Rudimentary All-Terrain Spherical Motor

ECE 445 Design Document

Team Members: Kang Zhaoyu, Tayyab Ibrahim, Jiang SiCheng,

Blackwell Heston Clagg, Wang Ruizhe

Project 37

14/4/2025

1 Introduction

1.1 Objective

The goal of our project is to reinvent the wheel. We aim to create a spherical wheel that has seamless movement across rough, uneven or multidirectional terrains. Spherical motors offer an alternative to the bidirectional motion of current All-terrain vehicles (ATVs). The motor is expected to achieve a high-level performance for the vehicle and enable energy efficiency in fields such as agriculture and exploration.

Our team is focused on developing a rudimentary spherical induction motor inspired by the "Six-Stator Spherical Induction Motor for Balancing Mobile Robots" (ICRA 2015). Using induction-based torque, this motor utilizes a hollow metallic sphere and six strategically positioned stators, enabling omnidirectional mobility and high torque output of up to 8 Newton meters for a feasible and scalable option for all-terrain robotic applications.

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. It will offer users 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. Our system will be compact, lightweight, and easy to install. The product will demonstrate a novel spherical rotor coupled with electromagnetic control, making it an attractive alternative for all-terrain applications.

1.2 Background

Traditional all-terrain vehicles (ATVs) rely on conventional wheel systems that limit maneuverability and adaptability across complex surfaces. Recent advancements in robotics have explored spherical motors as an alternative, offering omnidirectional mobility and smooth traversal over rough or inclined terrain. Inspired by prior work such as the Six-Stator Spherical Induction Motor (SIM) developed for balancing robots, our project seeks to implement a simplified, scalable version of this concept.

The spherical induction motor design uses electromagnetic induction to create torque within a hollow, copper-coated rotor. Six skewed stators arranged around the sphere generate a rotating magnetic field, enabling three degrees of rotational freedom. This technology has the potential to revolutionize compact mobile platforms in fields such as autonomous exploration, agriculture, and logistics by offering a compact, rugged, and energy-efficient alternative to traditional drivetrain systems.

1.3 High-Level Requirements

- This motor must generate at least 6-8 Newton meters of torque for pushing through uneven terrain.
- Support rotation along all three axes.
- The spherical rotor must respond to control signals within 100 ms latency for dynamic steering
- The design must maintain operational stability on 15° inclines**.**

2 Design

2.1 Subsystem Descriptions

A. Power Subsystem

- Supplies 24V to inverters and 5V to controller/sensors.
- Converts voltages using DC-DC converters.
- Includes fuses and temperature sensors.

B. Stator Drive Subsystem

- Each stator coil is energized by 3-phase AC current.
- Driven by inverter modules controlled via PWM.
- Needs to deliver ~1.2–1.5 A per phase.

C. Rotor (Aluminum Sphere)

- Conductive, non-magnetic.
- Interacts with stator fields to generate torque.

D. Controller (MCU)

- Coordinates stator phase signals.
- Receives IMU feedback and adjusts PWM duty cycle.
- Communicates over UART/I2C.

E. IMU Feedback Subsystem

- Measures pitch, roll, yaw.
- BNO055 or MPU-9250, interfaced via I2C.

2.2 Power Supply

The power supply subsystem is intended to provide a stable and efficient power supply to all components of the system used with the spherical induction motor. The system accepts 24V DC input from an external battery depending on the application (LiPo, lead-acid). The following subsystems are the highlights of power supply subsystems:

- **Voltage Regulation:** A DC-DC buck converter regulates the 24V input down to 5V for the controller (MCU), IMU, and other low-power sensors. The regulator must be rated for at least 3A to keep in account any peak loads.
- **Power Distribution:** The 24V rail powers the stator drive inverters directly, high-current draws are required (up to 10A total for six stators). A power distribution board with very low resistance traces to minimize voltage drop is designed.
- **Protection Mechanisms:** Overcurrent fuses (15A for the main rail, 5A for the 5V rail), reverse polarity protection using a P-channel MOSFET, and thermal shutdown circuits are provided to avert possible overheating. Temperature sensors (e.g., NTC thermistors) monitor heat sinks and power components, thus passing on information to the MCU for fault detection.
- **Efficiency:** The system aims for >90% efficiency for the DC-DC conversion to reduce energy loss, which is crucial for energy-efficient ATV applications. Low-power mode reduces quiescent current during idle states.
- **Physical Design:** Compact layout, with a maximum footprint of 100 mm x 80 mm, allowing for seamless integration into the motor assembly. Passive cooling, optional heat sinks available for high-current components.

