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Design and Development of an Independent Hub Motor Rear Drive Vehicle with Electronic Differential

Bernacki Mark[1], Pop-Iliev Remon[2]
[1]*UOIT, FEAS, 2000 Simcoe St. N, Oshawa, Ontario, Canada, L1H 7K4 – mark.bernacki@gmail.com*
[2]*UOIT, FEAS, 2000 Simcoe St. N, Oshawa, Ontario, Canada, L1H 7K4 – remon.pop-iliev@uoit.ca*

Abstract

With today's ongoing 'push' to electrify the common vehicle, there is an inherent need to develop innovative ways to propel such vehicles via electric motors. This paper concentrates on the design and development of a prototype vehicle utilizing an independent rear wheel hub motor design. The design will concentrate on metrics to benefit many aspects of vehicle development ranging from increased inboard space and direct drive efficiencies. Coupled with a series hybrid architecture with a hydrogen ICE generator this paper discusses the development of a rear drive, hub motor architecture with an electronic differential on a test bed vehicle.

Keywords: braking, PHEV, powertrain, permanent magnet motor, regenerative braking, transmission, wheel hub motor

1 Introduction

The electrifying of the modern day automobile provides many opportunities for innovative improvements over today's internal combustion (IC) vehicle. The onset of electric technologies has triggered much architecture to emerge in coupling electric motors into the existing power trains of IC vehicles. Such approaches include transaxle mounted electric motors as found in the DIY community and parallel/ series hybrid power train arrangements as seen in today's OEM market. Series and Parallel arrangements offer the benefit to be able to switch between power sources. All, however, still infringe on existing interior space constraints of today's passenger vehicles as well as utilize many inefficient mechanical power transfer devices which do not apply power directly to the wheels. By incorporating a hub motor or near wheel motor design, these interior space constraints are no longer a consideration as the entire power train has been moved outboard to a location of power transfer; the wheels. The design flexibility of inboard space will be increased dramatically and will have the potential to be used more effectively rather than for the storage of the engine. With such changes mechanical efficiencies are also introduced by the elimination of such power transfer devices.

1.1 Mechanical Losses

Automobile combustion engines encompass large envelopes of space in the forward compartment of the vehicle. The engines and transmissions occupy nearly one third of the vehicular space. More space constraints are introduced when transfer of motion mechanisms are considered. Mechanisms that allow power to be translated to the front, rear, or in many cases, all wheels with additional drive train transfer mechanisms. This includes transmissions, differentials, transfer cases, drive shafts, and CV shafts all require valuable inboard space. Some performance vehicles have engineered solutions to store the engine in the middle of the vehicle, thus distributing the weight more equally and improving handling performance with a broader, 50/50, weight distribution. Therefore, storage of the powertrain in the inner regions of the vehicle has its limitations.

1.2 Electric Motors

Electric motors have become more compact and extremely powerful while costs continue to plunge in their production. With developments in 3-phase AC motor technologies, controllers incorporate adjustable voltage and adjustable frequency inverters for torque management. The electric motor continues to show its automotive friendly characteristics: extraordinary high-low end torque curves, high peak horsepower all in an RPM range, which does not require any reduction in speed. To magnify this even further, the continued developments of permanent, rare, earth magnet motors have increased efficiencies of such motors as well as made them lighter.

The efficiency gains by moving the motor to the point of power use are apparent by the loss of all transport mechanisms such as transmissions, differentials, transfer cases, drive shafts, and CV shafts can be removed. Although advances in transmissions have been found in the form of CVT transmissions, the complexity of these devices has not decreased, nor has the cost. Investigations on the removal of such mechanisms will be tested with a prototype-based hub motor vehicle.

2 Powertrain Devices

The choice of a suitable motor is critical in propelling a vehicle. Characteristics such as high torque coupled with a moderate top end RPM are crucial for suitable vehicle performance. A feasibility study was performed on the current motor types, along with the financials to have them implemented into a production style vehicle. Such standards set for the vehicle were acceleration speeds of 0-100km/h in fewer than 7 seconds, as well as a top speed of 110km/h. As well complexity in controls was another factor considered, as an early development electronic rear differential would need to communicate and compute the speeds of the rear wheels during turning manoeuvres. This required an interface between the motor controllers capable of allowing the motors to operate independently.

