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Experimental Comparison of Load Sharing Techniques for Fast Motion in Industrial Machines

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EXPERIMENTAL COMPARISON OF LOAD SHARING TECHNIQUES FOR FAST MOTION IN INDUSTRIAL MACHINES

by

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ABSTRACT

EXPERIMENTAL COMPARISON OF LOAD SHARING TECHNIQUES
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by

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Load sharing and synchronization techniques are essential for modern automation applications where single motor systems cannot meet the application requirements. Evenly sharing the load between multiple motors can increase the output of processes and reduce maintenance efforts due to uneven wear and tear. Rockwell Automation has developed two load sharing techniques for fast motion control applications. In this Thesis, the two load sharing techniques are experimentally compared regarding their ability to evenly share loads and control synchronized motions in a multi motor setup for fast motion. The techniques are compared using a setup with two motors coupled by a timing belt and performing fast motion with moves times of 50ms, 100ms, and 200ms, with and without disturbance. The first load sharing Method utilizes the leader-follower method, where two drives are connected to two motors. In the second Method, one drive controls two motors. The challenge of load control in the single drive multi motor setup is solved by magnetically aligning the motors.

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LIST OF ABBREVIATIONS

PID	*Proportional-Integral-Derivative*
PI	*Proportional-Integral*
PLC	*Programmable Logic Controller*
PAC	*Programmable Automation Controller*
I/O	*Input/Output*
HMI	*Human-Machine Interface*
AC	*Alternating Current*
DC	*Direct Current*
V	*Volts*
Hz	*Hertz*
RMS	*Root-Mean-Square*
PWM	*Pulse-Width-Modulation*
IGBTs	*Insulated-Gate-Bipolar-Transistors*
CSI	*Connected Systems Institute*
MAG	*Motion-Axis-Gear*
IEC	*International-Electrotechnical-Commission*

1. Introduction

Over the past few decades, vast improvements have been made to electronic and mechanical systems. In particular, the fast developments in computing power allowed the design of new, more intelligent electronic systems and controls. These improvements allowed the development of new products and production systems to meet continuously increasing customer demands. One area that benefited from this improved computing power is load sharing systems of multi motor drive systems. Improved control systems and algorithms allowed the development of faster, more accurate, and more durable multi motor systems. These load sharing systems are necessary for industrial applications where a single motor system cannot meet the process requirements for a machine because the required torque to drive a particular mechanism of the machine exceeds the torque that a single motor can develop. With load sharing, two motors can be coupled to develop the required torque and used on the mechanism of the machine that is limiting the machine production to reach the required machine production.

The control of the multi motor systems is crucial to meet the set specifications of applications. The main goal of multi motor control systems is to ensure synchronized motions of all motors in the system. The term synchronized motions of the axes or motors in this Thesis refers to two parameters:

- Load sharing: The motors develop an even amount of torque to drive a shared load.
- Synchronized moves: The motors perform similar moves in regards to velocity and position.

This Thesis experimentally compares two load sharing multi motor control systems developed by Rockwell Automation. In this Chapter, the problem statement, objectives, and structure of the Thesis are stated.

1.1. Problem Statement and Objective

Load sharing is a technique in which multiple drives and motor sets are coupled to move or operate a common load.[5][17] These load sharing systems, also called multi motor or multi drive systems, are widely used in industrial applications where a single motor system cannot develop the required torque and therefore does not meet the process requirements. Examples of application areas of multi motor systems are

printing machines, machines used in the textile industry, belt conveyors, or continuous production lines.[2]. For example, single motor belt conveyors, especially with heavy loads, are limited in their length due to the high torque that must be applied to the belt to move the load. A single motor configuration requires stronger belts to absorb the higher torque and motors that can develop higher torque values to drive the load, which are more expensive than multiple smaller motors.[5] Multi motor systems are here beneficial since it is possible to spread the applied torque evenly over the length of the conveyor, decreasing the one point torque forces.[16]

In general, two different cases can be distinguished in which load sharing and multi motor systems are beneficial to drive the same load:

Case 1: The load must be moved from multiple points. An example of this case is car elevators where four motors mounted on each corner of the car elevator allow for "multi dimensional, multi directional and multi depth movements."[24] In this case, a single motor would not allow multi movements and limit the space utilization of the car elevator. Important for this application is that the movements of all motors are synchronized and share the load equally. Unequally shared loads and unsynchronized motors can lead to system failure due to uneven wear and tear, or uncoordinated movements. Another example of this case is electric vehicles.[10]

Case 2: The second case is applications where a single motor cannot provide enough torque to drive the load. This is especially the case for very fast moves of large loads where the required acceleration torque is very high. In this case, two motors are needed to double the amount of torque applied to the load.

In industrial applications, gearboxes are normally part of a multi motor system but since the test setup, further described in Section 5.1, does not include a gearbox, it is not included in this discussion. Single motor systems consequently consist of one motor, one drive, and frequently one gearbox. This Thesis is focused in the second case where multiple motors are required to drive a large load according to the process specifications. In Figure 1.1, an example of a motion profile where multiple motors are required to drive the load within the process specifications is shown. This can be seen as a simple index move, not showing the motion profile a specific application. Nevertheless, the parameters of the motion profile are realistic. In this example, the process specifications are as follows:

- Load inertia: 85 kg/m^2
- Move time: 54.5 ms
- Move distance: 2.7 deg
- Motion profile: Modsine
- Dwell time after move: 127 ms
- Overall machine cycle time: 181.5 ms

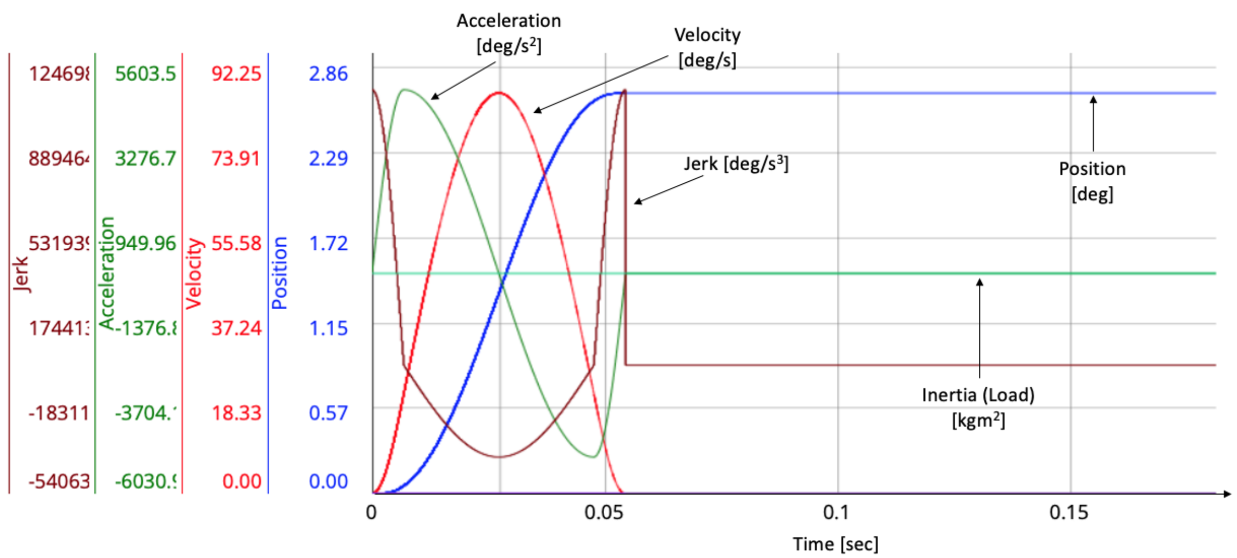


Figure 1.1.: Example of Application Motion Profile

The overall machine cycle time results in a production rate of 5 Hz or 330 $cycles/min$. Due to the short move time, the peak acceleration reaches 5025.65 deg/s^2. The high acceleration value in combination with the load inertia leads to the case that there is no out-of-the-box single motor system that can meet the process specifications, verified in Rockwell Automation Motion Analyzer online tool. This tool allows modelling an application and provides possible combinations of gearboxes, drives, and motors that can meet the defined process specifications. The Motion Analyzer tool allows to select solutions with Rockwell Automation equipment and third party suppliers that are partners with Rockwell Automation. Since the verification of possible single motor solutions with any available motor from any manufacturer is not an essential part of

this Thesis, only the components (motors, drives, and gearboxes) that can be selected in the Motion Analyser were selected. After modeling the mechanical system, designing the motion profile, and verifying the possible motor/drive solutions in Motion Analyzer, a multi motor system was selected and load sharing was utilized, allowing to use-out-of-the-box motors and drives that meet the process specifications and reduce the costs of the system.

To secure an efficient and reliable process, the multi motor control must ensure that both motors work synchronously. For fast, multi motor load sharing, this thesis compares two methods that aim to achieve a high level of synchronicity between the motors and even load sharing were compared in this thesis. The objective of this Thesis is to experimentally compare two load sharing techniques based on their ability to achieve synchronized movements of a multi motor system and evenly share the load. The evaluation criteria will be further discussed in Chapter 5.

Based on the objective of the Thesis, there are several challenges and limitations to the performed tests. The first limitation of this work is that the test setup allows the test of a dual motor system, but it doesn't have the same structure level of an industrial machine. The test setup only allows experimental comparison of the two load sharing techniques under theoretical conditions, not representing real application demands. The test setup will be further described in Section 5.1. Additionally, multi motor, multi drive systems can consist of more than two motors. Due to the test setup, the two compared load sharing techniques cannot be tested for triple, quad, or higher number motors. Conclusions will be made based on the dual motor test setup. The second limitation is based on the objective of this Thesis. The main interest of this Thesis is to experimentally compare the two load sharing techniques in their ability to synchronize and evenly share loads between the motors for fast moves. Fast moves require high acceleration and torque values. Therefore, comparisons of continuous moves are out of scope. Since this Thesis is only focused on the comparison of the two load sharing techniques, possible improvement strategies for the Methods themselves (the core control structure) are out of scope and will not be discussed in this Thesis. Nevertheless, possible improvements to setup procedures and guidelines accompanying the Methods will be presented.

1.2. Organization of the Thesis

As described in the previous Section, in this Chapter 1 the topic, the need for this study, and the objective of the Thesis are defined. In the following Chapter 2, the necessary theoretical background to the Thesis about load sharing techniques is presented. To provide a better understanding of the hardware and control techniques used in this Thesis, a description of these techniques is provided in Chapter 3. The objective of the Thesis is restated in Chapter 4 and the specific gaps identified in the literature review that this study seeks to fill are presented. In Chapter 5, the underlying methodology of the performed tests is described as well as the test setup. In Chapter 6, the test results are discussed. The conclusions of this study are discussed in Chapter 7. Additionally, a brief future outlook is given.

2. Literature Review

In this Chapter, the theoretical background for the comparison of the load sharing techniques is presented. The main fields covered are load sharing, motor control, and the *Proportional-Integral-Derivative* (PID) controller.

2.1. Multi Motor Load Sharing System

Load sharing is the core of this Thesis. In this Section, the theoretical background for the analysis of the two load sharing techniques that are experimentally compared in this study is presented. The existing literature was researched to identify research about load sharing.

2.1.1. System Definition

As defined in Section 1.1, load sharing is a technique in which multiple drives and motor sets are coupled to move or operate a common load.[5][17] Systems used in load sharing applications are also referred to as multi motor systems, as two or more motors are connected to drive a common load. A machine normally consists of multiple independent subsystems that are not mechanically interconnected. These subsystems can consist of multiple motors and drives, or be a single motor and drive. Nevertheless, multiple motors in an independent subsystem do not have to work in load sharing configuration. A load sharing system in this thesis is defined as a system where two or more motors are mechanically interconnected to drive a common load. In Figure 2.1 the differentiation between individual subsystems of a machine, and subsystems systems working in load sharing mode is visualized. This graphic visualizes a transportation system for example for metal sheets where the first conveyor rolls are individually controlled and driven. The first two subsystems are not mechanically interconnected and represent independent motor systems of the machine. The third subsystem is a conveyor belt where two motors are working in load sharing configuration to move the metal sheets over a longer distance. This third subsystem is as well an independent system of the machine but is working in load sharing configuration. Load sharing system are normally mechanically interconnected. In mechanically interconnected systems, the motors are coupled either rigidly, for example, with a gearbox that ensures minimal flexibility in the system, or flexible. A flexible coupling,

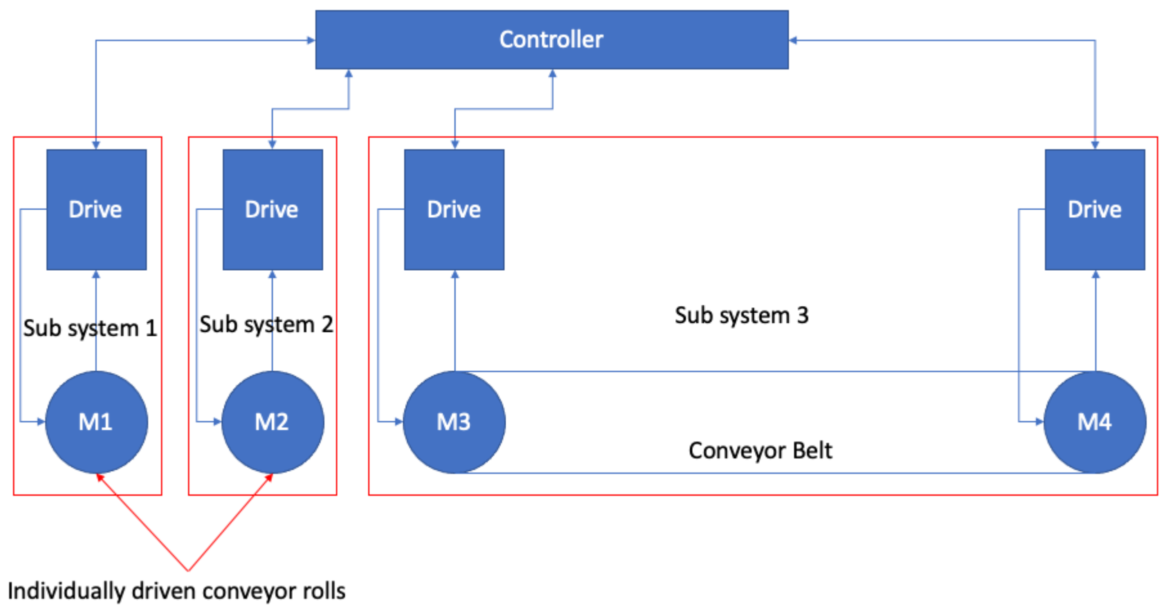


Figure 2.1.: Transportation System with Individual Sub Systems

as shown in Figure 2.1, mechanically interconnects the motors with for example a belt, but it causes a lower level of synchronization in terms of motion of the motors due to the increased compliance in the system in comparison to a mechanical rigid system. In the literature, for example in [21], this differentiation between systems in load sharing configuration and not load sharing configuration is often not made. The available research, for example, [2] or [14] often focus on general synchronization techniques of multi motor systems, where load sharing can be of interest, but must not be the main objective of the synchronization technique. This point will be further discussed in Section 2.1.2.

