3
		6	*Easy to clean*	3		4
		7	*Easy to operate/figure out*	3		3
		8	*Value*	1		3
		9	*Overall rating*	2		n/a
		10	The overall look is cool		Aesthetically pleasing	2
		11	I could do a better job cleaning the grill in 2 minutes with a sponge		Add value by increasing effectiveness	3
		12	[Almost dropped it]		Easy to grasp	2
		13	Moves around too much		Moves slower to clean one area at a time	1
		14	Not effective		Make more effective	3
Chase	7	1	*Grilling experience level*	2		n/a
		2	*Appearance*	4		3
		3	*Noise*	1		4
		4	*Effectiveness*	4		4
		5	*Easy to hold*	4		3
		6	*Easy to clean*	4		4
		7	*Easy to operate/figure out*	5		3
		8	*Value*	1		3
		9	*Overall rating*	3		n/a
		10	Too loud		Make quieter	2
		11	Sounds like a trapped animal, like if you tried to grill a live squirrel		Make quieter	2
		12	Could be heavier, needs more weight to properly clean		More forceful scrubbing action	2
		13	Could use a handle		Easy to grasp	2
		14	1 button = easy		Intuitive operation	2
		15	Looks good		Aesthetically pleasing	2
		16	I would never buy this, it only takes like 5 minutes to clean by hand		Add value by increasing effectiveness	3
Stephen	8	1	*Grilling experience level*	2		n/a
		2	*Appearance*	4		3
		3	*Noise*	2		4
		4	*Effectiveness*	5		4

		5	*Easy to hold*	4		3
		6	*Easy to clean*	3		4
		7	*Easy to operate/figure out*	5		3
		8	*Value*	1		3
		9	*Overall rating*	3		n/a
		10	I like that it is effortless and effective		Automatic function	4
		11	[Set it down on the ground hard and bent some brushes]		Easy storage solution	1
		12	Battery life is great. It's been cleaning for about an hour and still has more than half the battery life		Long battery life	3
		13	Taking off the brushes gets your hands dirty		Easy to disassemble	3
		14	I don't like that it's loud and very expensive		Make quieter and more affordable	2
		15	I wish it were self-cleaning		Easy to clean or self-cleaning	4
John L	9	1	*Grilling experience level*	4		n/a
		2	*Appearance*	4		3
		3	*Noise*	3		4
		4	*Effectiveness*	3		4
		5	*Easy to hold*	4		3
		6	*Easy to clean*	3		4
		7	*Easy to operate/figure out*	5		3
		8	*Value*	2		3
		9	*Overall rating*	3		n/a
		10	Does my cleaning job for me, I like that		Automatic function	4
		11	Price is too high		Add value by increasing effectiveness and/or lowering price	3
		12	I would change it so that individual wire brushes are longer and stretch more towards the center		Increase cleaning effectiveness for deep reach	2
		13	Doesn't take me long to clean my grill so this is unnecessary		Clean faster and better than hand brush	4

Connor 10	1	*Grilling experience level*	5		n/a
	2	*Appearance*	4		3
	3	*Noise*	3		4
	4	*Effectiveness*	4		4
	5	*Easy to hold*	5		3
	6	*Easy to clean*	4		4
	7	*Easy to operate/figure out*	5		3
	8	*Value*	2		3
	9	*Overall rating*	4		n/a
	10	I like how well it cleans the grill		Effective cleaning	4
	11	[Hesitates turning device on]		Intuitive operation	2
	12	Lower the price		Lower the price	2
	13	[Seems frustrated at loud beeping after he manually turned it off]		Attractive and helpful sounds	1
	14	I don't grill enough to justify buying this		Add value	2

Customer Ratings Aggregate

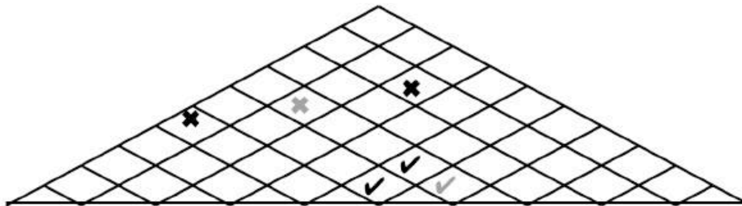
Customer:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Avg**	**Max**	**Min**
Grilling experience level	2	5	4	5	4	5	2	2	4	5	3.8	5	2
Appearance	4	4	4	5	4	4	4	4	4	4	4.1	5	4
Noise	1	3	1	1	1	2	1	2	3	3	1.8	3	1
Effectiveness	5	4	4	3	4	2	4	5	3	4	3.8	5	2
Easy to hold	2	3	5	3	4	5	4	4	4	5	3.9	5	2
Easy to clean	3	2	3	4	4	3	4	3	3	4	3.3	4	2
Easy to operate/figure out	4	4	4	5	5	3	5	5	5	5	4.5	5	3
Value	1	2	1	1	3	1	1	1	2	2	1.5	3	1
Overall rating	3	3	3	2	4	2	3	3	3	4	3	4	2

Customer Needs Summary

Customer Needs: Grillbot Grill Cleaning Robot			Weight
1	User Interactions		
	1.1	Easy to figure out	2
	1.2	Quick and simple operation	3
	1.3	Easy to hold and place on grill	2
	1.4	Easy to disassemble	3
	1.5	Easy to clean Grillbot	4
	1.6	Easy to clean brushes	4
	1.7	Safe operation	2
2	Aesthetics		
	2.1	Attractive appearance	2
	2.2	Quiet noise level	2
	2.3	Pleasing noises	1
	2.4	Informative beeping notifications	1
3	Portable		
	3.1	Compact size	3
	3.2	Easy to store	1
	3.3	Lightweight	2
4	Effectiveness		
	4.1	Long battery life	3
	4.2	Thorough cleaning	4
	4.3	Fast cleaning	4
	4.4	Does not damage grill	3
	4.5	Operates autonomously as a robot	4
5	Value		
	5.1	Reasonable purchase cost	2
	5.2	Good function for the price	3
	5.3	Long-lasting life of components	2
	5.4	Economical to operate	1

Relationships	
✔	Strong Positive
✓	Medium Positive
✗	Medium Negative
✖	Strong Negative

Appendix H: House of Quality (HOQ)

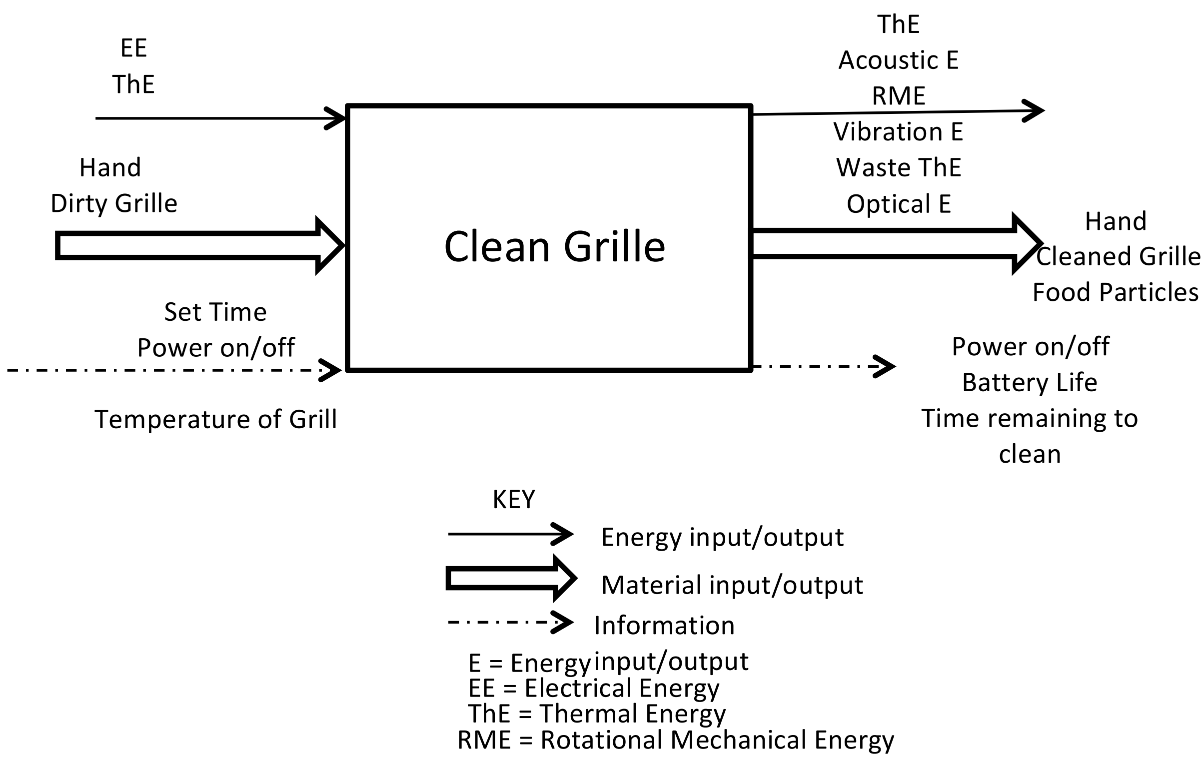


		Customer Attributes	Relative Importance / Engineering Characteristics	Mass of Grillbot	Strength of Wire Brush	Rotational Rate of Wheels	No. Color	No. Parts	Volume of Grillbot	Cost of Grillbot	Time to Charge Battery	Operating noise level	Beeping after shut down	Customer Perception
				How										Now
		Direction of Improvement		↑	↑	↑	-	↓	↓	↓	↓	↓	↓	
		Units		lb	MPa	m/s	#	#	in^3	$	h	dB	dB	
What	User Interactions	Easy to figure out	2											
What	User Interactions	Quick and simple operation	3								✖			4,5
What	User Interactions	Easy to hold and place on grill	2	✖					✖					3,9
What	User Interactions	Easy to disassemble	3	✗	✗			✖						
What	User Interactions	Easy to clean GrillBot	4					✖						3,3
What	User Interactions	Easy to clean brushes	4		✗									3,3
What	User Interactions	Safe operation	2											
What	Aesthetics	Attractive appearance	2				✔							4,1
What	Aesthetics	Quiet noise level	2		✗	✖						✖	✖	1,8
What	Aesthetics	Pleasing noises	1		✗	✖						✖	✖	1,8
What	Aesthetics	Informative beeping notifications	1									✖	✖	
What	Portable	Compact size	3						✖					
What	Portable	Easy to store	1						✖					
What	Portable	Lightweight	2	✖										
What	Effectiveness	Long battery life	3											
What	Effectiveness	Thorough cleaning	4	✓	✔	✔								3,8
What	Effectiveness	Fast cleaning	4		✔	✔			✗					3,8
What	Effectiveness	Does not damage grill	3	✗		✗								
What	Effectiveness	Operates autonomously as a robot	4											
What	Value	Reasonable purchase cost	2	✗						✔				1,5
What	Value	Good function for the price	3		✔					✔	✖			1,5
What	Value	Long-lasting life of components	2			✗				✔				
What	Value	Economical to operate	1							✔				
Met ric Tar gets		Our Grillbot		3,4	500		2	35	241	130	4	60	75	
Met ric Tar gets		**Target Values**		4	600		2	25	241	60	1	40	40	

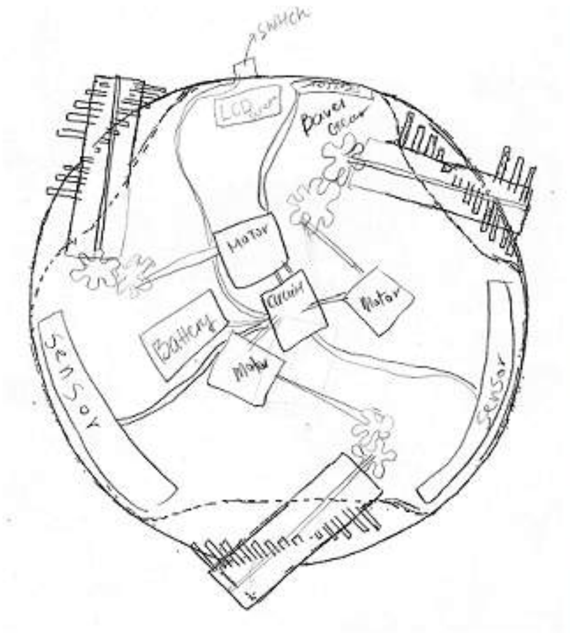
Appendix I: Specification sheet

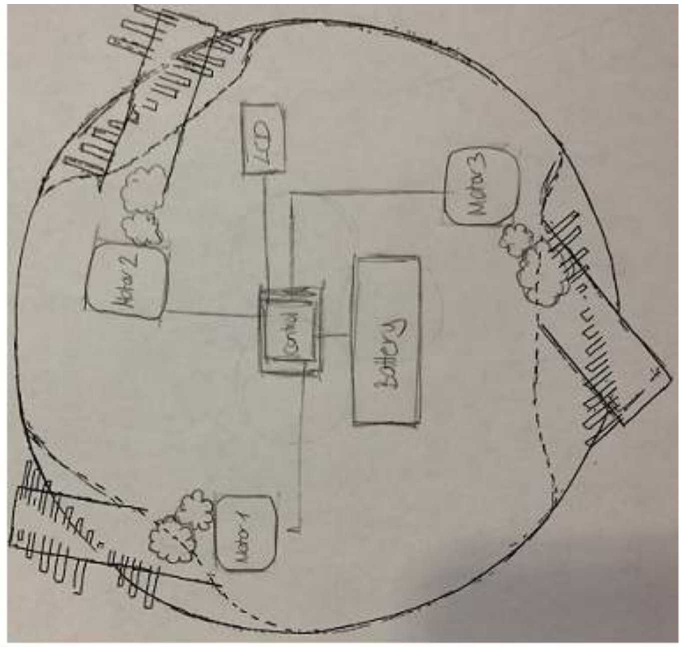
Date	Demand/Wish	Project: Design specification sheet for Grillbot	Responsibility	Test/ Verification
		Geometry		
2/15/15	W	Volume = 241.164 inches^3	All	Verify with Engineering Drawing
		Kinematics		
2/15/15	D	Rotation Rate of Wheels >	All	Verify with output torque of motor
		Force		
2/15/15	D	Mass > 4 lb.	All	Measure Weight
2/15/15	D	Strength of Wire Brushes > 600 MPa	All	Test through Tensile Strength Test
		Material		
2/15/15	W	Number of Colors = 2	All	Observation
		Assembly		
2/15/15	W	Number of Parts <25 (Assumption)	All	Count number of parts used
		Operation		
2/15/15	D	Operating Noise < 40 dB	All	Measure Sound with sound level meter
2/15/15	D	Beeping after shut down < 40 dB	All	Measure Sound with sound level meter
		Cost		
2/15/15	D	Cost of Product < $60	All	Perform Cost Assessment
		Schedule		
2/15/15	D	Time it takes to clean the grill = 10 to 30 min	All	Measure time required to clean the grill with stop watch
2/15/15	D	Time to wash the brushes < 10 min	All	Measure time required to clean brushes with stop watch
2/15/15	D	Time of Beeping after shut down	All	Measure time with stop watch
2/15/15	D	Time to charge the battery < 1 hour	All	Measure time with stop watch

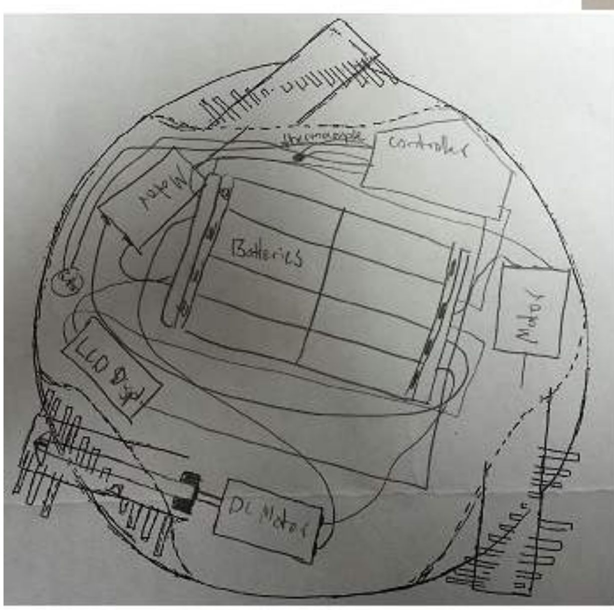
Appendix J: Black Box Diagram



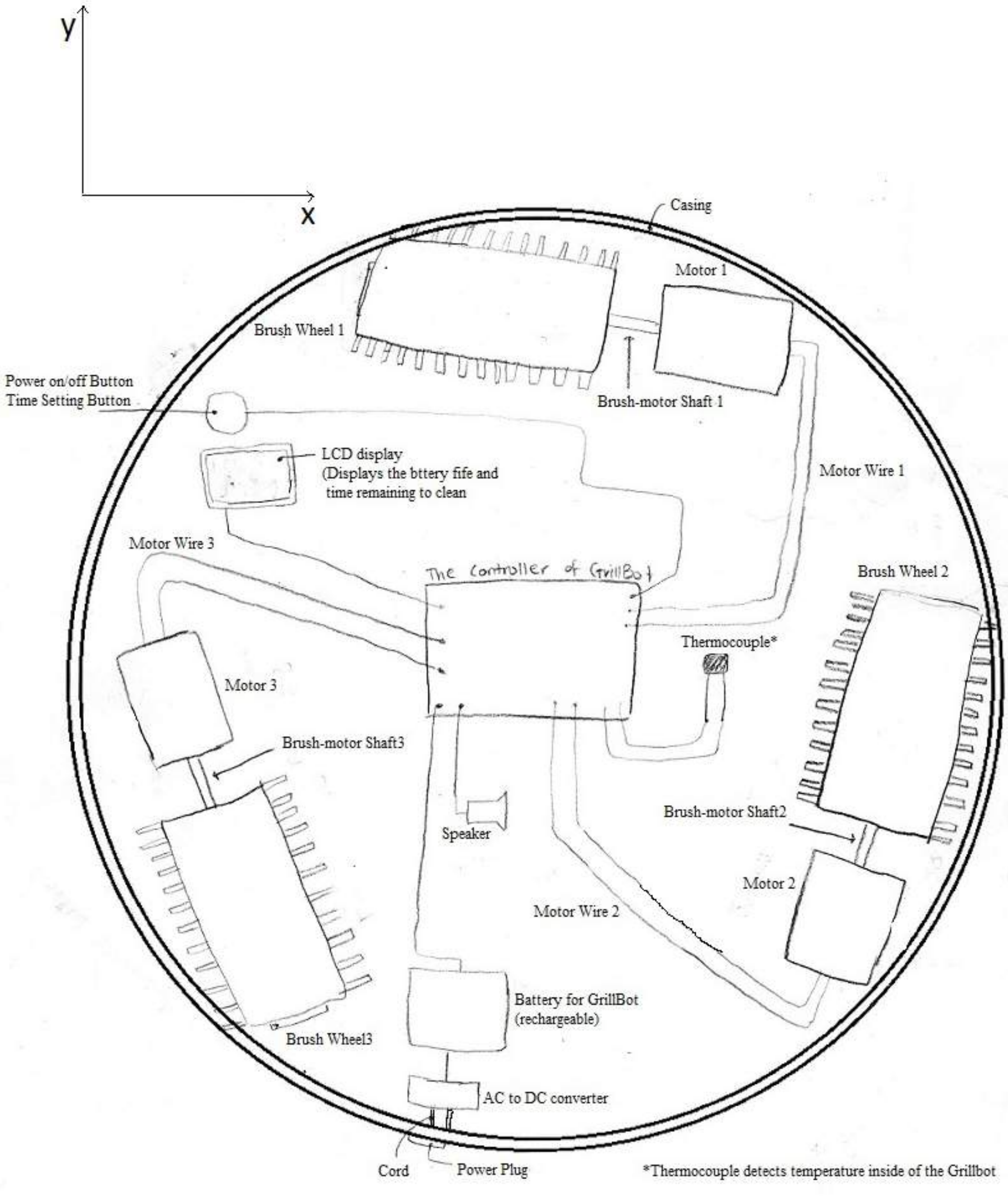
Appendix K: Brainstorming of Predicted Cross-Sectional Sketch



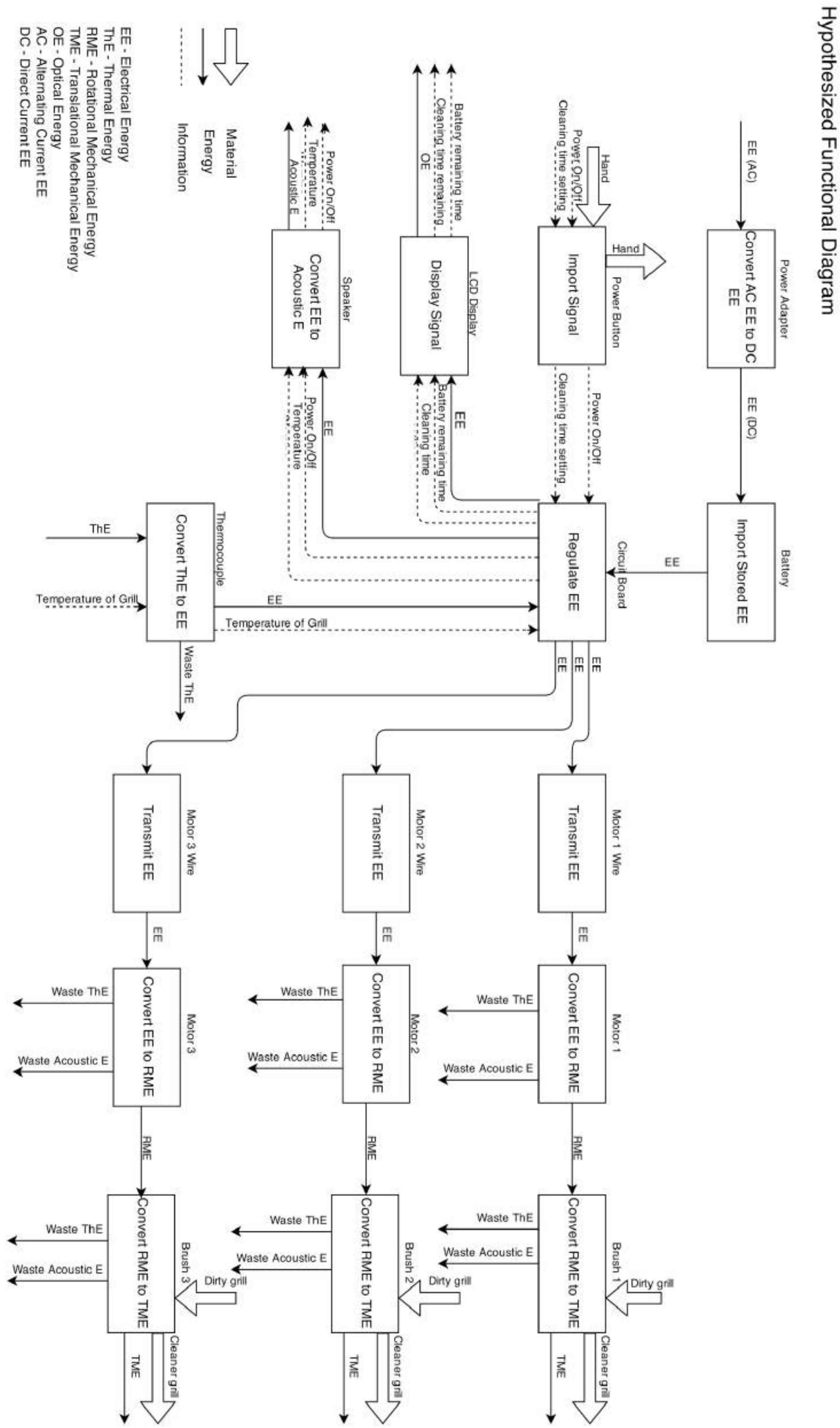




Appendix L: Predictive Cross-Sectional Sketch



Appendix M: Predicted Functional Structure



Appendix N: Product-Disassembly Plan

Step	Part	Task	Necessary Tools	Direction
1	Brush wheel (1)	Remove	Hand	-X
2	Brush wheel (2)	Remove	Hand	cos(45)i-sin(45)j
3	Brush wheel (3)	Remove	Hand	cos(45)i+sin(45)j
4	Top shell screw	Unscrew	Screwdriver	Z
5	Lower shell screws	Unscrew	Screwdriver	-Z
6	Lower shell	Remove	Hand	-Z
7	Top shell	Remove	Hand	Z
8	Handle	Remove	Hand	Z
9	Sub circuit screws	Unscrew	Screwdriver	-Z
10	Sub circuit	Remove	Hand	-Z
11	Rubber power button cover	Remove	Hand	Z
12	Power cord screw	Unscrew	Screwdriver	-Z
13	Power adapter	Pull out	Hand	Z
14	Main circuit screws	Unscrew	Screwdriver	Z
15	Battery	Pull out	Hand	Z
16	Battery cushion pads	Remove	Hand	Z
17	Shaft (1) screws	Unscrew	Screwdriver	-X
18	Shaft (1)	Remove	Hand	-X
19	Shaft (2) screws	Unscrew	Screwdriver	cos(45)i-sin(45)j
20	Shaft (2)	Remove	Hand	cos(45)i-sin(45)j
21	Shaft (3) screws	Unscrew	Screwdriver	cos(45)i+sin(45)j
22	Shaft (3)	Remove	Hand	cos(45)i+sin(45)j
23	Motor (1) screws	Unscrew	Screwdriver	-X
24	Motor (1)	Remove	Hand	-X
25	Motor (2) screws	Unscrew	Screwdriver	cos(45)i-sin(45)j
26	Motor (2)	Remove	Hand	cos(45)i-sin(45)j
27	Motor (3) screws	Unscrew	Screwdriver	cos(45)i+sin(45)j
28	Motor (3)	Remove	Hand	cos(45)i+sin(45)j
29	Bottom pad screws	Unscrew	Screwdriver	-Z
30	Pads	Remove	Hand	-Z
31	Thermocouple epoxy	Remove	Hand/screw drive	Z
32	Label screw	Unscrew	Screwdriver	Z
33	Label washer	Remove	Hand	Z
34	Label	Remove	Hand	Z

Appendix O: Bill of Materials

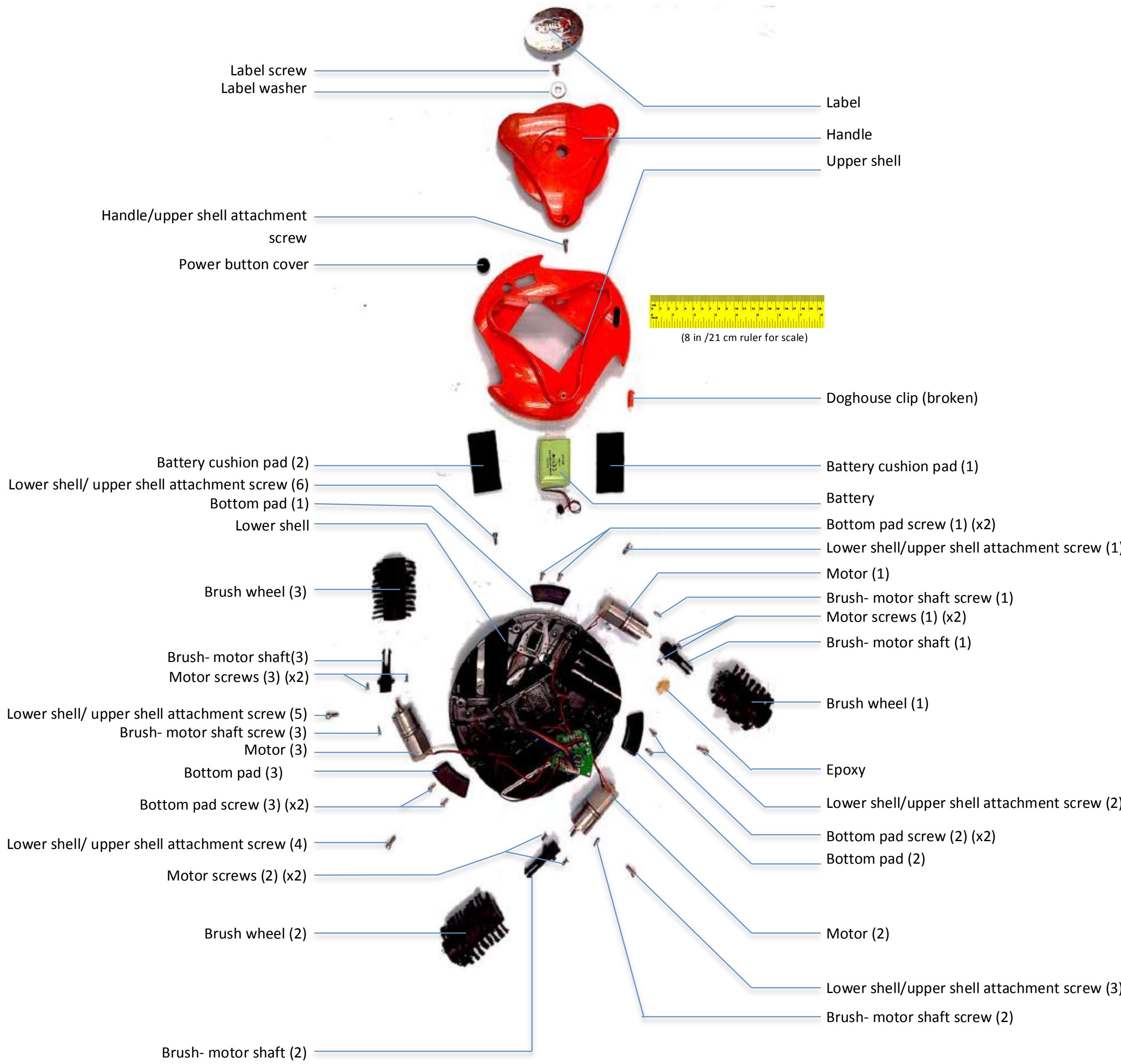
Bill of Materials
Team: The Grill Master
Date 3/9/2015