Hub motors must have high power and must be contained within the diameter of a vehicles wheel. Today's electric motors are on the brink of reaching these new standards of high power low volume packaging. Although hub motors have not reached main stream mass production, a few companies have emerged with options for outfitting a vehicle with a hub motor. In consideration of the overall cost needed to accomplish this type of research project, a near wheel motor solution will be used to simulate the behaviour of a hub motor.

Table 1 illustrates the available motors that combine both the power needed to propel a light duty vehicle as well as encompassing that power into the confines of a near-wheel packaging. Table 1 also includes specifications for actual hub based motors, although their costs are extremely high due to their technologically advanced design and limited availability they have been included as a comparison to a pancake style motor which can be used to simulate a hub motor design.

Table 1 - Motor Comparison

	Cost (USD)	Volts DC	Speed Max (rpm)	Cont. Current (A)	Current Max (A)	Output Max (hp)	Torque Max (Nm)	Weight (kg)	Power: Weight (hp: kg)	Cost:Power (USD: HP)	Eff. (%)	Style
ETEK-R	525	12-48	3700	100	330	15	42.9	13.6	1.1	35.0	91	Brushed DC
ETEK-RT	575	24-72	2400	150	330	18	52.8	12.7	1.4	31.9	91	Brushed DC
MARS PMAC	479.99	24-48	3500	100	300	15	42	10.0	1.5	32.0	90	Brushless AC
Lemco 200	1650	12-60	4000	100	400	21	60	10.7	2.0	78.6	91	Brushed DC
Lemco 170	1425	12-48	3264	140	300	16	33	8.5	1.9	89.1	88	Brushed DC
Lemco 130	1249	12-36	5400	75	100	5.3	6	3.0	1.8	235.7	88	Brushed DC
Hub Motors												
Csiro Solar Car	18,200	150	2865	N/R	N/R	2.4	50.2	10.9	0.2	7583.3	97	Brushless PM
Flightlink HPD30	~17,000	400	2000	N/R	N/R	54	350	18	3.0	314.8	N/R	Brushless PM
Flightlink HPD40	~30,000	400	2000	N/R	N/R	160	750	25	6.4	187.5	N/R	Brushless PM

The table concludes with two ratios: a power-to - weight ratio, and a cost-to-power ratio. These are both important when choosing a motor for a mass production environment, or in this case, a budgeted research project. True hub motors, originally developed by Flightlink, have a very high power-to-weight ratio ranging from 3-6.5 horsepower per kilogram, which exhibit an extremely dense ratio of power-to-weight. The Csiro motor however has been capped in power due to the Solar Car competition regulations and concentrates more on overall efficiency peaking at 97.4%. The cost—ranging from $17,000-$35,000USD each—of the hub motors is the major deterring factor from utilizing it. The estimated cost per horsepower is $187-$7583, and so the benefits of power-to-weight ratio simply cannot be justified his early in the design cycle when overall power-weight-cost ratio's are considered. Nonetheless, the ability to fit a vehicle with these types of motors is costly.

The pancake style motors range from 1.1-3.0 hp/kg, about a 1/3 that of the actual hub motors, however their cost-to-power ratio's are substantially less at $35-$85 per horsepower. The pancake style motor that was chosen for the simulation build was the ETEK-R motor. The decision to use this motor was based on its low cost-to-power ratio, as well as its ability to be used with flexible, readily available and easy to configure permanent magnet DC controllers. Their affordable cost and dense power make these the perfect choice to simulate a hub motor system by creating a near wheel setup.

3 Electronic Differential

The differential setup consists of two independently controlled hub motors, controlled by electronic speed controllers. The input of the throttle as well as the input of the steering angle is communicated by wire to a microcontroller setup. An algorithm was created in order to compute desired turning angle to outboard wheel speeds.

The steering input to the microcontroller consists of two potentiometers mounted on either side of the wheel in a gear setup. Two potentiometers were used to allow for the use of the linear portion of a potentiometers range; one for a left turn and one for a right turn. The resistance given by the potentiometers is then processed and converted into the desired steering angle.

