Development of an Educational Engineering Workshop on Electric Vehicle and Motor Technology

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Abstract: This paper describes the development of an educational program centered on electric motor and electric vehicle technology at the MIT Edgerton Center. The program, called the Summer Engineering Workshop, has matched students from local high schools with MIT undergraduate and graduate students sharing a common interest in electric vehicles, their propulsion systems, and their controls. Past projects included the creation of a "do-it-yourself" self-balancing scooter and an electric go-kart with a novel regenerative braking system. In the summer of 2009, the Summer Engineering Workshop developed a compact electric kick-scooter powered by two 500W brushless in-wheel motors. This project provided opportunity for the group to go beyond integration of existing components and into the field of electric machine design. We developed an understanding of the theoretical and practical considerations through many avenues: research of prior art, design from first principles, integrated magnetic and mechanical computer-aided design, and ultimately the real-world construction and testing of these motors. In the process, academic and industry professionals provided insight that benefited both the educational and the technical objectives of the project. The final product will become a valuable research and teaching tool, and the success of the program highlights some strengths of combined technical and educational development.

Introduction

The Edgerton Center, established in memory of Professor Harold "Doc" Edgerton, is at the center of hands-on learning at MIT. Over 20 student clubs and teams, building everything from robots to solar-electric vehicles, call the Edgerton Center home [1]. The Summer Engineering Workshop, one of many outreach and engineering programs hosted by the Edgerton Center, has been run for the past three years.

More of an ad-hoc group of students with similar interests than an organized outreach program, the Summer Engineering Workshop was first run in 2007, before it had an official name. It is a collaboration of MIT students and students from local high schools, formed as an outlet for local FIRST Robotics [2] teams interested in an offseason project workshop – something to keep everyone busy when not building competition robots. In contrast to the regulated competition structure, the workshop allows complete freedom in project selection and implementation, an engineering experience not typically seen until much later studies.

The group's focus on electric vehicle technologies was driven by a common passion among the founding members for "things you can ride," as well as shared experience within the field of mechatronics and robotics. In addition to being a multidisciplinary endeavor, the vehicle projects also enable contributions at many different technical and educational levels. Each student is teaching and learning at his or her own capacity with very little curricular overhead. This informal philosophy has allowed the group to pursue fun projects that are both technically challenging and educationally engaging.

Summer 2007: The D.I.Y. Self-Balancing Scooter

We completed our first project, a functional self-balancing electric scooter, in the summer of 2007. The scooter, which mimics the function of the Segway® Personal Transporter, is constructed mostly from off-the-shelf components from the competitive robotics market. 350W brushed DC motors with planetary gear heads drive each wheel. A feedback control system estimates the angle of the standing platform 100 times per second based on inertial sensor measurements. It then updates commands to the motors to correct for any leaning. The scooter, pictured in Figure 1 next to a real Segway®, is not as easy to ride as the commercial version and does not have as many safety measures, but it is lightweight (50lbs) and inexpensive ($800).

Figure 1: Our first project, a self-balancing electric scooter (left) built for under $1,000.

The home-made self-balancing scooter has served as an engaging demonstration of do-it-yourself engineering for students for the past two years, in some sense demystifying an iconic piece of hardware, while also revealing that there is much more that has to go into a commercial product. Since completing the self-balancing scooter, we have received over 100,000 web visits and numerous emails from around the world complimenting the project and requesting more information.

Summer 2008: The Cap Kart

In the summer of 2008, the workshop was awarded a $6,000 research grant to develop an electric go-kart with a novel ultracapacitor-based regenerative braking system. A more ambitious project in scope and scale, the Cap Kart required a step up in engineering and design maturity. It was also our graduation from the world of robotic components to the world of electric vehicle components.

The kart is powered by a 10kW separately-excited brushed DC motor made by D&D Motor Systems. The separately-excited topology is featured prominently in the regenerative braking scheme, where the field winding is used to regulate regenerated current into the ultracapacitor with no high-current switching. The motor also enables a fun student-driven addition to the kart: a simulated sequential manual transmission that manipulates the torque-speed characteristic through the field controller.