DFM Cost Analysis Data

Part #	Part Name	Quantity	Function	Mass (g)	Finish	Manufacturing Processes	Dimensions: Depth	Width	Height	Diameter	Diameter (inner)
E	**External Parts**										
1	Label	1	Display the logo of company	40.4	Ni plated steel	Plastic injection molding, Stamping the Logo	69.7		12.8	-	-
2	Label washer	1	Attaches label to grillbot	2.6	Zinc plated steel	Stamped	-	-	1.78	18.1	6.51
3	Top shell	1	Enclose components	164.2	TC-895 A/B BLACK	Plastic injection molding, dyed	50	-	17.5	190	-
4	Lower shell	1	Enclose components	269.2	TC-895 A/B BLACK	Dyed, Injection molding, cut, and coated on inside surface	48	-	5.13	195	-
5	Pads of lower shell	3	Supports grillbot	3.8	TC-895 A/B BLACK	Injection molding, dyed	43.9	20.4	4.92	-	-
6	Battery Charger	1	Charge the device	81.2	Plastic, Steel, Cu	OEM	76.25	49	30	-	-
7	Rubber power button cover	1	Provides soft cushion for button	0.6	Rubber	OEM (Molded, cutting)	-	-	5.58	14.7	-
I1	**Internal Parts**										
	LCD display, Subcircuit, and power buttom			12.4							
1	LCD display	1	Display time remaining to clean, battery life		Plastic	OEM, cutting, welding, and assembled					
2	Subcircuit	1	Transmit signal		Cu, Tin, Silicon	OEM, cutting, welding, and assembled	50.25	27	12.16	-	-
3	Power button	1	Import power on/off		Plastic	OEM, cutting, welding, and assembled					
I2	Assembly of motors, main circuit board, power adapter			264.8							
1	Motors	3	Convert EE to RME	86.666667	Steel and Cu	OEM	-	-	58.17	24.8	-
2	Brush-motor shaft	3	Transmit RME to the brush wheels	4.7333333	TC-895 A/B BLACK	Injection molding, dyed	-	-	46.7	13.7	9.1
3	Brush wheel	3	Transmit RME to the grill, Clean the grill	66.4	TC-895 A/B BLACK, Brass	Plastic injection molding, Wires: OEM, Cutting, Assembly to the brush	-	-	67.4	47.4	25.6
4	Battery	1	Import stored EE to the Maincircuit	110.2	Lithium Ion	OEM	54	36.3	31	-	-
5	Battery cushion pads	2	Provides soft support for battery	0.4	Heat resistant foam	Formed, dyed, slabstock process and cut	69	32.1	2.45	-	-
I3	Thermocouple and epoxy			0.6							
1	Thermocouple	1	Detect the temperature			OEM, Welding					
2	Epoxy	1	Fastens thermocouple to bottom of lower shell		Epoxy	Mixed and applied					
S	**Screws**						Nominal D	Body D	Length_total	Length_head	
1	Bottom pad screw	6	Fastens pads of lower shell to lower shell	0.7	Zinc plated screws	OEM (Turning, Plating)	6.49	3.83	10.18	2.57	
2	Lower shell and top shell screw	6	Attaches lower shell to top shell	1.5714286	Zinc plated screws	OEM (Turning, Plating)	6.67	3.89	13.74	4.18	
3	Power cord screw	1	Attaches power port to top shell	0.1	Zinc plated screws	OEM (Turning, Plating)	7.2	2.34	9.42	1.5	
4	Motor screw	6	Attaches motors to lower shell	0.3666667	Zinc plated screws	OEM (Turning, Plating)	5.43	2.87	7.67	1.49	
5	Shaft screws	3	Attaches brush shaft to motor spindle	0.4	Zinc plated screws	OEM (Turning, Plating)	6.63	1.95	10	1.95	
6	Subcircuit screws	4	Attaches subcircuit board to top shell	0.15	Zinc plated screws	OEM (Turning, Plating)	3.53	2.27	6.5	1.48	
7	Maincircuit screws	4	Attaches main circuit board to lower shell	2.5	Zinc plated screws	OEM (Turning, Plating)	3.95	2.66	9.33	1.94	
8	Label screw	1	Attaches label to grillbot	2	Zinc plated steel	OEM (Turning, Plating)	10	4.88	9.91	3.52	

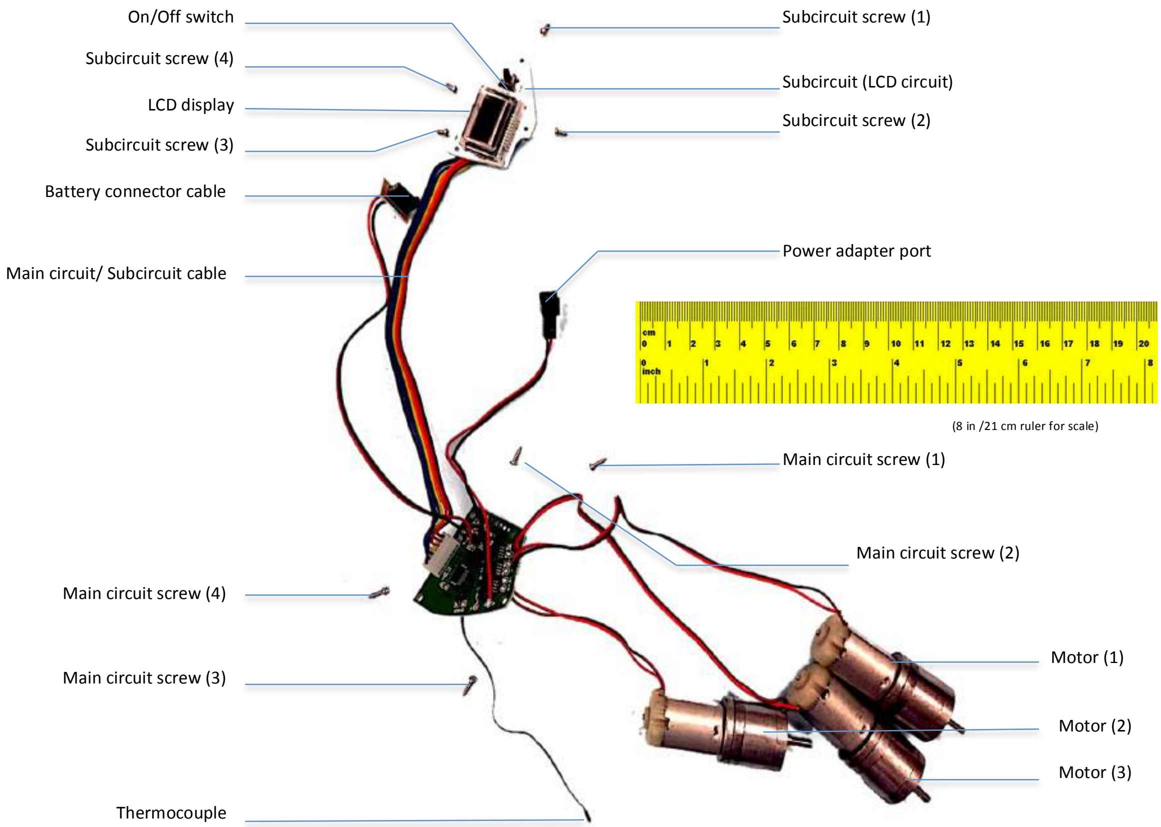
OME: Original Equipment Manufacturer
EE: Electrical Energy
RME: Rotational Mechanical Energy
D: Diameter
Ni:Nickel
Cu:Copper
LCD:Liquid Crystal Displays
E:External Parts
I:Internal Parts
S:Screws

Appendix P: Exploded Views



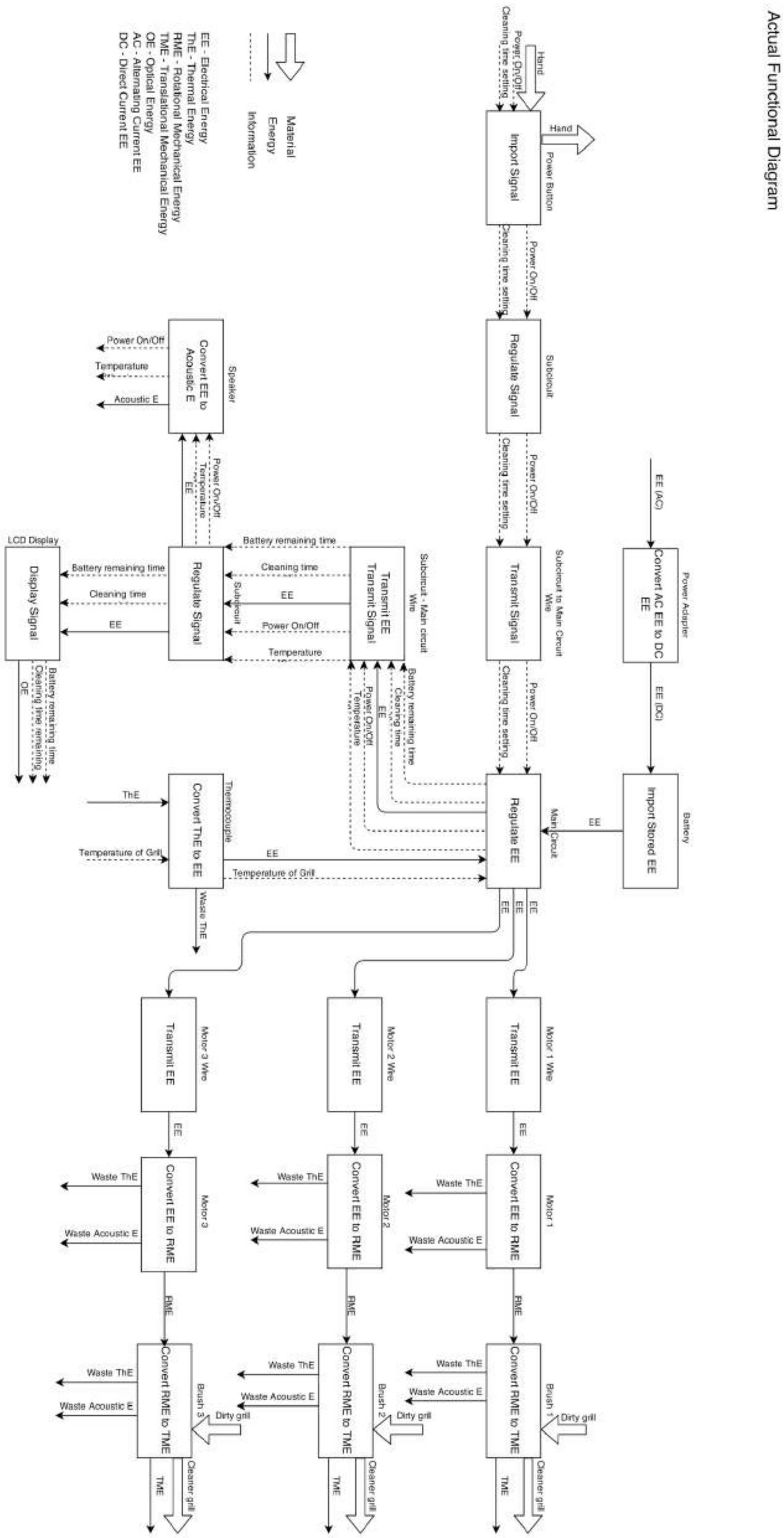
Label screw
Label washer
Label
Handle
Upper shell
Handle/upper shell attachment screw
Power button cover
(8 in /21 cm ruler for scale)
Doghouse clip (broken)
Battery cushion pad (2)
Battery cushion pad (1)
Lower shell/ upper shell attachment screw (6)
Battery
Bottom pad (1)
Bottom pad screw (1) (x2)
Lower shell
Lower shell/upper shell attachment screw (1)
Motor (1)
Brush wheel (3)
Brush- motor shaft screw (1)
Motor screws (1) (x2)
Brush- motor shaft (1)
Brush- motor shaft(3)
Motor screws (3) (x2)
Brush wheel (1)
Lower shell/ upper shell attachment screw (5)
Brush- motor shaft screw (3)
Motor (3)
Epoxy
Bottom pad (3)
Lower shell/upper shell attachment screw (2)
Bottom pad screw (3) (x2)
Bottom pad screw (2) (x2)
Bottom pad (2)
Lower shell/ upper shell attachment screw (4)
Motor screws (2) (x2)
Brush wheel (2)
Motor (2)
Lower shell/upper shell attachment screw (3)
Brush- motor shaft screw (2)
Brush- motor shaft (2)

Scale 1:8


On/Off switch
Subcircuit screw (4)
LCD display
Subcircuit screw (3)
Battery connector cable
Main circuit/ Subcircuit cable
Subcircuit screw (1)
Subcircuit (LCD circuit)
Subcircuit screw (2)
Power adapter port
(8 in /21 cm ruler for scale)
Main circuit screw (1)
Main circuit screw (2)
Main circuit screw (4)
Main circuit screw (3)
Thermocouple
Motor (1)
Motor (2)
Motor (3)

Scale 1:4

Appendix Q: Actual Functional Structure



Appendix R: Function-Component Matrix

		Components													
		Sub circuit	Main Circuit	Sub circuit-Main circuit wire	Brush-Motor Shaft	Motor wire	Motors	Power Button	Pads	Battery Cushion Pads	Battery	Speaker	Thermocouple	LCD display	Brush Wheel
Functions	Transmit RME				X										
	Transmit EE			X		X									
	Transmit Signal	X		X											
	Convert EE to RME						X								
	Convert EE to Acoustic E														
	Convert AC EE to DC EE		X									X			
	Convert ThE to EE												X		
	Import Stored EE										X				
	Import On/Off Signal							X							
	Import Time Setting Signal							X							
	Export Torque/RME														X
	Export on/off signal											X			
	Export Temperature Warning											X			
	Stabilize Machine								X						
	Stabilized the Battery									X					
	Display time remaining to clean													X	
	Display the battery life													X	
	Remove food on the grill														
	Detect temperature of inside of Grillbot												X		
	Regulate Signal														
	Regulate EE		X												

The: Thermal Energy
EE: Electrical Energy
RME: Rotational Mechanical Energy
AC: Alternating Current
DC: Direct Current
LCD: Liquid Crystal Displays

Appendix S: Noise-absorbing materials

Material	Cost/volume ($/cm^3)
Extreme Vibration Attenuation (EVA) pad	7,105E-03
Sound Dampening Pad	2,165E-02
RB Rubber	1,083E-04
AcoustiCORK RR300	8,476E-06
5mm Pre-Cut Rubber	1,559E-05

Appendix T: Updated Specification Sheet

Date	Demand/ Wish	Metrics	Value	Units	Responsibility	Test/ Verification
Geometry						
15/02/15	W	Volume	241.164	Inches^3	All	Verify with dimensions given by the Engineering sketch
Kinematics						
07/03/15	D	Rotation Rate of Wheels		rpm	All	Verify with output torque of motor
Force						
07/03/15	D	Mass	> 3.3	lb.	All	Measure Weight with a digital weight scale
Material						
15/02/15	D	Strength of Wire Brushes	> 600	Mpa	All	Test through Tensile Strength Test
Assembly						
07/03/15	W	Number of Parts	<25	-	All	Count number of parts used
Operation						
07/03/15	D	Operating Noise	< 40	dB	All	Measure noise with phone Application: dB
07/03/15	D	Noise level of beeping after shut down	< 40	dB	All	Measure noise with phone Application: dB
Cost						
15/02/15	D	Expected Cost of Product	< 60	$	All	From customer interviews
Schedule						
15/02/15	D	Average time to wash the brushes	< 10	Minutes	All	Measure time required to clean brushes with stop watch (3 times)
15/02/15	D	Time of Beeping after shut down	< 5	Seconds	All	Measure time with stop watch
15/02/15	D	Time to charge the battery	< 4	Hours	All	From the instruction user manual
Signal						
15/02/15	D	Actual time it takes to clean the grill	= 10 - 30	Minutes	All	Measure time required to clean the grill with stop watch
Appearance						
15/02/15	W	Number of Colors on Grillbot	2	-	All	Observation

Appendix U: To-do List and Gantt chart for Phase II

To-Do List Phase 2	
Task	Completed?
To-Do List	
Make the List	Completed
Distribute work	Completed
Gantt Chart	
Make the chart	Completed
Plan	Completed
Select Adaptive Avenues	
Select Adaptive Avenue	Completed
Write up for Functional Redesign Avenue	Completed
Write up for Industrial Redesign Avenue	Completed
Brainstorming	
Mind Maps (Industrial)	Completed
Mind Maps (Functional)	Completed
6-3-5 (Industrial)	Completed
6-3-5 (Functional)	Completed
Write up for Mind Maps	Completed
Write up for 6-3-5	Completed
Analogy for Functional Redesign Avenue	
Five Analogies	Completed
Write up	Completed
TIPS	
TIPS	Completed
Write up	Completed
Morphological Matrix	
Brainstorm Ideas	Completed
Make the Matrix	Completed
Write up for Morphological Matrix	Completed
Design Change Concept Generation	
Draw Functional Redesign Concepts	Completed
Draw Industrial Redesign Concepts	Completed
Write up for Functional Redesign Avenue	Completed
Write up for Industrial Redesign Avenue	Completed
Putting them together	Complete
Low Resolution Prototype	
Buy Materials	Complete
Building Prototype	Complete
Write up	Complete

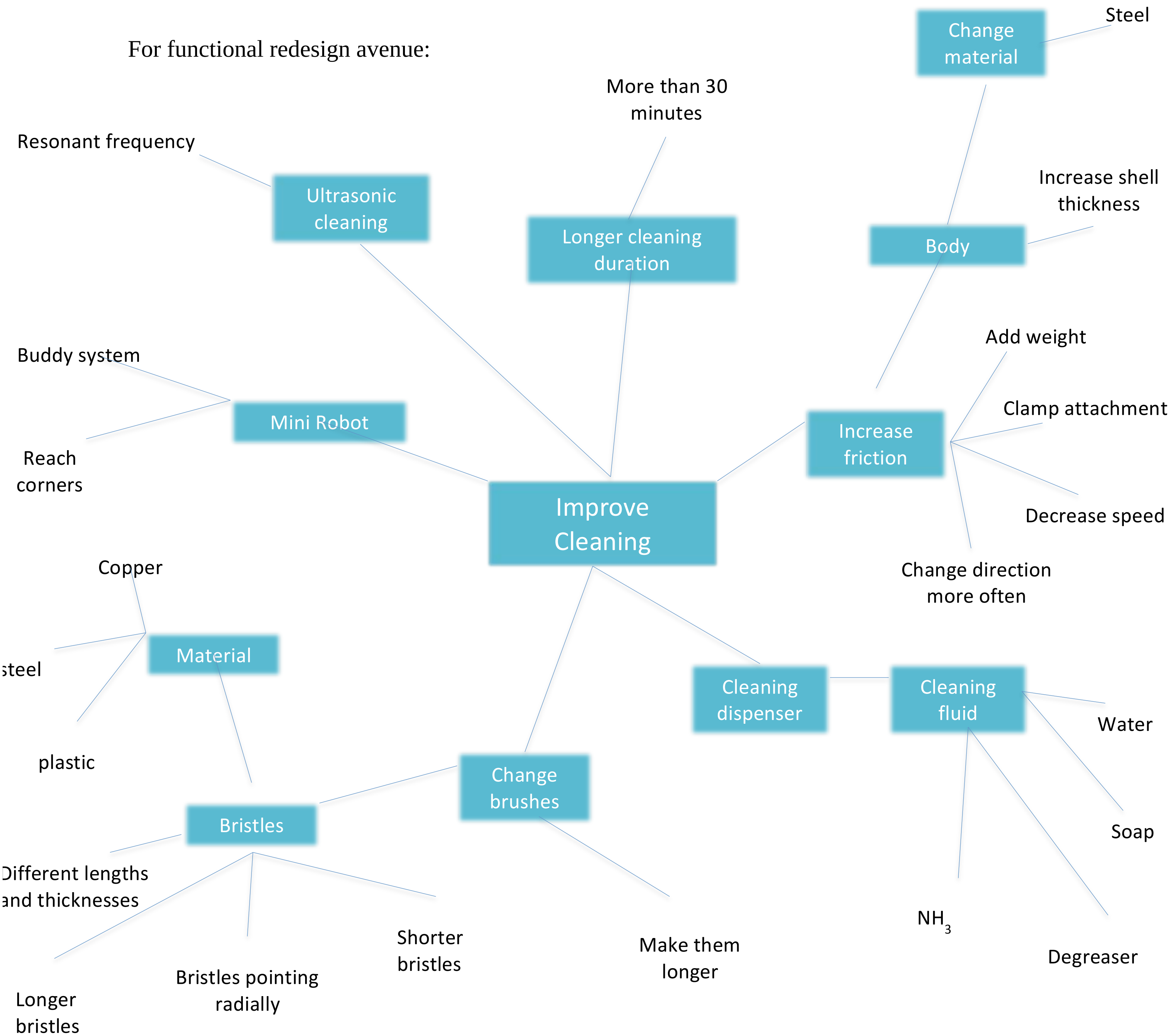
Order-of-Magnitude	
Calculation	
Concept Variant #1 and #5	Complete
Concept Variant #2 and #4	Complete
Concept Variant #3	Complete
Putting them together	Complete
Write up	Complete
Pugh Chart	
Mark the chart	Complete
Write up	Complete
Specification sheet and problem statement	
Spec. Sheet for functional redesign avenue	Complete
Spec. Sheet for functional redesign avenue	Complete
Problem Statement for functional redesign avenue	Complete
Problem Statement for industrial redesign avenue	Complete
Write up for Spec. Sheet	Complete
Write up for Spec. Sheet	Complete

roject			
enchmark			
hase 1			
Product Introduction	02/02/15	09/02/15	100
Background Literature	02/02/15	09/02/15	100
Customer Needs Analysis	02/02/15	09/02/15	100
Customer Interviews	09/02/15	16/02/15	100
House of Quality	09/02/15	16/02/15	100
Specifications Sheet	09/02/15	16/02/15	100
Activity Diagram	09/02/15	16/02/15	100
To-do List	2/16/15	2/16/15	100
Gantt Chart	2/16/15	2/16/15	100
Black Box Model	2/18/15	2/22/15	100
Hypothesized Function Model	2/18/15	2/22/15	100
Cross Sectional Sketches	2/18/15	2/22/15	100
Product Disassembly	2/25/15	3/1/15	100
Bill of Materials	2/25/15	3/1/15	100
Exploded Views	3/2/15	3/6/15	100
Actual Function Structure	3/2/15	3/6/15	100
Comparison	3/2/15	3/6/15	100
Function Structure	3/2/15	3/6/15	100
Summarize Entire Reverse Engineering	3/2/15	3/6/15	100
Update Specification Sheet and problem statement	3/2/15	3/6/15	100
hase 2			
To-do List	3/9/15	3/9/15	100
Gantt Chart	3/9/15	3/9/15	100
Select Adaptive Avenues	3/11/15	3/15/15	100
Brainstorming	3/11/15	3/15/15	100
Mind Maps	3/16/15	3/20/15	100
6-3-5	3/16/15	3/22/15	100
Design Change Concept Generation	3/16/15	3/22/15	100
Functional Re-design Concept Variants	3/23/15	3/28/15	100
Industrial Design Shift Concept Variants	3/23/15	3/29/15	100
Pugh Chart	3/30/15	4/2/15	100
Order-of-Magnitude	3/30/15	4/2/15	100
hase 3			
To-do List	4/6/15	4/6/15	0
Gantt Chart	4/6/15	4/6/15	0
Develop Experimental Model	4/6/15	4/11/15	0
Experimentation	4/6/15	4/12/15	0
Back-of-the-Envelope	4/13/15	4/16/15	0
FMEA	4/15/15	4/19/15	0
Design for Assembly	4/20/15	4/24/15	0
Design for Environment	4/20/15	4/24/15	0
Preliminary Drawings	4/20/15	4/24/15	0

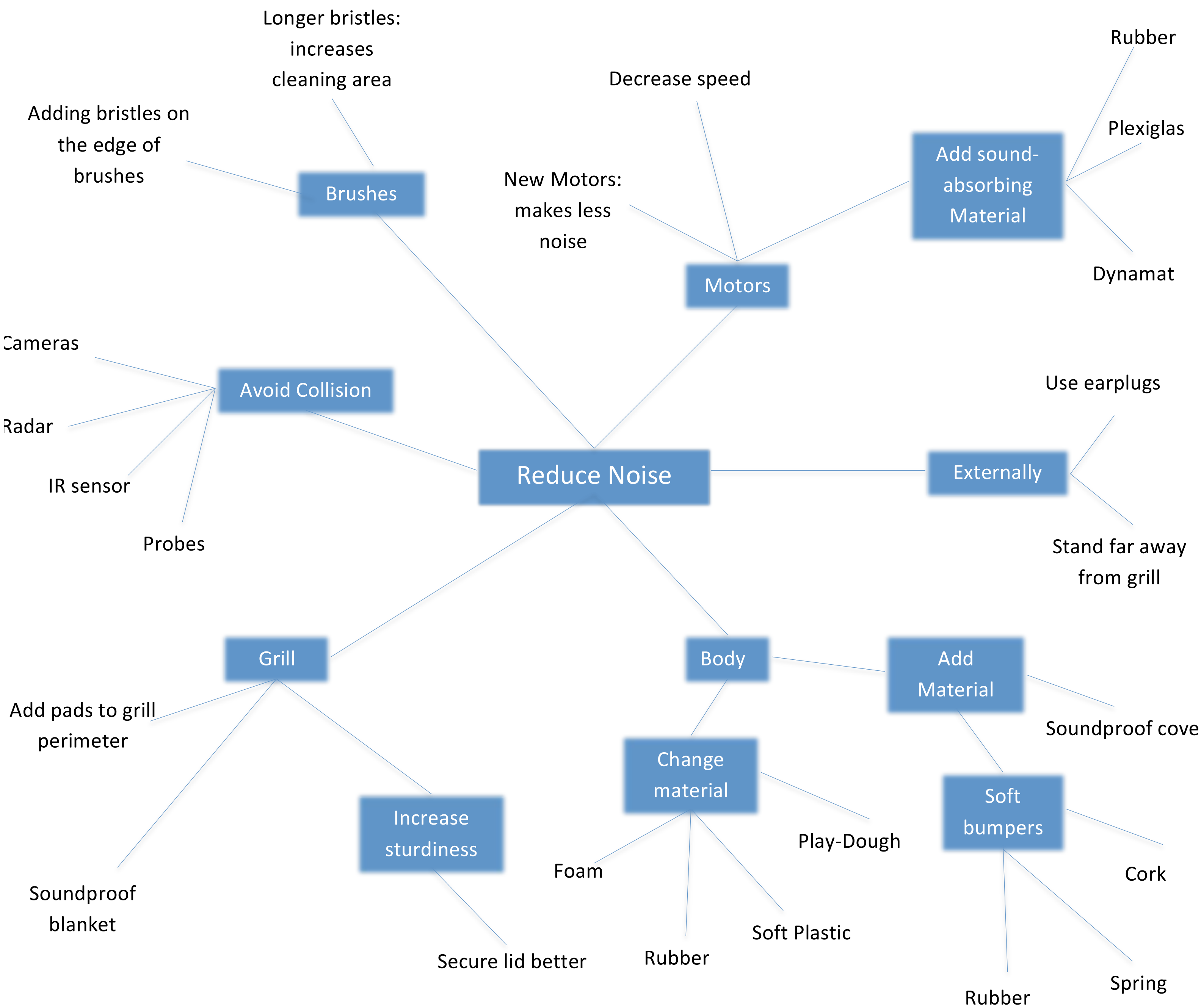
Appendix. V: Picture of the Wall

Appendix W: Mind Maps

For functional redesign avenue:



For industrial redesign avenue:

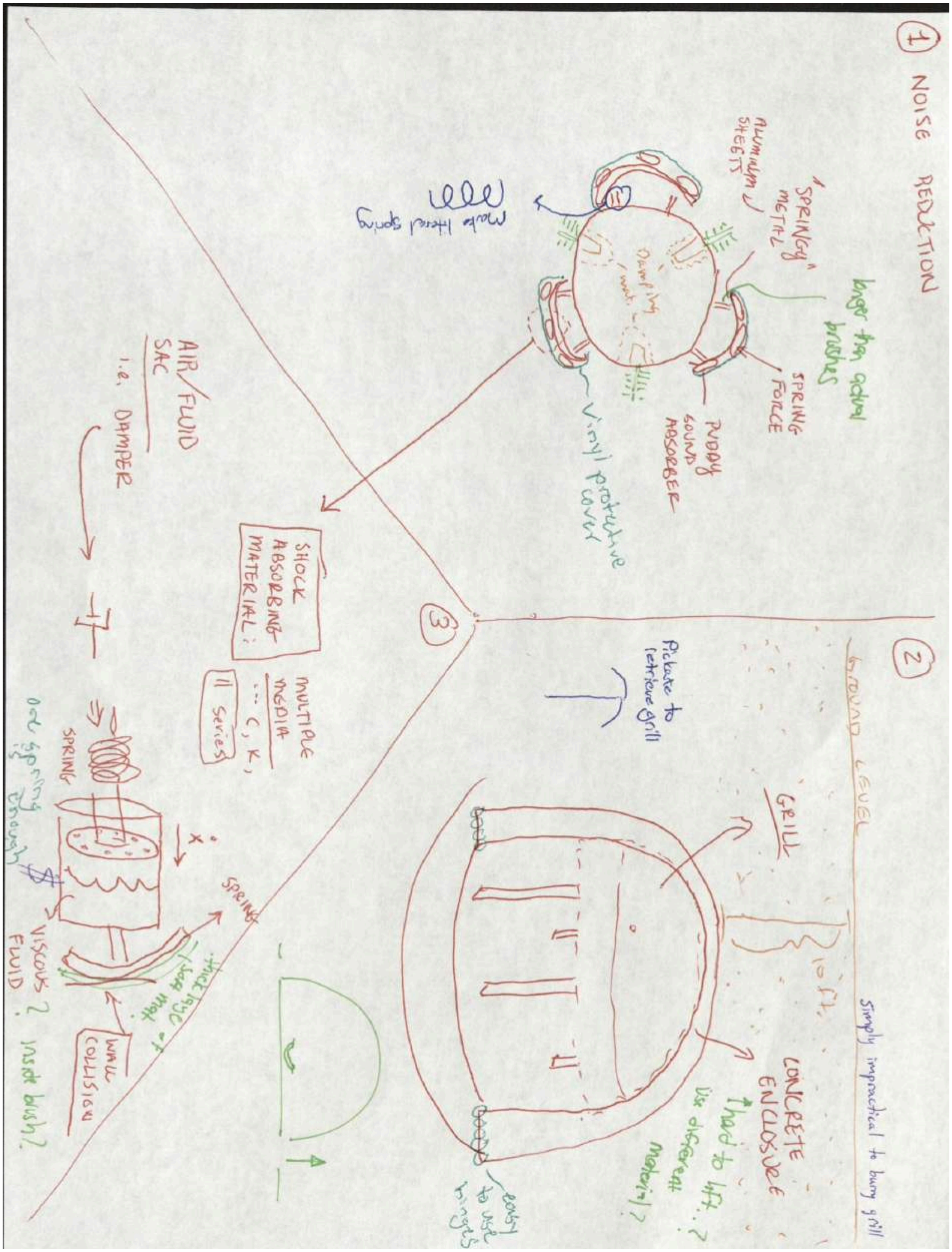


Appendix X: 6-3-5

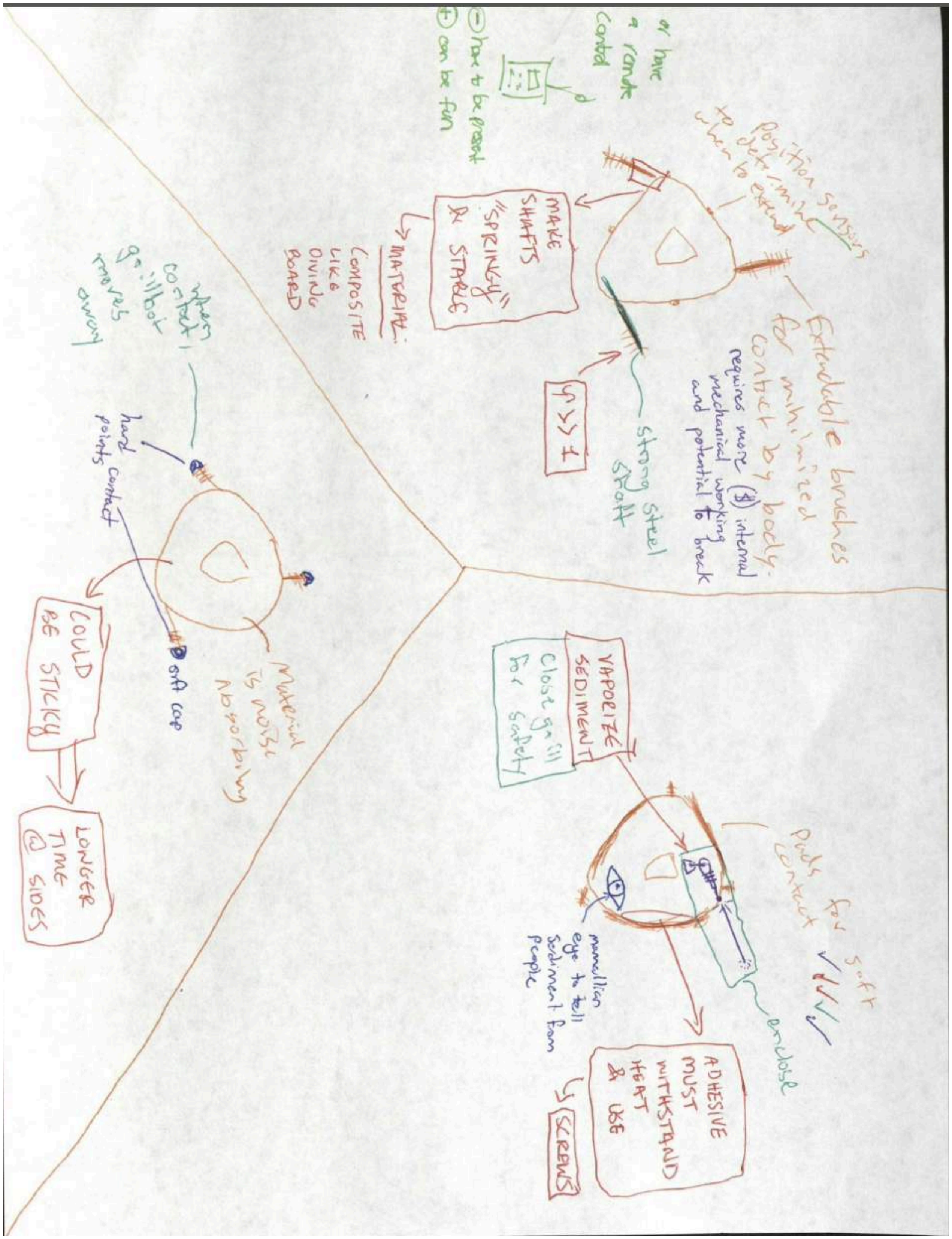
Industrial Redesign Avenue:

Student	Pen color
Hayden	ORANGE
Mark	RED
Blake	DARK GREEN
Maria	LIGHT GREEN
Mark*	BLUE
Sean*	PURPLE

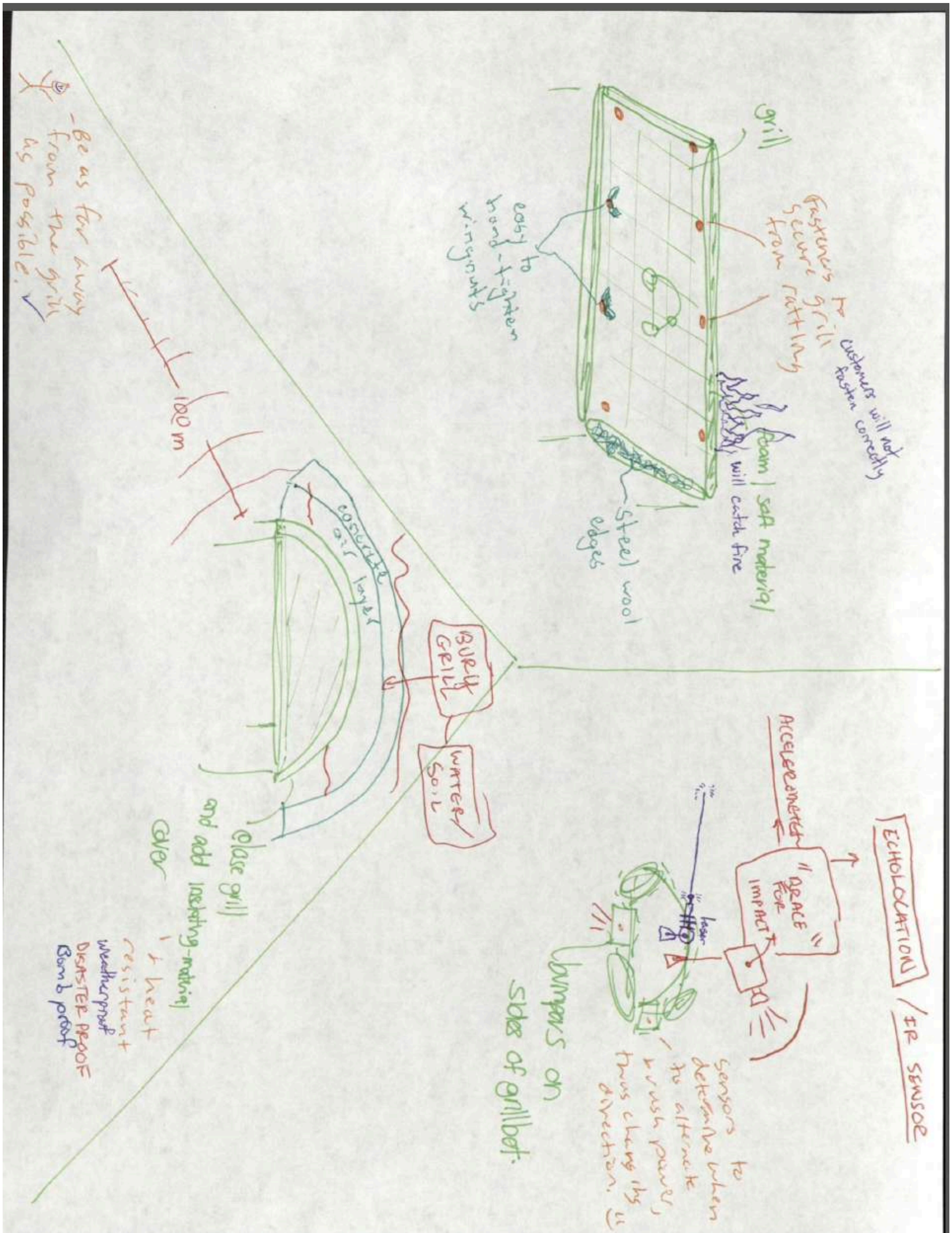
*Non-J students

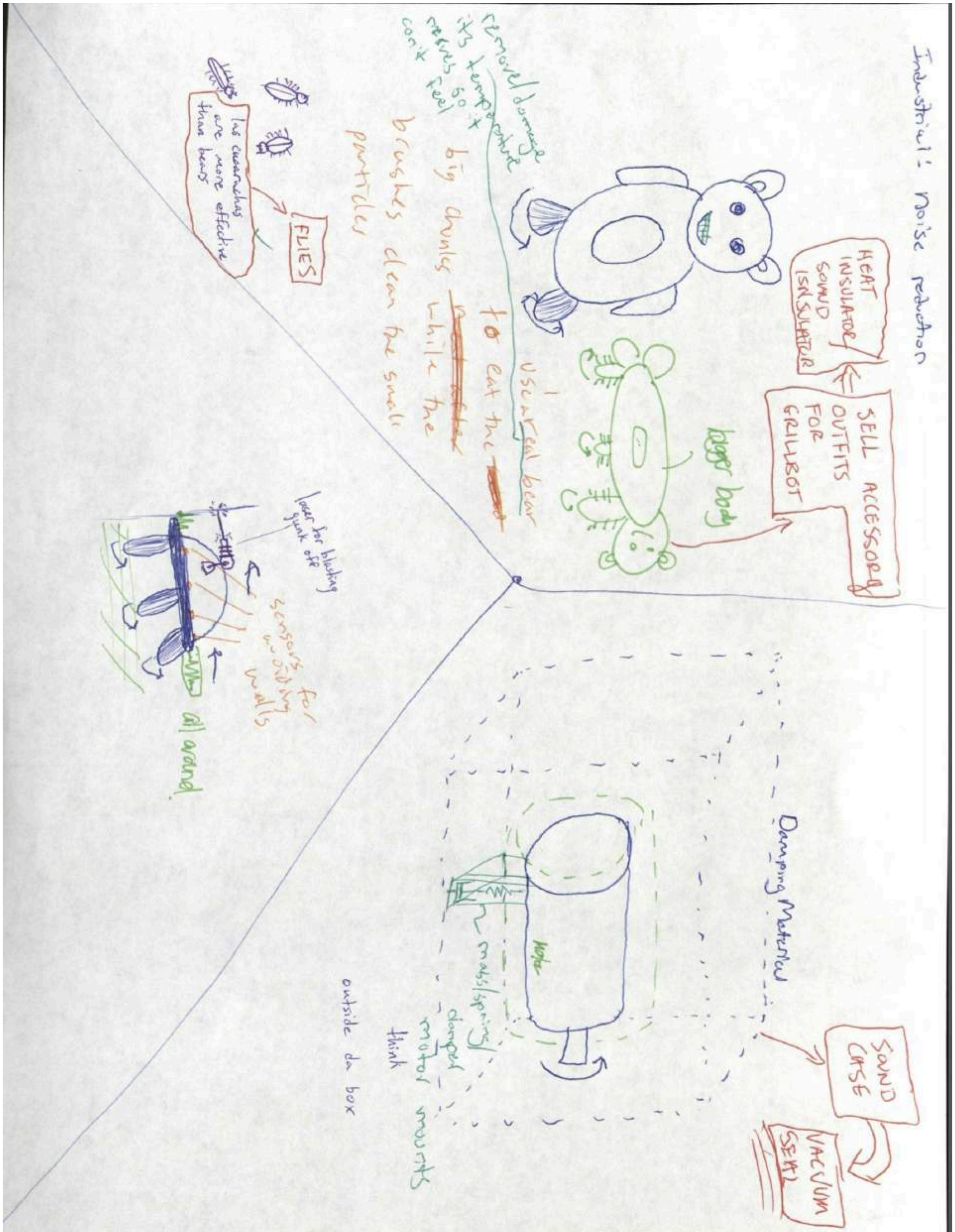


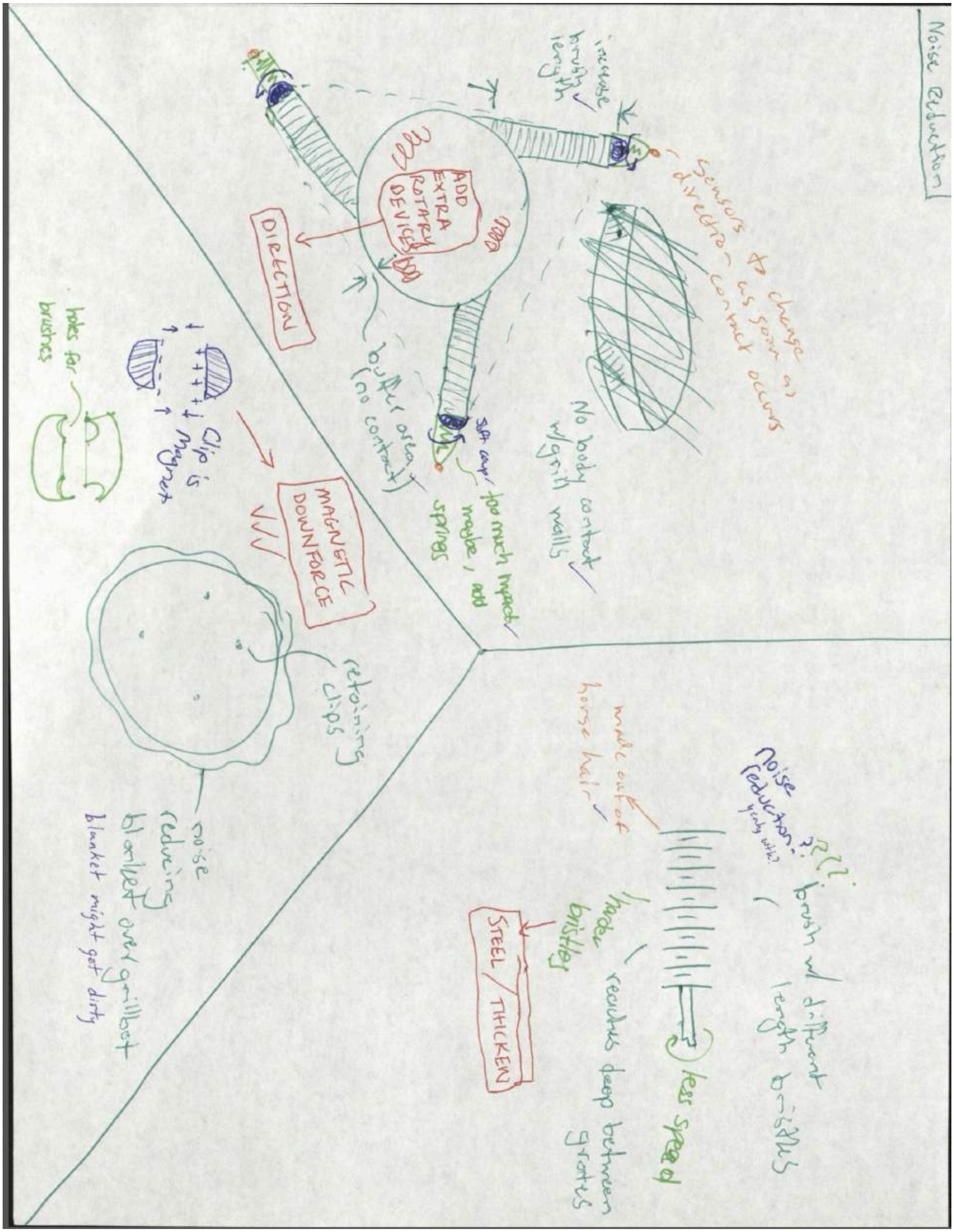
1 NOISE REDUCTION
ALUMINUM SHEETS
"SPRINGY" METAL
larger than actual brushes
SPRING FORCE
SOUND ABSORBER
vinyl protective cover
Damping mat
Make literal spring
2
GROUND LEVEL
Simply impractical to bury grill
Pickaxe to retrieve grill
GRILL
CONCRETE ENCLOSURE
hard to lift..?
Use different material?
easy to use hinges
3
SHOCK ABSORBING MATERIAL:
MULTIPLE MEDIA ... C, K,
|| series
AIR/FLUID SAC
i.e. DAMPER
SPRING
SPRING
WALL COLLISION
VISCOUS FLUID?
just brush?

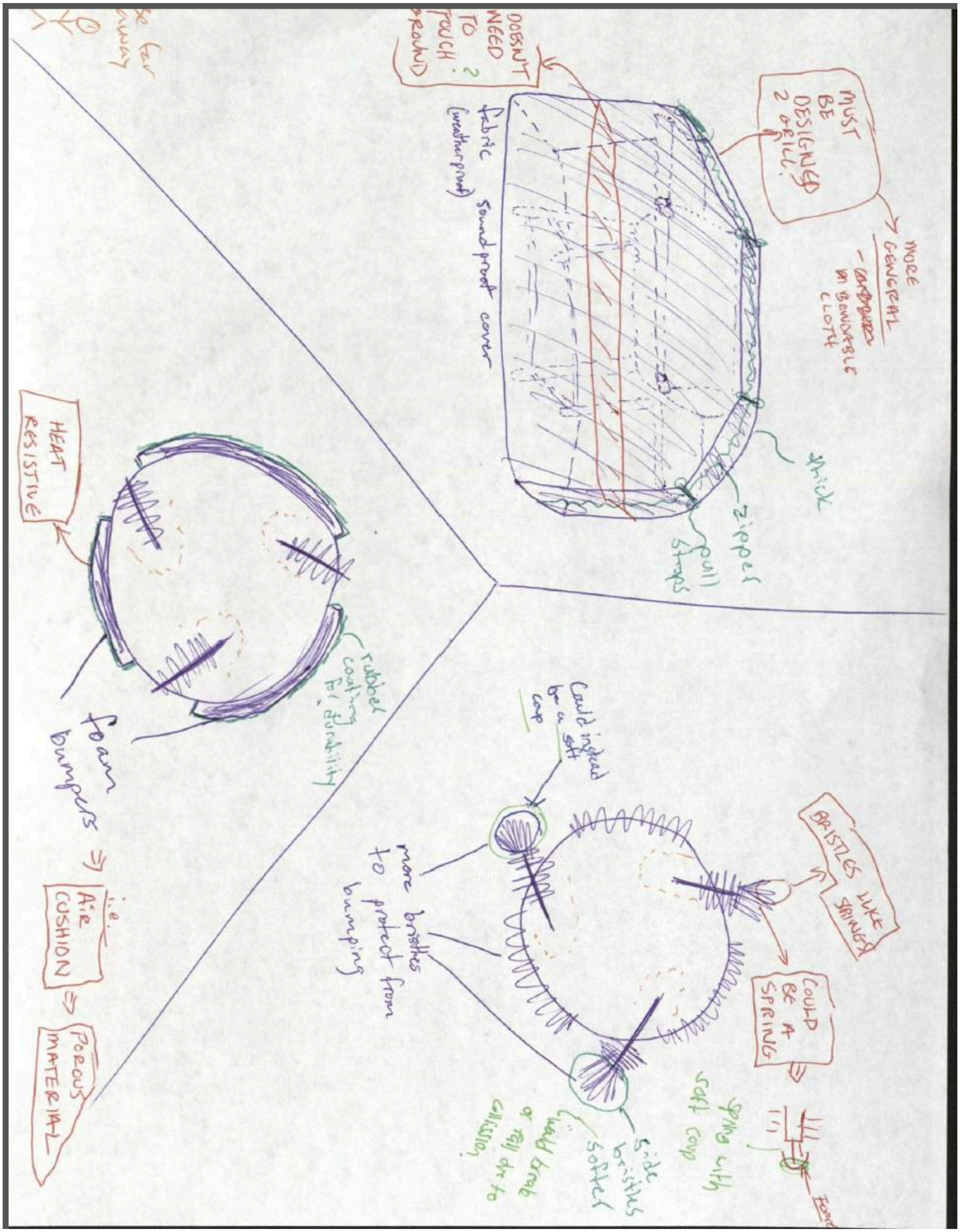


Extendable brushes
for minimized
contact by body.
requires more ($) internal
mechanical working
and potential to break
strong steel
shaft
position sensors
to determine
when to extend
or have
a remote
control
⊖ have to be present
⊕ can be fun
MAKE
SHAFTS
"SPRINGY"
& STABLE
MATERIAL:
COMPOSITE
LIKE
DIVING
BOARD
VAPORIZE
SEDIMENT
Close grill
for safety
pads for soft
contact
enclose
mammallian
eye to tell
sediment from
people
ADHESIVE
MUST
WITHSTAND
HEAT
& USE
SCREWS
when
contact,
grillbot
moves
away
hard
points contact
soft cap
Material
is noise
absorbing
COULD
BE STICKY
LONGER
TIME
@ SIDES


grill
fasteners to secure grill from rattling
customers will not fasten correctly
easy to hand-tighten wingnuts
foam / SEA material
will catch fire
steel wool edges
ECHOLOCATION / IR SENSOR
ACCELEROMETER
"BRACE FOR IMPACT"
laser
Sensors to determine when to alternate brush power, thus changing its direction."
bumpers on sides of grillbot.
BURY GRILL
WATER/SOIL
concrete
air layer
close grill and add insulating-material
cover
+ heat resistant
weatherproof
DISASTER PROOF
Bomb proof
100 m
- Be as far away from the grill as possible.


Industrial: Noise reduction
HEAT INSULATOR
SOUND ISOLATOR
SELL ACCESSORY OUTFITS FOR GRILLBOT
bigger body
its temperature reaches 60° + can't feel
to eat the
big chunks while the
brushes clean the small
particles
FLIES
are more effective than bears
laser for blasting junk off
sensors for avoiding walls
all around
Damping Material
SOUND CASE
VACUUM SEAL
motor
mass/spring/damped motor mounts
think
outside da box

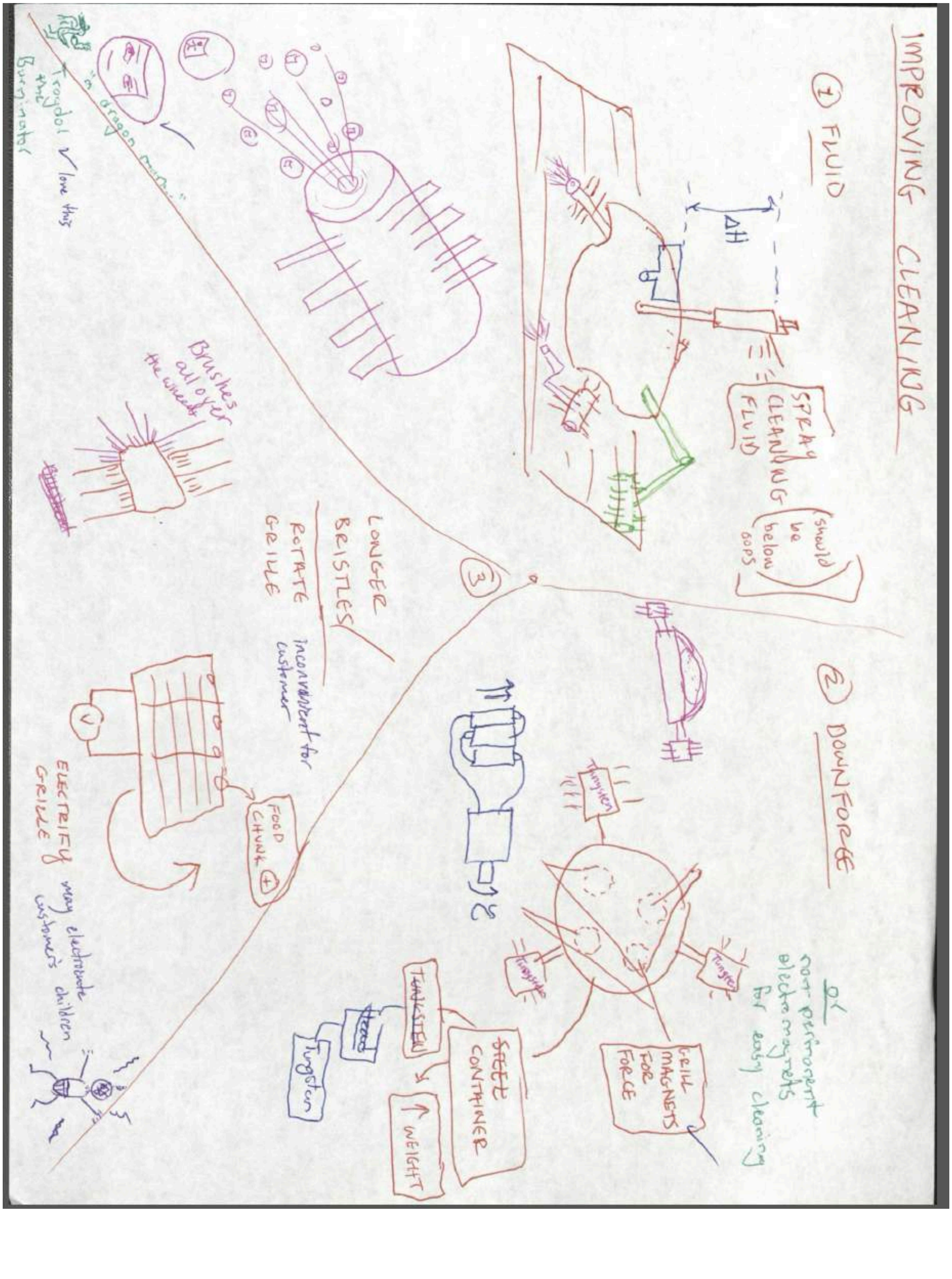

Noise Reduction
sensors to change direction as soon as contact occurs
increase brush length
No body contact w/grill walls
ADD EXTRA ROTARY DEVICES
soft cap/ too much impact maybe, add springs
buffer area (no contact)
DIRECTION
MAGNETIC DOWNFORCE
Clip is Magnet
holes for brushes
retaining clips
noise reducing blanket over grillbot
blanket might get dirty
noise reduction??? brush w/ different length bristles
less speed
made out of horse hair
harder bristles
reaches deep between grates
STEEL / THICKEN


MUST BE DESIGNED 2 GRILL
MORE GENERAL
DOESN'T NEED TO TOUCH GROUND?
fabric soundproof cover
(weatherproof)
thick
zipper
pull straps
HEAT RESISTIVE
rubber coating for durability
foam bumpers
i.e. AIR CUSHION
POROUS MATERIAL
BRISTLES LIKE SPRINGS
COULD BE A SPRING
spring with soft cap
Could instead be a soft cap
more bristles to protect from bumping
side bristles softer