For the purpose of experimentation two separate algorithms have been formulated into code to compare the results when real world testing begins. The first code is composed of Ackerman's formulae:

$$\delta = \frac{\delta_{in} + \delta_{out}}{2} \tag{1}$$

$$\omega_{in} = \frac{V}{r}\left(1 - \frac{d\tan(\delta)}{2L}\right) \tag{2}$$

$$\omega_{out} = \frac{V}{r}\left(1 - \frac{d\tan(\delta)}{2L}\right) \tag{3}$$

With Ackerman's formula the difference in angle of the inner and outer wheel are taken into consideration. In the following formula only inner and outer wheel speeds are considered with no compensation to the difference in angles on the front steering wheels:

$$v_{diff} = \frac{V_o}{v_{avg}} = \frac{R - r}{R_{avg}} = \frac{t}{R_{avg}} \tag{4}$$

Equation (4) shows the approximation of the dimensionless velocity differential between the outside and the inside wheels. This formula will be programmed with the necessary static parameters such as vehicle track in order to calculate properly defined independent wheels

Nomenclature

δ	Ackerman angle	v_{diff}	velocity at the differential
δ_{in}	Angle of inner tire	V	Voltage
δ_{out}	Angle of outer tire	v_a	armature voltage
ω_{in}	angular speed inner wheel	R_a	armature resistance
ω_{out}	angular speed outer wheel	t	time (S)
L	length	V	Linear speed
R	Outer radius	K	Fixed Motor Characteristic Constant
r	Inner radius	B	Flux density, lines/in^2
Φ	Flux	H	Magnet Field Strength
I_a	armature current	u	Resistance to magnetizing force,

speeds which would then be outputted to the corresponding motor controllers.

Additional inputs are required in order to be able to fulfil the needs of the above algorithms. A throttle input is required to allow the operator full control on speed; a resistive throttle input is currently incorporated and has the ability to bypass the microcontroller setup and input directly to the motor controllers themselves.

Feedback from the motor/wheel assemblies are needed in order to determine wheel speed on both the left and right rear wheels. Currently, armature feedback is being used to calculate wheel speed through the motor controllers. This will not, however, be accurate enough for a proper assessment of wheel speed. Experimentation with optic and reflective sensors, mounted on the gearbox output shaft, are being performed to achieve a resolution of 1600 checks/min.

Also, DC permanent magnet motors presently allow us to make several calculations based completely on the design characteristics of the magnet construction of the motors themselves. Torque can be calculated due to its dependency on armature current, and the flux stays relatively constant and torque can be described by (5).

$$Torque = K \times \Phi \times I_a \tag{5}$$

Torque and speed are greatly affected in slower speeds with the advancements in magnetizing force that are found in today's permanent magnet DC motors. This higher support for magnetism extends the linear characteristics for torque as well as speed down to the idle state of the motor. The magnetic force and its relation to the flux density of the motor is described by Rowland's law in (6). [1]

$$B = Hu \tag{6}$$

From this we can further calculate the speed of the motor by knowing the motor's terminal voltage (Vt) with the following equation:

$$S = (V_t - I_a R_a)/K \Phi \tag{7}$$

The efficiency of the motor is another critical design characteristic. The importance of efficiency in motor selection is twofold: the ability to transfer electrical energy to mechanical energy and the second being the opposite action, converting mechanical energy back to electrical energy in the aspect of regenerative braking. Efficiency can be measured in a motor with the relationship of its mechanical torque relative to the input of electrical power that is being supplied.

$$Efficiency = (Torque_{out} X\ RPM)/((V_t - I_t R_t)/ x\ I_t) \tag{8}$$

4 Prototype

A hybrid electric vehicle is needed to be built for the purpose of developing and simulating the near wheel simulation. The motors would be fitted to the prototype vehicle in a hub based fashion and an electronic differential control system would be added. A Baja style dune buggy (Figure 1) was chosen as a test bed vehicle. The vehicle would be a joint project that consists of converting the supplied 250cc, carburated, single cylinder, 4-stroke, internal combustion engine (ICE) to a hydrogen combustion engine that would in turn be a generator and supply power to a battery array. The objective is to have a series hybrid vehicle with Hydrogen as the generators fuel. This coupled with a simulated hub motor drive train and electronic differential.

The vehicle came equipped with a continuously variable transmission (CVT) mated to a rear differential setup. It had a top speed of 80km/h and reached that speed in 12 seconds. Complete specifications of the original test vehicle are listed in Table 2 - Test Vehicle Original Specifications Table 2.

Figure 1 – Baja Dune Buggy Test Vehicle

After the modifications are made to the vehicle in order for it to meet its design objectives its performance should meet or exceed the original OEM specifications. It is assumed that an a drastic increase in vehicle mass will be needed in order to achieve all design parameters listed.

