Modular Vehicle Design Concept

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(ABSTRACT)

Outlined herein is the Modular Vehicle [MODV] concept as a cost effective, utilitarian, and highly functional vehicle concept for the changing demands placed on a MAGTF[Marine Air-Ground Task Force] or SP-MAGTF [Special Purpose Marine Air-Ground Task Force] in the 21st century. A large focus is put on the importance of modularity and cost effectiveness of having a 24 hour configurable vehicle to a specific mission and area of operation. Off-road vehicle progression through history is presented and successful design features are noted in order to develop underlying goals for the modular vehicle. The thesis emphasizes recent technology advancements that can shift the foundations of vehicle design including wheel hub motors, high capacity batteries, solid oxide fuel cells, autonomy, structural health monitoring, energy harvesting shock absorbers, non-pneumatic tires, and drive-by-wire options. Predictions on the outlook for the technology progressions is discussed to give insight into the viability of basing a vehicle concept on these technologies. Finally, physical design bounds are presented to provide a foundation for the future design of such a vehicle.

Dedication

This thesis is dedicated to the men and women of the United States Armed Forces. The main motivation in the many hours of research and writing was knowing that this thesis may contribute to their safety in some capacity. Taking an oath to defend the United States in a time of need is a great sacrifice and service to our citizens. I hope this work gives back in some way to the people who have served, are serving, or will serve in the future.

Acknowledgments

I would like to thank the Marine Corps Warfighting Laboratory for supporting this work and my education through the Mechatronics Lab. Without their help this thesis would not have been possible. Putting my time and energy into a new vehicle concept was incredibly challenging, rewarding, and enjoyable. In many ways this project felt like a dream job, and I feel very fortunate to have been a part of it.

Dr. Alfred Wicks was instrumental in this project, and I want to thank him for giving me this task. His guidance was crucial in bounding the work on my thesis, and defining the project goals. I believe all of the Mechatronics Lab members would join me in saying his leadership has been a great asset to the success of our projects.

The Mechatronics Lab members are a great team and I thank them for promoting a workplace of innovation and respect. I will remember the productive environment at the lab and strive to impact my future places of work in the same way.

Finally, this project along with many other things in my life would not have been possible without the support of my family, the love of my wife, or the grace of God.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

For the past century the world's militaries have been deeply involved in finding ground vehicles that can support a nation's fighting ability on the ground. Locomotives, trucks, tanks, armored personnel carriers, and general utility vehicles have been the most common ones. It is always in a nation's interest to have the best types of these vehicles to obtain advantages in combat and supply.

To help gain the initiative in vehicle technology engineers are employed to improve existing designs and advance the state of the art. With today's rate of technological advancement it is as important now as it ever has been to maintain vehicles that exploit the cutting edge of technology. The goal of this paper is to present a vehicle concept to meet our nation's need for enhanced vehicle technology.

Today's conflicts are different from the conventional ones in the past. Today's warfighters need vehicles that can meet the diverse demands of fighting unconventional foes in almost every terrain and environment this world has. To meet this need most vehicles are designed to perform in this wide range but at the cost of being exceptionally well at negotiating any specific terrain. For example both tracked and wheeled vehicles can be made to adequately perform on roads, soil, snow, and sand but the designs will have to make compromises in performance on one terrain to properly negotiate another terrain. The wheeled vehicle design will have to give up road performance to perform adequately in snow, and vice versa for the tracked vehicles.

The optimal solution for this design problem is to have a modular vehicle that can be configured to overcome diverse terrain demands. This is where the Modular Vehicle concept is realized. A small utility vehicle that can be configured to perform exceptionally in any climate and terrain combination within a 24 hour period will meet the needs of a MAGTF.

Besides being mission configurable, a tenant of the MODV is to utilize the latest in engineering technology and stay relevant as technology advances in the following years. Wheel hub motors, high capacity batteries, advanced autonomy, and system health monitoring are all on the cutting edge of available technology. Since they are all advancing at a rapid pace the MODV concept is based on where these technologies will be within the next five years. Also, due to its modular design the MODV configuration components can easily be redesigned as needed and replace any components that become obsolete in the next 20 years.

1.2 Modular Vehicle Concept Overview

With the changing needs of a Marine Air Ground Task Force and today's warfighter a new utility vehicle is needed to support ground missions. Herein will be presented a vehicle concept that aims at performing in a diverse selection of environment and terrain combinations. The motivations for such a vehicle will be explained, an overview of the concept will be outlined, and the technologies the concept utilizes will be listed. A large focus will be put on the modularity and cost effectiveness of having a 24 hour configurable vehicle to a specific mission and area of operation.

1.2.1 Motivation

The conflicts the United States currently deals with today are mostly against non-conventional forces operating in a diverse set of terrain and climate conditions. The need to be in a dry mountainous area one day and a tropical wetland the next creates a great need for ground vehicles that can handle a long list of terrain challenges. Creating one vehicle design that can negotiate all terrain types yields an ATV that operates good in many terrains, but not exceptional in any specific terrain. This is the main motivation for the Modular Vehicle (MODV) concept, a vehicle that is 24 hour configurable to handle any type of climate and terrain combination.

Currently the Marine Corps has the ITV slotted to be its light strike vehicle but it has incurred many technical difficulties. Meeting the requirements to have an internally transportable vehicle in a V-22 Osprey is a monumental task using conventional vehicle design techniques, so thinking out of the box conceptually may be fruitful. The MODV concept is centered around utilizing advanced technologies to shift the foundations of vehicle design in order to meet the internally transportable requirements.

Another motivation for the MODV is the rate at which technology is advancing. There are current innovations that are not being utilized in vehicle design such as wheel hub motors, health monitoring systems, high capacity batteries, and advanced autonomy. The MODV concept is based around where these technologies will reach in the next 5 years to capitalize on the technological advancements in a timely manner.

Lastly, there are monetary motivations for the MODV given the recent trends in the political climate. The current outlook is that the US military will be smaller and cost less, but have advanced technology to make up for the smaller size. The MODV concept fits this future outlook.

1.2.2 Concept Highlights

The MODV will be a vehicle that is mission configurable in 24 hours. It will be very easy to change the vehicle from a wheeled to tracked configuration by simply swapping out the traction components. This idea is illustrated in Figure 1.1. Since wheel hub motors eliminate the need for a drivetrain all that will be needed for component changing is to physically mount the component to the frame, hook up the power cables, and hook up the communications cables. A wheeled configuration will simply have some wheels with the hub motors inside, and a tracked configuration can conceivably have a hub motor driving the main drive sprocket. Figure 1.2 shows the Polaris Ranger XP 900 in the wheeled and tracked configurations and is a real world implementation of a similar idea.

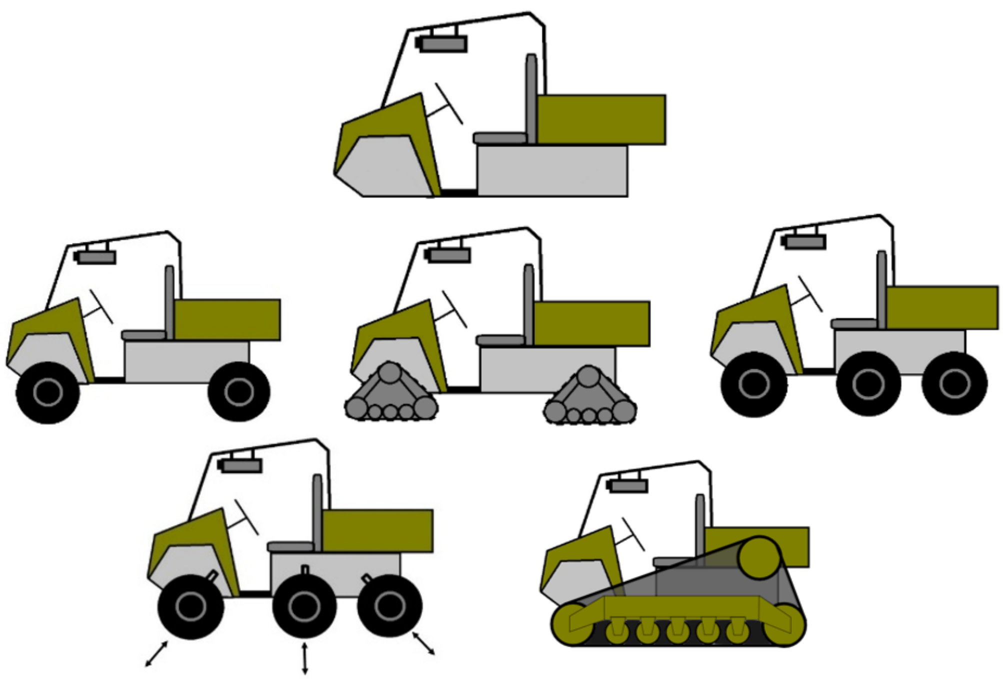

Figure 1.1: Possible traction configurations of the Modular Vehicle

Another advantage of this concept is the efficient transfer of energy. Power transfer from the batteries to the hub motors will be through electrical means and a higher efficiency will be achieved than conventional vehicles using a mechanical transfer of power. The motors themselves achieve efficiencies of 75% to 95% depending on the operating torque and rpm.

Figure 1.2: Polaris Ranger XP 900 wheeled and tracked configurations, http://www.polaris .com/en-us/home.aspx, 2014

The MODV's role in the Marine Corps would be like the Ground Unmanned Support Surrogate (GUSS) but smaller, faster, more energy efficient, and mission configurable. It will have autonomous capabilities, "follow me" capabilities, and a silent operation mode to fit whatever role the Marines need for the mission. It will be able to autonomously haul supplies from a FOB, evacuate casualties, or follow Marines with their gear. For the silent mode the MODV would make use of its quiet hub motors while Marines drive it to their destination undetected. It is also conceivable that the MODV would be used in an unmanned reconnaissance role, where a user can have the MODV silently survey an area and use its advanced sensor suite to scan the area for enemy activity. Figure 1.3 shows a summary of features, components, and configurations that are envisioned for this concept, and Figure 1.4 gives an idea as to what configuration options for a specific mission may be available.

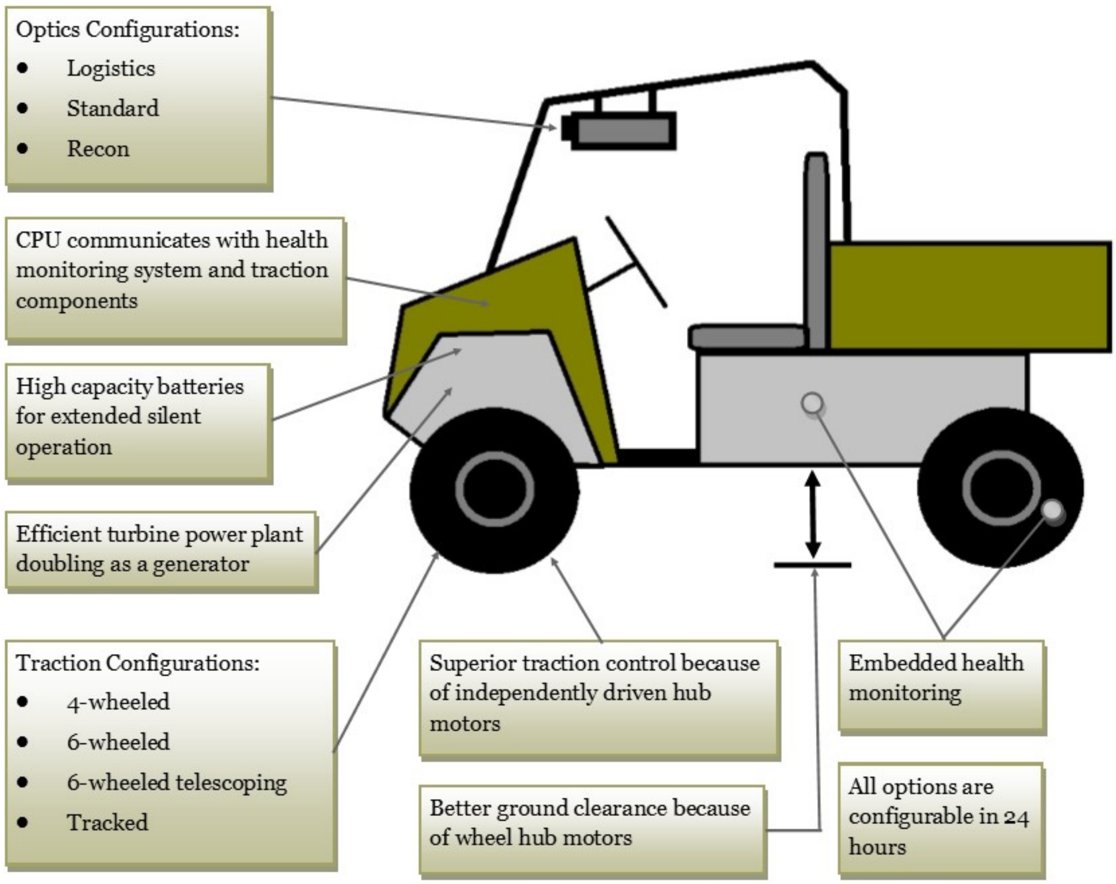

Figure 1.3: Modular Vehicle features, modules, and highlights

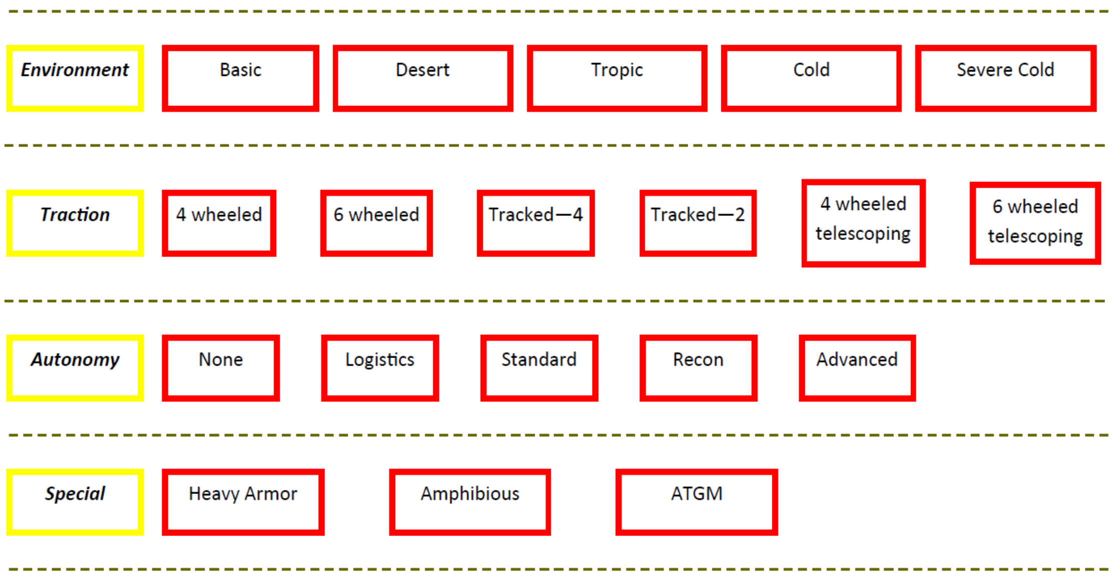

Figure 1.4: Modules available for vehicle configurations

Regarding the MODV's power specifications, it will easily be able to go 40 mph and have a payload of 1700 lbs (including passengers) with a 30 to 40 kW power plant. In fact 20 kW would adequately achieve this goal. Figure 1.5 shows the power required at the power source as a function of the maximum velocity. For this graph the calculations were based on a Polaris Ranger XP 900 since this vehicle is representative of the size and weight of the MODV, and they were made assuming an 80% energy loss from the power source to the wheels. For a reference, 25 m/s is about 55 mph, 18 m/s is about 40 mph.

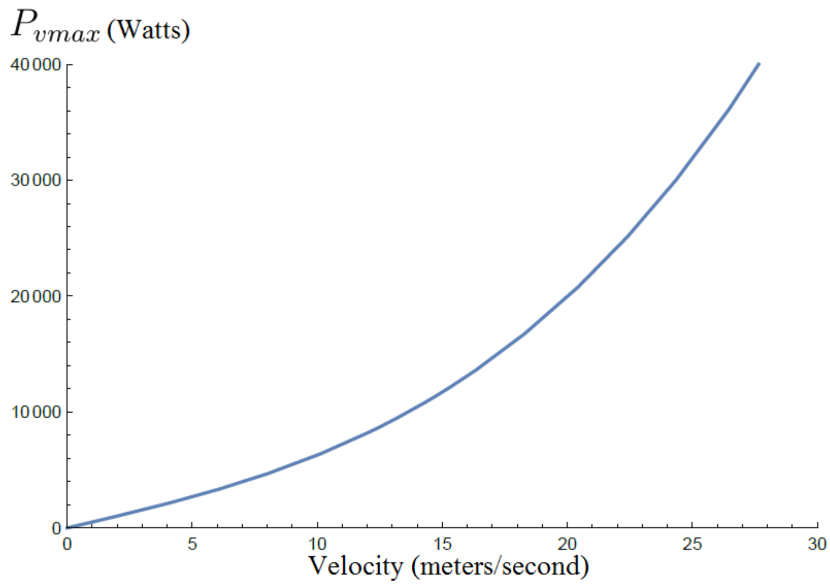

Figure 1.5: Power required at the power source as a function of maximum speed

Another strength of the MODV concept is the cost savings over current vehicles. The wheel hub motors free this vehicle from a transmission and drivetrain which will help reduce the overall unit cost and replacement part cost. It is also worth noting that the modularity of the MODV allows for the purchase of less vehicles. The MODV will be mission capable in any climate and terrain combination so all that is needed is to buy the respective components for the mission. Therefore the Marines would not need vehicles dedicated to a certain mission. All of these aspects of the MODV concept lead to a cost effective solution which is becoming a larger concern in today's political climate.

Last but not least is the vehicle's ability to be used as a mobile power generator for expeditionary power. The same high efficiency power plant and battery system used to propel the vehicle will be easily accessed to power Marine FOBs, recharge batteries, power laptops, and meet whatever other power needs arise. Of course, there will always be the need for dedicated FOB generators but having the ability to adapt to power needs by using vehicles on hand will always be an asset. When the MODVs are not in operation they can be parked and hooked up to the power system to provide up to 20-40 kW of power per vehicle. This aspect of the MODV offers tremendous advantages because it serves as an efficient generator in addition to its main role.

It is conceivable that the current tactical generators (which are quite heavy) would not be needed for longer missions if the Marines can use the vehicle to charge batteries. This means less batteries need to be packed for a certain mission which leads to sizable weight savings, or a higher weight budget for other supplies. It will also be possible for a MODV to have a refrigeration unit to store blood, a resource that when needed is needed immediately.

Having a quality, efficient power source wherever there is a vehicle is extremely advantageous to any mission and designing this feature into the MODV will come naturally. Since the MODV is a hybrid it will already need to have an efficient generation system to power the vehicle. All that would be required is to design external 'points of access' to hook up batteries or plug the MODV into a power network.

1.2.3 Designed for Technology Advancements

The MODV's terrain negotiation configurations are based largely around the wheel hub motor. The hub motor allows some non-conventional designs to be viable, and largely contributes to the modularity of the vehicle. Currently there are companies that have already developed vehicle designs around the hub motor and it is likely that there will be hub motors of the same quality available in the 10 kW range for the MODV in the next 5 years. Hobbyists are already putting wheel hub motors on their bicycles that are in the 10 kW range but these motors are not necessarily going to meet the heavy demands of military use.

Another technology advancement to consider is the performance of batteries. Battery performance will most definitely be advancing and therefore the MODV's design will take advantage of this. The size and weight budget for batteries in the MODV will be specified with regards to current battery performance. This means that in the future the MODV's silent operation range, energy density, and overall performance will improve as battery technology improves. All this would require is occasional upgrades. It would also be reasonable to specify the weight and space budget for the batteries based on where the technology will be in a few years as opposed to where it is right now.

One area of research that is currently receiving ample funding and attention is health monitoring. Currently the aerospace and civil infrastructure industries are largely invested, but it is something that will offer great advantages in the field of vehicle design. If a network of small sensors was integrated into the design of a ground vehicle then maintenance would be streamlined. Parts would not break down in the field because technicians would be alerted to maintenance needs beforehand and replace the part. The MODV will be designed to take advantage of this emerging field and incorporate a "nervous system" into the vehicle so the Marine Corps can have a logistically efficient vehicle.

Lastly the MODV concept will take into consideration the expected advances in autonomy. These advances would be easily adapted to with the replacement of the sensor suite and upgraded software in the MODV's CPU. Advanced autonomy is probably one of the easier technologies to keep up with since upgrading software and sensors has been done fairly easily with aircraft such as the F-16 and A-10.

