

# Design and Implementation of a High-Power Motor Controller for Bicycles

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**Abstract**—Electric bikes are becoming an increasingly attractive solution for transporting goods between short distances, especially in city-wide infrastructures. However, most commercially available controllers rely on complex integrated circuits making repair and local manufacturing difficult, particularly for organisations operating in resource-constrained or low-tech environments. The Manufacture Autonome Décentralisée (MAD) is developing products and solutions, particularly e-bikes, which are more repairable and sustainable. Previous studies have predominantly focused on performance optimisation of Field Oriented Control (FOC) and trapezoidal commutation strategies, with limited attention to repairability, component sourcing, and community-centred sustainability criteria. This project aims to design, assemble, and develop a functional, low-tech and open-source motor controller for electric cargo bikes. The current model uses an open-source motor control called VESC (Vedder Electronic Speed Controller) that allows precise control of electric motors. The controller needs to be compatible with a VESC controller and easily locally repairable by the MAD. By exploring the inner workings of the VESC project, modelling of the physical systems and the Printed Circuit Board (PCB) we investigated the ways we could do it in another way. We acquired a VESC controller to compare our system and a commercial product. Preliminary results demonstrate that the adapted VESC-based controller successfully drives the target motor under both commutation strategies, and that positional control is achievable with the current hardware configuration. Security vulnerabilities related to open Bluetooth access were identified. These findings suggest that open-source, locally fabricated motor controllers can meet the functional requirements of electric cargo bikes while significantly improving repairability.

**Index Terms**—VESC, Brushless DC motor, Field Oriented Control, Trapezoidal commutation, Low-Tech, PID-Control.

## I. INTRODUCTION

The fast urbanization of global logistics has positioned electric cargo bikes as a primary solution. At the heart of these vehicles is the motor controller. Current research and industry standards primarily focus on two methods of commutation for the controller: Trapezoidal commutation and Field Oriented Control (FOC).

As motor controllers become smarter, they increasingly incorporate wireless connectivity for tuning and diagnostics. Current research highlights that while Bluetooth Low Energy (BLE) and mobile app integration improve user experience, they often introduce vulnerabilities. Open-source projects, in particular, must balance ease of access for community developers with the need to secure the vehicle.

We also argue the need for general public's safety when it comes to these bikes, as it could be a danger to the traffic. This is especially true when it comes to vehicles carrying a substantial load. This needs to be considered by the MAD, where their responsibility and control begins and ends. Should there be a difference between the firmware loaded on a product from the MAD than what is publicly available?

## II. RELATED WORK

### A. Modeling of BLDC Motor

The electromechanical model of a BLDC (Brushless DC) motor is foundational for understanding its behavior under different control schemes. BLDC motors are categorized by their back-electromotive force (back-EMF) waveform: trapezoidal or sinusoidal. This distinction is crucial, as the trapezoidal shape inherently leads to torque ripple when the supplied phase currents are not perfectly aligned, directly influencing the choice and effectiveness of the control strategy [1]. For a BLDC motor with trapezoidal back-EMF, the electromagnetic torque is given by:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m}$$

where  $e_x$  is the back-EMF and  $i_x$  is the phase current [2]. The classical d-q reference frame model, ideal for sinusoidal machines, is less suitable for trapezoidal BLDC motors because it assumes sinusoidal flux distribution. Phase-variable modeling in the natural (abc) frame is therefore more appropriate, as it

directly accounts for the non-sinusoidal, trapezoidal nature of the back-EMF and the associated harmonics [3].

### B. Trapezoidal Commutation (Six-Step Control) for BLDC Motors

Trapezoidal commutation, or Six-Step control, uses bipolar conduction, with two motor phases conducting at any time and current commutation occurring every 120 electrical degrees [4]. As commutation depends on rotor position, Six-Step control requires either position sensors (e.g. Hall sensors, encoders, or resolvers) or sensorless estimation based on back-EMF detection or observers [4], [5]. This method is renowned for its simplicity of implementation and low hardware cost [6]. It enables effective torque control but introduces significant torque ripple during commutation events, especially under high load [7]. This ripple generates noise, increases mechanical stress, and reduces overall efficiency [3]. Although PWM techniques can mitigate this ripple, they do not completely eliminate it [2].

