Literature Review of "VESC – Open Source ESC" project by Benjamin Vedder

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Abstract

The VESC (Vedder Electronic Speed Controller) project is an open-source electronic speed controller for a brushless DC (BLDC) motor. The project's open-source hardware and software offer extensive customization possibilities and support various control modes, interfaces, and protection features. This versatility makes the VESC project applicable to many different contexts. In the context of a master thesis project focused on developing a BLDC motor controller, this document provides an extensive review of the VESC project, which serves as a foundational base for the future proposed solution, a modified version of the VESC project.

1 Introduction

This literature review document explores the details of the VESC project, an open-source electronic speed controller for a brushless DC motor. The purpose of this document is to provide a comprehensive overview of the VESC project, its features, and potential applications. This information will serve as an essential foundation for the project focused on developing an optimized open-source controller for BLDC motors intended for integration into robotic solutions used in agriculture.

The document is organized into several sections, each focusing on distinct aspects of the VESC project, investigating the project's hardware and software, detailing the project's various interfaces, protection features, and tools responsible for the close-loop control of the motor, its monitorization (GUI) and its adaptability for different applications.

The ultimate goal of this literature review is to provide an extensive understanding of the VESC project, its strengths, and, consequently, its potential areas of improvement. This understanding will be crucial for developing an open-source controller solution for a BLDC motor.

2 Motor Control Techniques and Algorithms

The VESC implements both sensored and sensorless FOC. Sensored FOC uses external sensors (like Hall effect sensors) for precise rotor position feedback, ideal for high-precision position control applications. Sensorless FOC, while less accurate at lower speeds, eliminates the need for external sensors, reducing complexity and cost. An essential feature of the VESC's FOC implementation is the auto-detection of motor parameters. This allows for a more precise setup process, automatically adjusting the system for optimal performance for different motors.

Motor Control Techniques

- **RPM-Based Phase Advance (Field Weakening):** This technique increases the motor's top speed beyond its base speed. By advancing the current phase in relation to the motor's back EMF, higher speeds can be achieved, although at the cost of reduced efficiency and increased heat generation.

- **Duty-Cycle Control:** This method controls the motor by varying the duty cycle of the PWM signal.
- **Speed Control and Current Control:** The VESC can operate in different control modes, including speed control (controlling the motor to maintain a set speed) and current control (controlling the motor to maintain a set current), providing versatility for different use cases.

2.1 Adaptive PWM Frequency for Optimal ADC Measurements

Accurate Analog-to-Digital Converter (ADC) readings are vital for precise motor control and monitoring. Better data leads to more efficient system management, enhancing energy efficiency and reducing potential component damage.

VESC has Adaptive Pulse Width Modulation (PWM) frequency to enhance ADC measurements. PWM regulates power by switching the supply on/off at a specific frequency. VESC adjusts the frequency of the PWM signals based on operational conditions, minimizing interference and noise in ADC measurements. This feature enables VESC to collect the best possible data from sensors, such as current and voltage measurements, which are critical for current control, voltage regulation, and system diagnostics.

3 Performance Characteristics and Limitations

3.1 Maximum Current and Voltage Ratings:

- Voltage Range: The VESC operates within a voltage range of 8V to 60V. This wide range makes it suitable for various applications, from low-voltage electronics to high-powered motors. The upper limit ensures compatibility with various battery types, including 3S to 12S LiPo batteries.
- Current Capacity: The VESC can handle up to 240A for brief periods, which is beneficial for applications requiring high start-up torque or sudden power spikes. It safely manages around 50A for continuous operation, depending on specific conditions, such as ambient temperature or system configuration.

3.2 Thermal Constraints

Thermal conditions significantly influence the VESC's performance. The continuous high-current operation generates heat, which can impact the efficiency and longevity of the system.

Proper heat dissipation is crucial. Heat sinks and good air circulation around the PCB can manage heat and ensure consistent performance.

Impact of Air Circulation: Air circulation plays a critical role in cooling the system. Inadequate airflow can lead to overheating, triggering thermal protection mechanisms and reducing the continuous current capability. Additional cooling methods, such as fans or liquid cooling systems, might be necessary to maintain optimal performance in enclosed or compact spaces with limited air circulation.

