Rudimentary Spherical Motor System for All-Terrain Vehicles

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1 Introduction

1.1 Objective and Background

- Goals: We set out to design a prototype of a simple spherical motor for all-terrain vehicles (ATVs) to achieve a compact and efficient propulsion system for rugged terrains. The motor is expected to achieve a high-level performance for the vehicle and enable energy efficiency in fields such as agriculture and exploration.
- Functions: A spherical rotor and electromagnetic field would be used by the spherical motor system to produce rotational motion, enhancing the mobility of ATVs without affecting weight while also making the system installable. This prototype will include PCB-based controllers to manage motor operation and ensure that the minimum required features are functional in bench test mode.
- Benefits: It offers the customer a flexible, small space, and energy-efficient motor, increasing the adaptability and performance of ATVs on different terrains while leading to lower energy expenditure than the conventional motors.
- Features: This system will be compact, lightweight, and easy to install. The outstanding item is a novel spherical rotor coupled with electromagnetic control, making it an avant-garde alternative for all-terrain applications.

1.2 High-Level Requirements List

- The spherical motor needs to achieve a minimum rotational speed of 500 revolutions per minute, demonstrate stable performance on flat and inclined surfaces reaching up to an incline of 15 degrees.

- A weight of no more than 5 kg is the upper limit of the total weight of the system components including the rotor, stator and PCB-based controllers, this is to attain a lightweight and installable design in ATVs.
- The motor is expected to operate stably without consuming energy above the 200-Watt limit in simulated all-terrain conditions during bench tests. The electromagnets are required to operate within +-5% of the target field strength. The system must also switch the electromagnets within a 5ms latency.

2 Design and Requirements

2.1 Block Diagram

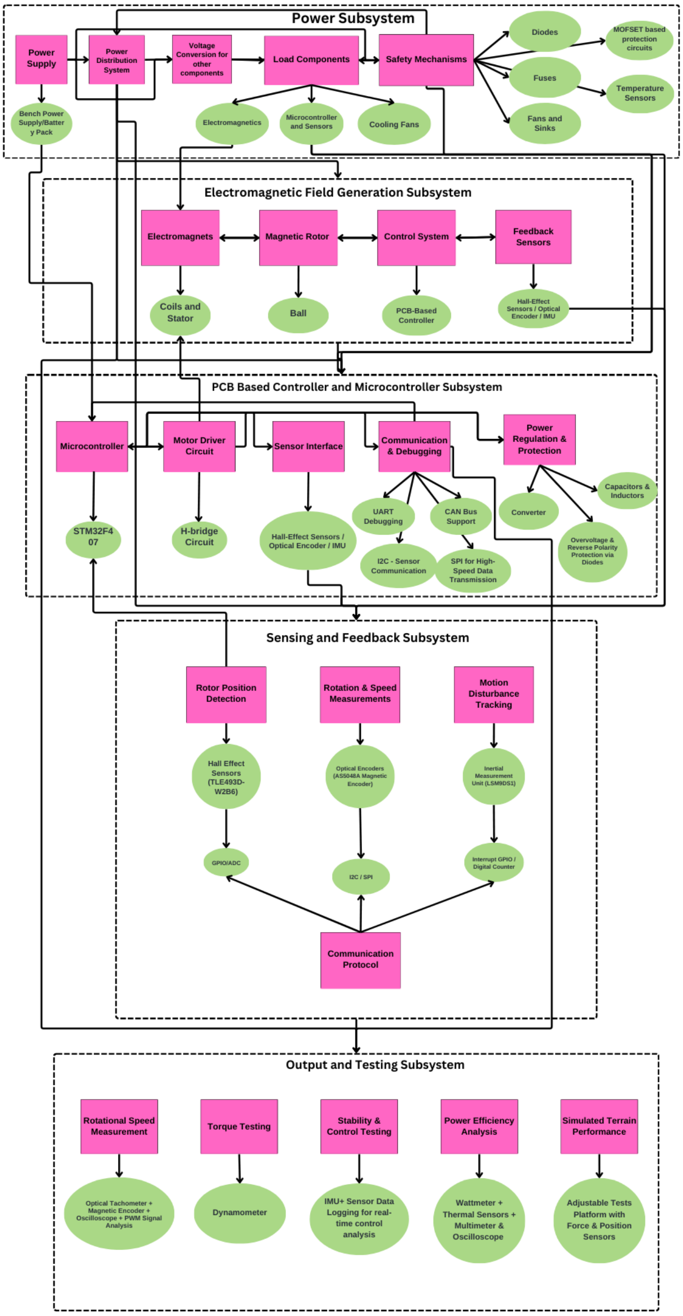

Figure 1: Rudimentary Spherical Motor System Block Diagram

2.2 Block Descriptions

Each block in this diagram relates to a functional subsystem in our design, developing a

Rudimentary Spherical Motor System. Below includes the functionality and the requirements of each major subsystem.

