The RoboScooter
a New Personal Mobility System

by

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Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

Master of Science in Media Arts and Sciences

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2010

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Abstract

RoboScooter is the result of the design workshop "Concept Scooter Project with Sang Yang Motors." During the design workshop held in 2007, I proposed an electric folding scooter. There are two main features of this scooter, folding and fully electric. These two features are designed to solve two critique urban problems, congestion and pollution.

Based on the MIT Smart Cities research group's Robot Wheel technology, I built two 2-wheeler prototypes. The project was divided into two different phases. Phase one was focused on figuring out a correct folding architecture, the folding mechanisms and the implementation of working scooter-size Robot Wheels. Phase one was completed on April 29th 2008 with an official press conference held in Taipei, Taiwan to announce the RoboScooter.The second phase was focused on improving the next generation of the scooter structure and folding mechanism. The RoboScooter "G2" was completed in spring 2009.

Designing the RoboScooter is an interesting story because of the conflicting factors such as the total weight, the load, different forces such as torque and bending forces to the chassis of the scooter. These numbers and the results can be simulated by using Finite Element Analysis (FEA) combining scooter manufacturer's experience. In the scooter industry, majority of the analysis requires experiences from dynamic structure experts. This is also how the initial drawing was created. I will clearly describe the design process and the rationale behind it later in the thesis.

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Acknowledgements

Mom, Dad, Gary, Becky, Wan-Ching Chang, Ryan Chin, Henry Chiu, Jeannie Finks, Eugene Hsiao, Wen-Jean Hsueh, Linden Huang, Hiroshi Ishii, Ana F. Martinez-Villalpando, William J. Mitchell, Raul-David "Retro" Poblano, Olette Trouve-Slate, Barry Vercoe, Grand Wu, Cynthis Wilkes, Allison Yiu

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Chapter 1

Introduction

1.1 Cities and Transportation

Ever since the invention of automobiles in the late 20th century, urban design has been greatly influenced by these moving objects; according to a Depart of Transportation study, up to 2006 there are 250,851,833 registered passenger vehicles in the United States. The growth of the automobiles inevitably leads to greater problems of environmental and urban natures. The numbers of vehicles are increasing rapidly, and urbanization becomes an unstoppable trend. Urban densities such as population and residential density are considered as important factors of understanding how a city works and where the demands are generated. Transportation planning strategies are based on satisfying all these different demands. Logistical networks such as streets and transportation hubs play an important role in dealing with these problems. These networks not only defined the efficiencies of the whole system but also shape the form of the city.

1.1.1 City Forms

How do we get around inside the city from one location to another and how do we perceive and understand how a city works? As American planner Kevin A. Lynch pointed out, we perceive and understand our physical surrounding in a consistent and predictable way and formed a mental map. This mental map is the mental representation of the city break down into the following five elements:

Paths: Paths are street systems that include sidewalks, railroad trails and canals where people move along in their travel.

Edges: Edges are usually the physical boundaries of a city, such as the shorelines, walls, highways, or any other road systems which clearly identify and differentiate the transportation patterns, buildings, or functions.
Districts: Districts are larger sections of a city which have an identifying character, for example, commercial districts, residential districts, and industrial districts.
Notes: Nodes are critical points in a city, such as traffic intersections, and church squares.
Landmarks: Landmarks are the monumental objects such as statues, buildings, mountains, rivers and nodes with significant meanings that aid the orientation of way finding.

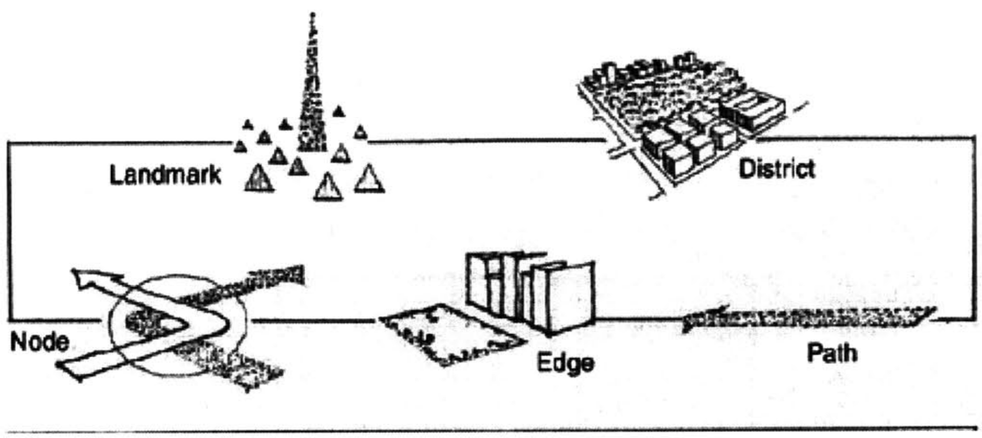


Fig. 1.2, Five Key Elements of Urban Form (Lynch, 1959, pp.47-48)

These five elements form the core concept of Lynch's study of place legibility and have greatly influenced modern urbanism and city planning. They are also the key factors in forming and deciding the characteristics of a city. Interestingly, three out of five elements are closely related to transportation.

1.1.2 Transportation

Fig. 1.3, I-80 Eastshore Freeway, May 14, 2005; image credit: Minesweeper

Since the Industrial Revolution in the late 18th century, urbanization has become widespread around the world, creating major metropolitan areas. This trend started in Europe – in London, Paris, Berlin – and then spread to other parts of the world such as New York and Tokyo. The movement resulted in the huge migration of people from rural to urban areas, and this urbanization movement continues up to this day. According to the UN's world population estimates report in 2008, half of the global population now lives in urban areas. Because of this urban densification, transportation has become a very important aspect in urban planning. Transportation and building operations typically account for at least 60% of the urban energy use. These numbers will just keep increasing as long as urbanization and densification continues around the world.

The improvement of automobiles and transportation infrastructure are the key factors that enabled this urbanization movement. Moving from one place to another has become easier than before. Transportation is characterized by three major components. First, there are the vehicles that move around the city. Second, infrastructures exist to satisfy the fundamental requirements of movement, e.g., pavement, roads, sidewalks, bridges and traffic control systems such as traffic lights. The last characteristic are the services which refer to the operation of different modes of transportation such as buses, trains and taxis.

Transportation acts as a cutting force through urban design master plan. It could be a *path* where people need for moving from one place to another, it could become the *edge* of certain *districts*. It also creates *nodes* in between landmarks or become the *landmarks*.

1.1.3 Vehicles

Different types of vehicles serve different purpose. Trucks are apparent for moving heavy or large objects. Buses move quantities of people around the city from one designated place to another on a specific predefined route. Most automobiles are designed to fit four people do not have to follow a specific route and can be move freely inside the city. Other smaller scale vehicles such as motorcycles, scooters and bicycles can move even more freely because of their size. With a variety of different vehicles found in an urban area, public and private mobility options often satisfy the complex needs of today's consumer.

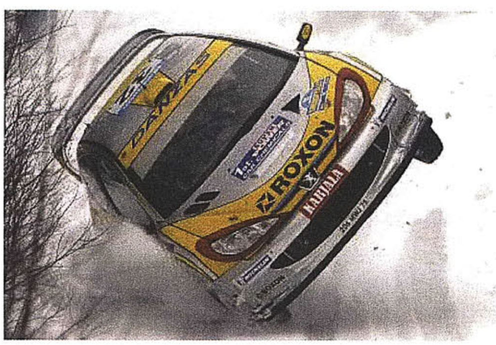


Fig. 1.4, Peugeot 206 WRC racing in harsh climates

1.1.4 Infrastructure

To support transportation demands, urban transportation infrastructure is comprised of three key components. The first component are the fixed permanent foundations including sidewalks, roads, bridges and highway systems. These elements provide the basic and permanent foundations for vehicles to move around. Physical installations such as street lights, traffic lights, and the basic control elements further characterize the urban landscape. These elements are often the reflection of local municipal control strategies. Lastly, the transportation nodes such as bus stops, subway entrances, train stations, and ports influence traffic patterns and are mutually dependent.

Fig. 1.5, Sun Yat-sen Freeway near Wugu interchange, Taipei, Taiwan, image credit: Jiang

1.1.5 Services

Transportation services refer to the operational side of the transportation system. They could be operated by either a public or private entity. These entities usually own the vehicles that provide these transportation services. Some examples of public transportation services are railroad trains, subway systems and bus systems. However, due to changing economies, some traditionally public transportation systems are now operated by private companies. Note that airports are exceptions, due to the national security issues; airports are usually operated by the government.

Smaller scale transportation services such as taxis and sometimes buses are examples of transportation services that are run by private entities. Usually, bus services have a predefined traffic model. Bus companies place transportation nodes or hubs inside the city and the buses make constant stops at the nodes. These nodes play a very important role in the urban transportation system. Taxi service is more of a personal mobility system. Passengers are able to hire a taxi anywhere in the city. Taxis do not have predefined nodes and they do not require specific locations for pick up or drop off. Due to the flexibility, taxi service has the highest utilization rate as passengers are able to get around so easily inside the city. The transportation service industry over the last five year has seen a successful adoption of self-service vehicle sharing systems. The Zipcar company founded in 2000 allocates a network of parking spaces for Zipcars within a given service area. People register online and receive an access key after the online registration is approved. Whenever they need a rental car, they can then make their reservations online and go to the Zipcar service point located in a dedicated parking space nearby to pick up the vehicle. The car is returned to the same parking space at the end of the agreed rental period. The Zipcar company usually rents one or two parking spaces from private and public entities in prominent parking facilities throughout the city. This strategy allows a wider range of selection for pickup points. However, it is still a one-way system. Ideally, a two-way rental system requires as many locations as possible for increasing the accessibility of the vehicle.

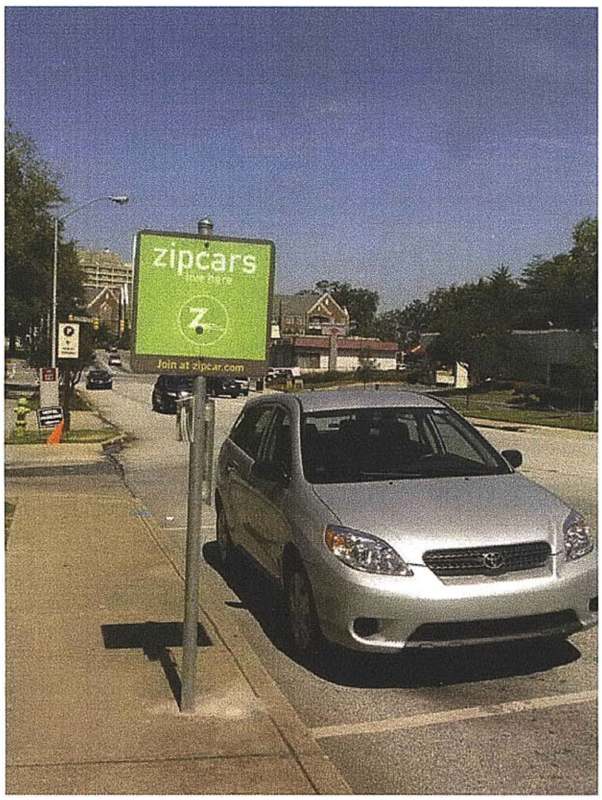


Fig. 1.6, a Zipcar parked in a dedicated parking spot, Decatur, GA; image credit: Penny White

1.2 Energy Efficiency

In the 21st century, about 90% of the world population growth will be within urban areas; these urban population growth account for 60% of the world population and 80% of the wealth. Hence, the pattern of future energy demand will be increasingly determined by urban networks.

With the rising awareness of global warming and the reality that a large portion of urban energy use is devoted to transportation and buildings, energy consumption has become one of the most important and urgent issues of current society.
The oil crisis in 1973 brought about a widespread energy panic to the world. Physicist Amory Loyins brought up the idea of "soft energy path" that highlights energy efficiency. The central idea of his concept, "Negawatts," is that instead of meeting the energy demand by increasing energy production, large amounts of power can be generated without building any new power plants or buying any fuel for existing plants, simply by increasing energy efficiency.

What is the energy efficiency of the internal combustion engine currently found in vehicles? Due to the 37% thermodynamic limits in traditional steel engines, the average efficiency of traditional engine is about 18%-20%. Given that these vehicles are the major consumers of gasoline, an alternative power source should be introduced in order to gain energy efficiency. Fig. 1.8, in the next page indicates that the electric motors have over 90% efficiency rate at the speed of 3200rpm to 7200rpm, resulting in a very high speed rotation and high torque output. Hence, it has become a good choice in alternative power source for vehicles.

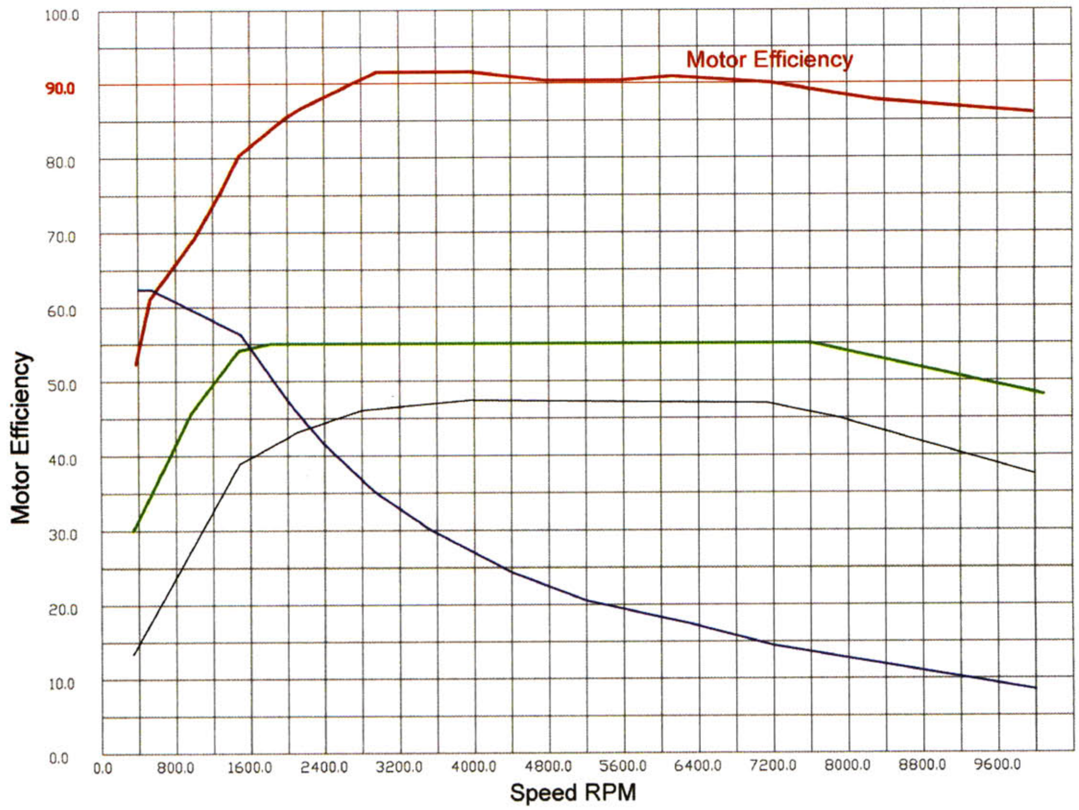


Fig. 1.8, MES 200-250 motor efficiency provided by Metric Mind Corporation

Battery technology is another essential part in both electric vehicle designs and energy efficiency. There have been many improvements in the battery technologies over the past ten years. Fig. 1.9 shows the comparison of different battery technology. Batteries have become lighter, smaller and more efficient in charging and discharging. We now have a smaller battery cell that contains a higher discharge rate. Take the famous A123 System's lithium iron nanophosphate battery cells for example. Its discharge rate can go all the way up to 80 amps and performs a turbo charging solution. The discharge rate of a normal lithium-iron cell is only 15 amps and the charging time is roughly 2-4 hours.

The capacity of a battery pack and battery charging time are two important issues for both vehicle design as well as urban design. Issues to be considered include, "What is the ideal traveling range for an electric vehicle?" and, "Is it the vehicle manufacturers or the battery providers that get to make these decisions?" This thesis sets out to demonstrate that this decision can be made by neither of them, and those solutions and answers to this issue are embedded within the urban design and transportation strategy.

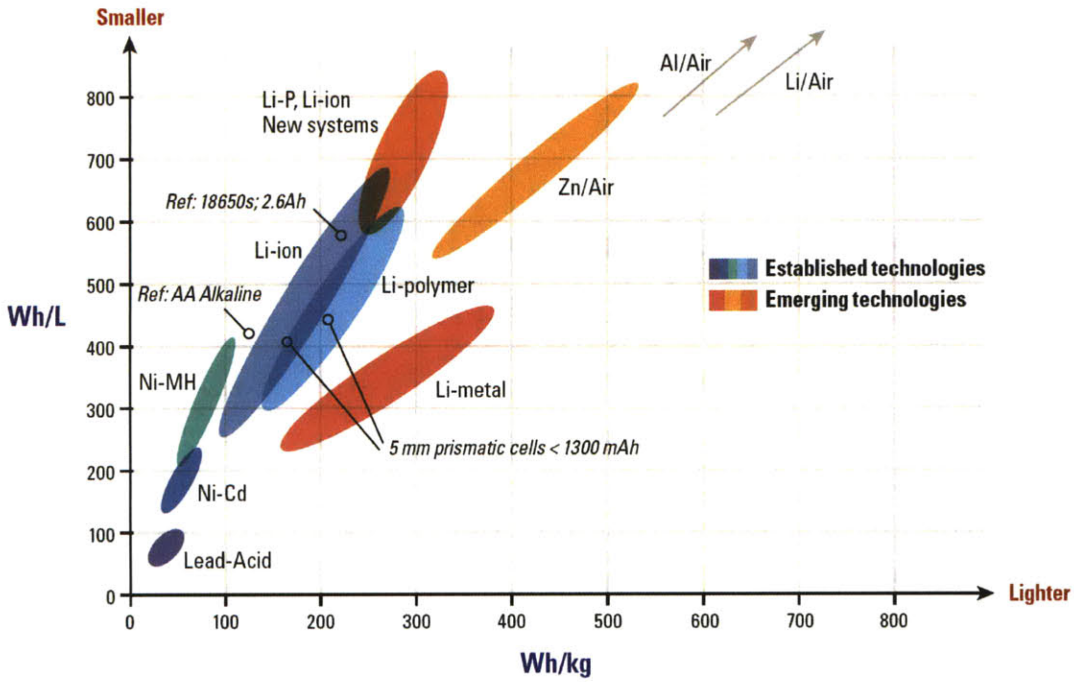


Fig. 1.9, energy density comparison of different battery technology (http://www.nexergy.com/battery-density.htm)

Chapter 2

the Rise of Personal Mobility

2.1 Mobility and Car Sharing

Mobility as a term used in logistics usually refers to shipping, trucking, aviation, vehicle, and any transportation-related states. Most cities around the world currently face three major transportation problems with the foremost problem being the traffic capacity overflow, meaning too many automobiles. According to the US Bureau of Transit Statistics in 2006, there are over 250 million registered passenger vehicles in the US. With this many vehicles on the roads, traffic congestion is unforeseeable. The second problem is that the density and coverage of public transportation system is not enough, which leads to the third problem, "the first and last 5 miles" problem.