3.2.1 Possible solution for thermal constraints

A possible solution to manage heat dissipation on the future modified motor controller could be adding more power MOSFETs to the system. The idea is to distribute the current load for a single phase of the motor's windings across multiple MOSFETs. The current passing through each MOSFET is reduced by dividing the total current among several MOSFETs. This reduction in current per MOSFET decreases the heat generated by each component.

Lower operating temperatures for each MOSFET not only improve the system's overall efficiency but also extend the longevity of the components. MOSFETs operating at lower temperatures are less likely to suffer from thermal stress and have a reduced risk of failure.

While adding more MOSFETs can be beneficial for thermal management, it requires careful consideration in terms of PCB layout and managing increased electrical complexity and potential cost implications.

4 System Structure

The VESC project is a complex system with several integral parts that work together to control a BLDC motor. These parts can be categorized into two main sections: Hardware and Software.

4.1 Hardware

The VESC project is built around several key hardware components that work together to control a BLDC motor. Each component serves a specific function within the system and is crucial for its operation. This section overviews these components, their roles within the system, and how they interact.

The main components of the system are:

- **STM32F4 Microcontroller:** This is the central processing unit of the VESC project. It receives inputs from the user (like desired speed or direction) and processes these inputs to generate control signals. These control signals are sent to the DRV8302 MOSFET driver. The STM32F4 microcontroller is also responsible for communicating with the user interface via USB, sending data about the system's operation and receiving commands.

- **DRV8302 MOSFET Driver:** The DRV8302 is a gate driver IC that takes control signals from the STM32F4 microcontroller and uses these signals to control the operation of the IRFS7530 MOEFETs, producing gate dr. In addition to driving the MOEFETs, the DRV8302 also has built-in current shunt amplifiers that provide feedback to the microcontroller about the current flowing through the motor. This current feedback is crucial for controlling the accuracy of the motor.

- **IRFS7530 MOEFETs:** The IRFS7530 MOEFETs are the power switches of the system. They control the actual flow of power from the battery to the motor. The DRV8302 controls the operation of these MOEFETs. The gate drive signals switch the MOEFETs on and off, effectively controlling the power flow from the battery to the motor.

- **Power Supply:** The main power source is an external battery or power supply, providing high voltage and current necessary for motor operation. This power supply is connected to the DRV8302 MOSFET driver's three half-bridges. The DRV8302 then controls the power flow to the IRFS7530 MOSFETs. Ensure the power supply voltage matches the voltage rating of the motor and VESC components, supporting 8V to 60V (suitable for 3S to 12S LiPo). The STM32F4 microcontroller requires lower operating voltages (5V). The DRV8302 includes a buck converter that steps down the voltage from the main power supply to power the microcontroller, ensuring safe and efficient operation (5V 1A output for external electronics from the buck converter).

In a simplified manner, the following block diagram shows how the different components interact, focusing on the primary functions of each component.

