Tampere University

Matias Aitolahti

ASSESSING THE FEASIBILITY OF BLDC MOTOR INTEGRATION IN A FFF EXTRUDER

Bachelor's Thesis
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Examiner: Damoon Mohamadi
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ABSTRACT

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3D printing has increased in popularity as a way of quickly and efficiently creating a multitude of different objects from raw materials. Filament based machines, referred to as Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM) machines, have become widely available to consumers and businesses alike.

One of the many considerations when comparing 3D printers has been print speed. Users understandably want print speeds to be as fast as possible without sacrificing print quality. As such manufacturers have been developing ever faster machines. One of the many difficulties in improving print speed while maintaining quality has been the weight of the extrusion head. A heavy extruder is hard to move steadily.

For a typical Direct Drive -style extruder, more than half of the weight can come from just the feed motor. While the standard setup in the industry has been to use stepper motors, a potential solution could come from Brushless Direct Current Motors (BLDC). BLDCs are typically much lighter than comparable stepper motors, and as such could help in making the extruder assembly lighter to enable faster print speeds.

The main objective of this thesis was to study the viability of replacing the feed motor in a filament-based 3D printer with a BLDC motor instead of the traditional stepper motor. This alternate approach was studied both by way of exploring relevant literature as well as designing, assembling and testing a simple prototype of a motor system. The motor was also shortly compared to a NEMA 17 stepper motor typically used in such applications.

After comparing the motors and analyzing the test results, it was noted that the subject has potential for further and more in-depth research. Despite requiring solutions to certain drawbacks of the different motor design, and as such appearing commercially non-viable, with more research a proper solution and a different perspective could be achieved.

Keywords: BLDC, FFF, 3D printing, control theory, motor control

TIIVISTELMÄ

Matias Aitolahti: BLDC-moottorin käyttötutkimus FFF-tulostuspäässä
Kandidaatintyö
Tampereen yliopisto
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3D-tulostus on kasvattanut suosiotaan tapana luoda monia erilaisia kappaleita raakamateriaalista. Filamenttipohjaiset tulostimet, niin kutsutut Fused Filament Fabrication (FFF) tai Fused Deposition Modeling (FDM) -tulostimet ovat nykyään sekä kuluttajille että yrityksille helposti saatavilla.

Yksi 3D-tulostimia vertailtaessa käytetyistä perusteista on tulostusnopeus. Käyttäjät ymmärrettävästi haluavat mahdollisimman nopeaa tulostusta kuitenkin niin ettei tulostuslaatu kärsi. Tällä pohjalla tulostinten valmistajat ovatkin kehittäneet jatkuvasti nopeampia laitteita. Tulostimia kehittäessä erääksi haasteista on muodostunut tulostuspään paino. Suhteessa painavaa tulostuspäätä on haastava saada liikkumaan nopeasti ilman että se vaikuttaisi tulosteen laatuun.

Tyypillisen suoravetoisen (n.k. Direct Drive) tulostuspään painosta jopa puolet voi olla syöttömoottorin painoa. Poiketen alan tavallisesta ratkaisusta käyttää askelmoottoreita, yksi mahdollinen vaihtoehto olisi sen sijaan käyttää harjatonta tasavirtamoottoria (Brushless DC Motor, BLDC). BLDC-moottorit ovat tyypillisesti kevyempiä kuin vastaavat askelmoottorit ja näin mahdollistaisivat tulostuspäätä keventämällä suuremman tulostusnopeuden.

Tämän työn päätavoite oli tutkia filamenttipohjaisen 3D-tulostimen syöttömoottorin vaihtamista askelmoottorista harjattomaksi tasavirtamoottoriksi. Tätä vaihtoehtoa tutkittiin niin relevanttia alan kirjallisuutta läpikäyden, kuin myös toteuttamalla ja testaamalla yksinkertaista prototyyppiä. Prototyyppiin valittua moottoria myös verrattiin lyhyesti monissa tulostuspäissä käytettyyn NEMA 17 -malliseen askelmoottoriin.

Moottoreiden vertailun ja prototyypin testauksen tuloksena saadut johtopäätökset osoittavat, että aihetta olisi mahdollista ja kannattavaa tutkia lisää syvällisemmin. Tästä huolimatta tutkittu vaihtoehtoinen moottorivalinta vaatisi useita ratkaisuita ongelmakohtiin. Yhteenvetona todettiin että vaikkei tämän tutkimuksen perusteella moottorityypin vaihto vaikuta kaupallisesti järkevältä, sen jatkotutkimus voisi tuottaa uutta näkökulmaa alan ratkaisuihin.

Avainsanat: BLDC, FFF, 3D-tulostus, säätöteoria, moottorisäätö

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

BLDC	Brushless DC Electric Motor
CSV	Comma Separated Values
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
IEEE	Institute of Electrical and Electronics Engineers
PID	Proportional-Integral-Derivative
PPR	Pulses Per Revolution
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute
SP	Set Point, setpoint
USB	Universal Serial Bus

1. INTRODUCTION

The landscape of 3D printing has continued to grow over it's commercial history of over 35 years [1]. This growth, driven by technological advancements and cost reductions, has led to large production of off-the-shelf printers by various brands. An important factor when comparing these 3D printers is the print speed of a printer. Most users understandably want fast prints, and as such print speeds have generally increased over time. Typical sources of faster speed have been changes to the movement components, upscaling of the printhead parts like the heater and feed motor as well as tool path optimizations [2].

One additional limiting factor to print speed has been the overall weight of the printhead. Moving a heavy printhead too fast can cause imperfections in the surface finish of printed objects due to undesired motion or vibration during acceleration and deceleration. Furthermore, improper print speed or temperature settings can cause clogging of the nozzle or incorrect extrusion [3].