In order to address these problems, many alternative mobility models had been invented and developed. The most successful model is the rental car share program, such as the Ucar Share program in Salt Lake City, Utah, and the previously mentioned Zipcar program that was started in Cambridge, Massachusetts. Naturally, the main idea of sharing cars is to maximize the utility of each vehicle and reduce the number of vehicles operating on the streets.

Fig. 2.1, MIT Media Lab Smart Cities research group's ideal Mobility-On-Demand system (Michael Chia-Liang Lin, Will Lark Jr.)

2.2 Vehicle Sharing

There are one-way rental systems and two-way rental systems, with most falling into the latter category. The fundamental difference between these two business models is that in a one-way rental system, users pick up vehicles at one location and drop off the rental vehicle at a different location; whereas in a two-way rental system, users pick up and drop off their rental vehicles at the same location.

2.2.1 Two-Way Sharing System

How common is the two-way sharing system being used in the car rental business? Well-known car rental companies like Hertz, Enterprise, and Budget are all functioning with this model. In order to be accessible to users, these companies usually set up branches near different nodes such as train stations, airports, or sometimes at shopping malls and in the city center. As explained, the nature of this system is to pick up and drop off vehicles at the same location, which logically and traditionally works better and easier for both the customers and the service providers. Users can choose to drop off the rental vehicle in a separate location by paying an additional fee, but the nature of this rental system is that the pick up locations and the drop-off location are the same. Two-way systems primarily serve people who already own a car, but either lack access to their vehicle or the vehicle does not meet a specific requirement, e.g., travelers who are from out of town or people who need a truck to move big objects.

2.2.2 One-Way Sharing Mobility-On-Demand System.

In comparison, the one-way sharing is a newly developed vehicle sharing system which is actually a result of improvements in the Global Position System (GPS), vehicle tracking and internet technologies. The concept of this system is to have the users pick up their vehicles at one place and drop them off at a different place. To increase the accessibility and to facilitate the demands of their customers, service providers need to allocate as many service points in the city as possible, so that users can have more selection for car pick up and drop off locations. Studies have shown that more and more cities are adopting this system in the last four years.

The bicycle sharing program is a good example of a one-way sharing Mobility-on-Demand system that serves city residents with a means to connect to other modes of transportation or for small-range daily trips. This system can either be operated by non-profit organizations, local communities, or implemented by municipalities or through public and private partnerships like the world-famous Paris bicycle sharing project, Velib.

Bicycle sharing programs are rapidly spreading around the world. By the end of 2009, more than eighty cities will be providing this service. Thirty thousand bicycles are rented each day in Paris. Velib introduced a successful example of urban vehicle sharing program that has also inspired New York City, Boston, and San Francisco to think about different solutions to the growing concerns of traffic congestion.

Fig. 2.2, Photo of the Paris bicycle sharing program, Velib (Andres Sevtsuk)

Sharing systems like Zipcar are also speedily expanding. Zipcar owns 5000 cars in the US, with up to 10% adoption rates in cities and over 600 cities world-wide will have Zipcars running on the streets in the near future.

Chapter 3

In-Wheel Power Modules

The principle of this new personal mobility design is to develop an extremely light weight and energy efficient vehicle. Weight is crucial when it comes to vehicle design; the more a vehicle weighs, the more energy is needed. A way to reduce weight of a traditional vehicle is to simplify its mechanical parts. Before we talk about the In-Wheel Power Modules, we need to figure out what are the possible components that can be integrated into the wheels.

3.1 Basic Components

Rim and Tire

A wheel is a circular shape structure which rotates on an axis; it facilitates the movement of the vehicle and consists of a rim structure and tire, which helps to absorb the shock and vibrations coming from the ground.

The wheel is driven by a power source such as an engine or a motor. This power source is usually located on the chassis of the vehicle away from the wheels; the energy is transformed through a transmission mechanism. The key concept of the Robot Wheels is to integrate the power source and transmission mechanism into the wheel so that the wheel becomes a power unit.

Brakes

Due to safety concerns and the need to slow down and stop the vehicle, motorized wheels are equipped with a braking system. There are two types of breaking systems: First, the drum breaking system. See Fig. 3.1.1, the rear brake assembly of a 10 in drum brake component. The drum brake is actuated by two arch-shape braking pads, the leading shoe and the trailing shoe located inside the rim hub along the inner hub wall. When the brake is actuated, these pads will press against the inner surface of the hub, providing friction to the inner wall which then stops or slows down the rotation of the tire. The drum braking system usually requires a big portion of the hub to host the mechanism.

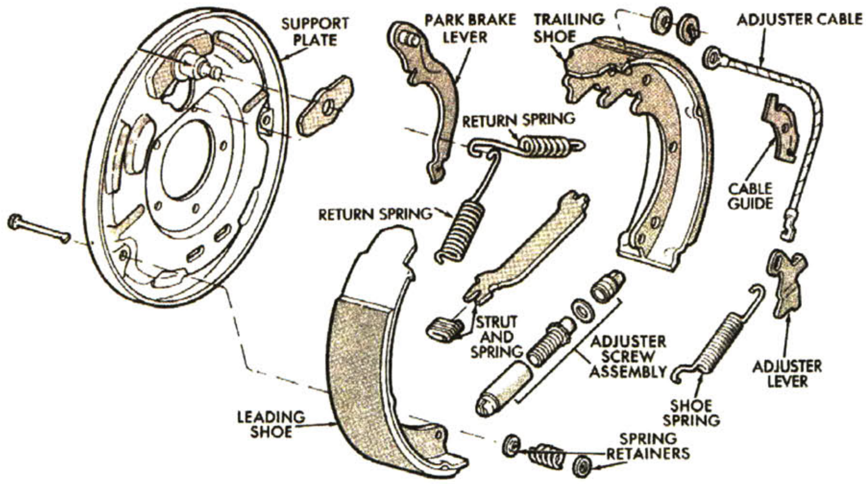


Fig. 3.1.1, rear brake assembly of the 10-inch drum brake components-MJ metric ton

The disk brake is another common braking system. It is also a friction system, but instead of providing the friction to the hub casing, it provides friction to a disk-shaped breaking plate that is attached to the side of the hub. Fig. 3.1.2 shows the photo of a Renault hollowed-out car disk braking system. The red caliper is where the breaking plates are located. This system requires less additional space inside the hub. It is a better solution for the scooter because of minimal space requirements for the system's installation.

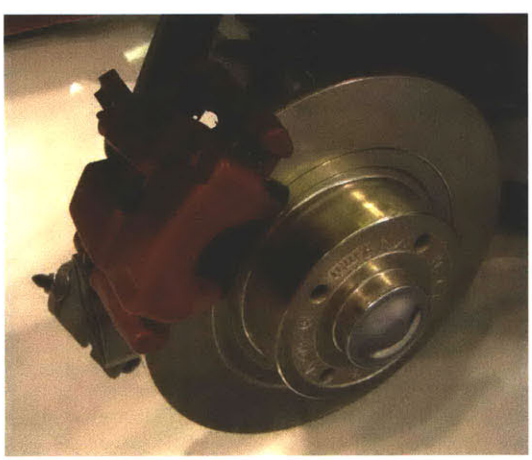


Fig. 3.1.2, a hollowed-out Renault's disk breaking system at the Salon Européen de la Recherche et de l'Innovation, June 5, 2005; image credit: David Monniaux

Suspension

The suspension system reduces the shocks and vibrations coming from the ground surface and provides a better driving experience and better vehicle performance. A suspension system has a spring, a shock absorber and linkages that control the suspension movement. Fig. 3.1.3 shows a coil spring suspension system. The system uses two A-shaped structures as the suspension linkage which supports the wheel spindle on one end and connects to the vehicle chassis on the other end. This is a parallelogram system which allows the wheel to move up and down vertically. The spring damper is located in the middle of the structure connects the bottom A-shaped arm and the chassis which absorb the vibrations from the ground.

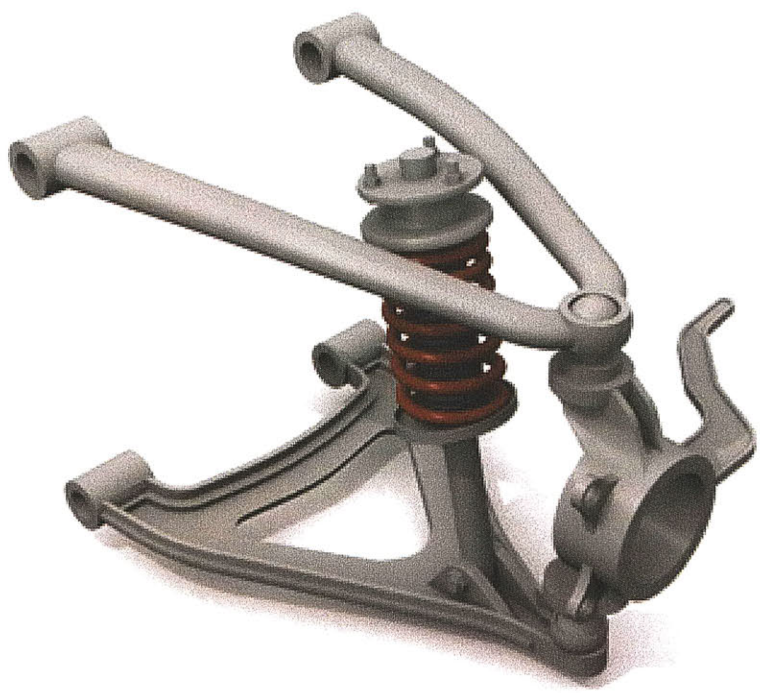


Fig. 3.1.3, coil spring suspension system (http://www.carbibles.com/suspension_bible.html)

Transmission

An internal combustion engine typically operates over a range of 600 to about 7000 revolutions per minutes while the car wheel rotates between 0 to 1800 revolutions per minutes. A transmission is the device between the engine and wheel which reduces the speed from a higher speed engine output into a slower but yet, more powerful output. It is also called the speed reduction mechanism or a gear reduction mechanism. There is also a multi-ration system in which the gear ration can be changed by engaging and disengaging different gears sets for different ratios. Fig. 3.1.4 shows a tractor transmission with 16 forward and 8 backward gears.

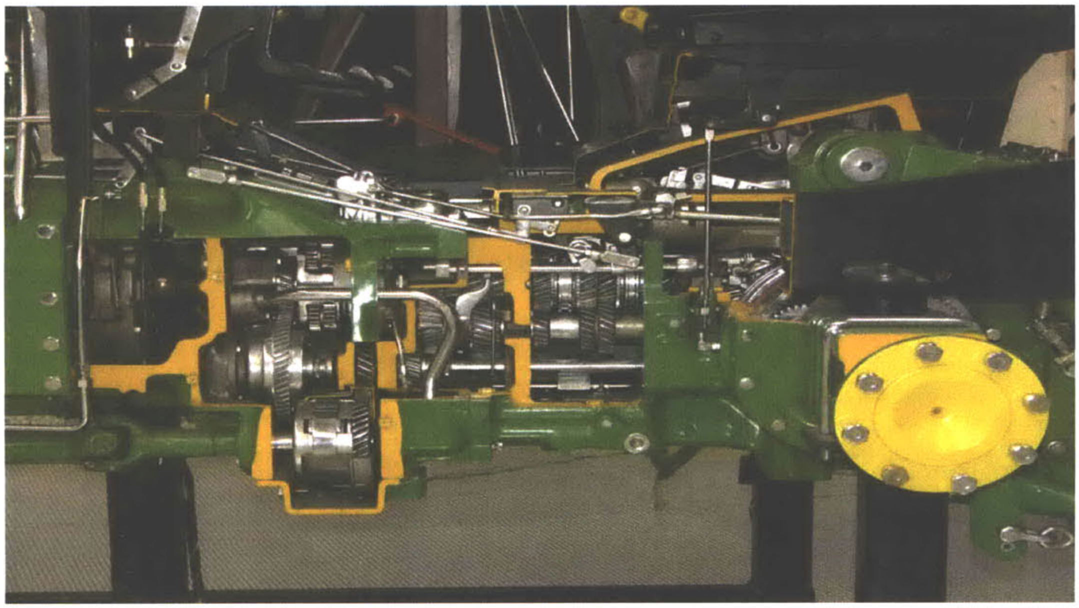


Fig. 3.1.4, John Deere 3350 tractor transmission cutout from Technik museum exhibit in Speyer, Germany; image credit: Kozuch

3.2 Hub Motors

Traditional engines are heavy and large in size, so our first attempt is to get rid of an internal combustion engine and replace it with a higher efficiency power source, an electric motor. Electric motors are relatively lighter and smaller. We also need to make changes to lighten other bulky fundamental components including the transmission and the suspension, and reinvent revolutionary new wheels that can integrate different components to make it as compact and as light as possible.

Current electric motor technology is very well developed, different power output, sizes, and control strategies for different applications and at very high efficiency. Motor diameters can be as small as 10mm to as large as one meter or even bigger, depending on its required power output. Motor-related applications are integrated in our daily experiences. Automatic car windows require a motor to lift up the glass; windshield wipers and industrial robot arms are actuated by motors, and of course, the hub motor that is designed specifically for in-wheel direct drive mechanism.

The hub motor is a specific kind of motor, the most common one for vehicle applications are DC motors. Fig. 3.2.1 shows a hub motor placed in the center of the wheel and the wheel is direct drive by the motor. The basic architecture of the hub motor is a stator attached to the front cap with windings, and a casing with permanent magnet attached to the inside worked as a rotor. The casing will start rotating on the axis of the motor when the electric current in the stator starts generating magnetic fields; the casing will rotate when the phase of the magnetic fields switched.

The hub motor is also known as the torque motor. It provides higher torque but the speed of rotation is smaller than normal motors. This is particularly good for a direct-drive mechanism in which the motor is directly attached to the rim and the wheel spines in the same speed as the motor output. This mechanism needs a relatively high torque at very low speeds, but provide the most efficiency. Therefore the hub motor is widely used as a direct drive mechanism.

Fig. 3.2.1, hub motor that is used on an electric bicycle

There are plenty of different hub motor designs. However, transforming the rotor into the casing which drives the wheel directly is the most common design. Some hub motors use a reduction mechanism embedded inside the hub casing. This reduction mechanism could be done through a planetary gearbox attached to the motor front cap or simple gearing reductions.

The advantages of having the hub motor directly driving the wheel includes reduce the mechanical complexity which leads to reduce the overall weight. Nevertheless, this is also the disadvantage because the motor has become part of the unsprung mass, which means that the weight of the motor is no longer being supported by the suspension system; impacts from driving on bumpy surface streets now go directly to the motor through the rim. Although pneumatic tires do provide a certain level of spring, heavier unsprung mass can still cause a massive load to the wheels and damage the hub motor. Therefore, the design of the Robot Wheel will be addressed to fix this issue.

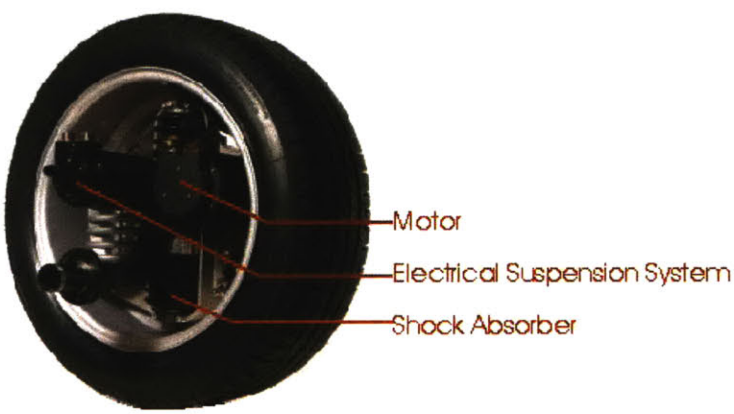


Fig. 3.2.2, Michelin Active Wheel with motor and electrical suspension system, image credit: Michelin Corporate

3.3 Robot Wheel

One of the core ideas of the Robot Wheel technology was to reduce the unsprung mass, turn a motor into a sprung mass. Rather than attaching the motor to the wheels, the motor of the Robot Wheels are attached to the vehicle chassis with an independent suspension system which carries the motor as part of the sprung mass.

Another concept of the Robot Wheel is to put as many vehicle components within the rim space as possible. Combinations of the components inside the wheels may vary to provide different solutions to meet different needs for different vehicles.

From 2004 to present, the MIT Media Lab's Smart Cities research group developed a number of different Robot Wheels by incorporating a variety of components and configurations. Take the suspension design on the two different prototypes done by MIT Smart Cities research group for example. The picture on the left of fig. 3.3.1 is the design of the Robot Wheel by Patrik Kunzler. It utilized two vertical shock absorbers as suspension mechanism while the design on the right used a swing arm suspension system.

