STEVENS INSTITUTE OF TECHNOLOGY

Magnetically Coupled Ball Drive
Phase 1 Report

ME 423: Engineering Design VII

Assigned: September 5th, 2019
Due: October 1st, 2019

"I pledge my honor that I have abided by the Stevens Honor System."

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I. Project Statement

Motivation

The Magnetically Coupled Ball Drive (MCBD) project focuses on the design improvement of a ball drive, which allows for the holonomic motion of driven platforms. The project is the continued evolution of previous design projects that have established spherical wheels as a proven method of producing the desired holonomic motion. The technology that motivates this additional work is the magnetic coupling of the spherical wheel and the drive mechanism. A previous version of this drive has utilized external support structures and ball transfers to maintain contact between the driving method and the driven sphere. Magnetic coupling serves to eliminate the need for an external support structure by substituting with a structure internal to the spherical wheel that is attracted to a magnet located on the wheel's yoke. Some issues arose due to the use of external structures being used in previous design iterations. As prototypes of these designs moved around, they could easily accumulate debris on their surfaces, which transferred to the ball bearings that contacted the spherical wheels. This increased rolling resistance, thereby decreasing the efficiency of the ball drives. An internal support structure and reduced contact with the spherical wheel seeks to eliminate the issues caused by the external support structure.

Goals & Objectives

There are four major goals for this project. The first goal is to develop a satisfactory design to be prototyped for proof of concept. This goal has a secondary objective of consideration of design for manufacturability of the concept. The design must meet the needs and specifications set forth, but consideration must also be given to the process by which the parts of this product are to be manufactured/assembled in the case of larger scale production. The second goal of this project is to actualize the design into a prototype. This will involve creating drawings of parts, ordering parts and/or making one-off parts using rapid prototyping techniques such as 3-D printing and/or laser cutting of materials. The third goal of this project is to develop a testing apparatus/methodology to determine the effectiveness of the design. Once this has been developed, the fourth goal of testing the prototype can be achieved, and the performance of the design can be assessed.

Major Issues

This project will present several challenges pertaining to design and analysis. The first of these challenges is creating an internal structure capable of withstanding specified loads and sustained loading. This will also include being able to absorb peaks as obstacles are traversed. The criteria for absorbing these peaks include a structure which will not experience plastic deformation or cracking when overcoming several obstacles during testing. This will require significant analysis of forces and prediction of "worst case" scenarios. In addition to being able to support the load, the spherical wheel must be capable of motion. This will be achieved via friction driving the wheel. The wheel must have sufficient coefficients of friction between the drive and the wheel as well as between the wheel and the traversed surface. To achieve the desired friction coefficient, material selection and geometry choice should be done carefully. The proper combination of omni-wheel-sphere, and sphere-driving surface must be determined to ensure efficient transmission of all driving forces. One aspect to also be considered at this point is the manufacturing and assembly of the wheel. The wheel must be designed in a way to allow the incorporation of an internal structure, and remain unpierced and conducive to rolling. Whether rigid or inflated, the wheel must be able to be realistically manufactured and assembled. Once these challenges have been considered, the maximizing of the drive efficiency can be addressed. This challenge concerns using efficient layouts of motors, the drive mechanism itself, the coefficients of friction involved, as well as the mass of the wheel. Another challenge of the design will be achieving the maximum coupling force between the drive system and the wheel. A larger coupling force between the omni-wheels and the sphere would allow for larger driving torques which increase the vehicle's ability to accelerate which is why magnets are being considered as the coupling device. The design will need to consider the mass of the wheel as well as the forces acting laterally to overcome the coupling forces.

This project will present several challenges pertaining to the prototyping of and experimentation on the design. Based upon the design, it is projected that the internal and external structures will be complex and consist of several unique parts. Some of the parts such as the drive system may not be readily available and will require individual production through machining, 3-D printing, laser cutting, or contracting through a third party for construction. One major challenge of the design will be the assembly of a prototype. The nature of the project involves a structure inside of a solid sphere. Finding an effective way to assemble the prototype will be a formidable challenge to overcome. In addition to the design and creation of the prototype, this project involves the creation of an experimental apparatus and methodology for testing the design. Developing testing equipment and procedures to effectively measure the design performance will involve consideration for expected performance scenarios and safety factors, but remain non-destructive. The parameters which must be tested to ensure reliable operation include maximum acceleration, and ability to overcome slopes and obstacles. The ability to climb up slopes and overcome obstacles can be determined by the maximum acceleration of the entire vehicle along with some specified factor of safety. Testing with varying slopes could also give insight into the coefficients of friction with which the omni-wheels, sphere, and road use to transmit forces. Another test parameter includes analyzing the forces which the entire structure may face when overcoming an obstacle to ensure there is no fracture of the internal or external components. Calculations can be made for impulse forces and acceleration and can be tested using some form of force gauge on a varying slope surface to observe scenarios.

II. Literature Review

State-of-the-Art Technology

In 1973, Bengt Ilon invented one of the first omnidirectional wheels, the mecanum wheel.[1] These wheels contain rollers along the rim of a wheel positioned at an angle. This allows for passive movement of the rollers when moving to the side and the full wheel can spin when driven forward. Omni-wheels are currently the go-to type of apparatus to gain holonomic motion but have many drawbacks. Most omni-wheels are rigid and cannot absorb shock, lack traction, and are generally inefficient.

In order to conduct a state-of-the-art technology review, professional papers and patents for spherical wheel designs were assessed. The goal was to identify current technologies that successfully implement driven spherical wheels or enable holonomic motion. The most notable and substantial articles found are outlined below.

Patent US 8,459,383 B1 was filed June 7, 2011 by Daniel Burget.[2] The patent encompasses a spherical drive system propelled by either omnidirectional wheels or electromagnets. In the first embodiment, omni-wheels mounted to an external support structure drive a spherical tire through friction. The second embodiment utilizes an aluminum external support structure and bearings to encapsulate a rubber tire that has permanent magnets embedded in it. External electromagnets create temporary magnetic forces to drive the spherical wheel. The proposed design found in Figure 2-1 is meant for full-scale vehicles.