In general, two main load sharing configurations can be distinguished:[5]

1. Each motor controlled individually by a separate drive
2. All motors controlled by a single drive

In the first case, each motor is controlled by a single drive. This setup allows for individual speed control of the motors and allows to individually monitor the motor parameters. As stated in [5], the drives can operate in their accurate closed-loop control mode to control the speed and torque of each motor. The close-loop control is described in Section 3.3. In the second case, multiple motors are connected to one single drive.

Cases, where this setup is of interest, can be applications where smaller motors can be used and additional drives would unnecessarily increase the costs. For this setup of multiple motors connected to a single drive, a gap in the literature can be identified. In [5], the author states that the drive should not operate in its accurate closed-loop control mode as this was developed for single motor setups. Additionally, in [17], it is stated that load sharing cannot be achieved with a single drive setup as the torque of the motors cannot be controlled. With the development of Method 2, which is further described in Section 5.2.2, the problem of torque control has been resolved by magnetically aligning the motors. The magnetic alignment is further described in Section 5.2. Nevertheless, operating multiple motors from a single drive does not allow to monitor all motor parameters of each motor individually. This issue is further described throughout Chapter 5.

2.1.2. System Classifications

As mentioned in the previous Section, load sharing control and configurations are often discussed in the literature as part of multi motor synchronization techniques. Multi motor synchronization techniques have different purposes based on the application, and represent a wider area of industrial control strategies. Papers specifically about load sharing are often case studies published by companies from the control industry but not based on academic research. Because of this limitation in the research, multi motor systems will be briefly presented in this Section while focusing on the load sharing aspects. In their study from 2020, Stil et al. differentiate four different categories where multi motor systems are used. Multi motor systems can work in load sharing configuration, but do not have to.[21]

1. Multi motor systems in continuous (production) lines
2. Multi motor systems in electrical vehicles
3. Multi motor systems in robotic manipulators
4. Specific multi motor systems

Additionally, the control objectives of multi motor synchronization techniques of the first three categories are shown in Figure 2.2. Specific multi motor systems are not included in Figure 2.2 since their objectives are too application specific to generalize them. As shown in Figure 2.2, six different objectives for multi motor synchronization techniques are differentiated. Out of these six different objectives identifies by Stil

et al. [2020], the load sharing objective is called "Equal Torque/Tension for All Motors". The objective "Torque Distribution" in the definition of the source is not an objective applicable to load sharing configurations. As possible to see in Figure 2.2, Stil et al. [2020] only see the need for the control of load sharing

Multi-Motor System Type	Equal Speed for All Motors	Equal Torque/Tension for All Motors	Torque Distribution	High Precision of Positioning	Adjustable Acceleration/ Deceleration Rates	Preset Motion Path
Continuous lines	+	+	−	−	+	+
Robotic manipulators	−	−	+	+	+	+
Electrical vehicles	−	−	+	+	+	−

Figure 2.2.: Objectives for Multi Motor Controls[21]

in continuous lines. These continuous lines can be conveyor belts as shown in Figure 2.1, or filling systems in the food and beverage industry. Perdukova et al. [2019] point out in their study that load sharing in continuous lines is important to keep the tension in the line strip constant to prevent uneven wear and tear of the line strip material (for example the belt) or for example to prevent the transported material from spilling in the beverage industry.

Specific multi motor systems are systems that cannot be singularly categorized as they require very specific, application-based solutions. In these specific solutions, load sharing configurations can be found in many different applications. Examples are cutting mechanisms for continuous fed materials, such as packaging material used in a form, fill and seal machines, or textile materials. Here, two or more motors can be required to work in load sharing configuration to develop the torque required to cut the material or to meet the system specifications regarding speed. Another example of load sharing applications is train car dumpers, where train cars are turned to dump the transported material. To turn the train car including the transported material, multiple motors are needed in load sharing configuration to develop the required torque.

In robotic manipulators, load sharing is in general not used. In robots, multiple motors work together in synchronized motion to allow the robot to move but are not working in load sharing configuration. The same applies to electric vehicles. Multiple motors are used to drive the car but are not working together in load sharing configuration.

2.2. Synchronization Techniques

In this Section the theoretical background for synchronization techniques is provided. As mentioned, load sharing is often discussed as part of synchronization techniques and one Method compared in this Thesis follows the approach explained following, this Chapter briefly describes synchronization techniques. Important for all load sharing systems regardless of their application is the ability of the control system to coordinate, and synchronize the motor movements to ensure efficient and equal load sharing between the motors. The control of two parameters is essential to control the load sharing system: the speed and torque of the motors.[21] To synchronize the motor movements, different control techniques are used. Stil et al. [2020] in their work divide multi motor synchronization techniques into classical and modern multi motor strategies.

Control Strategy	Speed Synchronization after Disturbances	Position Synchronization after Disturbances	Number of Controllers [1]	Number of Reference Signals [1,2]	Control Structure Complexity	Control Algorithm Complexity
Parallel control	No	No	n	1	Simple	Simple
Master–slave control	Yes	No	n	n	Simple	Simple
Cross-coupling mode	Yes	Yes	$2n + \frac{n(n-3)}{2}$	1	Very complex	Simple
Ring coupling control	Yes	Yes	$2n$	1	Rather simple	Simple
Relative coupling control	Yes	Yes	$2n$	1	Complex	Rather simple
Adjacent coupling control	Yes	Yes	$2n$	1	Rather simple	Rather simple
Combine cross-coupling control	Yes	No/Yes [3]	$2n - 1$	m	Rather simple	Rather simple
Coordinated coupling control	Yes	Yes	$n + 1$	1	Simple	Complex

[1] n denotes the number of electrical motors in the multi-motor system; [2] m denotes the number of subsystems in the complex multi-motor system; [3] Position after disturbances is not synchronized among subsystems, but in particular subsystems, the position is synchronized.

Figure 2.3.: Overview of Multi Motor Synchronization Techniques[21]

In Figure 2.3, an overview of classical and modern synchronization techniques considered in the study from Stil et al. [2020] is shown. The first three techniques, parallel control, master-slave (will be further referred to as leader-follower) control, and cross-coupling control are considered classical approaches while the rest of the five techniques are considered to be modern control strategies. In general, the control strategy is determined by the needs of the application while keeping the complexity as low as possible. It is for example often more important for a belt conveyor system that the motors are running at the same speed while an exact position synchronization can be less important. In this case, the leader-follower technique

can be the most efficient choice. Important when choosing a load sharing synchronization technique is the assessment of the application environment and determining if disturbances to the system are likely. As can be seen in Figure 2.3, parallel control and leader-follower control do not provide position synchronization after disturbance since there is no communication from the follower to the leader.[21]

Because the first Method tested in this Thesis is a leader-follower technique, only this technique will be further described. The second Method tested in this Thesis does not utilize any of the techniques shown in this chapter and will be further described in Chapter 5. In Perez-Pinal et al. [2004], the leader-follower technique is described as a system where the leader output speed is the reference for the follower.[15] This implies that the configuration in a leader-follower system is not bound to two motors and can be expanded to multiple followers as needed by the application. In a leader-follower system, the reference signal is only sent from the leader to the follower and there is no communication back from the follower(s) to the leader. Because of this one-way communication, speed or load disturbances applied to the leader are reflected by the follower, but, disturbances applied to the follower (or any follower in a multi-follower system) are not reflected by the leader and by other followers.[15] Stil et al. [2020] state that the speed of all motors equalizes after a delay but synchronization of position cannot be restored.[21] The statement regarding the position is true for flexible couplings of multiple motors. In systems where the motors are rigidly coupled, an unsynchronized position after disturbance is unlikely because of the strong coupling.

3. Automation Control Hardware

In this Chapter, the background for the two load sharing techniques compared in this Thesis is delivered. As defined in Section 1.1, a load sharing configuration consists of two or more motors mechanically connected to drive a shared load. The motors are powered by industrial drives, and the drives are controlled by a controller. The general setup and connection of a single motor system including the controller, drive, motor, and encoder is shown in Figure 3.1 and is the basic reference setup for this Section. Figure 3.1 is a simplification of the control unit that normally consists of additional modules like *Input/Output* (I/O) modules, but since this information is not essential for this Thesis, these components will not be further described. The controller is further described in Section 3.1. The controller can be directly connected to the drive. The communication between the controller and drive is a two way communication based on the EtherNet/IP standard in which the controller sends reference signals to the drive and receives feedback signals from the drive. Because controllers have a limited amount of EtherNet ports, an EtherNet/IP module is used to provide additional ports and connectivity. Via an internal connection, the controller communicates with the EtherNet/IP module. This module is connected for example to the drive(s), and a computer. The connection to the computer allows loading automation programs to the controller. The drive uses the posi-

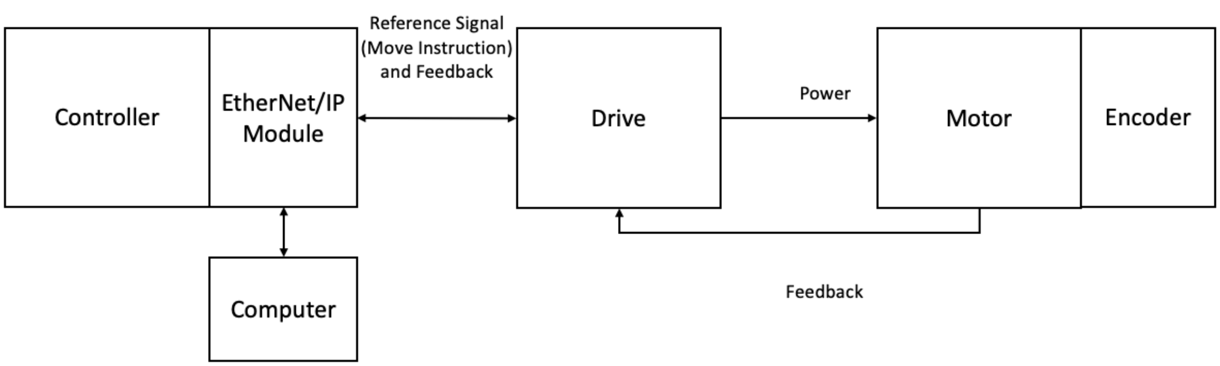


Figure 3.1.: Controller, Drive, Motor Setup

tion or velocity reference from the controller, sent via the EtherNet/IP module to regulate the motor torque and speed. This process with respect to the power side of the drive is described in Section 3.2. With respect to the control aspect of the drive, it receives feedback signals from the encoder attached to the motor via a

feedback cable. The control algorithm in the drive creates a power signal reacting to the actual motion of the motor compared to the command signal aiming to reduce the difference between the command values and feedback values. The control algorithm used in the drive is described in Section 3.3.

3.1. Controller

Controllers for industrial applications are specialized computers that allow for automation and control of manufacturing processes.[13] Controllers were first introduced in 1968 for General Motors. The need for controllers arose with the need to be able to quickly update electrical panels when production lines are changed or updated. With the classical electrical panels used, line changes required complicated and time consuming rewiring of the electrical panels.[28] With industrial controllers, it was possible to replace electrical panels as logical elements. The computer based controllers can perform and control tasks based on a changeable computer program rather than hardware based electrical wiring.[1] With the introduction of computer based controllers, line, process, or machine changes were easily possible, often requiring only program changes without physical rewiring. With the continuous development of technology, controllers today can control complex, highly automated machines and processes. Modern controllers in connected companies can be integrated into enterprise level systems to allow data sharing between the machine level and the enterprise level.

Controllers can be divided into two main categories: *Programmable Logic Controller* (PLC)'s and *Programmable Automation Controller* (PAC)'s. Both types, PAC and PLC controllers share certain characteristics such as the use of a high level programming language that is easily understandable by users. In [4], Danielle Collins states that there is no exact differentiation between PAC's and PLC's, but PAC's are normally designed with an open architecture and modular design allowing for simpler additions and layout changes. PAC's are normally providing more processing power and allow the control of more I/O modules than possible with PLC controllers.[4] Both, PAC and PLC systems consists of the controller for motion and machine control, analog I/O modules, digital I/O modules, communication modules and power supply. The I/O modules can be used to connect for example simple operation buttons that machine operators can press to start or stop the machine, or light signals indicating the status of the machine. *Human-Machine Interface* (HMI)'s are I/O modules that allow the operator to monitor the process more accurately by dis-

playing process parameters on a programmable computer monitor. Examples of very complex I/O devices are vision systems for quality control or vision-guided motion control.[7] PACs are also able to communicate with other PACs, which allows the creation of a distributed control system for large production lines or machines.[4]

The program loaded to the controller defines and controls the tasks that the machine needs to perform, including the and motion control tasks. PAC programs are written in languages defined by the *International-Electrotechnical-Commission* (IEC) in standard 61131-3. The languages defined in the IEC standard for controller languages include Ladder diagrams, functional block diagrams, sequential function charts, instruction lists, and structured text.[4] The program is normally written in software using one of the IEC defined languages. A common language used in PAC and PLC programming is the Ladder logic. This language is very visual, which makes it easy to read and program.[23] Examples of ladder programs are shown in Appendix A and Appendix B, displaying sample programs that were used to perform the tests of the two load sharing techniques in this Thesis. The sample ladder programs are further described in Chapter 5.

After the controller program is developed in the programming software of the controller and it is error free, the program is downloaded to the CPU of the controller. When the controller is set to run the program, the controller executes the program by following the defined instructions in the program. Instructions can, for example, command motion, perform calculations, or perform status checks. When the controller is executing a defined instruction, the controller performs four tasks:

- Input Scan: scans the state of input devices
- Program Execution: performs program tasks
- Output: sends commands to output devices
- Communication: shares data with other devices and diagnostics

Because in this Thesis motion instructions are of special interest, the following paragraph focuses on motion instructions. The four-step sequence is continuously repeated in a defined interval, also called the update time. The interval is defined in the ladder program and can be as little as 1ms or less. In the input scan phase,

the state of the motor defined in the motion instruction is sensed. This can include sensing the current rotor position, current speed, or if the motor is enabled or disabled. During the execution and output phase, the controller sends command signals to the drive based on the defined motion profile. In the communication phase, the received information from the input phase is shared with other I/O modules instances of the setup when used. For example, parallel or subsequent processes can be started when certain values of the performed motion profile are reached. This could be a motor opening a gate causing a pump to turn on when the gate is opened to a certain point.