1.2.4 Concept Conclusion

The MODV concept is aimed at being an adaptive, cost effective, mission configurable utility vehicle to meet the needs of current and future Marines. If a MAGTF is given the task of fighting in mountainous dry conditions one day and swampy humid conditions the next the MODV will be able to fit the utility vehicle role. It will be configurable to haul supplies or evacuate casualties autonomously, follow Marines with their gear, be operated manually like a normal ATV, or be an unmanned reconnaissance vehicle. The MODV will be cost efficient because of its rugged and adaptable design. Logistical strain will be minimized with the easily changeable components and health monitoring system. Overall, this concept is aimed at fulfilling what the Marines need now and staying relevant for what they will need in the coming decades.

1.3 Vehicle Progression Through History

For any engineering project it is important to investigate previous work to make the most of the advancements other engineers have made. For the MODV it will be helpful to look at successful vehicles throughout history that have developed excellent reputations for being highly mobile, reliable, and overall engineering feats. Since a focus of the MODV will be configurability to a certain terrain, many of these vehicles can serve as an inspiration to different traction systems. Many are rugged 4 x 4 utility vehicles that operate under the same traction principals, but they still stand as a testament to utilitarian design.

1.3.1 Jeep (Willys MB)

The Jeep is one of the most iconic American vehicles of all time, and showed the importance of a light utility vehicle. The Jeep boasts production numbers of over 600,000 of its main variants from 1941-1945. Its main strengths lie in the simple and rugged design. It could be used for towing, evacuating casualties, reconnaissance, and transportation. Overall, the Jeep is a testament to the importance of a light, general purpose utility vehicle that can negotiate a wide array of terrains and fill multiple roles.

In Figure 1.6 some British Special Air Service personnel can be seen on their modified Jeeps. These Jeeps were used to facilitate surprise attacks on Axis airfields in the North Africa Campaign of World War II. One of their highlights was a series of three attacks on Axis airfields that resulted in 60 destroyed aircraft without any friendly losses. The mobility and ruggedness of the Jeep aided in these raids.

Figure 1.6: British SAS on a Jeep operating in North Africa during WWII, [1] D. Stubblebine, "British SAS on a Jeep." [Online]. Available: http://ww2db.com/ image.php?image_id=11772, Used under fair use 2014

Table 1.1: Jeep Specifications from [20], and [21]

Jeep (Willys MB)			
Type	Wheeled Utility	MMP (Clayey Soil)	N/A
Place of Origin	U.S.	Operational Range	285 mi
Weight	2,300lbs	Fueld Capacity	15 gal
Payload	1,200 lbs	Land Speed	65 mph
Length	10 ft 11 in	Water Speed	N/A
Width	5 ft 2 in	Gradability	60%
Height, (top down)	6 ft, (4 ft 4 in)	Turning radius	17 ft 6 in
Ground Clearance	8.75 in	Fording Depth	21 in
Crew	4	Max Ditch Width	x
Engine	60 hp	Max Vertical Obstacle	x

Relevance to the Modular Vehicle

The Jeep shows the importance of having a general purpose 4-wheeled vehicle that is rugged and easy to maintain. This would probably be the 'basic' configuration that could perform logistics, reconnaissance, 'follow me' and fill in wherever needed. The Jeep also highlights the importance of simplicity. This will be intrinsic in the MODV's design since it will have less moving parts than conventional vehicles. More than anything, the Jeep gives insight into how useful the overall MODV concept is. Except now, the 'do anything' vehicle can be configured to whatever role it is needed for.

1.3.2 M29 Weasel

The M29 Weasel's design was born out of a need for the 1st Special Service Force, or the Devil's Brigade, in WW II. The Devil's Brigade was originally formed to support Project Plough, an operation that would handicap some of Germany's key infrastructure components and hamper heavy water production in Norway. Geoffrey Pyke, the visionary for this project and the supporting units, called for a small tracked vehicle that could transport the commandos and their equipment across snow-covered terrain in the harsh Norwegian north. While the original mission was abandoned the Devil's brigade operated extensively in Italy and France, and the M29 Weasel became a favorite among U.S. troops in both the European and Pacific Theaters [28]. Figure 1.7 from [2] shows some men of the 10th Mountain Division in April of 1945 on a ski patrol in the Apennine Mountains.

Figure 1.7: Soldiers from the 10th Mountain Division in a M29 Weasel in the Apennine mountains during WWII, [2], M. Bourke-White, "10th Mountain Div." 1945. [Online]. Available: http://g503.com/ forums/viewtopic.php?f=24&t=195935, Used under fair use, 2014

The task to build the highly mobile vehicle was given to the Studebaker Company, and after 60 days a prototype was being tested. The vehicle's technical specifications can be seen in Table 1.2. The M29 was a small simple vehicle that could traverse through thick snow and other challenging terrain. Often times it would be used to resupply troops at the front lines when wheeled vehicles could not. It was also used as a radio, command, ambulance, signal line laying, and light cargo vehicle. A later revision, the M29C Water Weasel, improved the vehicle's amphibious capabilities and saw extensive use after the war.

The Weasel's post war performance proved useful in harsh arctic climates. In 1962, two

Table 1.2: M29 Weasel vehicle specifications

M29 Weasel			
Type	Tracked Utility	MMP (Clayey Soil)	27 kPa
Place of Origin	U.S.	Operational Range	165 mi
Weight	3,800 lbs	Fueld Capacity	35 gal
Payload	1,200 lbs	Land Speed	36 mph
Length	10 ft 6 in	Water Speed	4 mph
Width	5 ft 6 in	Gradability	100%
Height	4 ft 3 in	Turning radius	12 ft
Ground Clearance	11 in	Fording Depth	Will Float
Crew	4	Max Ditch Width	36 in
Engine	70 hp	Max Vertical Obstacle	24 in

1943 Weasels were used in the Vostok Traverse, a 3,000 km four month trip to reach the abandoned Russian base of Vostok in Antarctica. These Weasels were modified so the crews were not exposed to the elements, and they made the trek in a safe manner. This epic journey is a testament to the rugged design of the weasel as it saw four months of continuous use in arguably the harshest environment on earth [29].

The M29 can attribute its mobility to the wide tracks and relatively low weight. This results in a ground pressure of only 13 kPa (1.9 psi). For comparison, a human foot exerts 60 to 80 kPa on terrain. In reality, the Mean Maximum Pressure [MMP] of the M29 was measured to be 27 kPa as shown in Table 3.2. Nonetheless that is among the lowest values for MMP in off-road vehicles rivaling the Hägglunds Bv 206 which is renowned for its off-road capabilities.

Relevance to the Modular Vehicle

The M29 Weasel's performance in snow can give valuable insight into how an arctic/boggy configuration would be realized. The M29 has proven itself as a rigorous design that can withstand extreme abuse. This is evident in its wartime use as well as the Vostok Traverse. Few vehicles can boast such an outstanding performance in harsh conditions and have an overwhelming amount of data to prove it. It is therefore a wise decision to look to its design as an inspiration for an arctic/boggy configuration for the MODV.

The Weasel's effectiveness lies in its simplicity. It is small, relatively light, and has wide tracks. It has a large amount of small wheels running along large tracks. The M29 could get away with the longer track pitch because its max speed was 36 mph and finer tracks pitches are needed for fast vehicles. As mentioned before the M29 exerts a very small pressure on the ground, and if a tracked configuration similar to the Weasel was designed for the MODV it is conceivable that the MODV would have similar terrain negotiation capabilities. The MODV is only predicted to weight 3,000 lbs fully loaded which is less than the dry weight of the M29. It follows that if the MODV was fitted with similar tracks it would have equal or better off-road performance.

The M29 Weasel's design was born out of a need for a rugged and highly mobile vehicle to support fast attacks by elite troops, and such a design would be relevant for use by the Marine Corps. A 'highly mobile' MODV configuration would be an excellent force multiplier since it would allow travel over difficult terrain thereby increasing the amount of maneuverable terrain. For such a configuration it would be in the designer's best interest to look to the M29 for guidance.

1.3.3 TPz Fuchs

The Transportpanzer Fuchs (Fox) is a six-wheeled armored personnel carrier that was originally developed for the West German Bundeswehr in 1979. Its upgraded versions are still in use by Germany, the United Kingdom, the United States (as the M93 Fox), and the Netherlands. It was designed as an all purpose armored vehicle that could fill multiple roles so its concept bears resemblance to the MODV. It can be used for tasks such as reconnaissance, electronic warfare, bomb disposal, engineer transport, and troop transport. Adding or modifying the armor to fit the vehicle's role is not difficult since the armor is modular. It can be made lighter for use behind the lines, or up-armored if it is likely to encounter enemy fire. The Fuchs the German Army used in Afghanistan were the 1A8 variants which were up-armored for protection from IEDs. There are over 90 possible configurations for the TPz Fuchs and 32 have been utilized to this point, making it a highly adaptable platform.

Figure 1.8: TPz Fuchs in a standard configuration, [3] Military-Today, "TPz Fuchs." [Online]. Available: http://www.military-today.com/apc/transportpanzer_ fuchs.htm, Used under fair use, 2014

Table 1.3: TPz Fuchs vehicle specifications from [3], and [22]

TPz Fuchs			
Type	6 x 6 APC	MMP (Clayey Soil)	N/A
Place of Origin	Germany	Operational Range	500 mi
Weight	18.3 t	Fueld Capacity	103 gal
Payload	6 t	Land Speed	65 mph
Length	24 ft 1 in	Water Speed	6.2
Width	9 ft 9 in	Gradability	70%
Height	7 ft 9 in	Turning radius	55 ft 9 in
Ground Clearance	1 ft 5 in	Fording Depth	Will Float
Crew	2 + 10	Max Ditch Width	3 ft 7 in
Engine	320 hp	Max Vertical Obstacle	x

Relevance to the Modular Vehicle

The TPz Fuchs displays the usefulness of having an adaptable multi-role vehicle. Since the vehicle was designed with modularity in mind it is easily upgradeable for use in 2014, almost 35 years after it was introduced. The modularity of its armor is especially useful. This allowed the vehicle to take immediate advantage of advanced armor materials, reducing the vehicle's weight and improving its combat effectiveness. It can be armed with a MILAN anti-tank-guided missile system to take out heavy armor, or outfitted with the appropriate electronics to take a command role as the 1A2 variant. This same modularity is envisioned for the MODV. Not just for the armament and armor but for the traction components as well. The MODV will be able to fill multiple roles, be retrofitted with advance armor, and configured for the terrain types a MAGTF would be encountering on their next mission.

1.3.4 Multi-function Utility/Logistics and Equipment Vehicle

The Multi-function Utility/Logistics and Equipment Vehicle [MULE] was an autonomous unmanned vehicle developed by Lockheed Martin for the United States Army. This vehicle was meant to have multiple roles in which it could support the warfighter. Its main configurations were for counter-mine, light assault, and transport roles. Ultimately this program was canceled by 2011 by the DoD mostly because the vehicle wasn't flexible enough with its air-assault capabilities. It was internally transportable in a CH-47 but had to be slung under a UH-60 and the Army saw this as a deal breaker because of the changing focus of the Army. The original intent was for the Army to field 1,530 MULE vehicles and there were no major technical flaws cited for the reason of program closure in either [23] or [4].

Figure 1.9: MULE displaying the mobility of the shoulder joints, [4] Defense Update, “Multifunction Utility/Logistics and Equipment,” 2007. [Online]. Available: http://defense-update.com/products/m/mule-load-carrier.htm, Used under fair use, 2014

Table 1.4: MULE vehicle specifications, [4], [23]

MULE			
Type	Multi-role	MMP (Clayey Soil)	x
Place of Origin	U.S.	Operational Range	x
Weight	2.5 t	Fueld Capacity	x
Payload	1 t	Land Speed	43.5 mph
Length	x	Water Speed	x
Width	x	Gradability (side)	40%
Height	x	Turning radius	0
Ground Clearance	x	Fording Depth	0.5 m
Crew	0	Max Ditch Width	1 m
Engine	x	Max Vertical Obstacle	1 m

One very unique aspect of the MULE that distinguishes it from other vehicles is its suspension. Similar to the MODV concept the MULE had six wheel hub motors. The wheel hub motors allowed for the possibility of articulating shoulder joints to be used and gave the MULE a very flexible mobility platform. The MULE could change its ground clearance based on the terrain, and raise one side of the vehicle higher than the other allowing it to navigate up to a 40 % side slope. It could also handle vertical (wall) and horizontal (ditch crossing) steps of 1 meter by articulating the "arms" correctly as displayed in Figure 1.9. The MULE certainly offered a unique and impressive approach to tackling difficult terrain.

The MULE concept resembles the modularity that the MODV concept is centered around. It was meant to be a highly mobile multi-role vehicle that could transport gear and supplies, clear mines, and provide a light support for combat troops. It had autonomous capabilities in that it could enter a 'follow me' role or be directed via GPS to waypoints. The vehicle did however have a fixed suspension system where the MODV seeks to have a wide variety of configurations with its suspension.

Relevance to the MODV

Despite the program closure this project give valuable insight into a concept that is similar to the MODV. At the very least the MULE proves the value of a highly mobile multi-role utility vehicle. This project utilized wheel hub motors with great success and displayed how a unique suspension design can be achieved. If the MULE was able to use the wheel hub motors to fulfill military applications then they must be suitable for rugged off-road use.

If the United States Army was willing to spend the money and time it did and plan on buying 1,500 units then this idea must have some significant value. In the author's opinion this program's closure did not have to do with a flawed concept, but rather some specific shortcomings in the design and a changing budgetary situation within the DoD.

Chapter 2

Literature Review

In order to see if the MODV concept is viable a review of the technologies proposed is needed. Through many hours of reading the author has compiled a review of the technologies that includes their current capabilities, the advantages they offer, concerns engineers have in using them, and their relevance to the MODV concept.

For the MODV to fulfill the role of providing expeditionary power it is important to review battery technology and solid oxide fuel cells since they are important parts of an efficient and power supply system. The advancements in battery technology may allow for higher power and capacity, and solid oxide fuel cells offer significant gains in energy density and efficiency.

For extended silent operation solid oxide fuel cells and high capacity batteries will be considered since they meet the high-capacity-low-power needs of operating as an electric vehicle. Solid oxide fuel cells are very efficient systems and it is theorized they can reach efficiencies of 90% when coupled with other systems. Currently they are to large for use in a small ground vehicle but large corporations are investing large sums of money into advancing this technology so it is likely a relevant system could be produced within the next five years.

Since the MODV is centered around being a modular and adaptive vehicle, technologies that aid in achieving this goal will be reviewed as well. The capabilities and reliability of a drive by wire system must be considered because it allows for easy attachment of traction components. If the vehicle is drive by wire then control of the traction components will only require an electrical connection to be made instead of various mechanical connections. Wheel hub motors also help achieve modularity because they are externally mounted by nature. It is easy to imagine that changing from a four-wheeled to six-wheeled configuration would be made easy with wheel hub motors because all that is required is physically mounting the motor/suspension system to the chassis, and then connecting the power and control cables.

To achieve advanced mobility characteristics wheel hub motors and non-pneumatic tires will be considered. Wheel hub motors offer very precise control of a vehicle because each wheel can be given precise amounts of power in short order, something that is very challenging to achieve through mechanical means. They also offer better ground clearance since neither a power train or differential is needed, and allow for larger travel in the suspension. Non-pneumatic tires are very rugged tires that can take a beating beyond any pneumatic tire and naturally adapt to the terrain to maximize their footprint. They offer advantages to mobility in such a way that they are given their own section for review.

Technologies that can help achieve a logistics demand reduction are autonomy, structural health monitoring, and all of the technologies that aid in making the MODV modular and an expeditionary power source. Autonomy can allow for a vehicle such as the GUSS that can follow Marines with their gear and take the load off of their backs. It also allows for large amounts of unmanned vehicles to cart supplies around thereby reducing the need for Marines to drive the vehicles. Structural health monitoring allows the vehicle to have a 'nervous system' so component failure can be predicted, and maintenance streamlined. The technologies that aid in modularity also aid logistically because a highly reactive vehicle can be repurposed when the need arises, reducing the amount of vehicles needed. Batteries and solid oxide fuel cells can also provide logistical advantages simply because they improve the MODVs capabilities in providing expeditionary power. More vehicles providing power means less generators and would Allow the Marines to be highly reactive with their power needs.

The Literature Review chapter was written from mid to late 2014 so the reader may need to research these technologies further if enough time has passed to make the following information out of date.

2.1 Wheel Hub Motors

2.1.1 Overview

A wheel hub motor [WHM] is an electric motor that is integrated into the hub of a wheel and drives the wheel directly. Figure 2.1 displays the basic design of WHMs and how they utilize the space in a wheel hub.

A conventional way to drive the wheels of a ground vehicles is through a drivetrain where the power of the engine is transferred through the transmission and a series of shafts and gears. This results in about 60% to 80% power transfer efficiency from the engine to the wheels and adds extra weight to the vehicle. Spatial design restrictions are also implemented using this method. This results in lower ground clearances, and reduced space for passengers, payload, and batteries in the case of hybrid vehicles.

Figure 2.1: Design of a wheel hub motor for automotive use attached to a suspension, [5], C. J. Ifedi, B. C. Mecrow, S. T. M. Brockway, G. S. Boast, G. J. Atkinson, and D. Kostic-Perovic, "Fault-Tolerant In-Wheel Motor Topologies for High-Performance Electric Vehicles," IEEE Transactions on Industry Applications, vol. 49, no. 3, pp. 1249–1257, May 2013. Used under fair use, 2014

With a hub motor much higher efficiencies can be achieved. First, electrical energy is transferred to the hub motors through wires where the energy loss is very low. This is a large advantage over the conventional method because the power transfer efficiency to the wheel is already superior. Once the energy is at the electric motors their high efficiency can be utilized. The wheel hub motor from [6] is very efficient and has typical efficiencies of 75% to 95% based on the operational torque and rpm. This WHM is made by Siemens and has an efficiency graph as seen in Figure 2.2.

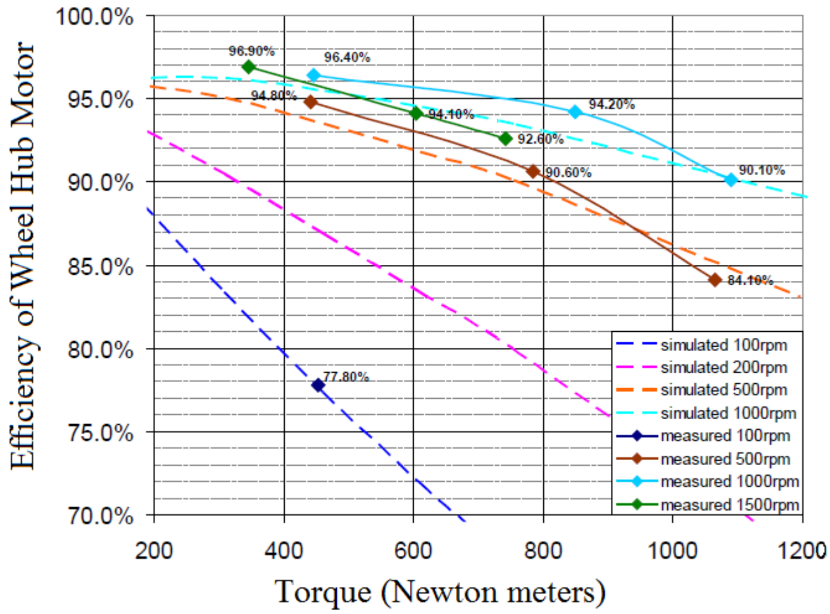

Figure 2.2: Efficiency lines of a wheel hub motor comparing simulated and measured efficiencies, [6] G. Freitag, M. Klopzig, K. Schleicher, M. Wilke, and M. Schramm, "High-performance and highly efficient electric wheel hub drive in automotive design," in 2013 3rd International Electric Drives Production Conference (EDPC). IEEE, Oct. 2013, pp. 1–7, Used under fair use, 2014

There are more advantages to the hub motor than just efficient energy use. Utilizing them in the design of a ground vehicle opens up design considerations that were not viable before. Driving wheel hub motors with batteries through wires results in large weight and space savings in the vehicle namely from the drive train and transmission. Higher ground clearance can be achieved, and the wheels are not fixed to a limited range of motion. The unique positioning of WHMs is displayed in the MULE vehicle in section 1.3.4. There are also higher space and weight budgets for batteries which is always advantageous for a hybrid electric vehicle.

Overall, the electric WHM allows for significant advantages in efficiency, space, and weight that were not available with previous ground vehicle designs and further advance the utility of a hybrid vehicle.

2.1.2 Current State of Wheel Hub Motors

Performance Specifications

The current performance characteristics of WHMs is well above what would be required for the MODV. The MODV will only need about 10 kW for each wheel and the ones currently being tested on road vehicles have a continuous power of 63 kW and a peak power at 120 kW [6].The peak and continuous torque ratings were 1250 Nm and 500 Nm respectively, which are also more than adequate for the MODV to negotiate a 60% grade in sand.

There are currently WHMs in the 10 kW range made by EnerTrac (http://www.enertrac.net) used in motorcycles that can output 10 kW continuous and 30 kW peak. Torque specifications were not provided so it cannot be stated if these motors would be valid for use in the MODV. It is safe to state that if WHMs are already being mass produced with these specifications then there should be ones that meet the performance requirements for the MODV in the future, and this will be covered further in section 4.1.1.