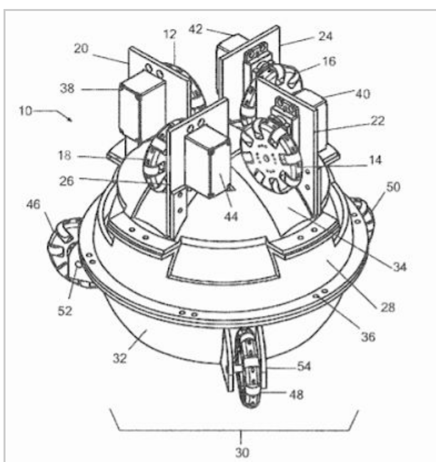

Figure 2-1: Burget’s Omni-wheel Spherical Drive System

Patent US 2013/0151043 A1 was filed on June 26, 2012 by Ui Jung Jung on behalf of the Hyundai Motor Company.[3] The patent is for an electromagnetically driven spherical wheel similar to Burget's. It utilizes permanent magnets embedded in a spherical wheel with an external case that has controllable electromagnets. A drawing of the spherical wheel and encasing structure can be found in Figure 2-2.

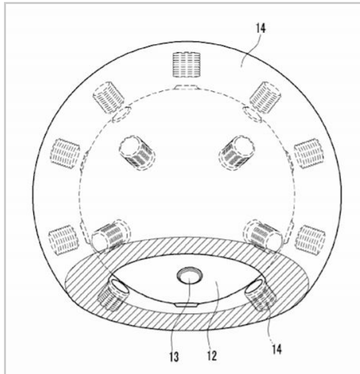

Figure 2-2: Jung's Electromagnetically Driven Spherical Wheel

The most substantial patent to affect this project is patent US 8,269,447 B2 filed March 17, 2010 by Lanny Smoot and Dirk Ruiken on behalf of Disney Enterprises, Inc.[4] The design aims to "utilize magnetic interaction to facilitate contact of the drive against the sphere" so that "a relatively small amount of the sphere is covered or obstructed from view by the drive." The design uses alternating permanent magnets embedded in an interior and exterior structure to sandwich a spherical tire between bearings. The spherical drive system can be found in Figure 2-3 and the magnetic coupling structures can be seen in Figure 2-4. The patent assumes a friction drive system of at least one omni-wheel and also claims the addition of different internal support structures such as an extended weight to stabilize the orientation.

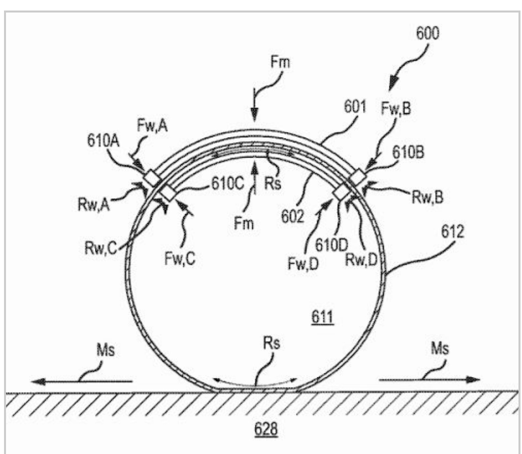

Figure 2-3: Smoot and Ruiken's Spherical Ball Drive

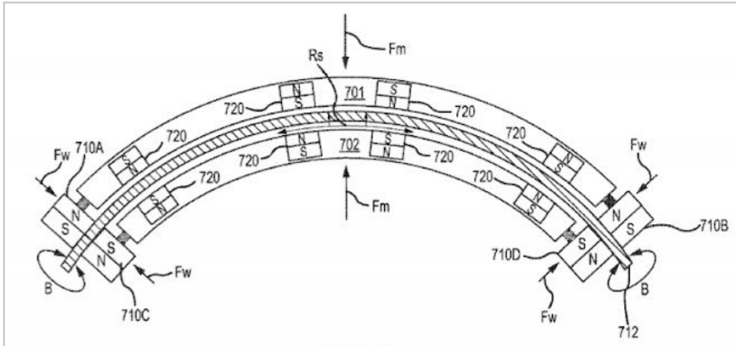

Figure 2-4: Smoot and Ruiken's Magnetic Coupling Structures

The IEEE paper *A Novel Spherical Wheel Driven by Chains with Guiding Wheels* was analyzed for its proposed implementation of an omnidirectional chain system.[5] The omni-chain aims to increase the contact area of an external drive and spherical wheel. An omni-chain such as the one found in Figure 2-5 could increase the efficiency of a friction drive system and also decrease the likeliness of slipping/loss of contact.

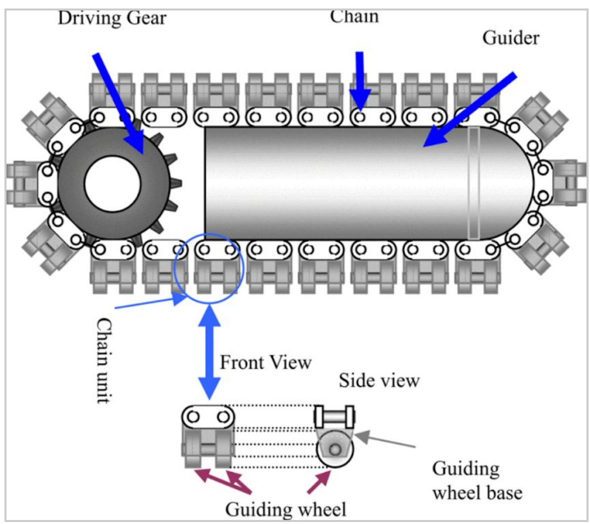

Figure 2-5: Omnidirectional Chain System

Many other papers and patents were found referencing spherical drive systems but these are the most substantial. There are also many implementations of spherical drive systems in amateur robotics but none are suitable for commercial applications. Spherical wheels have certainly been thought of as a future technology that will enable holonomic locomotion. The Goodyear tire company has repeatedly displayed concept spherical tires that they claim to be developing but no patents or prototypes have materialized.[6]

Commercial Applications

Besides a multitude of patents, it is clear that driven spherical wheels have yet to be implemented commercially. The applications of such a drive system are wide and varied as almost any form of locomotion could benefit from it. A friction drive is inherently inefficient but the benefits of holonomic motion can outweigh that cost for medium-sized applications. Warehouse robots that need to navigate tight corridors of product could benefit from the lateral movement. More notable is the implementation of a spherical drive system in electric wheelchairs. Holonomic motion would allow for increased quality-of-life for people utilizing electric wheelchairs for personal locomotion. In addition, spherical drives could be utilized in telepresence robots, surveying robots, smaller personal transportation vehicles, and mobile warehouse robots. There are many applications for a spherical drive system that enables holonomic motion and a patent to protect the successful implementation and design would be the best route to bring the technology to the market.