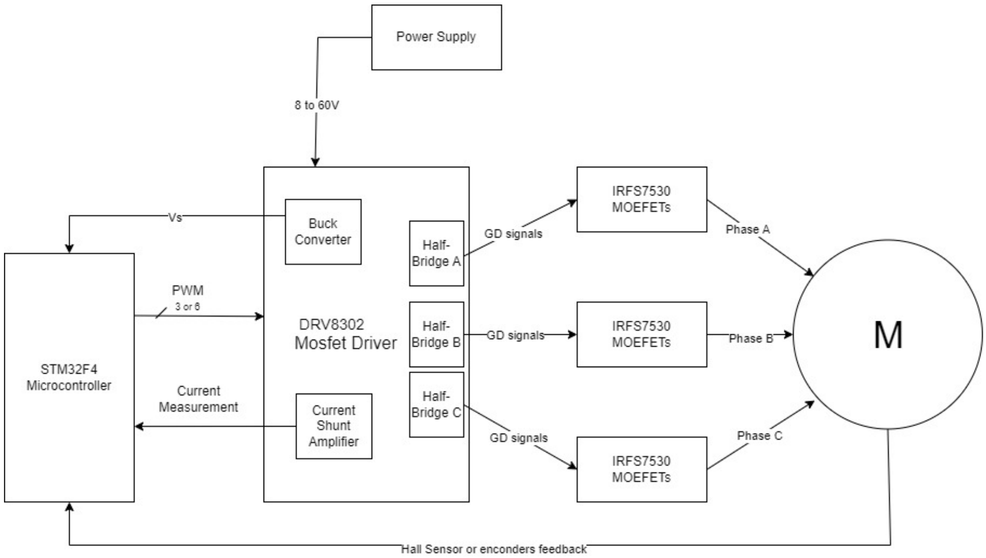

Figure 1: system's block diagram

4.2 Software

4.2.1 Firmware and Operating System

The firmware running on the VESC's STM32F4 microcontroller executes the control algorithms that drive the motor. These algorithms take input from the user interface and sensors to generate control signals for the MOSFET driver. The firmware supports several control modes, including duty cycle control, current control, and speed control, and it can be configured to use either sensorless control or sensor-based control with Hall-effect sensors or encoders. The firmware also includes features for protecting the system, such as under-voltage and over-current protection, and it provides diagnostic information like motor current, input voltage, and system status.

The firmware of the VESC project is based on the ChibiOS/RT real-time operating system (RTOS). An RTOS is an operating system designed to process data as it comes in, typically within a very short time frame. RTOSs are used in environments where high reliability is required, and tasks must be processed under strict deadlines.

ChibiOS/RT is a compact and fast RTOS supporting multiple architectures. It is designed for embedded applications on 8-, 16-, and 32-bit microcontrollers. The kernel of ChibiOS/RT can achieve over 220,000 created/terminated threads per second and perform a context switch in 1.2 microseconds on an STM32 @ 72 MHz.

4.2.2 Writing custom applications

The VESC has several extra ports and much extra computational power, so it can run custom user code to control a motor. This is convenient when there are space constraints, and it is also the best way to implement real-time control applications where timing is critical. The VESC code is organized, so it is easy to write and maintain custom applications while keeping the code up to date without having many conflicts when pulling updates using git. [https://vedder.se/2015/08/vesc-writing-custom-applications/]

The VESC project provides a tutorial on making a custom application to run a motor in a specific case: using speed control while a button is held with a speed proportional to the voltage on the ADC_EXT pin. To make a custom application, we can follow the steps provided by the project:

- **Preparation:** Ensure you can build and upload the firmware. We should be able to write and upload custom applications when we can successfully upload the firmware.

- **Connecting everything:** We must set everything up correctly depending on the application. The example used in the post is: When the pushbutton is held down, the VESC will run the connected motor in a speed control loop with a speed proportional to the position of the potentiometer between 0 and 10k ERPM.
- **Create the custom application:** In the VESC project post, all the steps necessary to implement a new application to the firmware are enumerated.
- **Using your custom application:** Configure the VESC as usual. Select the "custom user application" in the app configuration section and write the configuration. The next time the VESC boots, our custom example application will be loaded.
- **Some tips:** In the VESC project post, a list of valuable tips is provided when writing a custom application.

4.2.3 Graphical User Interface (GUI)

The VESC project includes a GUI known as the VESC Tool, which allows users to configure the VESC system, monitor its operation, and update the firmware. The VESC Tool is available for various platforms, including Windows, Linux, and Android, and it communicates with the VESC system via USB.

It allows users to select the control mode, set the motor parameters, configure the input sources (such as PPM, ADC, or UART), and adjust the system's protection settings. The VESC Tool also allows users to update the firmware on the VESC system via USB. This process enables users to upgrade to the latest firmware version or install custom firmware versions easily.

In addition to configuration, the VESC Tool provides real-time monitoring of the VESC system's operation. It displays information like motor speed, current, duty cycle, and input voltage, and it can plot these variables over time to help with troubleshooting and performance tuning.