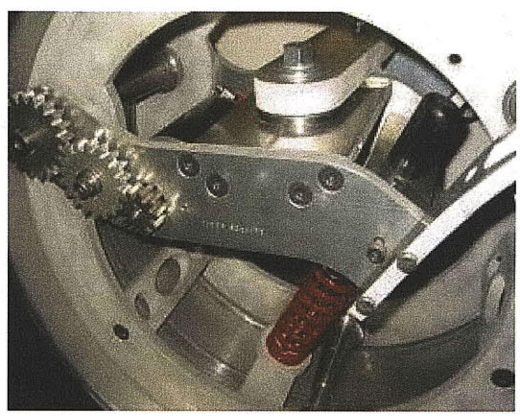


Fig. 3.3.1, MIT Media Lab Smart Cities research group's Robot Wheel modules, designed by Patrik Kunzler (left) and Peter Schmidt (right)

The two pictures in fig. 3.3.2 are designs of Robot Wheels in a four-wheeler configuration. Note that the additional connection between the Robot Wheel and the vehicle chassis. This mechanism serves as a steering mechanism. There are other different steering mechanism designs in the past two years at the MIT Media Lab Smart Cities research group. Some are done through linkages while others used a servo motor and an encoder to for positioning the wheels.

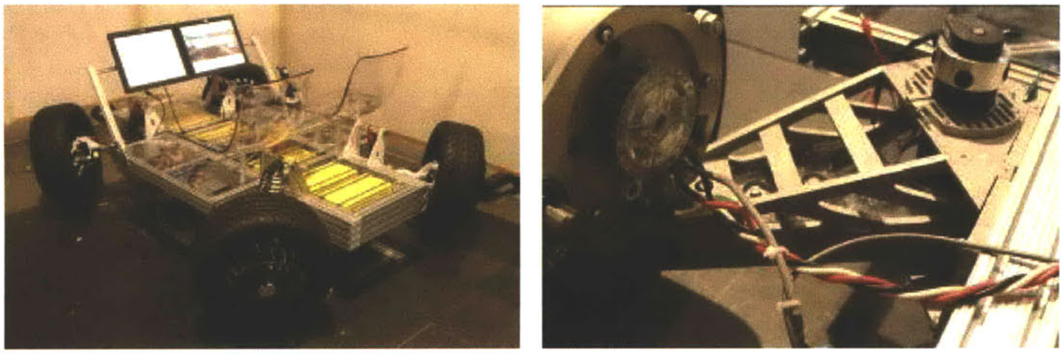


Fig. 3.3.2, Four-wheeler Robot Wheel designs by MIT Smart Cities group members, Will Lark and Raul-David Poblano (Retro)

The two-wheeler module for scooters and motorcycles is slightly less complicated than a four-wheeler module because the steering mechanism for two wheelers is usually directly connected to the handle bar and the additional steering mechanism will not be needed. The design challenge for this module is the space constraint.

Chapter 4

The RoboScooter

The RoboScooter is a lightweight, folding, electric motor scooter that is clean, green, silent, and compact. It is designed to provide convenient, inexpensive mobility in urban areas while radically reducing the negative effects of extensive vehicle use – road congestion, excessive consumption of space for parking, noise pollution, air pollution, carbon emissions that exacerbate global warming, and energy use.

The unique design of the RoboScooter is the outcome of a collaboration involving SYM (Sanyang Motors), ITRI (Taiwan's Industrial Technology Research Institute), and the Smart Cities group of the MIT Media Laboratory, led by Professor William J. Mitchell.

4.1 RoboScooter Robot Wheel Design

Based on the previous MIT Smart Cities group's Robot Wheel concept, the biggest challenge for the scooter size Robot Wheel is the geometry constraint such as the width of the rim and its diameter. How can we add more components into this tiny space and how can different components work together without interference with each other? Scooter has smaller tires and smaller rims. The diameter of the rim ranges from 8 inches to 12 inches; the size of the wheel is based on human ergonomics and overall performance. There are four main components of the Robot Wheel.

Fig. 4.1 shows the RoboScooter rim. The RoboScooter uses a 12-inch rim and a 100/60-12" tire. This combination provides the maximum space inside the rim. The overall dimension of the wheel is 435mm. This dimension plays a very important role for the overall length of the RoboScooter when folded. This selection of rim and tire allows more space for different components without sacrificing the overall length. Inside this scooter rim is where all the components need to fit.

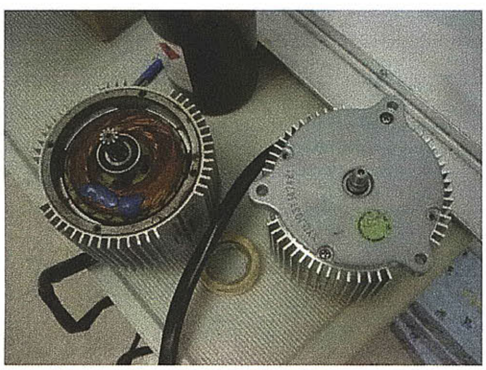
The effective diameter of a 12-inch rim is 280mm; placed inside this space will be a motor for power, a suspension system, a breaking system and a reduction system. All these systems have to work together without interfering with each other.

Fig. 4.1, RoboScooter rim, 12-inch

4.1.1 Motors

The general principle of an electric motor is that a rotating permanent magnet rotor and stationary windings (also called the stator) create electrical magnetic fields on the motor casing. The rotor with permanent magnets will start to rotate because of the changing of the magnetic fields from the windings on the stators. The DC brushless motor could be divided into two basic different types, an out-runner and in-runner.

An out-runner is a motor where the stator is inside, stable to the casing, and the magnet is rotating outside thee stators. And an in-runner has a rotating stator that rotates inside the permanent magnet. In general, for the same power output, the out-runner has a better efficiency than an in-runner. Another interesting characteristic of the out-runner brushless motor is that the temperature of the out-runner is lower than an in-runner motor. Both types of motors have been used in the RoboScooter prototype. Fig. 4.2.3 shows the Generation 1 in-runner motor on the left and Generation 2 out-runner motor on the right.



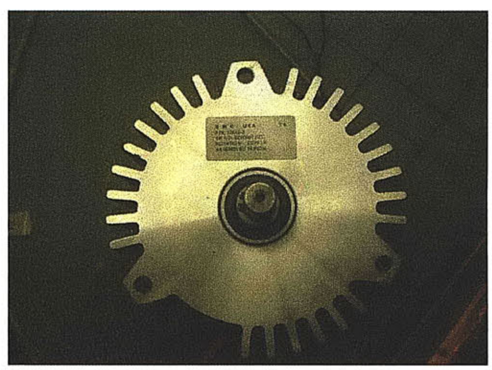


Fig. 4.1.1, RoboScooter G1 In-Runner Motor RoboScooter G2 Out-Runner Motor

If the motor is attached straight to the rim, meaning that the wheel is directly driven by the motor, then the motor needs to run at the same speed as the rim. For this to happen, a special motor called the torque motor is required. A torque motor is bigger in diameter, thin, and looks like a pancake. The area of the magnet field is in proportion to the torque output but inverse to the rotation speed. Because of this, a torque motor was not used due to limited space inside the rim. The motor chosen is smaller in diameter and wider in width than a torque motor. It does not provide a powerful torque output and runs at a fairly fast speed. A gearing mechanism can be added to reduce the speed and raise the torque output.

4.1.2 Reduction Mechanism

Reduction is necessary since electric motors tend to rotate in the 500-9000rpm range. The selected motor runs at 3200rpm and the wheel needs to spin at 520rpm, in order for the scooter to reach the speed of 30 kilometers per hour. Since there is a speed difference in the motor output and wheel speed, a reduction mechanism will be needed.

There are several different designs for speed reduction mechanisms. Fig. 4.1.2 is an example of a planetary gear box speed reduction mechanism with a motor attached to on end. The motor shaft is attached to the center sun gear, and there are three planet gears surrounding the sun gear. As the sun gears drive the planet gears, these planet gears drive the outer ring gear. Depending on where the rim is attached to the gear box and the number of teeth of the gears, this mechanism provides a one step reduction.

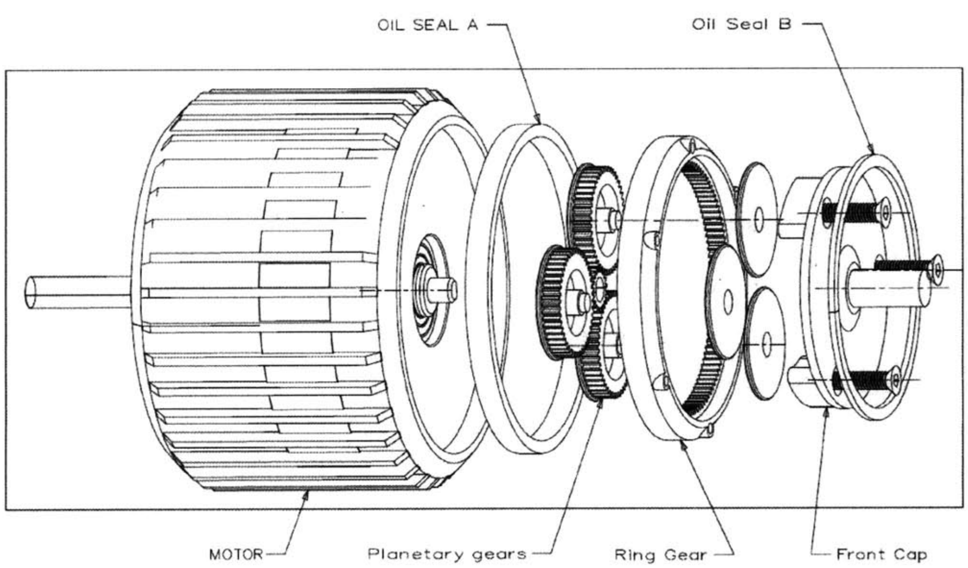


Fig 4.1.2, planetary gear speed reduction mechanism of the GreenWheel

The reduction ratio is determined based on the rotation speed of the motor and the speed of the wheel. Based on the target top speed of the RoboScooter at around 30 Km/h, calculation for the determination of the reduction ratio is as follows:

pi * (wheel diameter in inches) * (RPM) * (60min/hour) / (12 inches per foot) / (5280 feet per mile) = MPH

Since the RoboScooter uses a 12-inch rim, with a top speed of 30Km/h, 520 rpm is the required output of the gearbox. Since the motor rotates at 3200rpm, a reduction ratio of around 6:1 will be required in order to reduce the rotation down to 520rpm.

The power to maintain a light electric bike at a constant speed of 30 Km/h is only around 500 W. With the efficiency of whole propulsion system at 75%, the power from the motor should be around 500/eff. = 500 W / 0.75 = 670W at 30 Km/h. However, more power will be needed to get better acceleration during low speeds.

In order for the Robot Wheel G2 to climb up a 12-degree slope and accelerate from zero to 18 MPH, the torque and the power of the motor was increased to approximately 750W by switching to a different motor. This decision was made because although more power output can be obtained using the same motor by decreasing the reduction ration from 6 to 8, the top speed of the electric bike will be reduced.

4.1.3 Suspension System

Vehicle unsprung mass often causes damage to the wheel structure because the more weight that the tire is carrying, the more unsprung mass it generates. The concept of the Robot Wheel is to integrate as many vehicle components as possible, and also to prevent it from becoming part of the unsprung mass. In order to reach minimal unsprung mass, a four-bar linkage was introduced to handle this task, where the rim and disk break mechanism is connected to the rest of the components through this four-bar linkage. Fig. 4.1.3 shows RoboScooter G1 Motor with part of the four-bar linkage attached to the motor.

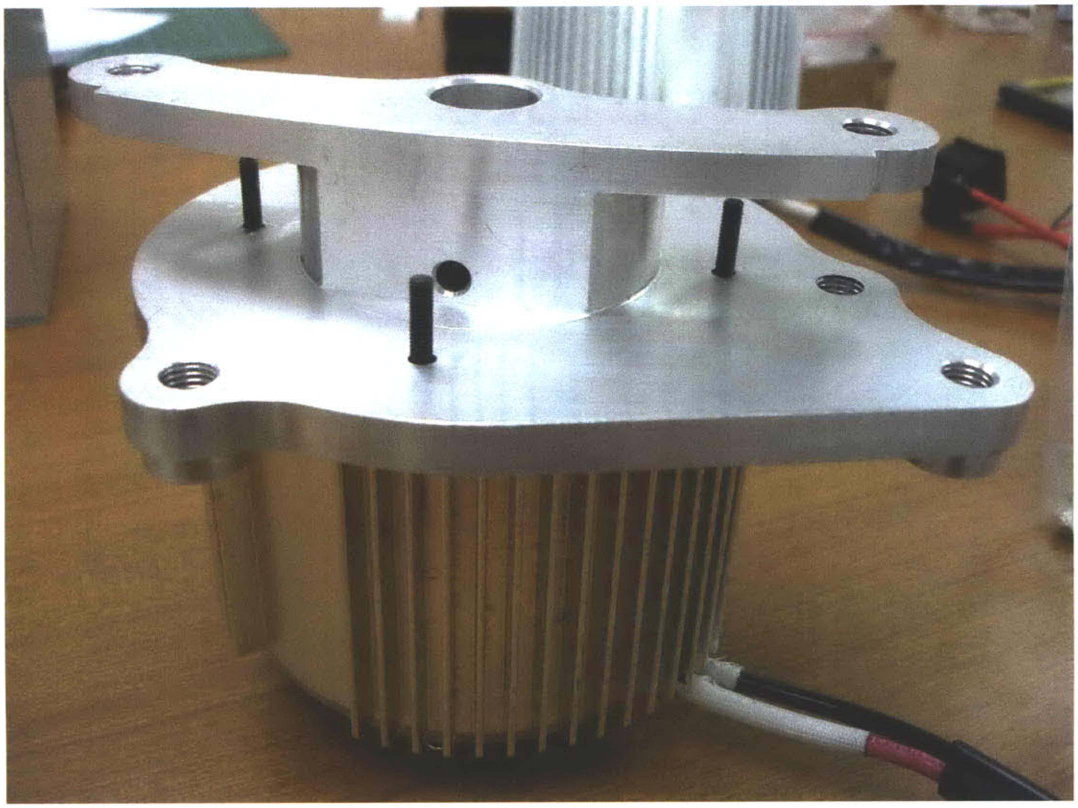


Fig. 4.1.3, RoboScooter G1 motor with linkage to avoid direct link to the rim which results in unsprung mass

Fig. 4.1.4, RoboScooter Robot Wheel with a four-bar linkage attached to the motor; the motor is secured to the scooter's rear chassis and front fork

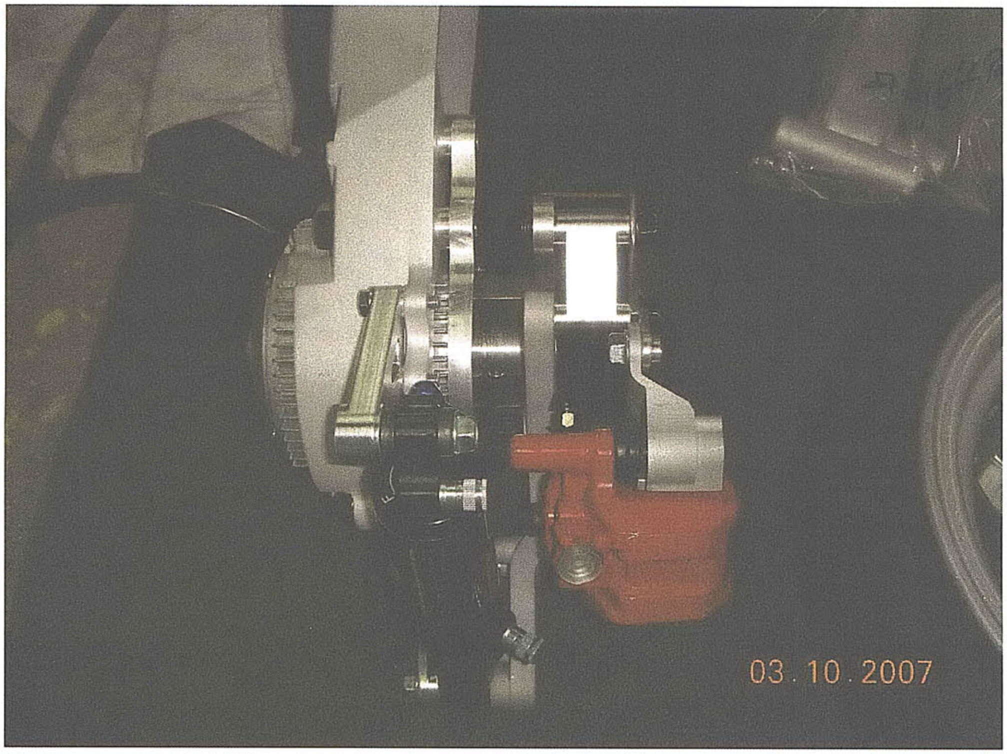


Fig. 4.1.5, top view of the suspension system and the relationship between this system and the rear frame

Fig. 4.1.6 shows how the wheel to moves up and down with a four-bar linkage which provides an 80mm travel distance. This is about the same travel distance as a standard scooter. There is an empty space in the middle of the four-bar linkage reserved for the speed reduction mechanisms.