III. Needs & Specifications

Societal

There are many limiting factors that exist in the current methods of mobility for any type of vehicle. The current methods are tailored to specific applications and environments, and any method used outside their specific application or environment work only to a limited extent. Because of this, there is a need for a more well-rounded and applicable mobility drive. An omni-wheel driven ball drive has the ability to work in many applications and for many environments with very minimal modifications. Omni-wheel driven ball drives have been proven to work supplying holonomic motion. Now getting omni-wheel driven ball drives up to the same efficiency is the challenge.

Holonomic motion is an efficient type of motion capable of being used in a multitude of vehicles. Some examples where omni-wheel driven ball drives can be utilized is in factories, cars, work site trucks, telepresence robots, and personalized forms of locomotion. In factories, being able to utilize multiple degrees of freedom robots allows for companies to move materials around in a much more efficient manner. For cars, it would make parallel parking and general control easier. Being utilized on work site trucks would allow for the big trucks to travel in all directions with little hindrances. Telepresence robots would have an easier time maneuvering around tightly confined office buildings. And, in personalized forms of locomotion, would allow for multi terrain travel as well as ease of mobility. One major application that would benefit from holonomic motion is electrical wheelchairs. Being able to maneuver through tight areas with ease, as well as being applicable on many different surfaces.

Customers

This omni-wheel driven ball drive is being geared toward electric wheelchairs, but can easily be modified to fit into the other vehicles as well. With being angle toward wheelchairs many needs have to be met. The ball drive has to be able to support the weight of a person as well as the wheel drive apparatus. This specifies a target weight the ball drive structure needs to be able to support. Additionally, this means the ball drive as well as the whole support structure need to be able to fit through a standard door, and ensure the person can fit under a standard sized table. All of these needs correlate to specific size dimensions that the ball drive can be before it becomes an inconvenience compared to existing wheelchairs.

Shown in Table A-1 of the Appendix are other customer needs pertaining specifically to a wheelchair. These correlate to specifications that need to be determined in order for the ball drive to function properly and effectively. These include sphere size, in order to overcome any obstacles that can be found on the ground. Additionally, being able to have great control over the wheelchair would be required, so actuation needs to be perfected. Being able to move in all directions quickly corresponds to the ability to power the wheelchair from rest very quickly, requiring a high acceleration, as well as use of good connection between the spherical wheel and the omniwheels. Lastly, being able to travel over many different terrains requires the used materials to have good surface contact and traction over a wide variety of surfaces.

The customer voice table was further utilized to create a QFD (Figure A-1 of the Appendix), which relates customer requirements to solid metrics that will be taken into account during the technical analysis of the chosen concept.

IV. Concept Generation & Selection

Concept Generation

The concept generation process began with breaking down the project into several smaller parts: the drive system, spherical wheel design, and internal support structure. The possible designs in each category along with their corresponding abbreviations are laid out in the table below.

Table 4-1: Concept Combination Table

Drive System	Spherical Wheel	Internal Structure
(OW) Omni-wheels (MOW) Magnetic omni-wheels (OC) Omni-chain (MOC) Magnetic omni-chain (IS) Induction sphere	(BAND) Multiple bands holding wheel together (RIGI) Rigid sphere with external tire/coating (FLEX) Flexible material sphere (SOCC) “Soccer ball” with varying materials (frame and panels) (INFL) Inflated wheel	(SP) Fully spherical (TH) Top hemisphere (BH) Bottom hemisphere (TB) Top/bottom hybrid (¾) Top ¾ sphere

The first major component of the ball drive was the design of the drive system, which is the part of the ball drive that contacts the spherical wheel and uses friction to propel it. The drive system concepts included omni-wheels, omni-wheels with embedded magnets, omni-chains, omni-chains with embedded magnets, and an induction sphere. The embedded magnet omni-wheel and omni-chain were intended to have corresponding magnetic components within the spherical wheel to attract the external drive component and improve contact between the wheel surface and drive system. An induction sphere could be used to replace the physical, friction-driving methods by using a fluctuating, induced magnetic field to cause the wheel to move. Basic concept sketches for an omni-wheel and omni-chain can be seen below.

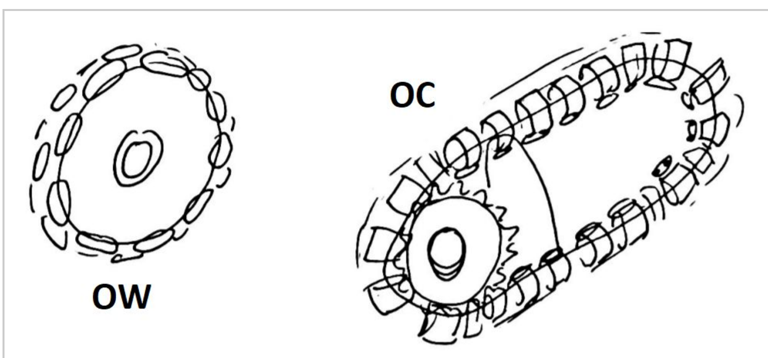

Figure 4-1: Omni-wheel & omni-chain concept sketches

The next component of the concept generation process was the spherical wheel design. The first spherical wheel concept was a previously prototyped design where two hemispheres were held together by bands of rubber-like material. Another concept involved two hemispheres made from a rigid material that get snapped together and covered with a tire or rubber coating.

The next concept was a spherical wheel made from a uniform, flexible material. A soccer ball design was created where a frame would be made from one material and the inner panels would be made from another material. Lastly, an inflated wheel design was considered because the air pressure could be changed to allow the ball drive to travel across obstacles and a variety of surfaces.