Practically all modern FFF printers use stepper motors for movement and filament feeding. Stepper motors have proven to be good choices thanks to their high movement accuracy and precise control characteristics. One of their main downsides is however that they are considerably bulky. This means that printers where the filament feed motor is mounted onto the printhead (i.e. Direct Drive) require sturdy movement axis components and careful speed control to move without causing imperfections in the print.

The main idea of this thesis is to study the viability of replacing the stepper motor used to feed the filament with a Brushless DC Electric Motor, also known as a BLDC motor. The approach taken in this particular case is to create a simplified prototype to test an example motor's operation and come up with a suitable control method for the motor in question. Tests were then performed to evaluate the pros and cons of the motor and control system.

Chapter 2 will explore related prior research and explain the background of the subject. Chapter 3 focuses on the design and construction of the motor system prototype, while also providing some comparison to the established stepper motor solution. Chapter 4 describes the testing process. Chapter 5 presents the testing results and chapter 6 gives discussion on the findings and limitations. Finally chapter 7 contains closing thoughts and conclusions.

2. LITERATURE BACKGROUND

By a simple definition, "a 3D printer is a device that creates an object by building it up one layer at a time" [4]. The most common type of 3D printers geared towards consumers, also called Fused Filament Fabrication (FFF) printers, use a polymer-based thin filament, that is fed through a heated nozzle to form lines of material on a build plate. This build plate is mounted on a moving axis, while the nozzle assembly, which is commonly also referred to as the printhead, is mounted on a separate movable axis frame. These axes (X-, Y- and Z-axis)[5] are combined to allow for unobstructed movement of the nozzle within the build space, thus resulting in the ability to create varying shapes and objects. The movement of the axes and feeding of the filament is typically controlled by stepper motors and a series of belts and gears.

The printhead of a typical FFF printer consists of a heated nozzle, heating element and a feed system of some kind. The motor that controls the feeding of filament can either be mounted directly to the printhead (referred to as a Direct Drive or direct extrusion system) or mounted onto the printer frame for a so-called Bowden system [6]. A notable exception to this common type are syringe-based systems used often in biomedical applications, such as the "Enderstruder: An accessible open-source syringe extruder" [7] developed by Cordova et. al. which does not require a heating element at all.

As far as factors that contribute to print quality and accuracy, in addition to machine settings and software configuration, printer component quality must also be considered. Especially for a commercial application the quality of components can make a notable change in print results. As highlighted by S. Simeonov and I. Maradzhiev in their article on stepper motor drivers, there are measurable improvements in both noise reduction and quality when using high-grade components [8].

Yet another factor that affects print quality is the choice of material in conjunction with proper machine settings for that material. The focus of this thesis is on the subject of printers using polymer-based filaments fed using lines of filament, but other suitable materials include ceramic and metal (often fed as beads of material). These types of more complex materials require additional considerations to maintain quality, and can be prone to print errors and defects as noted by Agarwala et. al. [9].

When it comes to motor control, it is important to consider the acceleration and jerk characteristics of the system. In their research on a motor feedrate profile algorithm, Erwinski et al. note that uncontrolled jumps in acceleration can cause unnecessary wear on components and result in inaccurate changes in direction [10]. These kinds of unwanted movement errors should be alleviated with proper control settings.

At the start of the control system design process for the prototype in this thesis, both PID feedback control and fuzzy control were explored. As shown by Legotkina et al. in their conference publication on modeling a fuzzy control system for extruder control, fuzzy control could be an effective solution [11]. However, it was assumed to be needlessly complex for this thesis and as such a more straightforward PID solution was chosen instead.

3. PROTOTYPE OVERVIEW

3.1 Prototype Design

The initial requirements for this project were:

1. A BLDC motor that follows a set speed profile
2. For a proper output torque either:
    (a) A geared motor housing
    (b) A separate gearbox (e.g. Harmonic Drive)
3. A Control device (e.g. an Arduino)
4. Control software solution suitable for the prototype setup

Throughout the process, the requirements were re-evaluated and adjusted as necessary. The initial requirements were intentionally very open-ended, since it was certain that they would need to be narrowed down once the process moved further. Some of the ideas for the prototype, namely the separate gearbox, proved to be unattainable and as such the scope of the work was adjusted accordingly.

Following the initial requirements, the next step was selecting components to match the requirements. In the case of this thesis, the main components listed earlier were sourced from multiple retailers. The primary criteria for the component choices made were ease of acquisition/fabrication, compatibility, price point and fulfilment of project requirements.

When originally designing the prototype, it was planned to include a separate gearbox. Initial concepts considered both a Harmonic Drive (i.e. Strain Wave gearbox) and a Planetary gearbox. On paper, they both had suitable gear reduction ratios, and could be relatively simply fabricated. The main problem with both designs ended up being weight. While multiple variations of both gearbox types were considered, all of them ended up being heavier than the benchmark stepper motor on their own, even without considering the weight of a suitably-sized BLDC motor.

3.2 Component choices

Following the realization that a separate gearbox was not viable for this comparison, a geared motor was chosen. Out of multiple variants, the one selected had both roughly the right specifications for torque and RPM (presented later in table 4.1), as well as a built in encoder and motor driver. The latter proved important as sourcing a suitable motor driver daughter board proved too expensive and time-consuming due to a long lead time.

The decision to use an Arduino micro controller for running the control system was made thanks to several good experiences from past usage of such boards. An Arduino has multiple inputs and outputs well-suited for controlling an electric motor. It is also simple to monitor and record any signal from the Arduino through USB to a computer.