3.2. Drives

Drives are of special interest for this Thesis due to the essential control mechanisms that are performed in the drive. As shown in Figure 3.1, the controller sends the command signals from the motion instruction defined in the ladder program to the drive via EtherNet/IP standard. The drive converts the digital motion instruction signals (reference signals) into a power signal of variable frequencies and voltage, which are applied to the motor. Varying the amplitude and frequency of the voltage applied to the motor allows the drive to control the velocity and torque of induction- and servo-motors. The ability to apply variable voltage and frequencies to motors makes modern automation and production tasks possible. Connected to a fixed frequency power source, motors would be fixed to a certain speed when power is applied, therefore controlling varying speed and torque would not be possible.[8][9] The use of industrial drives is also useful to reduce the overall power consumption of a system. Two main categories of drives can be differentiated:

- *Alternating Current* (AC) Drives
- *Direct Current* (DC) Drives

The drives used in the experiments in this Thesis are servo drives. Servo drives are types of AC drives. The different types of drives generally work in a similar manner as follows. In Figure 3.2, the general schematic of an AC drive is shown. AC is the predominant power supply mode in electrical grids worldwide and is therefore easily available for industrial plants.[3][27] AC drives do not require prior conversion from AC to DC, which makes AC drives common drives for industrial applications. In the United States, the common industrial power supply is the three-phase, 460 *Volts* (V) AC power with a frequency of 60 *Hertz* (Hz). As shown in Figure 3.2, drives consist of two main parts[3][25]:

- Power structure
- Control board

The control board contains a CPU, performing the control functions of the drive. The CPU reads the current signals from the motor, the position signal from the encoder, and the command signals from the controller, as previously shown in Figure 3.1. The control board includes the control loops that aim to reduce the following

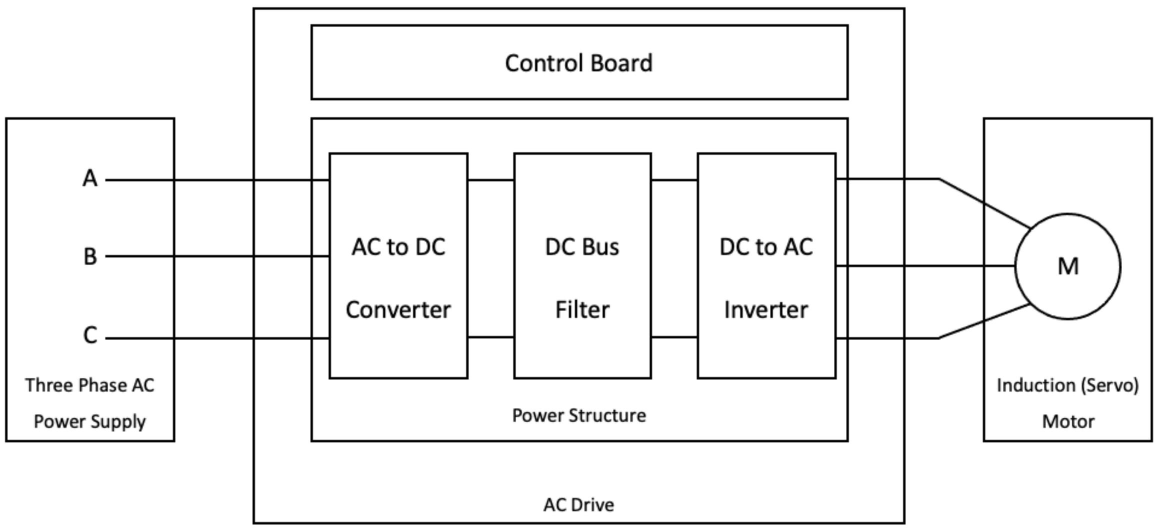


Figure 3.2.: Structure Industrial Drive[a]

[a] Based on graphic Aderiano da Silva

errors during motion execution. The control board and the control loops are further described in Section 3.3. The power structure of a drive as shown in Figure 3.2 is connected to the three-phase AC power supply and applies power to the connected motor at variable voltage and frequency. The motor can be an induction-, or, as in the case of this Thesis, a servo-motor. This Section focuses on the power structure of drives. As shown in Figure 3.2, the power structure of AC drives can be separated into three main components:[3][25][27]

- Three-phase full rectifier or AC to DC converter
- DC bus filter
- Inverter

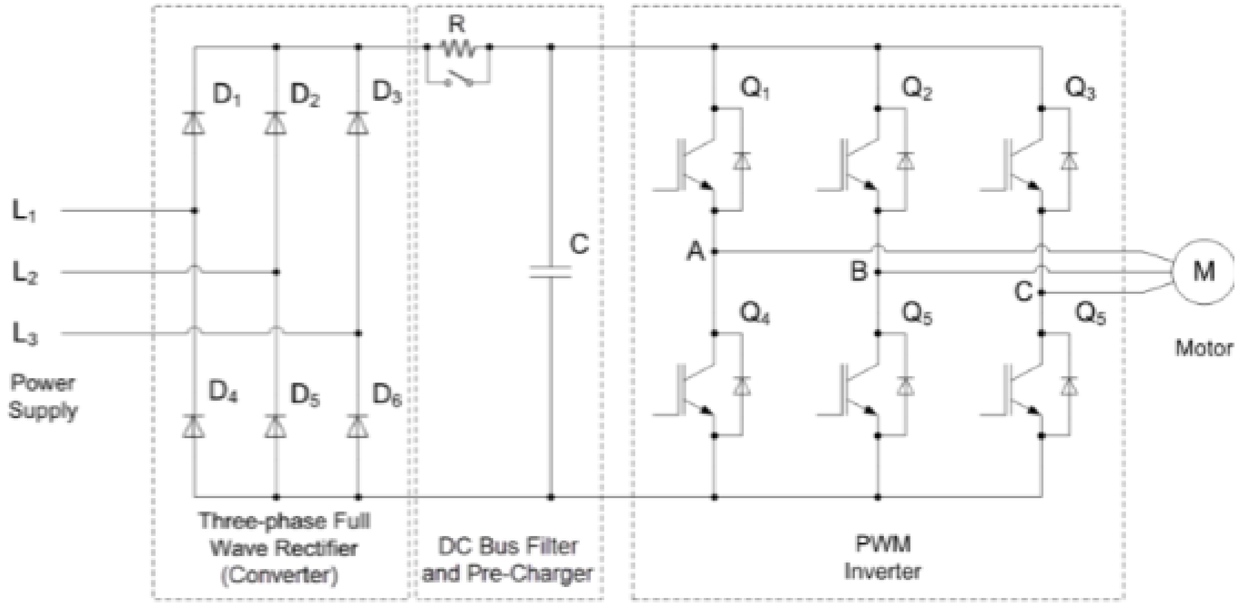


Figure 3.3.: Industrial Drive Power Circuit[a]

[a] Aderiano da Silva

Figure 3.3 shows a schematic rendering of the internal electrical circuit of an AC industrial drive. The three phases of the power supply in Figure 3.3 are numbered L_1, L_2, L_3 and correspond to the phases A, B, and C in Figure 3.2. The power from the power supply is converted from AC to DC in the converter. (a) in Figure 3.4 shows the sinusoidal curves of the common 460V, 60Hz three-phase AC power supply over a time of 0.03 sec. The stated common input power of 460V AC is the so-called *Root-Mean-Square* (RMS) voltage V_{rms}. The peak voltage V_{peak} of an AC power supply is calculated as follows:

$$V_{peak} = V_{rms} * \sqrt{2} \tag{3.1}$$

Thus, the peak voltage in the example is:

$$650.5V_{peak} = 460V_{rms} * \sqrt{2} \tag{3.2}$$

The peak voltage is shown in Figure 3.4 (a).

The converter is commonly a three-phase full-wave rectifier, consisting of six diodes, shown in

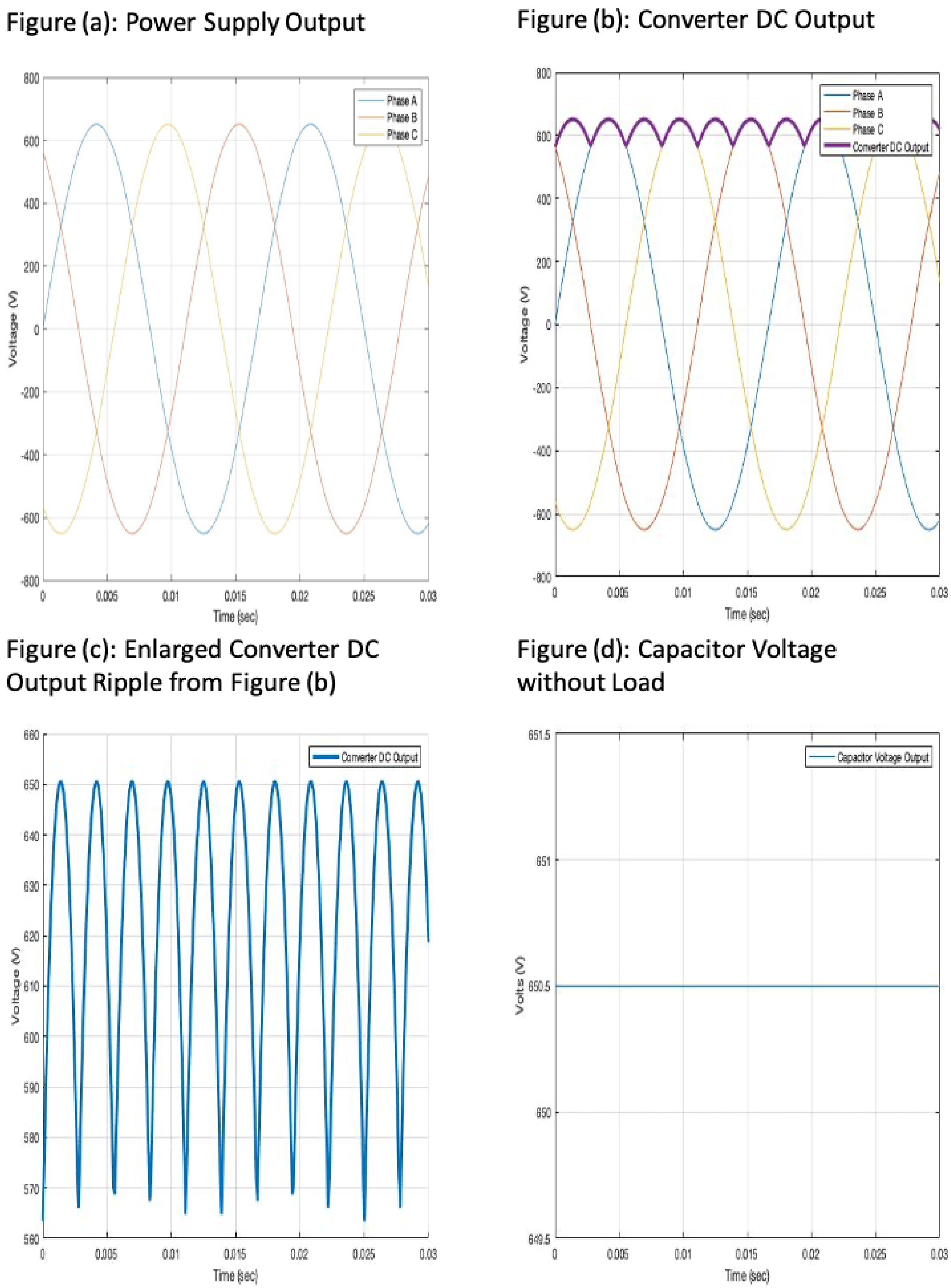


Figure 3.4.: Industrial Drives Current Curves

Figure 3.3 as D_1 to D_6. The diodes allow the flow of current only in one direction of voltage polarity. The six diodes can be opened, allowing current to flow, or closed, preventing the flow of current. The diodes are opened and closed in such a way that the positive and negative peaks are combined to form an almost constant DC voltage. In (b) of Figure 3.4, the output voltage from the converter with the combined peaks of the three phases is shown. As shown in 3.4 (b) and further highlighted in Figure 3.4 (c), the voltage output from the converter is not a constant DC line voltage. The voltage is "rippled" and is maintained between V_{peak} and a lower voltage that can be calculated with the ripple factor of the system. The ripple factor for the example used is approximately 0.87 or 87%.[27][25] Due to the focus of this Thesis, the ripple factor is not further described.

The second component of a drive power structure is the DC bus filter and pre charger, as shown in Figures 3.2 and 3.3. The bus filter consists of a capacitor, C, and a shunt resistor, R. The capacitor is charged to the sinusoidal peak voltage of the line-to-line input voltage V_{LL} from the converter and is noted as V_{dc} in Equation 3.3. One function of the capacitor is to reduce the voltage ripple from the converter. The smoothed output voltage from the DC bus filter is shown in Figure 3.4 (d). The V_{dc} voltage is calculated as follows:

$$V_{dc} = V_{LL} * \sqrt{2} \tag{3.3}$$

The V_{dc} is approximately equal to V_{peak}. Besides smoothing the voltage line, the main function of the capacitor is to stores regenerative energy produced by the motor during deceleration. When regenerative energy is produced during deceleration, a high voltage is stored in the capacitor. The shunt resistor, R, shown in Figure 3.3, is mainly responsible to protect the capacitor from over-voltage, which can cause damage to the system. When the capacitor voltage rises due to regenerative energy to a pre-defined value in the drive firmware, which is monitored by the control board, the shunt-resistor is turned on, providing a parallel by-pass to discharge the capacitor and to protect the drive. Thus, the resistor is able to dissipate the regenerative energy and reduce the voltage in the capacitor. When the voltage of the capacitor reaches an acceptable level, the shunt resistor is turned off. Shunt resistors can be placed within the drive or placed externally for machines and applications with high regenerative energy production such as high inertia systems or cranes during deceleration.[25][27][3]

The third component of the power structure of a drive is the inverter, utilizing *Pulse-Width-Modulation* (PWM) technique. The inverter converts the DC voltage to a variable AC voltage that can be applied to the motor. Switches, called *Insulated-Gate-Bipolar-Transistors* (IGBTs), are turned on and off by the control board of the drive, creating a variable AC voltage and frequency output. In Figure 3.3, the IGBTs are labeled as Q_1 to Q_6. In Figure 3.5, a PWM signal from the inverter is shown. The PWM