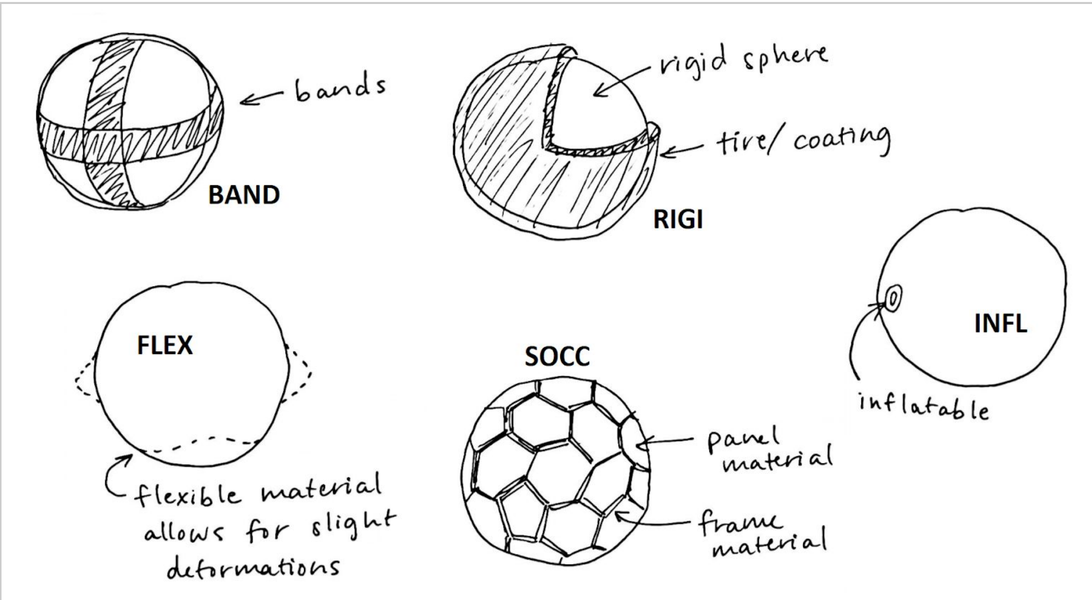

Figure 4-2: Spherical wheel concept sketches

The design of the internal structure of the wheel was determined as the last component, as a variety of structure shapes could hypothetically be implemented. The generated internal support structure designs utilized ball transfers between the support and the internal surface of the wheel. The first design was a fully spherical design, where the support structure was essentially a hollow sphere. Three of the designs were considered “partial” support structures where either half of a sphere or slightly less than a full sphere was placed at the top or bottom of the interior of the spherical wheel. These designs would be weighted appropriately to maintain a low center of gravity for the ball drive. The last design was a top-bottom “hybrid” internal support where the horizontal middle of the sphere was removed and a vertical support was added. In the concept sketches of Figure 4-3 below, cross-sections of each internal structure design are depicted.

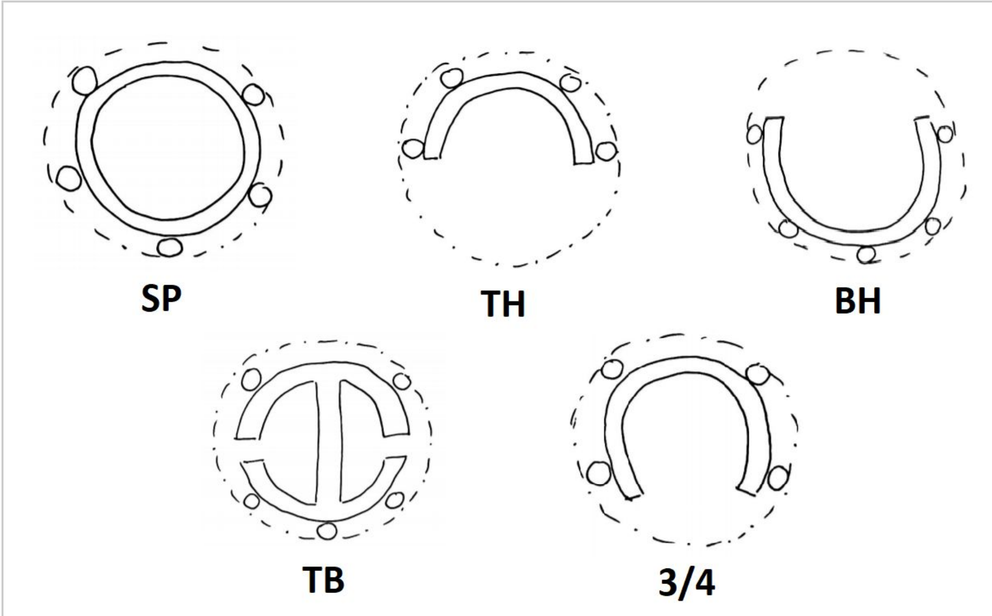

Figure 4-3: Internal support structure concept sketches

Concept Selection

One concept from each of the three categories was chosen and combined to create fifteen unique ball drive concepts. These designs were then compared to a baseline design, which was assigned as the most recent senior design ball drive iteration utilizing an omni-wheels, basketballs, and an external support system. This process can be seen in the concept screening matrix in Table A-2 of the Appendix. The top four designs from screening moved on to the concept selection matrix where they were ranked against each other using weighted values assigned to the various selection criteria. The ratings that were given for each selection criteria were done on a scale from 0 to 5. The concept selection table can be seen in Table A-3.

The selected concepts can be seen below in Figure 4-4, which includes: concept A (OW+RIGI+SP), concept B (OW+FLEX+TB), concept C (OC+RIGI+SP), and concept D (OC+FLEX+TB). Concept D ended up ranking first out of the four top concepts.

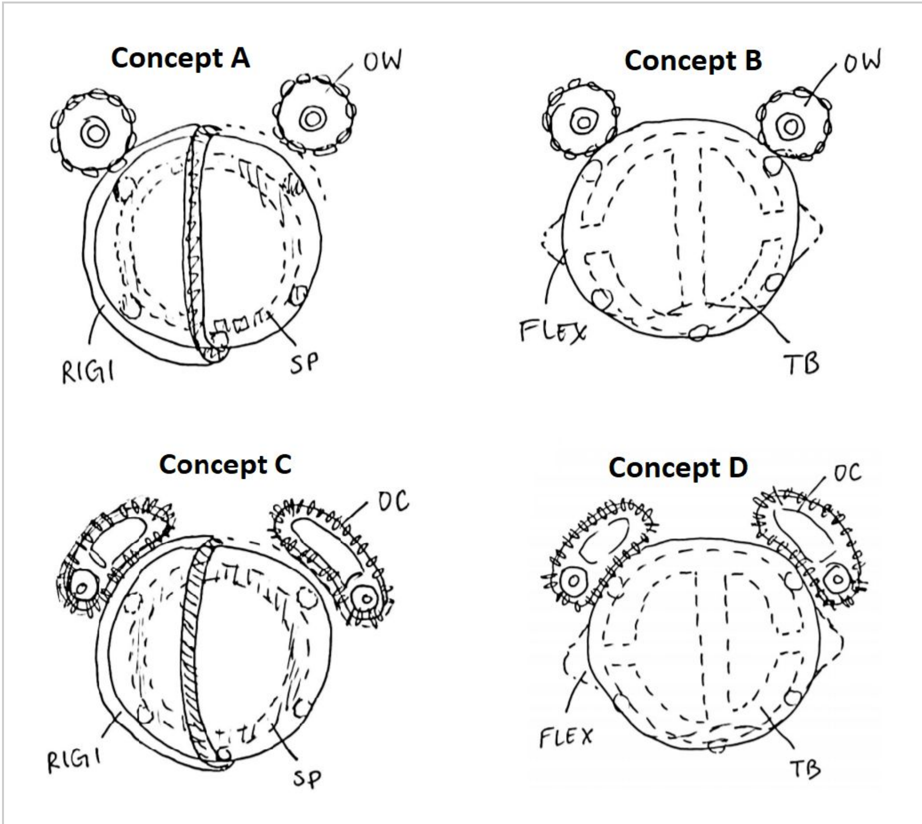

Figure 4-4: Sketches of selected concepts

V. Technical Analysis

Previous Research

In the 2012-2013 academic year at Stevens Institute of Technology, a senior design team worked on providing an omni-directional robot that was worked on as an alternative to common mobility methods. A robot was created with three spherical wheels that were driven by motor-powered omni-wheels, shown below in Figure 5-1. The omni-wheels are able to guide the spherical wheels in any desired direction. The spherical wheels are encased within a claw-like mechanism to ensure they will not detach from the robot.