Fault Tolerance

One issue of concern for WHM technology is the drag torque associated with degradation of the motor. If a WHM were to have internal changes in the windings as a result of extensive use or otherwise, it induces inefficiencies in the motor. If this happens while the vehicle is stationary there is no safety risk but if it were to happen while going 70 mph down the highway it will effect the stability of the vehicle. In order to prove that a WHM will be safe in this situation the authors of [5] performed extensive tests on the *Protean Electric in-wheel propulsion system*.

The standard for an unsafe drag torque is 280 Nm for 100 ms. In this study the single-phase, three-phase, and interturn faults had peak drag torques of 17 Nm, 50 Nm, and 2 Nm respectively. These are all well below the safety standard.

The fault tolerance of this specific WHM is aided by its physical design. The motor was divided into a series of eight independent submotors which helps reduce the fault currents. It was predicted that without this division the fault torque would be around 400 Nm which is well over the safety limit. For applications in the MODV the fault tolerance is satisfactory with the current technology.

Sealing

If WHMs are going to be on the MODV and in use for off road uses they will obviously need to have proper sealing from debris and water. WHMs are electric motors inside of the wheel so engineers instinctively worry that there will be sealing issues. As listed in [6] the Siemens

WHMs have an environmental protection class of IP67. This means they are dust tight and can be immersed in 1 m of water for 30 minutes.

There is currently a company called *e-Traction* (`http://www.e-traction.eu/en/`) that has performed extensive real world tests with their WHMs. They have been tested on public buses in the demanding winter conditions of northern Sweden and have performed exceptionally well. The unique ability to individually control each motor allows these buses to have good performance on icy roads which is very useful in colder climates. This company's application of their WHMs stands as a testament to the current environmental protection available.

More extensive testing should be performed on any WHM considered for the MODV the insure its operational capabilities. IP67 is without a doubt a good place to start, but these WHMs could potentially be submersed in over 1 m of water. This will be especially important if the WHMs will be placed on a telescoping wheel configuration.

Cooling

Cooling is a concern for any engine or motor and WHMs are no exception. One has to wonder if a powerful electric motor completely sealed off from the elements will be able to properly dissipate heat from energy loss. It is therefore important to discuss the information pertaining to this concern and offer evidence of the cooling measures built into WHMs.

A sophisticated FEM model was used in [30] to evaluated the energy losses in a WHM as a function of winding and stator temperature. While this article wasn't necessarily about the WHMs cooling measures it does show that rigorous analysis on the operating temperatures of WHMs has been performed. Comprehensive efficiency maps were generated showing the effects of temperature, rpm, and torque. Besides being evidence for the WHM cooling ability, this article should provide useful for engineers considering energy losses and power requirements for the MODV.

Another case was made for proper cooling in [6]. The WHM presented in this article delivered slightly more continuous torque than specified with a temperature rise of 100 K in the windings and 30 K in the magnets. This is only a moderate temperature increase and is less than modeled in [30]. The WHM achieves this through water jacket cooling which has proven to be adequate in the above test.

Through the articles presented it is evident that WHMs are already designed with proper cooling in mind, and will likely be more efficient in the future because of the performance benefits. It must also be considered that the engineers designing the WHMs are aware of the importance of cooling and would not deliver a product with a cooling handicap.

Concerns over Unsprung Mass

It is conventional wisdom among vehicle design engineers that adding unsprung mass, or mass that is not supported by the suspension, will adversely effect the handling characteristics of a vehicle. Since WHMs can have over 30 kg of unsprung mass there is a perception that the vehicle's handling characteristics might become unsatisfactory.

In [7] several approaches were used to tackle this concern. Subjective tests, objective tests, and numerical analysis were all presented as a multi-faced evaluation on the effects a WHM has on driveability.

The subjective tests used the "Vehicle Evaluation Rating" which is a standard for the automotive industry. A 2007 Ford Focus had 30 kg of extra mass added at each wheel, and was distributed in such a way that would largely replicate a Protean Electric PD18. The exact results with respect to ride, handling and steering are discussed in detail in the article. Essentially, certain aspects of ride and steering were effected while the handling remained largely the same. The components of ride and steering were not effected to the point where the vehicle was undriveable, and could be greatly improved upon in later design iterations. It is important to note that the vehicle's suspension was not designed with the added unsprung mass in mind. Accounting for this unsprung mass would greatly improve the ride and steering evaluations.

For the objective measurements accelerometers were attached to key locations on the wheel and suspension to obtain acceleration data. From the data shown in [7] it is clear that the ride behavior is not dramatically altered. The results do confirm the subjective evaluations in ride and handling and do not reveal any alarming data.

For the numerical analysis a two degree-of-freedom double spring-mass-damper system was used. Sprung mass, unsprung mass, spring rate, and damping coefficient were the variables for the system. The system from the study is shown in Figure 2.3, where z_u and z_s are the displacements of the unsprung and sprung mass respectively, k_t and k_s are the stiffness values of the tire and suspension, b_t and b_s are the damping coefficients of the tire and suspension, and u is the forcing function.

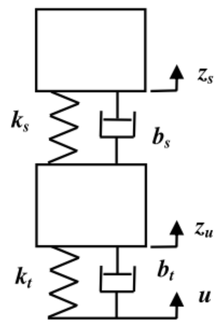

Figure 2.3: Two degree-of-freedom system simulated in [7] to analyze unsprung weight effect on vehicle ride, M. Anderson and D. Harty, "Unsprung mass with in-wheel motors-myths and realities," 10th International Symposium on Advanced Vehicle . . . , pp. 261–266, 2010. Used under fair use, 2014

The concern that arises over increasing the unsprung mass is that the force transmissibility to the sprung mass will increase. To understand how this increase in transmissibility will effect the operator Key Performance Indicators [KPI] were calculated for ride, refinement, active safety and driveability. The main conclusions for ride and active safety KPIs was that the influence of unsprung mass is minimal when compared to the road surface roughness. For refinement is was concluded that an optimization in suspension design could gain back any KPI loss. As for driveability the WHMs offer great benefits that can push the KPIs to top level performance and make up for any KPI degradation due to unsprung mass.

This discussion on the effect of unsprung mass on the driveability of a vehicle using WHMs should dispel any concerns with regard to vehicle handling characteristics. The benefits WHMs offer are worth the refinements required in suspension design and vehicle architecture. More articles can be found in the citations section of [7] and [5].

2.1.3 Importance to the MODV

As mentioned before wheel hub motors offer many advantages for the MODV concept. Since they are essentially an eternal power source for motion they help achieve the end goal of modularity. With no need for a powertrain or any mechanical connections to be made for power transfer it would make it easier to change the traction configuration. It could be as simple as making the physical connection of the WHM/suspension system to the chassis, and connecting the power and control cables.

Since the WHMs can offer advantages to making a modular system, it follows that they help achieve a logistics demand reduction. A modular fleet of vehicles that can be repurposed to the changing needs of a mission allows for less vehicles and a fluid change to demands.

WHMs also aid in advanced terrain negotiation. Firstly, they eliminate the need for a drivetrain thereby saving space and weight and increase the ground clearance. The ground clearance improvement can be thought of in two ways. The vehicle can either achieve an improved ground clearance for a given center of gravity, or it can have a lower center of gravity for a given ground clearance. The choice is up to the design team and either way the mobility will be improved. Secondly, the WHMs allow for precise control of each individual wheel, a feat that is difficult to achieve with conventional systems. This allows for the right amount of power to go to the wheels that have the best traction, thereby reducing the chance tires will 'spin out' if they go over very soft or slippery terrain. Thirdly, WHMs allow for some unconventional suspension designs. Telescoping wheels are now a viable design to consider which can help negotiate ditches, and could even help meet the internally transportable vehicle requirements that are a cornerstone of the MODV concept.

All in all, wheel hub motors offer performance and design improvements throughout the entire spectrum. They should be given serious consideration for the wheeled configurations and should in the very least be tested and experimented with to evaluate their performance.

2.2 Batteries

Batteries are very important for the MODV since it will be a hybrid-electric vehicle. The need for a better battery is a significant issue in society today because our technology revolves around batteries and their capabilities. Any designer or engineer will be interested in the current capabilities of batteries and how they can be utilized in the design of the MODV, so the following section is presented.

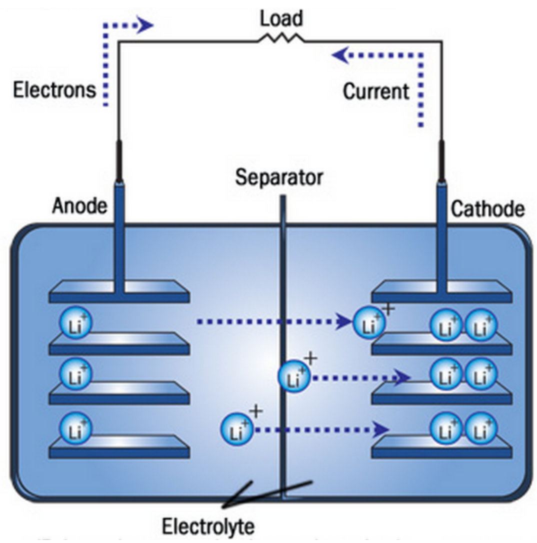

Figure 2.4: Lithium-ion rechargeable battery discharging, [8], H. S. Works, “Lithium-ion Battery Discharge.” [Online]. Available: http://electronics. howstuffworks.com /everyday-tech/lithium-ion-battery1.htm, Used under fair use, 2014

In order to jog the reader’s memory on the foundation of battery technology the process behind a lithium-ion battery is reviewed. As seen in Figure 2.4 the battery has an anode, cathode, separator, and electrolyte. The cathode is the terminal where the current exits the battery, and the anode is the terminal where electrons exits. Current is defined as positive in the opposite direction of the flow of electrons which is important to keep in mind because it seems counter intuitive. The anode is made of Lithium cobalt oxide in this case, and the cathode is made of carbon. When the battery is connected to a load current flows from the cathode and the positive lithium ions move to the cathode since it becomes negatively charged from the electrons. This attracts the positive ions in the form of Lithium. The separator keeps the anode and cathode from touching and but allows for the flow of ions. The ions flow through the electrolyte which is an organic solvent in this example [8].

2.2.1 Overview

Since the MODV will be a HEV [Hybrid Electric Vehicle] battery technology is a driving factor on the vehicle’s performance. It is the main hindrance of many HEV and EV [Electric Vehicle] designs in current commercial production because the vehicles have a limited range on battery-only operation. If a vehicle had batteries that matched the power and energy density of a tank of gasoline then the issue of range would disappear and the roads would be filled with EVs.

A battery with high energy density (Wh/kg) will improve a vehicle’s range because there is a large reserve of energy it can draw from. A battery with high power density (W/kg) can deliver high power which benefits a vehicle's acceleration and maximum speed. With current batteries there is always a trade-off between the two. A vehicle can have good acceleration and poor range or vice versa when only using one type of battery.

The MODV's use of batteries is unique in that it will have normal HEV operation where the batteries will be constantly charged, and also a silent operation where the power plant will be shut off and the vehicle takes on an EV role. During HEV operation it is best to have batteries with a high power density since they are constantly being charged and do not require a large capacity. On the other hand the EV operation would most benefit from a high energy density since the MODV would be able to operate in silent mode longer.

It is currently the goal of many research labs to push the limits of energy density and power density in batteries to meet high demand for better batteries. The demand for better battery technology is not limited to the automotive industry, in fact it is a demand that is almost ubiquitous. Any item that requires battery power would benefit from improved battery technology so it goes without saying that research and funding for better batteries will be present for the coming decades. For the needs of a MAGTF, better batteries means a significant logistics demand reduction because more energy and power can be transported with less space and weight. For the individual Marine this is also a benefit. Having enough batteries for radios on multi-day patrols can weigh down a group pretty quickly, and reducing this weight demand will only improve a Marine's effectiveness.

2.2.2 Battery Selection

As previously introduced batteries have a trade off between energy density (Wh/kg) and Power density (W/kg). Due to the chemistry of how a battery is designed they can be optimized more for power or energy, and as a result the batteries that have the best energy density have lower power density and vice versa. Batteries also have differing charge ranges that they can use. Some batteries can be deep discharged and retain high cycle life, while others have a limited range of discharge. Energy density, power density, and cycle life all affect the performance of a battery in a specific application and selecting the right combination is a challenging task that must be well thought out.

To give insight into battery applications in HEVs and EVs, it is necessary to further explain energy and power density.

Energy Density

Energy density is a measure of how much energy is present per unit weight or volume in a given battery. A high energy density is desirable for EVs or HEVs because they rely mostly on extended battery use. A vehicle designed for a typical daily commute that doesn't require high accelerations would use this type of battery. The silent operation mode on the MODV would benefit the most from this type of battery. Since stealth is the main goal of the silent operation the vehicle would not necessarily be going very fast or require high accelerations. It is also desirable that the range of the stealth mode would be sufficiently long so the vehicle wouldn't need to start its power plant at a bad time.

Power Density

Power density is a measure of how fast energy can be drawn from a battery per unit weight or volume. It is desirable for high accelerations, maintaining high top speeds, and towing up inclines. All of these aspects are extremely important for military and off road applications and can make or break a given vehicle. The MODV would benefit from a high power density when it is in normal use. When the power plant is recharging the batteries it doesn't necessarily matter that the batteries don't have the largest amount of energy. This way the vehicle would have a good reservoir of energy to draw from and still have adequate range.

Cycle Life

The cycle life of a battery is also an important consideration. The cycle life is the number of charge/discharge cycles a battery can go through before it is no longer usable. Regular use of the MODV would not see heavy charge/discharge cycles since the batteries are constantly being recharged. With the silent operation however the cycle life will play a factor. Extended use of the MODV without recharging will tax the batteries usable life.

Finding the Optimal Solution

The most likely solution for energy storage on the MODV will see a combination of batteries that either have high energy densities or high power densities. With a combined configuration the MODV CPU can switch where the power is being drawn from given the vehicle's current operation. If the vehicle is maintaining a low top speed it can switch the main power draw from the high energy density batteries. If a high acceleration is needed then the power can be drawn primarily from the high power density batteries. Finding the optimal battery combination will require calculations based on load histories the MODV would likely undergo.

2.2.3 Current Battery Performance

In order to properly predict where battery technology will reach in the next five years there must be a starting point. There are multiple kinds batteries utilized by today's vehicles. Lead acid, nickel metal-hydride, nickel-cadmium, and lithium-ion are the most commonly used, and Table 2.1 [9] displays some of the specifications for each battery type.

Table 2.1: Comparison of different battery chemistry types for use in ground vehicles, [9] W. Sutopo, D. I. Maryanie, a. Purwanto, and M. Nizam, "A comparative value chains analysis of battery technologies for electric vehicles," 2013 Joint International Conference on Rural Information & Communication Technology and Electric-Vehicle Technology (rICT & ICeV-T), pp. 1–5, Nov 2013. Used under fair use, 2014

Battery Type	Lead Acid	Ni-Cd	Ni-MH	Lithium -Ion
Energy Density[a] (Wh/Kg)	35	40-60	60	120
Power Density[b] (W/kg)	180	150	250-1000	1800
Cycle Life[c]	4500	2000	2000	3500
Cost ($/kWh)[d]	269	280	500-1000	1000-2000
Battery Characteristics	High reliability, low cost	Memory effect	Currently, best value and most popular battery for HEVs	Small size, light weight
Application	Car battery, forklift, golf cart, backup power	Replacement for Flashlight Battery	HEVs Replacement for Flashlight Battery	Consumer Electronics

Note (sources: Ref. [18], [20], [30], [33]):

a. Chargeable electric energy per weight of battery pack
b. Proportion of dischargeable electric energy to charged energy
c. The number of charging/discharging cycles in battery's entire life
d. Calculated exchange rate is $1=92,99 yen (05/14/2010)

Currently, the most commonly used battery in HEVs is the Ni-MH (Nickel Metal Hydride) type. It offers decent enough power and energy density at a reasonable cost compared to the Li-ion (Lithium Ion) batteries. For the consumer market cost is a driving factor so the Li-ion batteries have not been implemented. Cost is definitely a consideration for the batteries in the MODV but seeing as the Li-ion batteries offer superior performance these will most likely be used. It is also worth mentioning that the current research push is in Li-ion batteries and it is reasonable to expect improvements in performance and cost in the next five years [9].The following Figure 2.5 [9] displays the current trade off in Li-ion technologies. In this figure, life span is measured by the overall charge and discharge cycles along with the age the battery can reach, and performance refers to the peak power at low temperatures, charge measurement and thermal management. Cost is measured relative to other Li-ion batteries as is safety, and specific power and specific energy are simply the energy and power available per unit mass. From this diagram it is evident that the either Lithium-nickel-cobalt-aluminum or Lithium-nickel-manganese-cobalt batteries offer the best solution for military application. These batteries have the best overall performance for applications in a vehicle.

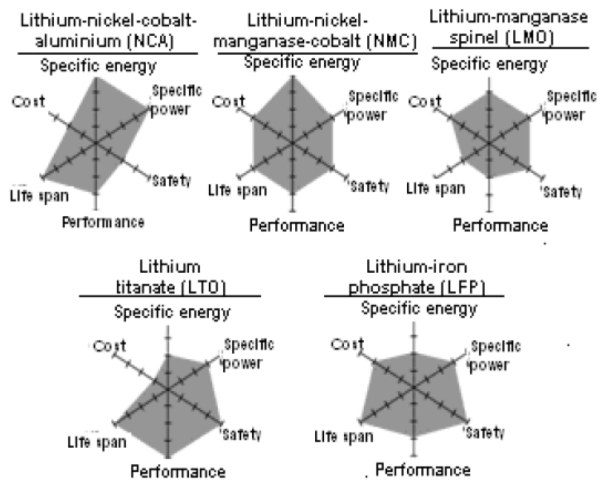

Figure 2.5: Comparing Li-ion battery types and relative strengths in specific energy, specific power, safety, performance, life span, and cost, [9] W. Sutopo, D. I. Maryanie, a. Purwanto, and M. Nizam, "A comparative value chains analysis of battery technologies for electric vehicles," 2013 Joint International Conference on Rural Information & Communication Technology and Electric-Vehicle Technology (rICT & ICeV-T), pp. 1–5, Nov 2013. Used under fair use, 2014

Table 2.2 [24] shows some of the current specifications for Lithium-Ion batteries compared to other batteries used in vehicles. It is easy to deduce that the Li-ion batteries have superior characteristics when compared to the Ni-MH batteries

Table 2.2: Battery technologies available for implementation in EVs and HEVs, [24] A. F. Burke, "Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles," Proceedings of the IEEE, vol. 95, no. 4, pp. 806–820, Apr. 2007. Used under fair use, 2014

Battery Technology	Applic. type	Ah	V	Wh/kg At C/3	Resist mOhm	W/kg Match. Imped.	W/kg 95%eff.	Useable SOC,
Lead-acid								
Panasonic	HEV	25	12	26.3	7.8	389	77	28%
Panasonic	EV	60	12	34.2	6.9	250	47	----
Nickel Metal Hydride								
Panasonic EV	EV	65	12	68	8.7	240	46	----
Panasonic EV	HEV	6.5	7.2	46	11.4	1093	207	40%
Ovonic	EV	85	13	68	10	200	40	----
Ovonic	HEV	12	12	45	10	1000	195	30%
Saft	HEV	14	1.2	47	1.1	900	172	30%
Lithium-ion								
Saft	HEV	12	4	77	7.0	1550	256	20%
Saft	EV	41	4	140	8.0	476	90	----
Shin-Kobe	EV	90	4	105	.93	1344	255	------
Shin-Kobe	HEV	4	4	56	3.4	3920	745	18%

Using the last Shin-Kobe battery, the 40 kW power requirement would be met with around 10 kg of batteries or 22 lbs. This is assuming the batteries are constantly being recharged in normal operation, and would not be used long on battery power alone. These batteries by themselves would only last 50 seconds on a 40 kW load and a final solution may have a larger amount of high power batteries to provide for a safety window of 'no charge' high power operation.

With the second Saft battery, if the MODV were going 22 mph (requiring 5 kW), and a silent run time of 3 hours was required (15,000 Wh) which matches the C/3 rate specified, then 107 kg of batteries would be needed or 235 lbs.

These are estimates that take ideal conditions into mind and should only be used as a ballpark estimate. They do not provide final numbers but they prove that with current battery technology we can achieve reasonable results. Table 2.3 shows how these results were calculated. The values in the green boxes were the ones selected to compute the total weight of the combined battery system.

While having 260 lbs of batteries sounds like a large amount of space and weight, it must be remembered that the wheel hub motors allow considerable space and weight savings because there is no need for a drivetrain and transmission. These computations are not to state that the final solution will have 260 lbs of batteries, they are only meant to give an idea of what

Table 2.3: Calculations for minimum battery pack weight combining high energy and power density batteries

						Power Requirements		Energy Requirements		Total	
Battery	Specialty	Energy Density (Wh/kg)	Power Density (W/kg)	Load (W)	Run Time (hrs)	Minimum Mass (kg)	Minimum Weight (lbs)	Minimum Mass (kg)	Minimum Weight (lbs)	Mass (kg)	Weight (lbs)
Shin-Kobe 2	Power	56	3,920	40,000	0.1	10.2	22.5	71.4	157.5		
Saft 2	Energy	140	476	5,000	3	10.5	23.2	107.1	236.2	117	259

a potential solution would look like and to prove the viability of a combined battery system.