Although we have not had many opportunities to drive the finished kart, pictured in Figure 2, the few test drives we did take were useful for collecting data on its features, including the ultracapacitor "boost" mode. Flywheel testing validated more of the regenerative braking models and the team presented the project results in Monaco at the EVER '09 conference [3].

Figure 2: Our converted electric go-kart from 2008.

Summer 2009: The B.W.D. Scooter

The technical report in this paper highlights the Summer Engineering Workshop's 2009 project, a compact electric "kick-scooter" (similar to a Razor®) with custom brushless in-wheel motors. Without the research budget of 2008, we wanted to instead build an inexpensive, lightweight, and readily-portable demonstration of electric vehicle technology. After briefly considering a simpler belt-driven rear wheel drive scooter conversion with a brushed DC motor, the team decided to pursue in-wheel motors for both wheels, leading to the name B.W.D., "Both Wheel Drive." More interesting from a technical standpoint, the in-wheel motors provided us with our first opportunity to go beyond off-the-shelf components and ask the question, "If we could have any motor we want, what would it be?" This design experience was very rewarding and added a new element of engineering to the workshop.

Design Process

The challenges of building in-wheel motors are many. Also called hub motors, all of the motor components exist within the volume of the wheel itself. The rim and tread are integrated with the rotor, while the stator sits on the inside of the hub, held in place by a stationary shaft. While this type of motor is less mechanically complex than a brushed motor, the fabrication was more involved than any of our previous projects. The workshop has access to only basic machining equipment, though we have used rapid prototyping services in the past to make custom parts.

One of the biggest unknowns for us was whether we would be able to get adequate torque from a direct-drive motor. All of our previous experience had been with motors that require gear reduction to achieve suitable performance for vehicles. The decision to use two motors was partially driven by this uncertainty. During the course of the design, we also developed an understanding of the theoretical and practical considerations influencing the performance of the motors through several methods: research of prior art, design from first-principles, simulation, and a single-iteration prototyping strategy.

Research of Prior Art

Though there are many applications of hub motors to electric-assist or fully electric bicycles and full-sized scooters, we know of only one other example of an in-wheel motor being used in a small-diameter kick-scooter wheel. The motor, designed by MIT student Charles Guan, served as the primary inspiration and proof of feasibility for this project. (In addition to being a working example of a kick-scooter hub motor, it was also built from scratch without advanced manufacturing facilities.) The motor, shown in Figure 3, uses a rewound stator from a photocopier motor and a custom-built rotor with NdFeB magnets [4].

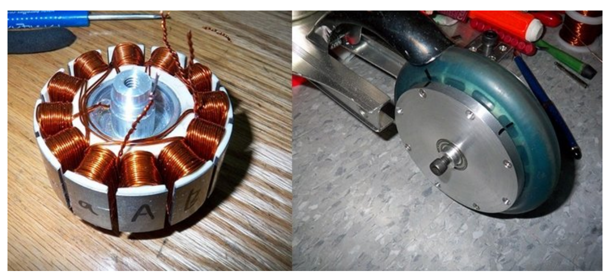

Figure 3: A kick-scooter wheel motor built by MIT student Charles Guan.

The motor is a 12-slot, 14-pole brushless "outrunner." A high pole count creates a low speed, high torque motor with more windings linking flux. The fractional slot:pole ratio is advantageous for minimizing cogging torque [5], which is especially important in a direct-drive motor. With this design, it is also possible to use an easy-to-assemble concentrated winding scheme, winding every other tooth with more turns [6]. Early in the design, we chose to use this proven motor design as our starting point.

Motor Mechanical Design and Proto Laminations Collaboration

We were aided greatly by the support of Proto Laminations, Inc., which donated laser-cut M19 steel laminations to the project. Steve Sprague, sales manager at Proto Laminations, came to visit our workshop during the summer and gave a presentation on the many interesting aspects of motor lamination technology and manufacturing. This was the first industry guest that the workshop has hosted and the collaboration added a new perspective to our design process.