### C. Field-Oriented Control (FOC) for BLDC Motors

FOC is a vector control strategy that decouples the stator flux and torque components. It transforms three-phase currents into orthogonal  $I_d$  and  $I_q$  components, enabling precise torque control and significant ripple reduction [7]. FOC is particularly effective for BLDC motors with sinusoidal back-EMF but can also be applied to trapezoidal back-EMF motors, albeit with less impressive ripple suppression results [2]. It requires greater computational power and more precise position sensors (e.g. encoders). Comparative analysis shows that FOC yields a more stable stator current profile and significantly reduces torque variations compared to trapezoidal control [1].

### D. Comparative Analysis: FOC vs. Trapezoidal for Light Electric Vehicles

1) *Torque Ripple and User Comfort:* Firstly, torque ripple can be reduced for both control methods by selecting appropriate motor parameters, such as the number of stator slots and rotor poles [5]. FOC substantially reduces torque ripple compared to Six-Step control, directly enhancing ride comfort and minimizing vibrations. Experimental results show a torque ripple of 18.38% for FOC versus 35.67% for Six-Step control at 500 rpm [7]. Commutation torque ripple (CTR), prominent in Six-Step control, can be specifically targeted and mitigated using advanced control techniques like Model Predictive Control (MPC) while retaining the fundamental simplicity of trapezoidal commutation [3].

2) *Energy Efficiency:* FOC optimizes torque per ampere (MTPA), improving efficiency at low loads. Six-Step control exhibits lower switching losses at high speeds [2].

3) *Complexity, Cost, and Low-Tech Suitability:* Six-Step control is inherently simpler, cheaper, and more robust, making it a prime candidate for low-tech applications. Research focused on reducing propulsion system costs proposes simplified hardware topologies, such as 4-switch inverters (instead of 6) coupled with direct current control strategies, maintaining

acceptable performance while significantly lowering hardware costs [8]. FOC, while superior in performance, is more complex to implement and carries higher hardware costs (sensors, processing power).

4) *Dynamic Response:* FOC provides faster response times and better load disturbance rejection [7].

## III. RESEARCH GAP

The literature presented in the previous sections shows that significant work has been carried out on BLDC motor control strategies, especially for torque ripple reduction, efficiency improvement, and dynamic performance optimisation. Open-source projects such as VESC also provide high-performance and flexible solutions for electric mobility systems.

However, most existing works mainly focus on control performance and do not consider low-tech constraints such as local manufacturing, hardware repairability, or component accessibility. In many existing controllers, the hardware design remains difficult to reproduce or repair without specialized equipment or advanced electronic knowledge.

In addition, the integration of wireless communication introduces new security concerns. While BLE connectivity simplifies configuration and monitoring, unauthorized access to controller parameters could create safety risks, especially for electric cargo bikes operating in public spaces.

To the best of our knowledge, there is currently no open-source motor controller that simultaneously addresses high-performance control, local manufacturability, repairability, and BLE security for decentralized cargo bike applications.

This project therefore aims to explore a modular and repair-oriented motor controller architecture compatible with VESC while remaining adapted to the constraints of the Manufacture Autonome Décentralisée (MAD).

## IV. AIM AND RESEARCH OBJECTIVES

This work presents the design and implementation of a motor control system for electric bicycles and cargo transport applications developed within the context of the Manufacture Autonome Décentralisée (MAD) initiative at INSA Toulouse. The main objective is to develop a modular, open-source, and locally manufacturable control architecture adapted to low-cost electric mobility systems.

To achieve this, the project is structured into four main technical contributions.

First, a low-cost motor controller is designed based on a six-step (trapezoidal) commutation strategy. The objective is to eliminate the need for a microcontroller by relying exclusively on discrete MOSFETs and standard electronic components, thereby improving repairability, accessibility, and ease of local manufacturing.