To simulate a load on the motor, a 3D-printed paddle wheel was fabricated, weighing 38g, with a diameter of 139 mm and height of 21 mm. It should be noted that this size wasn't iterated on due to material resources. The last major prototype component on top of these was a generic variable-voltage 2.5A power supply with swappable barrel jack connectors, that was connected to an adapter to allow connection to the components.

With these parts (and connecting hardware such as a breadboard and wires), the system shown in Figure 3.1. was assembled. The Arduino Uno R3 was responsible for sending PWM control signals to the MH37-3235 motor as well as reading the encoder output coming from the motor. It was also connected to a computer for data gathering and command transmission through a Serial connection. Both the motor and Arduino were powered using the same 9V/2.25A power supply to facilitate a common ground.

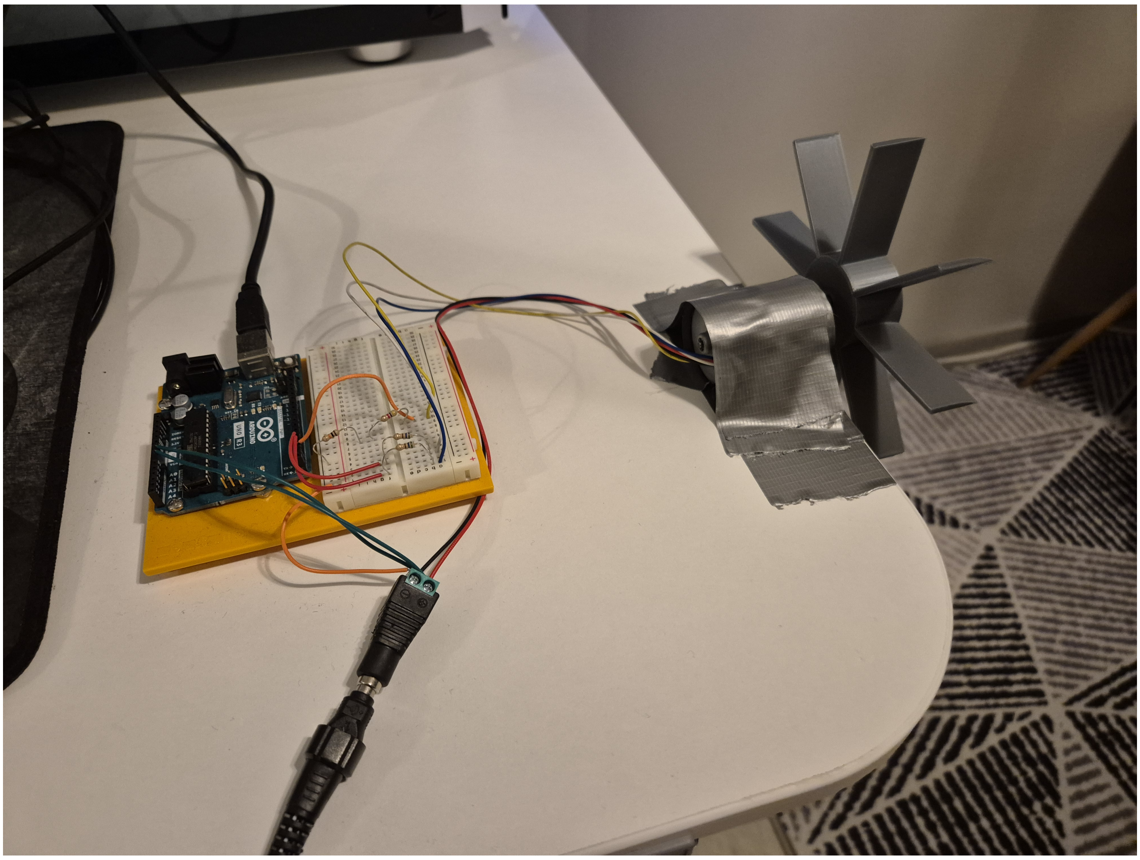

Figure 3.1. Prototype testing setup consisting of motor with PLA printed paddle wheel to act as a load as well as the Arduino controller and power supply connection.

3.3 Motor connections and control system

The motor has five connections shown in Figure 3.2.: Power (Red), Ground (Black), PWM Speed Control (Blue), Direction Control (White) and Encoder Feedback (Yellow). Power and Ground were connected directly to the power supply, while the rest connected to the Arduino pins. The PWM control wire was used to send 16 KHz control signal to control the motor speed, facilitated by a library[12] added to the Arduino software. The direction control wire simply used a binary signal to set the rotation direction. The feedback wire outputs 9 PPR (Pulses per revolution) when the motor is rotating. The sampling rate for RPM calculation was 5Hz, i.e. as sampling update time of 200ms.

To control the motor, a PID controller was implemented on the Arduino. An existing PID library[14] by Brett Beauregard was used to provide the actual implementation, while leaving the tuning to be done separately. The PID controller was given Setpoint (SP) values over Serial and used the encoder feedback described above to measure control response. The control output calculation interval was set at 100ms.