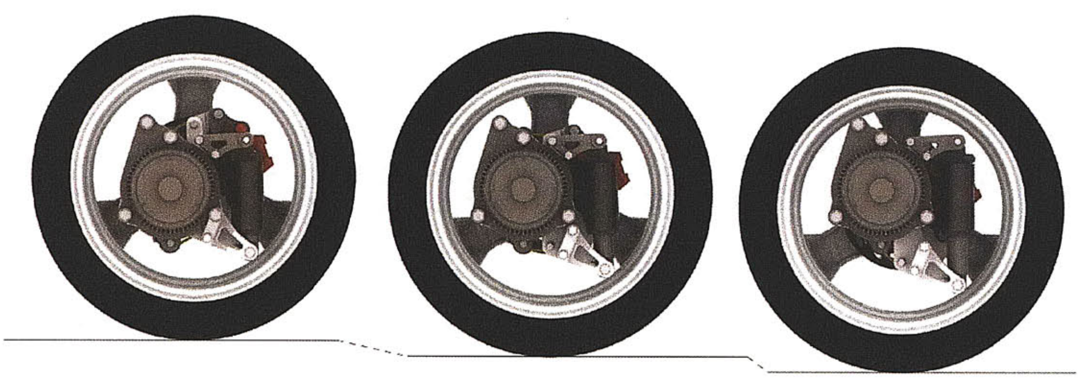


Fig. 4.1.6, actuation of the RoboScooter Robot Wheel

Standard scooter suspension travel distance is 80mm to 100mm and the size of the traditional scooter rim ranges from 9 inches to 12 inches. The diagrams above indicate how a wheel moves up and down when it runs over bumps. The area which will be occupied by different components during the suspension actuation is called the "Suspension Envelope". Therefore, the movement of the four-bar linkage has to be limited to the inside of the rim. Depending on different suspension mechanisms, a traditional suspension travel travels up and down for about 12mm in roughly 18 to 23 degrees. The linkages will need to provide the same actuation. Fig. 4.1.7 shows the RoboScooter suspension system. The motors are relatively frozen and the caliper is moving up and down and controlled by the yellow linkage on the top and bottom.

Fig. 4.1.7, RoboScooter suspension system

One interesting characteristic of the four-bar linkage is that the distance between these bars remains the same while moving up and down. This provides a perfect space to place reduction gears. Fig. 4.1.8 shows the exploded diagram of the RoboScooter Robot Wheel. The reduction gear set of located inside the suspension linkages. Fig. 4.1.9 shows one of the gears on the drive shaft.

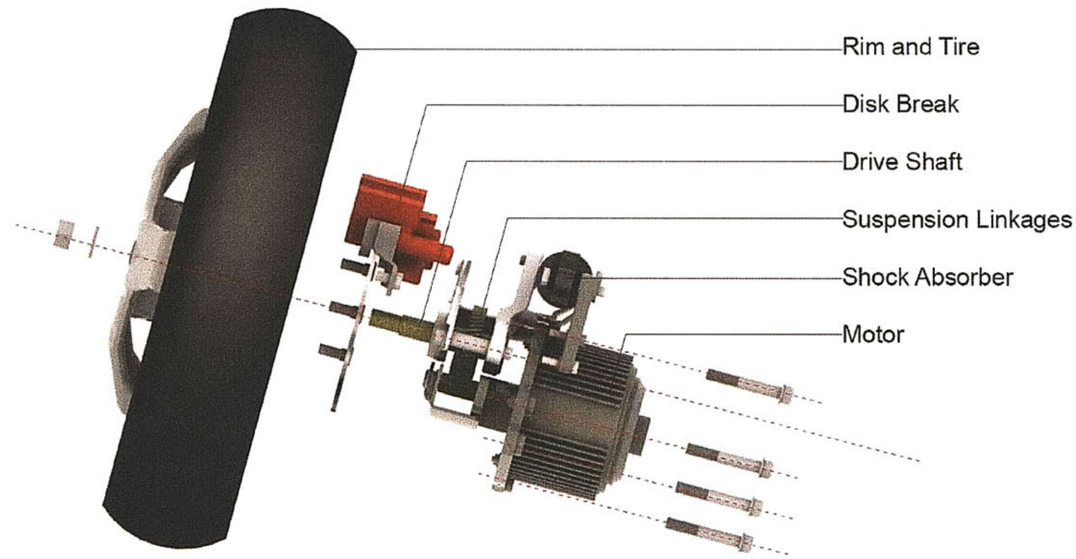


Fig. 4.1.8, exploded diagram of the RoboScooter Robot Wheel

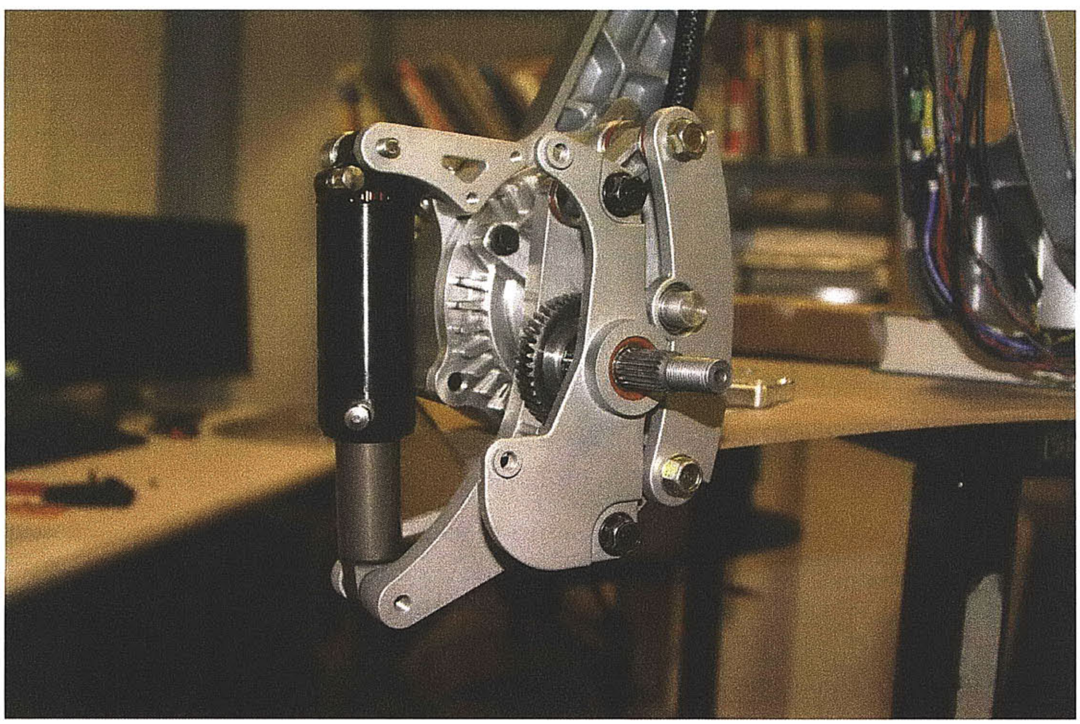


Fig. 4.1.9 RoboScooter G2 front suspension system

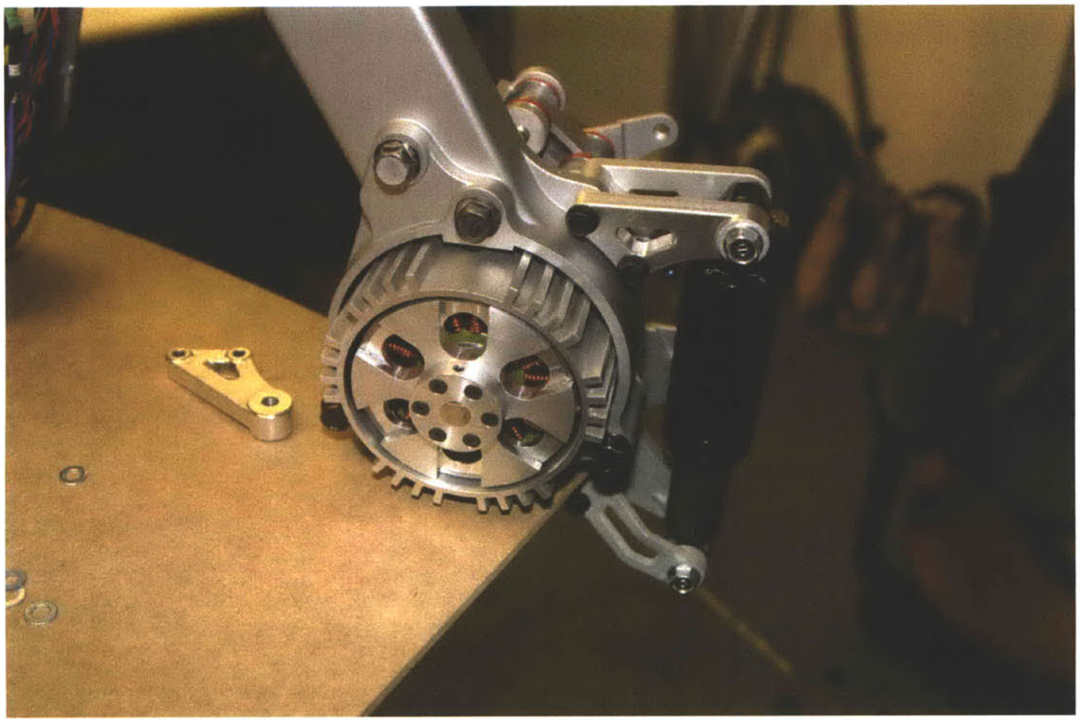


Fig. 4.1.10, RoboScooter G2 front Robot Wheel

4.2 Frame Design

The frame design of the RoboScooter needs to satisfy the folding function while maintaining the structure's rigidity. There are many different ways to fold a structure, but the goal for the RoboScooter is to fold it in the most efficient way with as few parts as possible. The most compact way to fold a linear object in one movement is to fold it in half. A tilted pivot was designed to be placed right in the middle of the scooter. The size of the pivot is related to the force that is going through this pivot. The tilted cylinder shape in Fig. 4.2.1 shows the location of the pivot. This pivot breaks the rigid body into two separate pieces, the front body and the rear body. The structure and the shape of these two pieces become very critical. Traditional scooter frames are made out of steel pipes and enclosed with plastic covers. In order to get the maximal freedom of the structure design and overall system rigidity, an aluminum frame was chosen for the RoboScooter.

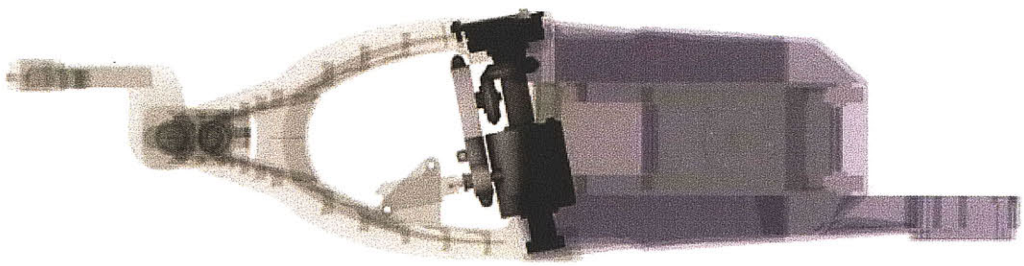


Fig. 4.2.1, RoboScooter G1 body frame render

4.2.1 Finite Element Analysis and Vehicle Dynamics

In most cases, during the process of scooter design, designers usually tend to work with clay models, thinking about the styling first and the mechanical engineering later. In recent years, as computer technology improved, the techniques of simulating different working environments have been greatly improved. This method is called the Finite Element Method or the Finite Element Analysis. The working environments that can be simulated include fluid, thermal, electromagnetic and structural working environments. SYM has been using this technical to run the crash test of the scooter.

After discussions with Professor Mitchell, this method was selected for structural optimization and to determine the outcome. By giving an overall shape of the front body and applying different forces to the structure, the test can show how the structure is deformed. The result will show where the structure needed to overcome certain force. Two most important vehicle dynamic parameters, the torque force and bending force, were examined and the results are shown below.

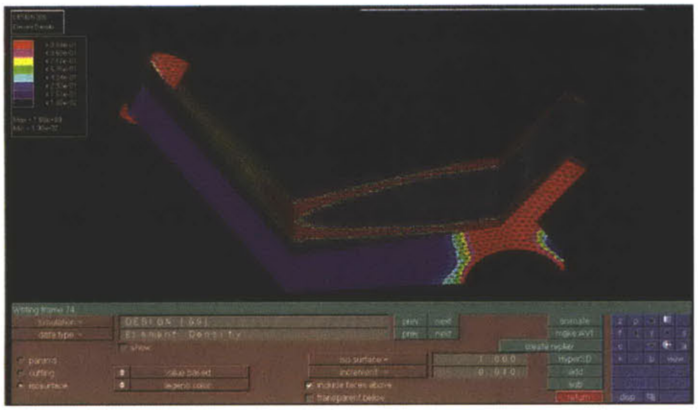


Fig. 4.2.2, result of the FEA analysis of bending simulation

Fig. 4.2.2 shows the FEA result of the bending test; the colors indicate the distribution of the stress and displacement. More red indicates more stress and more blue indicates less stress.

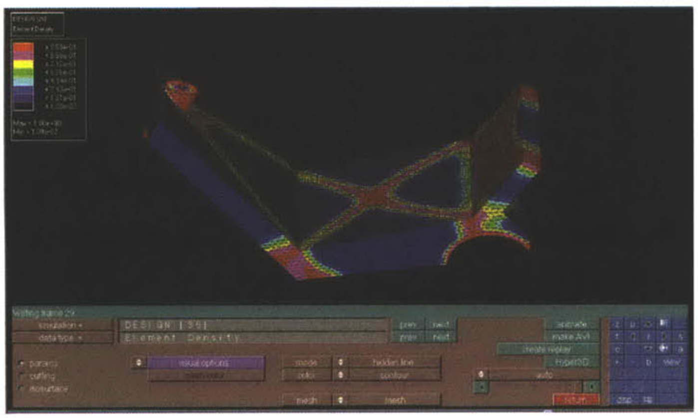


Fig. 4.2.3, result of the FEA analysis of torsion simulation

Fig. 4.2.3 shows the FEA result of the torsion rest.

4.2.2 Form Follows Function

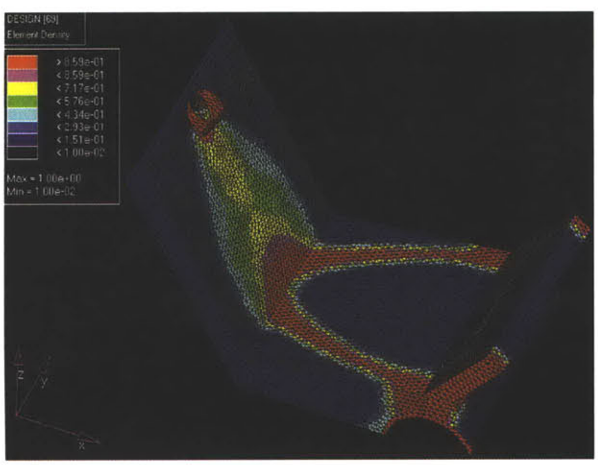
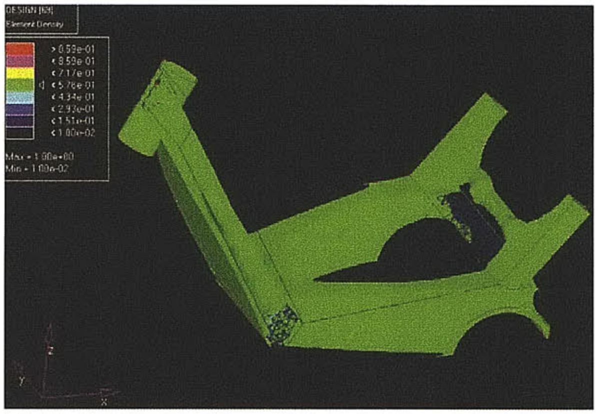


Fig. 4.2.4, result of the FEA analysis of bending simulation

Fig 4.2.4 shows the FEA results based on the distribution of the stress and displacement, the computer calculates in 3D shape. This shape represents the ideal distribution of materials for the aluminum frame. The result of the analysis also includes the material thickness. The red, yellow, light green and light blue indicates the optimized shape to overcome the bending force.



The green shape in fig. 4.2.5 is the representation of an optimized 3D shape of the front body structure.

Fig. 4.2.5, result of the FEA analysis of material distribution

The result suggests that in order to lighten the structure, the shape of structure of the shape needs to be hollowed. Based on the FEA results, the direction of the opening should be facing down instead of facing inside. This is very different compared to traditional aluminum scooter frames. Traditional motorcycle frames and scooter frames tend to have an opening facing inside, where the engine is, as this will provide a strong and rigid housing for the engine and many other components such as the oil tank and electronics.

The RoboScooter has a front body frame and a rear body frame; these two pieces are connected through a center shaft. In order to hold and secure these two frames together, the pivot needs to be extremely strong and the structures extended from the pivot need to overcome shocks and vibrations coming from the road. The structure extends along the longitudinal axis of the scooter and with a face down structure opening that provides more connecting surfaces to the pivot.

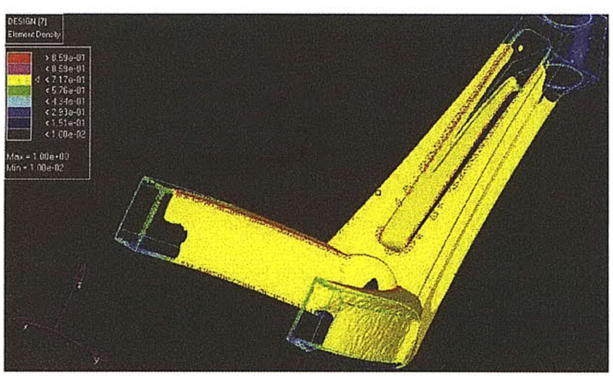


Fig. 4.2.6 shows the detail study of the structural optimization of the front frame. This simulation is done based on understanding how the structure should extend form the center pivot. The yellow indicates where the material

Fig. 4.2.6, results of the material thickness for the front body frame

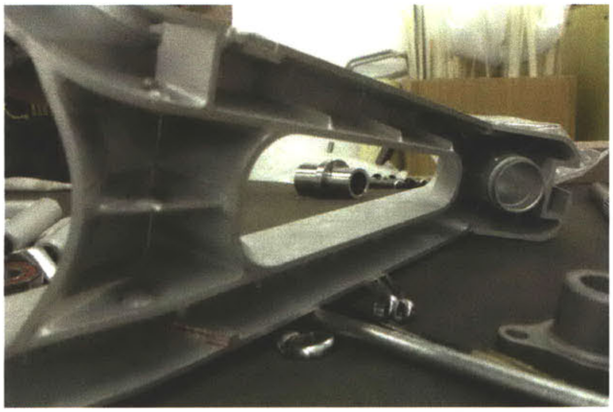


Fig. 4.2.7, results of FEA analysis reflects in the final prototype

should be distributed in the overall front frame. The opening of the material should be facing downward.