Second, a high-performance controller based on Field-Oriented Control (FOC) is developed using an STM32 microcontroller platform. This implementation leverages and adapts the open-source VESC firmware to ensure compatibility with the selected hardware while enabling advanced motor control capabilities.

Third, the security of the wireless communication interface is investigated, with a focus on Bluetooth Low Energy (BLE) vulnerabilities. A Flipper Zero device is used as a diagnostic tool to evaluate potential attack surfaces and identify weaknesses in the communication layer.

Finally, a dynamic model of the bicycle-cargo system is developed to improve rider experience. The objective is to minimize the perceived additional effort when towing a cargo cart. This is achieved through a PID-based (Proportional-Integral-Derivative) control strategy combined with distance sensing, allowing adaptive assistance based on system dynamics.

## V. HARDWARE-BASED SIX-STEP COMMUTATION CONTROLLER

### VI. STM32-BASED FIELD-ORIENTED CONTROL MOTOR DRIVE

This section presents the design and implementation of a high-performance motor controller based on Field-Oriented Control (FOC).

#### A. Choice of FOC Over Trapezoidal Commutation

Table I summarizes the key differences between the two commutation strategies, based on the literature reviewed in Section II.

TABLE I  
COMPARISON BETWEEN FOC AND TRAPEZOIDAL (SIX-STEP) COMMUTATION

Criterion	FOC	Six-Step
Torque ripple (at 500 rpm)	18.4%	35.7%
Low-load efficiency	High	Moderate
High-speed switching loss	Higher	Lower
Position sensor requirement	Encoder (high resolution)	Hall sensors
Implementation complexity	High	Low
Hardware cost	Higher	Lower
Dynamic response	Fast	Standard

For our cargo bike application, rider comfort and smooth torque delivery are priorities. FOC was therefore selected for the high-performance controller, while a separate low-tech six-step board (Section V) was developed for repairability.

#### B. Base Design: Cheap FOCer-2 Project

The starting point was the open-source *Cheap FOCer-2* project, which provides a complete KiCad design for a VESC-compatible board based on an STM32F405 microcontroller. This design includes:

- A three-phase MOSFET full-bridge power stage.
- Gate drivers with built-in dead-time insertion.
- Shunt resistors for phase current sensing.
- USB and CAN interfaces.
- An expansion header for encoder or Hall sensors.

The existing KiCad schematic and layout were used as the baseline for our adaptations.

#### C. Integration of the Rocacher FOC Tile

Mr. Rocacher provided the Kicad schematic of a ready-to-use FOC tile based on an STM32L476 microcontroller.

The initial idea was to make this tile *pluggable* into our carrier board, similar to an Arduino shield. This would allow:

- Easy replacement of the computing core without re-soldering.
- Modular upgrades of the microcontroller.
- Simplified repair and maintenance.

However, the Cheap FOCer-2 project was not designed for such modularity. Its routing is dense and highly optimized for a single, non-removable F405 chip. Adapting it to accept an L476 tile while preserving all critical functions (PWM, current sensing, USB communication) proved challenging.

#### D. Pin Compatibility Verification: L476 vs F405

Before modifying the PCB, a thorough pin compatibility check was performed between the STM32L476 and the STM32F405 (original Cheap FOCer-2 design). The following aspects were examined:

- Physical pinout in LQFP64 package.
- Alternate functions for PWM timers.
- USB DP/DM pins (PA11/PA12).
- Analog inputs for current sensing.
- UART for BLE communication.

Three pin conflicts were identified and resolved as follows.

First, the SPI\_MISO function on PA6 for the STM32F405 conflicts with a DAC output on the same pin for the STM32L476 tile. Since this pin is used for current sensing via SPI in the original Cheap FOCer-2 design, the SPI communication was remapped to PA5 on the L476, which provides a compatible alternate function.

Second, the gate driver enable signal (EN\_GATE) was originally assigned to PB5 on the F405. This pin is not accessible on the L476 tile. The signal was therefore moved to PC5, which is available and can be configured as a standard GPIO output.