2.2.1 Power Subsystem

The Power Subsystem supplies regulated power to each component in the system. It includes the power supply, which will initially include a bench power supply before we integrate a battery pack of 24 V DC into the system. It also attaches to a power distribution system or a power bus to connect the flow to each subsystem. The voltage conversion system decreases the voltage from 24 V to 12 V & 5 V using DC-DC converters. Finally, the safety mechanisms help protect the circuit through fuses, MOFSET protection and temperature sensors. This subsystem distributes to the Electromagnetic Field Generation & Motor Driver Circuits. It uses DC-DC converters to provide 5V microcontrollers & sensors. It also sends power to cooling fans for thermal regulation to ensure the temperature does not exceed 60 degrees Celsius.

2.2.2 Electromagnetic Field Generation Subsystem

This subsystem generates and controls the electromagnetic fields that direct the spherical rotor. It consists of electromagnets, or coils and the stator, which creates the magnetic field. The magnetic rotor, the ball, refers to the moving element controlled by the field inside the system and our PCB-Based Controller. This controller modulates the field strength and polarity. Lastly, the feedback sensors track rotor position for real-time adjustments. This system is receiving power from the power subsystem and is controlled by PWM signals from the microcontroller subsystem. The feedback sensors send rotor position data to the microcontroller, while the electromagnets receive current through the H-bridge circuit. The electromagnets are required to operate within +-5% of the target field strength. The system must also switch the electromagnets within a 5ms latency. The rotor movement should be stable under simulated terrain conditions.

2.2.3 PCB-Based Controller & Microcontroller Subsystem

This subsystem processes control signals, sensor data, and communication interfaces. It involves the use of a Microcontroller (STM32F407), which executes the control unit and algorithm. To drive the motor, the system will utilize an H-Bridge circuit, which regulates power to electromagnets. The microcontroller sends PWM signals to the motor driver circuit. The system receives power (5V) from Power Subsystem and receives feedback from the Sensing and Feedback Subsystem. The sensor interface will collect data from Hall sensors, encoders, and IMU in the Sensing and Feedback subsystem. The Communication & Debugging node facilitates data exchange between the microcontroller and external systems using UART, SPI, and I2C. These interfaces enable real-time debugging, sensor communication and high-speed data transfer. UART, universal asynchronous receiver-transmitter, uses asynchronous transfer. The serial peripheral interface, SPI, uses MOSI, MISO, SCLK, CS for fast data exchange, while the inter-integrated circuit, I2C, uses SDA, SCL lines for addressing multiple devices for motion tracking. Lastly, power regulation and protection ensure stable power to controllers. The requirements include processing sensor feedback within 1ms, generating precise PWM signals for motor control, and the H-Bridge must handle peak currents of 5A per coil.

2.2.4 Sensing and Feedback Subsystem

This subsystem ensures real-time tracking of rotor position, speed, and stability. It uses Hall Effect Sensors (TLE493D-W2B6), which detect rotor position, Optical Encoders (AS5048A), which measure rotational speed, and the Inertial Measurement Unit (LSM9DS1), which detects motion disturbances. The Hall Effect Sensors connects to the Microcontroller (ADC/GPIO) for rotor position tracking, while the Optical Encoders connects to the Microcontroller (I2C/SPI) for speed measurement. Finally, IMU connects to the Microcontroller (Interrupt GPIO / Digital Counter) for motion stability. The feedback signals influence the PWM control loop. The requirements of this subsystem include that the position detection must be accurate within ±1°, that the optical encoders must measure rotational speed up to 1000 RPM, and IMU must detect tilt/motion disturbances within 10ms latency.

2.2.5 Output & Testing Subsystem

This subsystem evaluates the motor's performance under different conditions. It includes rotational speed measurement using an optical tachometer and encoders, torque testing using a dynamometer to measure force output, stability and control testing through the utilization of IMU data logging, power efficiency analysis using wattmeter, thermal sensors and using simulated terrain performance through an adjustable test platform. This subsystem receives real-time data from the Sensing and Feedback Subsystem. It logs power efficiency data using thermal and wattmeter sensors. In addition, it feeds test results back to the microcontroller for software improvements. The system requires the motor to achieve 500 RPM minimum in standard testing and for the system to demonstrate stable performance on inclined surfaces (up to 15° slope). It also requires operation within a 200W power budget through power efficiency tests.