Having used rapid-prototyping tools (abrasive water jet) for projects before, the team was excited to have the chance to design the rotor and stator from scratch. Many of the workshop students have experience with SolidWorks CAD software, so the mechanical design went quickly. Shown in Figure 4, our design includes features for aligning magnets as well as a pin slot for the shaft. A bolt circle with seven holes on the rotor places bolts directly behind magnets where they will interact with the least amount of flux. All of these specifically-designed features would be difficult or impossible to create with basic machining processes, but are made feasible by the short turn-time laser cutting process. Table 1 lists the dimensions and mechanical properties of our wheel motor design.

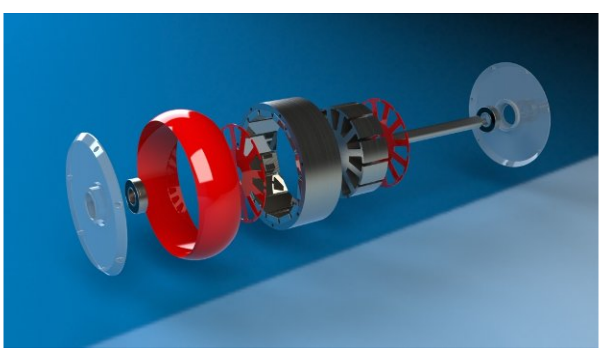

Figure 4: An exploded view of the mechanical design of our wheel motor.

Table 1: Motor mechanical properties.

Outer (Tread) Diameter	5.0” (127mm)
Air Gap Diameter	3.44” (87mm)
Total Width	2.0” (51mm)
Stator Active Width	1.0” (25mm)
Lamination Thickness	0.014” (0.36mm)
Weight	6lb (3kg)

Electromagnetic Design from First Principles

Although the majority of our experience is in mechanical engineering, we sought to understand the electromagnetic principles of the motors before attempting to build them. We were most concerned with the ability to produce enough torque with a direct-drive motor. Using only high-school level physics, we were able to make a first-order estimate of the motor performance. Most students see electromagnetic interaction first in the form of the Lorentz force formula,

$$\vec{F} = I\vec{L} \times \vec{B} .$$

From this elementary starting point, it was already clear that, in a direct-drive motor with no opportunity for gear reduction, the force at the wheel could only be increased by increasing current, field strength, or active length of windings. Without analyzing the full magnetic circuit, we could still assume that the stator steel would serve the purpose of “concentrating” the total winding current into an ideal location in the air gap.

Knowing that we would need a relatively high torque and low speed for this motor size, we chose N42-grade NdFeB magnets with a remanence of 1.3T. Since we were hand-winding the stators, anything larger than 16- or 18-gauge magnet wire would be difficult to work with. With a conductor area of approximately 1mm^2, and a per-phase duty cycle of 67%, this set a practical current limit of about 20A peak, 10A continuous. The degree of freedom remaining was the number of turns, which sets the active length of wire. From a simple power conservation argument, students could see the design tradeoff: more turns would give more torque, but a higher voltage would be required to achieve the same target speed. We chose to build the first motor with 60 windings per phase. Since two phases are driven at any given time in simple square-wave brushless DC controller, this gave us a peak air-gap force of:

$$F = (20A)(2)(2)(60)(0.0254m)(1.3T)$$
$$F = 158N = 36lbf$$

From this estimate, the torque or the force at the tread diameter could easily be calculated. The torque estimate is just the air-gap force multiplied by the air gap radius, which evaluates to 6.9N-m. We understood this to be a high estimate, assuming 1.3T uniformly in air gap and no leakage flux. But it served as confirmation that reasonable torque could be achieved without very high winding density. By power conservation, this first-order estimate also confirmed that the desired speed was achievable with a low-voltage (33V) supply.

Electromagnetic Design by Simulation

After doing a first-principles feasibility estimate, we sought to get a more realistic performance prediction by using finite element electromagnetic simulation software. One such 2D simulation package, called FEMM, is freely available and has the ability to import .dxf-format drawing files [7]. We were able to easily import our CAD files into this software and apply materials tags from the FEMM materials library. Figure 5 shows an example output of the FEMM simulation with 60 turns per phase and 20A current on the correct phases to produce peak torque.