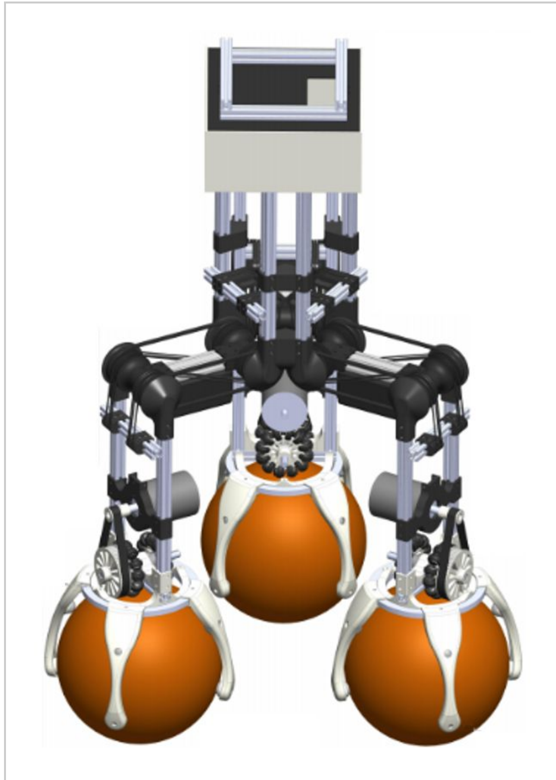

Figure 5-1: Previous design project concept

The following year, the same senior design project was offered, to build upon the work of the preceding senior design team. During the 2013-2014 school year, as well as adding in a terrain adaptive device to raise and lower different legs, a study into understanding how the locomotion of three and four spherical-wheeled robots were done. For three balls, the triangle configuration was looked at, and for four balls, the diamond and square configurations were looked at. For all three configurations, understanding how to move the robot forward, backward, left, right, and clockwise and counterclockwise rotations were determined.[7]

The following few years, Biruk Gebre, Kishore Pochiraju, and Akin Tatoglu, worked on fully programming and gaining control of the omni-wheel driven ball drive. It was tested and proven to be accurate to an extent, but would need to be further expanded upon for better accuracy.[8] Following this step, Biruk Gebre and Kishore Pochiraju conducted research on ball drive configuration and kinematics. These configurations each have different dimensions and areas they will take up when moving and spinning. Those values were determined as well as cataloged and compared. Furthermore, Gebre and Pochiraju determined equations for the actuation efficiency which could be used on all the studied configurations.[9]

At this stage the claw-like mechanism encasing the spherical wheels was observed to be picking up dust and debris, making the omni-wheels within each claw work against the holonomic motion. So after the study into motion plans, Gebre and Pochiraju worked on a new proof-of-concept for holding the spherical wheels in place. That was the idea of using magnets to couple the spherical wheel to the yoke of the robot, as seen in Figure 5-2 below.

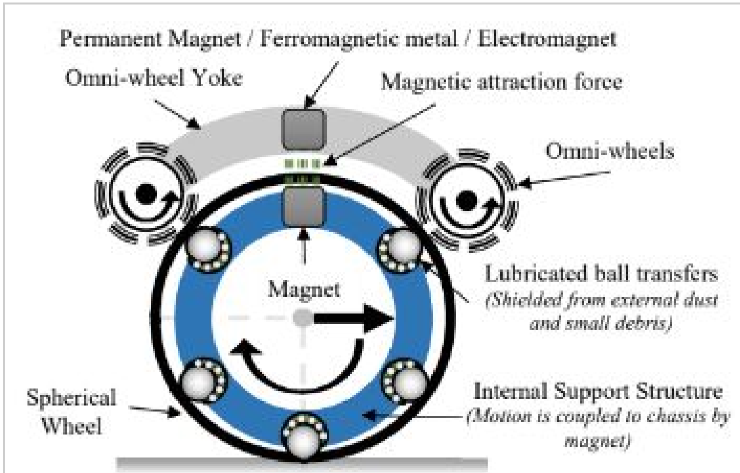

Figure 5-2: 2D model of a Magnetically Coupled Ball Drive

Utilizing a simplified 2D model, the concept was evaluated if it would be feasible to accomplish this idea. Once it was determined a viable concept, magnet types and configurations were studied to determine how strong and big the magnets would need to be in order to keep the spherical wheel coupled. Following this, a prototype using the data observed from the 2D model and the magnet tests was built. The final product, Figure 5-3, can be seen below.[10]

Figure 5-3: Magnetically Coupled Ball Drive Prototype

Once built, the spherical wheel was tested statically. From these tests, it has been shown that magnetically coupled spherical wheel built in Figure 5-3, is a viable option for holonomic locomotion. It is now senior design 2019-2020 and the task is to further redesign the magnetically coupled ball drive to be cheaper, easier to manufacture, and tested dynamically.

Looking Ahead

Depending on what concept is selected for the design, there will be a wide range of calculations which will be performed in order to fully understand the functionality of the vehicle. Some general calculations which will be necessary for all of the concepts is analyzing whether or not there is a high enough coupling force between the sphere and the vehicle structure provided by the magnet. The more coupling force between the sphere and the omni-wheels or omni-chain would allow for a higher torque transmission to the driven sphere. Another general set of calculations which will be analyzed is the coefficient of friction between the omni-wheels or omni-chain and the sphere which is being driven, and the coefficient of friction between the sphere and whatever surface it is being driven on. Understanding coefficients of friction add a critical level of insight into how efficient the device is operating and where it can be improved by simply changing materials. Additionally, calculations on impact loads from overcoming obstacles will be determined since it will be designed to go over small bumps in some cases with a rigid sphere.