Third, Hall sensor C was originally connected to PC8 (TIM8) on the F405. This pin is not available on the L476 tile. The Hall sensor input was therefore reassigned to PB3, configured as TIM2\_CH2, which provides the necessary input capture functionality for Hall signal decoding.

All other critical functions (PWM timers, complementary PWM, enable signals, encoder inputs, UART, USB, and CAN) remain fully compatible between the two microcontrollers. The ADC channel differences between the F405 (ADC123/ADC12) and the L476 (ADC3) must still be handled in firmware, as noted previously.

#### E. Schematic Design and KiCad Implementation

The original Cheap FOCer-2 schematic was modified in KiCad to replace the integrated F405 with connectors for the L476 tile. The main modifications included:

- Removal of the F405 and its associated passive components.

- Addition of two 20-pin headers to receive the Rocacher tile.
- Re-routing of PWM, ADC, and USB signals to the headers.

The schematic passed Electrical Rule Check (ERC) with no errors.

#### F. Routing Challenges and Current Status

The PCB layout was then started. The original Cheap FOCer-2 routing is very dense. Inserting connectors for the removable tile while maintaining signal integrity proved difficult.

The main issues encountered were:

- Some footprints for the tile connectors did not appear correctly in the layout after schematic import.
- Routing of high-current paths (battery, motor phases) around the connectors required additional vias, increasing resistance.
- Decoupling capacitors had to be repositioned, raising concerns about switching noise.

Currently, the schematic is validated, and the layout is under development. Once routing is completed, the board will be manufactured and tested with the VESC firmware adapted to the L476 tile.

## VII. SOFTWARE AND CONNECTIVITY

### A. BLE Compatibility With the VESC

1) *First Experiment:* VESC-controllers are not necessarily equipped with Bluetooth-modules by default. Often, it is necessary to add a BLE-module. A standard HC-05 bluetooth-module compatible with arduino is a great way to send and receive bluetooth-packets from a host, e.g. a mobile phone, via a bridge translating the bluetooth packets to the UART protocol. This could be demonstrated using a ESP8622's standard library with said module, by letting us send characters from one device to another.

2) *HC-05 and the VESC:* By flashing the VESC firmware on a discovery-card and connecting the HC-05 module to the PB10 and PB11-pins, which are the Rx and Tx-pins for the STM32F4xx chip, we discovered that the setup for the bluetooth module was not available in the VESC tool. The inherent BLE capabilities is an important limitation to consider when designing a VESC system. We learned therefore that the HC-05 is not originally adapted for BLE. The need for a bridge also adds on complexity and cost, in the form of extra components and another device to maintain the code of. For the future, choosing a bluetooth module supporting BLE will be the easiest solution. Preferably a module fitting the communication connector on the cheap FOCer project [9] could facilitate the relevancy of the PCB project with a microcontroller.

3) *BLE Vulnerability:* Bluetooth could be a vulnerability to a VESC if it is to be used as a controller in real-time, as the controller could be jammed. Our test with the Flipper Zero shows the disfunctionality of Bluetooth with different

use cases. We experienced with the jamming of a bluetooth speaker that the music completely stopped. It could also be investigated how the connection to the VESC could be modified using the vesc tool. We will touch more on the accessibility of the code within the vesc tool sooner.

### B. Code integrity

1) *Context:* As the project is open source, and the code is freely accessible, there should be no reason to hide the code. It could however be reasonable to protect the code from changes which could hurt other people. Changing following parameters should at least come with a disclaimer and clearly state the dangers possible by proceeding with said changes. We have in mind the maximum speed permitted and the power available to the motors.

2) *LispBM extraction:* We caught word that the lisp code for the VESC used by Maillon mobility was easy to extract. By building an older firmware with the Maillon mobility software, we observed this by going to the lispBM tab and clicking read. It's up to the MAD if they would like to reinforce this mechanism. A modification on a parameter and then clicking upload allowed us to easily change the speed limit. This could bring up a public danger. This raises questions on the use of the MAD's equipment which is in a traffic friendly manner.