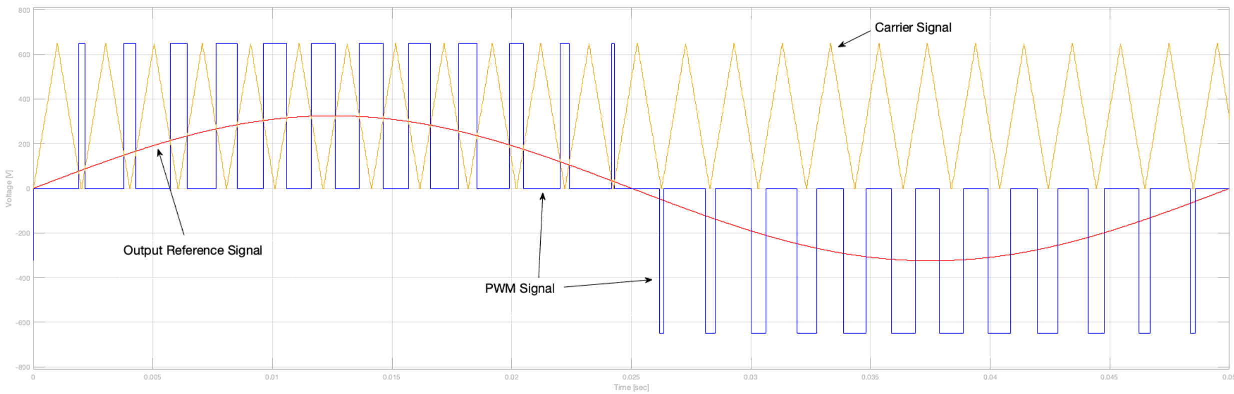


Figure 3.5.: Industrial Drives Inverter Output

output is not an actual sinusoidal waveform. The inverter applies pulses of voltage with constant magnitude to the motor. The magnitude of these pulses is given determined by the V_{dc} of the system.[27] The "Output Reference Signal" in Figure 3.5 is the fundamental component of the PWM signal at the output of the inverter. The control board commands the positive half or negative half IGBTs to open or close. The longer the IGBTs stay on, the higher the created output voltage. By increasing the closed time of the IGBTs, the output voltage can be decreased. The frequency at which the IGBTs are opened and closed is the so-called carrier or switching frequency, and it is fixed. Common carrier frequency for industrial drives ranges between 2 kHz and 12 kHz. Higher carrier frequencies produce smoother output waveforms, but with the disadvantage of increasing power losses in the IGBTs, which decreases the efficiency of the drive. The carrier frequency should be set (for drives that allow adjusting the carrier frequency) to the application needs while keeping in mind that higher carrier frequency results in lower drive efficiency and also requires derating the drive.[27][3]

3.3. Control System

The second important part of the drive, as shown in Figure 3.2, is the control board where the control system resides. The power structure of the drive generates and applies the required variable voltage and frequency to the motor that is calculated and regulated by the control system in order to follow the command signals as close as possible. The control system regulates velocity when the drive is configured to velocity mode, or position and velocity when the drive is configured to position mode.[22, Page 109] Because both load sharing methods compared in this Thesis heavily depend on the accuracy of this control system, further background information about control systems are provided in this Section. There are two major types of control systems:[11]

- Open-Loop Control
- Closed Loop Control

Open-loop controls work without the feedback signals from the system. In contrast, closed-loop control systems receive feedback signals from the controlled system, the so-called output. Based on the output received from the controlled system, the closed-loop control performs controlling actions to follow the input (reference) signals as close as possible. The output of the controlled system is continuously compared to the input, and the controlling actions are adapted accordingly. In the case of this Thesis, the input are the desired velocity and position of the motor. The output are the position and velocity of the motor (when performing in position mode), and the controlling actions are performed by the drive by adapting the applied voltage and frequency to the motor to reach the desired velocity and position. Since servo drives use closed-loop control systems to regulate position and velocity, this Section focuses on closed-loop controls. The typical closed-loop control strategy in industrial drives is the PID control. The PID algorithm is a simple but robust system that can be used for many control applications, achieving good results which leads to their wide acceptance in industrial control.[11] Another closed-loop control strategy is the *Proportional-Integral* (PI) control. Since the two load sharing methods compared in this Thesis use the PI control, this Section focuses only on the PI control system. William Palm summarizes the goals of a PI control system in three points:[12, Page 614]

- Minimize the steady-state error
- Minimize the settling time

- Achieve other transient specifications, such as minimizing the overshoot

In the case of this Thesis, the steady-state error is the difference between the reference signal provided by the controller, for example the velocity, and the feedback value from the motor.[26] in this example, the settling time is the time required by the drive to control the motor velocity within a range around the commanded velocity.[6] These PI gains have to be tuned to reduce the steady state errors in the system (differences between command and feedback values), and to improve robustness to load disturbance. The tuning of a drive will be further described in Chapter 5 as part of the Method 1 set up.

Industrial drives normally utilize the PI control system. The PI control loops allow the drive to control and regulate the position, velocity, and current of a motor. Based on the application, the drive is configured to work in either the position, velocity, or current control mode. Figure 3.6 shows a simplified control loop architecture of a drive. The reference signal R(s) is calculated in the controller and sent to the drive (see also Figure 3.1). The reference signal is either a position, velocity, or current signal, depending on the drive mode. The feedback signal E(s) for the current control loop is the motor current measured

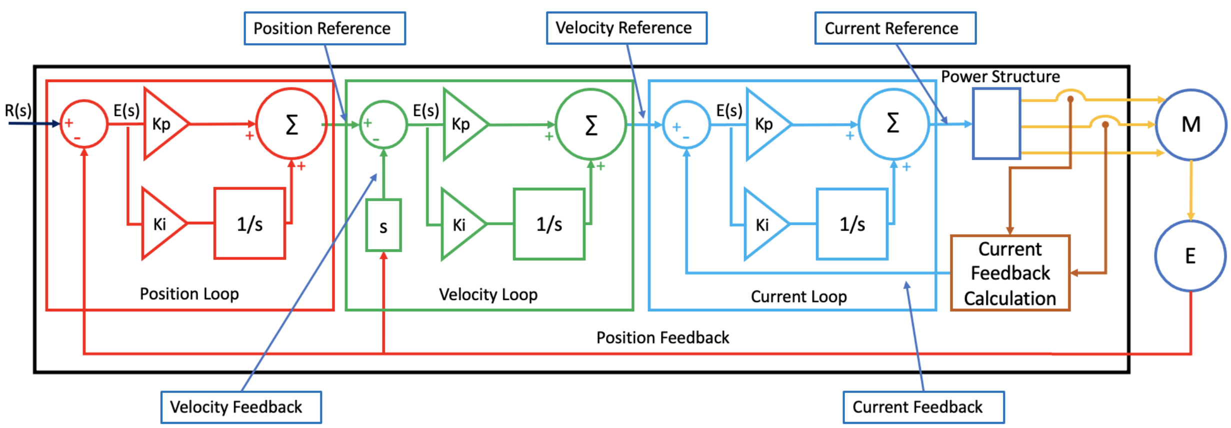


Figure 3.6.: Industrial Drives Control Loops

by current sensors placed on two phases of the three-phase power. The encoder connected to the motor measures the motor position that is used as the feedback for the position loop. For the velocity loop, the velocity of the motor is being derived from the position feedback.

4. Research Goal and Objective

The overall research goal of this Thesis is to experimentally compare two load sharing techniques. Since these methods were developed independently, no experimental comparison has been developed up to the time of this Thesis. Experimentally comparing the two load sharing techniques helps to identify the limitation of each method and to apply the proper load sharing techniques for each application. Since those methods haven't been published, these methods were not identified in the literature review, the two load sharing techniques were experimentally compared considering the following three points:

1. Ability of the motors to follow the command signals
2. Ability to control synchronized motions between axes
3. Ability for even load-sharing between motors

The ability of the two load sharing techniques to follow the position command is important to meet the application requirements and produce good quality products.

The ability to control synchronized motions between axes is more challenging with mechanically compliant multi motor systems since the elasticity in the coupling mechanism of the test setup can cause unsynchronized motions. The impact of the compliance of mechanical couplings on the test results will be described in the following Chapters. Obtaining experimental data and comparing the two load sharing methods in their ability to control synchronized moves with flexible coupling allowed to make conclusions about the ability to apply these methods in applications with flexible couplings.

The ability of the methods to share the load evenly is the main focus of this Thesis as these methods were designed to evenly share loads between multiple motors. Method 1 is a classical leader-follower technique where two motors are connected to two drives, while Method 2 consists of two servo motors connected to a single drive. Although it is stated in [17] that systems, where multiple motors are connected to a single drive, cannot employ load sharing because the developed torque of each motor cannot be controlled, Method 2 has addressed this challenge of torque control by magnetically aligning both motors

and properly configuring the drive. The magnetic alignment process and both methods will be further described in Chapter 5.

5. Methodology

An overview of the test methodology to compare different methods for load sharing in drive/motor systems for industrial machines is given in this Chapter. In Section 5.1, the equipment and test set-up used for performing the tests of the two load sharing methods are described. The load sharing techniques compared in this thesis are defined in Section 5.2. The performed tests, measured data, and applied data analysis techniques are provided in Sections 5.3 and 5.4.

The sequence of steps to experimentally compare the two load sharing methods is as follows:

1. Assemble the hardware setup for Method 1, see Sections 5.1 and 5.2
2. Tune drives for each test move, see 5.2
3. Perform tests for each test move with and without disturbance, see 5.3
4. Capture and save data, see 5.4
5. Assemble the hardware setup for Method 2, see Sections 5.1 and 5.2
6. Perform the software setup for Method 2 and change motor specifications, see 5.2
7. Perform tests for each test move with and without disturbance, 5.3
8. Capture and save data, see 5.4

The performed steps in this thesis are additionally visualized in Figure 5.1. The different steps of the Methodology shown in Figure 5.1 will be further defined in this Chapter.

5.1. Test Set-Up

The specifics of the test setup are provided in this Section. The hardware setup that was used to compare the performance of the two load sharing techniques is shown in Figure 5.2. The tests were performed at the *Connected Systems Institute* (CSI) at the University of Wisconsin-Milwaukee.