2.3 Solid Oxide Fuel Cells

Solid Oxide Fuel Cells [SOFC] are a recent innovation that can help convert conventional fuels into electrical energy in an extremely efficient manner. They have a direct application for the MODV because they could be utilized to bolster the system's overall energy density and help optimize the MODV's energy storage. As explained in section 2.2, the optimal energy storage solution will probably be realized with a combination of energy and power dense batteries. These fuel cells have an extremely high energy density so it is likely that they could be integrated into the energy storage solution.

2.3.1 Overview

To familiarize the reader with SOFCs it is necessary to dig into how they work. A fuel cell is a device similar to a battery that produces a current through a chemical reaction. As seen in Figure 2.6 the inside of a fuel cell resembles a battery. There is the positive cathode, a negative anode, and a solid ceramic metal oxide as an electrolyte. First, steam and fuel mix to reform the fuel, and hydrogen enters the fuel cell at the anode and the electrons are removed from the hydrogen. In the case of the SOFC the hydrogen is extracted from the fuel because of the high operating temperatures of 1000 °C, giving it a distinct advantage over other fuel cells. Then, warmed air enters the cathode side to supply the oxygen for the reaction. The oxygen travels through the electrolyte and combines with the ionize hydrogen to form water. This continuous process provides the current depicted via the chemical reaction in Figure 2.6. Relatively mall amounts of carbon dioxide are produced in this process and the water from the reaction is reused to help form the steam needed in the system. This leads to efficiencies of 60%, and 90% is achievable using methods discussed later in this section.

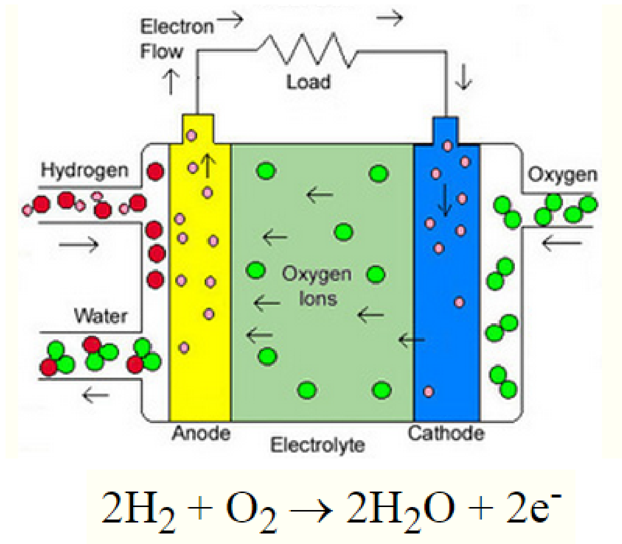

Figure 2.6: The internal workings of a solid oxide fuel cell [10] E. Garrison, "Solid Oxide Fuel Cells." [Online]. Available: http://mypages.iit.edu/ smart/garrear/fuelcells. htm, Used under fair use, 2014

As of 2011 the target size and weight for a 1 kW fuel cell was 13" x 13" x 28" and less than 75 lbs [31]. For reference, the SOFC in Figure **??** is 16" x 16" x 42" and 120 lbs. This means that these fuel cells may be a viable option for use on a ground vehicle. The size and weight requirements are not unreasonable since the MODV concept results in no drivetrain or transmission. This means extra weight for advanced batteries or power sources such as these fuel cells. Since 5 years has passed and multiple companies are now investing in SOFCs it can reasonably be assumed that the fuel cells will be smaller than the 2011 goal. This makes their use all the more possible.

One very important thing to remember is that SOFCs are not considered viable at this time for use in ground vehicles because of the high operating temperature of 1000 °C. However there is plenty of research going on to lower this operating temperature to make SOFCs viable for transportation use.

A fuel cell, by definition, is a unit that converts energy from a gaseous fuel to electrical energy and heat by combining a fuel with an oxidant electrochemically [32]. Fuel cells are very efficient with a typical SOFC system reaching 60% efficiency and even higher efficiencies can be reached when the high temperature output of the cell can be harnessed. SOFCs are also one of the most efficient fuel cells because of their high operating temperature. Energy harvesting methods could certainly be implemented on the MODV to reach the higher efficiencies of up to 80% reported by some companies.

In a SOFC the energy from the fuel is directly converted from gas into electricity which is why it can achieve efficiencies of above 60%. Its construction is simplest of the fuel cell types which should lead to easy reduction in production costs. As stated earlier the SOFCs have high operating temperatures of around 1000 °C which helps the efficiency and allows a wide array of fuels to be used. This is a tremendous advantage of the SOFC because it can convert many types of fuels into electrical energy including natural gas and JP-8.

2.3.2 Current Applications

The main areas of applications for SOFCs as of 2014 are residential, combined cycles power plant, and cogeneration/trigeneration roles. It is not currently being used in any ground vehicle application but it is valuable to understand that SOFCs are immediately applicable to certain industries. This ultimately means that the technology will be advancing and will likely be practical for use in vehicles in the next five years.

The residential applications are aimed at the typical power requirements for a home (1 to 10 kW). These fuel cells are the ones referred to at the beginning of this section where they could easily fit into the average basement and provide supplementary power to a home. If SOFCs in this power range could be made affordable for the average household income in the U.S. then it could possibly revolutionize the way Americans power their homes. It has been stated by Technology Management Inc. that vegetable oil could fuel SOFCs, and if this proved to be more cost effective than getting power conventionally from a power company then Americans could possibly power their homes in a very new way.

Cogeneration methods utilize the high temperature exhaust gases for additional power generation or heating purposes. When the fuel cells are used in tandem with this methods the efficiency of the overall system can be boosted significantly. Cogeneration or combined heat and power is the generation of two different forms of energy from a single main energy source. Essentially, a SOFC releases thermal energy and cogeneration utilizes this to drive up the system efficiency. In some cases the thermal energy can be used to directly heat water if hot water is needed for a home. It follows that steam could be produced to power turbines and generate electricity with the mechanical energy. Cogeneration can result in efficiencies of 80% and bolsters the desirable traits of a SOFC.

Trigeneration, as the name implies, takes things a step further than cogeneration. It is also known as combined heating, cooling and power. Essentially, it works similar to cogeneration but energy can also be harnessed for certain cooling purposes. This could be for air conditioning in a home or cooling purposes in a power plant. In any case, Trigeneration is a fast developing technology because of the high efficiencies that can be achieved.

SOFCs are especially attractive for industrial power production where size and space are generally not an issue. GE has recently announced that it will be commercializing its SOFC technology for use in megawatt scale industrial power applications [33]. This means that GE will be competing with Bloom, a multi-billion dollar startup that has looked to get an early edge on the SOFC market. With such high profile companies investing in this technology it seems that the benefits from SOFCs in industrial power must be valuable.

With the broad application base that SOFCs and fuel cells in general have it is safe to say that research for these technologies will continue well into the future. In the author's opinion if these technologies advance at a rapid pace in the next five years it will be imperative to keep up on the possibility for vehicle applications of SOFCs. The power plant for this vehicle will be converting fuel into electrical energy which is exactly what the fuel cells do. If a SOFC based power plant can be developed for use in a light utility vehicle, meeting weight and power density requirements, and can achieve the 60% and above efficiencies it is possible that fuel cells would be the exclusive power plant for the MODV.

2.3.3 Variety of Fuels

One very attractive aspect of SOFCs is their tolerance for fuels. Many different types of fuels can be used in a SOFC so their operation is not as dependent on the availability of specific commodities. For fossil fuels, propane, kerosene, JP-8, diesel, and natural gas can be used. For renewable fuels, biodiesel, vegetable oil, used cooking oil, jathropha, ethanol, digester biogas, and ammonia can be used [31]. This list of fuels constitutes many commonly available fuels which is not characteristic of many power producing technologies.

This extreme versatility could be a major motivator for SOFC use in homes and vehicles. If people could supplement the power to their home with used vegetable oil then SOFCs would look very enticing for the average homeowner. If the same technology were available for use in a vehicle then the appeal of SOFCs would be even greater. People around the world would be less dependent on gasoline and by using low cost fuels people could significantly reduce their transportation expenses.

The advantages of using a wide variety of fuels could help propel SOFCs to the forefront of power production. Having an off road vehicle that could be powered by many commonly used fuels would be extremely useful for the consumer and defense industries, so it is an important fact to note when considering the use of SOFCs in vehicles.

2.3.4 Disadvantages

The main disadvantages in using SOFCs for transportation applications are the high operating temperatures, slow startup time, and lowered operational life due to high temperature fluctuations.

SOFCs currently operate around 1000 °C which is considered a bit over the acceptable limit. Operating temperatures of 800 °C would be acceptable for transportation applications and there is ample research being performed to achieve this goal [32]. If this 200 °C drop can be achieved then it could change the way vehicles are powered, so naturally there is a great demand to do exactly that.

Currently SOFCs take a couple of minutes to reach operating temperature which is slower than needed for ground vehicles. This can easily be accounted for by having batteries on the vehicle that can provide the needed power until the SOFC warms up. While this startup time isn't a deal breaker, it does add extra load cycles to the batteries that could be avoided with short startup times.

Lastly, because a vehicle would demand a SOFC power plant to start and stop at a much higher frequency than an industrial power plant, the internal structure of the SOFC would have additional wear because of the temperature fluctuations. For any system there would be a given number of cycles to failure and this means a SOFC would wear out sooner in a ground vehicle. That being said, if these higher cycle lives are accounted for in the design of the fuel cell it shouldn't wear at an unreasonable rate.

2.3.5 Importance to the MODV

Having a high efficiency power plant is a benefit to any vehicle. Since the invention of automobiles, engineers and scientists have been striving to create more powerful and efficient power plants to put into vehicles. An immense amount of resources have been spent on improving internal combustion engines' power outputs and efficiencies and a typical engine will have an efficiency of about 30%. SOFCs have efficiencies of 60% as a starting point, and when cogeneration or trigeneration are used efficiencies of up to 90% are obtainable. If an SOFC system could be designed that was appropriate for use in a ground vehicle, then the vehicle would be able to convert the same amount of fuel to twice or three times the amount of electrical energy of a vehicle powered by an internal combustion engine. This is a tremendous jump in efficiency and would revolutionize personal transportation.

As it stands right now SOFCs do not have the power or energy density to be put to use as the prime engine in ground vehicles. Germany is using fuel cells in some of its newer submarines, and it has been shown that a Solid Oxide Fuel Cell-Gas Turbine system is feasible for use in locomotives [32], but that is the extent to which fuel cells have been used for transportation. It may be a while before a high power SOFC system is available for consumer vehicles that need 75 to 125 hp at the wheels, but for many off road vehicles only 25 to 45 hp at the wheels is needed. This is a reasonably obtainable goal for ground vehicles using wheel hub motors and SOFCs in the next decade. With the immense amount of research and funding going into advancing SOFCs it will be important to monitor the possible applications for SOFCs in vehicles.

2.4 Autonomy

2.4.1 Overview

Autonomy in ground vehicles has seen consistent advances in interest and capabilities for the past decade. The Mechatronics Lab has been a part of this research push with Victor Tango, Rocky, and GUSS just to name a few. Autonomy offers advantages that don't necessarily fit into vehicle performance but it opens a completely new box of ground vehicle applications.

Since the advent of the first automobiles every other ground vehicle following has required a human to provide control inputs. Autonomy obviously does away with that presumption. It has matured to a point where it can be properly implemented in military applications such as the GUSS. Having a vehicle capable of driving itself allows for 'follow me' capabilities where dismounted Marines can toss their gear onto the vehicle and have it carry most of the weight. It is also easily conceivable that multiple MODVs could be performing logistics functions behind the front lines hauling supplies autonomously and would only need human interaction when they are being loaded or unloaded. During a CASEVAC [casualty evacuation] it would be possible for a corpsman to perform his medical duties and help the Marine while the MODV is driving itself back to a safer area.

Autonomy offers many advantages that the MODV concept can make good use of. To gain an encompassing view of how these advantages can be realized requires a review of the current state of autonomous capabilities.

2.4.2 Ground Unmanned Support Surrogate

The Ground Unmanned Support Surrogate [GUSS] was developed by TORC Robotics and the Mechatronics Lab for use in the Marine Corps. The GUSS's main role is to haul around supplies for dismounted Marines. It can perform a 'follow me' function where it follows a specific Marine around to provide for the navigational input, and a way point function where the GUSS navigates to specific coordinates using GPS input.

Figure 2.7: Ground Unmanned Support Surrogate utilizing the Polaris MVRS 700 6x6 platform, [11] Mechatronics Lab, "GUSS." [Online]. Available: http://www. mechatronic.me.vt.edu/Projects/projectsPage.html Used under fair use, 2014

The 'follow me' function is where the GUSS simply monitors where the Marine is and controls itself to follow accordingly. This leaves the bulk of the navigation decisions up to a Marine and skirts fully autonomous navigation. Since the main role of the GUSS is to follow Marines with their supplies it makes complete sense to outsource the decision making to a Marine. It wouldn't be necessary for the GUSS to map out a complete route to the objective autonomously when its main goal is to follow Marines making that decision. This saves energy and provides for reliable autonomous navigation.

GPS navigation is a fairly straight forward autonomous operation. If the GPS coordinates are given as inputs to the GUSS then it simply monitors where it is in relation to that path and makes corrections accordingly. This is very useful when there is a road and the terrain does not demand rigorous examination by the sensors. The vehicle then drives itself along that path. However, GPS navigation is not ideal for off-road operation. The terrain is very diverse and necessitates more decision making. For off road, a fully autonomous vehicle is needed to process the terrain type and obstacles in order to successfully negotiate the vehicle to the objective.

The GUSS provides an example of the current state of autonomous capabilities. GPS navigation, and 'follow me' functions are currently mature enough to be experimented for use by the Marines and it follows that the MODV will be able to have the autonomous capabilities of the current GUSS system.

2.4.3 Oshkosh Truck Terramax™

Oshkosh Defense® currently has an autonomous appliqué kit called the Terramax™ that has some impressive capabilities. This system is capable of autonomous navigation in lead or 'follow me' roles with supervision. Up to five vehicles can be supervised by one operator in a convoy formation and navigate to an objective. If the convoy happens to go into an area with no GPS access, navigation can still take place for the next 10 km. The convoy can do this while traveling at 60 kph (37 mph). These are some impressive specifications especially for a vehicle being used in a logistics role. It is certainly reasonable to assume the MODV can be engineered to have the same capabilities or better in the next five years.

Figure 2.8: Oshkosh Truck Terramax™ [12] IMCDB, "Oshkosh Terramax." [Online]. Available: http://www.imcdb.org/vehicle_575614-Oshkosh-TerraMax.html, original image from BBC, Used under fair use, 2014

2.4.4 Google Car

Google has recently been leading the charge with developing self driving cars for domestic use. This car makes very good use of an autonomous system, and has displayed its capabilities in real world situations. Google's iterations of self driving cars have seen 700,000 miles of testing on public roads, 1,000 of which were in complex situations such as busy streets and the hills of San Francisco[34].The most recent vehicle can 'see' 600 feet in all directions so it can react to situations developing around 200 m in front of it. The range of the car is 100 miles and has a top speed of 25 mph. All of these performance parameters can give us insight into where autonomy stands today for application in the MODV for off-road use.

Figure 2.9: Early Google Car Iteration, [13] TechCrunch, “Google Car,” 2014. [Online]. Available: http://techcrunch.com/2014/05/14/googles-self-driving-car-project-is-a-worlds-fair-fantasy-turned-city-street-reality/, Used under fair use, 2014

The Google Car demonstrates that autonomous systems have matured enough for viable use in a logistics role. Since the Google Car has been operating almost exclusively on roads, it cannot be said that the same performance parameters can be met off road. However, in a logistics role the vehicle would most likely use predetermined routes along roads or flat terrain. Since the Terramax™ already demonstrates the logistical opportunities, it can be said that the Google Car further reinforces that notion.

2.4.5 Conclusion

The main question with the MODV’s autonomous capabilities is where the fully independent autonomy will be. This would be a great asset in a reconnaissance role where a MODV could survey an area and report suspicious activity without Marine supervision. The current state of many autonomous vehicles requires some human interaction in the system. Essentially, the less input needed from a human the more autonomous the vehicle is. Ideally, a Marine would only need to instruct a MODV to survey a certain location. The MODV would decide the best route to that point and then successfully negotiate the terrain on the way there. If it were to incur any enemy activity it would be able to report it and avoid detection. This is the ideal "full" autonomy capability, and the viability of getting there in the next five years is explained in section 4.1.4.

2.5 Structural Health Monitoring

2.5.1 Overview

Structural health monitoring [SHM] is a method of detecting and evaluating damage in any engineering structure. In the case of the MODV SHM would monitor various components critical to proper operation. In a way it is akin to having a nervous system in a vehicle. If one were to strain a ligament his body would let him know through pain. In the same way, strain sensors, accelerometers, and environment sensors can be used to monitor the physical condition of a vehicle's components and alert the user if any are compromised. Health monitoring is currently being utilized in aircraft, spacecraft, and buildings where component failures carries dire consequences.

2.5.2 Sensors Useful for Ground Vehicles

While health monitoring is technically being utilized in ground vehicles it is not necessarily used to monitor the structural performance. The "check engine light" is one example. There are various types of sensors placed in a vehicle that can trigger the check engine light so the user knows maintenance is required. The vehicle's CPU is constantly monitoring these sensors so the owner can be alerted to an issue quickly.

The MODV will definitely make use of health monitoring currently being used in ground vehicles, but there are many sensors that can be used to monitor the vehicle's physical components to allow for more efficient structural designs, lower frequency of inspections, and less in-field part failures.

Strain Sensors

Strain sensors measure the "stretch" or elongation of a specific location on a part. When properly placed on a component then the stress in that part can be calculated from the strain. This is useful because it can be recorded if a part has been overstressed and to what degree. With this information the user can be alerted if this part needs an inspection, early replacement, or immediate replacement etc.

It is easy to see how a network of strain sensors integrated into the components of a vehicle can provide a logistics demand reduction in terms of vehicle inspections. If no component are overstressed then physical inspections are not needed as frequently. If there were adequate memory storage on the MODV then the entire load history of a part could be analyzed to see if a part might need to be replaced from the cyclic loading it encounters. Monitoring the stresses in the components offers some very useful capabilities in insuring the physical integrity of a vehicle.

Another advantage strain sensors present is the possibility for lighter weight components. It is a common design practice to use a "safety factor" when designing a part to make it stronger than it needs to be given the operational loading it will encounter. This helps insure a component's physical integrity in the face of erratic loading, environmental effects, and wear but the part will weigh more. This adds unneeded weight to a vehicle. The safety factor is used because of the unknown, but with the strain sensors (along with environmental sensors) it is known what the part has been exposed to. Therefore, it is possible for a lower safety factor to be used. This reduces the weight of the vehicle and allows for better fuel efficiency, and larger payloads.

An interesting use of integrated strain sensors would be for vehicle design evaluation. Since the loading histories of all the parts could be recorded, it would be relatively easy to evaluate the designs efficiency and help with the prototype design iterations. The optimal design could be realized before mass production and reduce the possibility of unforeseen design flaws.

Accelerometers

Accelerometers are sensors that measure acceleration. These are useful in health monitoring because they can detect the location and severity of an impact. Figure 2.10 gives an example of how this can be done.

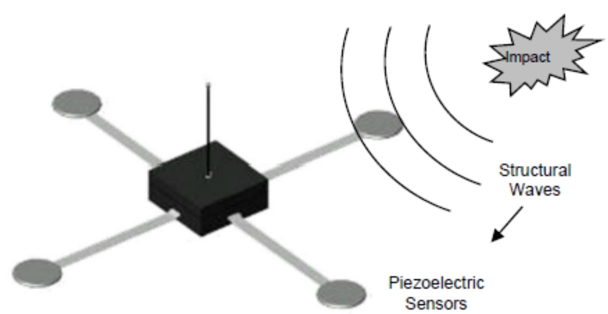

Figure 2.10: Locating an impact with accelerometers by triangulating the signals from structural waves, [14] W. L. Richards, E. Madaras, W. H. Prosser, and G. Studor, "NASA Applications of Structural Health Monitoring Technology Materials," Tech. Rep., 2013., Used under fair use, 2014

Finding the location of the impact can be done mathematically when comparing the signals in the array of accelerometers. The actual acceleration readings give insight into the severity of the impact.

Knowing the location and severity of an impact on a ground vehicle is very useful information. When an impact event is recorded, a mechanic can later extract the information from the

MODV's CPU and inspect the location of interest. This information could also be used in conjunction with the strain sensors so the CPU could check the strain information at the location of interest, and possibly avoid an inspection all together.