2.3 Control Module

The mind of the spherical induction motor; a control module becomes the central nervous system to guide the activation of the stator, rotor motion and feedback integration to provide precise omnidirectional control. Critical components and capabilities include:

- **Microcontroller Unit (MCU):** A 32-bit ARM Cortex-M4 (like the STM32F4 series) is clocked at least to 100 MHz to serve real-time application processing with floating-point support for extensive torque vector computation.
- **Control Logic:** the MCU generates six synchronized PWM signals (one per stator) to control all 3 phases inverters, at 20 kHz. Calculated using inverse kinematics for spherical motion, phase angles and duty cycles are always dynamically adjusted according to the required torque and rotation axis.
- **Feedback Integration:** This component interfaces with the IMU (via I2C) to collect pitch, roll, and yaw information at a rate of 100 Hz. To keep stator currents in balance for stability, a closed-loop PID controller is utilized with, <100 ms latency for dynamic steering.
- **Power and Size:** Supplying 5V from the power supply making it consume less than 500mA. The module can be housed in a 50 mm x 50 mm PCB, to be mounted near the motor cutting wiring length.

2.4 Motor Design Architecture

The architecture of our spherical induction motor (SIM) pulls design influence from Bhatia et al.'s six stator model. We have composed our mechanical section from two main systems: the stationary stator frame and the rotating spherical rotor, which both interact for a precisely controlled induction.

2.4.1 Rotor Design

Our rotor consists of a hollow sphere that is composed from an inner steel core and an outer copper shell. The steel core is fabricated from annealed SAE 1018 alloy, responsible for the magnetic conductivity. Our outer copper layer, 1.3 mm thick, enables a strong eddy current induction when it encounters a rotating magnetic field. The final rotor is ground to a diameter of ~203 mm in order to ensure high rotational symmetry and smooth motion.

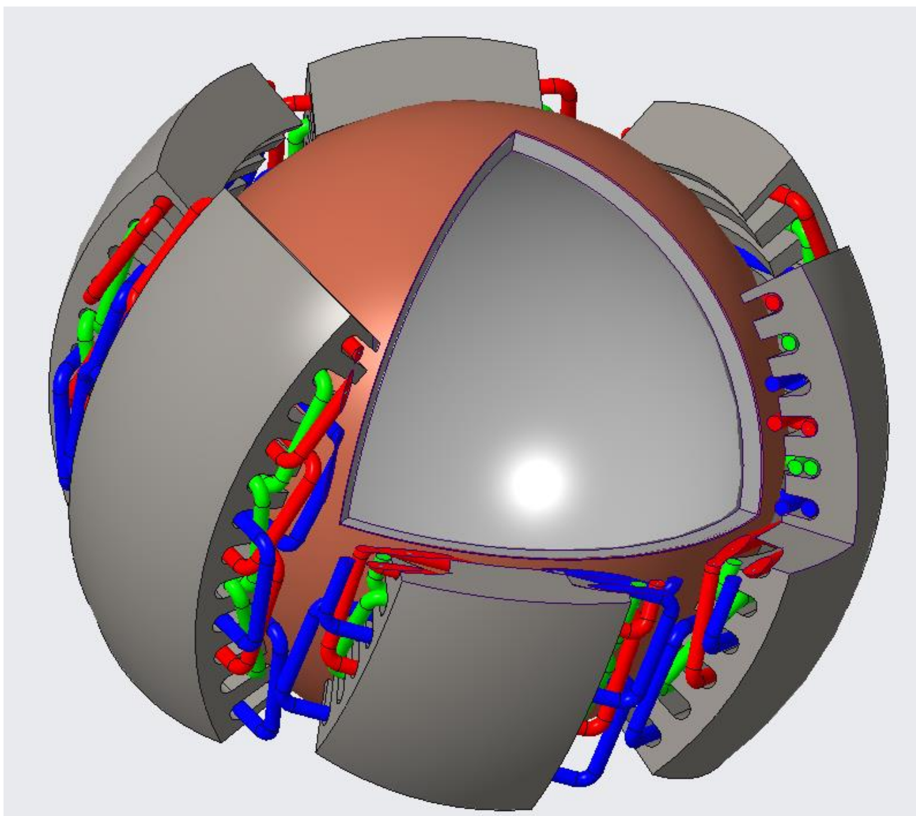

Figure 1: CAD modeling of 6-stator motor surrounding hollow sphere

2.4.2 Stator Configuration

The design of our stationary motor consists of six individual stators, skewed to a 10° from the polar axis and positioned 40° north of the rotor's equator. We will construct the stators from 72 M19 electrical steel laminations, while wound with 9 copper coils, 25 turns each, configured in a

3-phase set up with 4-pole delta arrangement. All stators will be capable of generating up to 40 N of continuous tangential force, peaking at 70 N. We aim to keep the air gap between the stators and rotor at ~1 mm in order to decrease the loss of torque and any mechanical interference.