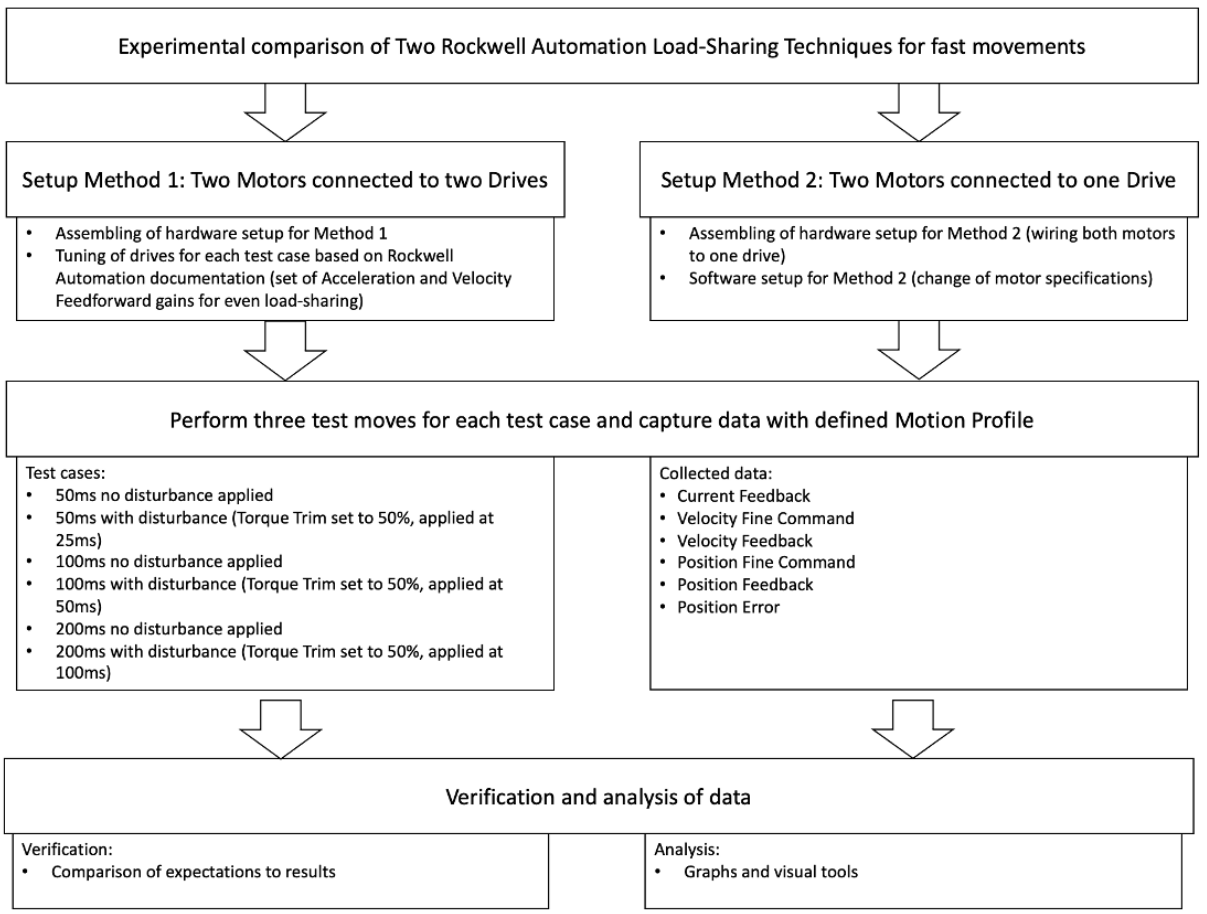


Figure 5.1.: Methodology Overview

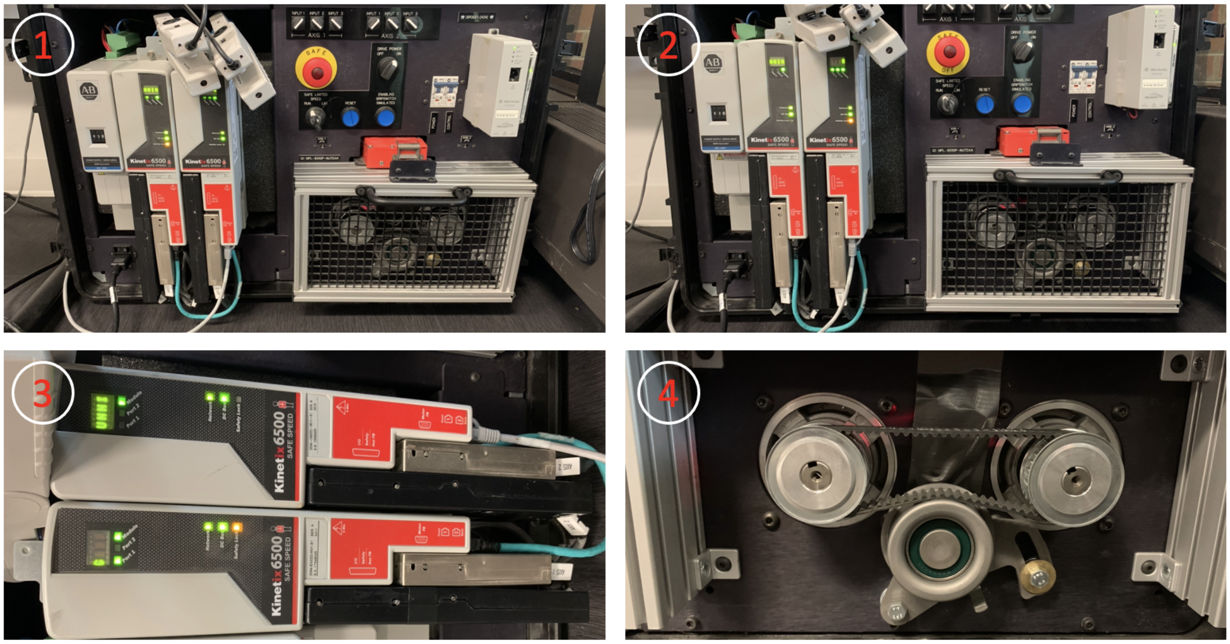


Figure 5.2.: Test Setup Overview

The main part of the hardware setup is the so-called demo box provided by Rockwell Automation. The demo box was built by Rockwell Automation to allow the simulation of a wide range of applications and contains equipment that was not used for the tests in this thesis. To simplify the description of the demo box and the hardware, only parts that are used for this thesis are being described. Regarding the drives, the Kinetix 6500 drives used in this hardware setup are rated at 460Vac, 3-phase, but are powered out of a 120Vac, single-phase power supply, which limits the drive output power, and the experiments described in this thesis take this limitation into account. Although the equipment does not allow testing the methods with maximum (acceleration/deceleration/speed) values, it is sufficient to perform the tests necessary for the experimental comparison of the two load sharing techniques. An overview of the demo box is shown in pictures 1 and 2 of Figure 5.2. The demo box contains two drives that can be seen more closely in picture 3 in Figure 5.2, the dc-bus converter (power supply) to the drives (left of the two drives) shown in pictures 1 and 2 in Figure 5.2, and two motors shown on picture 4 in Figure 5.2. For safety reasons, the motors are behind a door connected to a safety interlock to prevent contact with the motors while moving. As described in Chapter 1, the goal of this thesis is to compare two load sharing techniques for fast motion that requires two or more mechanically coupled motors. The mechanically coupled system in this thesis consists of a mechanism with low, but existing compliance (flexibility). In order to mechanically connect the two motors

in the demo box, a belt and pulleys were used. The belt/pulley setup can be seen more closely in picture 4 in Figure 5.2. A timing belt was used to prevent loose mechanical slip between the motors. Additionally, a variable belt tensioner was used to adjust the belt tension. For consistency, the belt tensioner remained in the same position to apply the same tension to the belt during all tests.

The test setup is connected and controlled as shown in Figure 3.1, with the difference that the demo box is equipped with two drives and two motors. In the case of the demo box, the controller sends the reference signals to both drives via the Ethernet module located in the demo box. The controller is placed in a separate demo box, provided by the CSI. As mentioned in Section **??**, the communication between the controller and the drives is based on the Ethernet/IP standard. More specifically, the list of equipment used in the tests described in this thesis is as follows.

- Controller: Rockwell Automation ControlLogix 5575
- Drives: Two Rockwell Automation Kinetix 6500 EtherNet/IP Servo Drives
- Motors: Two Rockwell Automation MPL-B310P-M Servo Motors
- Encoders: Rockwell Automation multi-turn Encoder providing absolute Position Feedback with 1024 Feedback Cycles per Revolution and interpolated in the drive 2048 times, yielding a resolution of 2097152 counts per motor revolution

The two Rockwell Automation servo motors have each a rated power of $0.77kW$, a rated speed of $5000RPM$, a rated current of $1.7rms$, rated torque of $1.58Nm$, and rotor inertia of $0.000044kgm$.

5.2. Methods Definition and Tuning

The two load sharing methods compared in this thesis are described in this Section. As mentioned throughout the previous chapters and stated in Chapter 1.1, the objective of this thesis does not include the analysis and improvement of these two techniques of load sharing, but the comparison of the two methods in terms of energy and positioning performance. Although the magnetical alignment of both motors is a step only required for Method 2, the magnetical alignment of both motors for both load sharing methods was performed to obtain oscilloscope measurements that provide a better comparison between the methods. The goal of the magnetic alignment is to minimize the phase shift between the current signals of the two

motors. Phase shifts cause the time difference between the phase currents, which would result in uneven torque development between the two motors. A phase shift between the current signals also results in higher peak-to-peak differences (magnitude) between the phase currents. By magnetically aligning the motors, they draw power synchronously from the same phase of a three-phase power supply. It was agreed to perform the magnetic alignment of both motors for both load sharing methods to reduce the impact of nonaligned motors on the degree of load sharing and compare the two load sharing techniques just based on their ability to control even load sharing between two motors. Figure 5.3 provides the block diagram of the magnetic alignment process of both motors in the test setup.

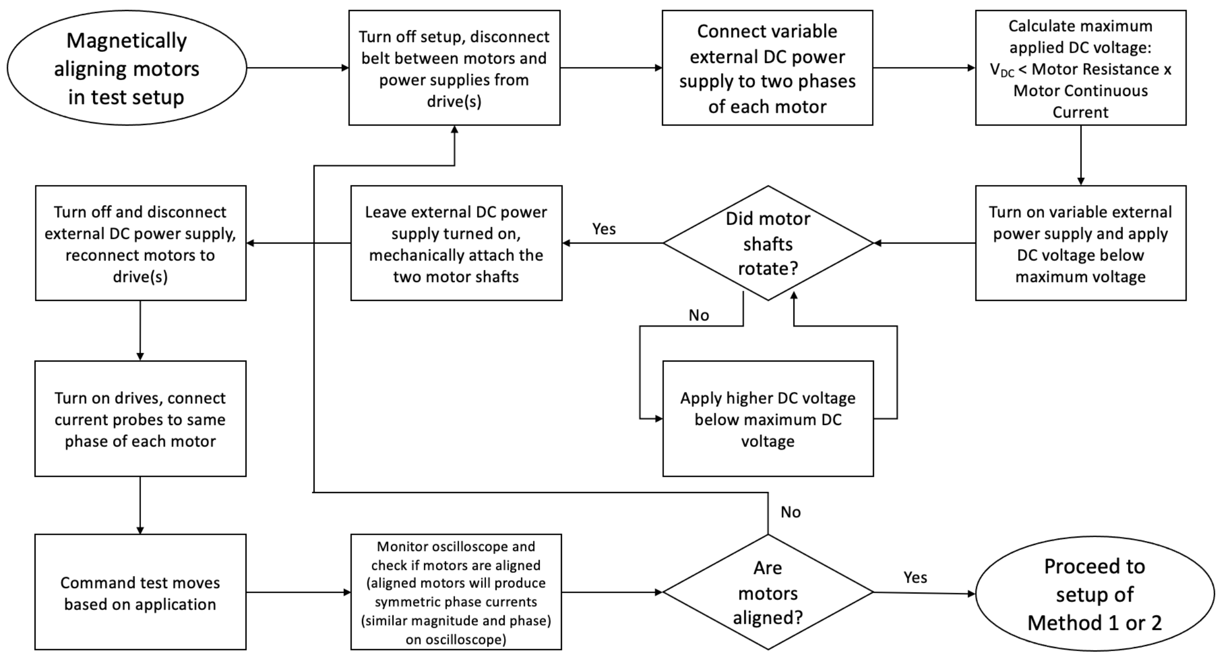


Figure 5.3.: Magnetic Alignment Process Overview

To magnetically align the motors, the power supply to the motors is turned off and the rotors must be able to rotate independently. To allow independent movement of each motor, the belt connecting the two motors has to be disassembled. Next, an external adjustable DC power supply is connected simultaneously to the same two phases of each motor. When connected, the external DC power supply is turned on. The maximum applied voltage to the motors is calculated as follows:

$$Max.VoltageApplied = WindingResistance(MotorResistance) * MotorRatedContinuousCurrent \quad (5.1)$$

The Winding Resistance in *Ohms* and the Motor Rated Continuous Current in *Amps* are obtained from the motor datasheet. When the external DC power supply is turned on, the rotors of the motors move, and the motors are magnetically aligned. In case the rotors of the motors did not move, the applied DC power voltage has to be increased till a movement of the rotors can be identified. It is important not to increase the applied DC voltage above the calculated maximum voltage as this can damage the motors. When a visible movement of the motor shafts was seen, the two motors were mechanically reconnected. To achieve a high degree of alignment, the external DC power supply should stay connected and powered while reconnecting the two motors by remounting the belt and applying the belt tensioner. Without the external power supply turned on while reassembling and applying the belt tensioner, it is likely that the rotors move unsynchronously. Unsynchronized movements during reassembly cause misalignment. When the belt is reconnected to the two motor shafts and the belt tensioner is set, the external power supply is removed. To check the alignment of the two motors, two current probes connected to an oscilloscope are connected to the same phase of each motor. Next, the drives were powered up, test moves commanded, and the current signals of the two motors monitored on the oscilloscope. In Figure 5.4, theoretical current readings with current probes from the same phases of two motors are shown. Observing different phases of the motors results in the wrong interpretation of the data and misaligned axes. The first example in Figure 5.4 shows slightly misaligned motors with a phase shift and a magnitude difference of 0.5 Amps.

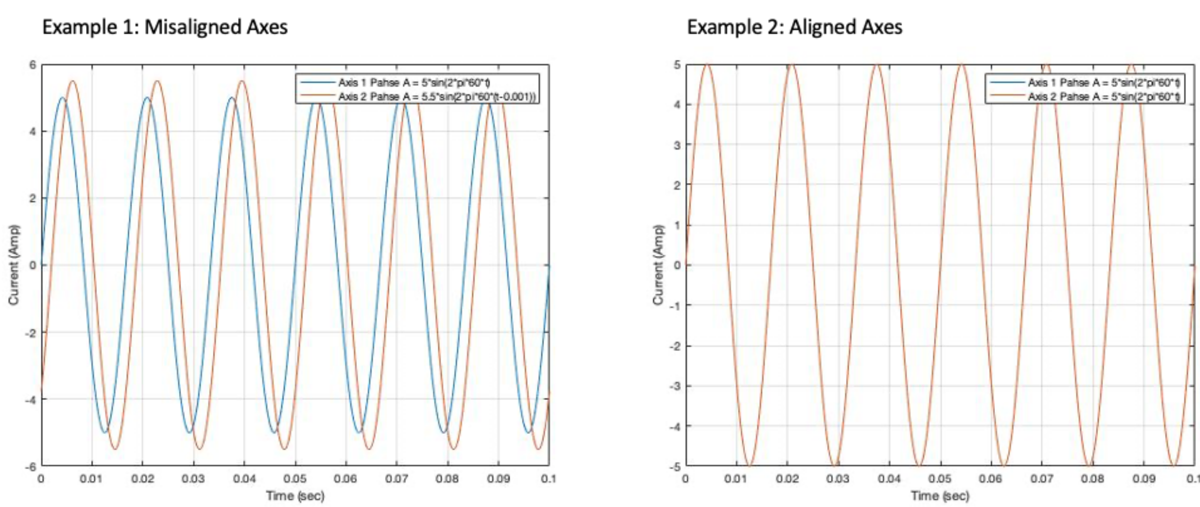


Figure 5.4.: Example of Phase Curves Magnetically Misaligned/Aligned Axes

Example 2 in Figure 5.4 shows aligned motors where the motors are synchronously drawing phase

currents. Once the motors show a high degree of alignment the experiment proceeds with the setup of the two load sharing methods. When the motors are not sufficiently aligned, the process shown in Figure 5.3 must be repeated. Since the test setup does not allow fine tuning of the alignment and the degree of alignment is very vulnerable during the mechanical reconnecting process of the two motors, a slight misalignment during the tests in this thesis was not preventable. Next, the setup process of the two load sharing techniques is described.

5.2.1. Load Sharing Method 1: Two Motors Controlled by Two Drives

As stated in Section 2.2, the first method is a leader-follower method. Not only are the motors connected to two drives and mechanically coupled by a belt as described in Section 5.1, but the drives also are electronically coupled in the motion program. In Figure 5.5, the setup of Method 1 is shown. The setup process of Method 1 is visualized in Figure 5.6. The electronic coupling is necessary to enable the controller to control two drives and motors. The electronic coupling of the axes is achieved by using the *Motion-Axis-Gear* (MAG) instruction in the Ladder program for the ControlLogix controller.

The Ladder program for the tests and the tuning of the drives for Method 1 can be found in Appendix A. Detailed descriptions of Rockwell's motions instructions can be found in [18].[18] The MAG motion instruction electronically couples, synchronizes, and gears two axes in "a specified direction and at a specified ratio".[18, Page 122] Since the two motors are mechanically coupled with a belt what results in a mechanical gear ratio of 1, the gearing ratio in the MAG is kept at 1 (gearing ratio 1:1) for all tests performed. Besides gearing the axes, the MAG instruction also allows determining different motion directions of the axes. Defining different motion directions of the axes is necessary when the motors are not mounted in line, but facing each other. Because the motors are mounted in the test setup next to each other facing in the same direction, the MAG instruction is set to command the motion of the same direction for both motors. The tests aim to investigate very fast, index moves. The position reference signal for the leader axis is derived from the desired motion profile, while the position reference signal for the follower axis is generated by the MAG instruction. The desired motion profile for an industrial application is defined as a function of the task that each motor needs to perform in a machine. In this thesis, the motion profile was defined as an index move. More details about the motion profile are provided next. The clutch function of the MAG instruction allows to "smoothly engage"[18, Page 129] the follower axis to the leader axis by defining an acceleration value. When the clutch function is enabled, the follower is only engaged by the