Another issue accelerometers could help with is harmful vibrations. Over time any ground vehicle will start to vibrate in undesirable ways. Parts wear out and alignments change in the structure, and this can cause vibrations that hinder performance or even prematurely wear out components. Accelerometers can be used to measure the frequency of the vibrations and could even detect the location of the vibration source. A Marine would not need to waste their time driving the vehicle around trying to figure out where the vibration is coming from because the MODV would already have the data pinpointing the location. This reduces the troubleshooting time required and avoids any guessing and checking.

Environmental Sensors

Environmental sensors could give insight into the environmental conditions the MODV would be exposed to. These are sensors that measure relative humidity, surface temperature, and wetness. Knowing these conditions can give insight into the possibility of corrosion. Corrosion is one of the chief proponents of part wear, and if its effects can be measured then the wear and remaining usable life of components can be predicted. One study [35] serves as an example of how these sensors can be applied to monitoring the corrosion on aircraft. Properly utilized environmental sensors can help predict probable development of corrosion, and eliminate environmental factors that promote corrosion.

With environmental sensors a definitive record can be kept of the exposure a vehicle has had to certain conditions. This is important to know because a vehicle that is in more corrosive environments will typically have faster wear than a vehicle in less corrosive environments. It's the same reason that people like to buy vehicles from the southern United States as opposed to the northern ones. In places like Wisconsin, vehicles are bombarded with cold weather and salt for at least four months out of the year. The southern states do have higher humidity but it doesn't seem to corrode as quickly as salt does. With environmental sensors a precise history of the vehicle's climate exposure conditions can be recorded and used to predict component wear.

Integrating environmental sensors into the MODV to monitor its corrosion history would be a great benefit to the vehicle's usable life and maintenance needs. Significant amounts of guesswork can be removed by correlating definitive data to known corrosion trends. Less time diagnosing the problem leads to quicker maintenance and more operation time.

2.5.3 Benefits

Specific benefits offered by each of the sensors has been discussed but it is important to consider the benefits heath monitoring adds to the larger picture. Health monitoring in essence gives the MODV a nervous system that can indicate specific components that are in need of repair or replacement. This provides for streamlined maintenance and a logistics demand reduction. The data collected through environmental sensors and accelerometers can also be used to give predictions on usable component life, and if component wear has accelerated.

Logistics Demand Reduction

Health monitoring will help with a logistics demand reduction in multiple ways. Firstly, it will allow for a lighter vehicle design. If 10% of the vehicle weight can be shed then this means for a given number of vehicles on an expeditionary vessel, there will be a higher weight allowance for other supplies. A lighter vehicle will also be able to carry a larger payload which is a benefit to any role of the MODV.

Autonomous detection of maintenance is a possibility with SHM. The MODV could report back to a maintenance team that it needs a replacement part while it is in the field. Less strain will be placed on Marines in regards to reporting any vehicle issues. Any impact event or overstraining of the components can be reported back with information on the component health status. All of these function would contribute to the efficiency of vehicle maintenance.

A vehicle breaking down in the field, besides being a hazard to the Marines, also causes a logistical strain. With health monitoring this will be less likely since the structural integrity of each part is constantly being monitored. If a part is found to be reaching the end of its usable life it can be replaced before it fails.

Health monitoring will also reduce the frequency and time commitment of vehicle inspections. A definitive record of component stresses, impact events, and environmental conditions will aide in predicting part wear. Knowing when a part will wear out reduces the need to periodically check to see if it is in good working order. If a vehicle hasn't been used as rigorously then it won't require an inspection as soon as one that has seen heavy field use. This frees the Marines to focus on the greater maintenance needs.

Streamlined Maintenance

Health monitoring will also help streamline vehicle maintenance. The combination of accelerometers and strain sensors will help pinpoint worn components, or warn the Marines that a certain part will need replacement soon. If a part is causing harmful vibrations then the vibration source can be pinpointed and no troubleshooting will be required to determine the defective part. The environmental sensors record the environmental conditions the vehicle has been exposed to and predict any component wear acceleration. Essentially the health monitoring system will drastically reduce any guesswork involved in vehicle maintenance allowing the Marines to focus on fixing the precise problem.

Component Life Prediction

Component life prediction has been touched upon in previous sections but its importance deserves further elaboration. The strain, acceleration, and environmental sensors all collect valuable data that allow reasonable estimates to be made on a component's remaining life.

Strain sensors allow stress calculations to be made. If the load history of a component is recorded then fatigue life calculations can be made to determine a part's remaining usable life. Crack growth, stress based fatigue, and strain based fatigue can all be compared and accounted for so that the best estimation can be presented. This is useful because a MODV being used for a logistics role could possibly see very light loading when compared to a MODV negotiating rough terrain. Instead of assuming that all MODVs are under strenuous use and inspecting them accordingly, the vehicle's inspection can be customized to its operational loading.

Accelerometers would acquire and record impact and vibration data. Shock loading can cause serious damage to a part and cause premature wear. If all shock events are recorded then proper warnings can be given if a part has experienced severe shock events. This can help prevent premature component breakdowns in the field. Vibration data could give insight into the misalignment of certain parts. A well maintained and working MODV will have mechanical vibrations correlating to a healthy structure. If vibration data is recorded that deviates from the norm, then the possible issues associated with the data can be brought to the attention of a mechanic.

Environmental sensors can be used to predict corrosion of components. The relative humidity, surface temperature, and wetness can be recorded and analyzed to give insight into the severity of corrosion the MODV might be experiencing. Corrosion is one of the largest factors in component wear and observing its effect can pay large dividends in predicting component life.

2.5.4 Conclusion

SHM will be an extremely valuable addition to any new vehicle concept, especially for off road vehicles. The rough operation and regular maintenance needs of off road vehicles means that it is very important to keep track of a vehicle's mechanical health. SHM helps eliminate guesswork and in doing so leads to lighter vehicle designs, logistics demand reduction, and streamlined maintenance. It must be a feature on the MODV concept and investments should be made to optimize the structural health monitoring system and form it into a powerful tool.

2.6 Energy Harvesting Shock Absorbers

2.6.1 Overview

The MODV concept seeks to take advantage of the most recent developments in technology not only to improve mobility, but also to improve efficiency. Energy harvesting is a fast growing field that has produced some innovative ways to make the most out of the energy put into a system. Energy harvesting shock absorbers [EHSA] are one of these recent advancements that can offer improved efficiency in a very simple manner: harvesting the energy of an oscillating vehicle.

Conventional shock absorbers dissipate vibrational energy in a ground vehicle through pneumatic fluids. This results in a more comfortable ride for the user since the car doesn't bounce around at the simplest maneuver or bump. While conventional shock absorbers work at creating a more comfortable ride, the energy is completely lost in pushing the fluid around. EHSAs are designed to harvest this vibrational energy and put it back into the system. Many of the products recently produced for this purpose can be easily integrated into current vehicles so EHSAs are definitely worth considering for use in the MODV.

One company that has been developing EHSAs is Levant Power [15]. Their system harvests energy by having the pneumatic fluid in the shocks power a small hydraulic motor on the exterior of the shock. This system is unique because it can either harvest or insert energy into the system. The result is a sophisticated system that can actively change the damping coefficient of the shock, and even produce force in the shock to push back on the terrain when necessary. Levant calls this technology the Activalve™ and it is seen in Figure 2.11 on the outside of a standard shock absorber.

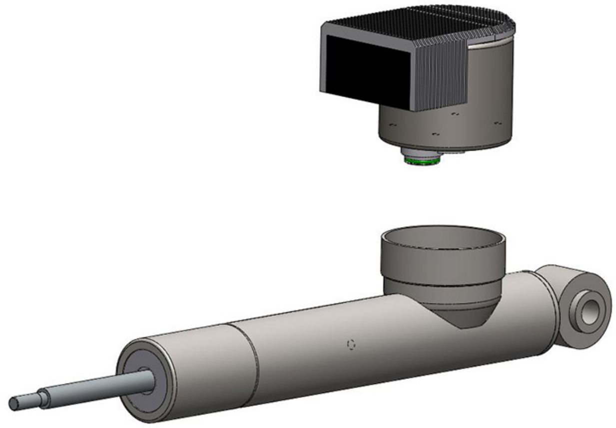

Figure 2.11: Activalve^{TM} from Levant on a standard size shock absorber, [15] Levant Power, "Levant Power," 2014. [Online]. Available: http://www.levantpower.com/, Used under fair use, 2014

Another type of EHSA comes from a group of researchers from the State University of New York at Stony Brook [16] seen in Figure 2.12. In this article the theory, design, and testing of a simple EHSA is presented. This particular shock absorber uses a very simple design to achieve its goal. A motor is placed on the inside of the shock, and the linear motion of the shock is transferred to a rotational motion input into the motor by using a rack & pinion and a bevel gear. With this setup they measured a peak power of 67.5 Watts and an average power of 19.2 Watts while traveling 30 mph on a paved road. While this system is not as intricate or capable of the complex control schemes of the Activalve^{TM}, it certainly offers a simple and robust design. It may very well be that the simpler EHSA will be a more robust solution and is worth testing. There is a certain value in a simple, low maintenance, and tough design especially for off road applications.

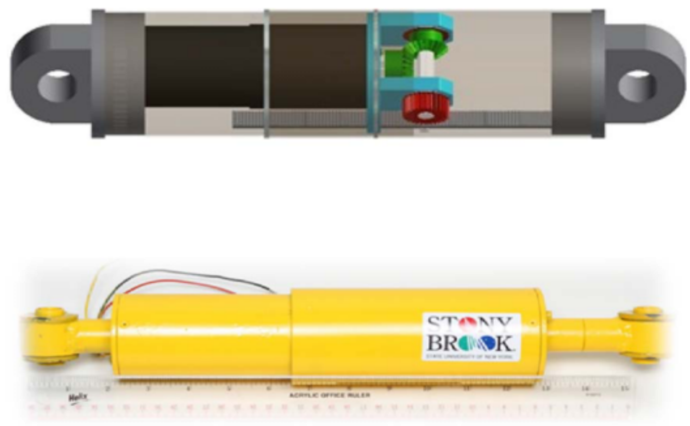

Figure 2.12: EHSA using an electric motor and gears to offer a simple energy harvesting solution, capable of a peak power of 67.5 Watts and an average power of 19.2 Watts while traveling 30 mph on a paved road, [16] Z. Li, L. Zuo, G. Luhrs, L. Lin, and Y.-x. Qin, "Electromagnetic Energy-Harvesting Shock Absorbers: Design, Modeling, and Road Tests," IEEE Transactions on Vehicular Technology, vol. 62, no. 3, pp. 1065–1074, Mar. 2013., Used under fair use, 2014

2.6.2 Applications for the MODV

Harvesting energy from the suspension system of the MODV would definitely add to the vehicle's efficiency and is worth exploring. The MODV will be an off road vehicle which makes EHSAs all the more relevant. Since the systems presented are easily integrated into the design of current vehicles it would be well worth evaluating them during the testing phases of the MODV.

Using a shock absorbing system such as the Activalve^{TM} would be doubly advantageous for the MODV. First, this system would help improve the efficiency of the vehicle especially during off road operation. On smooth roads a vehicle does oscillate, but not nearly as much as when the vehicle is off road. This maximizes the energy harvesting potential. Second, this active control system gives the MODV an advanced suspension system that can greatly improve ride quality and therefore reduce operator fatigue. For off road applications it is very important to minimize operator fatigue, especially during extended periods of use. It is therefore a wise choice to integrate an Activalve^{TM} system or an equivalent technology into the design of the MODV.

As mentioned before the EHSA from [16] would be a competitive candidate for use in the MODV. The strength of this system lies in its simplicity which is sometimes the superior engineering solution. A complex and sophisticated product may have unforeseen difficulties pertaining to reliability and maintenance. That is not to say that the EHSAs from Levant Power would be any less reliable than the ones from [16] because the author has no evidence to suggest that. The main point to understand is that evaluating both systems is a wise engineering choice.

In conclusion, incorporating an EHSA will improve efficiency and ride quality of the MODV without adding large amounts of weight or complexity to the system. It would be to the MODV's benefit to design a system such as the Activalve^{TM} into the vehicle from the project's conception.

2.7 Non-pneumatic Tires

2.7.1 Overview

Non-pneumatic tires are wheels that rely upon a flexible structure, usually polymers and composites, to provide the mobility needed for wheeled vehicles. They are not dependent on any internal pressure and are therefore more rugged and reliable than conventional pneumatic tires.

2.7.2 Highly Durable

These tires are very desirable for rugged off road use since they can take significantly more abuse than pneumatic tires. The Polaris Defense TerrainArmor^{TM} tires can be used for an additional 1000 miles with a railroad spike driven into the tire, and over 350 miles after being shot by a .50 caliber rifle. These characteristics are obviously attractive for any military or off road use since a pneumatic tire would come nowhere near those numbers. The need for spare tires is eliminated which means a higher payload. Since the MODV will likely see logistical roles this can greatly increase the payload capacity of a fleet of vehicles. Overall, non-pneumatic tires off significant advantages in reliability.

2.7.3 Reactive to Terrain Conditions

Non-pneumatic tires have structures that allow the tire to deform when high stress concentrations are applied. This allows the tires to 'hug' sharp edges that it comes into contact with which offers two benefits. Firstly, the sharp impulse of the terrain is impeded so the operator feels less of the shock. Secondly, a higher tractive effort is achieved because more of the tire is in contact with the terrain which leads to gains in mobility. Pneumatic tires must have active pressure systems to achieve the same results leading to added weight and system complexity. These advantages make non-pneumatic tires more attractive than conventional ones.

2.7.4 Performance in Sand

Since the MODV concept is centered around use in the Marine Corps it is vital that it has adequate performance in sandy terrain. Wet sand is not a problem for most ground vehicles but dry sand can offer a significant challenge. One important advantage that non-pneumatic tires offer is the possibility of better performance in dry sand.

Sand is a particularly taxing terrain in many ways. Anyone who has ever run in dry sand has experienced how much more energy is needed in comparison to asphalt. Much of the energy is put into 'bulldozing' the sand around and results in inefficient propulsion. In the same way that our feet dig into the sand, a pneumatic tire ends up pushing significant amounts of sand in front and to the side, hence the term 'bulldozing'. This is far from ideal and results in wasted energy.

Besides energy loss, dry sand can make it difficult for a ground vehicle to exert enough tractive effort on the terrain. Sandy terrain can incur sinkage of 5 cm at 75 kPa which is well below the stress that many light utility vehicles exert onto the terrain. As a guideline Table 2.4 displays some common military vehicles with values of mean maximum pressure [MMP] created from values found in [27]. The MMP method is covered in 3.3.

Table 2.4: MMP and weight values for some light utility vehicles

Vehicle	MMP (kPa)	Weight (tons)
Land Rover 1/2 ton	278	2.1
M998 Hummer	272	3.87
Ferret Scout Car Mk. 2	351	4.5
Fox	349	6.1
Panhard M11 VBL	276	3.54

The vehicles in Table 2.4 that fall into roles similar to the MODV concept have MMPs of 250 kPa to 350 kPa. These values are certainly enough to cause concern if the MODV needed to operate in dry sand. One way that off-road enthusiasts combat dry sand's low MMP tolerance is lowering their tires pressures to around 10 psi. Even with this extra distribution of stress great care is needed when operating the vehicle. Some APCs do this as well to optimize their tractive performance in different terrains. These techniques work but require extra weight, space, and power for an inflation system.

Tires such as the Tweel^{TM} achieve this intrinsically through their design. In [36] pressures exerted by a Tweel^{TM} on Lebanon Sand were modeled using FEM. This specific design achieved a very low maximum stress of 23 kPa. It is important to note that this study focused on terrain negotiation on the moon and the loading characteristics would be different if a similar tire were put onto the MODV. The article does however give insight into the stress distribution advantage that non-pneumatic tires have over pneumatic ones.

2.7.5 Applications for the MODV

Non-pneumatic tires offer many advantages that have been discussed in this section. They can offer advanced mobility and reliability, increase payload, and reduce the system complexity and maintenance. For proper application on the MODV the optimum tire size and structure should be sought out and implemented. As it stands, this technology can offer a good contribution to the MODV's performance and it should be sough after when designing this vehicle.

2.8 Protection from Electromagnetic Pulses

2.8.1 Overview

A main area of concern for vehicles dependent upon electric components is how well they are guarded against electromagnetic pulses or EMPs. An EMP can severely damage electronic components or render them completely useless. Since our world is so dependent upon electronics this is an important area of concern for military and domestic security applications, where a serious EMP could make endanger a large portion of people because of component malfunction. While extensive testing on certain vehicle's resilience to an EMP pulse has not been published, it is commonly known that man consumer cars can stop running the instant an EMP hits them. If this is elevated to a nation-wide scale the effects could be devastating.

2.8.2 Applications for the MODV

Since the MODV concept aims at being a hybrid-electric vehicle concept, it is important to consider how well such a vehicle would be protected from an EMP. Technology exists to protect electronics from EMPs, so it is reasonable to conclude that shielding the MODV's electronics is entirely possible given the correct designs. It is of particular concern that the power and control cables on the MODV would be protected from some sort of EMP so the vehicle could not be disabled so easily. The autonomy appliqué kit would have to be shielded especially well since most of its components and sensors would be mounted on the outside of the vehicle and could not take advantage of the metal components on the MODV.

Since the government and military have had a great interest and need for protecting vehicles from EMPs since the start of the cold war, it is well known what steps need to be taken to protect a vehicle. In [37] it was shown how easy it is to protect a vehicle's radio equipment from an EMP. This process required minimal rewiring and an off the shelf $1.50 varistor. In [38] it was outlined how simply internal electronics in a combat vehicle can be shielded, and how to protect the communications system as well.

It can safely be stated that the MODV will have adequate shielding from an EMP. The knowledge of how to do so has been known for a long time and the protection techniques are firmly established. With proper design the MODV will not be more susceptible to an EMP than other conventionally designed vehicles.

2.9 Drive by Wire

2.9.1 Overview

A very important technology that the MODV can utilize is a drive by wire [DBW] system. In most modern vehicles the driver provides mechanical input through the steering wheel which is then transferred to motion of the wheels. With DBW the user gives input to a steering wheel in the same way, but instead of a transfer of mechanical motion the input of the steering wheel will be interpreted electronically and the correlating signals will be sent to servos controlling the wheels. Essentially, instead of having mechanical linkages and hydraulics to control the steering of the vehicle, electrical signals and servos will be used.

This may sound alarming at first because there is a stigma of electronic devices being less reliable, but it should be noted that most commercial airliners are fly by wire. The control surfaces are controlled by servos receiving electrical inputs from the pilot instead of hydraulics. It goes without saying that if aircraft can be fly by wire machines with such confidence then the same reliability can be properly transferred to ground vehicles.

2.9.2 Advantages

Autonomous Appliqué Kits

One very desirable trait of a drive by wire vehicle is the inherent ease of converting the vehicle to an autonomous configuration. Currently, to develop an autonomous appliqué kit for a conventional vehicle a drive by wire system must be retrofitted. This includes a good amount of engineering time and prototyping and delays the conversion to an autonomous setup. If a vehicle is already a drive by wire system then an autonomous package can simply be integrated into the control scheme of the vehicle. Moreover if the vehicle was designed with an autonomous kit in mind then converting the vehicle to an autonomous configuration would be a plug-and-play operation.

Having an easily attachable autonomous appliqué kit will be a hallmark of the MODV. The applications for a modular off road vehicle that can be converted to an autonomous or tele-operated configuration by plugging in a module are great in magnitude. For instance, a search and rescue operation in volatile environments now has significantly lower risks to the human life involved. The autonomous vehicle can simply be told where to go and it will be able to operate in conditions that a human could not.

If the vehicle were searching in an intense blizzard it would be able to stand up to the high wind speeds where a human operator might become fatigued or simply couldn't operate. Low visibility is not an issue when the appliqué kit has an array of sensors to 'see through' the snow. If tele-operated the operator can be in a warm and comfortable environment while giving the MODV the next waypoint. In the meantime the operator would be monitoring the sensors readings and have lower stress levels while analyzing mission critical information. With a less fatigued operator the mission has a greater chance of success.

The same situation would apply for any austere environment. Whether it is intense heat, cold, wind, rain, snow or sand the main advantages would always be the same: lower operator risk and fatigue, and a higher chance of success. With an appliqué kit this role can be filled efficiently. Instead of having a dedicated autonomous vehicle that is to expensive for general use and ends up taking up space, the kit can be applied at a moment's notice to any available vehicle.

With the likelihood of self driving cars in the near future, as covered in section 2.4, it would be in a company's best interest to look at developing their cars with a drive by wire system so the cars can be converted with ease.

Weight and Space Savings

A direct advantage with DBW is the weight savings. The weight and space savings is what led the aerospace industry to adopt fly by wire systems for aircraft, which is easy to see because of the ever present drive for lighter aircraft. Hydraulic fluid, pumps, hydraulic housings, and backup mechanical steering components are no longer needed with a DBW vehicle. These are replaced with power cables, communication cables, and electromechanical devices. The extra space in a vehicle will allow greater design freedom for any components that would have been close to the conventional steering system. Less weight can mean greater mobility because of reduced ground pressure, or it can be seen as a higher weight budget for the vehicle's batteries.