There are four concepts which were selected from the concept selection matrix which will be analyzed more closely using specific governing equations.

The omni-wheel (Figure 4-1, OW), and omnichain (Figure 4-1, OC) with external rigid sphere and applied spray rubber (Figure 4-2, RIGI) and internal full sphere (Figure 4-3, SP) (Figure 4-4, Concept A, and Figure 4-4, Concept C, respectively) are the first concepts of concern in terms of deciding what the governing equations will be. In addition to the previously mentioned physics, there are several more properties of the two concepts which will determine how efficiently it may operate. For example, the OW design will have a larger focus on the coupling force of the magnet while the OC design will be more concerned with contact of the entire patch of the chain, considering it will have a more distributed load across the sphere. Larger torques can be created between the OC and the sphere without slipping which is something that will be analyzed further through experimentation assuming the entire chain is in contact with the sphere. The internal sphere, (SP) will also be of concern since it is rigid and will be subject to random loading as obstacles are met. Several impulse forces at different speeds will be calculated when the material is selected for the sphere to ensure it is capable of overcoming them without any deformation or cracking. Furthermore, the moment of inertia of the SP will have to be analyzed since, in the pursuit of durability, it may require the addition of extra mass in order to meet a specific factor of safety. The moment of inertia of the sphere will make it more difficult to be driven by the omni-wheels and will be a concern depending on the torque inputs which can be achieved without slipping. Lastly, the spray on rubber may or may not be a reliable method depending on how much it wears off during use which is one of the largest concerns for the material. Aside from the ability to stay adhered to the sphere, it would also need to be experimented on in order to ensure maximum frictional coefficient with the OW, OC and the driving surface.

The next two concepts which were chosen had the OW and OC components, with a flexible material sphere (Figure 4-2, FLEX) exterior, and a top/bottom hybrid inner shell (Figure 4-3, TB). The TB was proposed to be combined with a gas damper system which would dissipate the specified load of the vehicle for different impulses. The normal force of the entire body onto the ground would have to be analyzed since less mass would mean a decreased maximum force transmission on the ground. Despite the lower transmitted forces, the inertial load of the spheres would be lower which could be a more optimal tradeoff than having a full rigid sphere. One unique analysis from the other concepts would be seeing how the gas damper would react to impulses and whether or not it would be able to absorb and dissipate energy better than the rigid sphere. The OW, and OC analysis of normal force analysis would remain the same in this case but a different FLEX material could be selected which could be thicker and have a higher friction coefficient with the other components which would make it more beneficial than the concepts with the spray-on rubber.

VI. Project Plan

Deliverables

As per the Gantt Chart (Figure A-2), the next step is to perform an in-depth technical analysis of the selected concept in order to make a working prototype. By the end of the project the MCBD team expects to have a working prototype of the generated concept.

Up until now, the beginning steps in the design process were completed to lead up to the concept generation phase and the early stages of performing a technical analysis. A comprehensive list of tasks was listed in the Gantt chart in order to keep the team on schedule for the first phase of the project. The building blocks which led to the concept generation include critical steps such as the project motivation and goals. Previous years' work on other ball drive prototypes were taken into account in addition to further research to create a state-of-the-art review. The major issues with the current prototype were also identified in order to solidify the immediate problems to tackle and ways to possibly benefit the customer. This allowed for an analysis of the customer's needs. Research was done on existing concepts, and needs and specifications were decided and a technical analysis was conducted.

The goal by the end of the project is to create a prototype of the concept which will be decided on based on which has the highest score on the concept selection matrix. Along with creating a prototype, an experimental test plan is intended to be made for the collection of data on the performance of the omnidirectional vehicle. The test plan would be comprehensive as it would include objectives to climb certain slopes, overcome obstacles, and remain dynamically stable when moving or static in specific environments. In addition to the ability for the vehicle to be able to move in dynamic environments, it would also be expected to carry heavy loads for several reasons. Some of the best uses of a holonomic driving vehicle could be in aiding wheelchair-bound individuals who are reliant upon tank-driven methods to move around on a daily basis. Another reason the goal to carry heavy loads was created was so that it would be able to be used in a factory setting since forklifts and factory devices are also bound by tank-driven motion.

Budget

Table 6-1: Current estimated budget allocation

Component	Price	Quality	Total
Gas Spring (500 lb)	$ 100.00	1	$ 100.00
Spray on Rubber	$ 12.98	1	$ 12.98
Nitrile Rubber Material (0.0625" x 36" x 72")	$ 26.25	1	$ 26.25
Ball Bearings	$ 4.00	10	$ 40.00
Continuous Track	$ 179.00	1	$ 179.00
		TOTAL	**$ 358.23**

VII. Conclusions

The MCBD project is primarily tasked with improving the ball drive to the extent of creating a device that is capable of holonomic motion of driven spheres. The project is a continuation of previous years' work which was primarily focused on tasks such as efficient spherical wheel configuration and omni-wheel driven devices. After the experimentation of previous individuals and senior design teams, it was concluded that the best way to couple the holonomic vehicle to the load it was carrying is through a magnetic coupling that will eliminate the need for exterior ball transfers that can build up debris from the ground over time and steadily decrease driving efficiency. The goals of the project are to first develop a satisfactory and feasible concept while considering the manufacturability of the concept and assess its specifications. Secondly, developing the prototype, third, developing a test plan, and fourth, physically testing the prototype against the test plan are the last steps in the list of goals set out in the project plan. There are several issues concerned with designing the prototype around the specifications created which include ability to withstand long durations of loads, acceleration of the prototype, efficiency of the omni-wheels, orientation of the driven spheres, and coefficients of friction of the entire driving system since it is a friction driven device. Along with the physical parameters, there are challenges in producing a product which can be designed for manufacturability since the parts are very specific and likely cannot be found “off the shelf”, and testing will have to be nondestructive so the sphere should not be driven to the point of plastic deformation.

In reviewing what similar technology exists there were several patents which include an Omni-wheel spherical drive system (Figure 2-1), electromagnetically driven spherical wheel (Figure 2-2), electromagnetic spherical ball drive (Figure 2-3), and a chain drive system (Figure 2-5). The state of the art technology review provided the basis for several concepts which were considered and input into the concept selection matrix to be combined for a design that would fit the specified functionality of a MCBD. Along with researching specific technology different commercial applications were conceived as it appeared that a holonomic vehicle has yet to be implemented in any environment. The commercial applications for the MCBD were determined to be for a factory floor or an electric wheelchair.