Some screenshots of the configuration GUI:

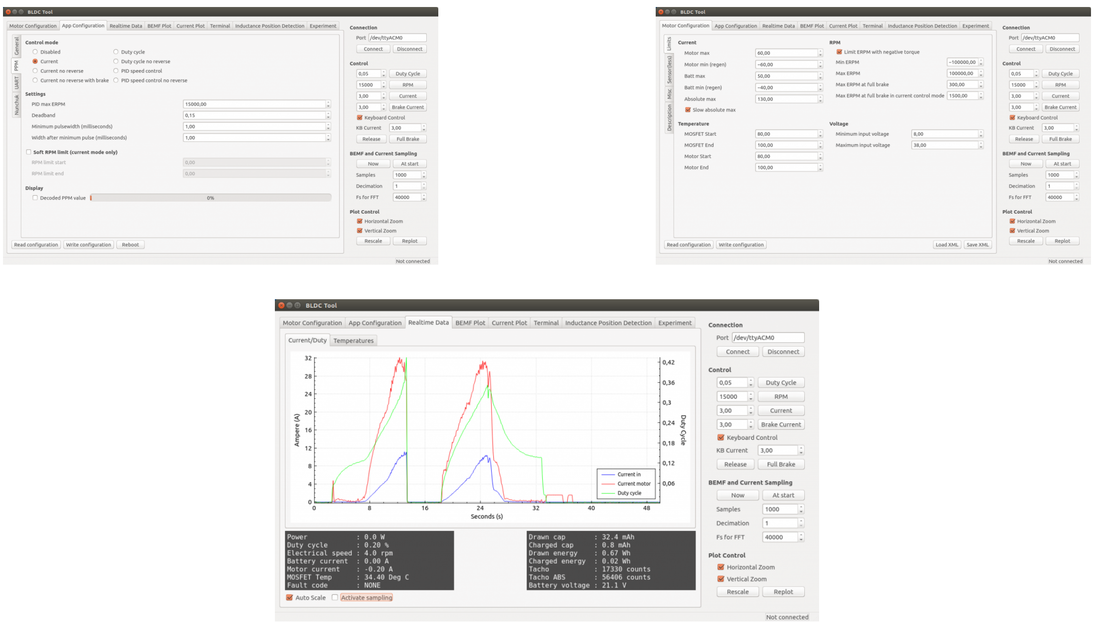

Figure 2: Some GUI screenshots

5 Interfaces

The VESC project provides multiple interfaces for controlling the motor and configuring the system. These interfaces allow the VESC to be controlled by various input sources and enable communication with external devices for monitoring and configuration.

5.1 PPM Signal

Pulse Position Modulation (PPM) is an analog signal interface primarily used in remote control (RC) applications. The position and duration of each pulse in the signal determine the control value. In the VESC project, PPM is used to adjust the motor's speed or duty cycle, making it ideal for applications in RC vehicles, such as cars, boats, or drones. Additionally, VESC incorporates an optional PPM output, which is useful when controlling devices like an RC car via external controllers like Raspberry Pi or Android devices. This expands the control possibilities beyond traditional RC transmitters.

5.2 Analog Input

Supports the integration of various analog sensors or control devices, interpreting analog voltage signals for motor control. These inputs control different motor aspects, like speed or duty cycle, offering a straightforward method for physical control interfaces.

5.3 UART

UART (Universal Asynchronous Receiver/Transmitter) is a serial communication protocol that enables bidirectional data transmission between the VESC and external devices. The VESC's UART interface allows it to send and receive data, enabling control and monitoring capabilities. For example, the VESC can send real-time data about the motor's operation, such as its speed, current and temperature, to an external device for monitoring or logging. The UART interface can also send commands to the VESC to control the motor or configure the system.

5.4 I^2C

The I^2C (Inter-Integrated Circuit) interface is a serial communication protocol for connecting low-speed devices. The I^2C port in VESC connects wireless controllers like the Nyko Kama Wii Nunchuk controller. This protocol allows for a user-friendly, wireless control interface, particularly beneficial for electric skateboards. Additionally, I^2C can be used to connect various sensors, enhancing the system's feedback and control capabilities.

5.5 USB

The VESC includes a USB interface for connecting to a computer or Android device. This interface primarily configures the VESC system using the VESC Tool software. The USB interface allows users to easily set the system's parameters, update the firmware, and monitor the system's operation in real-time. The USB port in VESC uses a modem profile, allowing for direct connection to Android devices without rooting. This feature is crucial for controlling and configuring the VESC via smartphones or tablets.