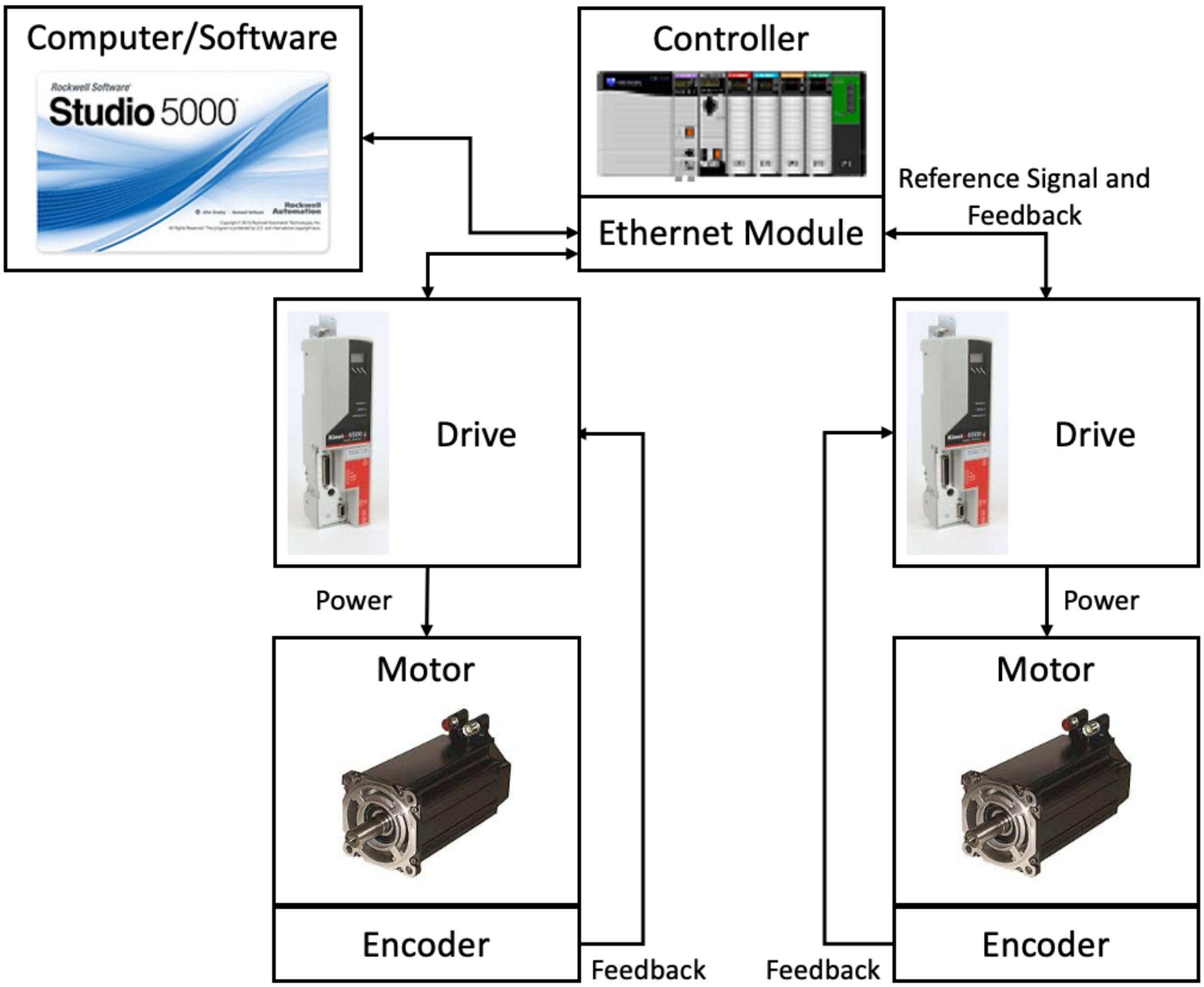


Figure 5.5.: Hardware Setup Method 1

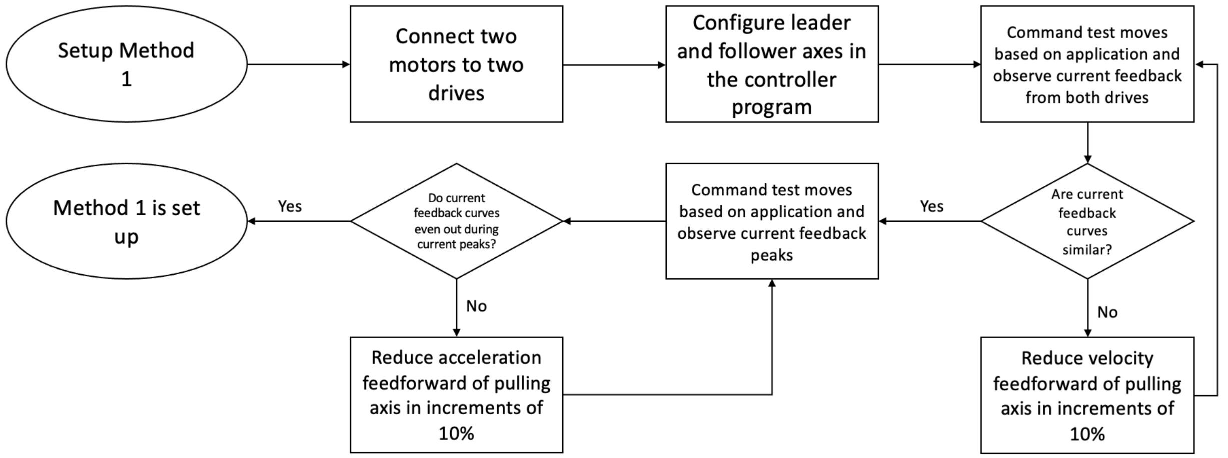


Figure 5.6.: Setup Process Method 1

motion instruction when it reaches the desired gearing speed. Although the tests are performed as index based start stop moves and the follower axis is engaged as soon as possible, the clutch function is enabled in the MAG instruction to reduce disturbances caused by command signal delays between the axes. Further information to the clutch function of the MAG instruction can be found on pages 129 to 131 of [18].[18]

The second step in Method 1 is the tuning of the drives. In this step, the current feedback signal from the drives is used to tune the drives to achieve an even level of load sharing between the axes. Proper load sharing between the axes is achieved when an even amount of torque is developed by the motors to drive the shared load. The current feedback signals are used for the tuning process. The developed motor torque (T_{dev}) in Nm of a motor can be calculated as a function of the current feedback (I_{fdbk}) signal. The current feedback signal is computed in the drive from the three-phase current measured by current sensors and can be monitored in the controller. The current feedback can be used to estimate the developed motor torque as follows:

$$T_{dev}[Nm] = I_m[A]K_t[Nm/A] \tag{5.2}$$

$$I_m[A] = I_{rated}[A]\frac{I_{fdbk}[\%]}{100} \tag{5.3}$$

Where, K_t is the motor torque constant which is provided by the manufacturer in the motor datasheet, and I_m being the motor current in $Amps$. I_{rated} is the motor rated current obtained from the motor datasheet. Since

the developed torque of the motors can be calculated based on the current feedback monitored during the test moves, it is possible to make conclusions about the level of load sharing between the motors based on the current feedback signal. The goal of the tuning process is to tune the drives in a way, that the difference between the current feedback signals from each motor is as low as possible during motion. To reduce the differences in the current feedback signals of the axes during moves, two parameters are tuned:

- Velocity Feedforward
- Acceleration Feedforward

The overview of control loops within the used drives can be found in Appendix C on page 68, retrieved from [19].[19] The velocity feedforward gain is part of the position loop and is used to reduce the position error. Meanwhile, the acceleration feedforward gain helps to reduce the velocity following error, but it causes the motor to perform more aggressive position moves. Both gains, velocity feedforward, and acceleration feedforward are defined in percentages. Higher percentages as much as 100% are possible to be set for the velocity and acceleration feedforward gains, and can be required by some applications. By decreasing or increasing the velocity feedforward gains, the load sharing between the motors is tuned. For example, when one axis is pulling the other axis, the pulling axis shows higher current feedback values than the pulled axis. By decreasing the velocity feedforward gain of the pulling axis, the difference in developed torque between the two axes is reduced. When the current feedback curves of the two axes perform similarly, the acceleration feedforward is tuned for further improvement. The acceleration feedforward is the second derivative of the position command loop and therefore has a higher influence during acceleration and deceleration. Current spikes that cause uneven load sharing during acceleration and deceleration can be evened out by tuning this gain. When the current feedback signals behave similarly in an acceptable range for the application, method 1 is fully set up.

5.2.2. Load Sharing Method 2: Two Motors Controlled by One Drive

As mentioned in Section 2.2, Method 2 is not a classical load sharing technique as defined in the literature. In the second load sharing method, the two motors are not powered by two independent drives as in Method 1, instead, the motors are powered by a single drive. This setup is shown in Figure 5.7. As mentioned in Chapter 4, in [17] it is stated that "multiple motors that are run from a single drive is not load sharing because torque control of individual motors is not possible."[17, Page 2] Method 2 addresses this

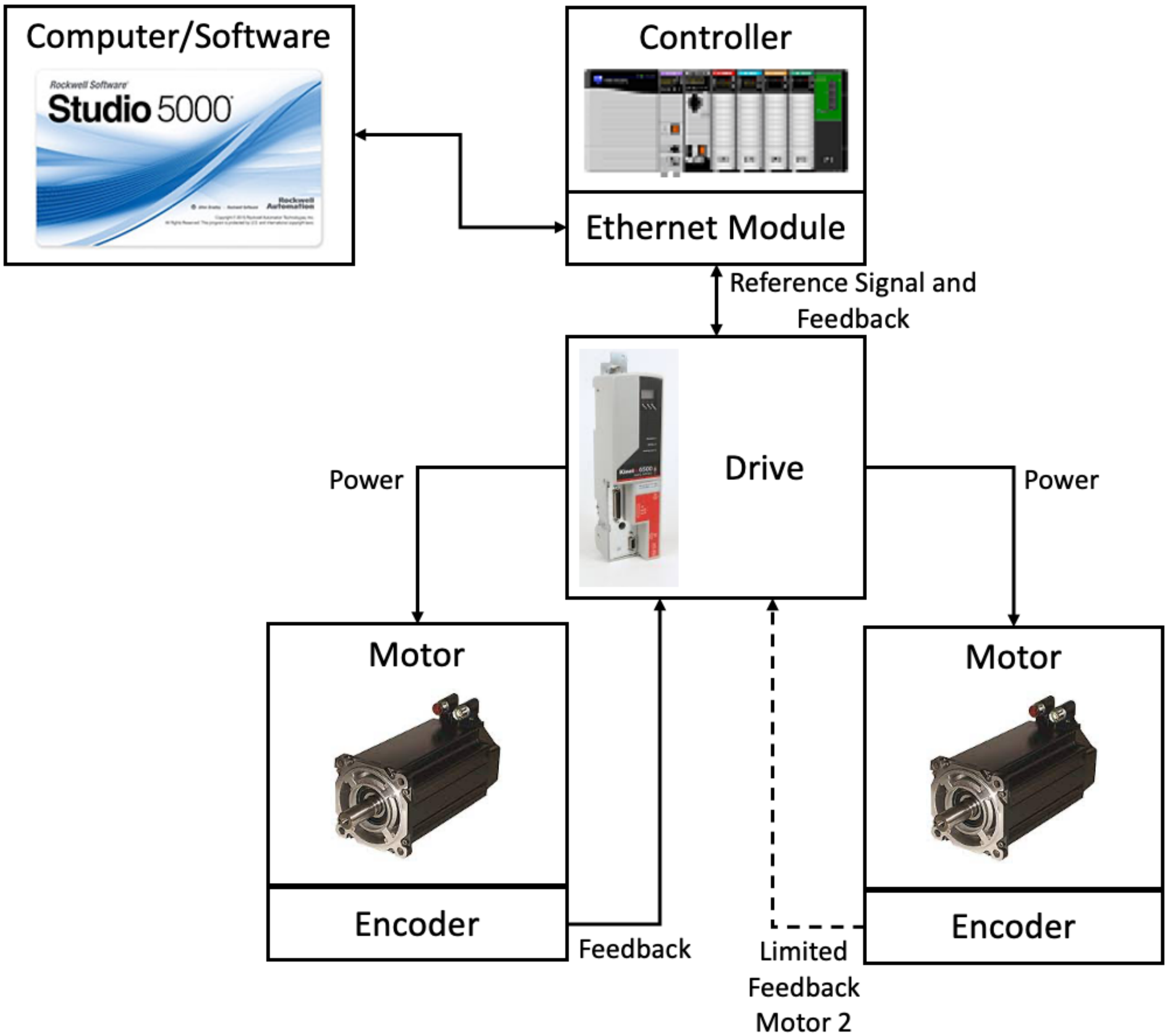


Figure 5.7.: Hardware Setup Method 2

challenge of torque control by magnetically aligning both motors. This also allows applying this technique primarily for very fast moves as this technique allows zero lag load sharing between the motors when the motors are rigidly connected. The setup process of Method 2 is visualized in Figure 5.8.

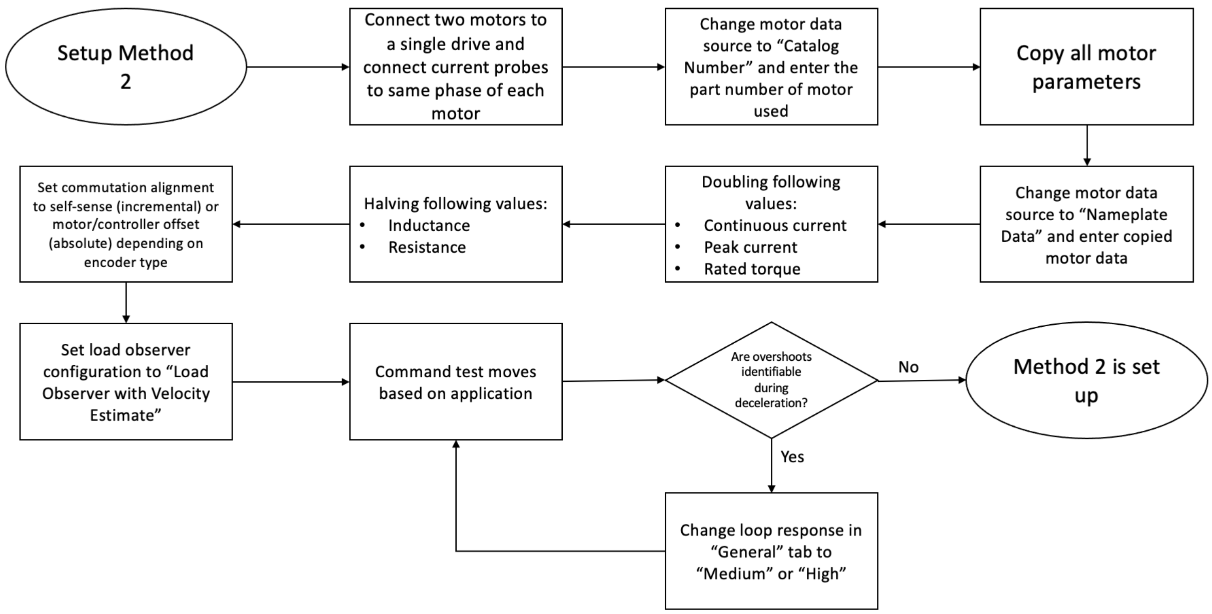


Figure 5.8.: Setup Process Method 2

Because the two motors are connected to a single drive in Method 2, it is not possible to monitor certain parameters for each motor individually. As the current feedback is monitored to determine the load sharing in Method 1, this is not possible for Method 2 as here only one current feedback is received for both axes. Method 2 requires an external oscilloscope and two current probes to monitor the actual current drawn by the motors to compare the ability of Method 1 and 2 to properly share torque. The current probes are connected to the same phase of the motors and enable the reading of currents on an oscilloscope. Next, the motors are connected and wired to one drive. Since one drive is powering two motors in Method 2, the configuration of the motor in the drive needs to be adjusted as follows so that the motor configuration is equivalent to two motors in parallel. In comparison to the one motor one drive setup with Method 1, the following configuration values are being doubled:

- Continuous Current

- Peak Current
- Rated Torque

Next, the following configuration values are being halved compared to the Method 1 motor setup:

- Inductance
- Resistance

The process setup guide of Method 2 defines the motor values and their proportional changes. It is not part of this thesis to further investigate the setup process, but to compare the load sharing methods as defined. The encoder type on the motors requires changing the commutation alignment either to self-sense or motor/controller offset. As the encoder connected to the two motors in the test setup are absolute encoders, the commutation alignment is set to controller offset. Next, the load observer setting is set to "Load Observer with Velocity Estimate" in the drive configuration. The load observer "simplifies the tuning process, provides robustness to the system and compensates for disturbances".[20] Next, test moves are commanded and the velocity feedback of the two motors are monitored. When overshoots (the motor reverses direction to move to commanded position) are identifiable in the velocity feedback, the overall loop response must be changed to medium or high. Setting the overall loop response to medium or high reduces overshoots as the control loops react faster and more aggressively on position or velocity errors. When overshoots are below a threshold of -0.1rev/s, Method 2 is fully set up.