3) *LispBM Code:* When we flashed newer firmware from the project made by Benjamin Vedder [9], we also observed some difficulties in uploading the lispBM script taken from the one on firmware version 6.06. This could indicate that there needs to be further maintenance of the code in order to get the software up to speed. This needs to be documented better for someone to continue the project. This could be a good investment for the MAD as well in the context of training for the people working on the motor control part of the e-bike.

This documentation could be as simple as referencing the relevant parts of the lispBM documentation [10]

4) *Proposed Solution:* This risk could be patched by developing a VESC application for the VESC controller or using a binary. This is a solution which is less open source, but which is make unlawful use of the material harder. The application could be created using C and use an algorithm known by the MAD in order to securise the access to someone to change the parameters only if they are the MAD certified personnel. This encryption would preferably be reduced to the most essential settings in order to align with what our impression of the philosophy of the MAD would be.

### C. VESC Compiling

As mentioned, we have been able to compile the VESC tool and the VESC firmware. This firmware has been put onto an STM32F4xx Discovery card. This card uses the same chip as the aforementioned "Cheap FOCer" project. The thought was that using something with the same chip would facilitate the switch from the discovery card to a PCB with the same target.

However, this choice posed several obstacles for our progress on the topic of cybersecurity. We will nonetheless



where a “follower” unit must synchronize its dynamics with a “leader” unit through precise feedback loops.

The proposed approach decomposes the complex task of “cart following” into manageable sub-tasks by nesting control loops:

- Outer loop: Position control layer. Using a linear encoder or distance sensor mounted on the trailer’s hitch, the system measures the relative displacement (error) between the bicycle and the cargo cart. This error is processed by a Proportional (P) Controller. The primary goal of this stage is to translate physical distance into a target velocity setpoint. By saturating the output of this loop, we can prevent the cargo cart from ever exceeding the bicycle’s speed, thereby ensuring it never “pushes” the cyclist.
- Inner loop: Velocity control layer. The velocity setpoint generated by the outer loop is fed into this internal layer, the inner loop is responsible for commanding the motor torque directly to compensate for immediate mechanical disturbances. Because this loop operates at a higher frequency, it can reject disturbances such as sudden changes in rolling resistance or friction, before they significantly impact the overall position error.

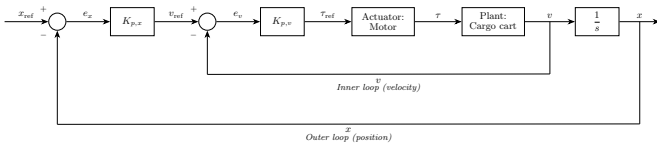


Fig. 2. Cascaded control architecture for the bicycle-cargo system.

Fig. 2 illustrates the cascade architecture for the dynamics of the cargo cart. In this scheme,  $x_{\text{ref}}$  denotes the desired position of the bicycle, whereas  $x$  represents the measured position of the cargo cart.

An outer Proportional Controller  $K_{p,x}$  converts the position error  $e_x = x_{\text{ref}} - x$  into a velocity reference  $v_{\text{ref}}$ , which serves as the set-point for the inner loop. The inner Proportional Controller  $K_{p,v}$  then transforms the velocity error  $e_v = v_{\text{ref}} - v$  into a torque reference  $\tau_{\text{ref}}$ . This command is processed by the motor/actuator block, which delivers the actual torque  $\tau$ . The model of the plant maps this torque to velocity  $v$ , and the integrator  $1/s$  reconstructs the position  $x$ .

The adoption of a cascaded loop architecture offers decisive advantages but comes with disadvantages. This precision introduces increased complexity: the multiplication of tuning parameters and the requirement for high-resolution feedback sensors, such as encoders, raise hardware costs and must come with high-performance software. These technical constraints represent a significant challenge and may raise other issues.

## IX. RESULTS

### A. FOC Controller Validation

1) *Current Status Summary:* Table III summarizes the current status of the FOC controller development.