The peak torque estimate from the FEMM simulation was 4.2N-m, which is significantly lower than the first-principles estimate. This was expected, since the simulation accounts for magnetic losses and leakages, as well as the non-uniform air gap field. (The simulation shows that the average flux density is closer to 1.0T.)

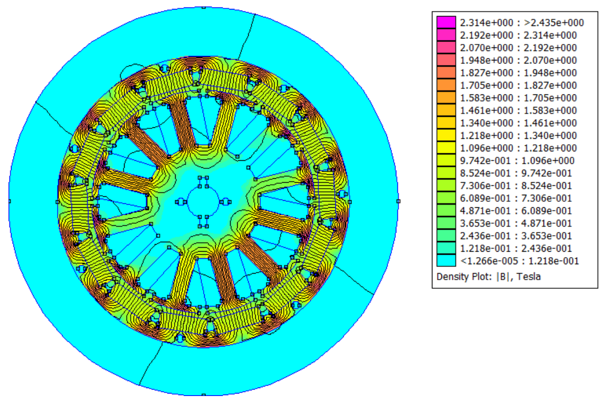

Figure 5: FMM simulation output for the 60 turn per phase motor at 20A.

The FEMM magnetic visualization also helped us determine ideal locations for bolt holes and other mounting features to minimize their effect on the flux paths. For example, the seven rotor bolt holes are placed directly behind magnets where the flux density is lowest.

Single-Iteration Design Verification

In addition to providing redundancy and more combined torque, the purpose of building two motors was to allow us one chance for design revision after the first motor was built and tested. This was a very important part of our design process. Our limited knowledge of motor design and the untested geometry of our custom motor meant that all the simulations and estimates had a degree of uncertainty that we could not approach analytically. However, we were confident enough in the underlying principles to know that if we built one motor, we could learn enough from its performance to easily adjust the number of turns in the second motor to achieve a desired torque and speed. Solving experimentally for the “geometry constant” and then scaling was the key to the single-iteration strategy.

Building and Testing

We used the first motor to develop an effective winding and assembly process. After bonding the rotor laminations with a surface coating of cyanoacrylate, the magnets were dropped into their alignment slots, with careful attention paid to the magnetic orientations. Figure 6 shows the rotor and its magnet alignment features in more detail.

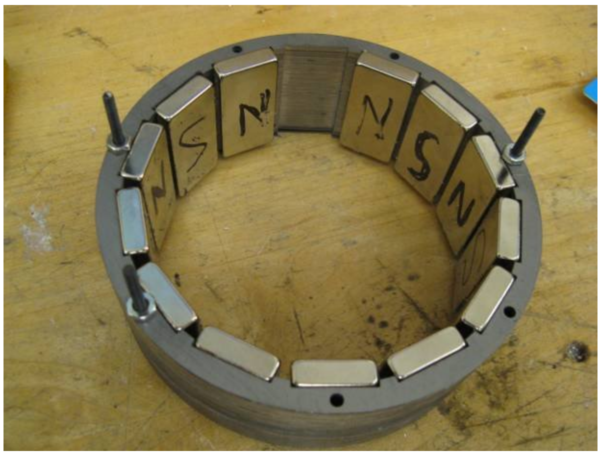

Figure 6: The rotor as it was fitted with magnets.

Winding the stator was the most challenging and time-consuming task of the project. After a test winding of the stator resulted in short circuits, we added oversized fiberglass end-laminations to insulate the corners of the stator. Three-phase windings were done on alternating teeth (A-b-C-a-B-c-) and connected in wye configuration to wires fed through the hollow 0.5” motor shaft.

Motor sides were fabricated from 0.25” polycarbonate disks. Bearings were pressed into these side plates. We chose to use semi-transparent plastic sides to keep the internal construction of the motor visible for demonstrations. The use of non-ferrous side plates also had an unintentional benefit: hall-effect sensors can pick up the position of the magnets from outside the motor, simplifying the control.