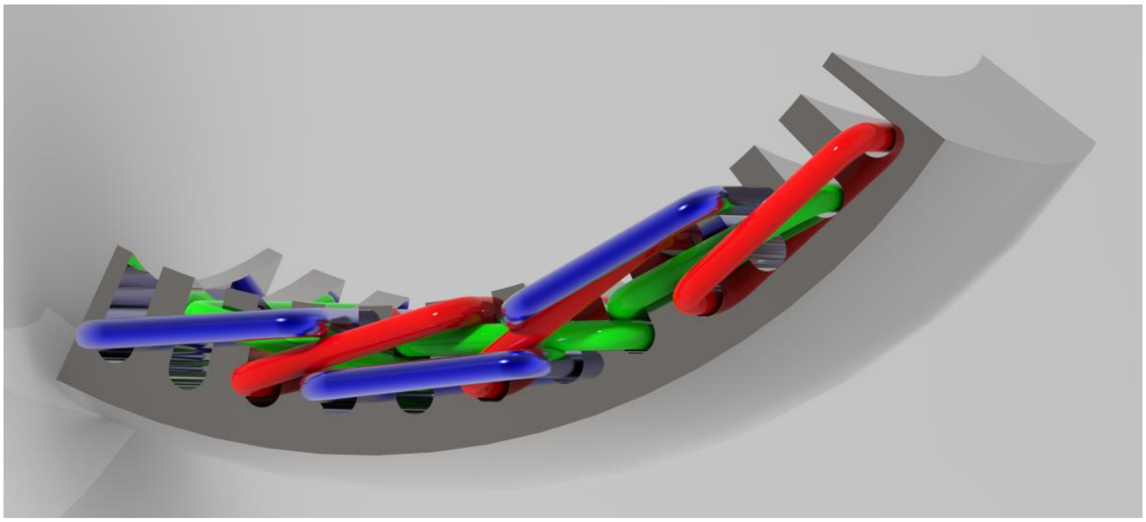

Figure 2: One of the six stators surrounding the rotor

2.4.3 Magnetic and Electrical Characteristics

As aforementioned, the stators use a 3-phase set up to excite a sinusoidal current, creating a rotational magnetic field, inducing currents in the rotor's copper shell. The relation between the stator magnetic field and the rotor induced eddy current will produce tangential force and rotational torque. The coils have a measured resistance of 0.37Ω and an inductance of 1.03 mH, which result in an electrical time constant of 3.5 ms, supporting a fast torque response.

2.4.4 Design Specifics

Parameter	**Value**
Ball radius	0.1013 m
Ball mass	7.46 kg

Copper shell thickness	1.3 mm
Steel core thickness	6.25 mm
Static friction torque	0.4 Nm

2.5 Schematics

2.5.1 Power Supply

The Power Supply Module converts a 24V input (via J1) to a stable 5V output using the LM2596S-5.0 (U1), supporting up to 3A for the control module. It features input overcurrent protection (F1, 1.5A), reverse polarity protection (D1, 1N5822), and output overcurrent protection (F2, 5A). The LM2596 is controlled via the ON/~OFF pin by the NTC_OUT signal from the control module, enabling or disabling the 5V output.