5.6 CAN-bus

The CAN (Controller Area Network) bus interface is a robust network protocol for efficient communication between multiple microcontrollers in automotive and industrial environments. The VESC project enables multiple VESC units to be linked, enabling coordinated control of multiple motors. This is essential in complex setups like four-wheel-drive electric vehicles or multi-motor robotic systems, where synchronized motor operation is crucial.

6 Protection Mechanisms

The VESC project incorporates a range of protection mechanisms designed to ensure the safety, reliability, and longevity of the motor control system and its motors. These mechanisms are critical for preventing damage due to irregular operating conditions, such as voltage spikes, excessive current draw, rapid changes in the duty cycle, and thermal overload.

- **Voltage Protection:**
  - Low Voltage Protection: Prevents the system from operating under a voltage that is too low, which could lead to inefficient motor performance or damage to the power electronics. This protection is essential for battery-powered applications, where low voltage may indicate a consumed battery.
  - High Voltage Protection: Protects the system against over-voltage conditions due to power surges. High voltage can cause excessive stress on electronic components, leading to potential failure.
- **Current Protection**
  - Motor Current Limiting: Monitors the current to the motor, ensuring it does not exceed a predefined threshold. Excessive current can cause overheating and damage the motor windings or the power MOSFETs.
  - Input Current Limiting: Similar to motor current limiting, but focuses on the current drawn from the power source (like a battery). This is crucial to prevent damage to the power source and the motor controller.
  - Regenerative Braking Current Limiting: Controls the current during regenerative braking, preventing excessive current flow back into the power source, which could be damaging.
- **Duty Cycle and RPM Protection**
  - Rapid Duty Cycle Changes (Ramping): Rapid changes in the duty cycle can lead to voltage spikes and mechanical stress on the motor. The VESC implements controlled ramping of the duty cycle to mitigate these risks.
  - High RPM Limits: Sets a maximum rotational speed for the motor to prevent mechanical and electrical overstressing. The limit can be set differently for each direction of motor rotation.
- **Thermal Protection**
  - Monitors the temperature of critical components and reduces output power or shuts down the system to prevent critical damage due to overheating.

Soft Back-Off Strategy: When any of the above limits are approached or reached, the VESC employs a soft back-off strategy. This strategy is designed to reduce the operational parameters (like current or duty cycle) in a controlled manner to bring the system back into a safe operating range. The approach is gradual to avoid sudden changes that could destabilize the motor control, offering a balance between maintaining performance and ensuring safety. If the parameters significantly exceed safe limits, the VESC may shut down the motor completely to prevent damage. This strategy is essential for applications where safety and reliability are paramount.

7 Other Features

7.1 Regenerative braking

VESC's regenerative braking converts kinetic energy back into electrical energy during braking, which is reused or stored for improved energy efficiency. The process inverts the energy flow, using the motor as a generator to capture energy generated during deceleration. The VESC manages this process, modulating the braking force based on the motor's speed and user input. This feature captures and reuses energy that would otherwise be lost as heat, extending the range of battery-powered vehicles. Regenerative braking can be customized through the VESC's software interface.

7.2 Seamless 4-Quadrant Operation

The "4-quadrant operation" concept is essential for vehicles and machinery that require bidirectional movement and dynamic speed control, such as electric vehicles, CNC machines, and automated guided vehicles (AGVs). In the context of the VESC project, seamless 4-quadrant[1] operation represents its ability to smoothly transition between four different modes of motor operation, enhancing control and efficiency. This capability allows for sophisticated control schemes, such as in robotics, where precise movement in multiple directions and modes is necessary.

- First Quadrant (Forward Driving): The motor operates positively under driving conditions. This is the typical mode for propelling a vehicle or machine forward.
- Second Quadrant (Forward Braking): The motor is still rotating forward but now in a braking or decelerating mode, associated with regenerative braking.
- Third Quadrant (Reverse Driving): The motor operates reversely, providing driving torque. This mode is crucial for applications requiring bidirectional movement.
- Fourth Quadrant (Reverse Braking): The motor rotates in reverse but in braking mode, similar to the second quadrant but in the opposite direction of rotation.