Fig. 4.2.7 shows the differences in the structure thickness. The material thickness is around 4mm for G1; 2.8mm for the G2.

Fig. 4.2.8 in the next page shows the final prototype of the exposed aluminum frame of the RoboScooter. The rear frame also provides strong aluminum housing for battery packs. The battery packs will sit right in the middle of the rear frame.

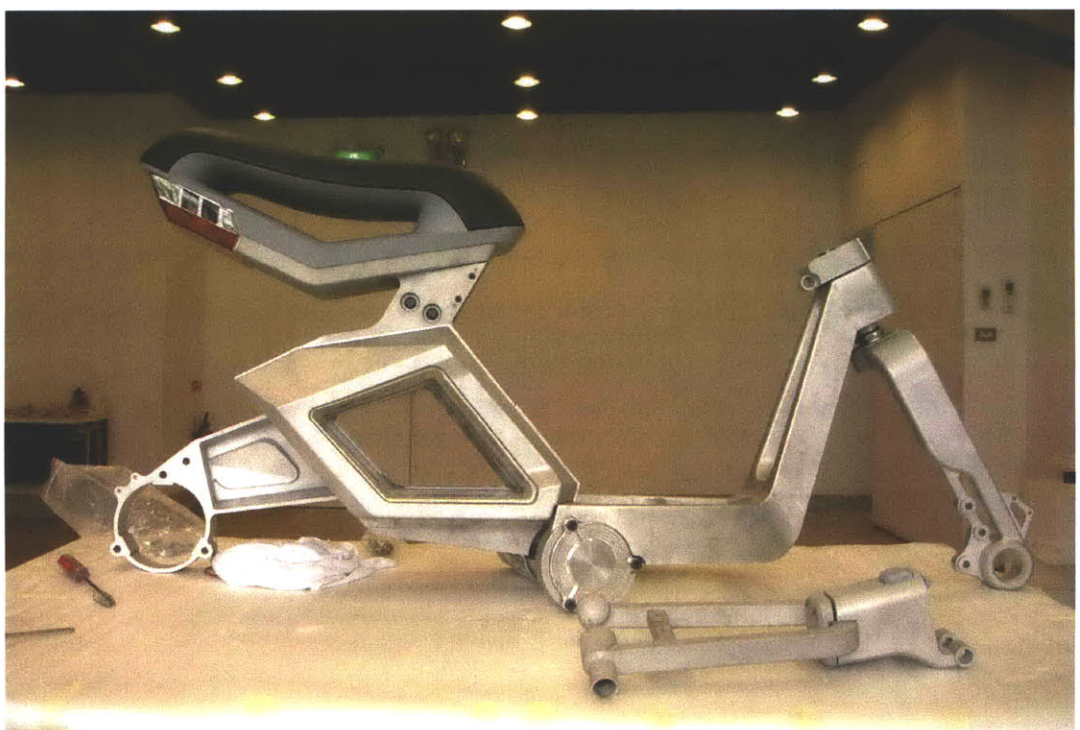


Fig. 4.2.8, the exposed aluminum frame of the RoboScooter G1

4.3 Pivot

The alignment of wheels also poses a big challenge. The wheels of the scooter need to be in a line when unfolded, but needs to be shifted when it is folded so that the wheels will not run into each other. To overcome this, a pivot, tilted by 22 degrees, was designed. Using this tilted pivot, the scooter wheels will be aligned in one line when it is unfolded but side-by-side when folded. There are two different designs for this tilted pivot. Fig. 4.3.1 shows the shaft of the RoboScooter G1. This shaft runs through the latitudinal axel of the scooter which is also tilted. The rear frame is secured and positioned on this shaft.

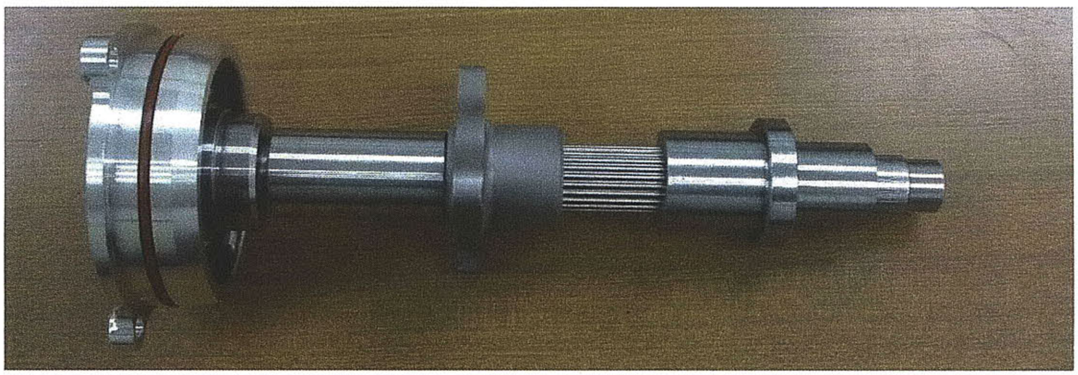


Fig. 4.3.1, the RoboScooter G1 shaft

Fig. 4.3.2 shows the different design of the Pivot for RoboScooter G1 and G2. On the rear frame of the RoboScooter G1, there is a rotor in the middle of the frame and this rotor is secured to this shaft. The shaft is connected to the front frame by ball bearings which allow the rear frame to rotate freely. The following diagrams demonstrate the changes between the two generations.

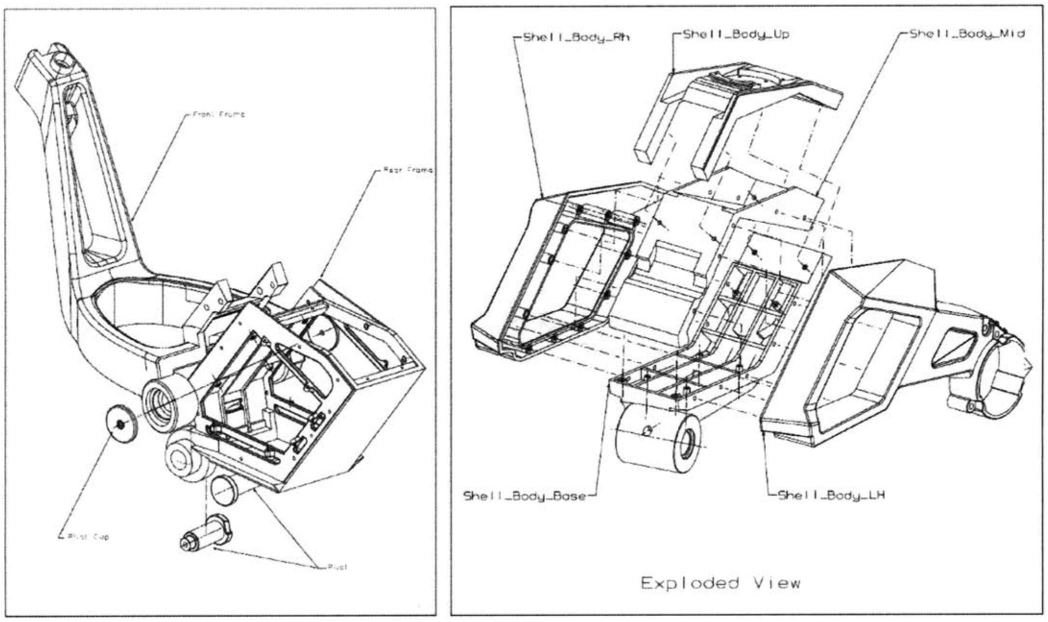


Fig. 4.3.2, G2 shaft design on the left and G1 rear frame design on the right

In G1, the shaft was too heavy and the rotor attached to the rear frame also increased the weight. Additionally, the rotor took up a lot of valuable space inside the RoboScooter. Therefore, in G2 the rotor was replaced by two structure pieces attached to the bottom of the rear frame. The shaft was also replaced by two smaller shafts which served the same purpose. Fig. 4.3.3 illustrates the location of the pivot in top and side view as well as a more detailed mechanical design. This center pivot mechanism consists of two rotational connectors to cover the shaft and a rotating axis which carries the rear frame.

The design of the axle as seen in fig. 4.3.3 in the following page shows how different components such as positions plate and bearing are secured to the axis. The engagement of the front and back is by an actuator with a position pin and two holes for hosting this position pin in different positions.

The folding axis is not perpendicular to the scooter's longitudinal axis but is tilted 22 degrees from the longitudinal axis. This tilt allows the wheel to be aligned side-by-side when folded and provides enough space for both wheels to be retracted while in the folded position.

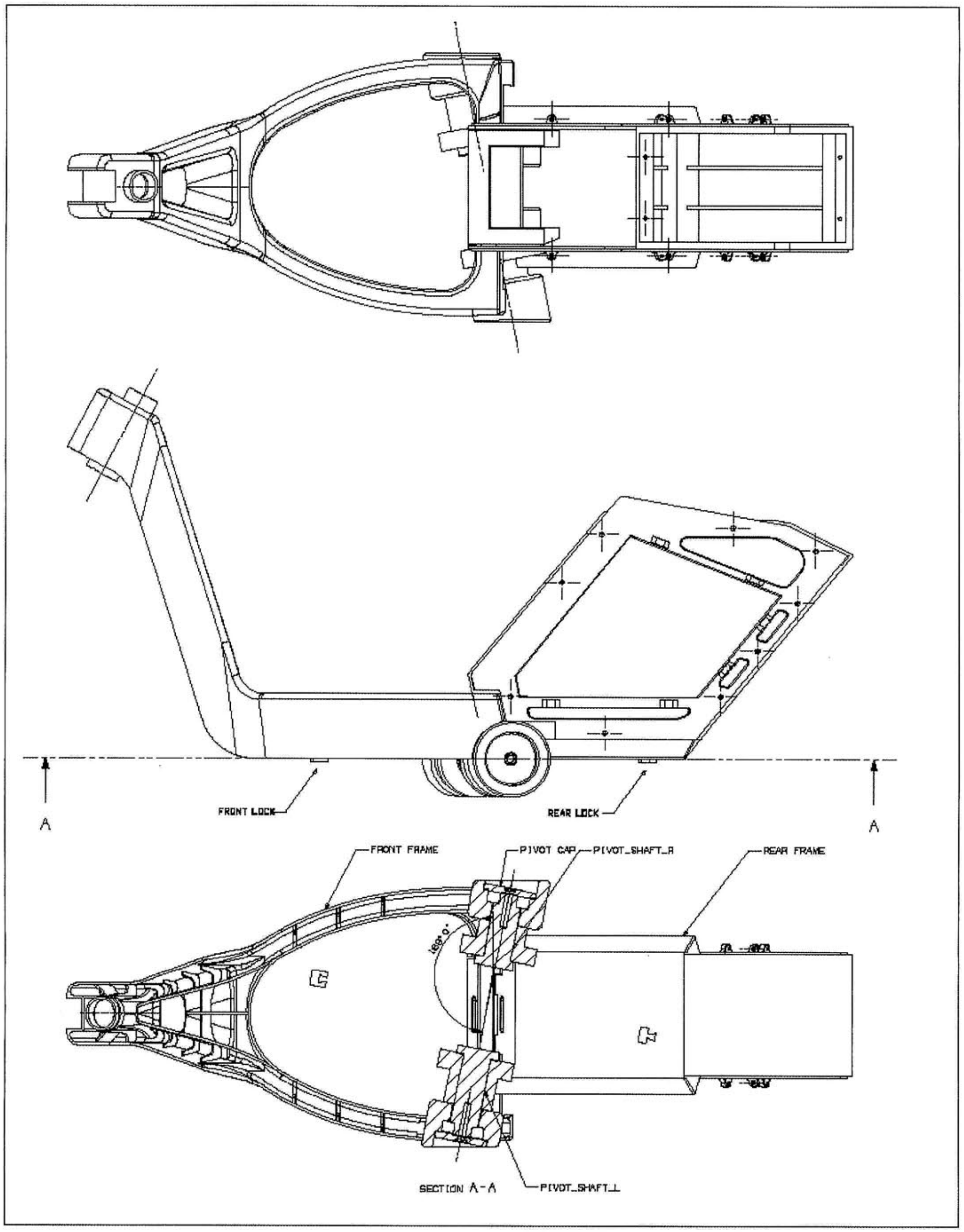


Fig. 4.3.3, center folding mechanism composite and section view of the RoboScooter G2

The folding pivot in the middle of the frame needs to be strong enough and rigid enough while in the riding/unfolded position. The drawing in the fig. 4.3.3 illustrates that the center of the pivot is right at the center line of front and rear wheel. When the RoboScooter is running, it takes infinite longitudinal force to lift up the front and rear frame, which provides an extra safety feature. However, this structure will easily break with a bottom up force. This kind of force happens a lot when the RoboScooter encounters a bump or a hole on the ground. However, this breakage can be avoided by introducing another lock on the top of the rear body frame which locks the seat. Fig. 4.3.4 shows the seat locking mechanism of the RoboScooter G1.

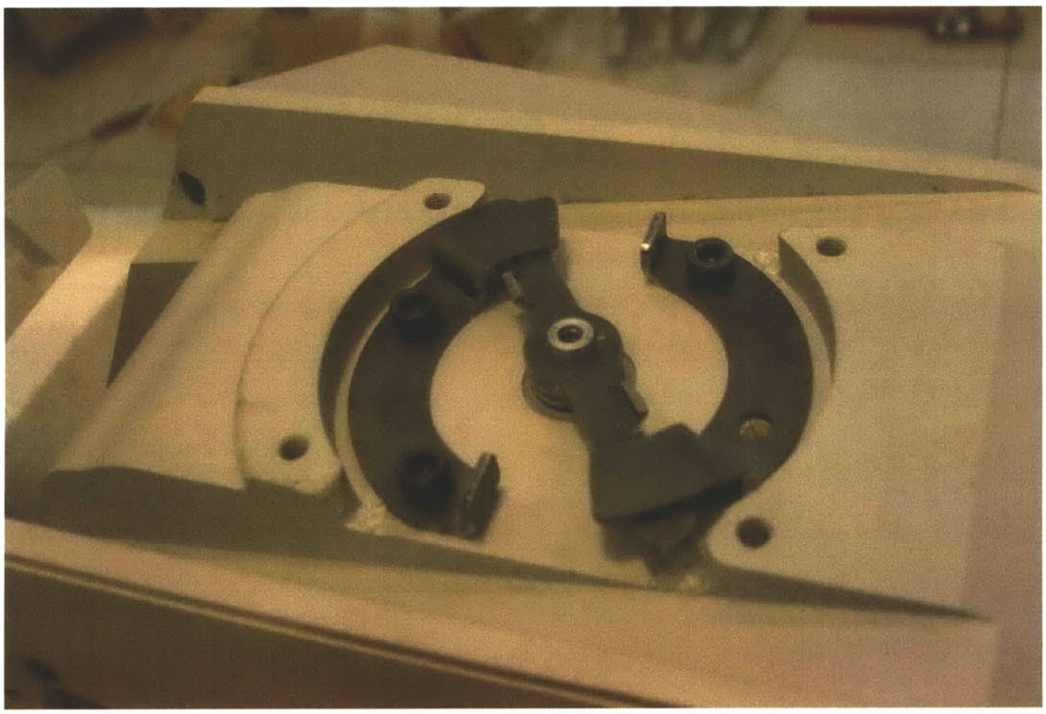


Fig. 4.3.4, the seat locking mechanism of G1

4.4 Seat

The seat is an interesting component in the design. Traditionally, the seat is located on top of a steel pipe frame, covered with plastic and with a storage space underneath. The RoboScooter does not have a steel pipe structure that runs all the way through the chassis, nor does it have plastic covers to form a storage space. The seat in the RoboScooter is designed purely for the folding functionality and structure logics.

Fig. 4.4.1 illustrates the seat structure whose purpose is to support human weight in the vertical direction. The seat is a flexible structure cantilevered from a bottom structure which attached to the top of the rear frame (fig. 4.4.2). The purpose of this cantilever was to reduce the weight, which also provides a possibility to utilize the space in between the seat and the rear frame. One of the benefits of this cantilevered structure is that the structure also acts as a shock absorber during the ride, which gives the rider more pleasure and fun.