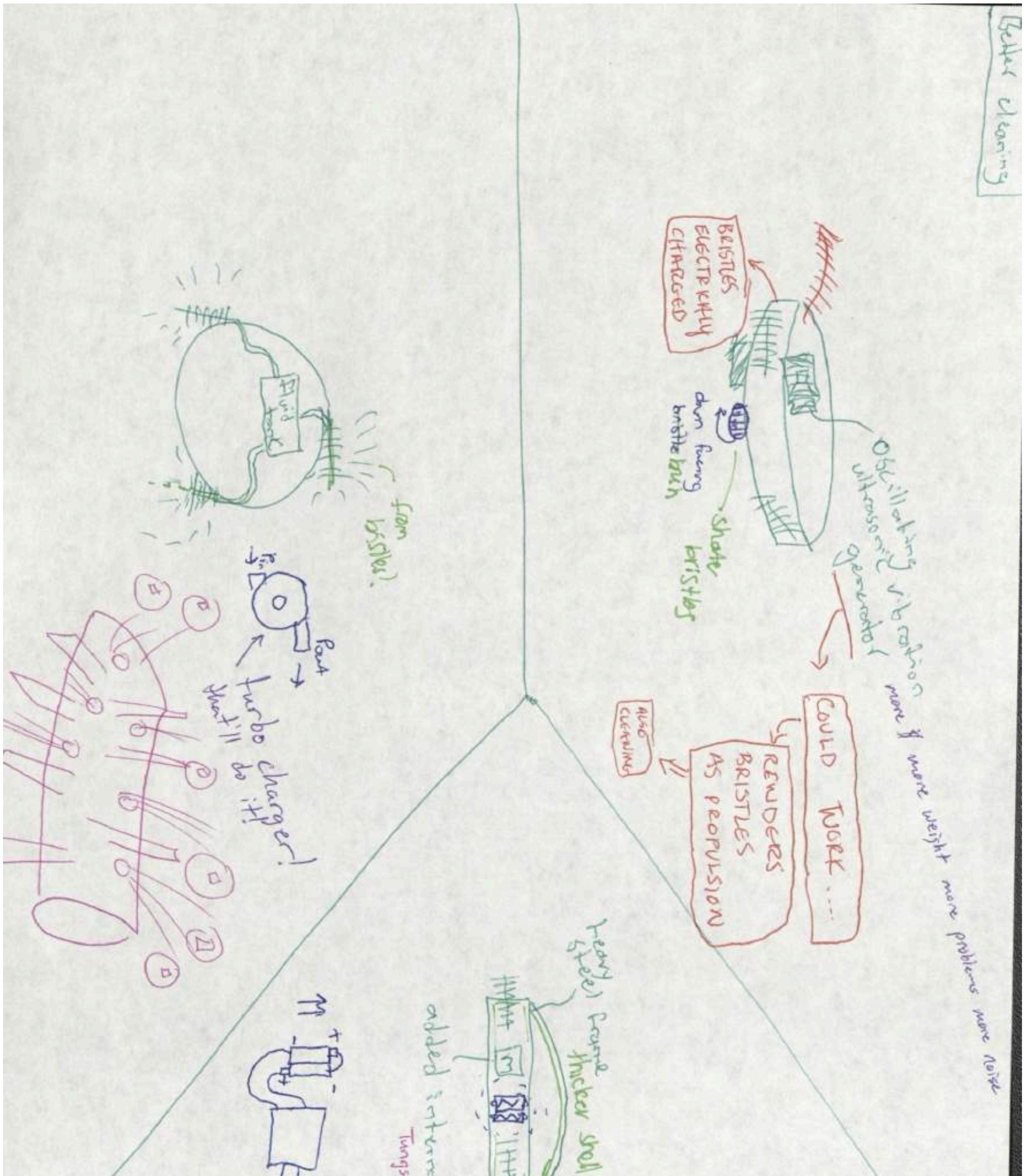
Functional Redesign Avenue:

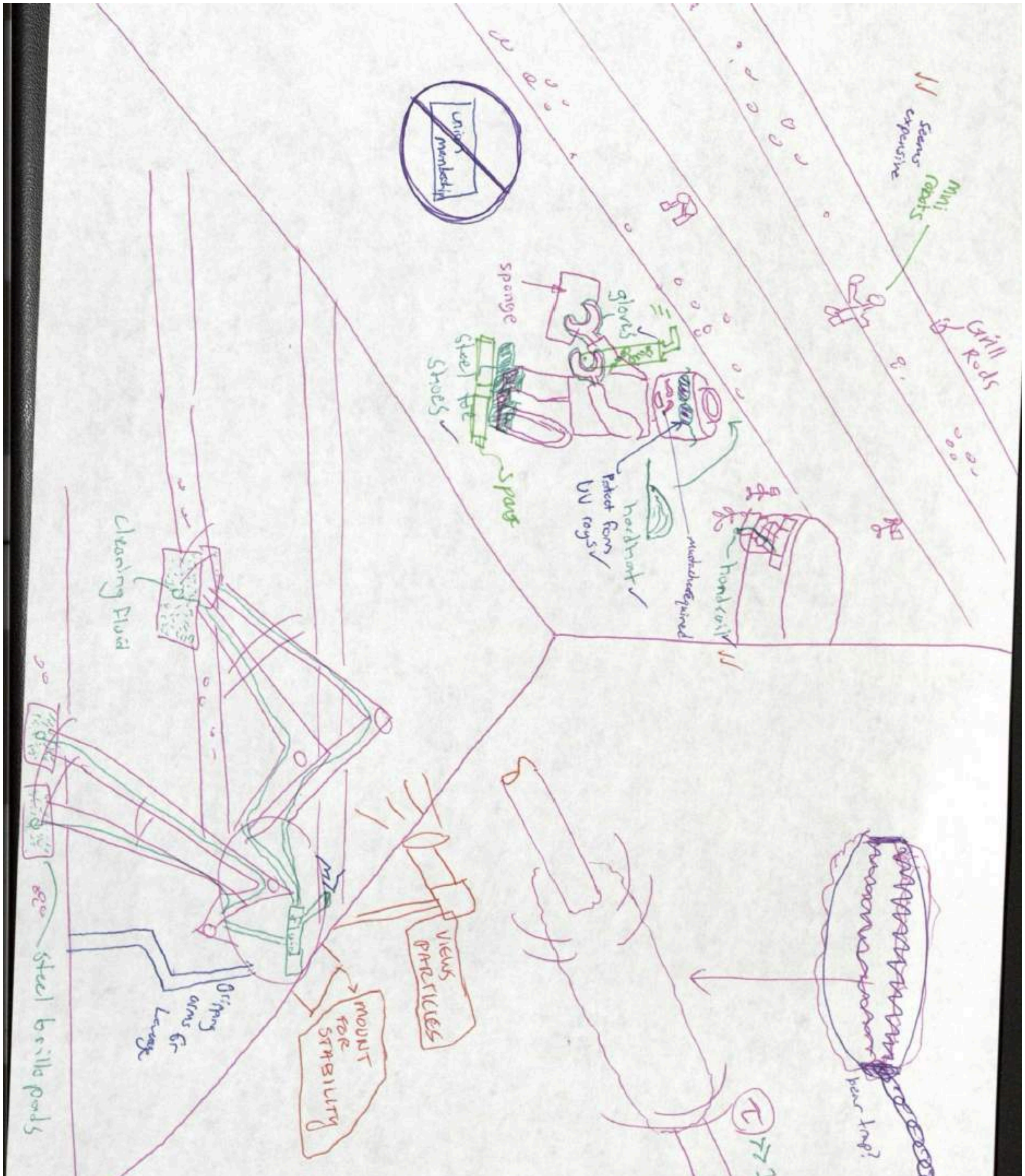
Student	Pen color
Jiin	PINK
Mark	RED
Blake	DARK GREEN
Maria	LIGHT GREEN
Mark*	BLUE
Sean*	PURPLE

*Non-J students

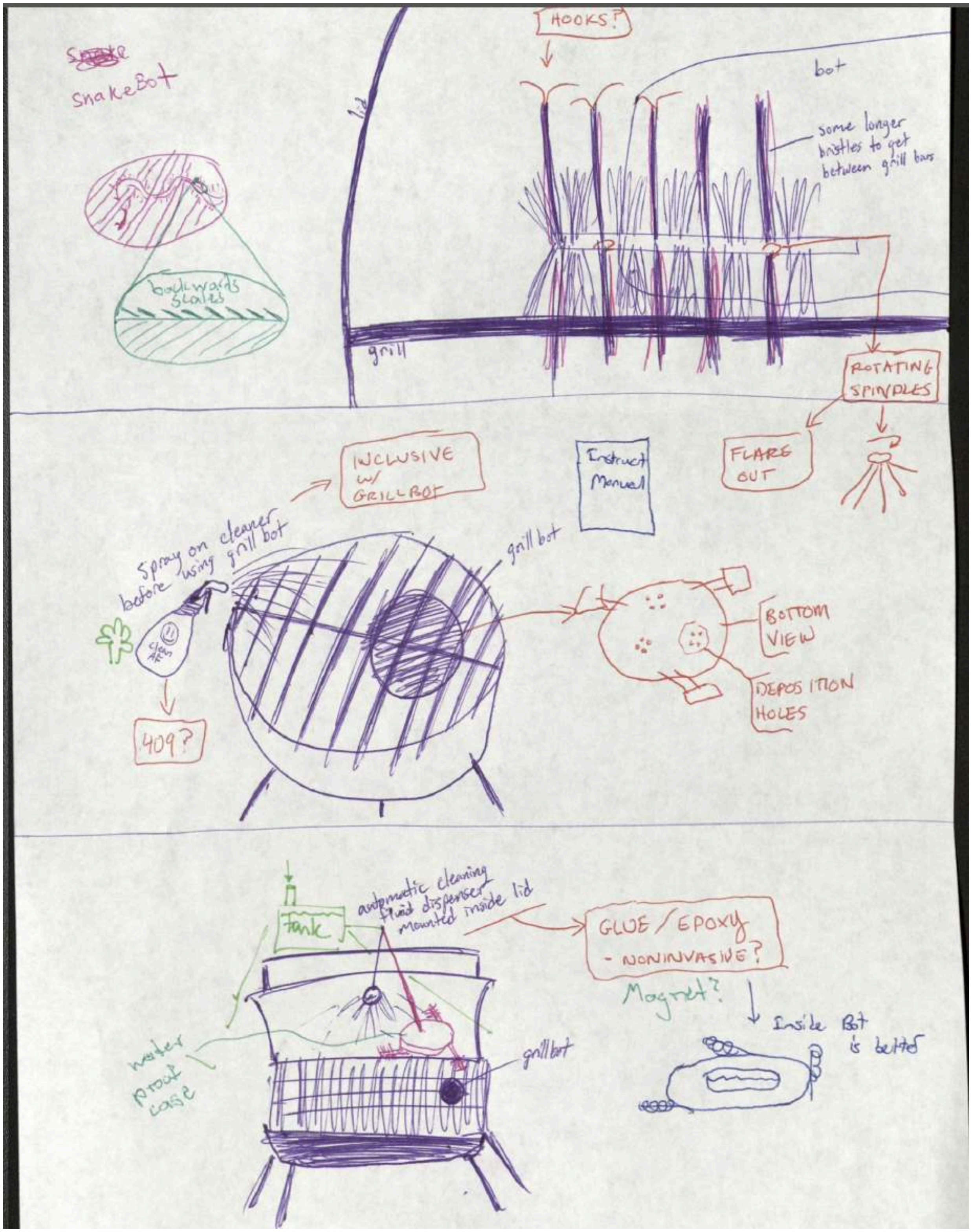


IMPROVING CLEANING
① FLUID
ΔH
SPRAY CLEANING FLUID
(should be below oops)
② DOWNFORCE
or
not permanent electromagnets for easy cleaning
GRILL MAGNETS FOR FORCE
STEEL CONTAINER
↑ WEIGHT
TUNGSTEN
Tungsten
③
LONGER BRISTLES
ROTATE GRILL
Inconvenient for customer
FOOD CHUNK
ELECTRIFY GRILL
may electrocute customer's children
Brushes all over the wheels
Trogdor ✓ love this
the Burninator

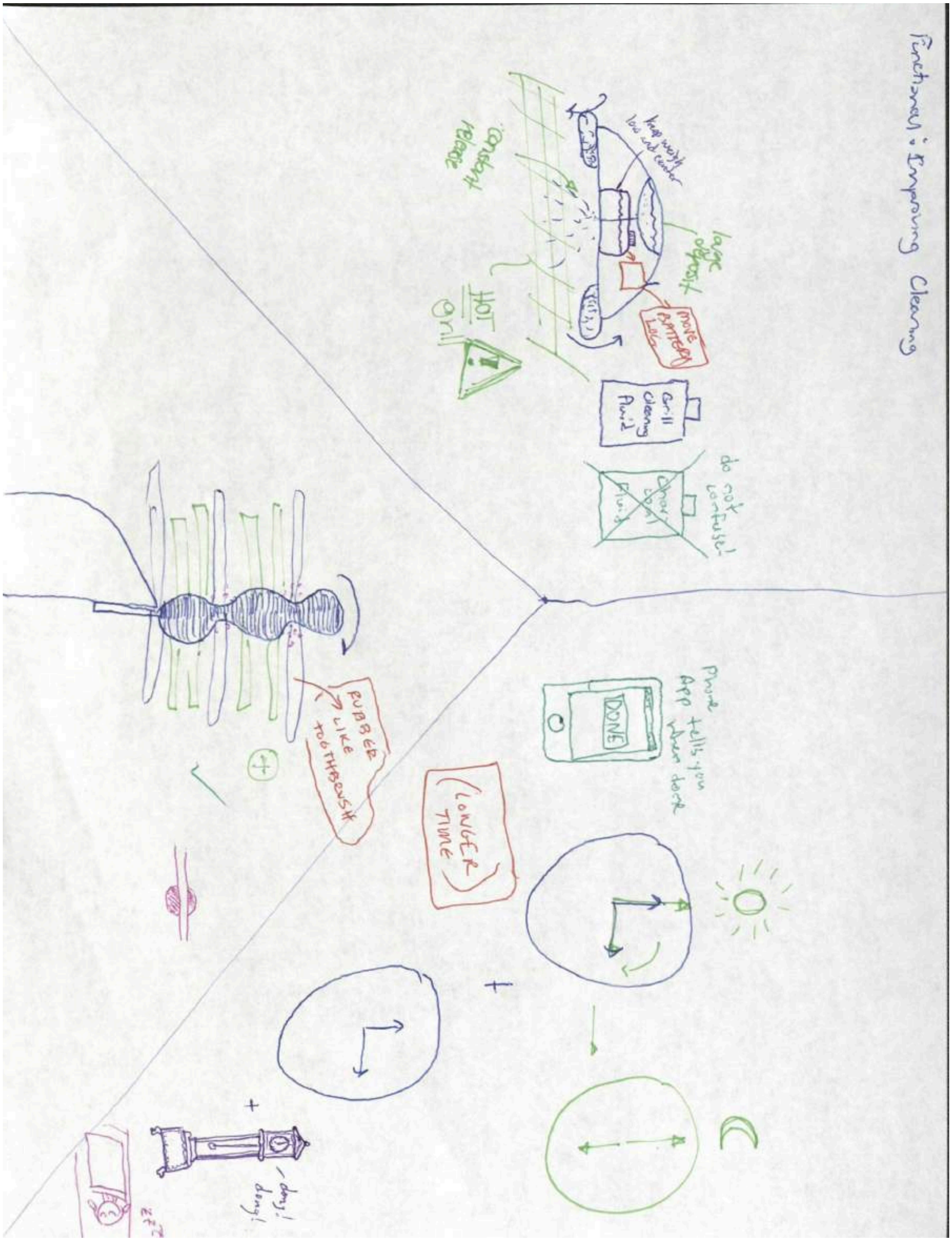

Better cleaning
Oscillating vibration
ultrasonic generator
more weight more problems more noise
COULD WORK....
RENDERS BRISTLES AS PROPULSION
AUTO CLEANING
BRISTLES ELECTRICALLY CHARGED
Fluid tank
Shake bristles
Foam bristles!
Heavy steel frame
thicker shell
added internal mass
Tungsten or Rock, stone
Cheap
turbo charger!
that'll do it!

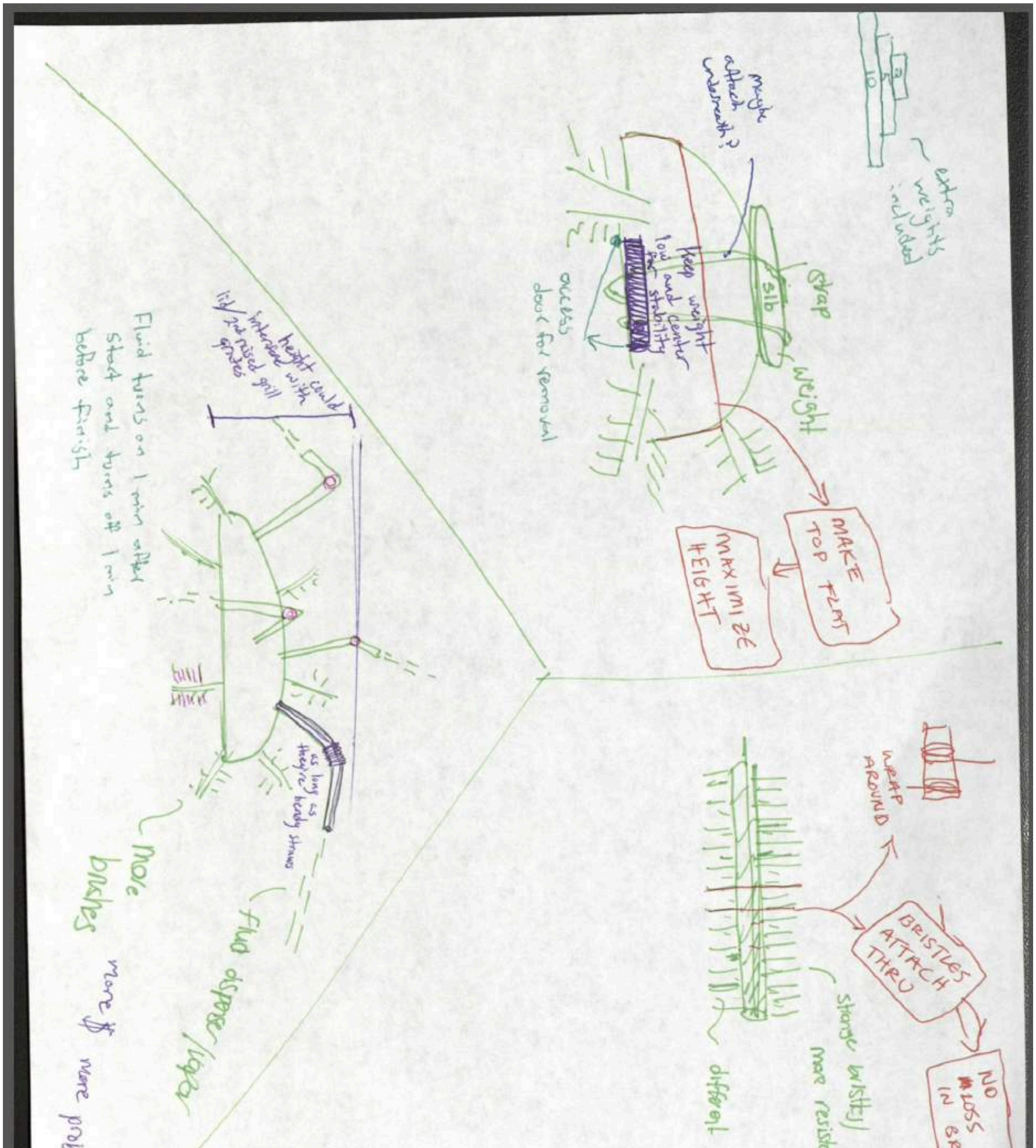


Grill Rods
Mini robots
seems expensive
gloves
sponge
steel toe shoes
Spare
hardhat
Protect from UV rays
handrail
Cleaning Fluid
steel grill pods
Gripping arms for Large
VIEWS PARTICLES
MOUNT FOR STABILITY
union membership



~~Snake~~
SnakeBot
backwards scales
lid
HOOKS?
bot
some longer bristles to get between grill bars
grill
ROTATING SPINDLES
FLARE OUT
INCLUSIVE w/ GRILL BOT
Instruct Manual
Spray on cleaner before using grill bot
grill bot
Clean AF
409?
BOTTOM VIEW
DEPOSITION HOLES
Tank
automatic cleaning fluid dispenser mounted inside lid
GLUE / EPOXY
- NONINVASIVE?
Magnet?
Inside Bot is better
water proof case
grill bot


Functional: Improving Cleaning
keep width low and center
large deposit
more EMITTERS
constant release
HOT Grill
Grill cleaning fluid
do not confuse!
Phone App tells you when done
DONE
RUBBER LIKE TOOTHBRUSH
LONGER TIME
dong! dong!


extra weights included
might attach underneath?
strap
5lb
weight
keep weight low and center for stability
access door for removal
MAKE TOP FLAT
MAXIMIZE HEIGHT
WRAP AROUND
BRISTLES ATTACH THRU
NO LOSS IN BRISTLES
stronger bristles / more resistant
different lengths / thickness
height could interfere with lid / raised grill grates
as long as they're bendy straws
Fluid turns on 1 min after start and turns off 1 min before finish
fluid dispense / spray
more brushes
more $ more problems

6-3-5 Summarization Table

Industrial Redesign Avenues: **Noise Reduction**

1) Shock Absorber on body	• Body material • Pads on body • Need to withstand heat • Mini Fluid Dashpot
2) Spring	• Aluminum spring • Bumper/ spring combo
3) Sound Absorbing Blanket	• Thick blanket
4) Extend shaft length	• Less surface area in collision • Change material - Steel - Structure support
5) Bristles on ends of brushes	• Act as spring / resist motion against walls
6) Wall detection	• Pressure sensor • Optical - IR • Radar/ Echolocation
7) Bracket to secure lid	
8) Make lighter	• Reduce momentum

Functional Redesign Avenues: **Improve Cleaning**

1) Fluid	• Water dispenser on the radial or axial part of the brush • Water dispenser coming out of the robot
2) Down force	• Thicker shell • Different material • Magnetic attraction • Added mass
3) Brush Consistency	• Material • Length • Attachment method • Geometry of the bristle • Toothbrush pattern
4) Ultrasonic Vibration	• Ultrasonic Vibration
5) Number of Passes	• Speed • Time duration

Appendix Y: Analogies for functional redesign avenue

Car Wash

Car wash is a facility used to clean the exterior of automobiles. One of the types of automatic car wash uses giant rotating brushes to clean cars. The brushes are located on the sidewalls and in the ceiling of a tunnel. When the car goes through the tunnel, the brushes are spinning. While the brushes are spinning, soap is dispensed and then water is sprayed to rinse it off ("Signature," n.d.).

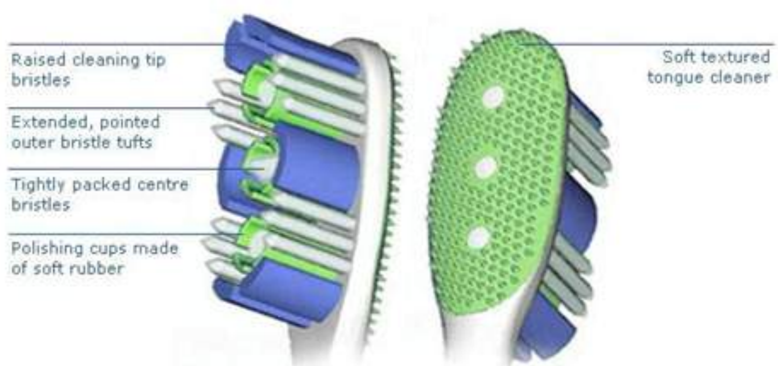
Car wash and Grillbot use a similar cleaning method: rotating brushes touch the surface. Therefore, if we also use water while the brush is spinning, it would definitely improve cleaning. Using water and cleaning fluid could sooth the dirt on the grill, and brushes would be able to get rid of food particles easier.



Toothbrush

A toothbrush is an oral hygiene instrument to clean teeth and gums. It is a stick with a tiny bristle mounted at the tip. You just grab the handle and brush your teeth with it. Since people eat food every day, it is easy to get food residue and plaque between teeth and gums (Panagakos & Migliorati, 2014). One of the factors that help getting rid of food residue is having a different pattern of bristles. Some toothbrushes' bristles feature a cup shape for cleaning around the teeth and a diagonal pattern of bristles to clean the sides of the teeth and along the gum. Wavy or V-shape patterns are used to give the bristles a better contact with the areas around the adjacent tooth surfaces ("Factors," n.d.).

Different patterns of toothbrushes inspired us to have different shapes of bristles. If we have brushes with various lengths our device would be able to get rid of food residue on the edges of grill (“Manual," n.d.).



Ultrasonic Glass Cleaner

Ultrasonic glass cleaning uses high-frequency sound waves to remove many types of contaminants from parts immersed in aqueous media. This could get rid of contaminants such as dirt, oil, grease, buffing/polishing compounds, and mold release agents ("Ultrasonic," n.d.).

Ultrasonic cleaning could get rid of dirt, oil, and grease, which we want to remove from the grill. Therefore, if we could make a Grillbot that had a big bath, it would clean effectively. Also, the user would not have to suffer from loud noises, which is the industrial redesign avenue.

Fig. 8- An existing tank coverted to a ultrasonic tank using two watertight immersible ultrasonic units.

Dental Floss

Dental floss is a cord of thin filaments used to remove food and dental plaque from between teeth where toothbrushes cannot reach. You break off a piece of about 18 inches long. You insert floss between the teeth and gently slide the floss between them in a zigzag motion. You could form a "C" around the teeth to get rid of food particles more effectively.

When the Grillbot is used, the brushes do not touch the edge of grill. Dental floss is used because toothbrushes cannot brush off between teeth. Therefore we thought it was a similar situation: the Grillbot does not touch the edges of grill as the toothbrush does not reach between teeth. If we used a sort of sponge belt and made it slide around the grill, it would get rid of food residue on the edges of grill.

Water jet cleaning

Water jet is a cleaning method where a nozzle sprays water at a high pressure to clean surfaces and materials.

Instead of using a brush, we thought outside of the box and came up with using a water jet. If we used a water jet, it would clean due to high-pressured water streams. Our ideas of adopting this method to our device are adding a water hose at the bottom of the Grillbot or have several nozzles sticking out of the bottom of it. However, we would need pumps and engines to adopt this method.

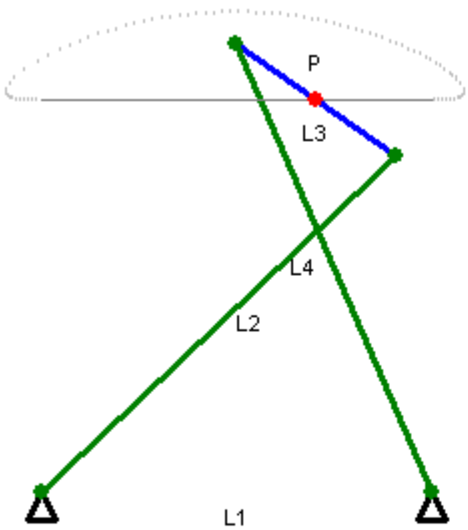
Appendix Z: Morphological Matrix

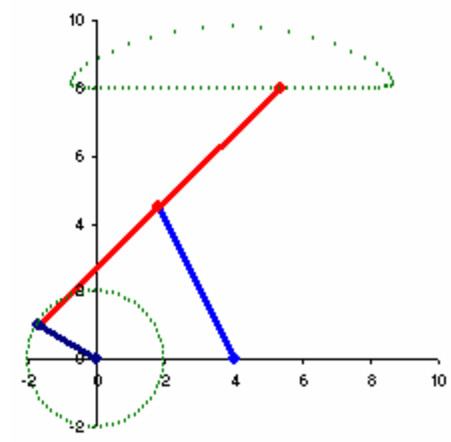
Redesign Avenue : Improve Cleaning

Types of Energy ->	EE	ME	ThE	Fluid	Acoustic E
Sub-Functions	Principles	Principles	Principles	Principles	Principles
Transmit RME		Brush-motor shaft Longer brush Hinged legs Clamp on the grille			
Convert RME to TME		Chebyshev linkage Hoekens Linkage Slider Three-wheeled omnidirectional robot Multi-wheeled omnidirectional robot			
Import Fluid	Electric Pump - Jet Pump Electric Pump - Three-Phase - W22 "JM" Type	Pump - radial Pump - axial Pump - Variety	Flammable Chemical - Bezene Flammable Chemical - Propane	Dispense soap from Brushwheel- radial * Dispense water from Brushwheel - radial* Dispense soap from Brushwheel - axial** Dispense water from Brushwheel- axial** Dispense water with a Nozzel attached on the body Water Jet	
Convert EE to ThE	Induction Heating Resistance Heating		Laser to burn the particles	Steam - radial Steam - axial	Radiowave
Regulate friction	Electric Sensitive Material (How hard the bristle function of voltage) Potentiometer (changes of angle of bristle, zero voltage = no angle) Potentiometer (Changes of angle of nozzle)	Brush - Copper Brush - Steel Brush - Rubber Heavier materials for the device Brush Pattern- Zig Zag Brush Pattern - Different Length Brush Pattern - Aligned in a straight line Clamp the grille			
Convert EE to Vibrational E		Vibration		Ultrasonic Bathtub	Ultrasonic Cleaning
Convert EE to ME	AC Motor - Induction AC Motor - Synchronous DC Motor - Brushes DC Motor - Without Brushes	Linear Motors - Guideway			

*radial : side of brush
**axial : ends of brush
RME : Rotational Mechanical Energy
TME : Translational Mechanical Energy
EE : Electrical Energy
ThE : Thermal Energy
Virbrational E : Vibrational E
AC : Alternative Current
DC : Direct Current

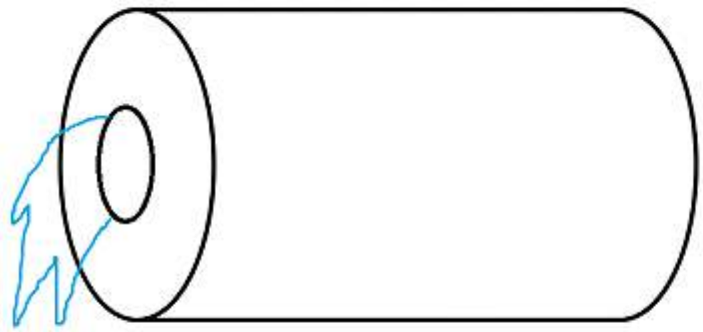
Appendix AA: Four-bar linkage



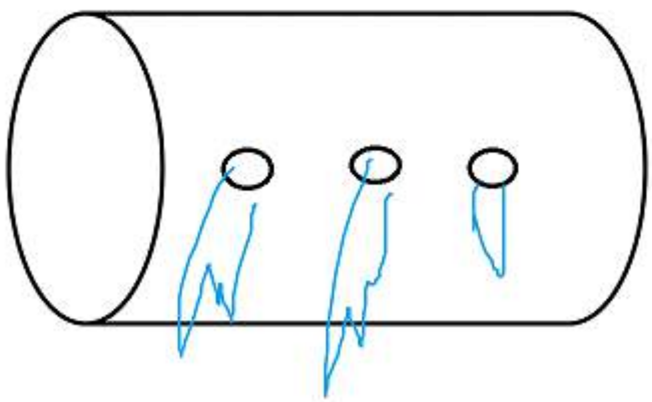


Chebyshev linkage (Left) and Hoekens linkage (Right)