Advanced Mobility

Another major advantage is the advanced mobility capabilities that a DBW system can achieve. The vehicle designer no longer has to limit the turning angle of the wheels because of physical connections to the steering system. This can reduce the turn radius and may even allow for pinpoint maneuvers especially when four wheel steering is factored in. It would be practical enough to place the servos close to the rear tires and run communication and power cables to the servos. Four wheel steering in conventional vehicles has been successfully achieved but the extra weight and space that comes with this feature will be reduced with DBW.

The drive by wire concept in conjunction with wheel hub motors allows for the implementation of telescoping wheels. Having an electromechanical device close to the wheel allows for this possibility which can be used to negotiate tall obstacles or deep ditches. This feature would be especially useful in a six-wheel configuration where the vehicle can retain three points of contact more easily than a four-wheel configuration. Nonetheless, telescoping wheels would still be useful for a four-wheeled configuration when the vehicle is traversing very rugged or rocky terrain. If one of the tires loses contact with the ground the wheel can telescope out and regain traction.

2.9.3 Fault Tolerance

Fault tolerance is a main concern for any electronic system. There is a stigma about systems relying completely on electronics among many engineers, technicians, and operators. Many people have had terrible experiences with electronic technology failing from computer crashes to file corruption, so most people are naturally hesitant to trust the steering on their vehicle to a purely electronic system. These concerns naturally lead to a section discussing how drive by wire systems can be protected against faults. In short, it is entirely possible for a drive by wire system to be engineered to a high degree of safety considering fly by wire systems in aircraft have been very successful in achieving high safety standards. By extension, if a purely electronic system can be made safe enough for aircraft it can surely be made safe for ground vehicles as well.

Analyzing the Safety of a System

In order to evaluate the safety of a system against faults there are general procedures followed in industry. First, to achieve reliability and safe a system must have fault avoidance, removal, tolerance, detection and diagnosis, and protection and supervision [17]. It is best practice to remove and avoid faults during the testing and design phases. This helps minimize the cost of system faults and results in a better prototype. The analysis methods used to determine the effects faults have on the reliability and safety of the system include reliability analysis, event tree analysis and fault tree analysis, failure mode and effect analysis, hazard analysis, and risk classification. Since the purpose of this thesis is not to provide a rigorous description of these processes, it is best for the reader to refer to [17] for the details on these methods. However, it is useful to present Figure 2.13 from [17] to show the general flow of the processes.

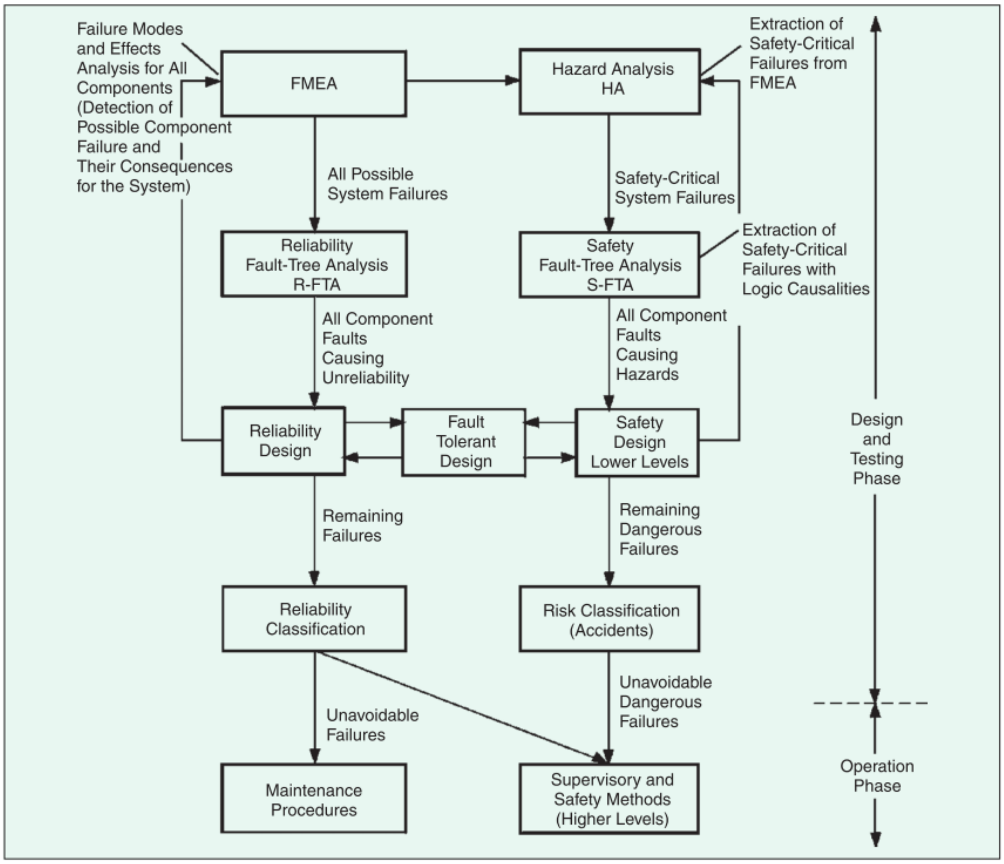

Figure 2.13: Analysis procedures for the reliability and safety of a system, [17] R. Isermann, R. Schwarz, and S. Stolzl, "Fault-tolerant drive-by-wire systems," IEEE Control Systems Magazine, vol. 22, no. 5, pp. 64–81, Oct. 2002., Used under fair use, 2014

Redundant Structures for Fault Tolerant Components

The simplest and in many cases most effective way to protect against faults is with redundancy. For instance, most every car has a spare tire in case one of the regular tires fail and are no longer usable. The redundancy with that system is simply adding another tire so the vehicle can at least get the owner home or to a garage where they can find an adequate replacement. For steering a vehicle there can be a simple mechanical linkage coupled to the steering system that allows 'limp home' steering if the hydraulics system fails. In the same way, modules in hardware and software can be redundant so a certain signal or computation can be verified.

There are two fundamental approaches for fault tolerance. One is static redundancy, and the other is dynamic redundancy [17]. Static redundancy is where three or more modules work in parallel that all have the same signal input and are all active. A voter then compares these signals and decides the correct signal by majority. Dynamic redundancy on the other hand doesn't have as many modules but it does require more processing power. It is a 'smarter' system since it processes the signal itself to decide if it is sending a faulty one. This system switches the faulty module off if the signal is recognized as incorrect, and the redundancy of the modules allows the system to analyze the non-faulty signal and continue operating.

For hardware this redundancy can be achieved through multiple sensors sending signals to the processing unit. For sensing temperature, static redundancy could be 3 thermocouples sending a voltage to the 'voter' which then decides what the proper temperature reading is. Dynamic redundancy would be two thermocouples sending a signal, but now the signals are processed to determine their validity. If one signal is out of the normal range or perhaps sending an erratic signal, the processing unit could choose to ignore it and use the other one.

A safe drive by wire system for the MODV would mostly consist of hardware redundancy in its sensors and electromechanical devices. The decision to use static or dynamic redundancy is better left to an experienced systems engineer but there are some safe assumptions to be made.

Detecting the basic inputs from the driver would be achieved by sensing the angle of the steering wheel, and force exerted on the brake and acceleration pedals. For the steering wheel angle multiple absolute rotary encoders could be used, or perhaps a combination of rotary encoders and other angular displacement sensors. This coupled with a force feedback for the driver would provide a system that is fault tolerant as well as intuitive for the operator to use since most people are used to some feedback in the steering wheel. For the brake and acceleration pedals it would be important to detect when the user is exerting force but filter out forces exerted to the pedal through the vehicle itself. This is especially important for off road vehicles because rugged terrain would cause significant accelerations at the pedals. Perhaps a combination of force sensors and deflection sensors on the pedal would suffice for this input. In any case redundancy would be designed into the system to provide fault tolerance for the input signals.

For redundancy in the actuators and/or servos controlling the steering angle in the wheels, multiple devices could provide the motion necessary at the same time or there could be a backup device that was dormant until needed. Optimizing this steering system would be a good challenge for a mechanical engineer since it would require some out of the box thinking with conventional steering mechanisms. Ultimately, achieving redundancy in the steering system is entirely plausible and could easily be engineered to be as reliable as conventional mechanical systems.

Chapter 3

Theory

3.1 Environments and Areas of Operation

For the MODV to operate effectively anywhere in the world its design must take the diverse climates of the world must be considered. Temperature and humidity conditions must be accounted for in any design of military vehicles, and most modern designs can perform adequately in most of the earth's climates. However, since the MODV will have configurations that will specialize the vehicle to a certain terrain it is also worth designing for the correlating climatic conditions

3.1.1 The World's Environments

The following Figures 3.1, 3.2, and 3.3 show the climate types and extreme temperature ranges that can be expected in the different places on earth [18].

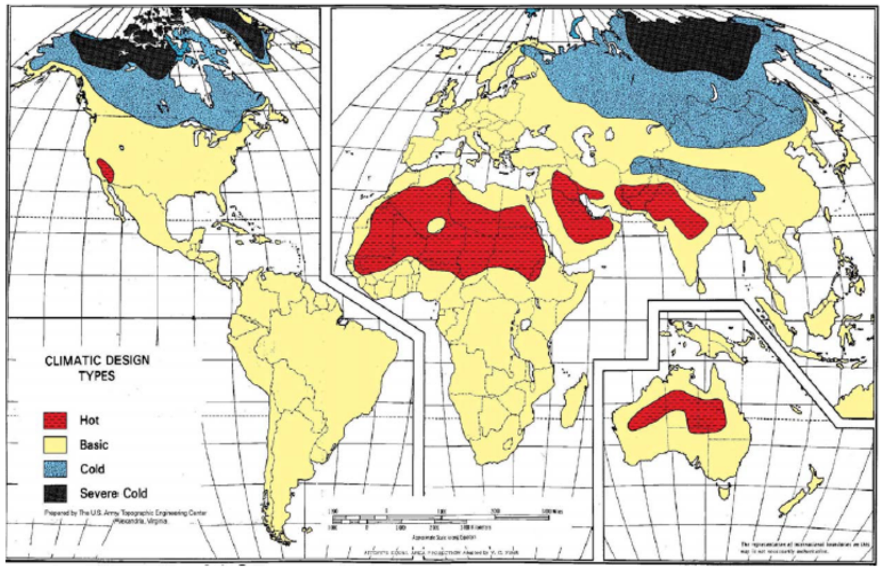

Figure 3.1: Climate design types depending on area of operation, [18], [public domain]

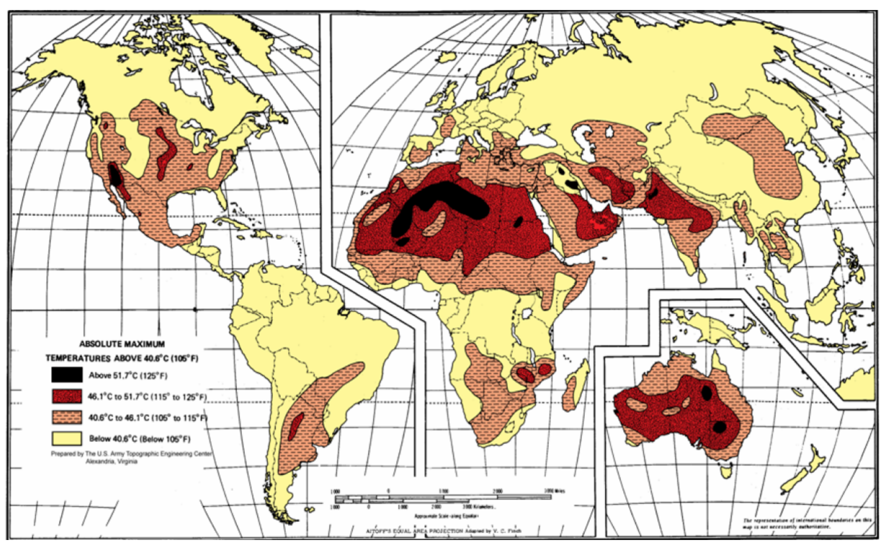

Figure 3.2: Maximum temperatures depending on area of operation, [18], [public domain]

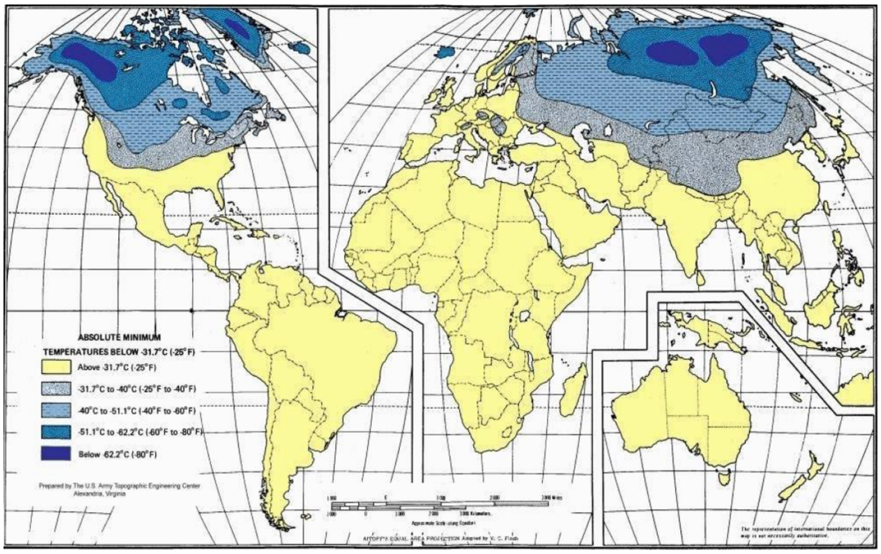

Figure 3.3: Minimum temperatures depending on area of operation, [18], [public domain]

When designing a configuration to operate in a specific area it is important to take note on the conditions encountered there. Even though the climate design types can be broken down into hot, basic, cold, and severe cold, some areas of the world see drastic temperature and humidity fluctuations.

3.1.2 Temperature and Humidity Bounds

The author has formed Table 3.1 to give guidance on the climatic conditions the MODV should be designed for.

Table 3.1: Climatic design bounds for MODV configurations

	Temperature (°C)		Humidity (%RH)	
	Max	Min	Min	Max
Desert	58	0	2	10
Hot - Humid	48.3	20	59	100
General	40.6	-30	59	88
Cold	20	-46	Saturation	
Severe Cold	0	-90	Saturation	

The desert climate type is self explanatory. High temperatures, low humidity, and sealing for fine particulates are the design highlights. Typically, many ground vehicles can operate in this environment as long as they are guarded against fine dust and sand.

Hot-Humid is typical of tropical areas. This design type must guard against high humidity exposure for extended periods of time.

The general climate type is the one that a large portion of the world experiences. Humidity can get up to tropical conditions and temperatures can reach well into cold conditions, but only for extended periods. This design type sees the largest fluctuations throughout the year but isn't considered an extreme condition.

The cold climate is one that can see temperatures well into -40°C but still remains hospitable enough for humans to live in most off the year. The cold conditions must be accounted for when selecting materials and lubricants because some can become unusable in such low temperatures. Large areas of Russia and North America see this climate type.

The severe cold climate type is the most challenging to account for in designs. The extremely low temperatures push the boundaries of many conventional engineering materials. It might seem odd to consider these conditions for a ground vehicle because it is difficult for humans to survive in the severe cold climate, but it is important to remember the MODV will have unmanned capabilities and would serve as an invaluable tool in such austere climate conditions. Therefore, it will be relevant to design a MODV configuration for this climate type.

It is worth noting that most ground vehicles can operate in the desert, hot-humid, and general climatic conditions. The main challenge for current vehicles is operating in the cold and severe cold environments. Polymers, rubbers, oils, and lubricants see drastic changes in material properties when temperatures get low enough. Therefore, configurations for the MODV could be optimized for protection from two main groups. The first group being desert, hot-humid, and cold, and the second group being cold and severe cold.

3.2 Wheeled vs. Tracked Vehicles

When selecting the configuration components for the MODV it will be important to understand the pros and cons of wheeled and tracked vehicles. Since the MODV will be mission configurable the traction layout can specialize more than current vehicles allow. Conventional vehicle design requires some sort of generalization of all vehicles because they are made with limited modularity. While all MODV types will be able to negotiate many different terrains, the designs can be tuned more towards a specific terrain.

When considering the selection of a wheeled or tracked vehicle, it is useful to consider the drawbar-pull-to-weight ratio,

$$\frac{F_d}{W} = \frac{c}{p} + \tan\phi - f_r \tag{3.1}$$

Where F_d is the drawbar pull, W is the weight, c is the cohesion, ϕ is the internal shearing resistance, p is the contact pressure, and f_r is the coefficient of motion resistance. It follows that the lower the contact pressure and motion resistance then the higher the drawbar-pull-to-weight ratio. This makes the MODV configuration selection extremely important since p and f_r depend on the design [25].

3.2.1 Wheeled Vehicles

Wheeled vehicles are typically preferred for their high road speeds, fuel economy, low maintenance, and overall utility advantages. Typically, a tracked vehicle will have a superior drawbar-pull-to-weight ratio than a wheeled one. Meaning, if the same vehicle had a design optimized with tracks and wheels the tracked version would have better off-road performance. Even with the added weight of tracks the ground contact pressure is reduced, improving the drawbar-pull-to-weight ratio.

Nonetheless, if a wheeled vehicle can be optimized to the point where it has adequate performance given the mission needs, then the tracked advantages become moot. This is especially prevalent when there is heavy road use. A wheeled vehicle has superior speeds and economy on the roads with high reliability. An 8-wheeled vehicle has 8 rotating wheels compared to 4 sprockets, 10 wheels, and dozens of track links on the same vehicle with a tracked configuration. The wheeled vehicle can lose function of multiple wheels and still 'limp' back to base, while the tracked vehicle's components are connected and mostly dependent on one another. The low maintenance of wheeled vehicles is preferred by the Marine Corps, especially since much has been done to optimize the performance of wheeled vehicles.

One feature of wheeled vehicles that has helped close the gap between tracked and wheeled performance is the ability to change the tire inflation pressure on the move. When the tire pressure is lowered the tire contacts more ground, thus decreasing the contact pressure on the terrain. This allows the crew to negotiate softer terrain when needed, while retaining high speeds and economy on the roads. Table 5.2 shows this phenomenon for some possible MODV configurations. The terrain performance still doesn't match a tracked vehicle but it can help close the gap enough to make a wheeled vehicle viable for a given mission.

3.2.2 Tracked Vehicles

Tracked vehicles by and large have superior off-road performance compared to wheeled vehicles. Lower contact pressures are inherent in the design because the wheels of the vehicle are rolling on top of the tracks, spreading the force out over a larger area. The tracks can also 'dig' into the terrain, providing extra drawbar pull.

The low pressures associated with tracked vehicles are displayed in Table 3.2 using data from [25], and [26]. It is clear to see that the pressure exerted on the ground can be reduced immensely by using tracks. Vehicles such as the Leopard 2 and M1 Abrams which weigh 55 and 51 tons respectively, have mean maximum pressure values close to the M998 Humvee which only weighs 4 tons. The M29 Weasel weighs slightly more than the Land Rover, but exerts one tenth the pressure. Clearly, with proper design tracks can offer vastly superior tractive performance.

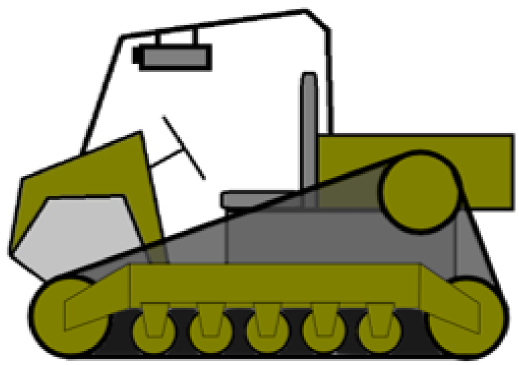

Figure 3.4: A tracked MODV configuration for use in demanding terrain

It can easily be presumed that having a tracked configuration on the MODV as depicted in Figure 3.4 will mean exceptional terrain performance. In the simplest scenario, one could take the track configuration for the M29 Weasel and put it onto a compact utility vehicle such as the MODV. If the MODV weighs 3,000 lbs fully loaded it would weigh half as much as the M29. It follows that the MMP would be less than 27 kPa, which is already exceptional. This means that the MODV would be able to negotiate deep snow or boggy terrain in the same way if not better than the M29.

Table 3.2: Values of the Mean Maximum Pressure of wheeled and tracked vehicles, [25], [26]

Tracked Vehicles	Weight (t)	MMP (kPa)	Wheeled Vehciles	Weight (t)	MMP (kPa)
M29 Weasel	2.7	27	Land Rover 1/2 ton	2.1	267
M60	52.4	230	Saxon AT105	11.7	430
M1 Abrams	51.4	210	V-150	N/A	355
M113	11.6	121	M998 Hummer	3.87	228
Leopard 1	44.4	235	Luchs (8 x 8)	19.5	371
Leopard 2	55.2	220	Panhard M11VBL	3.5	252
Challenger	62.0	282	Ferret Scout Car Mk. 2	4.5	320
FV101 Scorpion	8.3	106	Saladin	11.6	462
T72	N/A	257	BTR 60P	N/A	320

(N/A) indicates that the MMP is from unconfirmed data.