Table 2 - Test Vehicle Original Specifications

Engine/Transmission	
Displacement (cc)	250cc
Transmission	Auto – CVT
Engine Type	Single Cyl., 4-stroke, Water Cooled
Power (Max)	10.5kW/7000rpm
Torque (Max)	17.6Nm/5500rpm
Drivetrain	Shaft Drive, Rear Differential
Speed (Max)	80km/h
Dry Vehicle Weight	385kg

The initial testing of the vehicle yielded performance results that were less than exciting for a vehicle built for off-road entertainment and such performance would be increased in the test vehicle. Handling characteristics as well as overall ride quality was noted during test drives as to compare when the final build has been completed.

The final prototype will be a test bed for multiple technologies. It is currently equipped to run dual fuels, both petroleum gas and hydrogen to generate electricity to charge a battery array consisting of 32 Lithium Iron Phosphate cells which are wired in series to give a total of 48V of power at 200Ah. The vehicle is designed to be charged via an electric outlet for the period of 6 hours, and to be driven on all electric power until battery levels reach 50%, at which time the range extender generator will power up to recharge the batteries in order to power the vehicle for an extended range. The vehicle's overall specifications can be seen in Table 3.

Table 3 - Prototype Specifications

System	Specification
Battery Array	48V, 200Ah, 9.6 kWh, C3 600A, 59 kg, 0.06 m^3, Cycles > 2000
Hydrogen Storage	7000 psi, 1m x 0.4m, 94.3L, Gas EV. 10.9L, 53 kg
Gasoline Storage	11L, 90+ Octane Unleaded
ICE	250cc, Four Stroke, NA, Carbureted, 10.5 kW, 17.6 Nm
Electric Motors (2) + Generator	Brushed DC, 12-48V, Continuous 100A, Peak 330A 2min, 11.2kw Peak, 6kw Continuous, 13.6kg
Controller (2)	24-48V, 200A Max, 3.6kg, Battery Protection, Regen.
Charger	120-240 VAC, Charge Time: 6 hours at 48VDC
Electronics	11 kg
Fuel Delivery System	15 kg
Gauges/Displays	H_2 Pressure, Gas Level, Batt. Status, Speed, Range
Vehicle	523 kg

4.1 Hub Motor Concept

To construct a vehicle for further research and testing, utilizing state of the art hub motors that have not reached the public market, was not feasible for this prototype. The costs (as outlined in Table 1) and availability for hub motors to academia are nearly nonexistent. A near wheel motor approach was adopted to simulate a hub motor setup. A true hub motor has an RPM range between 0-2000 rpm for usable top-end speed of 143km/hr on a 15" tire.

The selection of the ETEK-R motor with a maximum speed of 3700rpm at 48volts as well as the unique 22" diameter off road mud tires give two unique challenges to our design. A direct drive setup with the ETEK-R would yield astronomical speeds of 390km/h which is unpractical and out of the scope of the design project. The solution was to add an additional inline planetary gearbox with a high efficiency. The ETEK-R motor coupled with a 4:1 planetary gearbox (Figure 2) allowed for speeds of up to 97km/h, as well adding a multiplier for torque for dead stop starts.

Figure 2

Motor + Planetary Gearbox = Hub Motor Simulation

Additional advantages of a direct drive system include: direct control of individual wheels along with possible closed loop control of each individual wheel, true all wheel drive setups when a motor is affixed to all four individual wheels, and possible advancements in stability/traction control systems due to the increased control that a direct drive system offers. The positioning of the motors at the four corners of the vehicle also offers the enhancement of equal weight distribution to become closer to the ideal 50/50 distribution of today's sports cars.

The efficiencies gained by removing all power transfer devices can be seen when analyzing the losses of a traditional vehicle. The efficiencies of transaxles have been calculated to be as much as 91% overall on a front drive helical gear transaxle. For rear drive configurations efficiencies drop as low as 82-85% due to the rear differential and driveshaft configuration. [2]

The solution of mounting the motor and gearbox assembly to the existing architecture of the vehicle was given as a design challenge for a group of four undergraduate students to work concurrently with graduate students in a true engineering work environment. Their solution to mounting the gear boxes consisted of several tubular support braces surrounding the motor and gearbox assembly, with 3 cross plates for stability. The entire assembly was made from 6061 aluminium to keep the unsprung weight to a minimum without sacrificing strength in critical areas that were identified using Visual Nastran's finite element analysis ability. Hub mounting blocks were added to the vehicles hub assembly so that the entire assembly could be easily dismounted.