TABLE II  
FOC CONTROLLER DEVELOPMENT STATUS

Task	Status
VESC firmware compilation	Completed
Pin compatibility (F405 / L476)	Completed
Schematic design (KiCad)	Completed
ERC validation	Completed
PCB routing	In progress
Tile footprint correction	In progress
Board manufacturing	Planned
Hardware testing	Planned

### B. Bicycle-Cargo System Control Results

1) *Simulation Results:* The closed-loop Simulink model presented in the subsection VIII-B was used to evaluate the performance of the proposed PI-based (Proportional-Integral) control strategy.

Figure 3 shows the evolution of the tracking error between the bicycle and the cargo cart during simulation. The response exhibits an initial transient phase followed by a progressive convergence toward the desired equilibrium position, demonstrating stable closed-loop behaviour and satisfactory tracking performance.

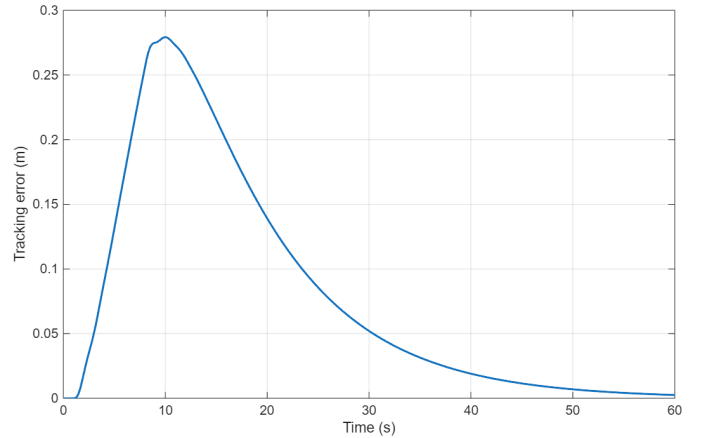


Fig. 3. Position tracking error between bicycle and cargo cart.

2) *Experimental Load Characterization:* Experimental tests were conducted on flat terrain in order to evaluate the influence of mechanical load on the motor current consumption of the cargo cart system. The system was powered using a 48 V battery pack.

Current measurements were acquired using an Analog Discovery 2 connected to a computer running the WaveForms software environment. A current clamp probe was used to measure the motor current, and the signals were sampled at 1 kHz.

During each test, the throttle command was set to its maximum value in order to produce the highest possible acceleration. Once the maximum speed was reached, the motor current naturally decreased and stabilised as the motor only compensated for rolling resistance and friction effects.

Three loading conditions were investigated corresponding approximately to one, two, and three passengers inside the cargo cart. The motor current measured during these experiments is shown in Fig. 4.

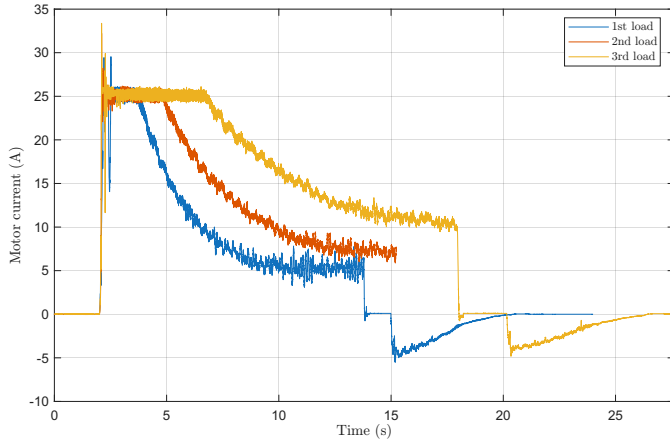


Fig. 4. Measured motor current under three loading conditions.

The results show a significant current peak during the acceleration phase, reaching the controller limit of approximately 25 A. After this transient phase, the current decreases and converges toward a lower steady-state value corresponding mainly to friction and resistive force compensation.

As expected, higher loading conditions resulted in higher steady-state current consumption, indicating an increase in the required motor torque. In addition, the duration during which the current remained close to the maximum controller limit also increased with heavier loads, reflecting the longer acceleration time required to reach steady-state operation. These variations are mainly attributed to terrain irregularities, throttle response fluctuations, and limitations associated with the measurement setup and current probe acquisition chain.