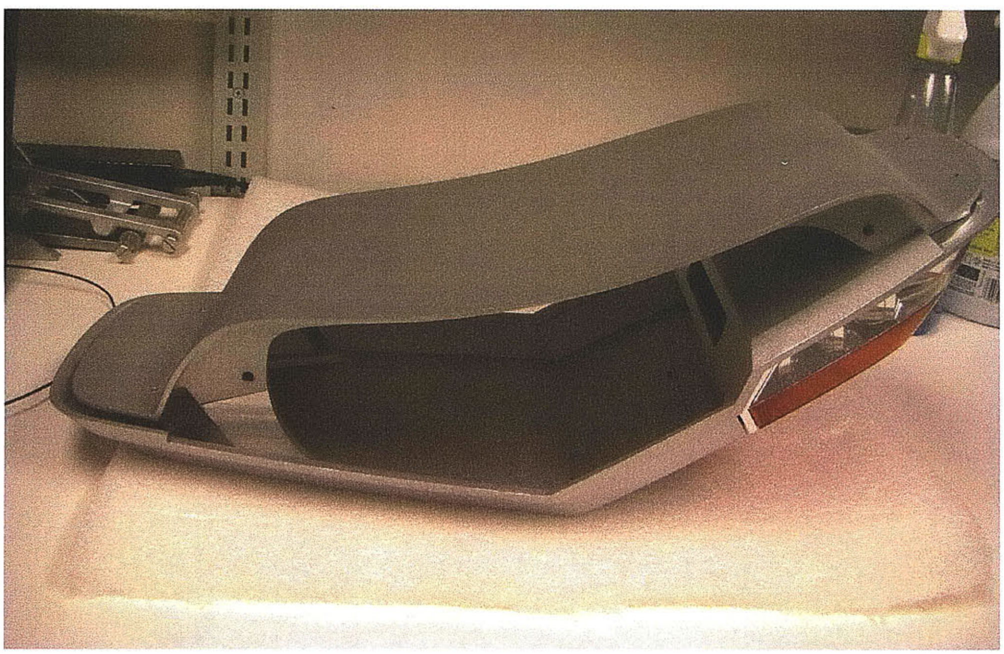


Fig. 4.4.1, RoboScooter G2 seat structure

The cantilevered seat structure is actuated by a four-bar linkage. It could be actuated automatically or manually. In order to simplify the electrical system and reduce the overall part count of the RoboScooter, both generations of the prototype have been actuated manually. This design opens up a new possibility for scooter seat design, as well as a removable storage unit inside the cantilevered structure. A-four bar linkage is coupled to the front frame on one end and to the seat support structure on the other end. Fig. 4.4.3 illustrates how the four-bar linkage is connected to the bottom of the seat structure.

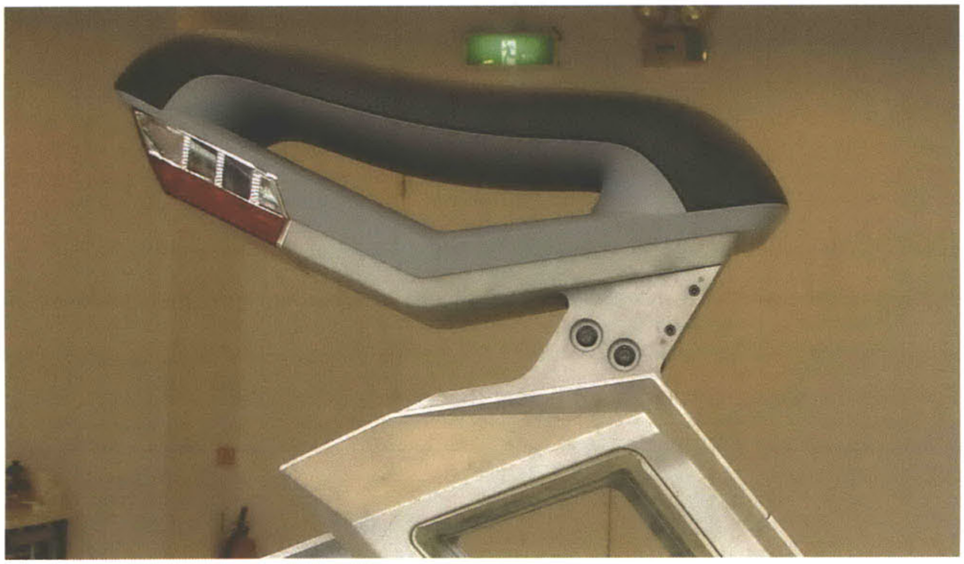


Fig. 4.4.2, the RoboScooter G1 seat assembly

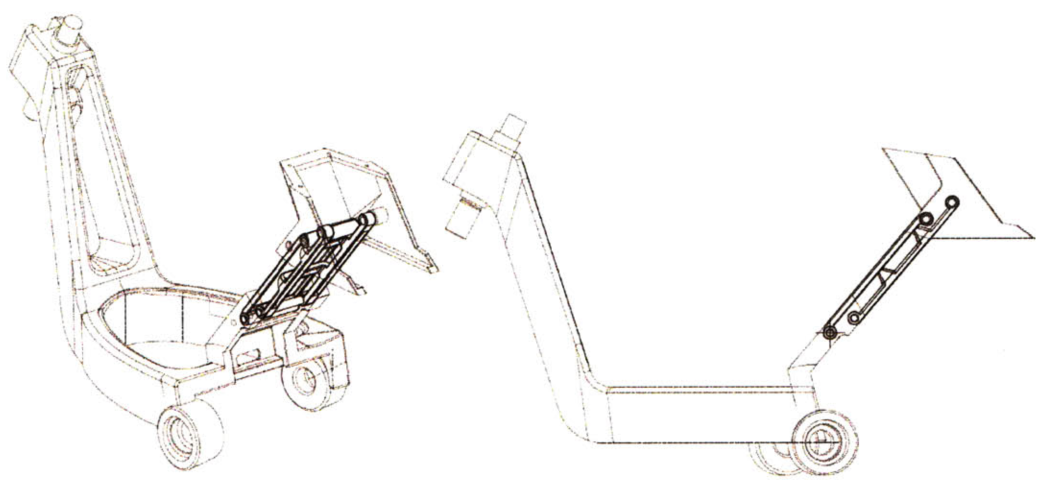


Fig. 4.4.3, RoboScooter front frame is connected to the seat through a four-bar linkage

As Fig. 4.4.3 shows, the linkages are stored under the rear frame and are secured by a rotational locking system on the top of the rear frame. (fig. 4.3.4). The linkage is fixed to the front frame by a rotational pivot but locked on the rear frame by a rotational locking mechanism, making these two rotations perpendicular to each other. This four-bar linkage results in a very rigid locking mechanism to secure the front and rear frame when the RoboScooter is unfolded.

4.5 Head Folding Mechanism

The handle bar of the scooter is a very critical piece because it handles the steering and the users control the scooter by grabbing onto the handle bar. When the scooter is folded in half, this part of the RoboScooter becomes extended horizontally. In order to minimize the scooter's length, a folding mechanism to reduce the overall length when folded needed to be designed. The design included a rotating pivot on the handle bar base and a two-way locking mechanism to keep the handle bar in place when in the folded and unfolded position.

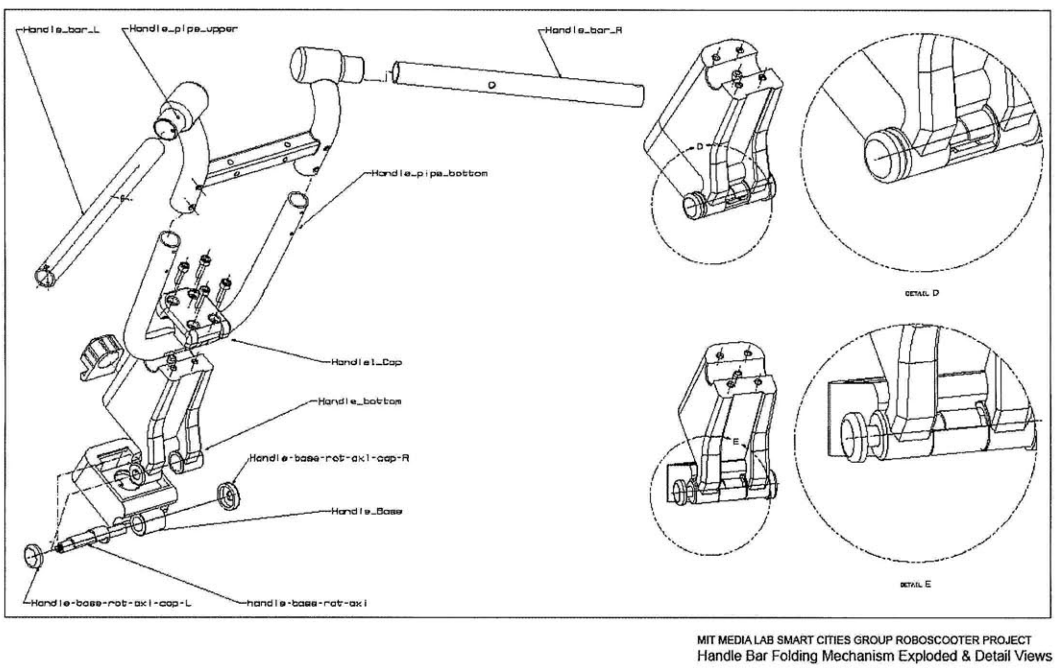


Fig. 4.5.1, the head folding mechanism exploded and detail views

Fig. 4.5.1 shows the exploded and detail views of the head folding mechanism. The head folding mechanism includes a handle cap, a handle bottom structure, a handle bar base, handle bar locking cap (located on the left side of the handle bar base) and a release button on the right-hand side of the handle bar. Inside the rotation axis, there is a handle bar rotation axis which is connected to the release button on one end and supported by a spring on the other end. The handle cap connects to the bottom handle pipe and creates a link through the handle bar base and connects to the front fork which holds the wheel. The handle bottom is locked to the handle base when the scooter is in the driving position.

4.5.1 Control Console

The handle bar includes a left handle bar, a right handle bar, an upper handle pipe with connects to both the left and right handle bars, and a bottom handle pipe which connects to the handle bar folding mechanism. The control console (or so called meter) is located right in the middle of the left and right handle bars. The shape of these two handle bars not only provides a place for the driver to handle the scooter but also plays an important role in the stylistic design.

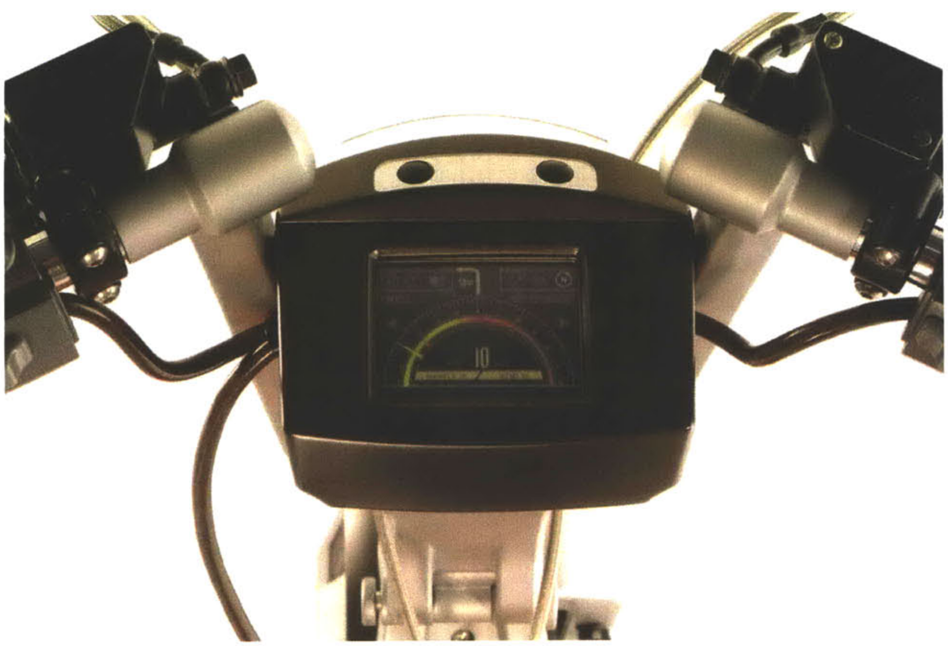


Fig. 4.5.2, control console of the RoboScooter G1

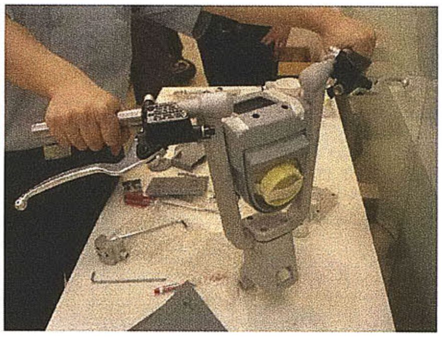


Fig. 4.5.3, control console and the head folding assembly of G1 on the left and the control console and handle bar pipe assembly of G2.

The image on the left of fig. 4.5.3 is the prototype of the G1 control console. The design of this piece follows the overall styling of the RoboScooter. The image on the right of fig. 4.5.3 is the prototype of the G2. The handle bar pipe is different from the G1 version. The G1 has a cast aluminum rectangular pipe to connect the handle to the handle bar base. The G2 has a tubular shape which reduced the weight and made it easier to manufacture. The handle pipe is angled 23 degrees to the ground for ergonomic reasons. The angle not only affects the vehicle performance but also brings the handle bar to the right position for easy handling.

The RoboScooter control console is located in a rigid front exposed aluminum structure. The location of this console unit is not only for better aesthetics but also provides protection against front impact.

Fig. 4.5.4, the headlight is located in the front of the control console; it is powered by LED lights.

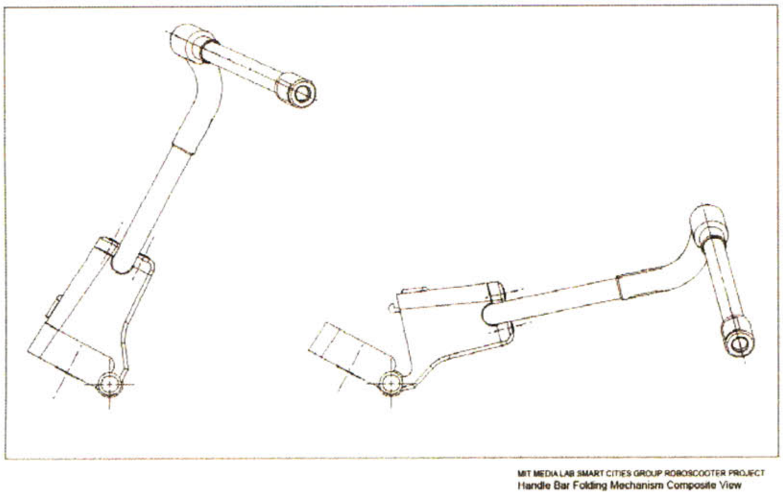


Fig. 4.5.5, diagrams of the head folding mechanism in unfolded (left) and folded positions (right)

To fold the handle bar, the release button on the front handle bar locking mechanism is pressed to unlock the handle bottom from the handle base. This release button is the orange button in fig. 4.5.6. As illustrated in fig. 4.5.5, after being unlocked, the handle base is rotated along the rotation axis toward the scooter. This folding action adds to the compactness of the scooter when in the folded position. When the driver presses the release button, the folding mechanism will unlock again, allowing the handle bar to be unfolded into the riding position.

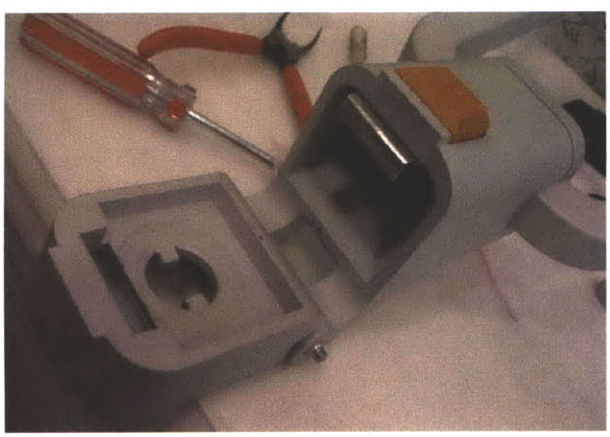


Fig. 4.5.6, detailed photo of the RoboScooter G1 head folding mechanism

4.6 Design Process

The RoboScooter project is a design project which also deals with a show quality physical prototype. It was also a journey for me to transform myself into a mechanical engineer. As an architect by training, I am familiar with papers, plastics, wood, or 3D print-outs. Because of the physical size of architectural projects, I was not used to real-scale prototyping. The RoboScooter project requirements extended from concept design to real-scale prototyping. All the details had to be fully developed. The computer aided design software that I am familiar with from architecture school helped me in visualizing my ideas as well as in some very basic fabrications. However, this software became very limited during the mechanical development. This is the result of different modeling precision and the difference in the logic of modeling methods of the software. In order to get a better control of the design and to act as a bridge with the sponsors and fabricators in terms of file formats, I needed to learn new modeling software and fabrication methods. Accordingly, I learned the software that the scooter manufacturer uses: Unigraphics NX. By acquiring knowledge of this software, I was able to jump around between different software to incorporate both styling and functionality.

Fig. 4.6.1, the computer renderings of the RoboScooter in folded and unfolded positions

4.6.1 Computation

The styling of the RoboScooter was done mostly in CAD software, such as Rhino and 3ds Max for visual studies. The first image is the 3D model of the overall design base of FEA results.

The second image is the image from the Unigraphics NX3. All the mechanical and structural design was done using this software, and the image is the outcome of mechanical engineering and some basic styling. The exposed frame and many of the folding mechanisms are part of the styling and part of the engineering; therefore, most of the design decisions were focused on the function just as much as the style.

The third image is the overlay of the styling design from NOVA Design, a design house which the sponsor hired to help with fabrication and styling. I was awed and asked the designer to design the 3D files that I provided. The last two images are some other potential designs of the RoboScooter done by NOVA designers.

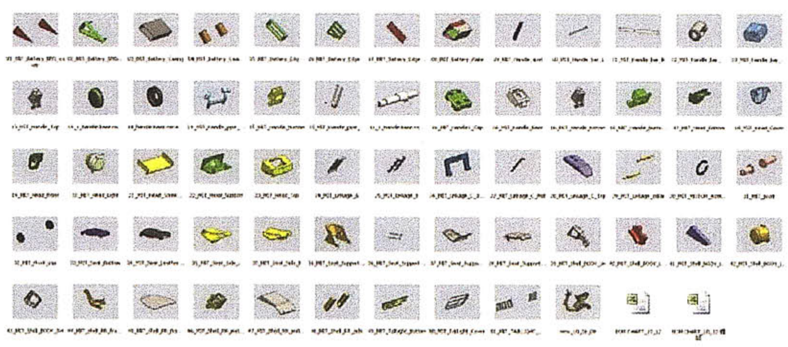


Fig. 4.6.1, part list of structural components

This is the part list of basic structural components of the RoboScooter, mostly metal parts. These files were created on my computer and then sent to the fabricators in Taiwan via email. Parts will be fabricated based on these 3D files.

