Integrated Brushless Motor Exploration Platform

Project Proposal

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Introduction

1. Problem

   As technology continues to develop, the electrification of mechanical loads continues to increase, such as the use of electric motors in robots and vehicles, where hydraulics and engines once were used. With the increased prevalence of electric motors in the coming years, there will be a growing field of study in motor controls. Currently, exploring topics in motor control requires at least a moderate knowledge of electronic hardware systems on top of the control theory being tested. Even when using commercial off-the-shelf motor drivers, system circuitry such as microcontrollers, power regulators, and power supplies still need to be properly chosen and connected together, which can be daunting.

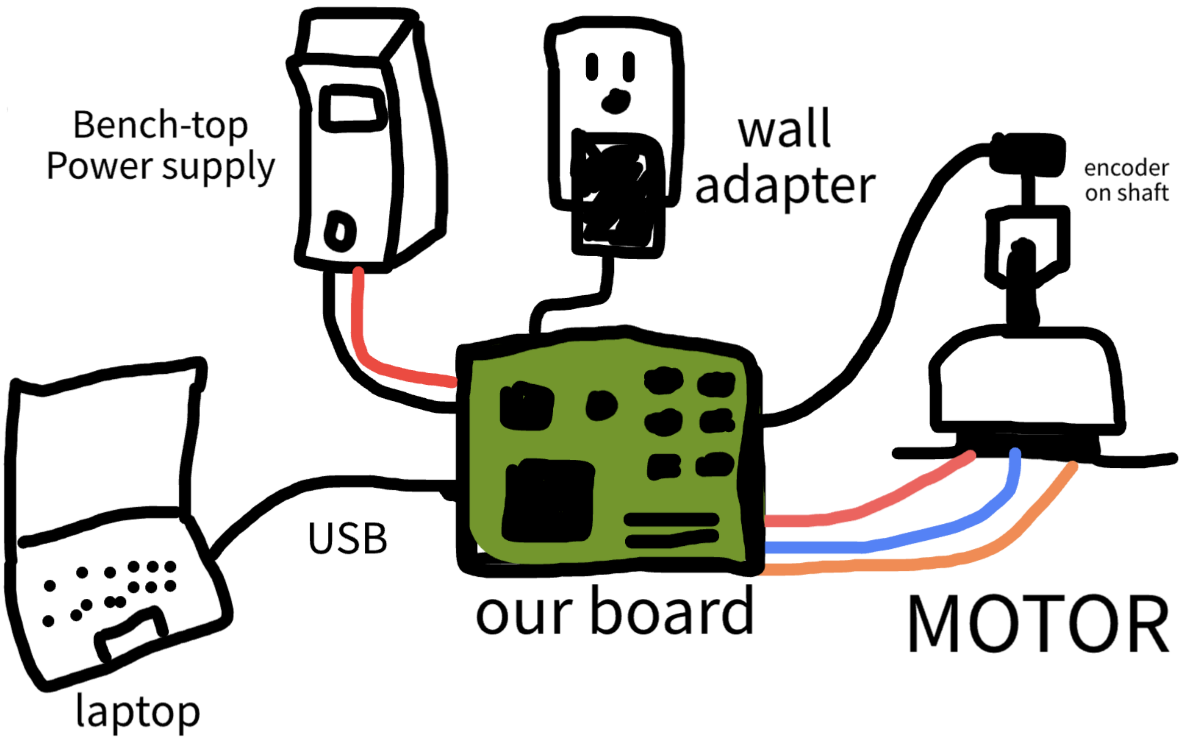
   There are individuals in math and controls heavy backgrounds, like aerospace engineers, which are likely lacking much of the electrical engineering background needed to get a motor even spinning, but they have the advanced knowledge of control systems to implement and test different algorithms for efficient motor control. There does not exist a simple solution for an all-in-one motor control platform designed for an educational use, as almost all commercial subsystems are optimized for application in products. This application focus removes all but the necessary circuitry for any subsystem to allow system designers to fit these modules in a wider array of products. This versatility however, places a problematic burden on a novice user to understand exactly how to connect every part of each subsystem, preventing people from exploring motor controls until they understand much of the electrical background behind them.