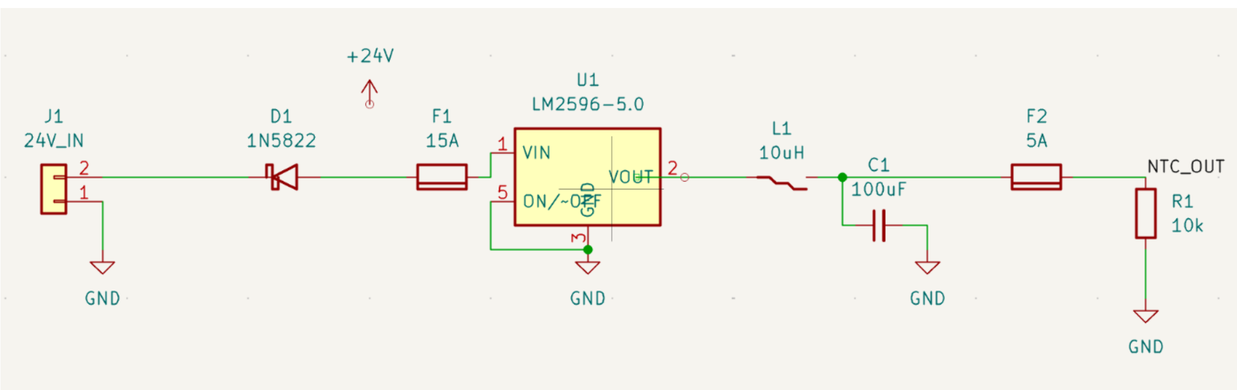

Figure 3: Power Supply Schematic

2.5.2 Control module

The designed circuit acts as a control module based on the STM32F401RETx microcontroller, interfaced with an MPU-6050 sensor to detect motion and offer multiple control outputs. The main task of this circuit is to measure motion (acceleration and gyroscope) data from the MPU-

6050 via I2C, process the measurements in the STM32, and issue control commands for the driving of external apparatus. The circuit is powered with the help of a +5V input, which is dropped to +3.3V by AMS1117-3.3 for supplying the microcontroller and sensor.

Inputs:

- +5V Power Input: Power for the circuit having input to be converted to +3.3V to supply the components.
- MPU-6050 I2C Data (SCL, SDA): Data related to motion (acceleration and gyroscopic) from the MPU-6050 connected to pin PB6 (SCL) and PB7 (SDA) of STM32.
- ADC1 (PC0): Analog input for external sensor signals (like temperature, voltage, etc.) 0-3.3V range.
- UART_RX (PA10): Serial input for communication with external devices.

Outputs:

- PWM Signals (PWM1 to PWM6): Six PWM outputs (on PC6, PC7, PC8, PC9, PA8, PA9) for controlling external devices like motors, LEDs, or servos.
- UART_TX (PA9): Serial output for communication with external devices like a PC or another microcontroller.
- +3.3V Output: Available output of regulated power from AMS1117-3.3 for external use.

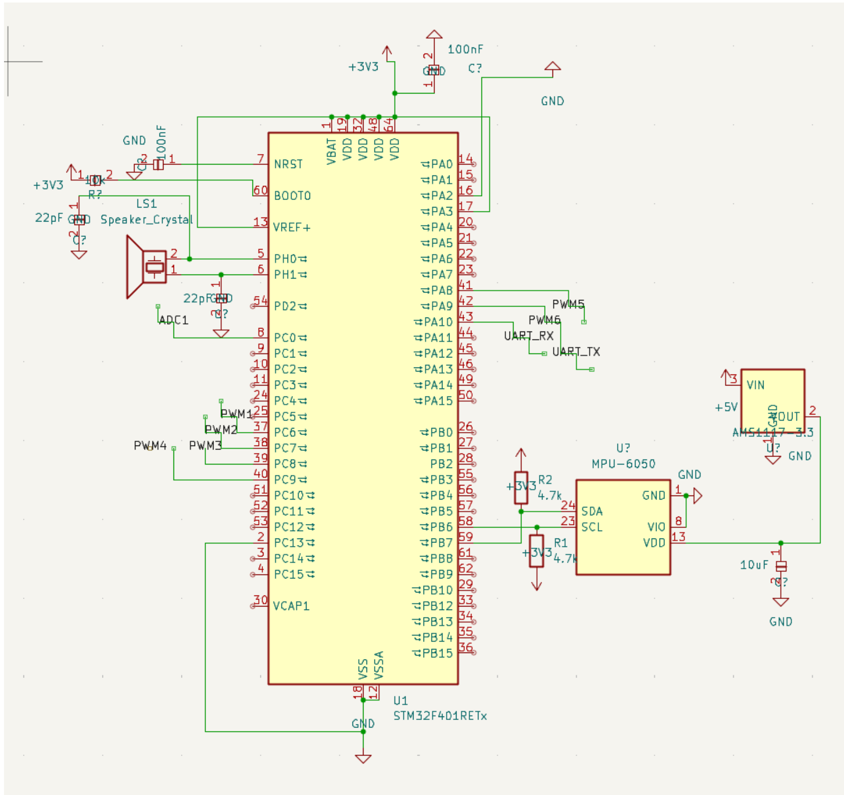

Figure 4: Control Module of Schematics

2.7 Tolerance Analysis

A critical section of our section is the relationship between the stator coils and the spherical rotor itself, producing the necessary torque induced by the alternating magnetic fields. In order to function effectively, we must take into account that the generated torque is enough to rotate under the load and still remains responsive to control inputs. Torque can be approximated using the formula:

$$\tau \propto \frac{I^2 f^2}{g}$$

Where:

I, the coil current

F, the frequency of the AC supply

G, the air gap between the stator and the rotor

Since we aim to get torque in the range of 6-8 Nm, focusing on the minimum of 6 Nm, we determine that we need a current of 1.5 A, f = 3kHz, and g = 4mm. In order to validate this magnetic field distribution, we will need to verify torque production across varying air gaps and current levels. We will measure the actual draw and temperature in operation to ensure thermal limits are not exceeded. The worst-case tolerance margin includes a ±0.5 mm deviation in the air gap from vibration or misalignment, possibly reducing torque by ~20%. This leads to the conclusion that precise stator mounting, and rigid housing are critical for effective performance. We will also need to ensure the PWM generation keeps stable frequency and duty cycle under timing constraints from the microcontroller. It is essential for our system to have a control latency below 100 ms in order to be responsive, making it a high-level requirement. We will test this using testing routines in our system.

3 Costs

Component	**Specification**	**Quantity**	**Unit Price (CNY)**	**Total (CNY)**
Spherical Rotor	Steel core + copper shell (Ø202.7 mm)	1	¥300	¥300
Stator Laminations	M19 silicon steel, 72 laminations per stator	6 sets	¥100	¥600
Copper Wire (AWG 19)	Double polyimide insulated	3 kg	¥60/kg	¥180
Ball Transfer Units	Nylon supports for rotor	3	¥15	¥145
Optical Sensors	Avago ADNS-9800	3	¥50	¥150
Microcontroller (MCU)	ARM Cortex-A/R, ~1 GHz	1	¥250	¥250
Power Drivers (IGBT)	600V/20A vector control modules	3	¥300	¥900
Aluminum Frame	7075-T6 CNC mounting structure	1	¥800	¥800
Power Supply	24V 5A regulated	1	¥200	¥200
Miscellaneous	Wiring, PCBs, fasteners	—	—	¥300

Estimates Labor Cost: 5 Members x 10 hrs/week x 5 weeks x $25/hr x 2.5 = $15,625

4 Schedule

Week	Task
1	Finalize + Order Parts
2	Coil Winding + Frame Build
3	Control PCB + Firmware Setup
4	Integration + Testing Begins
5	Final Testing + Terrain Evaluation

5 Ethics and Safety

Electrical Safety

The system operates at 24V DC and currents exceeding 1.5 A per stator, needing the use of insulated wiring, overcurrent protection (fuses), and secure electrical housings. All motor driver circuits are designed with MOSFETs that include thermal shutdown and current limiting features.

Thermal Safety

The stators and drivers may generate significant heat under sustained operation. Heat sinks and forced air cooling (small fans) will be installed to ensure components remain below their rated thermal limits (< 60°C).

Mechanical Safety

The rotor is fully enclosed in a rigid frame to prevent accidental contact during operation. All moving components are kept internal, and exposed wires are shielded or routed through protective tubing.

Environmental Responsibility

Materials are selected to be as recyclable as possible (e.g., aluminum shell, off-the-shelf coils). The system is designed for low power consumption (target $\leq$ 200W under load).

Right to Repair

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

References

[1] A. Bhatia, M. Kumagai, and R. Hollis, “Six-Stator Spherical Induction Motor for Balancing Mobile Robots,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Seattle, WA, USA, May 2015, pp. 2719–2724.

[2] G. Seyfarth, A. Bhatia, O. Sassnick, M. Shomin, M. Kumagai, and R. Hollis, “Initial Results for a Ballbot Driven with a Spherical Induction Motor,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Stockholm, Sweden, May 2016, pp. 3771–3776.

[3] M. Kumagai and R. L. Hollis, “Development and Control of a Three DOF Spherical Induction Motor,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Karlsruhe, Germany, May 2013, pp. 1520–1527.

[4] R. L. Hollis and M. Kumagai, “Spherical Induction Motor,” U.S. Patent 9,853,528 B2, Dec. 26, 2017.

[5] Tohoku Gakuin University and CMU, “Additional Motor Hardware and Control Summary Presentation,” unpublished internal slides, 2013.

[6] M. Rashid, *Power Electronics Handbook*, 4th ed. Burlington, MA, USA: Butterworth-Heinemann, 2017.

[7] Blues University, “Understanding Sensor Interfaces – UART, I2C, SPI and CAN,” *Blues Developer Hub*, 2024. [Online]. Available: https://dev.blues.io/