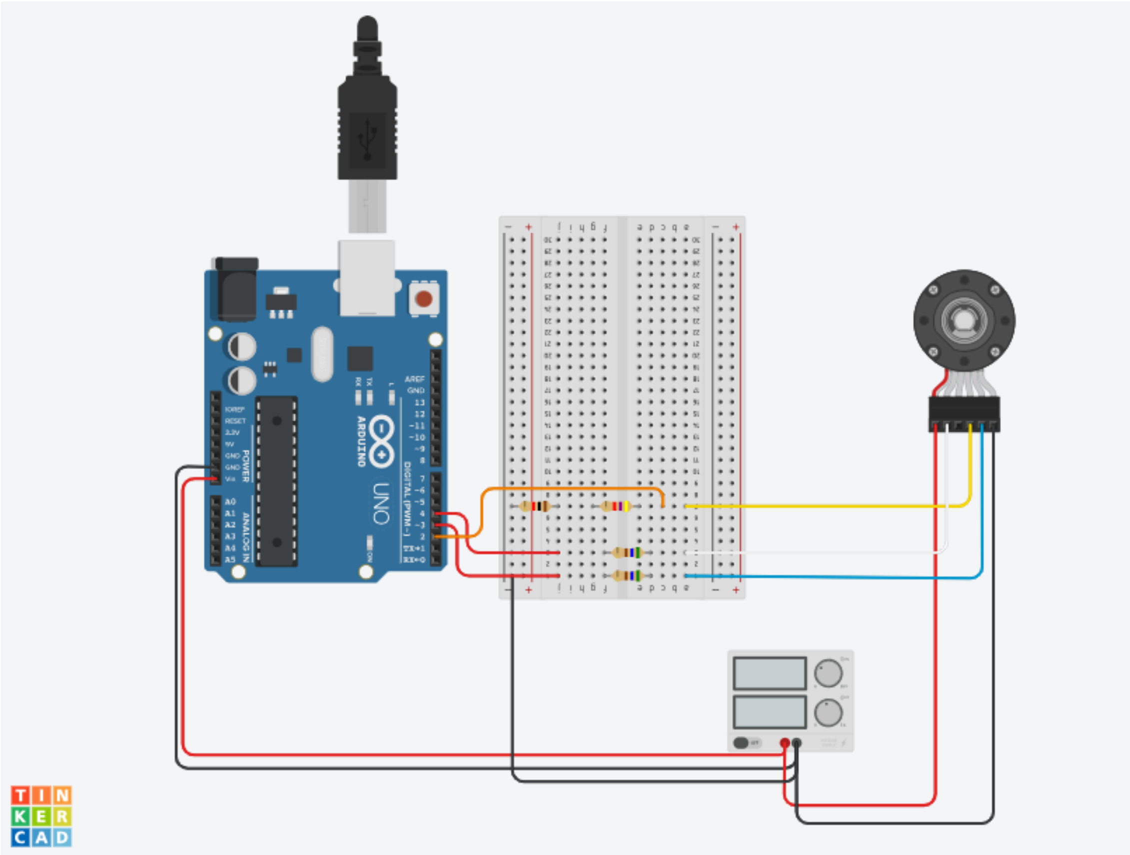

Figure 3.2. *Circuit diagram showing the connections of the motor system prototype. Created using Tinkercad [13].*

For tuning the PID controller, a variation of the well-proven method presented by John Ziegler and Nathaniel Nichols was used [15]. This approach employed a process of first setting an initial gain value for the proportional part of the control equation, while setting the integral and derivative gains to 0. After adjusting the proportional gain to a point where the system displayed a consistent oscillation, the ultimate gain K_u and the oscillation period T_u were used to continue tuning the P, I and D portions of the controller in sequence. For this, the initial proportional gain was calculated as $K_p = 0.6K_u$, the integral gain was calculated as $K_i = K_p/T_i$, where $T_i = 0.5T_u$ and finally the derivative gain as $K_d = K_p \cdot T_d$, where $T_d = 0.125T_u$. The values that were settled on for the controller were $Kp = 0.25$, $Ki = 4.5$ and $Kd = 0.032$.

The required Arduino operating code as well as the Python script for running the commands through Serial can be found on GitHub [16].

4. METHODS

After assembling the prototype, the next step was testing to gauge how the motor and control system would perform, and what strenghts and weaknesses the prototype system had. For a reference point to compare against, a stepper motor used in commercial 3D printers was chosen. The particular stepper motor (a NEMA 17 42-40) has a rated torque of 0.42 Nm and weighs 0.4 kilograms [17]. By contrast, the MH37-3235 motor that was selected for the prototype has a rated torque of 0.65 Nm and weighs 200 grams [18]. These motor specifications are displayed in Table 4.1. below.

Table 4.1. *Prototype motor specifications with comparison to stepper motor equivalent.*

Attribute	MH37-3235	NEMA 17 42-40
Weight (g)	200 ± 50	400 ± 50
Operating voltage (V)	$6 - 12$	$12 - 24$
Rated maximum speed (RPM)	320	1000
Reduction ratio	$19 : 1$	$1 : 1$
Rated Torque (Nm)	$0,65$	$0,42$

While the comparison with the stepper motor was only on paper due to project limitations, a series of tests was designed to further evaluate the prototype. The types of tests conducted facilitated testing the limitations and actions of both the motor as well as the control solution. Multiple tests where eventually condensed into a single test sequence, which focused on several key points of interest:

- Having the motor reach and maintain a set speed profile
- Testing the limits of acceleration/deceleration
- Measuring the accuracy and limits of multiple sequential directional changes

The test command sequence, presented in Appendix A, contains a series of tuples. These are structured to provide the command string to be sent to the Arduino over Serial, as well as a delay (in seconds) that will follow after each sent command. A Python script was used to send the commands over Serial, and subsequently handle the delay calculation. The command strings are explained in Table 4.2. below, and contain either a Setpoint (SP) setting or a direction change.

Table 4.2. *Command strings for motor control*

String	Name	Action	Limit
S123	Speed	Set SP, direction "R" if stopped	0-235
R	Reverse	Direction "R"	-
F	Forward	Direction "F"	-
P	Pause	Set SP 0	-

This test sequence was the result of multiple iterations, and was settled on as a reasonably comprehensive way to showcase the prototype's capabilities. The tests were run multiple times, and once it was verified that multiple runs produced similar results, one set was chosen for display.