2. Solution

   Our goal is to create a single PCB which combines as much circuitry as possible for the operation and advanced control of common electric motors. Specifically, we have focused on brushless DC motors in our solution, as they are incredibly common and are a prime target for control theory students with subjects such as field oriented control. The hardware platform would specifically combine the motor driver circuitry, microcontroller used for control, supplemental programming circuitry, and sensors required for the operation of the motor. The power supply used to power the phases of the motor will be external, but the board will have easy access points to use any common benchtop power supply. The main goal is to limit the number of physical connections required by the user, with only a USB for communication between the controller and a computer, a small wall plug for logic power, a benchtop power supply for motor drive power, and the motor phases themselves. As wall plugs and USBs are quite commonplace, ideally the user of our project would only need to connect two unfamiliar components, being the benchtop power supply, and motor phases. The motor controller would then communicate with an application on the computer, allowing users to modify and switch between the control algorithms used to spin the motor, as well as monitor real-time motor performance and PCB system health.

With a highly streamlined hardware platform, we aim to get more people interested in the field of electronic motor control. The motor driver circuitry would also be built out of discrete components where possible to encourage the natural development of hardware knowledge as the user explores motors. By breaking circuits out into individual components, we allow the user to see and understand each hardware block in the system, and eventually even experiment with changing hardware components as they become more advanced, such as changing FET technology or gate driver components. Ultimately, we aim to develop a hardware platform that lowers the barriers of entry to studying brushless motors, by allowing users to work backwards from a spinning motor and topics in motor control, back to fundamentals of hardware to allow them to begin designing motor systems independently.