With the stator and rotor sub-assemblies complete, the motor was assembled using a drill press and simple jig to keep the stator from moving under the force of the magnets. Once the rotor bolts engaged with the side plates, these held the stator in place and the jig could be removed for final tightening. Figure 7 shows the stator being lowered in during final assembly.

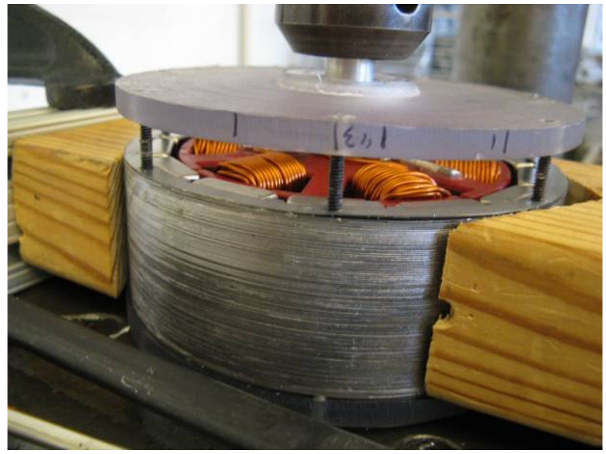

Figure 7: The stator and second side plate are dropped into the rotor with the aid of a drill press.

With the first motor assembled, a simple test of the no-load speed at 36V was done to find the motor constant. The external hall-effect sensors were positioned to give the lowest stable speed. Data from this test, shown in Figure 8, placed the motor constant at 47RPM/V or 0.20V/(rad/s). Assuming an equivalent torque constant, 0.20N-m/A, this put the motor peak torque at 4.0N-m, very close to the FEMM estimate.

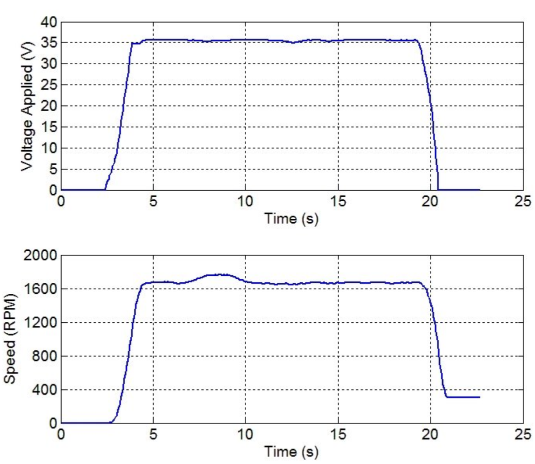

Figure 8: Test data to determine the motor constant of the first motor.

Based on the test data from the first motor, we decided to use 90 turns per phase on the second motor to achieve 50% more torque and a lower no-load speed. The second motor would become the rear wheel of the scooter, providing more starting torque during acceleration. The first motor would become the front wheel. The two motors, shown together in Figure 9, differ only in the number of turns per phase. Testing of the second motor confirmed a motor constant of 0.30V/(rad/s), which gives a peak torque of 6.0N-m at 20A. Table 2 lists some more detailed specifications for the two motors. Each is capable of producing approximately 500W peak.

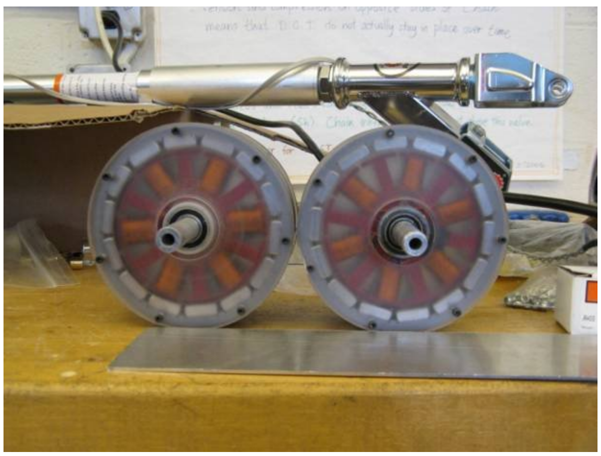

Figure 9: The rear motor (left) and front motor (right) differ only in the number of turns per phase.