5.3. Performance Measurement Procedure

Based on the definitions of the setup process in Section 5.2, in this Section the details of the performed measurements and collected data to evaluate the methods regarding their degree of load sharing and synchronization in a multi axis setup are presented.

As defined in Section 1.1, the interest of this thesis is to compare the two synchronization and load sharing methods for fast index motion profiles. Index motion profiles are defined by three parameters:

- Time
- Distance

- Motion Profile Type

The time parameter refers the time needed to accomplish the move distance according to a given motion profile type. The move distance can be, for example, a defined number of turns or degrees the motor is intended to travel. Normally, the application defines the desired move time and distance. Because this thesis does not test the methods for a defined application, the following assumptions and definitions are made:

1. "Fast" movements are movements with move times in the low millisecond [*ms*] range with move distances requiring maximum motor current values
2. The move times are fixed
3. Travel distances are dependent on the set move time and adapted to require maximum motor velocities
4. The motion profile used is the Modified Sinusoidal Acceleration, also called Modsine profile

The term "fast" is defined as move times of 50ms, 100ms, and 200ms are typically applied in very fast and high performance machines. The tests with 50ms moves represent an extreme testing value to identify the maximum capabilities of the methods. The Modsine motion profile was chosen for the tests as it has lower maximum acceleration values than other motion profiles, for example, the Cycloidal profile, so that 50ms moves with reasonable move distance would be able to achieve before saturating the drive due to excessive current. The Modsine profile is also a commonly used motion profile for industrial applications. As a note, this chapter is written in past tense to describe the procedure that was followed.

Based on the defined move times, the move distances were experimentally found by gradually increasing the move distance while monitoring the output current signal. The output current is the current the drive applies to the motors to follow the position reference signal. When the tested travel distance for the set move time requires motor velocities above the maximum value, the output voltage saturates or plateaus out. A saturated output voltage means that the drive cannot apply the required voltage to the motor to meet the move requirements. When this point was found, the next lower move distance was taken that does not require a higher level of an applied voltage to the motor than the drive can provide. As stated in Section 5.1, the limited power supply (single-phase $120V_{ac}$) prevents fully utilizing the capabilities of the motors. Table 5.1 shows an overview of the motion profile parameters for each move time. Figure 5.9 shows as an

example the resulting motion profile of the 200ms test move with a move distance of 3.6 revolutions and the Modsine motion profile.

Table 5.1.: Performed Test Values

Move Time $[ms]$	**Move Distance** $[Rev]$	**Max. Velocity** $[Rev/s]$	**Max. Acceleration** $[Rev/s^2]$
50	0.7	24.63	1547.81
100	1.6	28.15	884.46
200	3.6	31.67	497.51

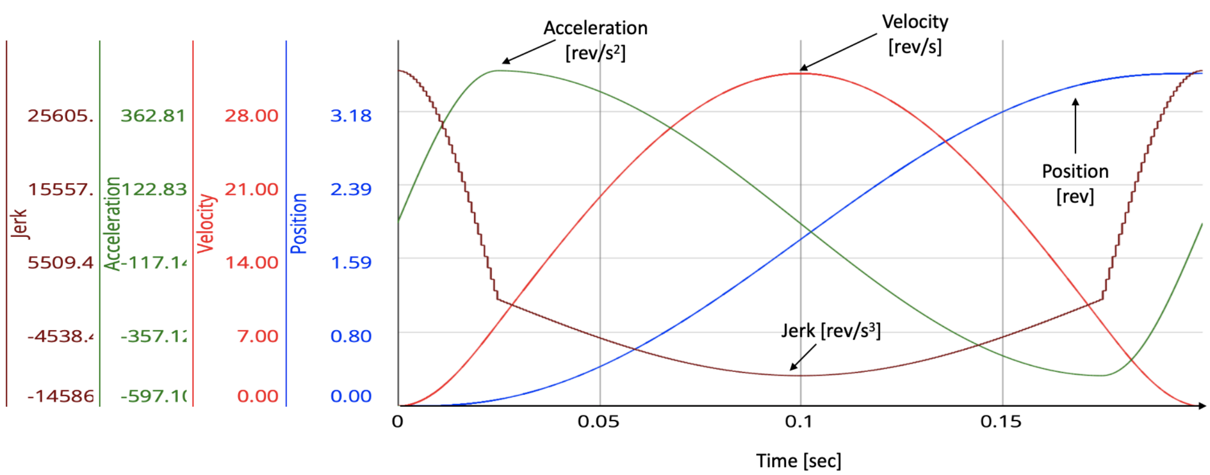


Figure 5.9.: Motion Profile 200ms Move

In addition to testing the behavior of the two load sharing techniques in the defined motion profiles, the behavior of the two methods under disturbances was also evaluated. Disturbances are common effects in industrial applications. Examples of such disturbances include vibrations in the system or applied external force. In case one method is not able to restore a steady movement after a disturbance, it is would not be advisable to use this method in an environment prone to disturbances. While the test setup does not allow to test the reaction of the system to externally applied disturbances, it does allow to simulate disturbance by applying an internal torque step to the control loops of the drives to emulate a disturbance. This torque step is applied to a variable called torque trim that is given as a percentage of the motor rated current and can be applied to the axes to simulate a disturbance during the move. As the torque trim is a percentage of the motor rated current, it is not advisable to exceed a value of 50%. In the tests with applied disturbance, the torque trim was applied at half of the total move time (25ms, 50ms, 100ms) to simulate disturbance

at the point of maximum velocity. Applying the disturbance at the point of maximum velocity shows best the ability of the two load sharing techniques to react to disturbance and maintain or regain control of the system. As the goal of this thesis is to evaluate the synchronization and load sharing abilities of the two compared methods under the most demanding conditions, the torque trim is set for the disturbance tests to the maximum recommended 50% of the motor rated current. The program of the controller to apply the torque step to the drives is found in Appendix A and B. The torque trim is located and applied to the control loops that are provided in Appendix C. The control loops are described in Section 3.3.

The data to compare the two load sharing techniques were captured using the trending function of Rockwell Automation's Studio 5000 software. Each data point was captured with a sampling rate of 2ms. Shorter trending intervals are possible but were prevented by the test setup's controller drive communication bandwidth. Shorter capturing intervals exceeded the available communication bandwidth and may result in erroneous data captured. After capturing, the data were saved and exported into Microsoft Excel files for further analysis. The list of signals that were captured from the two load sharing methods is as follows:

- Current Feedback
- Velocity Fine Command
- Velocity Feedback
- Position Fine Command
- Position Feedback
- Position Error

These six signals were captured for each axis in Method 1. Since in Method 2 the two motors of the test setup are wired to one drive, see also Section 5.2, it is not possible to capture certain data from both axes in Method 2. For the velocity and position feedback values of the second axis in Method 2, encoder data was captured. Even though the encoder of the second axis was not used in the control of the motors, it was still wired to the drive to evaluate the behavior and performance of the second motor. This will be described next.

The current feedback is a percentage of the motor's continuous rated current. As described in Section 5.2, the current feedback allows calculating the developed torque by a motor. The current feedback also

allows making conclusions about how well the motors are sharing the load. Because the current feedback is measuring the sum of the current applied to both motors in Method 2, it is not possible to capture the current value for each motor individually in Method 2. It is not possible to determine the difference in power consumption between the two motors. Since the motors are wired and supplied by the same drive, the current feedback can be assumed to be equal. The velocity fine command is the velocity command derived in the drives for the motors to follow. The velocity fine command value is generated in the drive control loops and eliminates communication delays between controller and drive. The communication delay between the controller and drive is minimal (2ms) but measurable. This delay is caused by the natural time it takes to transport information from the controller to the drives. The velocity feedback is derived from the position measured by the encoder. The position fine command is the position command value in the drive that is used as the reference signal to control loops that control the motor. The position feedback is the angular position measured by the encoders and read by the drive. In Method 2, the position feedback value for the second motor is captured by monitoring the encoder position feedback value, but it is not used in the control loops, it is used only for monitoring. The last value captured is the position error. The position error is the difference between the commanded position and the feedback position. In Method 2, the position error can be only monitored for one axis. Monitoring position error, position command, and position feedback values allow evaluating the ability of the motors to follow the command signal. Analyzing the ability of the motors to follow the velocity and position command signals allows us to make conclusions about how effective the two load sharing techniques are to control and evenly share torque, and for what applications the two methods can be used.

In total, 6 different test cases were studied, as listed below following the three Modsine motion profiles shown in Table 5.1. Three replicates were carried out for each test case for a total of 18 test moves.

- 50ms Moves without Disturbance applied
- 50ms Moves with Disturbance set to 50% of Torque Trim and applied at 25ms of Move
- 100ms Moves without Disturbance applied
- 100ms Moves with Disturbance set to 50% of Torque Trim and applied at 500ms of Move
- 200ms Moves without Disturbance applied

- 200ms Moves with Disturbance set to 50% of Torque Trim and applied at 100ms of Move

After commanding the three moves per test case, the moves were visually compared in Studio 5000 and the outcomes were validated. To ensure qualitative data, the data were critically evaluated based on:

- Shape of monitored data curves
- Magnitude of data curves
- Plausibility of data curves based on experience with other tests and reasonable expectations

Comparing the shape and magnitude of the data was the first step to ensure qualitative data during the collection process. It is expected that the feedback values do not precisely follow the command value but are within a reasonable range around the command values. When feedback values differ significantly from the command values in magnitude or shape, the test for this data point was repeated. For example, a 50ms move requires a higher acceleration and velocity than a 200ms move as shown in Table 5.1. Therefore, it can be expected for the 50ms to reach higher current feedback values than a 200ms move as the motors require lower energy to reach the commanded acceleration values. In case one-, or multiple moves fail to meet these criteria for one test case, the entire test case was repeated and three new moves were captured (recollection of all three move data for the test case in question).

5.4. Data Analysis

In this Section, the steps to analyze the collected test data is described. Once the three moves per test case were commanded and performed by the motors, the data collection was stopped, the data were collected and analyzed. The first step was to identify the data points when a move was commanded, extracting the relevant data points from the total data set and summarizing them. Since the data were collected at a 2ms sampling time, a 50ms move should be covered by 25 data points, a 100ms move with 50 data points, and a 200ms move with 100 data points. During analysis, it was identified that although this number of data points is sufficient to capture the command signals, this number of data points cannot fully capture the feedback signal due to overshoot, phase shift, and damping time. Thus, the following scheme was used to extract the data points for every move:

- 4 data points before the first commanded velocity data point

- All data points till current feedback values stabilize around 0

Based on this definition, for a 50ms move, 46 data points were collected, for 100ms moves 76 data points, and for 200ms moves 126 data points.

Based on the captured data in the test cases, five additional values for the data analysis were calculated. The averages were, if possible, calculated individually for each axis based on the three move data per test case.

- Average Current Feedback for Axis 1 and 2 in Method 1 based on three moves per test case for each axis (NOTE: Since Current Feedback for Method 2 is the combined current feedback for both motors, the individual average Current Feedback for Axis 1 and 2 can not be calculated. The average for the combined Current Feedback was calculated based on the three move data per test case)

- Individual Average Velocity Feedback Axis for 1 and 2 in both Methods based on the three move data per test case

- Individual Average Position Error for Axis 1 and 2 in Method 1 (Note: Since Position Error for Method 2 is the combined Position Error for both motors, the individual average Position Error for Axis 1 and 2 can not be calculated. The average combined Position Error was calculated based on the three move data per test case)

- Difference between Axis 1 Command Velocity and Feedback Velocity

- Difference between Axis 2 Command Velocity and Feedback Velocity

- Difference between Velocity Feedback Axis 2 and Velocity Feedback Axis 1

- Motor Current with Method 1 (See calculation in Section 6.1)

- Motor Current with Method 2 (See calculation in Section 6.1)

To get a better understanding of the data and the behavior of the motors, the same data points of the three commanded movements were averaged to create an average value for the current and velocity feedback, and the position error. The average current value smooths out differences between the moves and gives a better picture of the average behavior of the system and the two synchronization techniques. The average

current I_{mA} was calculated for each axis with Method 1, and the combined current feedback of both axes with Method 2 summing up the captured current feedback I_{fdbk} for all three test moves and each time point. The equations used to calculate the average current feedback values are as follows:

$$I_{mA} = \frac{\sum_{i=1}^{n} I_{fdbk_{TimeX}}}{3} \tag{5.4}$$

With i being the three test moves 1,2,3 per test case. The same equations were used to calculate the position error based on the three move data per test case. Since it is possible in Method 2 to calculate individual average velocity feedback values for Axis 1 and 2, average values for each axis were calculated individually. Figure 5.10 shows the collected data for three test moves of the current feedback of Axis 1 with Method 1, 100ms without applied disturbance test case.