Appendix AB: Fluid Dispenser Location



a. Fluid dispenser on a radial position of brush



b. Fluid dispenser on a axial position of brush

Appendix AC: TIPS

Feature to improve : 3 -Length of moving object

Undesired results (conflict) : 9 - Speed

Principles :

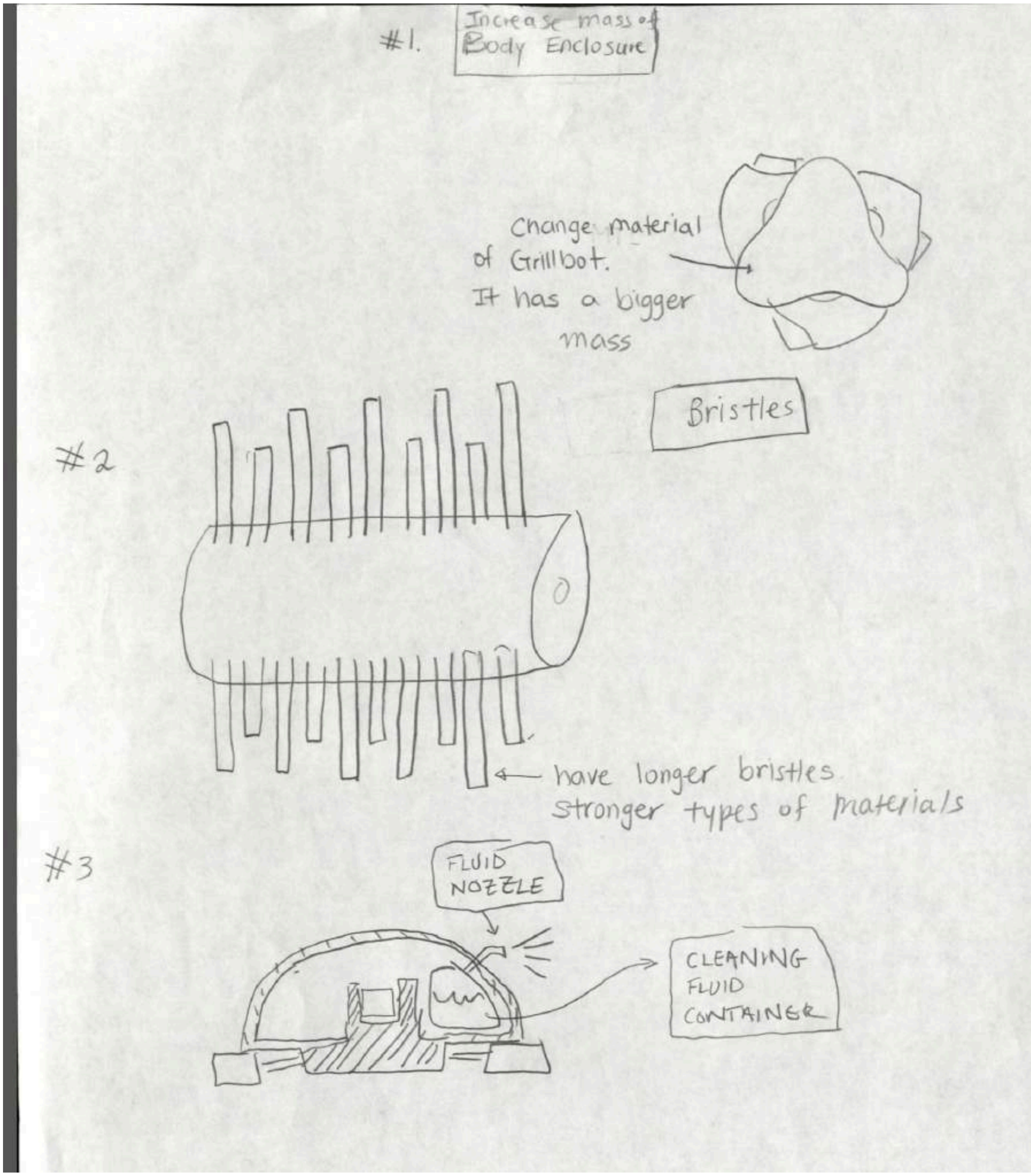
13 Other way around [10]

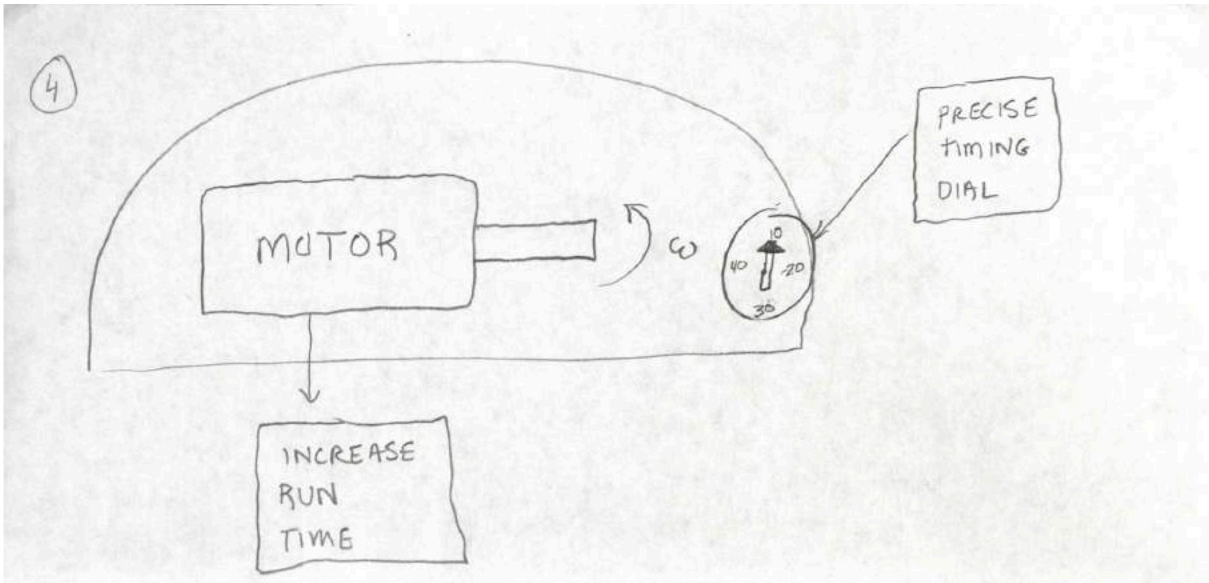
4 Asymmetry [24]

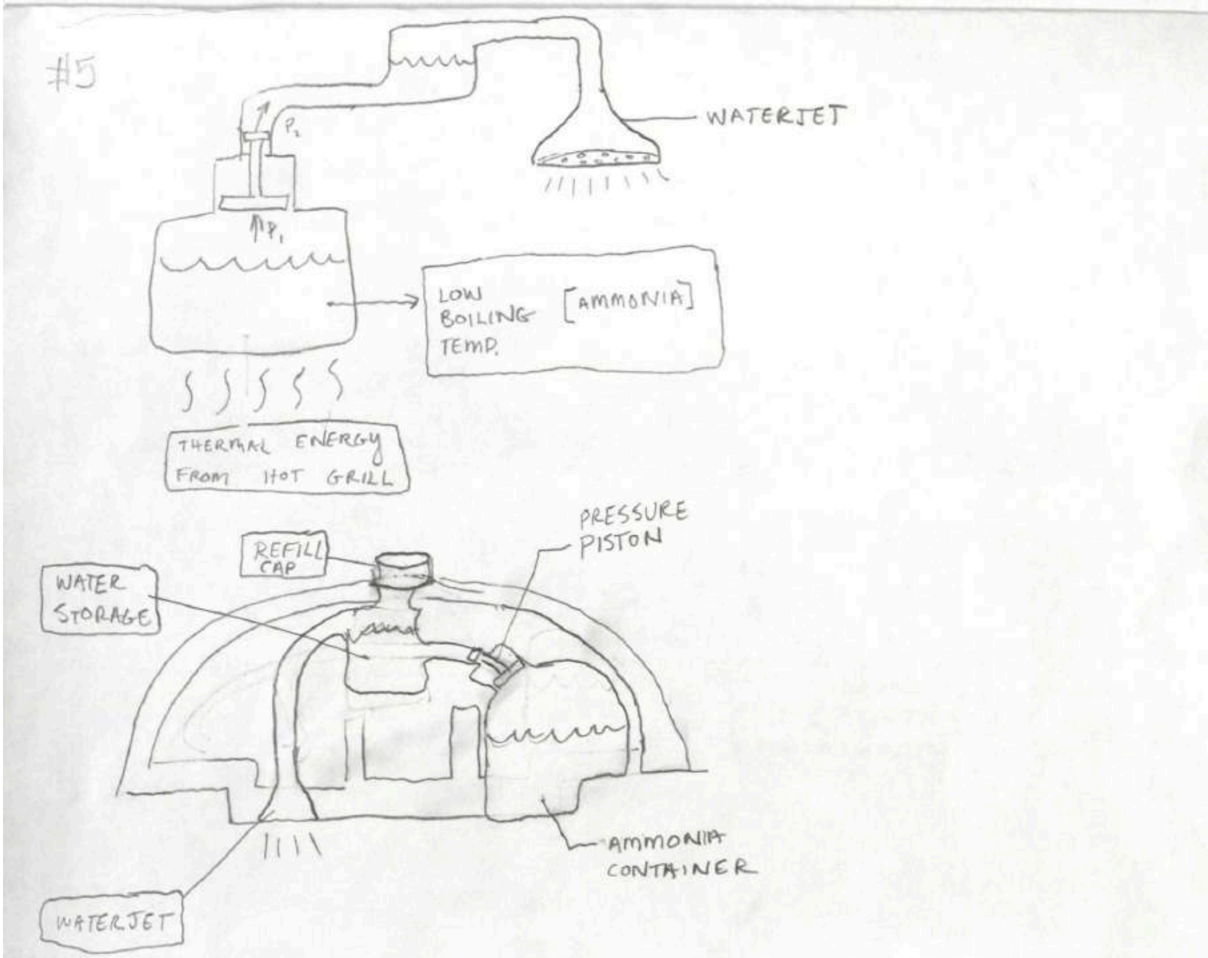
8 Counter-weight [32]

Appendix AD: Concept Variants

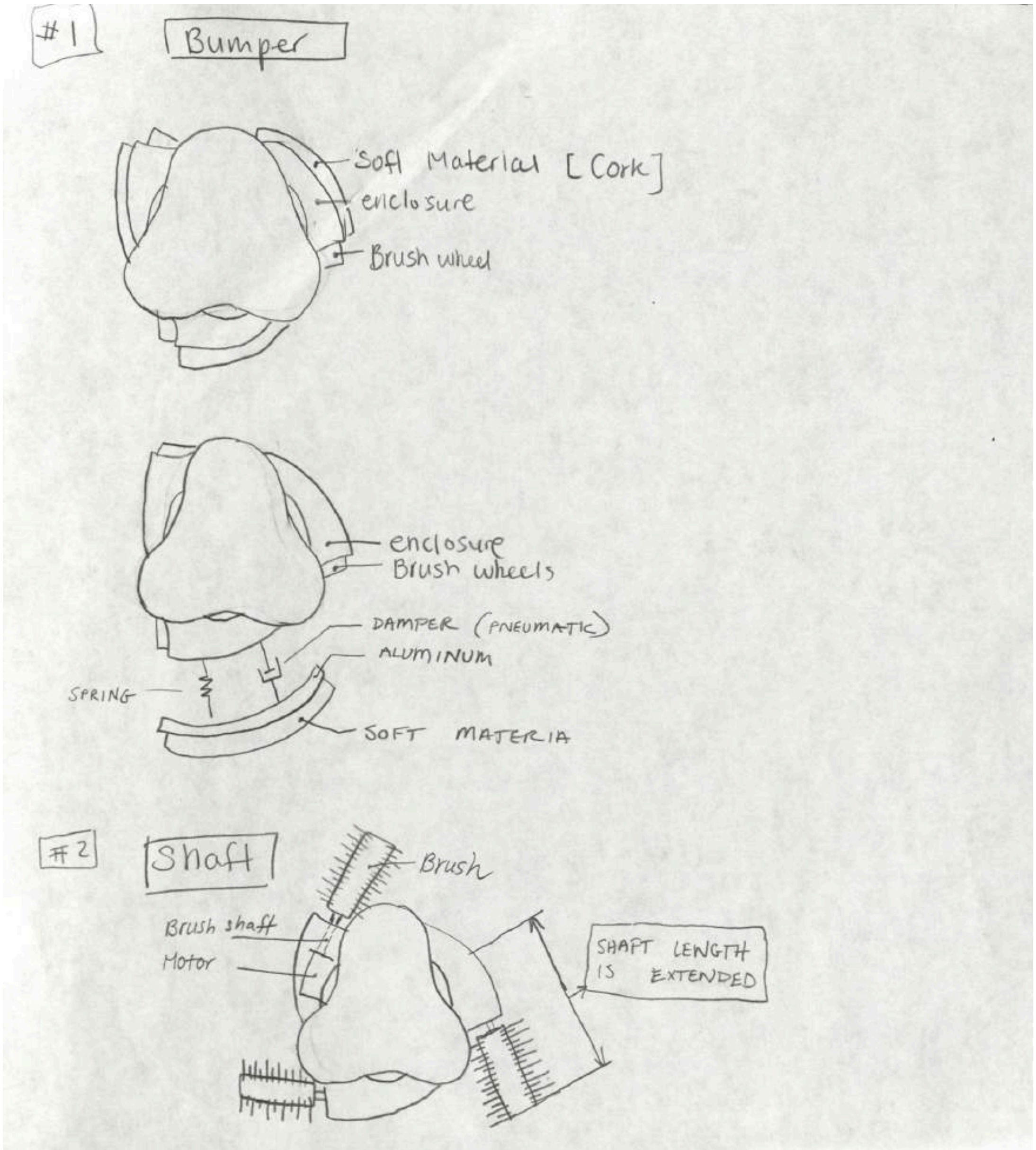
Functional Concept Variants

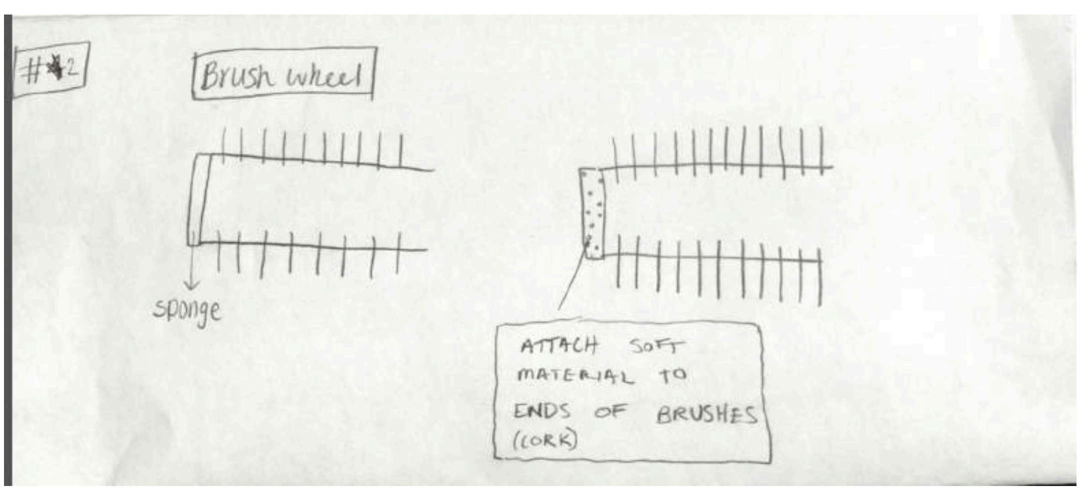


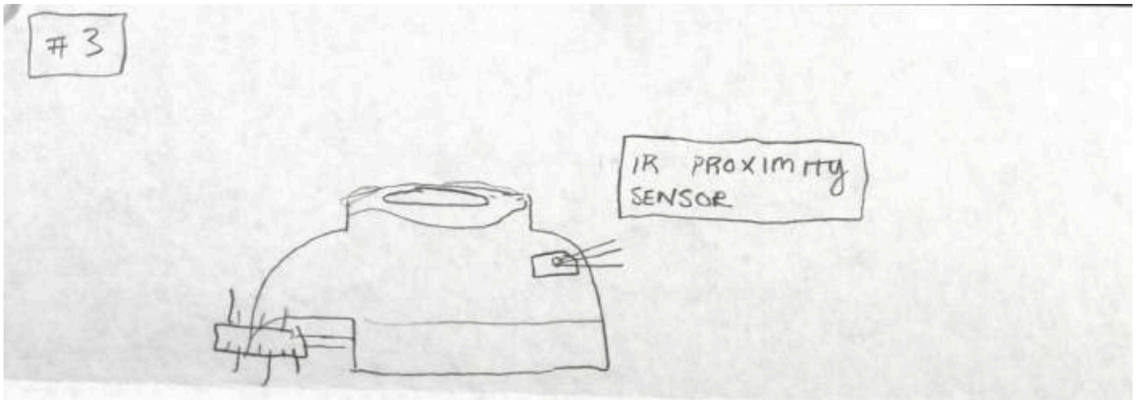

4
PRECISE TIMING DIAL
10
20
30
40
MOTOR
ω
INCREASE RUN TIME

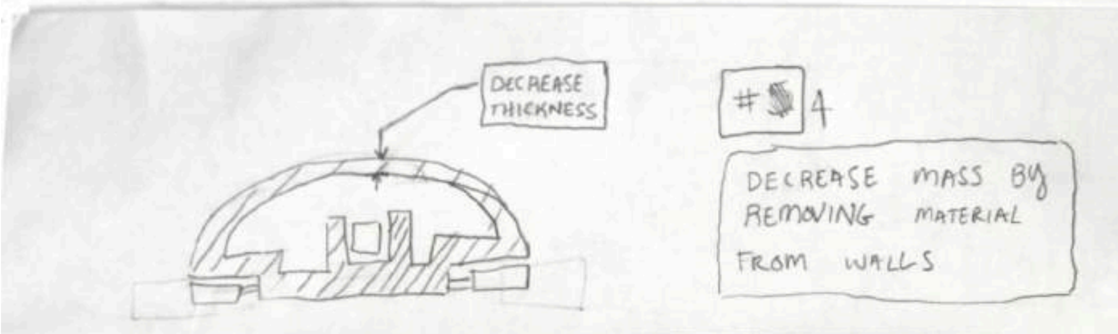

#5
WATERJET
P₂
P₁
LOW BOILING TEMP.
[AMMONIA]
THERMAL ENERGY FROM HOT GRILL
REFILL CAP
PRESSURE PISTON
WATER STORAGE
AMMONIA CONTAINER
WATERJET

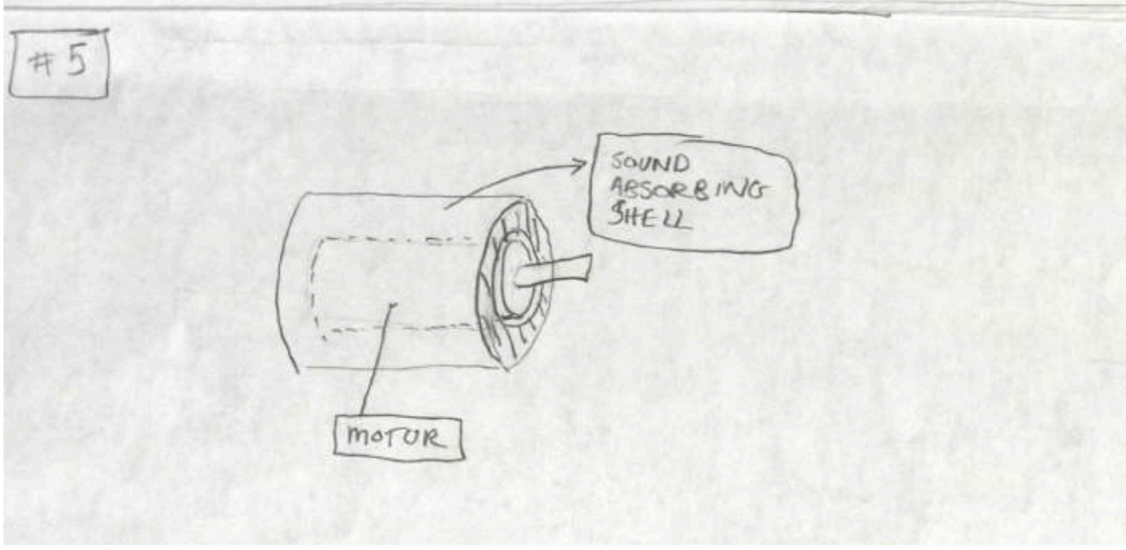
Industrial Concept Variants



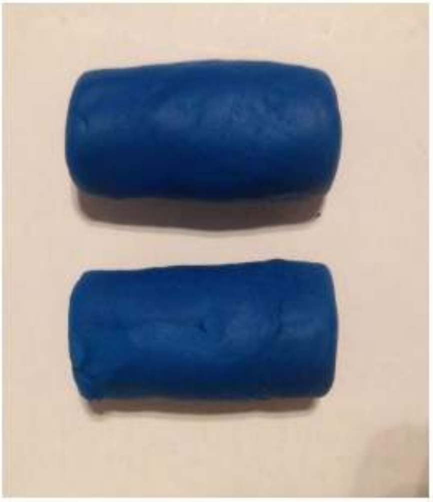
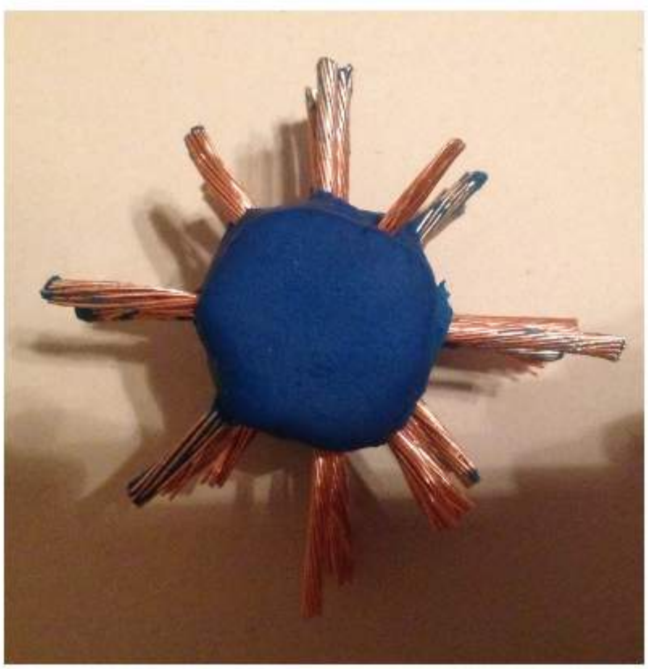


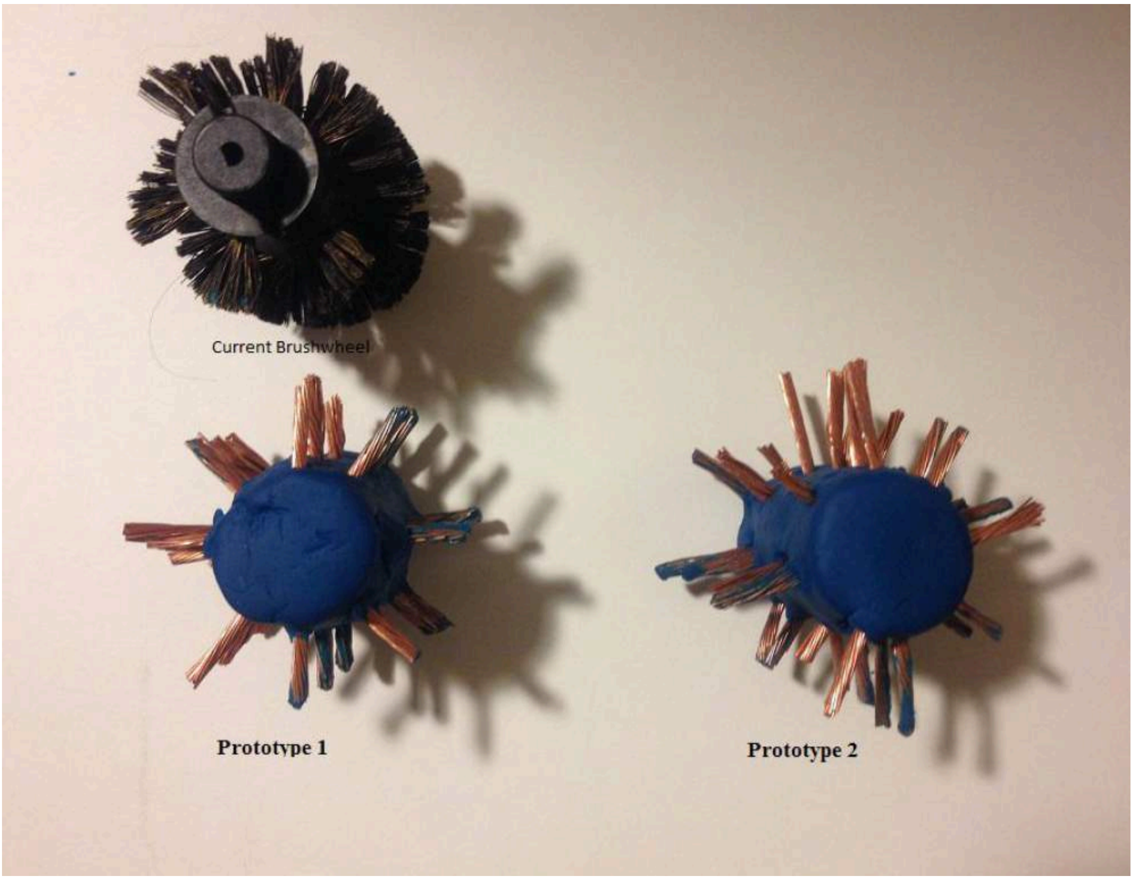

#3
IR PROXIMITY
SENSOR

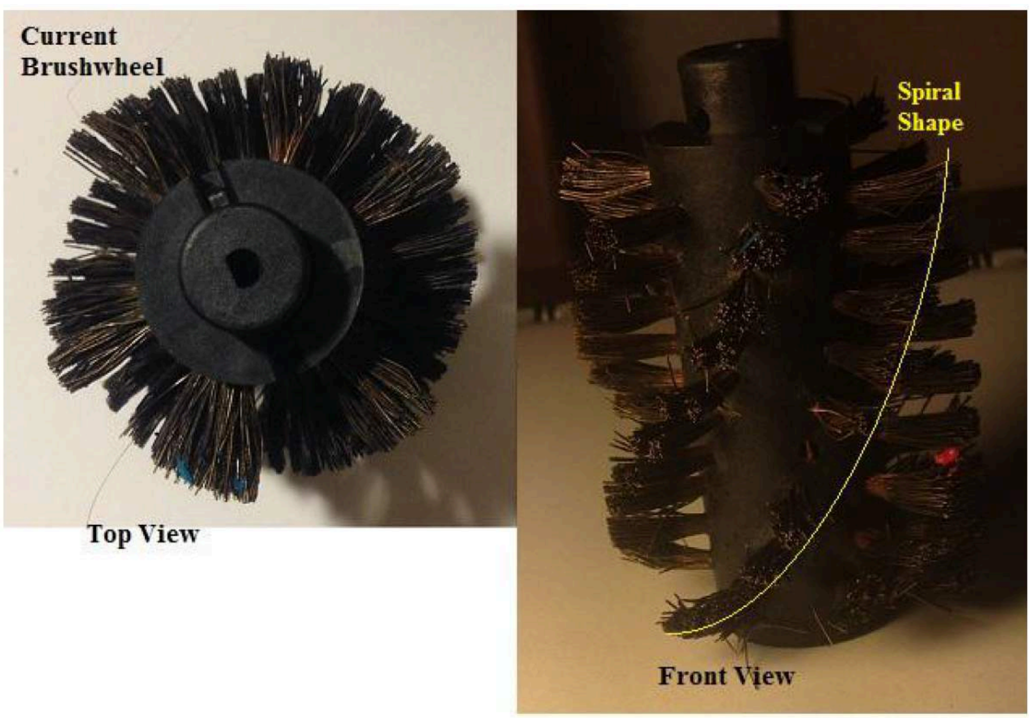

DECREASE
THICKNESS
#4
DECREASE MASS BY
REMOVING MATERIAL
FROM WALLS

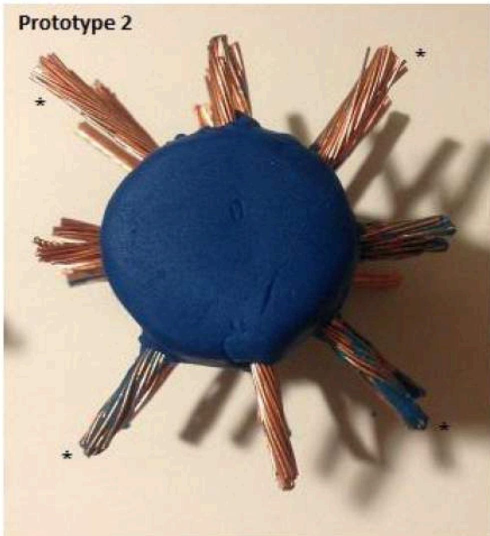

#5
SOUND
ABSORBING
SHELL
MOTOR

Appendix AE: Low Resolution Prototype (Construction Process, Result, and Customer Interview)