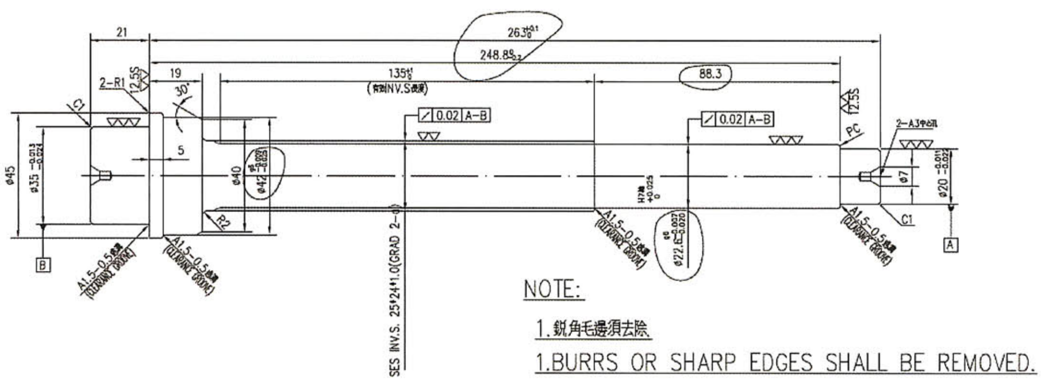


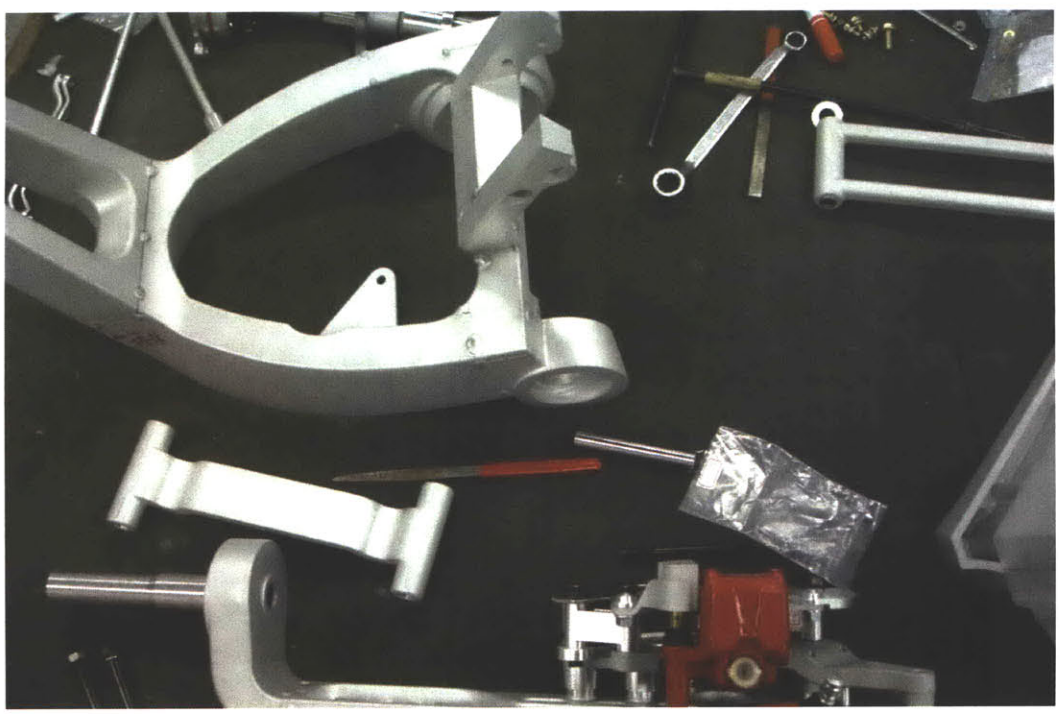
Fig. 4.6.2, fabrication drawing of the center shaft

Fabrication drawings provided more detailed information regarding the 3D files. This information includes the materials, surface treatment as well as material tolerance. Fig. 4.6.3, are the photos of the fabrication process, i.e, polishing the surface.

Fig 4.6.3, photos taken during the fabrication process

Pieces of RoboScooter G2 components lying on the table for future examination and assembly.

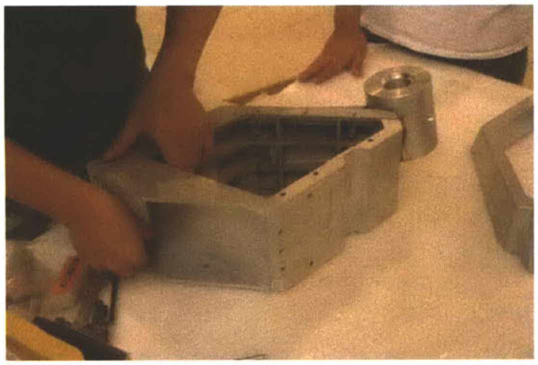
Some parts still needed to be preassembled first before shipping to the lab from the fabricators.



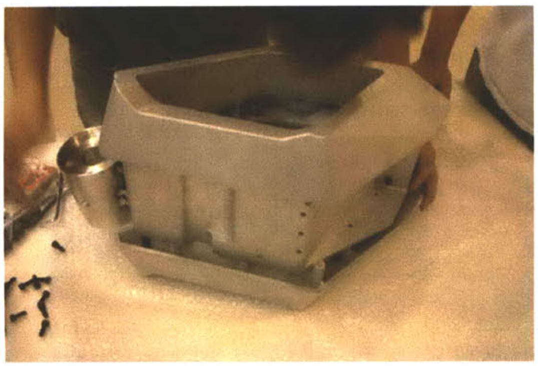
4.6.2 Prototyping

Fig. 4.6.4, RoboScooter G2 parts

Fig. 4.6.2 is the photo of the RobScooter Generation II (G2), pieces that are preassembled before the final assembly. G2 was assembled at the lab inside room E15-020G and was completed two days after Christmas 2008. The assembly process was carefully documented by video. The assembly for the RoboScooter G1 occurred in Taiwan. The assembly process of the G1 is shown in a series of photos showing the different steps of the assembly process.

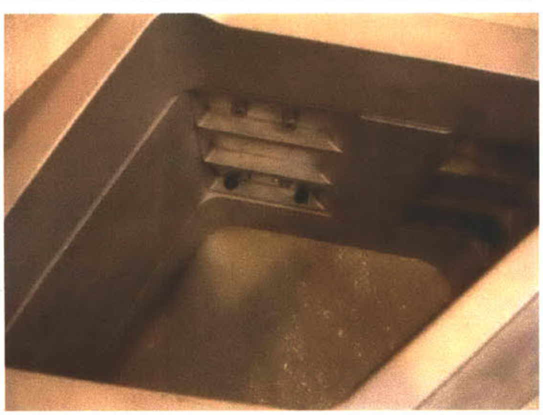


Assembly of the rear body frame consisted of four aluminum pieces and a rotor welded to the bottom. The pieces were held together by nuts and bolts.



By adding side reinforcement structures to increase the rigidity of rear body frame, it provided a strong protection for the battery housing and electrical control system.

One side of the reinforced structure extends to the rear wheel. It looks like a swing arm of a traditional motorcycle, but the suspension was done with the Robot Wheel; therefore the swing arm becomes the extension of the rear body frame.

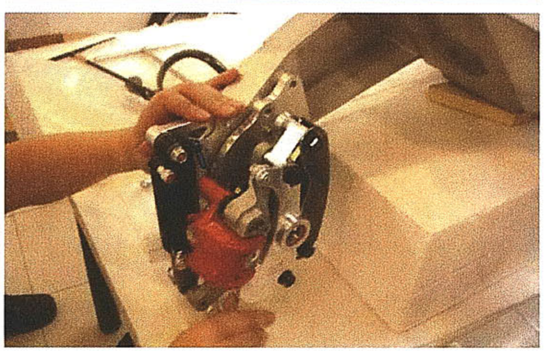


The opening in the middle of the rear body frame forms a space for the battery pack. All the screws, nuts and bolts were hidden inside the structure, leaving a clean exoskeleton frame structure outside.

Placing the center shaft into the pivot of the front frame through the rotor on the rear body and connecting the front and rear frame together. The shaft helped the position and alignment of the front and rear body.

After the front and rear body frames were assembled, the front fork was added to the front body so that the handle bar assembly can be attached.

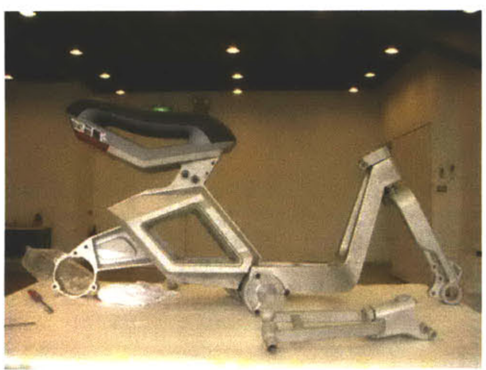
The four-bar linkage is coupled to the front body frame on one end and to the seat on the other end. These structural components not only helped the movement of the seat during folding and unfolding process, but also played an important role in the overall structure locking strategy.



Adding the rear RoboScooter Robot Wheel, preassembled and then placed into the rear body frame; the rim and tire was added on later.

Adding front Robot Wheel to the front fork, the front Robot Wheel shares the same components as the rear ones. The only difference is that one of the linkages is connected to the front fork instead of the motor.

Overall aluminum structure assembled. This photo was taken during the first test assembly. The goal was to figure out how well pieces fitted with each other. Further tuning was be needed based on the result of this test.



Seat structure completed. This was the second test assembly and the goal was to test the folding mechanism. The front handle bar was removed and placed on the table because the shaft of the two way locking mechanism was broken during the test.

This photo was taken during the third assembly. Most of the mechanical issues were solved in the previous assembly. This is the first time that the electrical control system was installed.

Fig. 4.6.5, RoboScooter G1 final assembly was done by NOVA in Taiwan

Fig. 4.6.6, RoboScooter G2 final assembly was done in the MIT Media Lab

Chapter 5
System Design

Traditionally, scooter designs are produced by industrial designers and mechanical engineers focusing on different aspects. The industrial designers are focused on the styling of the scooter and mechanical engineers solve the vehicle's mechanical problems, such as engine performance, chassis rigidities, and overall vehicle handling. Together, designers and engineers are required to meet specifications derived from marketing strategies and user surveys; yet to the limited understanding of urban forms and urban infrastructures, their scooter designs failed to complement the urban landscape and often the overall strategy of urban infrastructures.

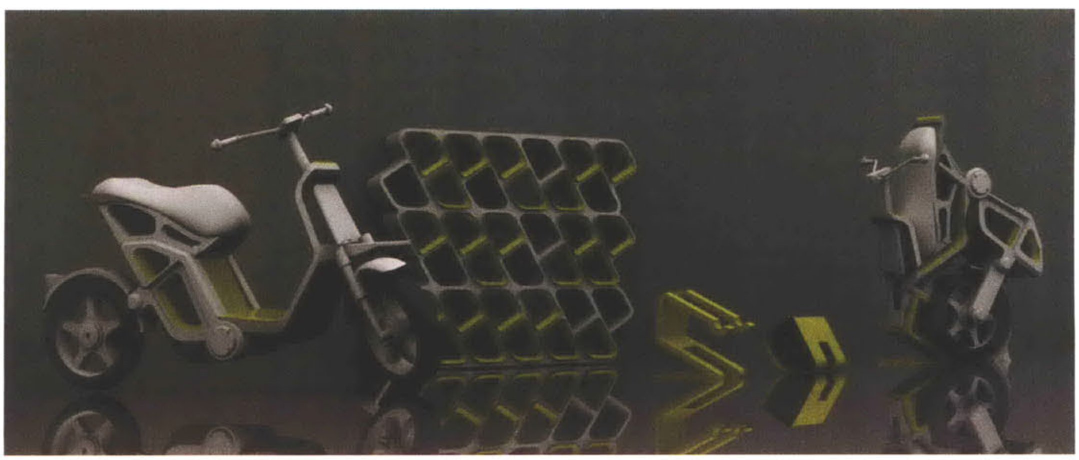


Fig. 5.1, the RoboScooter in folded and unfolded positions, battery dispenser, charging rack and swappable battery pack

The RoboScooter is the outcome of combining architectural aesthetics, industrial design and mechanical engineering, aiming to create a new expression of personal urban mobility. The RoboScooter addresses what future cities will require and its operational concept, the Mobility-On-Demand. Besides the styling and folding mechanisms mentioned in the previous chapter, the overall RoboScooter system also includes the swappable battery function, charging stations and the Mobility-On-Demand urban strategy. Fig. 5.1 shows basic components of the RoboScooter Mobility-On-Demand system.

5.1 Swappable Battery Pack

Electric vehicles are powered by different types of batteries. The most common ones are lead-acid batteries; these batteries are inexpensive but have a very low ratio in energy-to-weight and energy-to-volume. Newer developed battery technology such as Lithium-Ion batteries have a better energy-to-weight ratio, fast charge and less in memory effect. Therefore, they are increasingly popular in the automotive, aerospace and consumer electronic industries. There are many other different battery technologies such as fuel cells, or even hydrogen power packs, but most of these are still under development.

Even though the charging time has been greatly improved from eight hours to two hours, this still adds a delay to the trip. Because of the lighter weight, it is possible to get rid of the trip delay by a battery swapping mechanism. This is a very simple idea: imagine there are a lot of battery vending machines and users can have easy access to these battery packs. When the battery runs out, instead of find a charging station and having to wait for 2 hours for the battery to charge, users can simply swap in a fully charged battery pack and then continue onto their destination.

This idea also opens up the possibility of having a professional team or even the battery manufacturer performing the battery management. Having a professional battery management team and distributor will not only increase the life span of the battery packs, but also reduce the scooter price. This swapping of batteries also means that the user does not need to "own" a battery pack. Instead of paying for the costly battery, they can lease it. At a minimum, a decent 36V 10 Ah Lithium-Ion battery pack for the electric scooter costs $700 USD, approximately one-third of the total scooter price. By leasing the battery pack, users pay for the battery service instead of owning the battery pack.

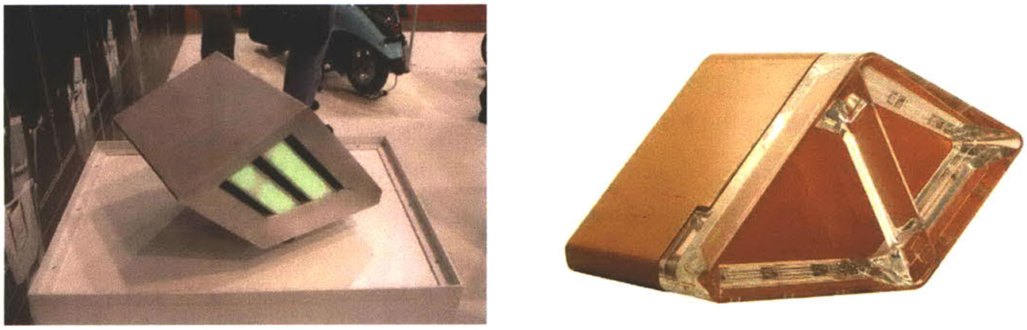


Fig. 5.1.2, RoboScooter G1 battery pack designed by MIT Smart Cities research group member Arthur Petron (left) and RoboScooter G1 battery pack, 36V 10AH (right)

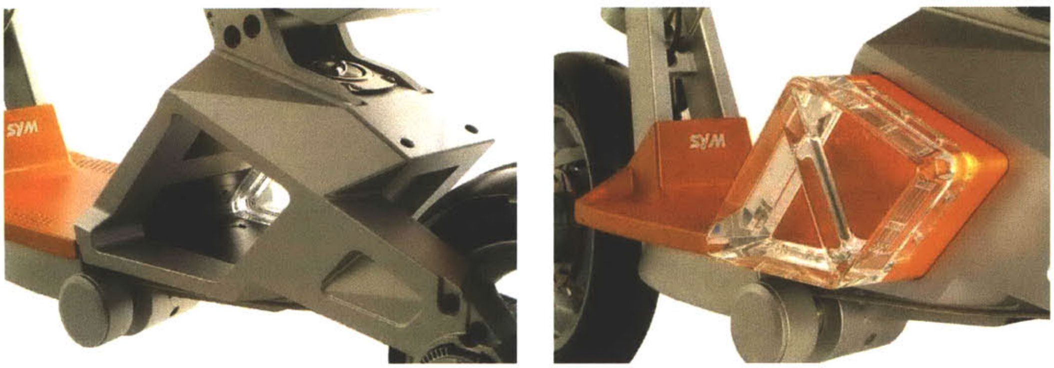


Fig. 5.1.3, RoboScooter G1 battery housing and the battery pack

Fig. 5.1.2 shows two different battery packs of the RoboScooter G1. Both battery packs use Lithium-Ion battery technology at the capacity of 36V 10Ah and the weights is around 15 pounds. In Petron's purposed design, the battery casing is made out of aluminum and the design further utilized the aluminum structure for heat ventilation. The side panel contains LED lights to indicate the voltage of the battery pack. This is an interesting design because user can identify the remaining energy by the color of the battery pack.

The photo on the left of fig. 5.1.3 shows the battery housing area and the rigid aluminum structure surround it. Users will insert the battery pack into this area; the aluminum structure provides extra protection for the battery pack. The battery packs provides 20 miles of traveling range at the speed of 18 miles per hour.

Due to the limited traveling range of 20 miles, one of the goals for the RoboScooter G2 is to increase the traveling range by increasing the battery capacity. Instead of building up a bigger battery pack, the design was focused on make the existing battery pack smaller but increase the number of battery packs. In G2, by moving some of the electronics and part of the battery management system into the rear frame, the battery packs becomes roughly half the size of G1. The shape of the rear body frame also changed slightly so that two battery packs can be fit into the housing. Fig. 5.1.4 shows the RoboScooter G2 battery pack on the right, and the new battery housing on the left.