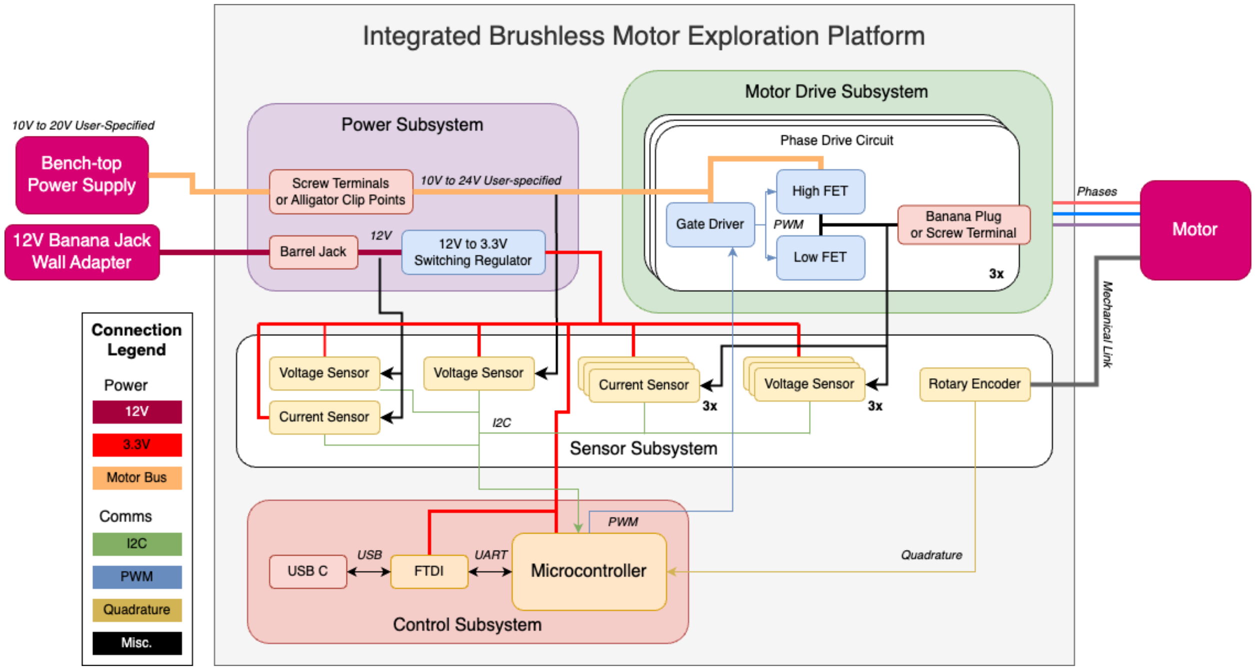
3. Visual Aid



4. High-level Requirements
    a. *Motor operation and control* - The PCB should properly operate a brushless DC motor with rated voltage between 12V and 24V. The user should be able to use a program on a computer to start and stop the motor rotation and control the speed of operation. This operation should require minimal external connections, only a laptop, the power supplies for our board as specified, and the motor itself.
    b. *Configurability* - The user should have the ability to modify the way the motor is being controlled by switching between at least two main control algorithms, such as trapezoidal and sinusoidal motor control. Fine adjustments such as tweaking control loop coefficients, output voltage, or frequency should also be possible to explore the way a motor in a real system reacts to different control algorithms.
    c. *Motor performance and system health monitoring* - The user should be able to view motor phase voltages, phase currents, motor speed, shaft position, and the voltage of any power converter on the PCB in real time (>1Hz rate, <500ms latency) as well as trends over time.

Design

1. Block Diagram



2. Subsystem Overview
    a. *Control Subsystem* - The control subsystem is responsible for driving and monitoring all other subsystems. It will periodically read data from the sensor array, monitor the health of the power subsystem, and generate PWM signals for the motor drive subsystem. It will also communicate with the PC app, updating the GUI periodically and allowing the user to start and stop motor rotation, control speed setpoints, and change between at least two motor control algorithms, such as the trapezoidal and sinusoidal drive algorithms. Main subsystem components include:
        i. System Microcontroller (STM32F446RET6)
    b. *Power Subsystem* - The power subsystem is responsible for generating the needed voltages for components on the board such as sensors and the microcontroller. A small 12V DC wall adapter will plug into a banana jack on the PCB, which is converted using a buck regulator to our logic voltage of 3.3V. We also require the user to connect a benchtop power supply which will provide motor bus voltage directly. This avoids needing to integrate a complex, multiple hundred watt converter into our PCB, which would be unrealistic given the timescale of this project. Main subsystem components include:
        i. Adjustable buck regulator IC (TPS562201DDCR)
    c. Sensor Subsystem - The sensor array is responsible for recording data related to the motor's operation and the overall health of the board. This subsystem will monitor both current and voltage of the three-phase signals driving the motor

outputs of the voltage regulators to track power subsystem health. This subsystem will also use a physical encoder connected to the motor shaft to measure the motor speed and position. Main subsystem components include:

  i. Current/voltage sensors (INA230AIDGSR)
  ii. Physical encoder (PEC11R-4220K-S0024)

d. Motor Drive Subsystem - The motor drive subsystem is responsible for generating the AC waveforms supplied to each phase of the motor. This is done using half-bridge inverters for each phase, and given a specific PWM signal from the microcontroller a wide array of AC waveforms can be generated. Dedicated gate drive circuitry will also be needed to ensure the high-side MOSFETs can properly switch, and both high-side and low-side FETs switch quickly enough. Main subsystem components include:
  i. MOSFETs for the half-bridges for each phase (IRFI1310N)
  ii. Half-bridge gate driver ICs for each phase (DGD05473)

3. Subsystem Requirements
   a. Control Subsystem
      i. *Programming* - Microcontroller code must be able to be updated over USB
      ii. *Data reporting* - Microcontroller should report motor data and system health metrics in real time (less than 500 ms latency) to the laptop so the GUI program can display this data to the user.
      iii. *Link clarity* - A failed data link between the laptop and microcontroller should be made apparent to the user and safely stop the motor from spinning.
   b. Power Subsystem
      i. *Power sources* - All voltages used on the board except the motor bus voltage shall be generated on the PCB with regulators off a main input voltage of 12V.
      ii. *Regulators* - Any voltage regulation greater than 2V between input and output voltage will use a switching regulator to increase efficiency and reduce the losses introduced with linear regulators. At small voltage differences this loss is less significant and the simplicity of a linear regulator can be beneficial again.
   c. Sensor Subsystem
      i. *Phase sensing* - Each motor phase output should have the voltage and current reported to the microcontroller to detect possible motor driver faults, as well as report this data back to the user for performance analysis.
      ii. *Accuracy* - Phase voltages measured by sensors should have less than 150mV of error to allow for better AC waveform generation by the motor driver as the feedback for control is higher quality.

iii. *Health monitoring* - Any voltage generated on the board should be monitored by voltage sensors so the microcontroller can detect possible regulator faults or other issues with the PCB.

iv. *Speed* - The motor speed should be reported back to the user as an RPM number, either through the physical encoder sensor, or through back EMF sensing and speed estimation calculations.

d. Motor Drive Subsystem

i. *Bus voltage* - The motor drive system should support a motor bus voltage range of 12V to 24V or wider. These values were chosen as they are within the common range of voltage operation for affordable and reasonable brushless DC motors, such as those used in the remote control drone and car communities.

ii. *Output waveforms* - The motor drive system should be capable of generating both trapezoidal and sinusoidal output waveforms on each phase to support the two primary motor control algorithms.