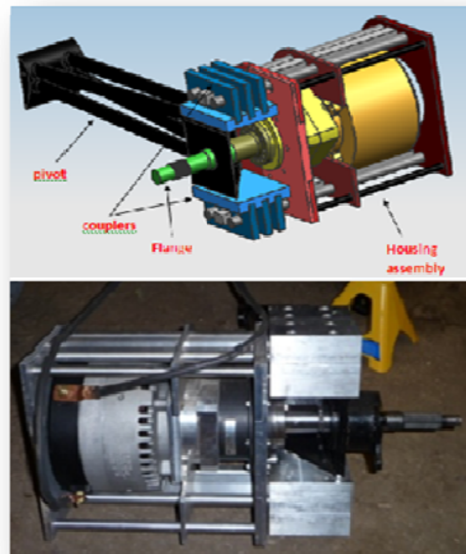

Figure 3 - Motor/Gearbox Mount Assembly

A secondary design iteration of the above concept will be performed to optimize its weight and strength properties through extensive Finite Element Analysis. The external plates will be removed and the entire mounting assembly will be integrated into the existing hub mount supports. This will further reduce the overall size of the structure and critical unsprung masses.

4.2 Independent Electronic Drive

The prototype that has been developed allows for a revolutionary style of independent drive. Currently, mechanical transfer devices incorporating differentials, viscous couplings, and limited slip setups utilize electrical subsystems to apply logic to the systems to allow them to become responsive to driving conditions. Despite the advancements made with these mechanical devices, the limitations stem from their mechatronic systems and complexity. The hub motor arrangement changes the limitations of logic controlled systems.

Algorithms can be created to increase the flexibility of the system since both wheels can be controlled completely independent of each other. An independent electronic direct drive train allows for advanced controls systems such as, direct control of individual wheels along with possible closed loop control of each individual wheel, true all wheel drive setups when a motor is affixed to all four individual wheels, and possible advancements in stability/traction control systems due to the increased control that a direct drive system offers. The overall vehicles mass factor is also reduced by removing all power transfer devices such as the transmission, drive shafts, CV shafts and differential components. The positioning of the motors at the four corners in a traditional all wheel drive setup of a vehicle also offers the enhancement of equal weight distribution to become closer to the ideal 50/50 distribution of today's sports cars.

In order to achieve true independence of control for both motors on the rear wheel setup that has been produced mirrored electronics system was needed to be created with a central device to send feedback from one controller to the other. The microcontroller used for the electronic differential also doubles as a means of monitoring the entire system. (Figure 4) Input devices such as throttle, brake, forward reverse selector, steering are inputted through the microcontroller in order to be processed to determine the overall status of the vehicles controls.

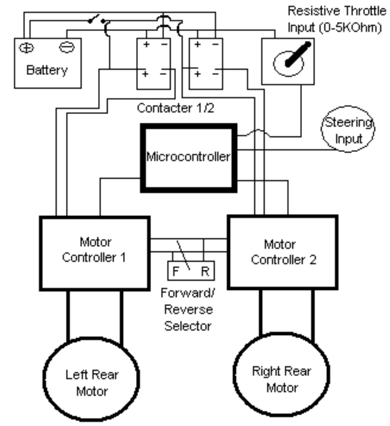

Figure 4 - Rear Drive Hub Motor Schematic

A suitable controller for the permanent magnet motor had to be selected from an extensive list. (Table 4) Specifications of the controller will have to match the permanent magnet ETEK-R motor discussed in section 4.1. The controller will have to meet or limit the maximum current requirements of the motor, and will have to maintain a set supply of current for various durations. These set durations would resemble normal driving scenarios such as short bursts of power needed during brief acceleration periods, or moderate power during cruising.

In addition, stalled motor scenarios were considered and analyzed to ensure protection is accommodated when over current situations are met. When a DC permanent magnet motor is stalled and the armature locked armature current spikes the controller along with other means such

Table 4 - PM Motor Controller Comparison

	Controller Comparison										
	Cost	**Volts DC**	**Current Limiting**	**Torque Control**	**Max Current**	**Closed Loop Control**	**Thermal Protection**	**Battery Protection**	**Weight (lbs)**	**Progr.**	**Regen.**
Kelly KD72401	$438	24-72	Yes	Yes	400	Armature Current	Yes	Yes	8	Limited	Yes
Alltrax AXE4845	$495	24-48	No	No	400	Armature Current	Yes	Yes	5lb 8oz	Yes	NO
Navitas TSP400-48	$245	36-48	Yes	No	400	Armature Current	Yes	No	NL	No	NO
Millipak 4 Quadrant	$452	24-48	Yes	Yes	325	Armature Current	Yes	Yes	6.5	Limited	Yes
Robeteq AX2850HE	$700	40	Yes	No	120Ax2	Yes - Encoder/ Tach	Yes	Yes	3.3	Yes	Yes