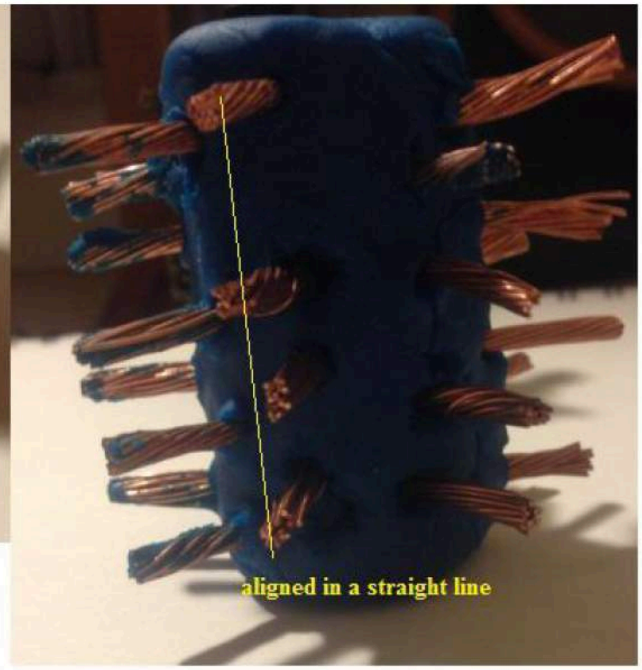
	**Step 1. We used play-dough to make the brush. We thought it is a great idea, because play-dough is soft when we open the jar and it allows us to stick copper wires into it. It gets hardened after it is exposed to the air for a certain amount of time. After we opened the jar, we tried to shape the clay to be like the brush we currently have.**
	**Step 2. We stripped off the coat and got the copper wires from it. We twisted a little bit so that they do not get separated and stay together.**
	**Step 3. Finally, we stick the copper wires into the clay. We let it sit for two day.**


Current Brushwheel
Prototype 1
Prototype 2


Current
Brushwheel
Top View
Spiral
Shape
Front View

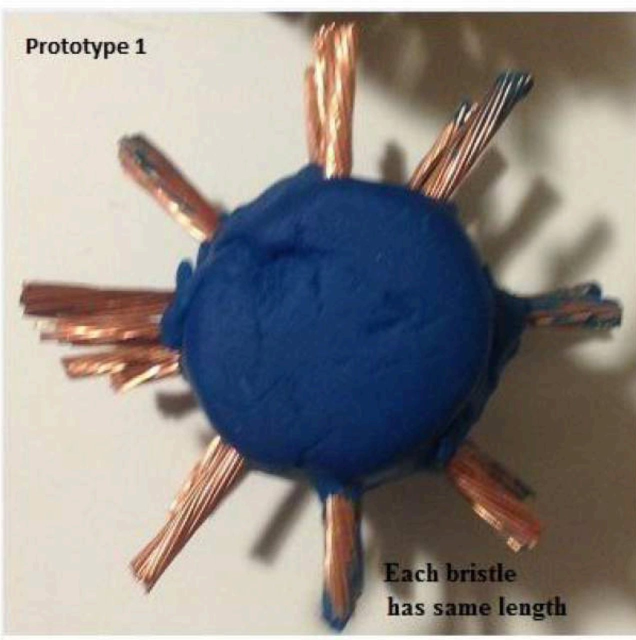


Top view of Prototype 2

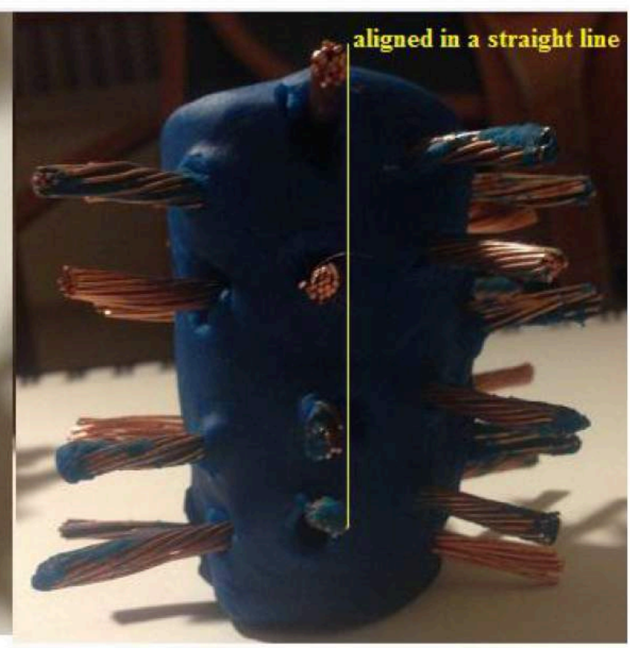


Front view of Prototype 2

* indicates it is longer bristle



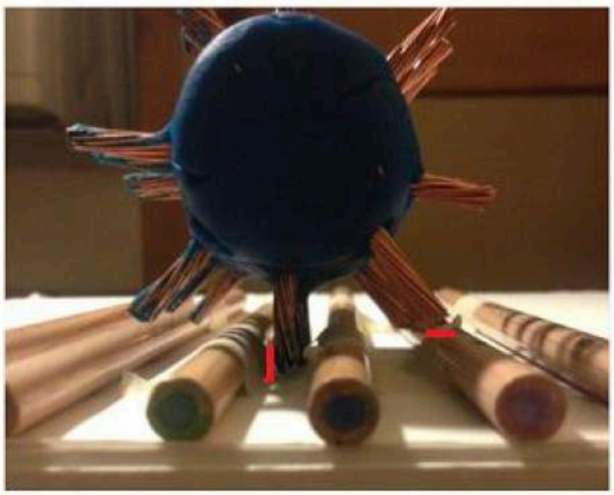
Top view of Prototype 1



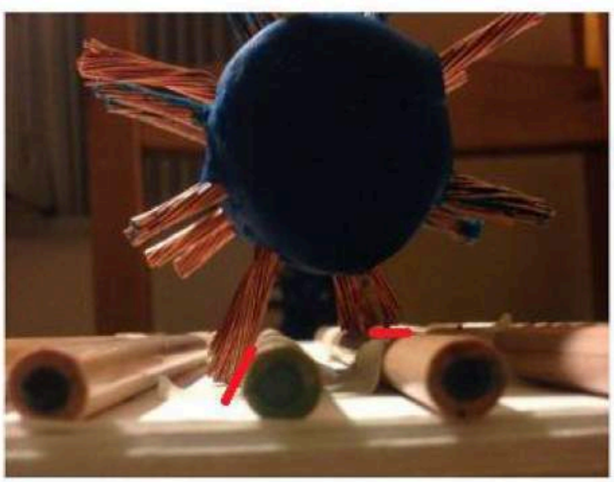
Front view of Prototype 1


Grill!

Current Brushwheel on the grill



Prototype 1 on the grill



Short bristle cleans the top part of grill
Long bristle cleans the side of grill

Prototype 2 on the grill

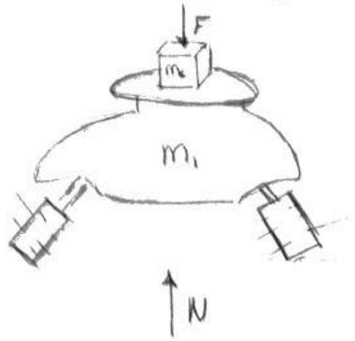
Customer Feedback

Customer 1	I like prototype 1 for the grill better because the designs seems to clean more than the current design. Prototype 1 cleans in between the wires in the grill instead of just brushing the top. I do not think the long-short design (prototype 2) offers more benefit than the brushes being all the same length
Customer 2	I like prototype 2 for the grill cleaner because it cleans down further between the grill edges. When compared to the current design I think that the copper wire should be shaped more like bristles like in the current design.
Customer 3	I think this is an excellent prototype. The fact that the bristles can touch the surface of a grill. Also, the facts that the bristles are different lengths allow the user an easy way to fit the cleaner in the desired orientation. Lastly, I love the color! It looks fun to use!
Customer 4	I like the idea of the long and short bristles. It will provide the same cleaning potential as the current product and also provide extra cleaning in the grooves. The longer bristles are a bad idea. They will not provide enough cleaning on the top of the grill where the food will be touching mostly.
Customer 5	Prototype 2 is good, because the longer bristle cleans the side of the grill and the short bristle cleans the top party. It is more efficient because it takes care both top and the side.

Appendix AF: Order-of-Magnitude Calculation

#1 INCREASING FORCE: demonstrate why this will improve cleaning.

• INCREASING FRICTION



$m_1 \equiv$ mass of Grillbot

$m_1 \simeq 5kg$

$\mu_k \equiv$ kinetic coefficient friction

$\mu_k \simeq 0.5$

$N_1 = m_1 g = 5kg\,(10m/s^2) = 50N$

$F_f = \mu_k N_1 = (0.5)(50N) = 25N$

Assume $m_2 = 5kg$

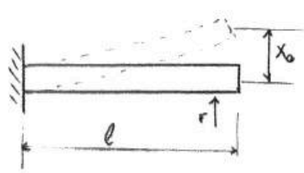
$N_2 = (m_1 + m_2)g = (10\,kg)(10m/s^2) = 100\,N$

$F_f = \mu_k N_2 = (0.5)(100) = 50N$

→ If we double the mass we double the coefficient of friction, assuming a linear friction response.

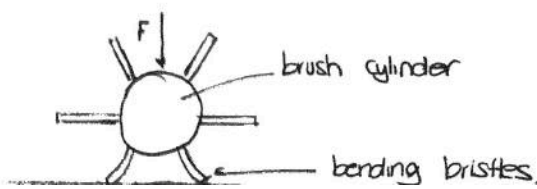
INCREASING FRICTION INCREASES THE "RUBBING" FORCE OF THE BRISTLES, THEREBY REMOVING MORE PARTICLES THAT HAVE LARGER STICKING FORCES

① Assume bristles act as an ideal cantilever beam in bending.



② The constitutive relationship for this static relationship is. $F = kX_0$

③ The force F is proportional to the amount of down-force because as you increase the load, the deflection at the bristles also increases



④ The energy stored in the bristles is the amount of energy released.
For an ideal spring the energy equation is:

$$\Delta E = \frac{1}{2} k x^2$$

⑤ The energy will be converted to kinetic energy assuming all of the energy is released once the force is removed

$$\frac{\partial}{\partial t}(T+U) = 0 \Rightarrow \frac{1}{2} k X_{max}^2 = \frac{1}{2} m V_{max}^2$$

⑥ We will be increasing the stored energy by increasing the "beam's" initial displacement, X_{max}. Therefore, we will also be increasing V_{max}. So lets assume k_{eff} & m_{eff} remain constant

⑦ COMPARISON OF ENERGY W/ AND W/O FORCE APPLIED

No force applied: $f_0 = k X_0$

$\boxed{\text{Additional}}$ force applied: $f_0 + F_1 = k X_1$

$$\boxed{X_1 > X_0}$$

$$\frac{1}{2} k X_0^2 = \frac{1}{2} m V_0^2 \qquad V_0^2 = \frac{k}{m} X_0^2$$

$$\frac{1}{2} k X_1^2 = \frac{1}{2} m V_1^2 \qquad V_1^2 = \frac{k}{m} X_1^2$$

$$\boxed{V_1 > V_0}$$

$P = mV = \int F dt \longrightarrow$ IMPULSE IMPARTED TO FOOD MASS

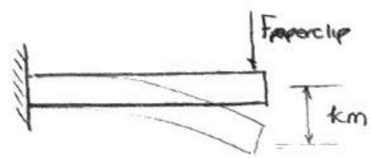
$$m_{eff} V_0 = \int f_0 \, dt$$
$$m_{eff} V_1 = \int F_1 \, dt$$
$$\rightarrow \boxed{F_1 > F_0}$$

* Assuming dT is constant

→ Therefore, because the force applied to the food particle is greater when more force is added, we will remove more particles with additional down force.

Approx. Values:

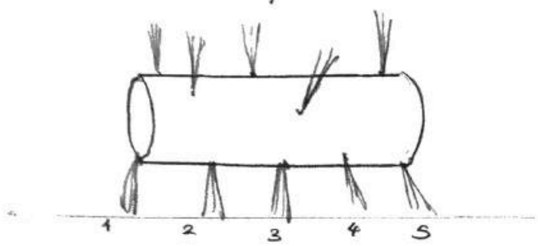
After conducting a deflection test of 1 group of bristles, we found these will bend 0.2 cm for every 100 paper clips (a paper clip is about 1g)



$F = (100g)(9.81 m/s^2) \simeq 1N$

$F = kx \rightarrow \boxed{k = \frac{F}{\lambda} = \frac{1N}{0.002m} = 500N/m}$

The mass of the Grillbot is approximately 5kg. Lets assume 1/5 of the weight is transfered to a bristle at each time (NUMBER OF BRISTLES IN CONTACT W/ SURFACE)



The bristles will bend:

$F = 1kg(9.8) \approx 10N = kx = \left(500 \frac{N}{m}\right) x$

$\rightarrow X_{BRISTLE} = 2cm$

* This is an unrealistic deflection since the bristles are about 3cm, which suggests non linearity under large deflections. However, for modeling purposes, this is satisfactory.

$\frac{1}{2} kx^2 = \frac{1}{2} mv^2 \qquad m_{BRISTLE} \simeq 20g$

$\frac{1}{2}\left(500 \frac{N}{m}\right)(0.02m)^2 = \frac{1}{2}(0.02kg) v^2$

$\rightarrow v = 3.16 m/s$ + Rotational velocity of BRUSH : $\omega(l + r)$

<u>If we double the mass:..</u>

$F = 20N = 500 \frac{N}{m} x \quad \Rightarrow x = 4cm$

$\left(500 \frac{N}{m}\right)(0.04m)^2 \rightarrow v = 6.324 m/s$

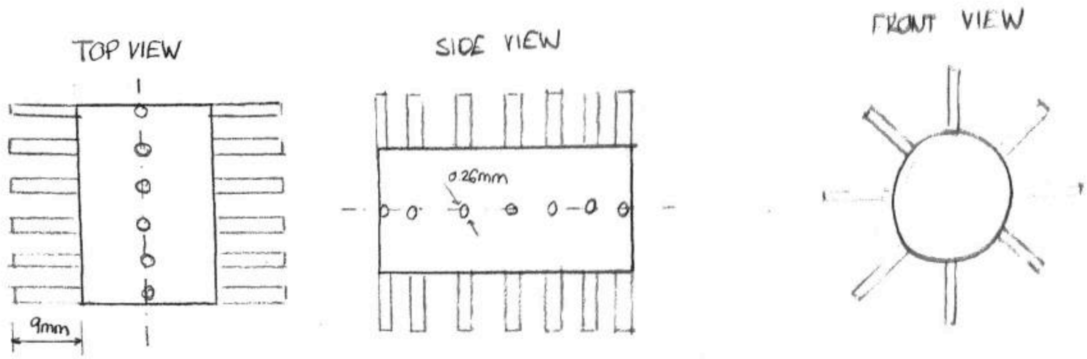
... we double the velocity. The larger the velocity the greater the force.

* These velocity values are very high because of the unrealistic linear deflection.

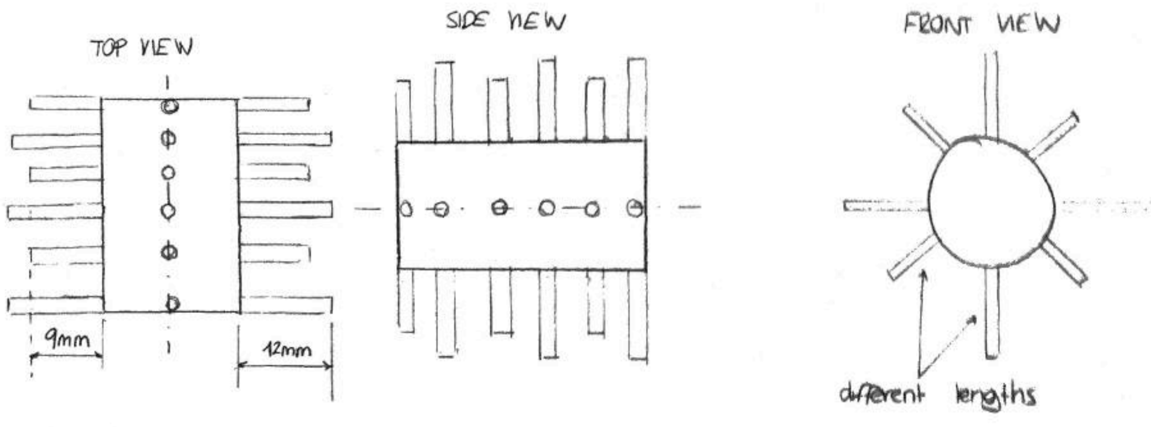
→ Increasing the down-force will ultimately result in larger frictional forces and larger whiplash velocities. Both of these factors are advantageous in removing particulate sediment that have high intermolecular forces.

#2

Current Brush



New Brush



Calculation of cleaning area of current brush

Cross-sectional area of one bristle strand $= \pi\left(\frac{0.26mm}{2}\right)^2 = 0.0531mm^2$

# of bristle strands in one group of bristles $\simeq 70$

Area of one group of bristles $= 70 \times 0.0531 = 3.717mm^2$

# of bristles in one brush $= 60$

Total cleaning area of current brush $= 60 \times 3.717 = 223.02mm^2$

Calculation cleaning area of New Brush

Total cleaning area of new brush = cross-sectional area of long bristles + cross-sectional area of short bristles + extended area.

current bristle length = 9mm

Target of larger bristle length = 12mm

Target # of long bristles = 30

Target # of short bristles = 30

ϕ of one group of bristles = $\sqrt{\frac{2\times 3.717}{\pi}}$ = 1.538 mm

Extended area = $\pi D \times \ell = \pi \times 1.538 \times 3 = 14.5mm^2$

cross-sectional area of short bristles = $30 \times 3.717 = 111.51mm^2$

cross-sectional area of long bristles = $111.51mm^2$

total extended area = $14.5 \times 30 = 435mm^2$

Total cleaning area of new brush = $111.51 + 111.51 + 435 = 658.02mm^2$

$$\frac{658.02}{223.02} = 2.95 \text{ X}$$

→ The new brush will clean an extra area of : $435mm^2$

#4 from previous calculation:

total cleaning area of current brush = $223.02mm^2$

Maximum cleaning time of current motor : $t_{current} = 30min = 1800s$

Target maximum cleaning time : $t_{new} = 60min = 3600s$

Calculation for rotational speed :

	Time it takes to complete 15 cycles
1st record	4.81 seconds
2nd record	4.81 seconds
3rd record	4.76 seconds
AVERAGE	4.79 seconds

→ rotational speed = $\frac{15 cycles}{4.79s}$ = 3.13 cycles/s

$t_{current}$ × rotational speed = 1800s × 3.13c/s = 5637 cycles

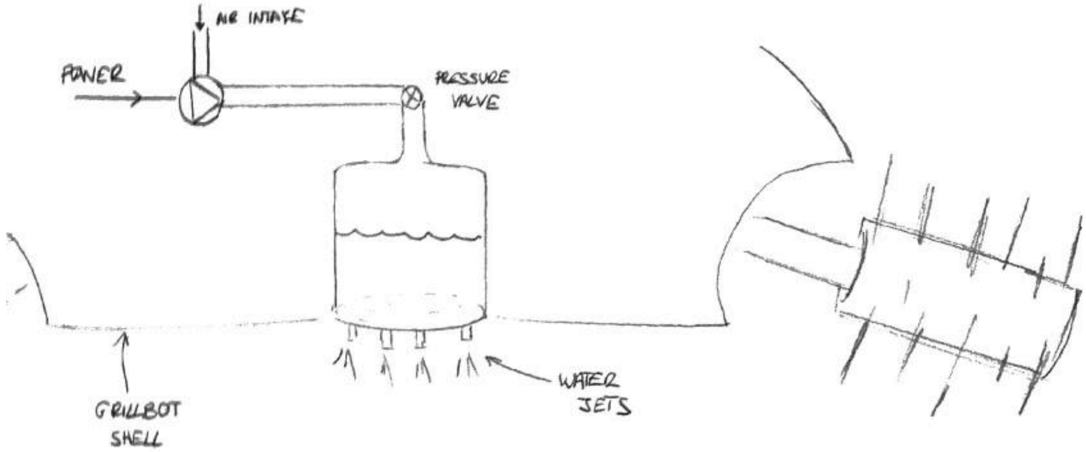
t_{new} × rotational speed = 3600s × 3.13cycles/s = 11274 cycles

Area cleaned with current motor = 5637 × 223.02 = $1.26m^2$

Area cleaned with target motor = 11274 × 223.02 = $2.51m^2$

→ with target cleaning time, it will clean an extra area of $1.25m^2$

#5 PRESSURE JET



1. ASSUME $\boxed{V_{out} \simeq 15 m/s}$: The outlet velocity of a pressure washer.

2. BECAUSE OF WATER STORAGE LIMITATIONS : $\boxed{V = 1L}$,

   volume of a large soda bottle = $1000 cm^3$

   (we can add extra volume to the sides)

   we will need to pulse-width modulate the flow such that 1L lasts 10 minutes.

3. ASSUME outlet holes to be $\boxed{1mm \text{ in Diameter}}$

4. ASSUME 10 outlet holes : $A_{out} = 10 \times \frac{\pi (1mm)^2}{4} = \boxed{\frac{5}{2}\pi \; mm^2}$

5. RUN a cycle every 1 Minute : $\boxed{10 \text{ Cycles}}$

$$Q = VA = \left(15 \frac{m}{s}\right) \times \left(\frac{5\pi}{2} \cancel{mm^2}\right) \times \frac{1m^2}{1000^2 \cancel{mm^2}} = \frac{3\pi}{80{,}000} \; m^3/s$$

$$t = \frac{V}{Q} = \frac{\cancel{1L} \cdot \frac{1000 \cancel{cm^3}}{\cancel{1L}} \times \frac{1 \cancel{m^3}}{100^3 \cancel{cm^3}}}{\frac{3\pi}{80{,}000} \; \frac{\cancel{m^3}}{s}} = \frac{80}{3\pi} \simeq 10s$$

Therefore, total time at $V = 15 m/s$ for 1L is 10s, so for each of the 10 cycles, we can obtain 1 second spray-time.

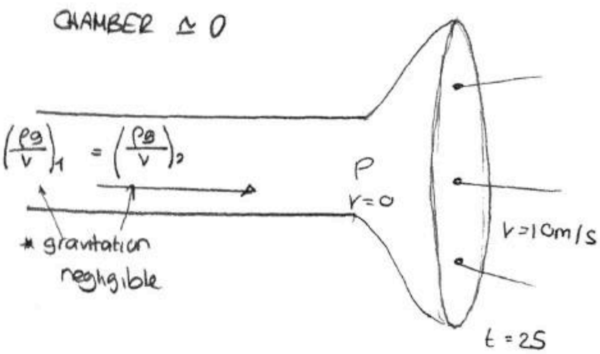
→ THIS IS NOT ENOUGH.

Every 10s : 60 cycles

Every 30s : 20 cycles – 1s/cycle

* lets run the cycle for 1 second every 30s with a jet velocity of 10m/s

VELOCITY IN A PRESSURE CHAMBER ≈ 0



The pressure required to "force" the liquid out at 10m/s in an area of $\frac{5}{2}\pi mm^2$ is related to Bernoulli's equation

$$\rightarrow P_1 + \cancelto{0}{\tfrac{1}{2}\rho V_1^2} + \cancelto{0}{\rho g h_1} = \cancelto{0}{P_2} + \tfrac{1}{2}\rho V_2^2 + \cancelto{0}{\rho g h_2}$$

$$\boxed{P_1 = \tfrac{1}{2}\rho V_2^2}$$

Assume the density of water is: $\rho_w = 1000 kg/m^3$

$$P = \tfrac{1}{2}(1000\ kg/m^3)(10\ m/s)^2 = \boxed{50{,}000 Pa} = \underline{\underline{7.25\ Psi}}$$ FEASIBLE!

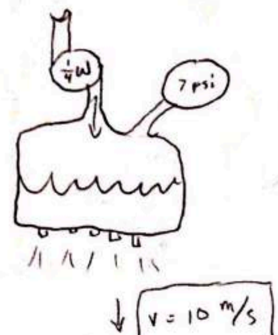
Therefore the peak power required :

$$P_{peak} = P\underset{\substack{\uparrow \\ \text{adjust} \\ \text{to } 10m/s}}{Q} = 50{,}000 \times \frac{3\pi}{120{,}000} = \boxed{5W}$$

Total energy $= P \cdot t = 5W \cdot (2s) = \boxed{10J}$

If we want to build up the capacitance continually in the storage tank, every 30s, $\underline{\underline{P}} = \frac{10J}{30s} = \underline{\underline{1/3\,W}}$

Because hydraulic pumps are very expensive, we will use an air compressor to pressurize the Air / water cylinder

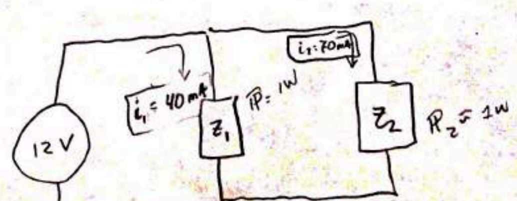


mini - air compressor = $30.00

- the air compressor will regulate the pressure

To get 5 W of power is unrealistic considering our 12 V battery can supply 3 W with no other loading.

However, if we split the required 20 J of energy into 30 s as "rise-time" of the air pressure, we only need $\frac{1}{3}$ W of continuous energy. This is a much more practical energy draw.



Z_1 = COMPRESSOR

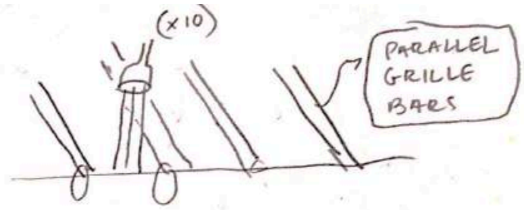
Z_2 = MOTORS

$i_2 = 70\,mA_{MAX}$

$P_2 = 12V(70mA)$

$\approx 1W$

Therefore, our power draw is about 1.5 W maximum. Our battery can support this



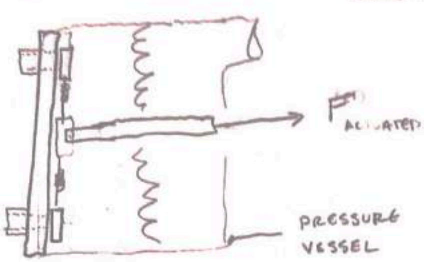
$$P_{EACH\ JET} = \frac{5W}{10} = \frac{1}{2}W = F \cdot V$$

Velocity = 10 m/s

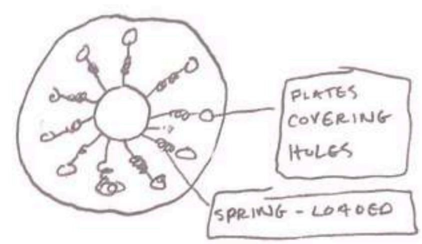
$$\boxed{F_{APPLIED} = 20\ N}$$

this force will overcome most intermolecular binding forces between particles and the surface of the grille. Therefore, in addition to the forces of the brush spindles, the added pressure jet will make cleaning with the Grillbot much more effective.

when engaged: ACTUATED FORCE ON SPRING-LOADED ASSEMBLY

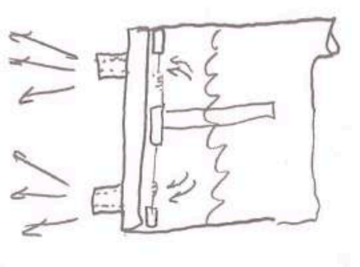


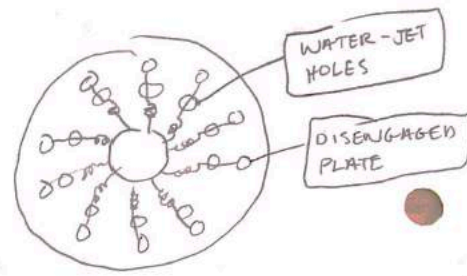
SIDE VIEW



TOP VIEW

DISENGAGED :





Description of Order-of-Magnitude Calculation

The first concept is increasing down force. To begin analysis of how increasing down force affects the function of our product, we extracted two key components that are involved with the removal of matter and associated with down force: surface kinetic friction and “whiplash” force from the bending of the bristle.

Part 1: Increase kinetic friction forcing

The assumptions made for increasing the kinetic friction of the contact between the copper and the grille are:

- The grill is made of Iron
- The relationship $F = \mu N$ is a good approximation of the force of friction because
    a. Contact is always constant between the copper bristles and the iron grille
    b. The friction coefficient is constant : $\mu = 0.5$ (i.e. linearity applies)
    c. The surface of the grille is the same everywhere
- The mass of the Grillbot is lumped as a 5 kg effective mass

The result of calculation using these parameters is that by increasing the downforce with a 5kg mass, we can double the force to friction to the surface of the grille from 25N to 50N. By increasing the frictional force, we are increasing the forcing leverage to removing grime and particulate matter, thereby improving the cleaning performance of the grillbot.