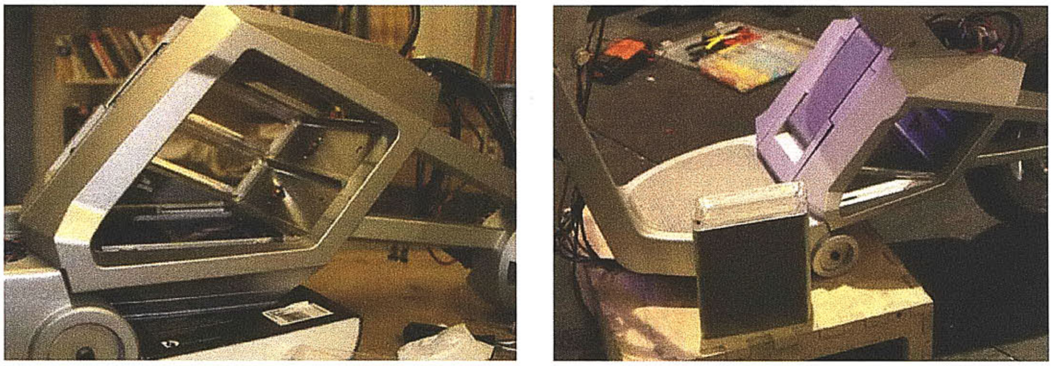


Fig. 5.1.4, RoboScooter G2 battery housing and the battery pack

5.2 Charging Stations

Charging stations in the RoboScooter system are placed throughout the city base on urban planning strategies. In order to maximize the traveling range of the RoboScooter and enlarge the coverage of the system, the location of the charging station is chosen based on average traveling distance within a city. Because users in different cities have different travel range requirements, the RoboScooter battery capacity will need to be sufficient to cover the average travel distance. Take Taipei, for example: 80% of scooter users travel less than 15 kilometer a day; therefore this battery pack will need to provide enough traveling range. Electric vehicle users often worry about running out of the energy, but the greater traveling range a battery pack provides the heavier it becomes. Carrying too much unnecessary weight also reduced the efficiency of the whole system; therefore how to optimize the travel range and the battery capacity becomes a very complex problem to solve. However, the problem is not so complicated if the urban infrastructures provide a charging mechanism.

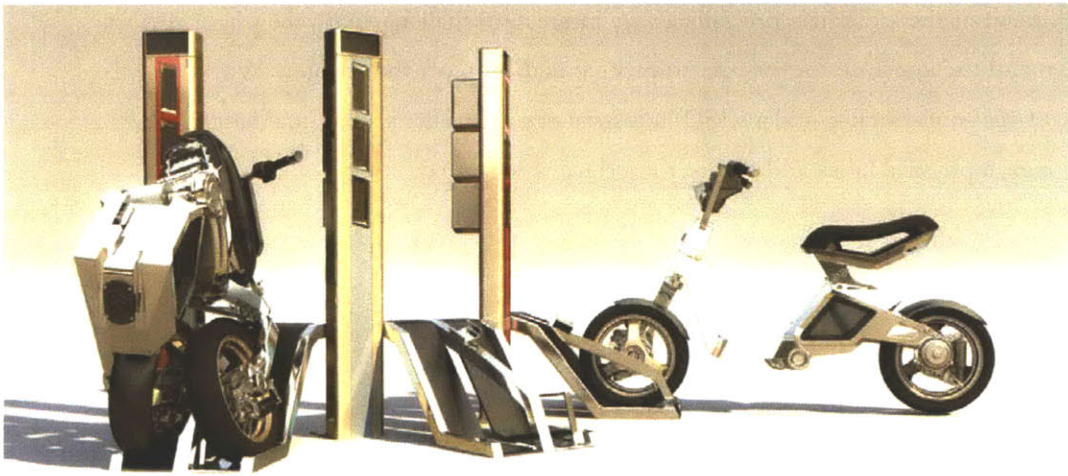


Fig. 5.2.1, RoboScooter kiosk design by Smart Cities collaborator Ana Fabiola Martínez (RISD 2009)

The charging station, also known as the scooter kiosk is the key component of solving the range and capacity problem. Fig. 5.2.1 shows the RoboScooter charging kiosk design. This kiosk works as a battery charging station as well as the pick up and drop-off location for the RoboScooter system. The kiosk could be either installed base on the Mobility-On-Demand requirement or utilizing existing urban infrastructures such as bus stops and subway entrances. Fig. 5.2.2 is a scenario of the implementation of the RoboScooter kiosk in Harvard Sq., Cambridge, MA.

Fig. 5.2.2, RoboScooter kiosk scenario of Harvard Square, Cambridge, MA, by Smart Cities collaborator Ana Fabiola Martínez (RISD 2009)

The design of the kiosk also presents a very interesting challenge with the physical kiosk design and the interface for the user to pick up and drop off the scooter. Working with Smart Cities collaborator and a RISD industrial design master's student, Ana Fabiola Martínez, a physical kiosk and the user interface was created.

5.3 Urban Strategy

Cities have different forms of densities. Examples are population density, building density, and street network density. In general, urbanization leads to densification because of the increasing demands of daily living, including transportation. Larger-scale infrastructure such as roads, bridges, tunnels and highway systems will keep expanding. Subway systems and bus lines will get more and more complicated as these cities grow.

Instead of building new infrastructure, which requires huge investments of capital and time, existing infrastructure such as street lights, bus stops, subway entrances, and community or neighborhood service centers such as post offices, schools and convenient stores are ideal to be retrofitted into RoboScooter nodes. Because of the size of the RoboScooter and the modularity of the system, the RoboScooter system can be easily adopted by any of the locations mentioned above.

Fig. 5.3.1, earlier computer scenario of the RoboScooter system utilizing the 7-Eleven store fronts

Fig. 5.3.1 shows the RoboScooter system added to 7-Eleven store fronts. In Asia, 7-Eleven and other convenience stores are popular destination nodes for a wide variety of activity. Aside from food and retail consumption, local people often use them for common city services. Residents may pay telephone bills, send and receive faxes and recently, pick up and drop off for packages. This provides a great opportunity for smaller scale mobility systems such as the RoboScooter Mobility-On-Demand system.

Fig. 5.3.2, RoboScooter as an extension of an existing mass transit system

Besides utilizing the convenient store front, there are many other locations which may provide ideal locations for RoboScooter nodes. Fig. 5.3.2 shows a good example of utilizing the subway stations. In most cases, a subway stations becomes a transportation node. This node is associated with existing transportation infrastructures such as train stations, bus stations, taxi stops and ports. By adopting the RoboScooter system, the system will work as an extension of an existing transportation system.

Chapter 6

Conclusions and Physical Demonstrations

This section is the conclusion of the RoboScooter project to date. The words in this chapter are a collection of the works of the group members and Professor William J. Mitchell. The RoboScooter was successfully demonstrated at the Milan Motor show in November 2007 and there was an official press release with ITRI and SYM on April 2008.

Final prototype of the RoboScooter showcased at Milan Motor Show November 2007; members of the Smart Cities research group with Media Lab sponsors from ITRI and SYM.

Final prototype of the RoboScooter showcased at the joint press release in Taipei, Taiwan, April 2008; members of the Smart Cities research group with Media Lab sponsors from ITRI and SYM.

6.1 Conclusion

6.1.1 Electric Power with Automatic Battery Charging

The RoboScooter is electrically powered, which means that it is silent and has no tailpipe emissions. Its batteries recharge automatically whenever it is parked in the specially designed scooter rack. This arrangement is very convenient for users for unlike traditional scooters, users never have to fill the tank with gasoline and unlike other electric scooters, and users never have to plug the scooter in for recharging.

Battery packs can quickly and conveniently be removed and replaced. This facilitates battery management and recycling, and it provides an effective way of re-activating the scooter if it runs out of battery power. Removable battery packs enable an alternative business models under which users lease rather than buy batteries – this reduces the purchase price of scooters and cleanly separates out the business of electrical supply to between the manufacturer and the consumer.

6.1.2 Robot Wheel

Fig. 6.1.1 shows the exploded diagram of the RoboScooter Robot Wheel. The RoboScooter utilizes a newly developed, patented robot wheel technology. The electronically controlled robot wheel, which contains drive motors and suspension, eliminate the need for the traditional central motor. This greatly reduces the overall complexity of the scooter, simplifies manufacturing, and provides the freedom to introduce new design features. The robot wheel architecture enables the RoboScooter to be produced in both a one-wheel-drive and two-wheel-drive versions. The two-wheel drive, which is complex and difficult with a more traditional location of the motor, offers many potential performance advantages.

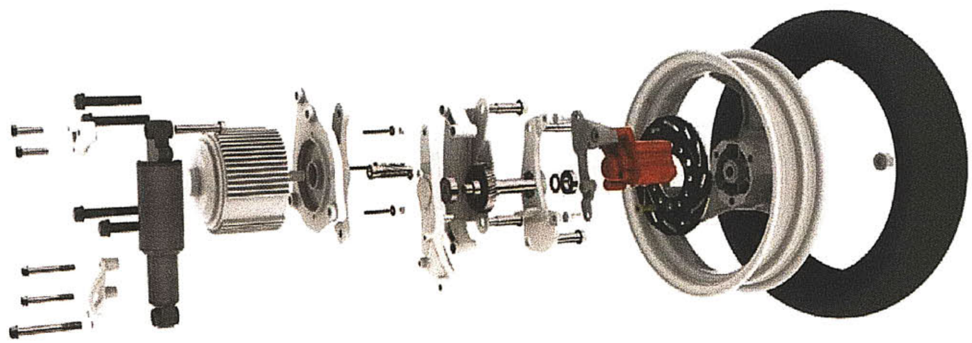


Fig. 6.1.1, exploded diagram of the RoboScooter Robot Wheel

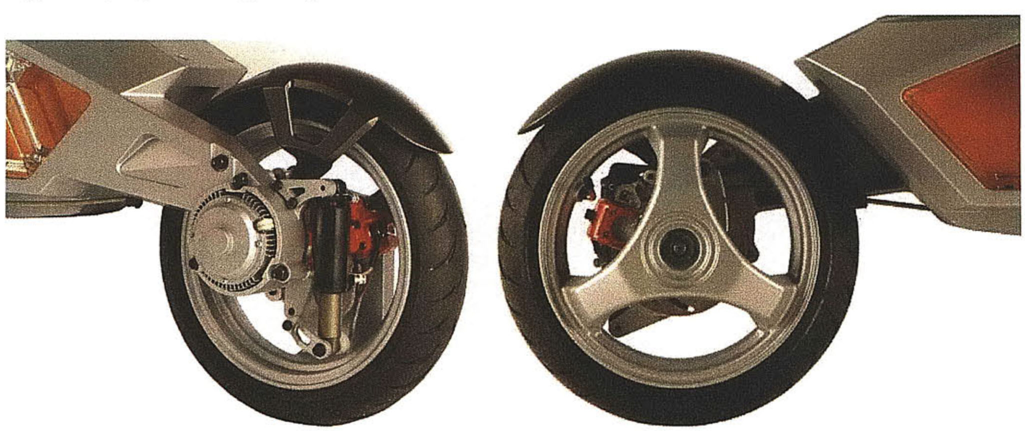


Fig. 6.1.2, final photos of the RoboScooter G1 Robot Wheel

6.1.3 Exposed Aluminum Frame

The RoboScooter has a structurally optimized exposed aluminum frame. Plastic and sheet metal panels are minimized. This gives the scooter a unique look and feel, and showcases its innovative character.

Furthermore, this structural principle, combined with the use of the electric robot wheel, greatly reduces the number of parts in the RoboScooter as compared to the more traditionally designed scooters. This enables significant manufacturing economies and makes the RoboScooter an extremely economical vehicle to produce. Fig. 6.1.2 shows the front aluminum frame of the RoboScooter. The structure contains two wall structures on the side and the rib shape reinforces structures in between the side walls.

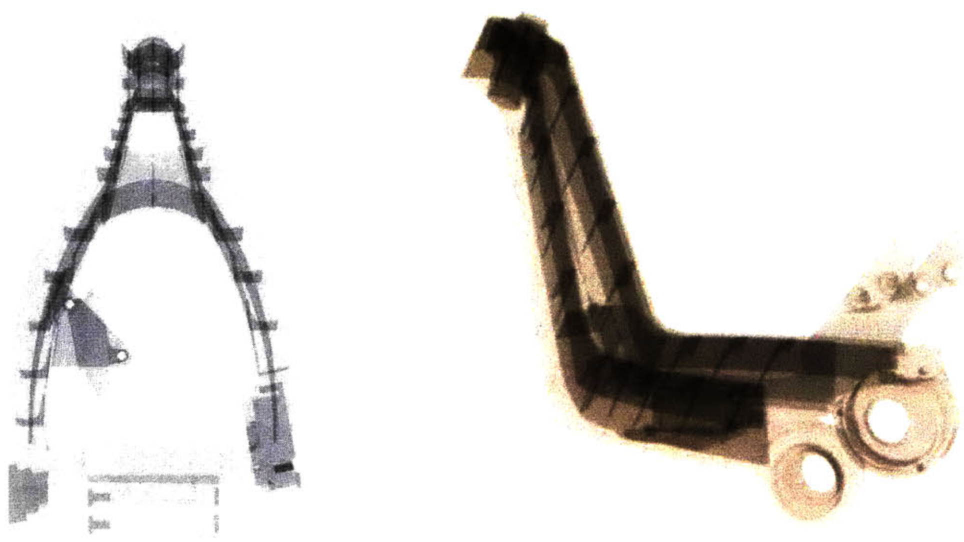


Fig. 6.1.2 renders of the front frame structure

6.1.4 Intelligence

Fig. 6.1.3 is the photo of the RoboScooter control console. The RoboScooter makes maximum use of digital control technology which is highly synergistic with its robot wheel architecture. Its overall effect is not only to provide excellent performance, but also to simplify and lighten the scooter. The RoboScooter is equipped with GPS navigation, and provides a unique, single-screen display for all driver information – eliminating traditional dials and indicator lights.

Fig. 6.1.3, final photo of the RoboScooter control console

6.1.5 Folding

Once folded, a RoboScooter is no larger than a trolley suitcase, and it can easily be rolled along with a small amount of power assist from its wheels. It can be carried onto trains, and can be compactly stored indoors. Folding is accomplished by means of a special central pivot which shifts the wheels in and out of alignment as required.

Folding is automatic and powered by the wheel motors. It does not require manual effort by the user. For extreme compactness when parked, the RoboScooter folds to half its size. This greatly reduces scooter parking space requirements – a crucial feature in cities where scooter parking space is insufficient to meet the demand, and cannot easily be expanded. Fig. 6.1.4 shows the folding sequence of the RoboScooter.

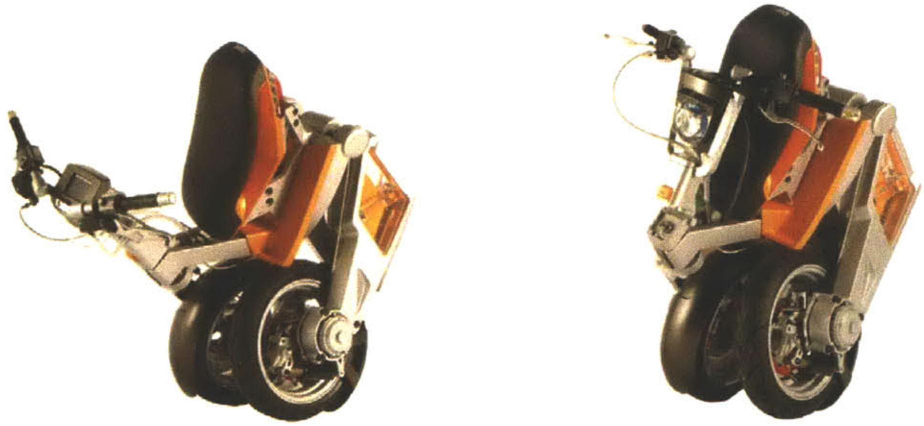


Fig. 6.1.4, the folding sequence of the RoboScooter

6.2 Shared-Use Model

The RoboScooter is also designed to be effective in one-way, shared-use mobility systems, similar to the one-way bicycle rental system that has recently been successfully implemented on a large scale in Paris.

Fig. 6.2.1, scenario of RoboScooter system utilizing the street sidewalk

In one-way shared-use systems, RoboScooters are available in parking-and-charging racks throughout the city. When a user wants to go somewhere, the user just swipes a credit card to unhook a scooter from its rack, drives it to where they want to go, and drops it off again at another rack. It is like having valet parking everywhere.

Fig. 6.2.2, scenario of RoboScooter system utilizing existing urban plaza

Because of the compactness of the RoboScooter system, it can be adopt to different existing urban spaces. As we can see in the fig. 6.2.2, currently most of the plaza inside the mid-evil ring of the Folorence city had been transformed into parking spaces. The RoboScooter system could provides an alternative transportation solution for the vehicles that are going into the city. Travelers would rent a scooter on the outskirt of the city, roam around the city with these share used RoboScooters. This provides an opportunity to reduce the vehicle congestion inside the popular historic plazas and return it to the local community.

Fig. 6.2.3, scenario of the RoboScooter system utilizing the existing public transportation system, Duomo Station in Milan, Italy

The one-way shared-use model is particularly effective in highly congested urban centers and in synergistic combination with transit systems – where scooter racks can be located at transit stops. The scenario above illustrates the RoboScooter Mobility-On-Demand system installed at the entrance of the Milan metro system.

6.3 Summary

The RoboScooter is designed to be easy, safe, and fun to ride. It is inherently economical to produce and operate. Its use of electric rather than gasoline power, its extreme compactness, and its suitability for use in shared-use systems provide many environmental advantages. This makes it particularly attractive for use in todays increasingly congested, noisy, and polluted urban areas.

The clean, light, robot-wheeled RoboScooter provides a new kind of riding experience, and should be particularly appealing to young, environmentally conscious scooter riders.

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