2.3 Tolerance Analysis

The most critical and high-risk component of the rudimentary spherical motor system is the electromagnetic field generation subsystem as it is responsible for creating, modulating, and controlling the electromagnetic forces that move the spherical rotor. The complexity comes from the real-time control, field stability, and heat dissipation that makes this the most difficult part to implement. The system requires precise control of electromagnetic fields to move the rotor smoothly and accurately. Any delays or inaccuracies in the PWM modulation might cause unstable or erratic movements. Electromagnetic interference (EMI) could affect sensor readings, leading to incorrect position feedback. Methods we plan to mitigate these risks include the use of PID (Proportional-Integral-Derivative) control to fine-tune coil activation and by implementing Kalman filtering for sensor data processing to reduce noise. Finally, using shield sensor wires and using twisted pair cables to minimize electromagnetic interference will help us mitigate risk.

The electromagnets draw high currents (up to 5A per coil), causing significant heat generation, which also poses a risk. Excessive heat may reduce efficiency and damage components if not taken into account thus MOSFETs in the H-Bridge circuit must switch large currents efficiently without overheating. To address this, we may use heat sinks & cooling fans to dissipate excess heat. Another way is through the implementation of PWM-based current limiting to prevent coil overheating. Lastly, selecting MOSFETs with low

Rds(ON) to reduce power losses will help us with this risk.

The system relies on sensors (Hall Effect, Optical Encoder, IMU) to track position and speed, but any sensor errors or delays could lead to incorrect rotor movement. The IMU (LSM9DS1) may also drift over time, reducing long-term accuracy. For error management, we may cross-check Hall Effect, Encoder, and IMU data for accuracy, while implementing real-time error correction algorithms (sensor fusion) and using interrupt-based reading for time-sensitive sensor inputs.

The microcontroller (STM32F407) must process sensor data, compute PWM signals, and communicate over UART, SPI, I2C in real-time. Slow computation or communication bottlenecks could cause delayed motor response and task scheduling conflicts could result in missed sensor readings. We will reduce these risks by optimizing code using Direct Memory Access (DMA) for fast sensor reading. Another approach is the use of real-time operating systems (RTOS) or interrupt-driven loops for efficient processing and setting high-priority tasks for sensor reading and PWM updates.

The rotor must maintain stable movement without excessive vibrations or instability. Poor structural design can cause misalignment between coils and the rotor and external disturbances (e.g., uneven terrain in testing or impact) can cause unexpected movement deviations. To help with this, we must ensure coil alignment using precise stator mounts and conduct vibration analysis while also applying mechanical damping techniques and adaptive control algorithms to compensate for unexpected disturbances.

3 Ethics and Safety

3.1 Safety of the System

- Electrical Safety: The system operates with high currents (up to 5A per coil) and voltages (24V DC). Proper insulation, fuses, and circuit protection mechanisms (e.g., MOSFET protection, temperature sensors) must be implemented to prevent short circuits, overheating, or electrical fires. We must ensure all components are rated for the expected operating conditions and use heat sinks and cooling fans to manage thermal loads, where deemed necessary.
- Mechanical Safety: The spherical rotor must be securely enclosed to prevent accidental contact during operation, which could cause injury or damage. Vibration and misalignment risks should be minimized through robust mechanical design and testing.
- Fail-Safe Mechanisms: Implement fail-safe mechanisms such as emergency shutdown procedures in case of system failure, overheating, or unexpected behavior.

3.2 Environmental Impact.

- Material Selection: Use environmentally friendly and recyclable materials where possible. Avoid hazardous materials in the construction of the motor, PCB, and other components.
- End-of-Life Disposal: Design the system with disassembly and recycling in mind to minimize electronic waste.
- Energy Efficiency: The motor system must operate within the 200W power budget to ensure energy efficiency, reducing the environmental footprint of ATVs. Optimize the design to minimize energy losses in electromagnetic field generation and mechanical

motion.