Although a tracked configuration can achieve greater tractive performance it doesn't mean that a vehicle designer will arrive at the optimal design easily. To achieve this the track-roadwheel system must be properly engineered [25]. Parameters such as track-pitch, number of wheels, diameter of the wheels, suspension travel, overall track length and width, and track material must be combined properly for the optimal design.

The main hindrances of using a tracked configuration are fuel economy and maintenance. Power is wasted in rotating more parts and the friction between components such as the sprocket and tracks. More moving parts means more components that can fail which ultimately leads to higher levels of maintenance and inspection. The components on a track are all connected so the vehicle is more prone to break down while operating. This also creates a higher logistics demand which can have a larger effect on a task force as a whole.

3.3 Mean Maximum Pressure

One useful method that can be employed to understand a vehicle's performance is the Mean Maximum Pressure method [MMP]. This method's formulas are based off of actual pressure measurements and gives a reasonable estimate to the vehicle's performance on certain terrains. Equations are first presented in [27] and then refined in [26].

As the name implies, this method uses the mean of the peak pressure values exerted on the terrain to give insight into the vehicles performance on said terrain. For a wheeled vehicle on fine-grained soil, equation 3.2 can be used to evaluate the MMP in kPa. MMP calculations for possible MODV configurations are shown in section 5.2.

$$MMP = \frac{K'W}{2mb^{0.85}d^{1.15}(\frac{\delta}{d})^{0.5}} \tag{3.2}$$

Where W is the vehicle weight in kN, m is the number of axles, d is the unladen tire diameter in m, b is the unladen tire breadth in m, δ is the tire deflection on hard ground in m, and K' is a factor depending on the number of axles and proportion of axles driven. For the MODV these factors will be 1.83 and 1.95 for the four wheeled and six wheeled configurations respectively.

For a wheeled vehicle on dry coarse-grained sand soil the equation changes,

$$MMP = \frac{STW^{1.3}}{2mb^{1.5}d^{1.5}\frac{\delta}{d}} \tag{3.3}$$

Where S is the constant of proportionality 0.31, T is the tire road factor; 1 for a smooth tire, 1.4 for a road tire, 2.8 for a road/CC tire, and 3.3 for an earth mover tire. All other constants are the same as in equation 3.2.

Since the MODV will have tracked configurations it is useful to include the MMP calculation for a tracked vehicle,

$$MMP = \frac{1.26W}{2mcb(pd)^{0.5}} \tag{3.4}$$

Where W is the vehicle weight in kN, m is the number of axles, d is the wheel diameter in m, b is the track width in m, p is the track link pitch in m, and c is the track link profile factor: area/pb.

Once the MMP for a vehicle is calculated, it must be compared to the MMP values that a certain terrain can tolerate. Table 3.3 shows terrain values collected from [25] and [27].

Table 3.3: Mean Maximum Pressure values for traversing common terrains, [25], [27]

	Mean maximum pressure (kPa)		
Terrain and Condition	Ideal	Acceptable	Maximum
Basic climate,wet, fine-grain soil (clay)	150	200	300
Tropical climate, wet fine-grain soil	90	140	240
European bogs	5	10	15
Muskeg	30	50	60
Over-snow	10	25-30	40

An ideal condition is where multiple vehicles can pass over the same terrain path, which is essential for some tactical applications. The maximum allowable condition means that the terrain will only be negotiable for one vehicle.

With any empirical measure there are certain limitations that must be taken into consideration. It is important to note that the MMP does not take into account the vehicle operator's skill, which can significantly impact the pressures exerted on the terrain. There is also no allowance for steering effects. A vehicle with skid-steering abilities can exert harsher pressures onto the terrain and will need some 20 % lower MMP values if the vehicle is handled in this way. Lastly the MMP method assumes the soil is homogeneous, and deep enough such that the soil will act like an infinite medium. This means it cannot account for the size of the vehicle in relation to the soil's underlayers, which may be firmer and more trafficable [27]. Ultimately, finite and discrete element methods will give the most accurate overview of the pressures a vehicle exerts onto a given terrain. Nonetheless the MMP method is a useful way to gain valuable insight into a vehicle's design constraints.

Chapter 4

Predictions

When reading the predictions section it is important to note that these are to be used as general guidelines for where the following technologies could be in five years. Ultimately, it is up to the individual engineer's discretion on how to design the MODV to meet these future trends. These predictions are the result of intensive research into the technology trends and are meant to give the author's engineering opinion on reasonable expectations for advances in the respective categories. It would be best practice not to take these predictions as absolute, but to combine them with the engineer's judgment to arrive at a solution.

It is very likely that one or more of the critical technologies discussed will have dramatic breakthroughs in the near future, so it is important for any engineer using this thesis as a reference to perform their own research on a technology of interest to confirm the results. This thesis was published on January 21, 2015 and the more time that passes from this point the more likely it is that some predictions may be moot.

4.1 Expected Technology Advancements

4.1.1 Wheel Hub Motors

The wheel hub motor's performance as outlined in [6] is a testament to the viability of using an electric wheel hub motor in the design of future ground vehicles. The motors evaluated in that experiment were 63 kW (85 HP) each and for the MODV motors of 7.5 to 10 kW (10 to 12 HP) are required. The power of the hub motors is not in question, rather the availability in the 10 kW (12 HP) range. If there are already hub motors that can be used for automotive design at this time it goes without saying that the quality and availability of these items will improve because of the advantages that they present. Therefore, WHMs will adequately meet the performance demands of the MODV concept.

4.1.2 Batteries

Battery Future

Predicting the future of battery performance is best done by showing upper and lower bound predictions. Some scientists are very optimistic about the next couple of years but it is important to be conservative in the estimates. The predicament that GM and Envia found themselves in a few years ago is a testament to the dangers of being overly optimistic.

For the past decade both energy and power density have been increasing by about 6% per year. Using this metric we can predict the battery performance outlook in 2019 as outlined in Table 4.1.

Table 4.1: Predictions of battery weight savings given a 7 % increase in performance per year

			Energy	Power		Run	Power Requirements		Energy Requirements		Total	
	Battery	Specialty	Density (Wh/kg)	Density (W/kg)	Load (W)	Time (hrs)	Minimum Mass (kg)	Weight (lbs)	Minimum Mass (kg)	Weight (lbs)	Mass (kg)	Weight (lbs)
2014	Shin-Kobe 2	Power	56	3,920	40,000	0.1	10.2	22.5	71.4	157.5		
	Saft 2	Energy	140	476	5,000	3	10.5	23.2	107.1	236.2	117	259
2019	Shin-Kobe 2*	Power	75	5,246	40,000	0.1	7.6	16.8	53.4	117.7		
	Saft 2*	Energy	187	637	5,000	3	7.8	17.3	80.1	176.5	88	193

** Denotes that these are 5 year advancements at 6% increases in power and energy density per year.*

The total weight is calculated based on the assumption that there will be batteries specializing in power delivery and energy delivery. Intelligent use of the batteries based on the operating conditions helps optimize the weight of the vehicle. The values selected for the final weight are shown in the green boxes. While the final vehicle design may see a total battery weight above or below the presented numbers, it can be stated that the weight budget could be reduced by 25% if the energy and power density increase by 6% per year.

Solution Outline

It is safe to say that whatever the advancements may be in battery technology, there will be batteries specializing in energy density or power density. The basic rule of battery design is that given a certain battery chemistry it can be optimized more towards energy or power. Therefore the likely solution will be a combination of batteries specializing in certain load requirements. The CPU of the MODV can, either by user input or autonomously, optimize the power use. During silent operation where low power is required the power can be drawn mainly from the high capacity batteries. When the MODV operates in a HEV mode or needs high acceleration then power can be drawn from the high power batteries.

Engineering the optimal battery setup will require a more in depth analysis than presented in this section. Different loading conditions must be considered such as towing up an incline, high accelerations on differing terrain, and acceptable accelerations during silent mode.

It is possible, however, with the MODV's modular nature that the battery setup will be modular as well. It is easily conceivable that a battery setup can be outlined for certain mission specifications. All this would require is for the batteries to be physically secured, and power and communications cables hooked up. Then the CPU would have the information on the amount of batteries and their characteristics.

If a logistics MODV were needed then the vehicle would see significant weight savings. There would no longer be a need for all of the high capacity batteries required for silent mode which contribute to the bulk of the weight. Only 10 kg is needed for the power requirements while 110 kg is needed for the silent mode requirements. Less weight for batteries means more weight for supplies.

4.1.3 Solid Oxide Fuel Cells

There are many reasons to believe that SOFC technology will advance enough for use in ground vehicles, at least in a limited capacity, within the next five years. One of the main ones is that a SOFC driven vehicle can offer the extended range that so many electric vehicles fall short of. Many consumers choose not to have a purely electric vehicle because the range is limited. Even though conventional vehicles only have 30% efficiency, a tank of gas has so much energy in it that a vehicle running off of gasoline will have a greater range. Technically a vehicle powered by SOFCs isn't purely electrical because the energy is from a liquid fuel, but the electrical energy in the batteries of current electric vehicles comes an outside source as well. In any case, a vehicle supplemented or completely powered by SOFCs would be very desirable for the average American consumer because the cost per mile of operation would be vastly superior to cars using internal combustion engines. This fact is obviously a huge source of motivation for extending the capabilities of SOFCs, and the demand for cheaper transportation will not go away in the near future.

Another area that SOFCs are seeing a significant investment of resources is industrial power production. Both General Electric and Bloom Energy are investing heavily in this application. Since size and weight are not critical constraints for industrial power production SOFCs are very attractive with their conversion efficiencies of up to 90%. High efficiencies really pay dividends when the power production is on the mega watt scale. The fact that a wide array of fuels can be used is also an extremely attractive aspect for industrial power. Both Ethanol and vegetable oil can be used in SOFCs which means that the United States could use excess crop production to power its infrastructure. With the big push for renewable energy this makes SOFCs all the more attractive for industrial power uses. With all of the motivations that exist to apply SOFCs in industrial power, it easily follows that ample resources will be committed to the technology's advancement. With such large companies pushing for better SOFC technology it is likely that the technology will advance enough to where it is usable in ground vehicles.

The confidence that can be found in the advancement of SOFCs stems from the fact that this fuel cell system is not theoretical, it actually works and is in use today. This has not been lost on major companies who are rushing to take advantage of system's excellent performance. The main hindrances for its use in ground vehicles are its energy and power density, and its high operating temperatures. The reason the author is confident that these issues will be worked out is that these issues are not holding back major companies form investing in SOFCs for industrial power application. Companies such as GE are already investing in applying SOFC systems, so they will be invested in research to advance the technology in the future. With this large investment it follows that these systems will see increases in power and energy density, and see a reduction in cost. These advances wouldn't just benefit industrial production because companies could sell smaller units for residential use. It just so happens that SOFC systems for residential use would be about the right size and weight for vehicle use.

The advancements in SOFCs must be monitored so that their high efficiency benefits can be taken advantage of in a timely manner. A ground vehicle that could be powered by a SOFC and battery system would have many advantages over conventional vehicles. Especially if the MODV concept were powered by such an efficient and reliable power plant. The SOFC system has no moving parts, and this coupled with wheel hub motors would mean a very low maintenance vehicle. All in all, it is in the MODV concept's best interest to integrate a SOFC into the system as soon as the technology can be reasonably used on a ground vehicle.

4.1.4 Autonomy

To gain insight into the future of autonomous capabilities it is helpful to look at where the technology is heading in the domestic world. Cisco's technology trend watchers stated that in 5-7 years it could cost people more to drive their own cars than to let the cars drive themselves [39]. This is a best case but possible estimate. Autonomous vehicles will be able to avoid accidents easier than human drivers which should drive the cost of owning a car down. In the US vehicular accidents inflict $450 billion in annual costs and it is estimated self-driving cars could reduce human caused crashes by 80% [39]. This should lead to lower insurance rates and car ownership rates in general. As far as the number of self-driving cars on US road goes, IHS estimates 230,000 by 2025 and 12 million by 2035. With such a large savings to be had and the ample number of vehicles predicted it is a certainty that vehicle autonomy will see heavy investments and advances in the commercial market.

The future for autonomous vehicles is looking bright. Research and development of autonomous ground vehicles is here to stay with massive demands from the consumer and defense industries. Current vehicles such as the Google Car, Terramax™, and GUSS provide a baseline for off road autonomous applications While it is hard to put exact numbers on the specifications of autonomous vehicles in the future, it is certain that autonomous capabilities will improve and be a valuable asset to the MODV concept.

4.1.5 Structural Health Monitoring

With the resources being spent on research in structural health monitoring it is safe to say its capabilities will only expand over the next five years. The demand that our civil infrastructure and aerospace industries have for better SHM is too great for the research to stop.

Predicting exact specifications for the future is difficult for SHM because its application has mostly been in aerospace and infrastructure. Continuous monitoring has been successfully implemented for rotating machinery for the past three decades, so it is reasonable to state that health monitoring advances can be applied to ground vehicles. Since the main focus on SHM has been on aerospace and civil infrastructure there is not rigorous data to back up the claim that SHM can help ground vehicles the same way that it does other industries. However, simple applications of fiber-optic strain gages, accelerometers, and environmental sensors can surely be used to help monitor a vehicle's structural health. The real question is the economic feasibility of applying current SHM techniques to ground vehicles.

Since there is a lack of applied examples where SHM is used on ground vehicles, it is not possible quote specific numbers signifying its capabilities in the next five years. It is the author's opinions that it will be possible and reasonable to use SHM on the MODV, but the unknown is how that solution will be realized. Special attention should be paid to the state of SHM in order to properly utilize it and exploit its advantages for a modular, utilitarian, and rugged vehicle.

4.1.6 Energy Harvesting Shock Absorbers

Incorporating an EHSA into the MODV's design scheme would be a wise decision given the present technology available. This means that the outlook five years down the road should yield proven EHSA systems that can properly harvest energy and aid in the control of the vehicle. The engineers involved in this project would benefit from researching the advancement of EHSAs since this thesis's publish date (January 21, 2015) and find a product that can adequately meet the demands of rugged off road use.

4.1.7 Non-pneumatic Tires

Since this technology is already established as an applicable product it is safe to say the variety of tire sizes and geometries will increase in the future. Currently it is a proven system for ATVs and skid-steers, and applications for road vehicles are being explored. With the excellent advantages these tires can offer for off road use it is worth looking into a tire that can fit the mission needs of the MODV.

4.1.8 Protection from Electromagnetic Pulses

Since this technology is already mature and readily applicable to off road vehicles it can be stated that a shielding solution can be found for the MODV now as well as five years from the date of publication. Shielding from EM pulses should be given special attention in the MODV because of the breadth of electronics used in the MODV that are not used in many vehicles at this time. Structural health monitoring for instance hasn't been used in ground vehicles therefore shielding systems may not have been designed specifically for it. That being said, proper shielding can be developed given conventional design practices.

4.1.9 Drive by Wire

Drive by wire systems are already available for use in off road and road vehicles. It is a proven technology that must be implemented in the MODV because it allows quick attachment of an autonomous appliqué kits. The fault tolerance and reliability of drive by wire systems should also increase as the technology matures, making it even more attractive for use.

Chapter 5

Design Bounds

The design bounds for the MODV are meant to be taken as a first step and give insight into the physical requirements for a light utility vehicle that is internally transportable in a V-22 Osprey. As with any engineering project the design bounds should retain some fluidity in order to adapt to possible changes in requirements.

5.1 Physical Vehicle Constraints

Table 5.1 shows some spatial constraints for the MODV based on terrain negotiation, ITV specific requirements, and general constraints for a light utility vehicle as outlined in [26]. In order to meet ITV requirements some of these constraints are rigid and denoted as such. The best way to understand the ITV requirements is to study the documents outlining the specifications, but the table offers valuable insight into the main requirements.

It is important to mention that some of the ITV requirements are not related to physically transporting the vehicle. Maximum paved road speed, operational range, and power plant are all related to the mission performance. In section 1.2.2 it is mentioned that MODV can reach 40 mph with a 20 kW power plant on level ground. Since this does not meet the 65 mph requirement it must be decided if going to a 40 kW power plant is worth the extra weight to achieve a higher top speed. Figure 5.1 shows a graph of the power plant required as a function of maximum speed on a paved road. This graph assumes 90% energy loss and 40 kW results in a maximum speed of 29.2 m/s or 64.4 mph.

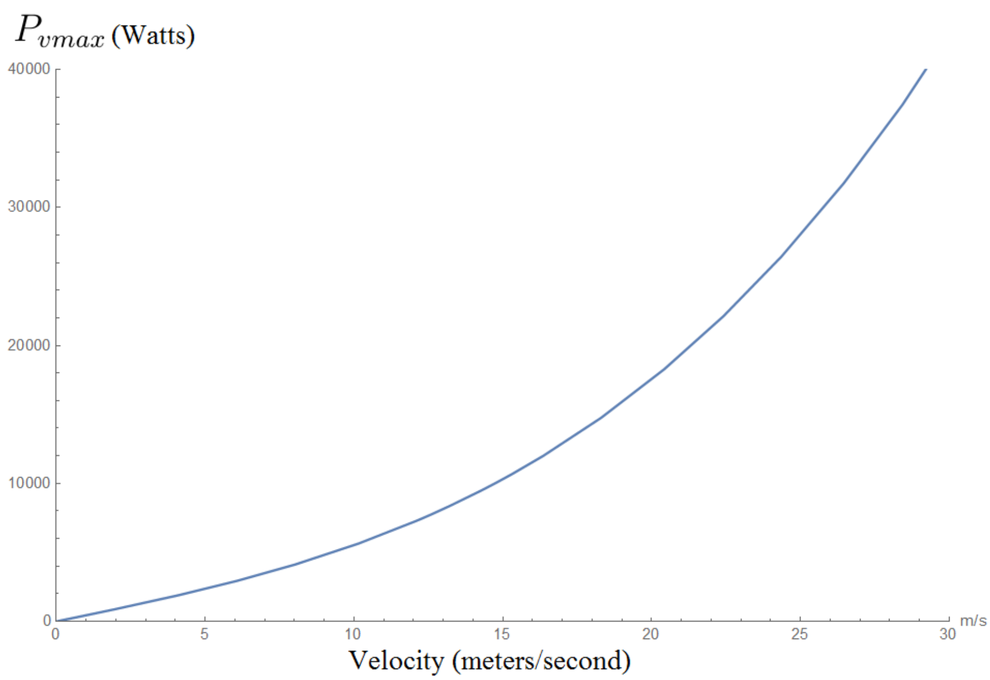

Figure 5.1: Power required vs. maximum speed, 90% efficiency from battery pack to wheels

Table 5.1: Spatial vehicle bounds for MODV design drawing from ITV requirements and parameters listed in [27]

Criteria	Range	Desirable	V22 ITV Specific
Length (m)	3 to 4.1	< 3.5	
Width (m)	1.4 to 1.5	< 1.5	
Height (m)	1.2 to 1.8	< 1.2 (stowed)	*
Weight (lbs)	1400 to 1900	< 1900	
Ground clearance (mm) (1)	400 to 700	> 400	
Approach Angle	50° to 75°	> 50°	*
Under-Vehicle Angle	100° to 130°	< 130°	
Departure Angle	45° to 75°	> 45°	*
Suspension travel (mm)	300 to 400	> 310	
Fording Height (m)	0.76 to 1.5	> 0.76	*
Ditch Height (m)	0.72 to 1.2	> 0.72	
Ditch Width (m)	0.72 to 1	> 0.72	
Vertical Step (mm)(2)	355 to 460	> 355	*
Payload (t)	1/2 to 1	> 3/4	
Turning Radius (m) (3)	0 to 8	< 6	*
Crew	0 to 4	> 3	*
Casualty Transport (no. of litters)(4)	3 to 6	> 3	*
MMP (Clayey Soil) (kPa)	25-250	< 280	
Tractive Effort / Weight	0.53 to 1	> 0.53	*
Power Plant (kW)	10 to 20	> 20	
Gross power to weight ratio (kW/t)(5)	13 to 26	> 22	
Operational Range (mi)(6)	350 to 450	> 400	*
Max Paved Road Speed (mph)	40 to 75	> 65	*
Max Crawl Speed (mph)	1 o 3	< 3	*
Water Speed (mph)	4 to 6	> 4	
Gradeability	60% to 100%	> 60%	*
Side Slope Gradeability	20% to 40%	> 35%	

Notes:

(1) Ground Clearance will be telescoping on some configurations, so the range listed is for normal driving operations.

(2) With telescoping suspensions the MODV may be able to negotiate higher steps.

(3) Turning radius is zero because of wheel hub motors or skid steering.

(4) Litters must be attached to framework of the vehicle such that the casualties will not extend horizontally outside the vehicle and rescue personnel will have access to all patients.