The source of the measurement data was the integrated encoder built into the motor itself. As mentioned in chapter 3, the sampling rate of RPM calculation was 5Hz. This meant that while the system did continuously collect rotation speed measurements, the calculated RPM is based on 200ms segments of data points. This 200ms is also the interval of timestamps on the measurement data. Shorter intervals of 5ms and 20ms were also tested, but these proved to cause excessive control error despite extensive tuning. This testing data was output from the Arduino over Serial connection in a CSV-compatible format, and was collected into a file using the same Python script that was sending the control commands.

When it comes to sources of error, the main unknown was the accuracy of the encoder feedback. While it was assumed to be accurate enough for the scope of this testing and overall motor control operation, it was not objectively verified to confirm actual accuracy. There were however steps taken to minimize interference, and options such as the use of a pullup resistor on the Arduino's measurement input port were used to prevent "hanging" of the control signal.

RPM error types (severity/likelihood of effects)

- Measurement error due to feedback pulse "hanging" (major, mitigated)
- Measurement error due to inaccuracy of sensors (moderate)
- Control system error due to suboptimal tuning (moderate)
- Voltage/Current fluctuations at high load (minor)
- Electrical noise/interference (minor)

5. RESULTS

To showcase the measurement results of the tests conducted, the test data that was collected over Serial was plotted using MATLAB. The plots all contain both the (SP) set by the control command sequence, as well as the calculated RPM at each moment in time. The RPM measurement is color-coded to show when the motor is set to stop (black), spin forward (dark blue) and backward (teal blue).

Figure 5.1 shows the first section of the test sequence, intended to visualize the motor behaviour at slow to moderate RPMs. As can be noted from the first portion where $SP = 50$, the motor follows the given value within 5 RPM once settled. Some overshoot can however be observed at higher SP changes.

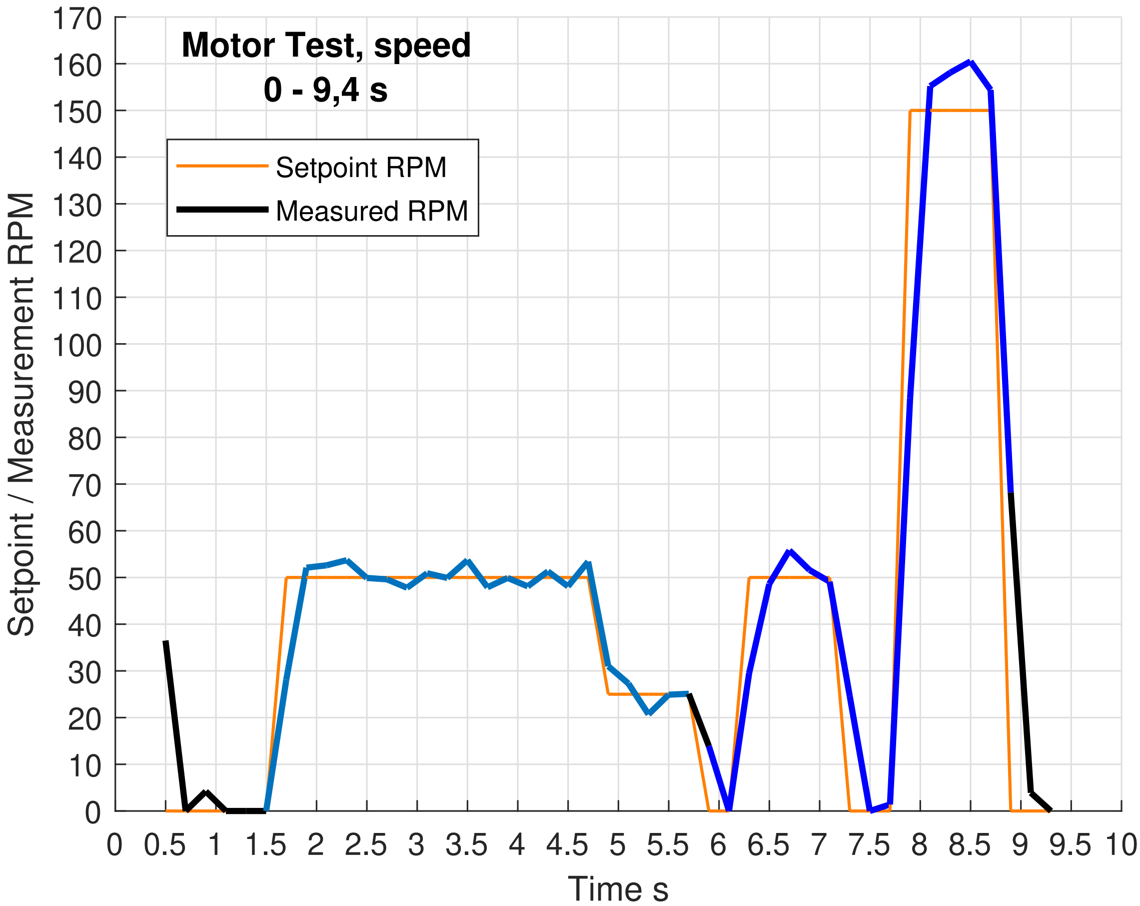

Figure 5.1. *Plot of the first section of the test sequence, highlighting low to moderate motor speeds.*

Figure 5.2 shows the second section of the test sequence, meant to showcase behaviour when the SP is changed by a large degree. As the motor was run at 9 Volts, the maximum measured RPM was just below 235 instead of the rated 320 at 12V. Here, when set to exactly 235, it appears to be that the measurement accuracy of the encoder feedback is not responsible for the variations noticed at lower SP values, but they are rather be caused by the controller. This is noticed as the measurement becomes very even around the maximum RPM that the motor can provide. This could be considered a tuning issue, and could have possibly been reduced with further tweaking.