Holonomic motion can be used to enhance virtually any type of vehicle from cars to telepresence robots and the MCBD can theoretically be applied to any of these cases. Holonomic motion can turn parallel parking into a one step process from a process that usually takes several steps depending on the driver, and can minimize the turns a wheelchair bound individual must make for basic motion in everyday activities. As long as the ball drives are efficient enough to transport loads at minimal torques with optimized accelerations, any customer would be satisfied. The MCBD is being designed to carry the load of an individual because if the concept is supported and it functions properly, it can very well be scaled to support larger loads. The customer voice table contains what a how a wheelchair bound individual would want which was then translated into specifications to design the wheelchair around.

When the customer voice was considered (Table 3-1) and the research was completed, the two components were combined in order to generate concepts for the design of the MCBD in the concept generation table (Table 4-1). Driving mechanisms, external spherical structures, and internal structures were derived from the conducted research. When all of the separate components were derived, they were combined in a concept selection matrix with specific weights designated for different traits of its operation. Concepts A, B, C, and D were all created based off of the design selection matrix and are depicted in Figure 4-4.

In analyzing the feasibility of the design, there were technical considerations which had to be made. First, previous years’ research of similar projects was analyzed to become familiar with the nature of the project. With the generation of the new design, it was decided that some technical considerations for experimentation and calculation included normal forces (since it is friction driven), driving torques, moments of inertia, and contact patches of the omni-chain.

When it comes to experimentation, the entire system will be put to the test against impulse forces, and will be analyzed to ensure cracking is not a possibility in the use of the prototype since it would render it destroyed. Another analysis which is included in experimentation with a test apparatus is gaining insight into how much the rubber of the spherical wheel wears as it is used since it would have to maintain friction for long periods of time.

The MCBD team is continuing to follow the Gantt chart (Figure A-2) to take steps into making the final prototype and test apparatus. Currently, the concepts have been generated and the latest prototype from the last senior design team was analyzed to consider any inefficiencies which may exist. The goal for the end of the project is to create a prototype with a test apparatus and a test plan. The prototype shall be able to overcome slopes and obstacles and can be tested as if it were to be used by an actual wheelchair bound person or on a factory floor.

VIII. References

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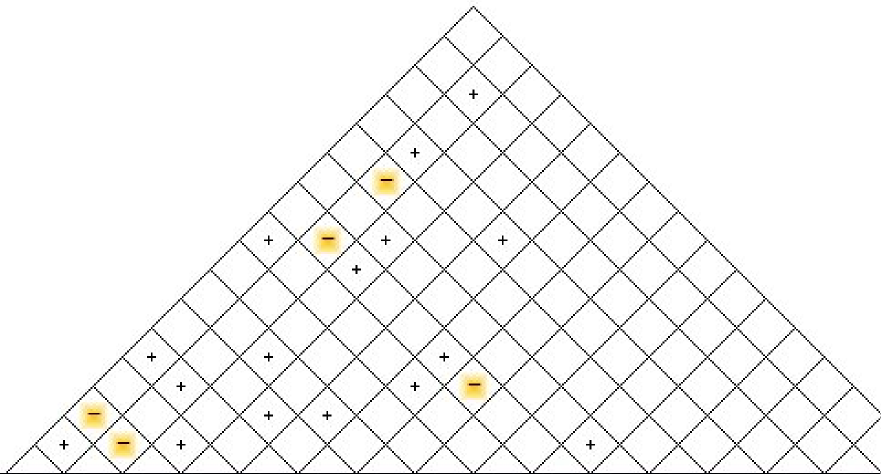
IX. Appendix

Table A-1: Customer Voice Table

Customer Statement (Voice of Consumer)	Interpreted Customer Need	Requirement	Priority
"I need the robot to be able to travel on various surfaces"	The ball drive can overcome different coefficients of friction	Surface contact, Friction coefficients	***
"I don't like when dirt gets trapped in the wheels"	The ball drive has an internal (magnetic) support structure to prevent trapped dirt	Support structure	***
"I need maximum manuverability"	The ball drive has wheels of the proper diameter and a compact platform	Spherical wheels & Driving omniwheels	**
"I prefer an affordable product"	The ball drive has been designed for manufacturability	Design for Manufacturability	*
"I would like a robot that can withstand extended use with good durability"	The ball drive was designed well and with the proper materials	Durability	**
"I want a robot that can move me quickly"	The ball drive has high torque, low slip, good controls	Torque, Control system	*
"I want it to be responsive"	The ball drive has high acceleration, high velocity, low slip, and low inertia	Control & Actuation	**
"The robot can traverse over obstacles (wires, debris, etc)	The ball has a radius large enough and the torque to overcome obstacles of X size	Torque, Radius, Surface friction	***



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Direction of Improvement	▲	▲	◇	◇	▲	▼	◇	◇	◇	◇	◇	▼	▲	◇	▲
Metrics / Customer Requirements (Explicit and Implicit)	Coefficient of Friction with Ground	Acceleration	Weight	Size	Torque	Cost	Velocity	Tire Material Properties	Internal Structure Material Properties	ISS Weight	ISS Size	ISS Coeff of Friction (Rolling Resistance)	Magnetic Coupling Force	Omni Wheel Diameter	Omni Wheel Surface Coeff of Friction
Durable								○	●						
Able to drive on different surfaces	●			●				○							
Responsive	●	●			●		●					●	▽		●
Afforadable						●			▽		▽				
Maneuverable	●	●		●				●			○		○		
Wheel surface remains free of debris	○								○						
Supports 200 pounds									●	●			○		
Minimize Decoupling													●		

Figure A-1: Quality Function Deployment (QFD) Table

Table A-2: Concept Screening Matrix

Concept Combination →	0	1	2	3	4	5
Selection Criteria	(Baseline) External Support Structure	(Initial MCBD Design) OW + BAND + SP	OW + BAND + TH	OW + RIGI + SP	OW + FLEX + TB	OW + SOCC + 3/4
Drive System Effectiveness	0	0	0	0	0	0
Durability	0	-	-	+	0	0
Performance on Multiple Surfaces	0	0	0	0	+	+
Suspension	0	-	-	-	0	-
Minimized Decoupling	0	+	+	+	+	+
Ease of Implementation	0	0	0	+	+	-
Maintenance	0	0	0	+	+	-
Cost	0	0	0	0	0	0
Pluses	0	1	1	4	4	2
Sames	8	5	5	3	4	3
Minuses	0	2	2	1	0	3
Net	0	-1	-1	3	4	-1
Rank	8	12	12	2	1	12
Continue?	No	No	No	Yes	Yes	No