However, due to the absence of direct velocity measurements during the experiments, only qualitative observations could be extracted from these tests. Consequently, a precise estimation of dynamic friction parameters and energy efficiency could not be achieved.

### C. FOC Controller Validation

1) *Current Status Summary:* Table III summarizes the current status of the FOC controller development.

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## X. DISCUSSION

This project could be seen as an introduction to the VESC project for someone who don't know about it from beforehand, the challenges the new users face during setup, as well as a demand for clear expectations concerning documentation on the subject. The project the MAD is leading should probably not be a fork of the project, as the project is still in development.

As a final note, this proved to be a project which could easily be developed into several different projects in different fields. Some projects could be continued later on as a different PIR subject, other could be proposed to later years in different specialisations like TLS SEC, ESPE. Our thoughts on the following projects that could be explored are the following.

The fabrication line for electronics is globalised. This is okay in a stable world, but it could be a problem in a world full of instability, be it war, blockages, or tariffs. The idea of opening a specialisation in cooperation with AIME came up as an idea.

For TLS SEC the subject could be the design for a fitting mechanism to restrict certain privileges to certified personnel that could be used in the C programming language. Later down the line we could also see the possibility to analyse the Bluetooth frames in order to manipulate them in order to change important parameters.

The continuation on the PCB could be a subject fitting an ESPE specialisation.

The proposition of and supply of a vesc system to play with and troubleshoot could be a good rule of thumb, which allows for a quicker start and gives among other things an idea of the budget and the supply line used by a entity in the sector. Proposing a visit could also be one way to familiarise students with the association.

What should be a clear conclusion from our test with the jammer is that a controlles based on Bluetooth alone should be avoided when possible and practical. Examples where this could be relevant include electric skateboards, as cables could impose a tripping hazard. There, an encapsulation of an encrypted control frame could be an thought.

## XI. PERSPECTIVES AND FUTURE WORK

Based on the results obtained and the limitations identified during this project, several directions for future work are proposed.

### A. Hardware Completion and Testing

The VESC-based FOC PCB requires routing completion and prototype manufacturing. Once fabricated, the board must be tested under real operating conditions (varying loads, road profiles, and battery voltage).

### B. Control Strategy Enhancement

Future work includes the implementation and comparison of the PI controller and the cascaded control structure on the cargo cart, in order to evaluate their performance under different conditions (load variations, road profiles, etc.).

In addition, the lack of direct velocity measurements limited the ability to fully characterise the system dynamics. Adding a speed measurement or improving state estimation would allow a more complete analysis of the model.

## XII. CONCLUSION/SUMMARY

### ACKNOWLEDGMENT

The authors would like to thank Pascal Acco and Thierry Rocacher for their continuous technical guidance and support throughout this project. Their expertise in power electronics, embedded systems, and PCB design was invaluable.

We also thank La Manufacture Autonome Décentralisée (LaMAD) for providing the use case, the technical requirements, and the cargo bike platform used for validation.

Finally, we acknowledge the INSA Toulouse GEI department for providing access to laboratory facilities, measurement equipment, and the necessary components for prototyping.

This work was carried out as part of the 4th-year research project (PIR) at INSA Toulouse.

### STATEMENT ON AI USAGE

The authors acknowledge the use of generative AI tools during this project, both for the development work and for writing this paper.

AI was used as a helper in several parts of the project. This includes support for understanding and structuring technical ideas, and giving suggestions during the development of different subsystems. It was also used to help with writing, rephrasing, and improving clarity in the report.

However, all final decisions, implementations, and validations were done by the authors. The AI outputs were always checked, corrected when needed, and adapted based on reliable technical sources and our own experiments and understanding of the system.

We consider AI as a useful tool to speed up thinking and writing, but not as a source of final technical truth. Everything related to design choices, analysis, and results was verified and fully controlled by the authors.

The use of AI tools in this work follows the IEEE guidelines for generative AI usage in publications.

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