(5) Gross power to weight ratio (kW/t) is specified for conventional vehicles that lose 60 to 80 % of their horsepower from the engine to the wheels, so the minimum desired is more around13 kW/t. This was calculated without payload.

(6) 45 mph on level paved roads.

5.2 Mean Maximum Pressure

Table 5.2 shows the calculated MMP values for 4-wheeled and 6-wheeled MODV configurations, using the values from Table 5.3.

Table 5.2: MMP calculation results for MODV configuration in clay-like soil

MODV Configuration	Tire Deflection	
	1.3 x road	2 x road
	MMP (kPa)	
4-wheeled	248	200
6-wheeled	197	159

Table 5.3: Tire geometry values used for MMP calculations in Table 5.2

4-wheeled MODV; Clay		6-wheeled MODV; Clay	
w = 13.44	kN	w = 13.44	kN
d = 0.6604	m	d = 0.6604	m
b = 0.2286	m	b = 0.2286	m
δ_{road} = 0.01	m	δ_{road} = 0.008	m
m = 2		m = 3	
k = 1.83		k = 1.95	

These calculations were done using equation 3.2 and assuming that the MODV had a weight of 13.44 kN (3,000 lbs) which is the approximate weight and the full payload added together. The tires used in the calculations are from the 26 x 9-12 tires from the Polaris Ranger XP 900, and it can be assumed that the tires selected for this vehicle will perform better. The deflection values used are also reasonable approximations and not measured values. Since the MMP calculations are sensitive to deflection further research would be needed for a more definitive evaluation. These results should therefore be considered as a worst case scenario, as they are simply meant to give insight into possible terrain negotiation issues.

When compared to the values given in Table 2.4, it is clear that both vehicle types have lower MMP values than typical light vehicles. This means that both of these MODV configurations, in general, should be able to perform just as well if not better than these vehicles on a given terrain.

Chapter 6

Conclusion

6.1 Concept Realization and Design

It goes without saying that in order to develop a working prototype of a MODV proper engineering judgment must be used throughout the design process. This section aims to give insight into what can and can't be compromised in the design. There is give and take in every project and maintaining that balance will be vital to meet the final design goals of the MODV.

6.1.1 Concept Pillars

The first and most obvious thing is that the vehicle must be internally transportable. The MODV has an advantage in that it will be designed from the ground up to meet this requirement and not modified after the fact. This coupled with the wheel hub motors should result in a very capable vehicle that is also compact. Meeting the ITV requirements should be considered a design anchor as it is essential to fulfilling the mission of the MODV.

Another important design aspect is the vehicle's modularity. This facet of the MODV design must be adhered to because it is the foundational principle the vehicle is built upon. Modularity results in major logistics demand reductions and should be pursued regardless of the state of the technologies discussed. Wheel hub motors and using electric motors in general allow for more flexibility in designing a modular vehicle since the power source can be localized, and those advantages should be utilized when developing the vehicle configurations.

The MODV must be a drive by wire vehicle that can easily accept autonomous appliqué kits. The trend in every branch of the military is toward retrofitting vehicles with autonomous kits, which basically requires making the vehicle drive by wire. The MODV will be designed with drive by wire capabilities from the start making autonomous appliqué kits a plug and play operation. Some are concerned with the reliability of such a system, but drive by wire systems have been used successfully in aircraft so there certainly is a solution reliable enough for use in a ground vehicle. Using a drive by wire system in the MODV will reduce weight, increase vehicle mobility, allow for easier design of vehicle configurations, allow for plug and play autonomy, and be an overall benefit to the realization of the MODV concept.

6.1.2 Power Plant Considerations

Selecting the power plant and battery packs for the vehicle will be a challenging task and extensive thought should be given to balancing range, top speed, and acceleration. Through some calculations the author found that the vehicle will need a 20 kW power plant to maintain a top speed of 40 mph, and a 40 kW power plant to maintain a top speed of 65 mph. 65 mph is listed as the speed for the ITV requirements, but meeting this need may see significant reductions in range and especially silent operation due to the increased weight. Ultimately, this design optimization must be given great care to meet the goals of the MODV concept.

6.1.3 Wheel Hub Motors

Using wheel hub motors in the design is advised due to their compact nature and the interesting vehicle configurations that can be achieved. Significant weight and space savings can be achieved by the elimination of a drivetrain. Suspensions have longer stroke lengths since there is no mechanical power transfer from the drivetrain. A traction configuration with telescoping wheels becomes a significantly easier design because of this. The vehicle can also sit lower to the ground because there is no differential protruding from the bottom of the vehicle. The concerns over using wheel hub motors is covered in Section 2.1.2 and there exists no reason not to evaluate and find out how to best exploit the advantages they offer.

If wheel hub motors are not found to be the optimal solution it is likely that pursuing a design using electric motors will be fruitful. Several automotive companies have developed roadworthy EVs without WHMs, and normal electric motors could still help achieve the modularity goals of the MODV concept.

6.2 Modular Vehicle Advantage

All of the technologies reviewed offer distinct advantages. Some of these advantages build off one another and coalesce to offer considerable performance gains. Utilizing these technologies in the MODV concept will yield a vehicle that is highly mobile, modular, provides a logistics demand reduction, expeditionary power, has extended silent operation range, and provides plug and play autonomy.

6.2.1 Advanced Mobility

Advanced mobility will be achieved through the modularity of the MODV, the use of wheel hub motors, and energy harvesting shock absorbers.

From Modularity

The modularity of this system means that the optimal traction kit can be selected based on the terrain. A four wheeled configuration will surely be a general purpose vehicle that can negotiate most conditions fairly well and will be used for missions involving heavy road use. A six wheeled configuration will be able to negotiate boggy terrain better than the four wheeled and could be used when more harsh conditions are expected. The telescoping wheel configurations could be used for very rocky terrain that might demand large suspension travel, or when deep ditches may be encountered. A tracked configuration would be used for the most demanding terrain such as light snow or boggy soil. With the MODV's light weight it will easily be able to achieve MMP values below 30 kPa, rivaling that of the Weasel from Section 1.3.2.

It is also worth recalling Table 5.2 seen here as Table 6.1 to show predicted MMP values for the MODV, and compare them with Table 3.2 seen as Table 6.2 and see how it compares with legacy ground vehicles. Equation 6.1 shows how the values for Table 6.1 were found, and is covered in depth in section 3.3. W is the vehicle weight in kN, m is the number of axles, d is the unladen tire diameter in m, b is the unladen tire breadth in m, δ is the tire deflection on hard ground in m, and K' is a factor depending on the number of axles and proportion of axles driven. For the MODV these factors will be 1.83 and 1.95 for the four wheeled and six wheeled configurations respectively.

$$MMP = \frac{K'W}{2mb^{0.85}d^{1.15}(\frac{\delta}{d})^{0.5}} \tag{6.1}$$

It is clear that the theoretical MMPs for the four and six wheeled MODV configurations will be less than other light utility ground vehicles. The Land Rover 1/2 ton is probably the most similar to the MODV concept and the highest MMP value for the MODV at 248 kPa is almost 20 kPa less than the MMP of the Land Rover at 267 kPa. A 20 kPa difference is considered large enough [26] to state that the four wheeled MODV will be able to negotiate terrain better than the Land Rover.

Table 6.1: MMP calculation results for MODV configuration in clay

MODV Configuration	Tire Deflection 1.3 x road	2 x road
	MMP (kPa)	
4-wheeled	248	200
6-wheeled	197	159

Table 6.2: Values of the Mean Maximum Pressure of wheeled and tracked vehicles, [25], [26]

Tracked Vehicles	Weight (t)	MMP (kPa)	Wheeled Vehciles	Weight (t)	MMP (kPa)
M29 Weasel	2.7	27	Land Rover 1/2 ton	2.1	267
M60	52.4	230	Saxon AT105	11.7	430
M1 Abrams	51.4	210	V-150	N/A	355
M113	11.6	121	M998 Hummer	3.87	228
Leopard 1	44.4	235	Luchs (8 x 8)	19.5	371
Leopard 2	55.2	220	Panhard M11VBL	3.5	252
Challenger	62.0	282	Ferret Scout Car Mk. 2	4.5	320
FV101 Scorpion	8.3	106	Saladin	11.6	462
T72	N/A	257	BTR 60P	N/A	320

(N/A) indicates that the MMP is from unconfirmed data.

From Wheel Hub Motors

Wheel hub motors allow for precise and independent control of each individual wheel. In a four-wheeled configuration this would be very advantageous which is why many premium road vehicles have this feature. With a mechanically powered system it can be expensive to achieve independent control of the wheels, but by using WHMs or even electric motors mounted close to the wheels independent control is intrinsic. If the front and rear right wheels drive over soft ground and start spinning, the power can be throttled back to an appropriate level. A mechanical differential, by nature, supplies the same amount of power to both wheels so when one starts slipping the other loses the torque necessary to propel the vehicle forward. This is overcome by locking the differential, but a locked differential has its own disadvantages at higher speeds. With independent electric motors there is no mechanical coupling and no differential or locking mechanism is needed. It is a simple and effective design that allows for superior traction control.

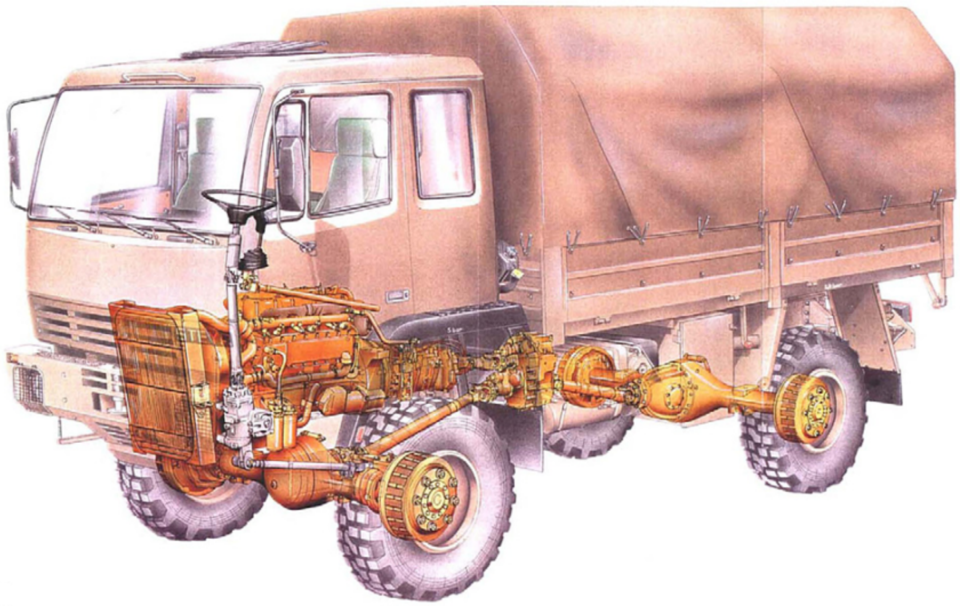

Figure 6.1: A typical military truck design showing differentials, [19] G. H. Hohl, "Military terrain vehicles," Journal of Terramechanics, vol. 44, no. 1, pp. 23–34, Jan. 2007., Used under fair use, 2014

An improved ground clearance and lower center of mass can be achieved by using wheel hub motors. Consider the 4x4 off-road truck shown in Figure 6.1. Both the front and rear tires are connected via an axle to a differential fixed at the middle of the vehicle. With this design the ground clearance is less than the radius of the tires being used, because the bottom of the differential sits lower than the center of the tire. Now imagine that both axles and differentials are gone because the vehicle uses wheel hub motors. The ground clearance is improved without raising the center of gravity. For the current ITV the ground clearance could improve 5 to 6 inches. The inverse of this advantage is that the rest of the vehicle could be lowered to lower the center of gravity while maintaining the same ground clearance. This would mean the vehicle has a lower profile and is less likely to roll, both of which increase the safety of the operators in the vehicle. Either way, having electric motors, and wheel hub motors in particular, directly driving the wheels offers ground clearance and center of mass improvements.

Articulating suspensions, or ones that can be raised or lowered actively, are a viable option for this vehicle because of its use of wheel hub motors. In a conventional design this would be hard to achieve because a mechanical transfer of power needs to reach the wheel, and designing a coupler to have the required degrees of freedom is possible but adds more complexity to the system. With WHMs, all that is needed is for power and control cables to be connected so a flexible design is easily achieved. The articulating suspension may be an important component in meeting ITV requirements, because one of the main challenges is getting a vehicle up the ramp of a V-22. The suspension could be lowered in a timely manner and then the MODV could drive up the ramp. When the MODV drives out of the V-22, the suspension can then be raised on-the-go for a smooth transition.

From Energy Harvesting Shock Absorbers

Energy Harvesting Shock Absorbers offer a twofold advantage. Firstly, they harvest the energy being put into the suspension as the vehicle traverses. Conventional shocks absorb the energy and dissipate it by pushing around pneumatic fluid and as a result the energy is lost. The EHSA absorbs this energy and can offer efficiency improvements of up to 10%. This will be especially advantageous for the MODV since it will be an off road vehicle, thereby maximizing the energy potential.

The next advantage is that the EHSA can perform work on the suspension, and adds another dimension to maximizing terrain performance and operator comfort. Vehicle manufacturers have been attempting to do this for a while using means other than EHSAs but their solutions have been too heavy to implement. Levant Power is a recent startup that has seen significant growth because they have an EHSA that can achieve both the energy harvesting and control advantages.

6.2.2 Logistics Demand Reduction

The MODV concept provides a logistics demand reduction in many ways. Its modularity, ability to be used for expeditionary power, and structural health monitoring capabilities all help achieve this aspect of the MODV concept.

Modularity

Modularity allows for a very adaptive and easily maintainable vehicle fleet. Instead of having a large amount of vehicles to meet a diverse array of needs, vehicles can be repurposed in a timely manner to adapt to the current situation.

Maintenance is streamlined with a modular vehicle. If, on a four-wheel configuration, one of the wheel/hub motor/suspension modules needs service, it could simply be detached from the chassis to be fixed, and a spare module could be placed in its stead. This means the vehicle is not out of commission while a mechanic looks for one issue on the module. The broken module can be troubleshooted and the vehicle can be up and running in short order.

Expeditionary Power

If each modular vehicle being driven around can be used to charge batteries, power a FOB, or provide efficient power for any need, this reduces the amount of stationary and tactical generators needed in theater. This aspect is especially useful for a vehicle deployed with a V-22 as it may have a certain amount of logistical isolation depending on the mission.

Since the MODV is a hybrid vehicle it is essentially an electric generator that can easily be utilized wherever needed. Incorporating this functionality into the MODV will not be difficult and will be a special advantage.

Structural health monitoring

Structural health monitoring offers a logistics demand reduction and streamlined maintenance in a novel way. Giving the MODV a 'nervous system' means that it can monitor the health of critical components and notify mechanics if a component will wear prematurely. Military vehicles sustain large impacts because of how they are used to negotiate terrain, and structural health monitoring allows these events to be recorded and quantified.

Besides providing early warning, structural health monitoring can also pinpoint damage. Instead of inspecting multiple components for damage, the damaged part will be known immediately. This means less trouble shooting and less down time for the vehicle.

6.2.3 Efficiency

In order to note the power savings of the MODV it is first necessary to show how the power consumption was calculated. In Equation 6.2 the power needed as a function of maximum velocity is shown. The terms inside the parenthesis is the total force acting on the vehicle at a given velocity, so there is no acceleration. This force is multiplied by the velocity to find the required power at a given velocity. v is the velocity, A is the frontal area of the vehicle, C_d is the drag coefficient, ρ is the density of air, m is the mass of the vehicle, g is acceleration due to gravity, C_{rr} is the rolling resistance, and grade is the grade of the slope.

$$P_{vmax} = v\left(\frac{1}{2}AC_d\rho v^2 + mgC_{rr} + \frac{mg\text{grade}}{100}\right) \tag{6.2}$$

Figure 6.2 is the resulting plot of the power calculation, assuming a 90% efficiency for wheel hub motors and 70% for a conventional drivetrain.

Since wheel hub motors easily achieve power-source-to-wheel efficiencies of 80% to 92%, as opposed to 60% to 80% for a mechanical system it can easily be seen that a significantly

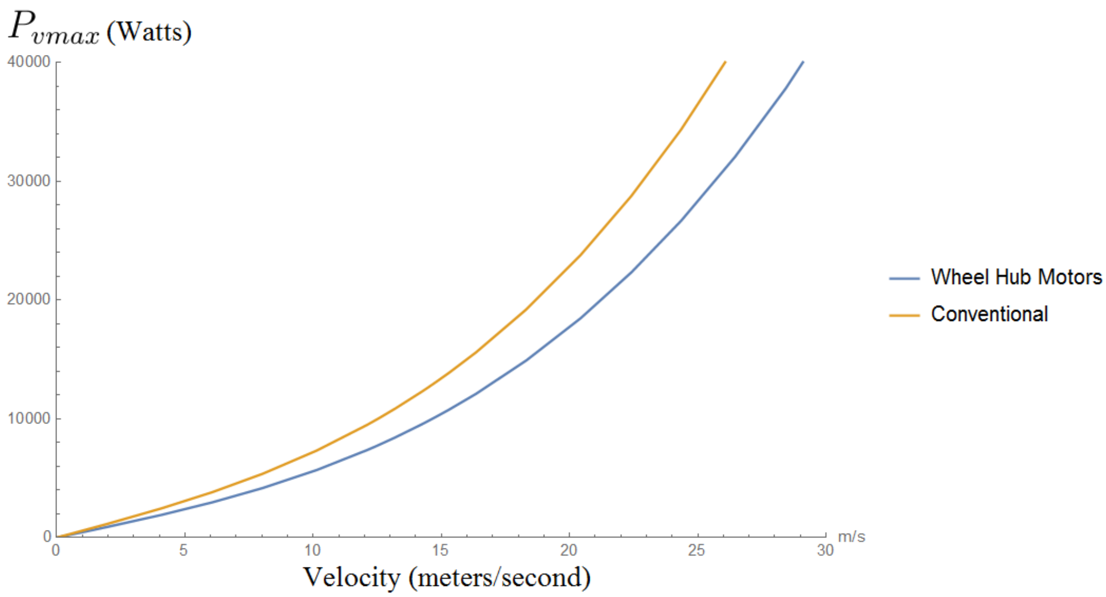

Figure 6.2: Power required vs. maximum speed of Wheel Hub Motors and Conventional Drivetrain

higher maximum velocity can be achieved. This not only achieves a better maximum speed, but increases the range of the vehicle as well.

6.2.4 Silent Operation

The MODV will be capable of silent operation which is a distinct advantage over conventional vehicles. There may be some instances where the operators of a MODV will want to remain undetected. To help achieve this goal the MODV can switch to silent mode and run off of battery power only. The MODV should be a very quiet vehicle because it will have a small amount of moving parts and will be using quiet electric motors for propulsion.

6.2.5 Plug and Play Autonomy

The MODV will be designed to accept autonomous appliqué kits from its inception, and will therefore be a drive by wire vehicle that can easily be made autonomous. All branches of the military are investing in retrofitting vehicles with autonomous capabilities, and the MODV will have this option from unit number one. This means that the modularity extends to the autonomy as well, as the vehicle can operate with no autonomy (manual), or any number of autonomous kits that have different perception capabilities for unique missions. An autonomy kit for reconnaissance will have distinct sensors and capabilities from a logistics kit, so the deployment of appliqué kits can be optimized along with the mobility kits. With plug and play autonomy the MODV will achieve the advantages of an autonomous vehicle in a streamlined manner.

6.3 Concept Viability

Through the hours of research put into ground vehicle theory and emerging technologies it is the author's opinion that the modular vehicle concept is completely viable and worthy of pursuit. All of the technologies reviewed in Chapter 2 offer distinct advantages in the design of a ground vehicle and can play an important role in the design of the MODV. Technologies such as wheel hub motors, advanced batteries, energy harvesting shock absorbers, non-pneumatic tires, and control via drive by wire are currently mature enough to start testing in real-world applications. Solid oxide fuel cells may not quite be ready for use in a light ground vehicle, but their capabilities should be monitored with a close eye because of the advantages they offer and all of the research being put into them. Structural health monitoring is currently being used in the aerospace industry so it is reasonable to assume a vehicle health monitoring system can be developed for a ground vehicle and then subsequently tested and evaluated. Autonomy and protection from EMPs are technologies currently being utilized in ground vehicles and their practicality has been proven.

Implementing these technologies into a cohesive vehicle design will be a challenge because it has not been done before. However, the design of the MODV should be pursued because of the unique advantages that can be achieved in such a vehicle. Extended silent operation, a logistics demand reduction, expeditionary power, and the ability to easily fit autonomous appliqué kits are the main benefits this concept offers over conventional designs, all the while fulfilling the main roles of the ITV.

There is never a guarantee of success with any engineering project, and indeed many of the force multipliers utilized today underwent growing pains in the initial phases of their implementation. Nonetheless, the clear viability of implementing these technologies coupled with their advantages makes the MODV a worthy undertaking.

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