as inline fuses will have to monitor and limit current draw. The stalled condition mimics that of a short and can be described by the following:

$$I_{max} = V_{battery}/R_t \tag{9}$$

A regenerative braking circuit built into the controller is a must in today's EV marketplace. The ability to store energy upon braking by utilizing permanent magnets ability as a generator, while slowing a vehicle, is the ultimate means to recoup energy lost while slowing a vehicle. Such a circuit, situated within a controller, monitors for a brake-on condition and allows for the monitor to act as a generator and feed its counter EMF back to the batteries in a controlled fashion. Controllers may also possess such features as variable regenerative braking where regeneration maybe customized according to driving conditions or magnitude of braking.

Since a controller feeds a motor, the necessary power to operate, a battery protection circuit or logic is necessary in order to prevent under charge conditions for the battery array, and in the case of regeneration and overcharge condition. A battery protection circuit would monitor the battery charge state and either cut power to the motors if an under charge state is dedicated or disable regeneration if an over charge state is detected.

Additional characteristics necessary in a modern day controller would include MOSFET technology, analog resistive throttle input, closed loop control (encoder/tachometer).

The Kelly KD72401 permanent magnet controller offers all the specifications needed in order to power and allow for seamless transition into the microcontroller logic system. It offers a peak of 400 amps to allow the motors plenty of current to operate as well the voltage range spans from 24 to 72 volts allowing for possible increases in power levels if needed during the experimental and testing stage of research. The standard options consist of current limiting, thermal protection and battery level protection (in which nearly all the controllers offer) are included and the entire system is managed through a simple graphical user interface.

5 Future Development

The development of this vehicle will continue for years beyond the initial concept that has been created in this project. The foundation that has been created is a stepping stone in order to study emerging technologies such as hub motor drive train setups, series electric hybrid architectures and by-wire/wireless control systems.

The addition of motors to the front wheels of the vehicle will make the vehicle function with a truly independent, all wheel drive, setup. This setup will allow for traction control and stability control algorithms to be tested on a real world test vehicle which can allow for all wheels to act and respond independently, or in unison, from one another.

5.1 Challenges

Many challenges exist in the further development of the hub motor architecture presented. By incorporating dense, permanent, magnet motors into the wheels of vehicles unsprung mass is increased. Design and development is needed in the housings for hub motors to be light weight, yet robust enough to survive in harsh automotive environments. Suspension designs can also combat the issue of unsprung mass, with the development of active suspension design utilizing magnet polymers to increase or decrease dampening as needed. Finally, motor development in the area of hub motors will need to be completed in order to reduce cost, maximize power and minimize weight.

6 Conclusions:

The prototype series hybrid electric vehicle that was created for the purpose of exploring new technologies in the extended range electric vehicle sector has been created, however, by no means completed. The fundamental creation of the vehicle is only the start of further research and development into the technologies that will make tomorrow's electric vehicle more efficient, more powerful and fun to drive.

The current vehicle has displayed how power train devices in a traditional vehicle can be moved outboard to the wheels in order to allow for internal space optimization from the space they would normally occupy. In the current prototype stage, the near wheel motors occupy far more space than a hub motor setup, however, the gains in inboard space can still be seen by the dense power setups and lack of transmissions and transfer devices.

All related maintenance that was needed for transmissions, differentials and CV joints has been eliminated when the associated components were eliminated. The current permanent magnet motors require brush changes during wear intervals but can be exchanged with more efficient and reliable brushless motors in future design iterations.

The dual drive rear wheel setup allows for endless possibilities for independent control logistics and opens up avenues which were not available for similar mechanically driven systems. Overall, the design freedom for future electric vehicles has been shown in the existing prototype which will see further development in the years to come.

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Authors

Mark Bernacki began part-time studies in the M.ASc Mechanical Engineering program at UOIT in 2007. Mark is a formal full-time employee of General Motors and his research interests include: by-wire technologies and automotive design.

Dr. Pop-Iliev is an endowed NSERC-GMCL Chair in Innovative Design Engineering since October 2005. His mission is to provide meaningful contributions towards substantially improving Canada's capacity in design engineering through establishing a Centre for Innovative Design Engineering and Research (CIDER).