Part 2: Increase whiplash force

To calculate the improvement from the resulting whiplash velocity that occurs from the potential energy storage of the brushes, we modeled each brush as a cantilevered beam. The first step for finding the output velocity is to find the stiffness coefficient (k).

We approximated the k-value experimentally by attaching a container to a sample spindle which was fixed at one end. First, we measured the bending from the container, which was less than 1 mm. We then measured the amount of bending that resulted from adding 100 paper clips to the container and found that the bending was approximately 2mm. The assumptions made in finding the k-value is that mass has a linear relationship to displacement bending by a factor of k/g. We also approximate the displacement by only considering the vertical displacement and disregard the horizontal change. Although this linear approximation only applies to small displacements, calculating it will help to show that increasing the downforce increases the whiplash velocity and, as a result, also increases the impact force to each particle.

The next critical assumption made is that energy is conserved. Therefore, the assumption implies that there is no friction from air resistance or from contact with the grille. By making this assumption, we are able to say that the potential energy stored as a result of the bending of the brushes converts entirely to kinetic energy at the point of largest velocity (the resting x-coordinate of the brush). The following assumptions are made when relating velocity to displacement in the form of

- Energy is conserved
- Energy has a constant exponential relationship with regards to energy flows
- Gravitational forces are ignored (even though the spindles are rotating)

What we found from doing these calculations is that by doubling the mass, we will be doubling the resulting spring-velocity from the energy stored in the bristles. By increasing the velocity of impact as well as the friction of impact, increasing the downforce is a viable way of increasing the cleaning performance.

The second concept was extending bristle length. Our assumption is that the ends of each bristle will sweep the grille and the extended area would also sweep the grille, the edges of grill specifically. We measured the dimensions first. We calculated the cross-sectional area of one bristle strand and estimated the number of bristle strands in one bristle group. We then counted the numbers of groups of bristle. By multiplying those three, we were able to get the cleaning area. For the calculation for new brush, we just need to set the target length and calculate the area of extended part. Our target length is .12mm and current bristle length is .09mm. However, when we were calculating the area of the side, we set the length as .02mm, because there would be a deformation. We multiply this area by total number of brush strands. We targeted the half of the bristle group will have longer length. Then it gives you the cleaning area of current brush and new brush.

The third concept was to add cleaning fluid that will dispense through a nozzle to soak the grill surface in a soapy mixture. This soapy mixture will loosen stubborn grime and food particles stuck to the grill. Detergents and soaps contain both hydrophobic and hydrophilic chains attached to the same molecule, forcing the mixture of both polar and non-polar molecules. This emulsifies the soap and grime mixture. Forcefully agitating the soap-grime emulsion by the rotation of the Grillbot's brushes will remove the dirt from the grill (Helmenstine, 2014). In order for the soap to emulsify the oil and water components, it must wet the particles. Wetting is the ability for a liquid to maintain intermolecular connections between a liquid and solid surface. To increase wetting ability, soap reduces the surface tension of water. The surface tension of plain water is 0.073 N/m while the surface tension of soapy water is approximately 0.025 N/m.

For fourth concept, we first determined the target cleaning time. We recorded the rotational speed. For each condition, we multiplied the rotational speed by the cleaning time and the cleaning area. It gives you the total cleaning area of current cleaning time and target cleaning time.

The order-of-magnitude calculation for designing a pressure jet actually led to the development of the design itself. The primary limiting factor that we considered was the volume of water storage that would be portably attached to the product. For our purposes, we assumed a 1L liquid volume container would be the maximum capacity. Another limiting factor is the load of the compressor that would be attached to the battery. Our battery output is approximately 3W with a very low impedance. Because our motors require an approximate output of 0.5W each, we only have about 1W of power to use. Finally, we want the output velocity to be as high as possible. From online specs, we found that many pressure washers have velocity steams of 15 m/s; using this as our starting value, we found the flow rate is much too high for practical distribution purposes and reduced the velocity instead to 10 m/s, which will still create a significant amount of applied force on the grille debris. From these limitations, we developed a design that would be able to modulate the output flow such that we can send water out of 10 nozzles with a velocity of 10m/s for 1 second every 30 seconds. By using a liquid jet steam, the Grillbot can reach spaces in between the grille bars that are too deep for realistic brush penetration. Additionally, the inclusion of water will help to increase the cleaning efficacy by means of increasing lubrication.

The assumption

- Power is conserved
- Head pressure is negligible and the velocity of the water in the pressure tank is zero
- We can build a tank that supports 50 kPa (without exploding)
- We can divide distribute the pressure buildup across 30 s charging time
- The air pressure on top of the water creates an equivalent internal pressure in the water

- The battery can consistently output the required power

The result of this order-of-magnitude calculation is that it is physically feasible to introduce this system. However, because the price of a mini portable air compressor is around $30.00 and building a pressure vessel for our specs will require a metallic structure with sufficient sealants (O-rings) will cost at least $20.00, this idea is very expensive compared to our other redesign avenues.

Process of Recording the Rotational Speed

We marked at the end of brush with a tape. Then we turned on the device and videotapeed it with an Iphone. We watched the video and counted how many times the mark has passed and recorded the corresponding time. We repeated counting 3 times and averaged the values. This is how we recorded the rotational speed.

Appendix AG: Specification Sheets

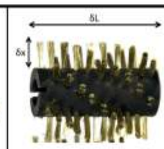
Industrial Redesign Avenue

Date	Demand/Wish	Metrics	Value	Target Value	Units	Responsibility	Test/ Verification
Geometry							
04/04/15	W	Volume	241.164	241.164	inches^3	All	Verify with dimensions given by the Engineering sketch
04/04/15	D	length of shafts	46.7	62	mm	All	Measure with a ruler
Kinematics							
04/04/15	D	Rotation Rate of Wheels	3.13	3.13	cycles per second	All	Verify with output torque of motor
Force							
04/04/15	W	Mass	> 3.3	-	lb	All	Measure Weight with a digital weight scale
Material							
04/04/15	W	Strengh of Wire Brushes	> 600	-	Mpa	All	Test through Tensile Strength Test
Operation							
04/04/15	D	Operating Noise	< 40	25	dB	All	Measure noise with phone Application: dB
04/04/15	D	Noise level of beeping after shut down	< 40	25	dB	All	Measure noise with phone Application: dB
Cost							
15/02/15	W	Expected Cost of Product	< 60	-	$	All	from customer interviews

Functional Redesign Avenue

Date	Demand/Wish	Metrics	Value	Target Value	Units	Responsibility	Test/ Verification
Geometry							
04/04/15	W	Volume	241.164	241.164	inches^3	All	Verify with dimensions given by the Engineering sketch
04/04/15	D	length of bristles	9	12	mm	All	Measure with a ruler
04/04/15	D	total cleaning area of brush	223.02	3653.64	mm^2	All	Calculate from dimensions of the bristles
04/04/15	D	total area of grill cleaned	1.26	2.51	m^2	All	Calculate from rotational speed, cleaning time and cleaning area
Kinematics							
04/04/15	W	Rotation Rate of Wheels	3.13	3.13	cycles per second	All	Verify with output torque of motor
Force							
04/04/15	D	Mass	> 3.3	4.3	lb	All	Measure Weight with a digital weight scale
Material							
04/04/15	D	Strengh of Wire Brushes	> 600	-	Mpa	All	Test through Tensile Strength Test
Cost							
04/04/15	W	Expected Cost of Product	< 60	-	$	All	from customer interviews
Signal							
04/04/15	D	Cleaning Time	30	60	minutes	All	Measure time required to clean the grill with stop watch

Appendix AH: Pugh Chart

			Legend	+ 0 -	Better Same Worse
Concept Variants					
Criteria	**Increasing Weight**	**Modifying Brush**	**Water Dispenser**	**Water Jet**	**Increase Cleaning Time**
Purchase cost ($)	**0**	+	+	+	-
Cleaning time (minutes)	**0**	0	-	+	-
Development risk (# of OEMs and vendors to source parts)	**0**	0	-	-	+
Durability (months of operation)	**0**	0	-	-	-
Maintenenace and product cleaning time (minutes per use)	**0**	0	-	-	+
Ease of use	**0**	+	-	-	+
Battery life (minutes)	**0**	+	+	-	+
Cleaning ability	**0**	+	-	+	0
Total +	**0**	4	2	3	4
Total -	**0**	0	6	5	3
Net total	**0**	4	-4	-2	1
Purchase cost ($)	+	**0**	-	-	+
Cleaning time (minutes)	0	**0**	-	+	-
Development risk (# of OEMs and vendors to source parts)	+	**0**	-	-	+
Durability (months of operation)	0	**0**	-	-	+
Maintenenace and product cleaning time (minutes per use)	0	**0**	-	-	+
Ease of use	-	**0**	-	-	+
Battery life (minutes)	-	**0**	0	-	0
Cleaning ability	-	**0**	-	+	-
Total +	2	**0**	0	2	5
Total -	3	**0**	7	6	2
Net total	-1	**0**	-7	-4	3
Purchase cost ($)	+	+	**0**	-	+
Cleaning time (minutes)	0	+	**0**	+	-
Development risk (# of OEMs and vendors to source parts)	+	+	**0**	-	+
Durability (months of operation)	+	+	**0**	-	+
Maintenenace and product cleaning time (minutes per use)	+	+	**0**	0	+
Ease of use	0	+	**0**	0	+
Battery life (minutes)	-	0	**0**	-	0
Cleaning ability	0	+	**0**	+	-
Total +	4	7	**0**	2	5
Total -	1	0	**0**	4	2
Net total	3	7	**0**	-2	3
Purchase cost ($)	+	+	+	**0**	+
Cleaning time (minutes)	-	-	-	**0**	-
Development risk (# of OEMs and vendors to source parts)	+	+	+	**0**	+
Durability (months of operation)	+	+	+	**0**	+
Maintenenace and product cleaning time (minutes per use)	+	+	0	**0**	+
Ease of use	0	+	0	**0**	+
Battery life (minutes)	+	+	+	**0**	+
Cleaning ability	-	-	-	**0**	-
Total +	5	6	4	**0**	6
Total -	2	2	2	**0**	2
Net total	3	4	2	**0**	4
Purchase cost ($)	-	-	-	-	**0**
Cleaning time (minutes)	+	+	+	+	**0**
Development risk (# of OEMs and vendors to source parts)	0	0	-	-	**0**
Durability (months of operation)	-	0	-	-	**0**
Maintenenace and product cleaning time (minutes per use)	0	0	-	-	**0**
Ease of use	-	0	-	-	**0**
Battery life (minutes)	0	+	+	-	**0**
Cleaning ability	+	+	+	+	**0**
Total +	2	3	3	2	**0**
Total -	3	1	5	6	**0**
Net total	-1	2	-2	-4	**0**
Sum of Net Totals	**4**	**17**	**-11**	**-12**	**11**

Appendix AI: To-Do List and Gantt chart for Phase III

To-Do List Phase 3		
	Task	Completed?
To-Do List		
	Make the List	Complete
	Distribute work	Complete
Gantt Chart		
	Make the chart	Complete
	Plan	Complete
Parametric Interest		
	Determine Parametric Interest	Complete
	Write-up	Complete
Develop Experimental Model		
	Design experimental setup	Complete
	Fabricate experimental setup	Complete
	Design factorial experiments	Complete
	"Back of the envelope" predictive calculations	
	Write-up for experiment	Complete
Experimentation		
	Conduct experiments	Complete
	Analyze experiment results	Complete
	Compare results to prediction	Complete
	Write-up	
FMEA		
	Table for original product	Complete
	Table for redesign product	Complete
	Write-up	Complete
Presentation		
	Make Slides	Complete
	Intro, Customer Interview	Complete
	Redesign Avenue	Complete
	Low resolution prototype	Complete
	Result	Complete
	Record Video	Complete
	Put them together	Complete
Design for Assembly		
	Scan pictures	Complete
	Write-up	Complete
Design for Manufacturing		

	Scan pictures	Complete
	Write-up	Complete
Design for Environment		Complete
Preliminary Drawings		Complete
Revision of BoM		
	Revise BoM	Complete
	Write-up	Complete
Extra Credit		
	Model prototype on Solid Works	Complete
	Buy material	Complete
	3D print prototype	Complete
Provide recommendations for future redesign work		Complete

Week	Start Date	Target Date	Status (%)	3	4	5	6	7	8	9	10	11	12	13	14	15	16
				02/02 /15	09/02 /15	16/02 /15	23/02 /15	02/03 /15	09/03 /15	16/03 /15	23/0 3/15	30/0 3/15	06/04 /15	13/04 /15	20/04 /15	27/04 /15	04/0 /1
roject enchmark																	
hase 1																	
Product Introduction	02/02/15	09/02/15	100														
Background Literature	02/02/15	09/02/15	100														
Customer Needs Analysis	02/02/15	09/02/15	100														
Customer Interviews	09/02/15	16/02/15	100														
House of Quality	09/02/15	16/02/15	100														
Specifications Sheet	09/02/15	16/02/15	100														
Activity Diagram	09/02/15	16/02/15	100														
To-do List	2/16/15	2/16/15	100														
Gantt Chart	2/16/15	2/16/15	100														
Black Box Model	2/18/15	2/22/15	100														
Hypothesized Function Model	2/18/15	2/22/15	100														
Cross Sectional Sketches	2/18/15	2/22/15	100														
Product Disassembly	2/25/15	3/1/15	100														
Bill of Materials	2/25/15	3/1/15	100														
Exploded Views	3/2/15	3/6/15	100														
Actual Function Structure	3/2/15	3/6/15	100														
Comparison	3/2/15	3/6/15	100														
Function Structure	3/2/15	3/6/15	100														
Summarize Entire Reverse Engineering	3/2/15	3/6/15	100														
Update Specification Sheet and problem statement	3/2/15	3/6/15	100														
hase 2																	
To-do List	3/9/15	3/9/15	100														
Gantt Chart	3/9/15	3/9/15	100														
Select Adaptive Avenues	3/11/15	3/15/15	100														
Brainstorming	3/11/15	3/15/15	100														
Mind Maps	3/16/15	3/20/15	100														
6-3-5	3/16/15	3/22/15	100														
Design Change Concept Generation	3/16/15	3/22/15	100														
Functional Re-design Concept Variants	3/23/15	3/28/15	100														
Industrial Design Shift Concept Variants	3/23/15	3/29/15	100														
Pugh Chart	3/30/15	4/2/15	100														
Order-of-Magnitude	3/30/15	4/2/15	100														
hase 3																	
To-do List	4/6/15	4/6/15	100														
Gantt Chart	4/6/15	4/6/15	100														
Develop Experimental Model	4/6/15	4/11/15	100														
Experimentation	4/6/15	4/12/15	100														
Back-of-the-Envelope	4/13/15	4/16/15	100														
FMEA	4/15/15	4/19/15	100														
Design for Assembly	4/20/15	4/24/15	100														
Design for Environment	4/20/15	4/24/15	100														
Preliminary Drawings	4/20/15	4/24/15	100														

Appendix AJ: Brush Prototypes

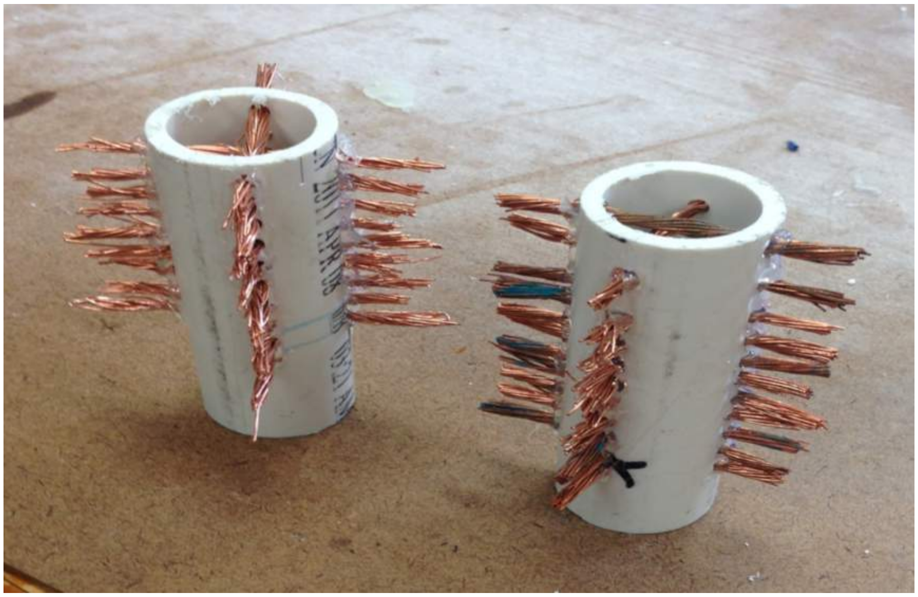
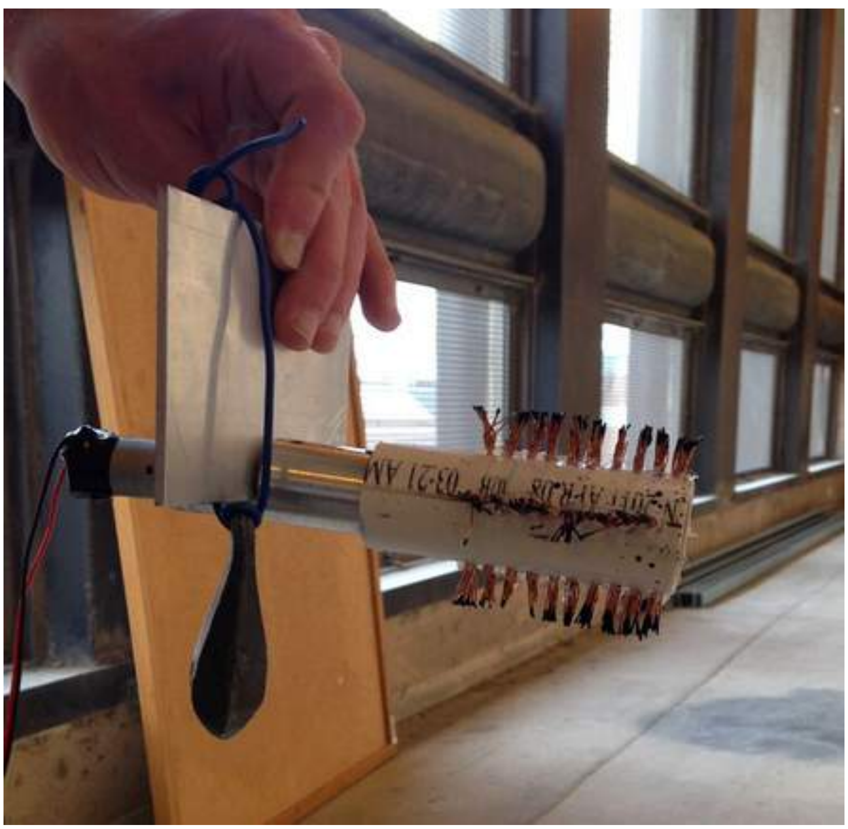
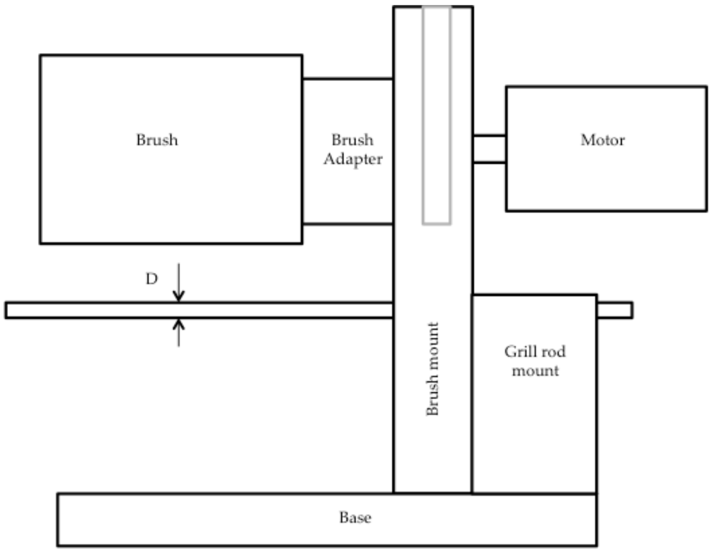


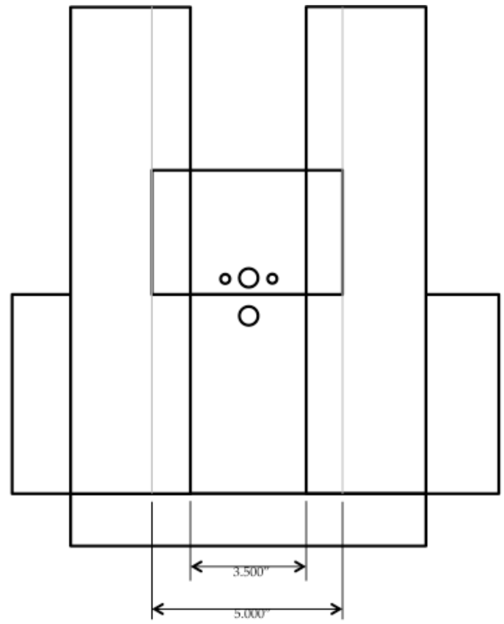
Figure AJ-1: Experimental Prototypes



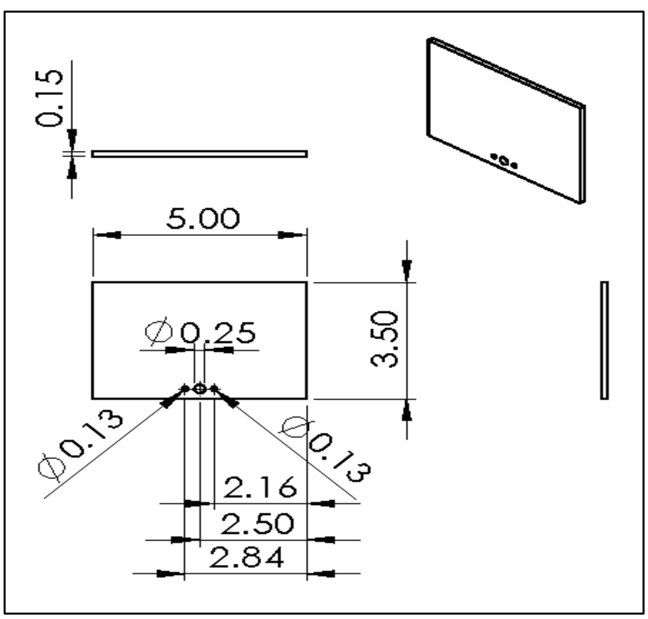
Appendix AJ-2: Prototype with the weight

Appendix AK: Pictures of Experimental Model

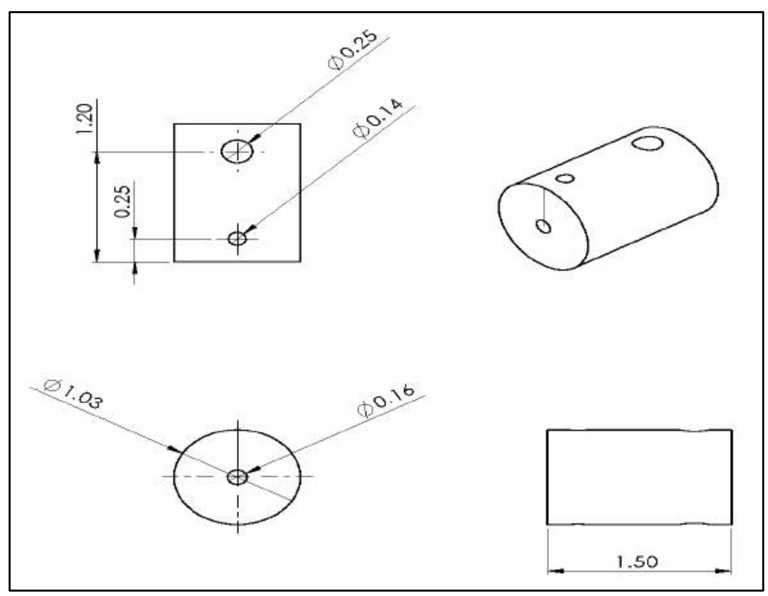




Sliding plate:



Brush adapter:



Appendix AL: Experiment Results

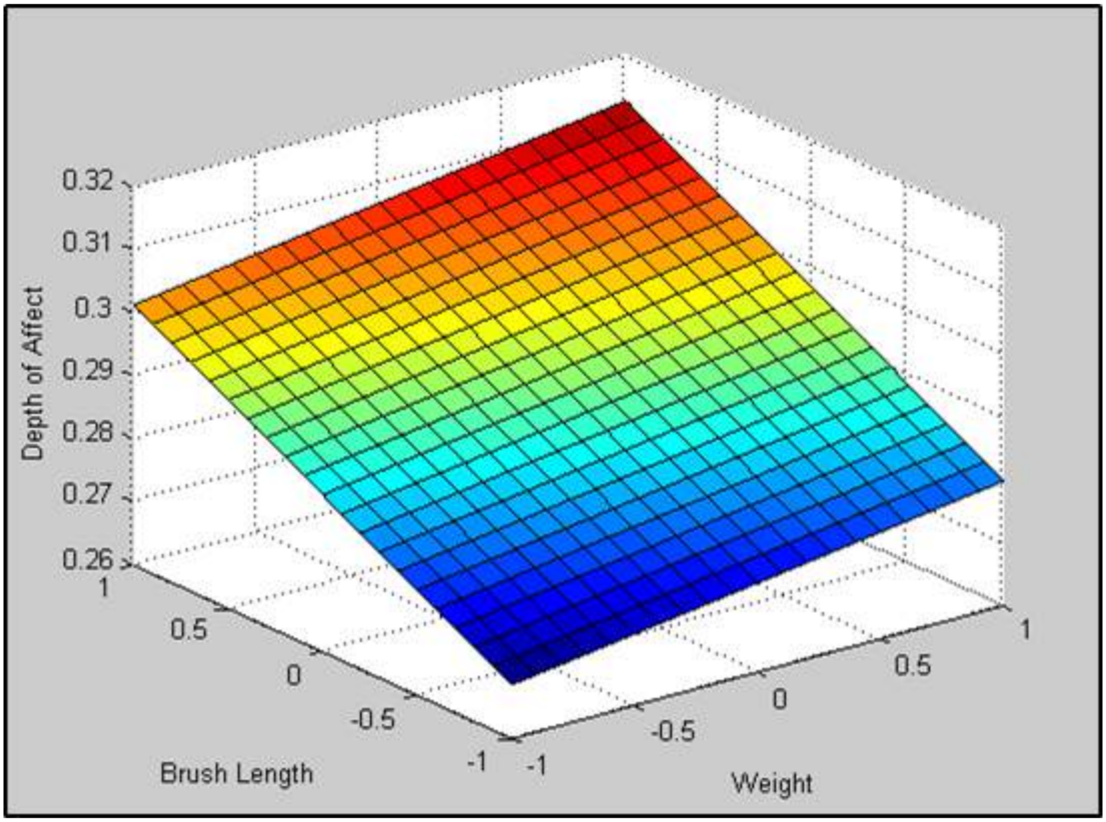
Table 1. Depth of the penetration

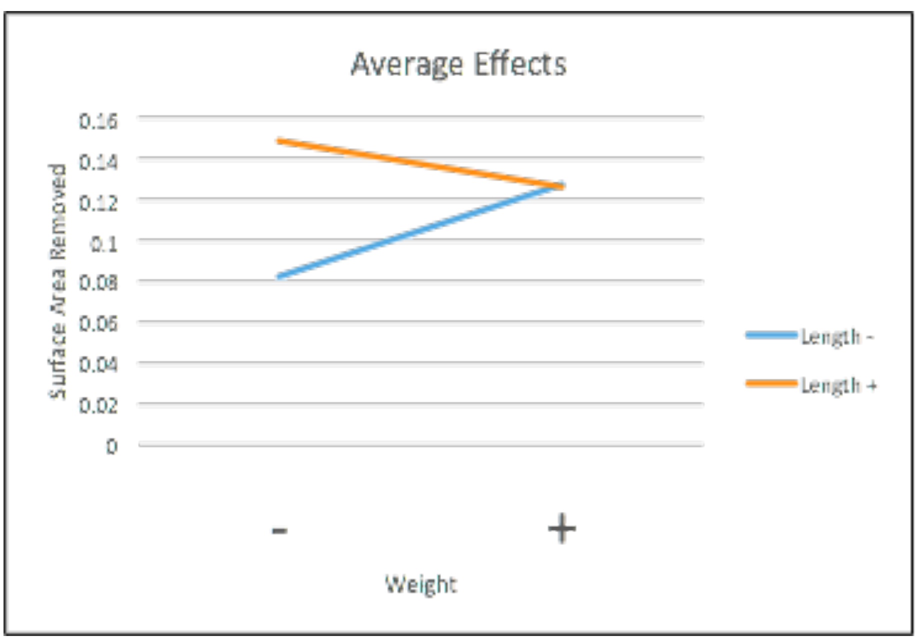
	Weight	**Length**		
Trial	X_1	X_2	Y1_1 (inches)	Y1_2 (inches)
1	-1	-1	0.078	0.086
2	1	-1	0.134	0.121
3	-1	1	0.164	0.134
4	1	1	0.128	0.124