3.3 Right to Repair

- Commonly Available Parts: Design the system using widely available, off-shelf components where possible to ensure easy repair and maintenance.
- Modular Design: Use a modular design approach, allowing individual components (e.g., electromagnets, sensors, PCB controllers) to be replaced without requiring specialized tools or expertise.
- Open-Source Software: Consider making the firmware and control software open-source to enable further research and work in this field.

References

[1] Blues University, “Understanding Sensor Interfaces - UART, I2C, SPI and CAN,” *Blues Developer Hub*, 2024. https://dev.blues.io/blog/blues-university-understanding-sensor-interfaces-uart-i2c-spi-can/

[2] “Buck converters - DC/DC step-down regulator ICs - STMicroelectronics,” *www.st.com*. https://www.st.com/en/power-management/buck-regulators.html

[3] “Custom Signal generation using PWM and DMA,” *community.st.com*, Oct. 06, 2021. https://community.st.com/t5/stm32-mcus/custom-signal-generation-using-pwm-and-dma/ta-p/49809

[4] “Dynamometer Testing Methods for Electric Motors,” *Aiptesting.com*, 2024. https://www.aiptesting.com/dynamometer-testing-methods-for-electric-motors.html (accessed Mar. 17, 2025).

[5] F. Yang, Y. Xie and W. Cai, "The Magnetic Field Analytical Calculation in a Novel Double Air-Gaps Permanent Magnet Vernier Synchronous Motor," in *IEEE Transactions on Magnetics*, vol. 57, no. 9, pp. 1-9, Sept. 2021, Art no. 8107409, doi: 10.1109/TMAG.2021.3093669.

[6] Fitan, Eric & Messine, Frederic & Nogarede, B.. (2004). The Electromagnetic Actuator Design Problem: A General and Rational Approach. Magnetics, IEEE Transactions on. 40. 1579 - 1590. 10.1109/TMAG.2004.827183.

[7] Jakstas, Arunas & Spruogis, Bronislovas & Turla, Vytautas. (2007). Vibration dampers for transmission of mechatronic systems. Journal of Vibroengineering. 9. 41-44.

[8] M. Official, “Real-Time Operating Systems (RTOS) in Embedded Systems,” *MosChip Technologies Limited*, Feb. 26, 2024. https://moschip.com/blog/semiconductor/real-time-operating-systems-rtos-in-embedded-systems/

[9] “Motor Categories | Characteristics and Applications of Electromagnetic Motors | Overview of Motors and Motor Driving | TechWeb,” *Rohm.com*, 2025. https://techweb.rohm.com/product/motor/motor-driver/18980/

[10] Rashid, Muhammad & David, Elizabeth & Torshin, Ivan. (2023). Power Electronics Handbook" by. 10.13140/RG.2.2.26720.25606.

[11] S. Daniluk, “Ghost IV — Sensor Fusion: Encoders + IMU - HackerNoon.com - Medium,” *Medium*, Mar. 12, 2017. https://medium.com/hackernoon/ghost-iv-sensor-fusion-encoders-imu-c099dd40a7b (accessed Mar. 17, 2025).

[12] “TLE493D-W2B6 Low Power 3D Hall Sensor with I2C Interface and Wake Up Function 1 Overview Quality Requirement Category: Automotive | Industry,” 2019. Accessed: Mar. 17, 2025. [Online]. Available: https://www.infineon.com/dgdl/Infineon-TLE493D-W2B6-DataSheet-v01_20-EN.pdf?fileId=5546d462617643590016189ec158943a4

[13] “Understand the Thermal Effects of Power Electronics,” *Ni.com*, 2024. https://www.ni.com/en/shop/electronic-test-instrumentation/application-software-for-electronic-test-and-instrumentation-category/what-is-multisim/understand-the-thermal-effects-of-power-electronics.html?srsltid=AfmBOoq3IUy0I6pUrSSpINNiRZt1XkqU7e3gncXzWzF8VqK5zWg1pAI6 (accessed Mar. 17, 2025).

[14] “Using MOSFET Drivers for Motor Drives | Article | MPS,” *Monolithicpower.com*, 2024. https://www.monolithicpower.com/en/learning/resources/using-mosfet-drivers-for-motor-drives?srsltid=AfmBOorvkNB060bWN9gGsRrNl3ofFSPJ2XZ4za-kk_b5vXZAnk97SfRV (accessed Mar. 17, 2025).

[15] W. Kester, “MT-029 TUTORIAL Optical Encoders.” Accessed: Mar. 17, 2025. [Online]. Available:

https://www.analog.com/media/en/training-seminars/tutorials/mt-029.pdf