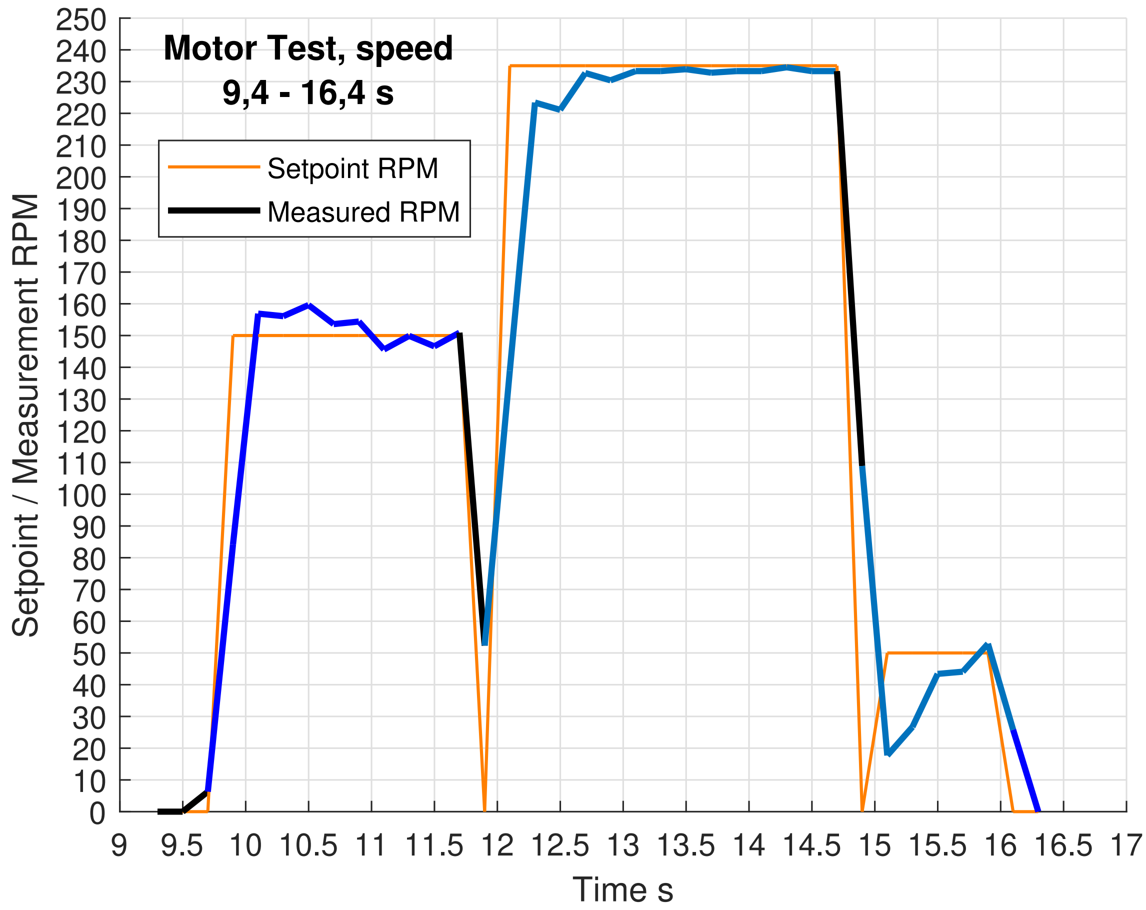

Figure 5.2. *Plot of the second section of the test sequence, highlighting high motor speeds.*

Figure 5.3 shows the third section of the test sequence, testing rapid changes in SP. This section clearly demonstrates one of the main drawbacks of the motor type used, i.e. the inertia added due to the gearing. Because of the added inertia, the motor is unable to reach the requested speeds in the short (200ms) cycles. It is important to note however that the requested accelerations are very high.