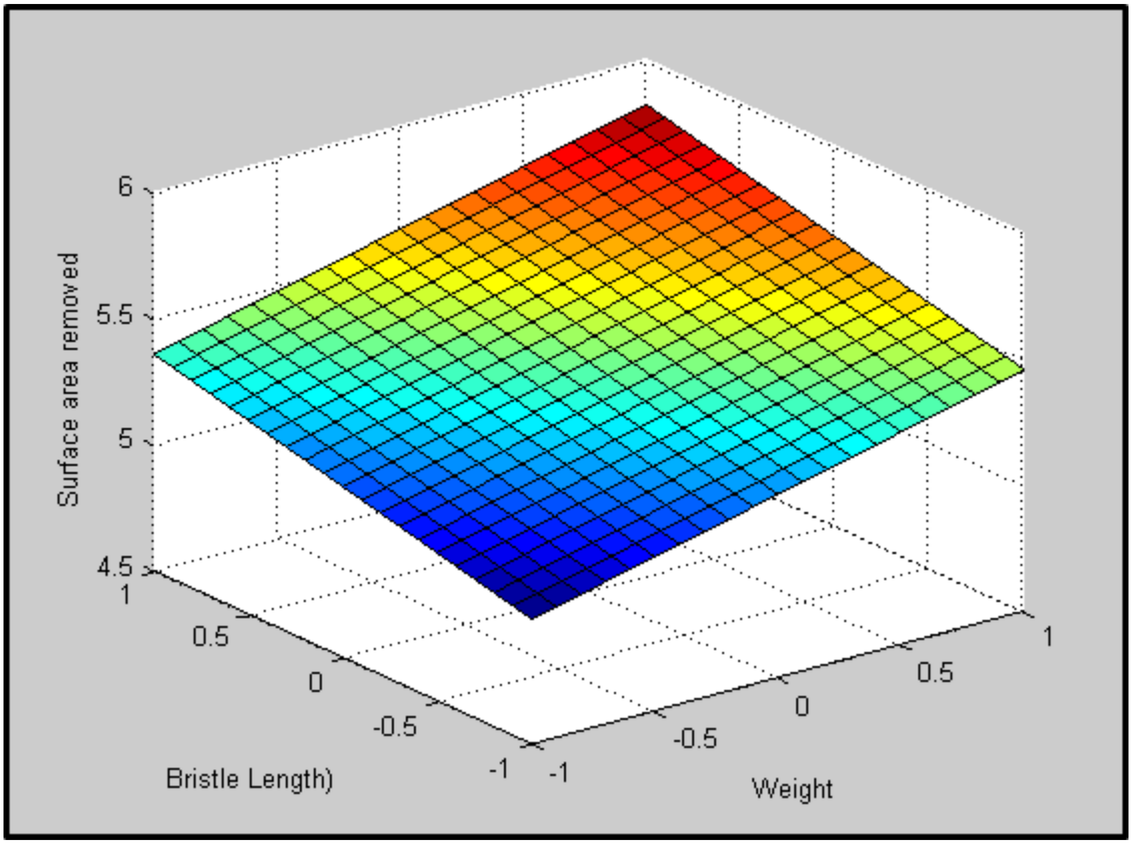
Table 2. Area removal

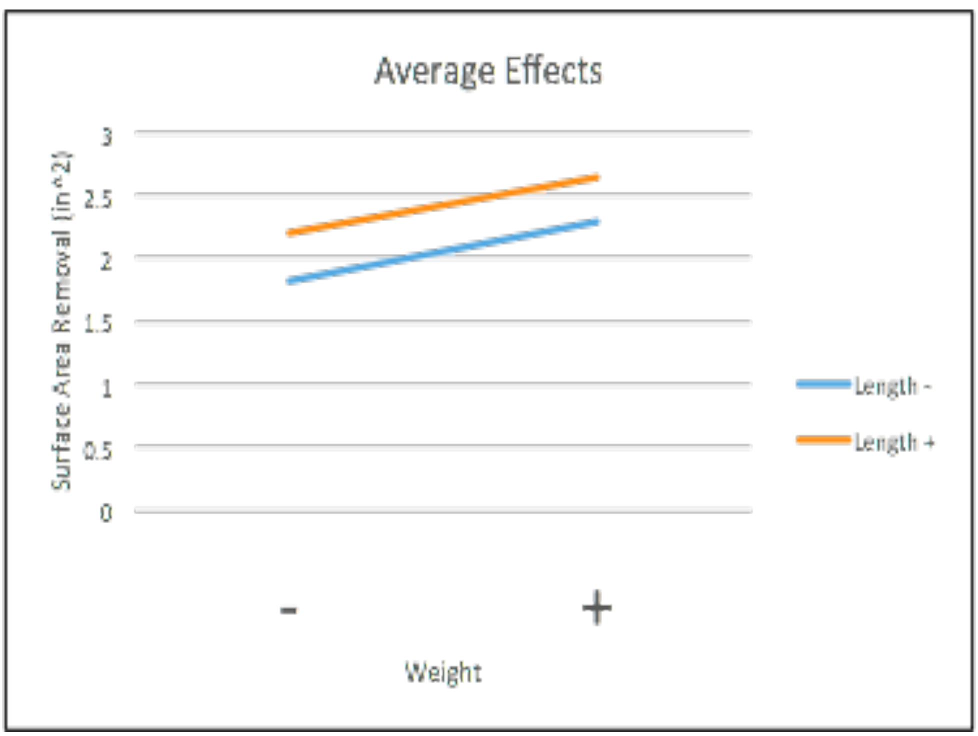
	Weight	**Length**		
Trial	X_1	X_2	Area1 (in^2)	Area2 (in^2)
1	-1	-1	1.901404402	1.737385
2	1	-1	2.27091049	2.329374
3	-1	1	2.141896836	2.262686
4	1	1	2.559488795	2.7231

Appendix AM: Statistical Analysis






Surface area removed
6
5.5
5
4.5
1
0.5
0
-0.5
-1
Bristle Length)
-1
-0.5
0
0.5
1
Weight


Average Effects
Surface Area Removal (in^2)
3
2.5
2
1.5
1
0.5
0
-
+
Weight
Length -
Length +

	Depth		Area	
	X1	*X2*	*X1*	*X2*
Multiple R	**0.230982**	**0.672414**	**0.785243**	**0.618161**
R Square	0.053353	0.452141	0.616607	0.382123
Adjusted R Square	-0.41997	0.178211	0.42491	0.073184
Standard Error	0.033508	0.025491	0.256415	0.325516
Observations	4	4	4	4

Table: R^2 values for control variables

	Regression: Depth		
	Bi	Bi2	Bi12
	0.005625	0.016375	0.022
Significant?	0	1	1

Table: Coefficient Values for depth reached

	Regression: Surface area		
	Bi	Bi2	Bi12
	0.229938	0.181012	0.41095
Significant?	1	1	1

Table: Coefficient Values for surface area removal

Appendix AN: Failure Mode Effect Analysis (FMEA)

Original Product

				Current Situation						Improved Situation			
Failure Location/Component/Category	Failure Mode	Failure Effect	Failure Cause	Current Detection Steps	S	O	D	RPN	Suggested Remedial Measures	S	O	D	RPN
Main Circuit	Overheat	inefficiencies, fail to operate	faulty electrical connection	Current meter	2	6	2	24	Have a sensor to shut down the device when it overheats	2	6	2	24
	Soldering failure	inefficiencies, fail to operate	Weakening Solder	Current meter	2	2	2	8	Solder neatly	2	1	2	4
Power button	Wear	cannot start the machine	overuse	Visual	1	6	2	12	Use a stronger material to prevent wear	1	3	2	6
	Tear	cannot start the machine	misuse	visual	1	7	7	49	Use a stronger material to prevent wear	1	3	5	15
Motors	Stator	Motor shutdown, Inefficiencies	Physical Damage, Contamination, corrosion, high temperature, voltage impbalance, borken supports, and rewind burnout procedures.	Motor Longevity test	6	4	4	96	Use a more efficient motor or have the toppings be mixed manually	4	3	4	48
	Stall	Imprecise function fulfillment	Fatigue	Motor Longevity test	6	4	4	96		4	3	4	48
	Come loose	Lose contact with ball,	wear &tear, poor assembly, faulty equipment	Motor Longevity test	6	4	4	96		4	3	4	48
	Housing	Motor shutdown, Inefficiencies	Improper installation, physical damage, corrosion and material buildup (soft food)	Motor Longevity test	6	4	4	96		4	3	4	48
Brush-motor shaft	Wear		overweight, overuse	visual	1	3	2	6	Different material that is less prone to wear	1	2	2	4
	Fracture/Material yield		Fatique/Abuse, misuse, overweight	visual	1	3	5	15	Different material that is less prone to fracture	1	2	5	10
Brush wheel	Wear	inefficiencies	Fatique/Abuse	visual	1	7	2	14	Different material that is less prone to wear	1	2	2	4
	Oxidation	inefficiencies	Corrosion	visual	6	4	6	144	Different material that is less prone to oxidized	2	2	6	24
Battery	Electrical connection failure	It will not charge	misuse, faulty electrical connection	voltage test	3	7	3	63	Store under proper position	3	5	3	45
Battery connection	Electrical connection failure	It will not charge	misuse, faulty electrical connection	voltage test	1	7	3	21	Have a stronger port	1	5	3	15

Redesigned Product

				Current Situation									
Failure Location/Component/Category	Failure Mode	Failure Effect	Failure Cause	Current Detection Steps	S	O	D	RPN	Suggested Remedial Measures	S	O	D	RPN
Brush wheel (difference)	Inefficient	It does not create enough friction to clean	hardware failure	visual	2	3	6	36	Develop a different pattern	2	2	6	24
	Unbalanced	Will not clean thoroughly	human error	visual	2	4	6	48	Proper measurement prior to manufactur	2	3	6	36
	Bonding Failure	The bristles will fall off	misue, abuse	visual	5	7	6	210	Use a stronger glue material	4	2	6	48
brush-motor shaft (more weight)	Fracture/Material yield	The brush falls off	Improper material choice	visual	4	5	6	120	Different material that is less prone to fracture	3	4	6	72
	Unstable	inefficiencies	Improper installation	visual	4	5	6	120	Proper measurement prior to manufactur	3	4	6	72
	Loose	The brush falls off	Improper installation	visual	4	5	6	120	Proper measurement prior to manufactur	3	4	6	72
Motor	Open Circuit	fails to operate	miss soldering	voltage test	4	8	8	256	Solder neatly	3	2	8	48

Appendix AO: Updated Bill of Materials

Part #	Part Name	Quantity	Function	Mass (g)	Finish	Manufacturing Processes	Dimensions				
E	**External Parts**						Depth	Width	Height	Diameter	Diameter (inner)
1	Label	1	Display the logo of company	40,4	Ni plated steel	Plastic injection molding, Stamping the Logo	69,7		12,8	-	-
2	Label washer	1	Attaches label to grillbot	2,6	Zinc plated steel	Stamped	-	-	1,78	18,1	6,51
3	Top shell	1	Enclose components	164,2	TC-895 A/B BLACK	Plastic injection molding, dyed	50	-	17,5	190	-
4	Lower shell	1	Enclose components	269,2	TC-895 A/B BLACK	Dyed, Injection molding, cut, and coated on inside surface	48	-	5,13	195	-
5	Pads of lower shell	3	Supports grillbot	3,8	TC-895 A/B BLACK	Injection molding, dyed	43,9	20,4	4,92	-	-
6	Battery Charger	1	Charge the device	81,2	Plastic, Steel, Cu	OEM	76,25	49	30	-	-
7	Rubber power button cover	1	Provides soft cushion for button	0,6	Rubber	OEM (Molded, cutting)	-	-	5,58	14,7	-
I1	**Internal Parts**										
	LCD display, Subcircuit, and power buttom			12,4							
1	LCD display	1	Display time remaining to clean, battery life		Plastic	OEM, cutting, welding, and assembled					
2	Subcircuit	1	Transmit signal		Cu, Tin, Silicon	OEM, cutting, welding, and assembled	50,25	27	12,16	-	-
3	Power button	1	Import power on/off		Plastic	OEM, cutting, welding, and assembled					
I2	Assembly of motors, main circuit board, power adapter			264,8							
1	Motors	3	Convert EE to RME	86,666667	Steel and Cu	OEM	-	-	58,17	24,8	-
2	Brush-motor shaft	3	Transmit RME to the brush wheels	4,7333333	TC-895 A/B BLACK	Injection molding, dyed	-	-	46,7	13,7	9,1
3	Brush wheel	3	Transmit RME to the grill, Clean the grill	66,4	TC-895 A/B BLACK, Brass	Plastic injection molding, Wires: OEM, Cutting, Assembly to the brush	-	-	67,4	47,4	25,6
4	Battery	1	Import stored EE to the Maincircuit	110,2	Lithium Ion	OEM	54	36,3	31	-	-
5	Battery cushion pads	2	Provides soft support for battery	0,4	Heat resistant foam	Formed, dyed, slabstock process and cut	69	32,1	2,45	-	-
I3	Thermocouple and epoxy			0,6							
1	Thermocouple	1	Detect the temperature			OEM, Welding					
2	Epoxy	1	Fastens thermocouple to bottom of lower shell		Epoxy	Mixed and applied					
S	**Screws**						Nominal D	Body D	Length_total	Length_head	
1	Bottom pad screw	6	Fastens pads of lower shell to lower shell	0,7	Zinc plated screws	OEM (Turning, Plating)	6,49	3,83	10,18	2,57	
2	Lower shell and top shell screw	6	Attaches lower shell to top shell	1,5714286	Zinc plated screws	OEM (Turning, Plating)	6,67	3,89	13,74	4,18	
3	Power cord screw	1	Attaches power port to top shell	0,1	Zinc plated screws	OEM (Turning, Plating)	7,2	2,34	9,42	1,5	
4	Motor screw	6	Attaches motors to lower shell	0,3666667	Zinc plated screws	OEM (Turning, Plating)	5,43	2,87	7,67	1,49	
5	Shaft screws	3	Attaches brush shaft to motor spindle	0,4	Zinc plated screws	OEM (Turning, Plating)	6,63	1,95	10	1,95	
6	Subcircuit screws	4	Attaches subcircuit board to top shell	0,15	Zinc plated screws	OEM (Turning, Plating)	3,53	2,27	6,5	1,48	
7	Maincircuit screws	4	Attaches main circuit board to lower shell	2,5	Zinc plated screws	OEM (Turning, Plating)	3,95	2,66	9,33	1,94	
8	Label screw	1	Attaches label to grillbot	2	Zinc plated steel	OEM (Turning, Plating)	10	4,88	9,91	3,52	
	Total parts	57									

\-

OME: Original Equipment Manufacturer
EE: Electrical Energy
RME: Rotational Mechanical Energy
D: Diameter
Ni:Nickel
Cu:Copper
LCD:Liquid Crystal Displays
E:External Parts
I:Internal Parts
S:Screws

Appendix AP: Design for Assembly Guidelines

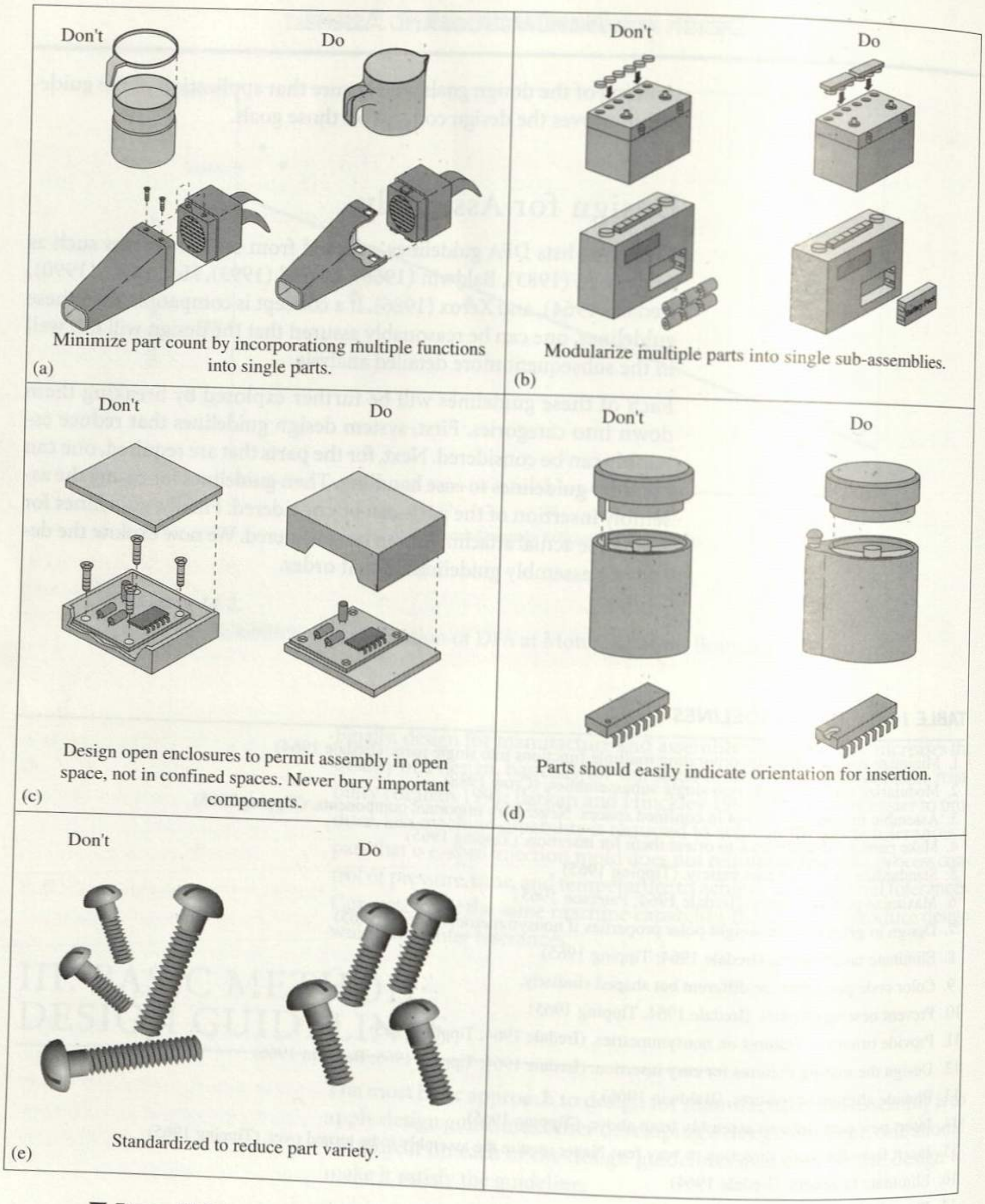
Appendix AQ-1: DFA Guidelines

----

1. Minimize part count by incorporating multiple functions into single parts. (Iredale 194)
2. Modularize multiple parts into single subassemblies (Crow 1988)
3. Assemble in open space, not in confined spaces; never bury important components or components that require maintenance. (Tipping 1965)
4. Make parts such that it is easy to identify how they should be oriented for insertion. (Tipping 1965)
5. Standardize to reduce part variety. (Tipping 1965)
6. Maximize part symmetry. (Iredale 1964; Paterson 1965)
7. Design in geometric or weight polar properties if nonsymmetric. (Tipping 1965)
8. Eliminate tangly parts. (Iredalte 1964; Tipping 1965)
9. Color code parts that are different but shaped similarly.
10. Prevent nesting of parts. (Iredale 1964; Tipping 1965)
11. Provide orienting features on nonsymmetries. (Iredale 1964; Tipping 1965)
12. Design the mating features for easy insertion. (Iredale 1964; Tipping 1965; Daldwin 1966)
13. Provide alignment features. (Baldwin 1966)
14. Insert new parts into an assembly from above. (Tipping 1965)
15. Insert from the same direction or very few. Never require the assembly to be turned over. (Tipping 1965)
16. Eliminate fasteners. (Iredale 1964)
17. Place fasteners away from obstructions.
18. Deep channels should be sufficiently wide to provide access to fastening tools. No channel is best.
19. Providing flats for uniform fastening and fastening ease.
20. Proper spacing ensures allowance for a fastening tool.

(Telenkom et al., 2008)

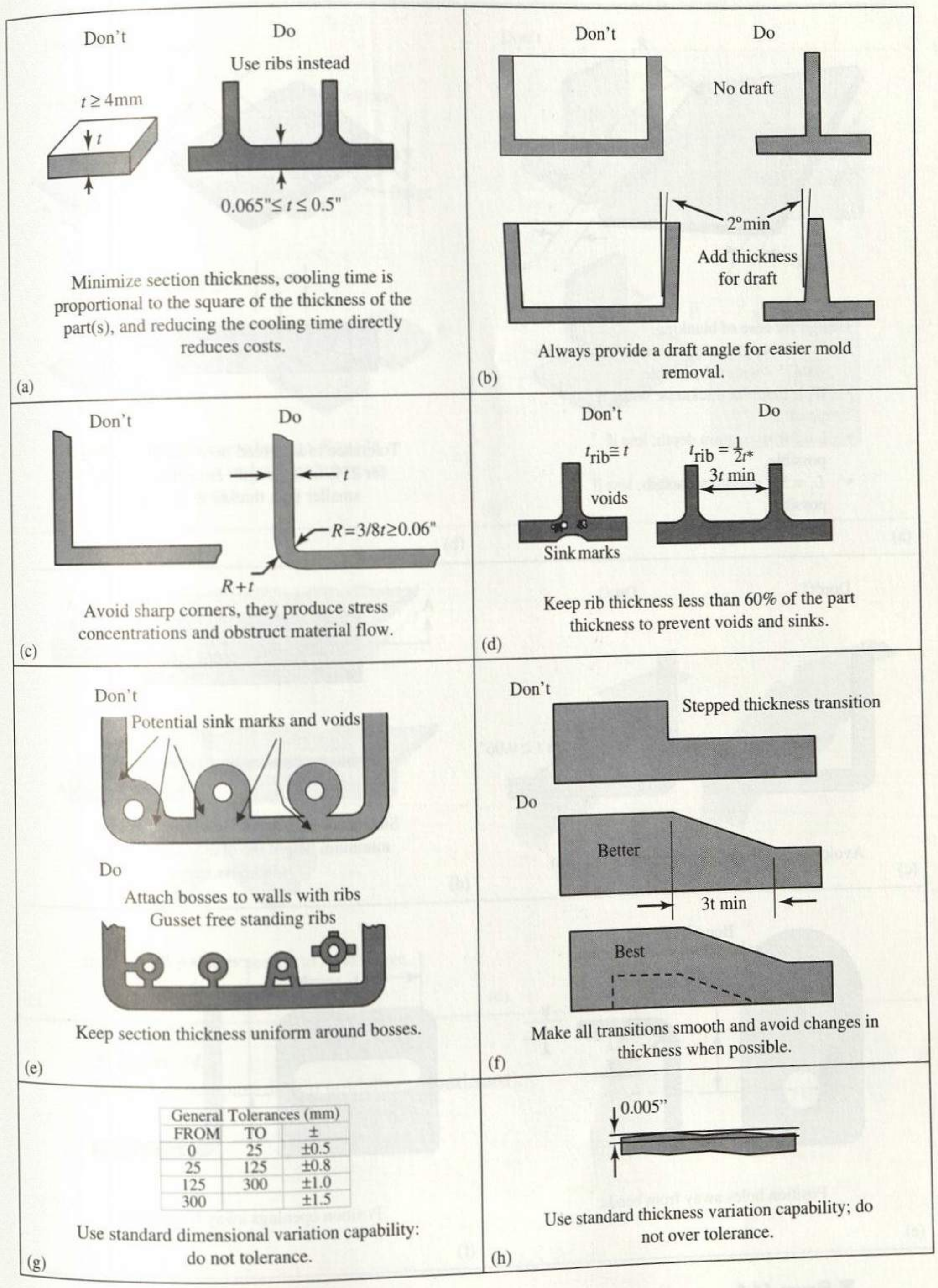
Appendix AP-2



▼ ***Figure 14.3.***
Design for assembly system guidelines.

Appendix AQ: Design for Manufacturing Guidelines

(Telenkom et al., 2008)



General Tolerances (mm)		
FROM	TO	±
0	25	±0.5
25	125	±0.8
125	300	±1.0
300		±1.5

▼ ***Figure 14.7.***
Injection-molded part design guidelines.

Appendix AR: Design for Environment (DFE) Guidelines

Principle A. Ensure sustainability of resources by: [5; 9; 21]

1. Specifying renewable and abundant resources [4; 5; 7; 8; 25]
2. Specifying recyclable, or recycled materials, especially those within the company or for which a market exists or needs to be stimulated [5-9; 16; 25; 28-32]
3. Layering recycled and virgin material where virgin material is necessary [7; 25]
4. Exploiting unique properties of recycled materials [7; 25]
5. Employing common and remanufactured components across models [6-8; 16; 31; 32]
6. Specifying mutually compatible materials and fasteners for recycling [4; 6-8; 16; 25; 28-32]
7. Specifying one type of material for the product and its subassemblies [6; 7; 9; 16; 24; 25; 28; 30-33]
8. Specifying non-composite, non-blended materials and no alloys [6; 24; 25]
9. Specifying renewable forms of energy [5; 6]

Principle B. Ensure healthy inputs and outputs by: [21; 24]

10. Installing protection against release of pollutants and hazardous substances [7; 25]
11. Specifying non-hazardous and otherwise environmentally "clean" substances, especially in regards to user health [5; 7-9; 25; 28-32]
12. Ensuring that wastes are water-based or biodegradable[5; 6; 16; 30]
13. Specifying the cleanest source of energy [5; 7; 25; 31]
14. Including labels and instructions for safe handling of toxic materials [7-9; 29-33]
15. Specifying clean production processes for the product and in selection of components [7; 16; 29; 30]
16. Concentrating toxic elements for easy removal and treatment [7; 24; 25; 29; 30; 33]

Principle C. Ensure minimal use of resources in production and transportation phases by: [24; 32]

17. Replacing the functions and appeals of packaging through the product's design [7; 25]
18. Employing folding, nesting or disassembly to distribute products in a compact state [7; 25]
19. Applying structural techniques and materials to minimize the total volume of material [4-9; 16; 24; 25; 28-30; 32]
20. Specifying lightweight materials and components [6; 8; 16; 25]
21. Specifying materials that do not require additional surface treatment or inks [5; 7; 25]
22. Structuring the product to avoid rejects and minimize material waste in production [4; 7; 16; 25]
23. Minimizing the number of components [7; 16; 25; 31]
24. Specifying materials with low-intensity production and agriculture [8; 25]
25. Specifying clean, high-efficiency production processes [5; 8; 16; 25; 30]
26. Employing as few manufacturing steps as possible [30]

Principle D. Ensure efficiency of resources during use by: [5; 9; 21]

27. Implementing reusable supplies or ensuring the maximum usefulness of consumables [5; 7; 10; 16; 25]
28. Implementing fail safes against heat and material loss [7; 10; 25; 29; 31]
29. Minimizing the volume, area and weight of parts and materials to which energy is transferred [7; 10; 25; 31]
30. Specifying best-in-class, energy efficient components [7; 8; 10; 25; 29; 31]
31. Implementing default power down for subsystems that are not in use [5; 7; 25; 31]
32. Ensuring rapid warm up and power down [10]
33. Maximizing system efficiency for an entire range of usage conditions [9; 10; 25]
34. Interconnecting available flows of energy and materials within the product and between the product and its environment [9; 21]
35. Incorporating partial operation and permitting users to turn off systems partially or completely [7; 9; 25; 31]
36. Using feedback mechanisms to indicate how much energy or water is being consumed [5; 8]
37. Incorporating intuitive controls for resource-saving features [8; 10]
38. Incorporating features that prevent waste of materials by the user [7; 25]
39. Defaulting mechanisms to automatically reset the product to its most efficient setting [7]

Principle E. Ensure appropriate durability of the product and components by: [5; 16; 21; 24; 29]

40. Reutilizing high-embedded energy components [21]
41. Planning for on-going efficiency improvements [9; 29]
42. Improving aesthetics and functionality to ensure the aesthetic life is equal to the technical life [5; 7; 25; 29; 30]
43. Ensuring minimal maintenance and minimizing failure modes in the product and its components [6-9; 30; 32]
44. Specifying better materials, surface treatments, or structural arrangements to protect products from dirt, corrosion, and wear [4; 24]
45. Indicating on the product which parts are to be cleaned/maintained in a specific way [7; 25]
46. Making wear detectable [4; 7; 25]
47. Allowing easy repair and upgrading, especially for components that experience rapid change [4; 24]
48. Requiring few service and inspection tools [4]
49. Facilitating testing of components [4]
50. Allowing for repetitive dis- and re- assembly [4]

Principle F. Enable disassembly, separation, and purification by: [21]

51. Indicating on the product how it should be opened and make access points obvious [5; 7; 25; 28; 31]
52. Ensuring that joints and fasteners are easily accessible [28; 31; 32]
53. Maintaining stability and part placement during disassembly [4; 31]
54. Minimizing the number and variety of joining elements [7; 16; 24; 28; 31-33]
55. Ensuring that destructive disassembly techniques do not harm people or reusable components [4; 31; 32]
56. Ensuring reusable parts can be cleaned easily and without damage [4]
57. Ensuring that incompatible materials are easily separated [6-8; 31; 32]
58. Making component interfaces simple and reversibly separable [6-8; 25; 31-33]
59. Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol [4-8; 16; 25; 28; 29; 31; 32]
60. Implementing reusable/swappable platforms, modules, and components [4; 6; 8; 29-32]
61. Condensing into a minimal number of parts [5-9; 30-32]
62. Specifying compatible adhesives, labels, surface coatings, pigments, etc. which do not interfere with cleaning [5-8; 16; 25; 28; 31-33]
63. Employing one disassembly direction without reorientation [7; 16; 25; 31]
64. Specifying all joints so that they are separable by hand or only a few, simple tools [7; 16; 25; 31; 32]
65. Minimizing the number and length of operations for detachment [16; 31]
66. Marking materials in molds with types and reutilization protocols [4; 5; 8; 9; 16; 25; 28; 30; 31; 33]
67. Using a shallow or open structure for easy access to subassemblies [7]

Appendix AS: Final Prototype