Concept Combination →	6	7	8	9	10
Selection Criteria	OW + INFL + BH	MOW + RIGI + SP	MOW + FLEX + BH	OC + RIGI + SP	OC + FLEX + TB
Drive System Effectiveness	0	+	+	0	0
Durability	0	+	0	+	0
Performance on Multiple Surfaces	+	0	+	0	+
Suspension	-	-	-	-	0
Minimized Decoupling	+	+	+	+	+
Ease of Implementation	-	-	-	0	0
Maintenance	0	+	+	+	+
Cost	0	-	-	0	0
Pluses	2	4	4	3	3
Sames	4	1	1	4	5
Minuses	2	3	3	1	0
Net	0	1	1	2	3
Rank	8	5	5	4	2
Continue?	No	No	No	Yes	Yes

Concept Combination →	11	12	13	14	15
Selection Criteria	OC + SOCC + 3/4	MOC + RIGI + SP	MOC + FLEX + TB	IS + BAND + TH	IS + RIGI + SP
Drive System Effectiveness	0	+	+	+	+
Durability	0	+	0	-	+
Performance on Multiple Surfaces	+	0	+	0	0
Suspension	-	-	0	-	-
Minimized Decoupling	+	+	+	+	+
Ease of Implementation	-	-	-	-	-
Maintenance	-	0	0	0	0
Cost	0	-	-	-	-
Pluses	2	3	3	2	3
Sames	3	2	3	2	2
Minuses	3	3	2	4	3
Net	-1	0	1	-2	0
Rank	12	8	5	16	8
Continue?	No	No	No	No	No

Table A-3: Concept Selection Matrix

		0		A		B		C		D	
		(Baseline) External Support Structure		OW + RIGI + SP		OW + FLEX + TB		OC + RIGI + SP		OC + FLEX + TB	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Drive System Effectiveness	20%	3	0.6	3	0.6	3	0.6	5	1	5	1
Durability	15%	2	0.3	3	0.45	2	0.3	3	0.45	2	0.3
Performance on Multiple Surfaces	20%	2	0.4	2	0.4	3	0.6	2	0.4	3	0.6
Suspension	5%	3	0.15	0	0	1	0.05	0	0	1	0.05
Minimized Decoupling	15%	2	0.3	4	0.6	4	0.6	4	0.6	4	0.6
Ease of Implementation	10%	2	0.2	3	0.3	3	0.3	3	0.3	3	0.3
Maintenance	10%	3	0.3	4	0.4	4	0.4	4	0.4	4	0.4
Cost	5%	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15
#REF!			0		0		0		0		0
#REF!			0		0		0		0		0
Total Score		2.40		2.90		3.00		3.30		3.40	
Rank		5		4		3		2		1	
Continue?		No		No		No		No		Yes	

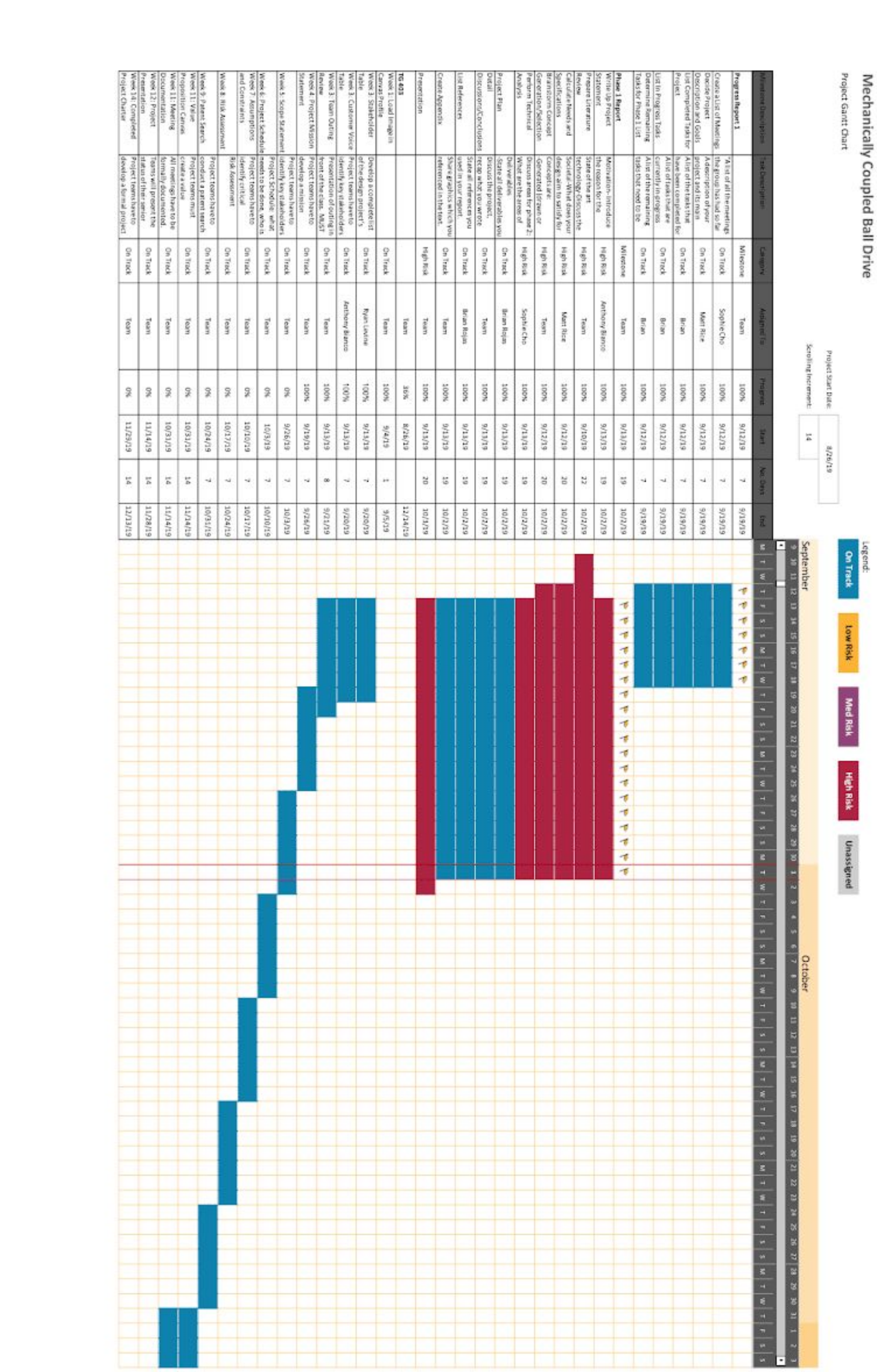


Figure A-2: Gantt Chart