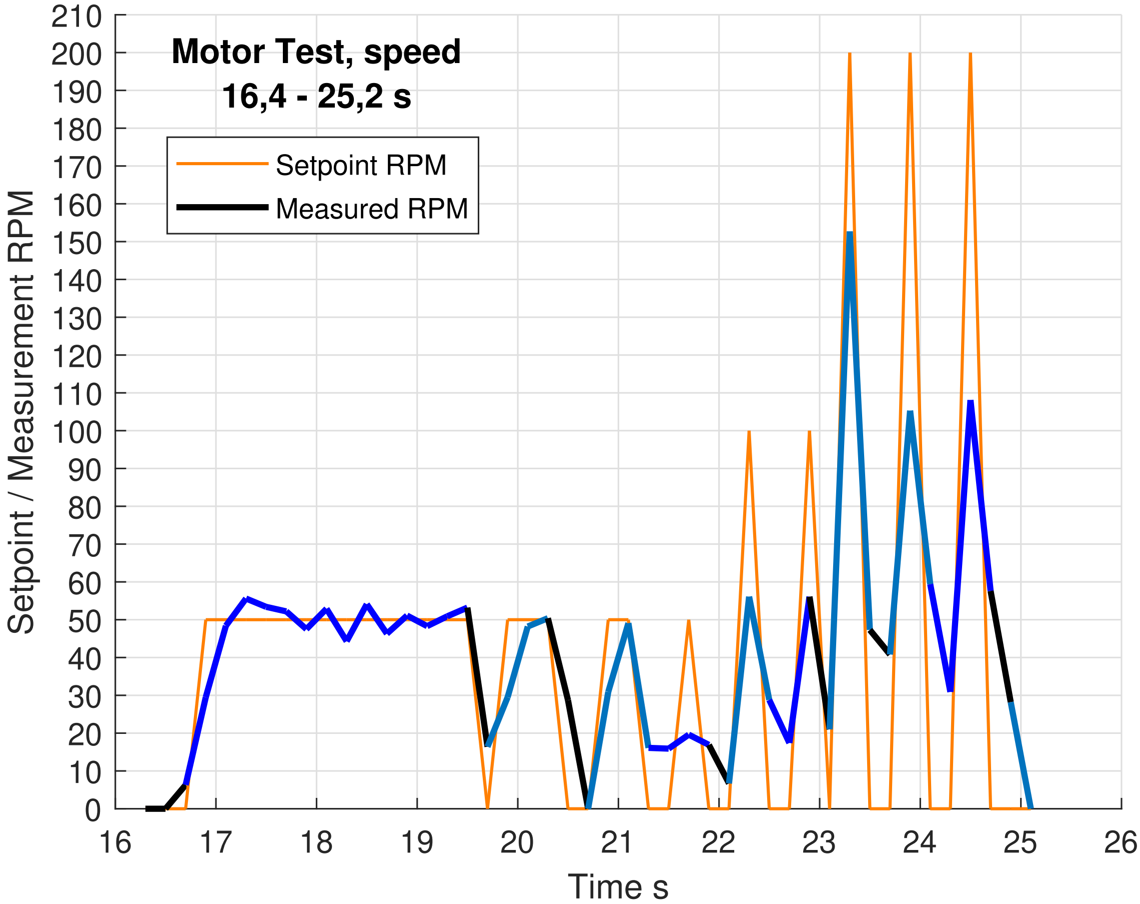

Figure 5.3. *Plot of the third section of the test sequence, highlighting rapid speed changes with different SP values.*

Finally, figure 5.4 displays the behaviour of the motor when simulating a layer print. This was tested as having the motor accelerate up to and maintain a set speed for some time, after which a fast reversal of the rotation was requested. The latter was to simulate the retraction of filament needed at the end of a print line. This type of retraction helps avoid dripping of the filament when moving between layers. It was noted that once again the inertia of the motor/gearbox prevented the system from reaching the requested value fast enough, though it is difficult to assess if this deficit would prevent operation in an extruder.

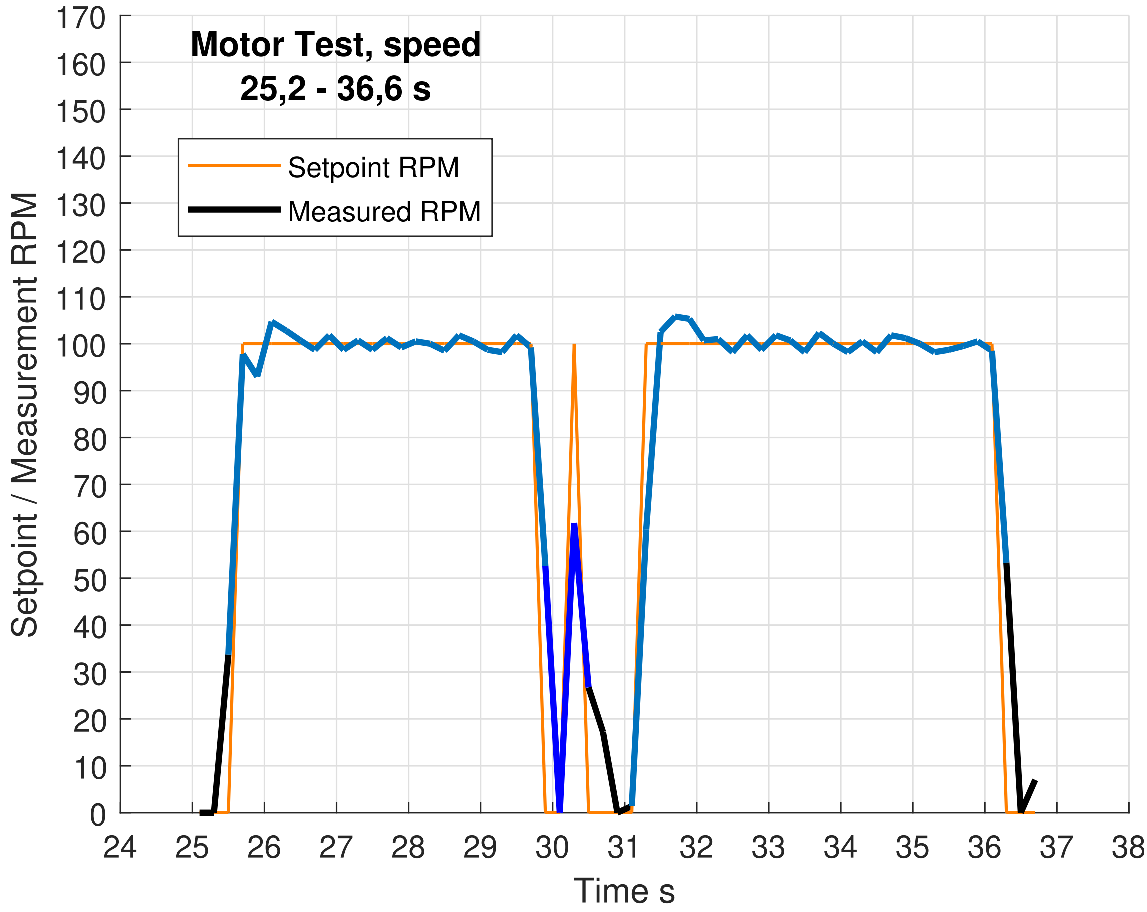

Figure 5.4. *Plot of the fourth and final section of the test sequence, simulating print lines and fast retractions with direction reversal, showcased by colors.*

It should be be noted that for these tests, the acceleration of the motor was not limited. This did not appear to cause significant issues in the tests, as even when unlimited, the acceleration was observed not to be enough for large SP changes. For a practical application a solution to limit acceleration or make it proportionate to the SP change would likely be necessary to avoid unnecessary vibrations and make the motor more precisely controllable.