4. Tolerance Analysis

High accuracy sensing is incredibly important in any control loop, as if a control algorithm is changing system outputs based on inaccurate data, the system outputs are highly likely to be of poor quality and cause the control loop to fail to reach the setpoint. This issue is present in several areas of our system, one of the most important being the phase voltage sensing. Without accurate phase voltage sensing, it's not clear to the system what type of electrical signals are truly being supplied to the motor phases. If the phase waveforms are not controlled very carefully, the motor could fail to even spin, let alone achieve precise control. The metric we chose was less than 150mV of voltage error.

The sensor being used is the INA230AIDGSR. The phase voltage will be measured as the "bus voltage" in the sensor. The datasheet reports an LSB sensing value of 1.25mV and a gain error of 0.3% worst case for the bus voltage measurement [2]. The motor bus voltage range of our PCB is 12V to 24V. When the analog value is sampled in the ADC the smallest resolution is 1.25mV, so the worst case is to assume the quantization process introduces the full error possible of 1.25mV. Since the error metric is in mV, the highest operating voltage will introduce the most error since the percentage error will scale off a higher base value. Given an ideal 24V input, the ADC could quantize up or down by 1.25mV to give 24.00125V or 23.99875V, which can then be scaled by 100.3% or 99.7% respectively, to report 24.0733V or 23.9268V. If both errors are worst case overestimates, 24.0733 - 24 = 0.0733 = 73.3mV of error is introduced, or if both errors are worst case underestimates, 24 - 23.9268 = 0.0732 = 73.2mV of error is introduced. Either way the sensor is accurate enough to stay within our goal of 150mV of error.

Ethics & Safety

1. Ethics
   In considering the ethics surrounding the development and existence of this project, two main points in the IEEE code of ethics stand out in their relation to this project. The central focus of the project is to be an educational platform for the driving and control of brushless DC motors, an already highly utilized and increasingly important technology. The IEEE code of ethics mentions in point 2 the ethical need to improve the understanding of people in the capabilities of conventional and emerging technologies [1]. It also highlights the necessity of treating all persons equally and with respect, regardless of background in point 7 [1]. We believe the existence of our project is closely linked with these two points, as it will provide a way for a wider array of people to understand brushless DC motors. Additionally, as we aim to make the platform as accessible as possible, we lower the barrier of education which can be frequently apparent in hardware systems, where price of equipment can make learning less accessible. By making an open learning platform using common and cheap components, students from less wealthy backgrounds may be able to study a subject they were previously unable to gain hands-on experience with.

   It's also very important to follow all aspects of the IEEE code of ethics during the development process of the project, including supporting one another as teammates as outlined in point 10 [1].

2. Safety
   As our project involves a spinning object in the motor and interacts with unknown external components like the bench-top power supply, there are some safety concerns for the user. While bench-top power supplies are generally a safe option, requiring an inexperienced user to control one is potentially dangerous. For example, if the user supplies power to the motor at an excessive bus voltage, this could cause damage to the system's components and harm to the user. As such, we plan to design safety into our system using overvoltage protections and eFuses. In addition, we will design our software to be as safe as possible, prompting the microcontroller to stop the motor if the computer connection is lost or if the system health sensors report any potential problems. Lastly, we will protect the user from accidentally starting the motor using confirmation messages in the GUI and a large and obvious stop button.

References

[1] - IEEE, "IEEE Policies - Section 7-8 - IEEE Code of Ethics," [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 13-Feb-2025].

[2] - Texas Instruments, “INA230 36V, 16-Bit, I2C Output Current, Voltage and Power Monitor With Alert,” [Online]. Available: https://www.ti.com/lit/ds/symlink/ina230.pdf. [Accessed: 13-Feb-2025]