Table 2: Motor Specifications.

	Rear	Front
Turns per Phase	90	60
Motor Constant	0.30N-m/A	0.20N-m/A
Winding Resistance	0.333Ω	0.221Ω
Peak Torque (20A)	6.0N-m	4.0N-m
No-Load Speed (33V)	1,050RPM	1,575RPM
Peak Force at Outer Diameter (20A)	63N (14lbf)	94N (21lbf)
No-Load Linear Speed at Outer Diameter (33V)	7.0m/s (15.6mph)	10.5m/s (23.4mph)
No-Load Current (33V)	0.85A	1.50A
Estimated Peak Power (20A, 33V)	510W	537W
Estimated Efficiency at Peak Power (20A, 33V)	77%	81%

The last step for us was integrating the motors, batteries, and controller into a custom scooter frame. The chassis is a simple sheet aluminum box with a carbon fiber deck. We used the handlebar and folding mechanism from an existing scooter. A custom 145W-hr pack of $LiFePO_4$ batteries, fixed inside the chassis, gives the scooter a range of approximately five miles. The controller is also fixed inside the volume of the chassis. The assembled scooter is shown in Figure 10.

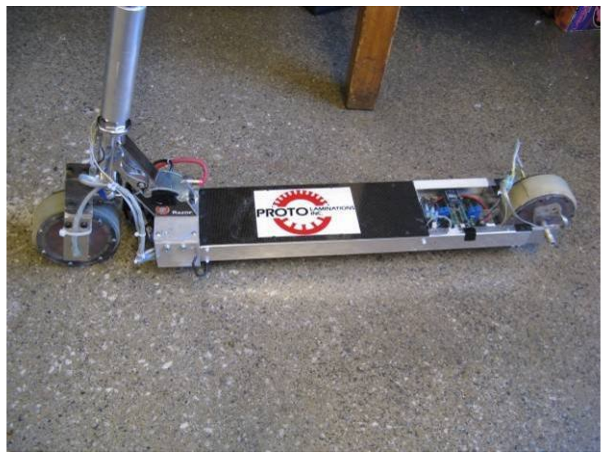

Figure 10: The assembled scooter with two motors installed.

Conclusion and Future Work

The B.W.D. Scooter is now a functional vehicle with two working motors. The combined torque of the motors is more than adequate, giving impressive acceleration even uphill. With a total weight of just over 20lbs, the scooter is light enough to carry up stairs or through buildings. More vibration- and water-proofing would be required for long-distance outdoor operation.

This project was a successful and rewarding experience for the Summer Engineering Workshop team. Starting with only a limited knowledge of brushless motor technology, we were able to step through the design process of a custom motor in a simple and quick way that coincided well with our prototyping experience. The support of Proto Laminations made the creation of these motors feasible and the collaboration contributed a new industry perspective to the workshop. The design experience and new set of knowledge and skills will certainly guide our future projects.

The workshop has, over its three years, matured in its engineering process and focus while retaining a "do-it-yourself" philosophy that puts most of the design in the hands of its students. The rich field of electric vehicles and motors provides opportunity for technical research that is interesting and relevant to today's world, but also a fun platform for education using tools that appeal to many types of students. The models and methods used are simple, but can still yield accurate results that can be verified in real life with hands-on prototyping. The success of the workshop is a strong case for the combination of technical and educational development focused on current engineering challenges.

Acknowledgements

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References

[1] For more information about The Edgerton Center, its outreach programs, and the student groups it hosts, refer to: http://web.mit.edu/edgerton/.

[2] For more information about For Inspiration and Recognition of Science and Technology (FIRST) and the FIRST Robotics Competition, refer to: http://www.usfirst.org/.

[3] S. Colton, "A Simple Series Battery/Ultracapacitor Drive System for Light Vehicles and Educational Demonstration," in Proc. *EVER '09*, Monaco, 2009.

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[7] Finite Element Method Magnetics (FEMM) homepage and software download: http://www.femm.info/wiki/HomePage.