In addition to acceleration, jerk (the rate of change of acceleration) should also be mentioned. Excessive jerk can cause issues when rapidly changing the requested speed and/or acceleration. This, again, would likely benefit from a proportional limitation if designing a more complete system.

6. DISCUSSION

When it comes to the overall feasibility of the change in motor technology for the implementation of a FFF extruder, there is promising evidence to suggest that with the right component choices and proper control design it would be possible to make the change. The more challenging question to answer is whether it would be a viable or commercially realistic change.

The test results showed that the prototype setup was able to operate at requested speeds adequately, but struggled to match demands of fast directional changes. How this performance and the limitations would translate to the application remains to be determined.

As far as the prototype was concerned, the choice of this specific design of motor proved important in having a meaningful comparison. The vast majority of affordable BLDC motors would have needed many additional parts or modifications (such as additional encoders and separate driver boards) to have comparable capabilities to a typical stepper motor used in extruders.

Regarding further research work, there is potential to look more into different sizes of motors and different control solutions. Limitations of budget and availability of parts for this thesis resulted in the lack of multiple comparison pieces. Having access to different sizes of BLDC motors with different gearing solutions and RPM ratings could have yielded additional and more diverse results. Further, more direct comparison could also be done with access to various stepper motors.

Another limitation with this thesis stemmed from a testing environment standpoint. The limiting factor having been that the motor wasn't mounted to a test printer at all. Testing the motor on a printhead would have allowed further, more application-specific testing of details such as calibration and load tolerance. This would also open up the opportunity to change the control system to accept Gcode inputs, which in turn would allow a more thoroughly like-for-like comparison to established solutions.

Finally, the testing setup could also have been improved to be more accurate and comparable to the intended application. Having access to external measuring equipment such as a dynamometer and a more capable, more accurate power supply would likely have yielded improved results.

7. CONCLUSION

Overall, the research question of the viability of BLDC usage in FFF printers was answered when considering the scope of this thesis. The main takeaway would be that while commercially the solution doesn't appear to be very viable without significant additional work, at least based on the results here, there is potential for further research into the subject. Having access to better resources and more thorough testing could lead to finding a solution to the challenges mentioned.

The prototype went through multiple iterations during the research process, including both the part choices and control solutions. The result could feasibly be used to replace a stepper motor in the print head of a printer, at least with additional tuning and adjustments. The amount of work required to get a system using such a motor however would appear to be not insignificant, and as such it still remains to be determined whether it would be worth it to "reinvent the wheel".

Testing within the scope of this thesis did highlight several areas in need of further tweaking, namely figuring out a solution to efficient control during rapid, small movements as well as maintaining accuracy during directional changes.

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APPENDIX A: MOTOR TEST SEQUENCE

Listing A.1. *Python code for the test sequence.*

```
test_sequence = [
    ("P", 1),
    ("S50", 3),
    ("S25", 1),
    ("P", 0.1),
    ("F", 0.1),
    ("S50", 1),
    ("S0", 0.5),
    ("S150", 1),
    ("S0", 0.5),
    ("S150", 2),
    ("P", 0.1),
    ("S250", 3),
    ("P", 0.1),
    ("S50", 1),
    ("S0", 0.1),
    ("F", 0.1),
    ("S50", 3),
    ("P", 0.1),
    ("S50", 0.5),
    ("P", 0.5),
    ("S50", 0.2),
    ("S0", 0.01),
    ("F", 0.01),
    ("S50", 0.2),
    ("S0", 0.01),
    ("P", 0.01),
    ("S100", 0.2),
    ("S0", 0.01),
    ("F", 0.01),
    ("S100", 0.2),
    ("P", 1),
    ("S200", 0.1),
    ("S0", 0.01),
    ("P", 0.01),
    ("S200", 0.1),
    ("S0", 0.01),
```

```
    ("F", 0.01),
    ("S200", 0.1),
    ("S0", 0.01),
    ("P", 0.01),
    ("S200", 0.1),
    ("P", 0.5),
    ("S50", 3),
    ("S0", 0.01),
    ("F", 0.01),
    ("S50", 3),
    ("S0", 0.01),
    ("P", 0.01),
    ("S150", 0.1),
    ("S0", 0.01),
    ("F", 0.01),
    ("S150", 0.1),
    ("S0", 0.01),
    ("P", 0.01),
    ("S150", 0.1),
    ("S0", 0.01),
    ("F", 0.01),
    ("S150", 0.1),
    ("P", 1),
    ("S100", 5),
    ("S0", 0.01),
    ("F", 0.01),
    ("S100", 0.1),
    ("S0", 0.01),
    ("P", 1),
    ("S100", 5),
    ("S0", 0.01),
    ("P", 1),
    ("F", 0.01),
    ("S100", 0.1),
    ("S0", 0.01),
    ("P", 1),
    ("S100", 5),
    ("S0", 0.01),
    ("P", 1),
]
```