The VESC is designed to transition smoothly between these quadrants without noticeable draws or delays. This seamless transition is crucial for applications requiring precise and responsive motor control. The VESC's firmware manages these transitions by adjusting the power and phase of the motor's electromagnetic field, ensuring smooth and efficient operation across all four quadrants. Particularly in regenerative braking (quadrants 2 and 4), the VESC can recover energy, making the system more efficient and sustainable.

7.3 The Motor as a Tachometer

In the VESC project, the motor's capability to function as a tachometer[2] represents a creative use of the existing hardware for an additional purpose. This is achieved by interpreting the motor's back EMF (Electromotive Force). The VESC system processes this signal to accurately determine the motor's rotational speed. This feature benefits applications like odometry[3] in modified remote-controlled (RC) cars.

By using the motor as a tachometer, the VESC can continuously monitor the wheel speed of an RC car. This information is vital for calculating the vehicle's distance travelled and changes in position (odometry). This method is cost-effective and space-efficient as it eliminates the need for additional sensors. Moreover, it leverages the existing motor hardware, reducing complexity and potential failures.

[1] The term 'quadrant' refers to one of four modes of operation that a motor controller can engage in, based on the direction of rotation (clockwise or counterclockwise) and the nature of the torque (driving or braking).

[2] A tachometer is a device that measures the rotation speed (RPM) of a shaft or disk.

[3] Odometry is the use of data from motion sensors to estimate the change in position over time.

7.4 Consumed & Regenerated Amp-Hour and Watt-Hour Counting

The feature of counting consumed and regenerated amp-hours and watt-hours in the VESC project is a sophisticated energy management tool. It provides critical insights into the energy usage and efficiency of the motor control system, which is particularly useful for applications where energy consumption and regeneration are key considerations.

Amp-Hour (Ah) Counting: This refers to the measurement of current flow over time. By counting the amp-hours, the VESC can track the total amount of electrical charge consumed or regenerated by the motor system. This data is crucial for understanding the battery usage and remaining capacity in battery-powered applications.

Watt-Hour (Wh) Counting: Watt-hour counting extends the concept to power, considering both the current and voltage. It measures the total energy consumed or regenerated by the system. This metric is more comprehensive than amp-hour counting as it reflects the actual energy usage, accounting for changes in voltage during operation.

Advantages of Integrated Energy Counting

- **Real-Time Data Access:** Having real-time access to energy consumption and regeneration data helps make immediate adjustments to improve efficiency or extend battery life.
- **Predictive Maintenance and Diagnostics:** Monitoring energy consumption and regeneration can also serve as a tool for predictive maintenance. Unusual energy patterns could indicate potential issues with the motor or battery.
- **Customizable Energy Management:** Users can tailor their motor control strategies based on precise energy usage data, leading to more efficient and sustainable operations.

The VESC project's ability to count both the consumed and the regenerated amp-hours and watt-hours exemplifies its advanced capability in energy management. This feature enhances the efficiency and sustainability of motor control systems and provides valuable data for optimizing performance and battery life.

7.5 Advanced Commutation techniques

The VESC project stands out for its sophisticated commutation techniques, providing optimal motor control even under rapidly changing speeds. Two key features contribute to this advanced capability: integration of magnetic flux after zero crossing and tracking commutations when the motor spins with the controller off.

7.5.1 Perfect Commutation with Rapid Speed Changes

Traditionally, commutation is timed based on the motor's previous speed, leading to inaccuracies during rapid speed changes. The VESC, however, integrates the magnetic flux after the zero crossing – a point where the current through the winding changes direction. This method allows for more precise commutation timing.

This approach ensures that the motor's electromagnetic forces are more accurately aligned, even when the speed changes rapidly. It leads to smoother operation, better torque control, and reduced noise and vibration, especially in applications requiring quick acceleration or deceleration.

7.5.2 Commutation with Motor Rotation When Controller is Off

An innovative aspect of the VESC is its ability to track the motor's rotation and commutations even when the controller is powered off. This feature is particularly beneficial when the motor is moved manually or by external forces.

When reactivated, the VESC can calculate the required duty cycle to match the motor's current speed, enabling a smooth and gradual reactivation of the motor when it's already spinning.