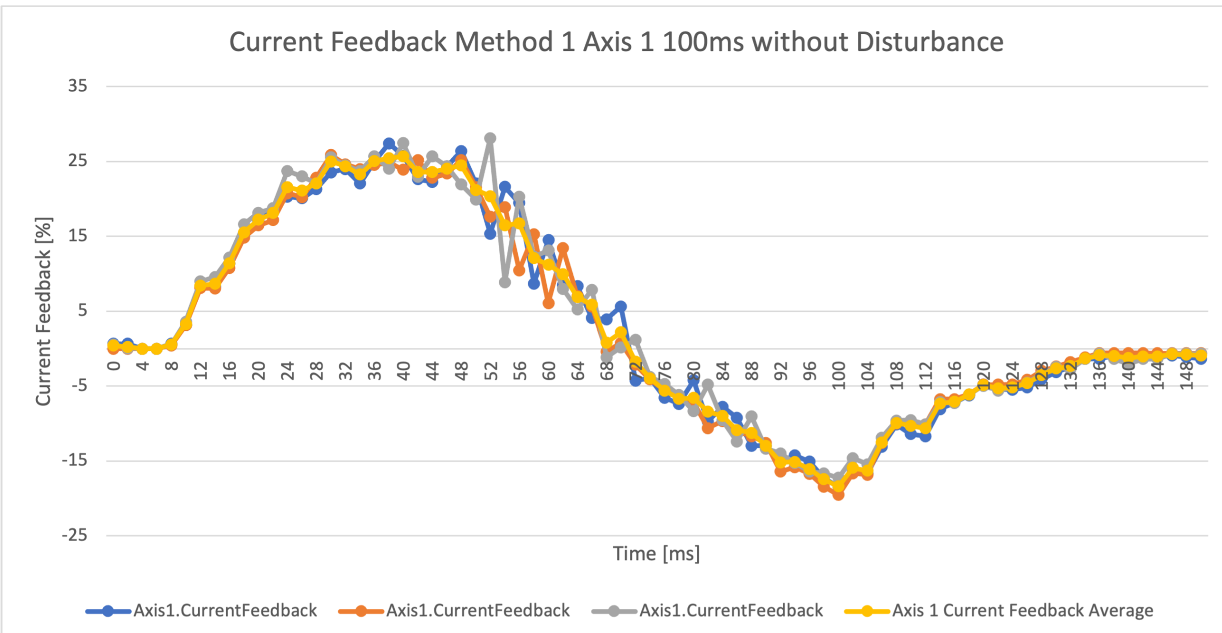


Figure 5.10.: Example of Current Feedback Average Calculation

The synchronization of the feedback signals to compute the average values was obtained by aligning the command signals. Because the command values are the same for all three moves per test case, it is not necessary to average over the command values. The difference in the two axes commanded velocities and feedback velocities represent the velocity error. The velocity error is a second value besides the position error to evaluate the method's ability to control the motors and to follow the commanded values. The dif-

ference of the two axes velocity feedback values allows evaluating the synchronization between the motors. A load sharing method with high differences in velocity feedback values is not able to control the motors in a synchronized way. Calculating the energy for each test case allows evaluating the energy consumption of the load sharing methods.

6. Presentation Test Results

The results of the tests that were performed to experimentally compare the two load sharing techniques are presented in this chapter. To allow for easy comparison of the test results, this chapter is organized in tests with, and without disturbance, as described in section 5.3. The amount of collected data prevents the presentation of all data in this chapter.

6.1. Tests without Disturbance

The test results for the test cases (50ms, 100ms, 200ms move time) where no disturbance was applied to the load during the tests are provided in this section. The plots with the data collected for the 50ms test case are shown in Figure 6.1. The same data was collected for each test case. The data collected for Method 1, two motors connected to two drives, are shown on the left side of Figure 6.1, and the data collected for Method 2, two motors connected to one drive are shown on the right side. Since the collected data for all test moves (50ms, 100ms, 200ms) present similar behavior, only the results for the 50ms moves are shown in Figure 6.1. The important data points of the 50ms test moves are summarized in Table 6.1. The important data points of the 100ms and 200ms test cases are summarized in Tables 6.2 and 6.3.

It should be noticed that all current feedback values in this Chapter are given in Ampere although the current feedback is captured from the drives during the test moves in percent of the motor continuous rated current as described in Section 5.3. This conversion from percent to A is necessary to better compare the motor current feedback between the two load sharing methods. As stated in Section 5.2.2, the motor rated current in the drive settings has to be doubled for Method 2 compared to the drive settings with Method 1 since two motors are connected to one drive. Because the motor rated current is doubled in the drive configuration with Method 2 compared to Method 1, the measured current feedback in percentages from Method 1 cannot be directly compared to the measured current feedback in percent measured with Method 2. To be able to compare the energy drawn by the two methods, the total motor current drawn by both motors I_{mT} is calculated. The calculated total motor current takes into account the differences in the drive settings between the two methods with respect to the motor current. As it is not possible to capture the

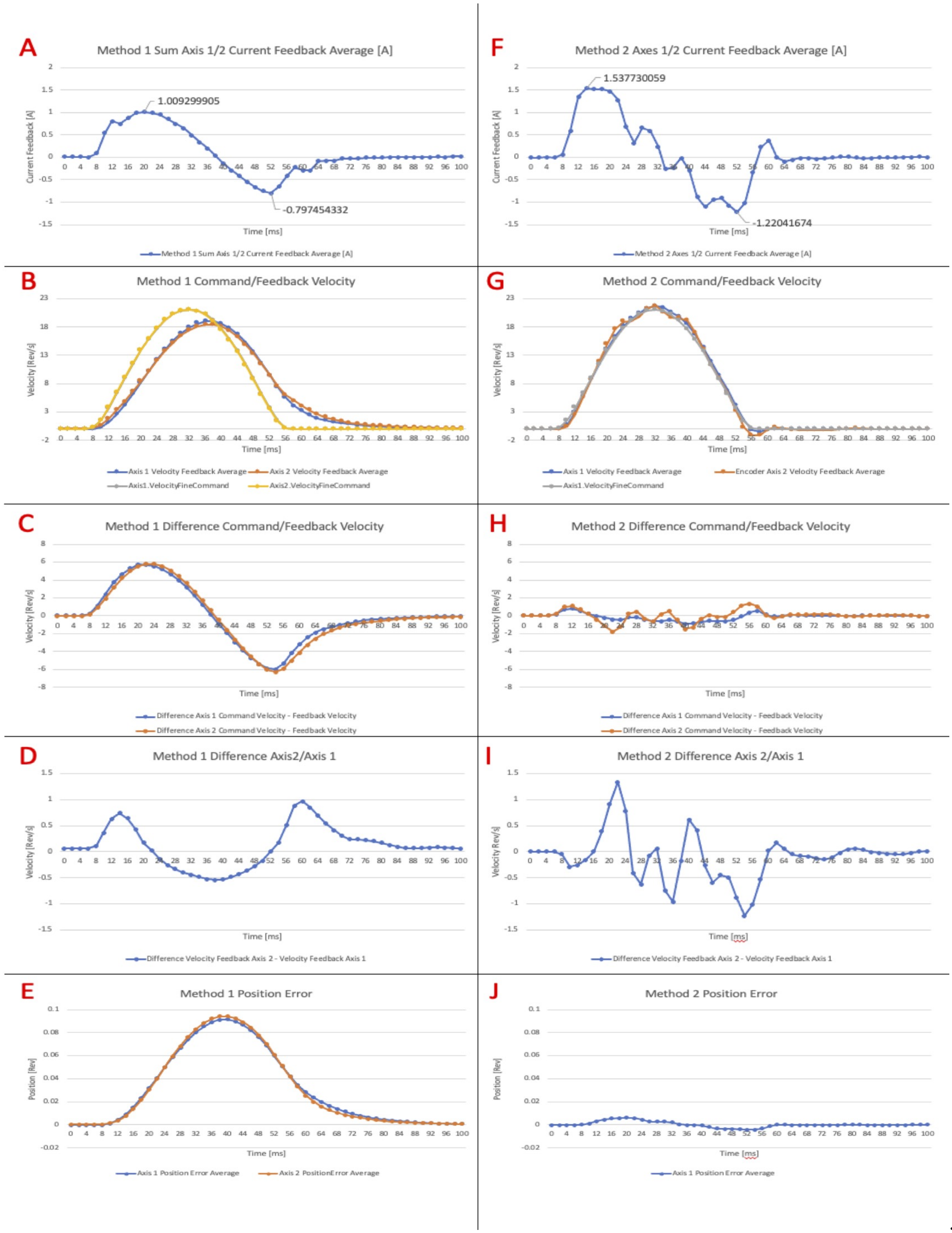


Figure 6.1.: Overview of Test Results 50ms Move without Disturbance. (a-e) Method 1, (f-j) Method 2

current feedback individually for each motor with Method 2, the calculated motor currents for each motor with Method 1 are summed up to allow to compare the methods. The total motor current I_{mT} for Method 1 is calculated as follows:

$$I_{mT_{Method1}}[A] = I_{m_{rated}}[A]\frac{I_{fdbk_{Axis1}}[\%] + I_{fdbk_{Axis2}}[\%]}{100} \tag{6.1}$$

Where $I_{m_{rated}}$ is the motor rated current which is $1.7A_{rms}$ for a single motor used in the tests, $I_{fdbk_{AxisX}}$ is the current feedback captured during the test moves in percentages for each axis.

Because two motors are connected to one drive in Method 2, the $I_{m_{rated}}$ of $1.7A_{rms}$ per motor has to be doubled in Method 2 ($3.4A_{rms}$). Thus, the total motor current, I_{mt}, with Method 2 is calculated as follows:

$$I_{mT_{Method2}}[A] = 2I_{m_{rated}}[A]\frac{I_{fdbk_{total}}[\%]}{100} \tag{6.2}$$

Where $I_{fdbk_{total}}$ is the total current feedback of the only drive powering the motors which corresponds to the current of both motors in percent, captured during the test moves for Method 2.

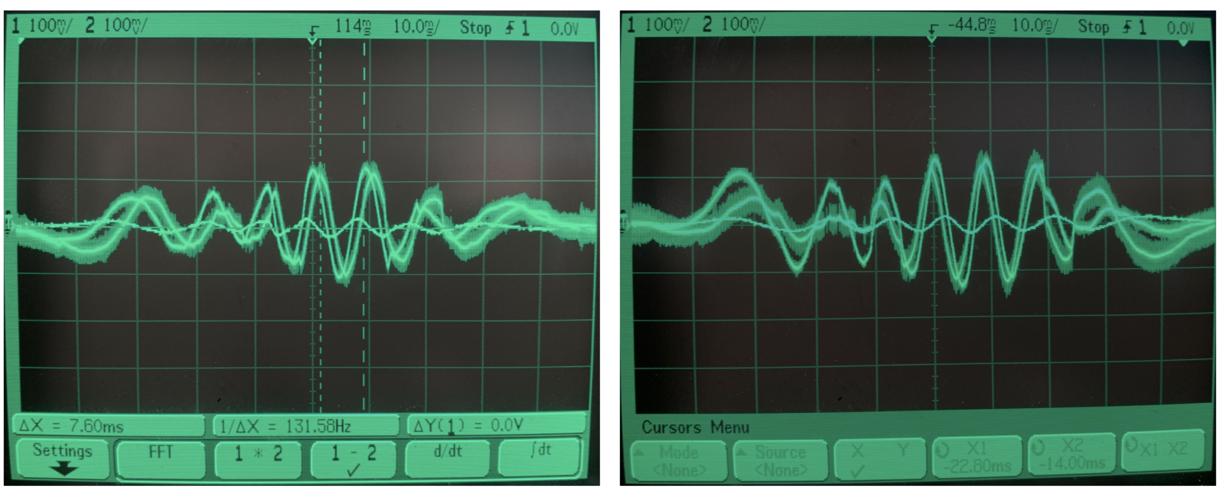
Table 6.1.: Test Results 50ms Move without Disturbance

	Method 1		**Method 2**	
	Axis 1	**Axis 2**	**Axis 1**	**Axis 2**
Current Positive Peak [A]	1.01	Combined with Axis 1	1.54	Combined with Axis 1
Current Negative Peak [A]	-0.78	Combined with Axis 1	-1.22	Combined with Axis 1
Velocity Feedback [Rev/s] Max.	18.99	18.48	21.72	21.78
Delay between Command and Feedback Velocity [ms]	4	4	0	0
Difference Command - Feedback Velocity Max. [Rev/s]	5.72	5.78	0.81	1.36
Difference Command - Feedback Velocity Min. [Rev/s]	-5.99	-6.28	-0.89	-1.77
Difference Axis 2 - Axis 1 Max. [Rev/s]	0.97	See Method 1 Axis 1	1.34	See Method 2 Axis 1
Difference Axis 2 - Axis 1 Min. [Rev/s]	-0.55	See Method 1 Axis 1	-1.23	See Method 2 Axis 1
Position Error [Rev] Max.	0.09	0.09	0.006	Not Measurable

In plots A and F in Figure 6.1, the results of the motor current calculation for the 50ms test moves are shown. For the 50ms moves, the motors with Methods 1 show a peak to peak current of 1.01A to -0.78A. Method 2 shows a peak to peak motor current of 1.54A to -1.22A. Method 1 shows lower motor current values for all test cases without disturbance. As discussed next, Method 2 can follow closer the command signals. Since Method 2 yielded lower velocity following errors than Method 1, Method 2 draws more energy to develop higher motor torque and keep the velocity following error low.

As outlined in Section 5.2.2, to further investigate the load sharing between the motors during

the moves, two current probes were used to monitor the motor currents for both methods. Analyzing the load sharing between the two motors with the two methods requires analyzing the current feedback of both motors as the drawn current is directly related to the developed torque, as outlined in Section 5.2.1. Since one drive powers two motors in Method 2, it is not possible to capture the current feedback individually for each motor, thus the captured current feedback is the combined current feedback from both motors. As the captured signal is the combined current feedback signal of both motors, it is only possible to evaluate the load sharing abilities of the two methods by comparing the captured currents on the oscilloscope. An example oscilloscope trend captured of a 100ms move without disturbance is shown in Figure 6.2 (Note: This is a single move overview and not an average of all three test moves per test case). Due to limitations regarding the oscilloscope, it is only possible to visually compare the methods as the oscilloscope did not allow the data to be saved electronically. The visual comparison was performed for all test cases. Comparing the current shown in the left picture of Figure 6.2 for Method 1 with the current for Method 2 shown on the right side in Figure 6.2, a significant difference at the beginning of the move can be seen. It is possible to see in Figure 6.2 that the motor current curves with Method 2 show a stronger unbalanced current behavior when compared to Method 1 at the beginning of the move. With Method 1, this behavior as pronounced is not seen in the test cases. Since Method 2 follows the command signals more closely, resulting in higher



(a) (b)

Figure 6.2.: Oscilloscope Motor Current without Disturbance. (a) Method 1, (b) Method 2

acceleration values at the beginning of the move, it can be assumed that this phenomenon is due to the elasticity of the belt. This assumption is further supported by the fact that Method 2 was designed for rigid

mechanically coupled systems where the mechanical coupling is achieved by for example a gearing system, allowing for minimal mechanical flexibility in the system. The mechanical coupling in the test setup is a compliant system, allowing some flexibility in the system and likely causing the observed unbalanced current waves in Figure 6.2 with Method 2. Comparing the shape and magnitude of the currents during the move, it can be seen that Method 2 shows a higher peak-to-peak current than Method 1, while both Methods show a slight phase shift caused by magnetic misalignment and compliance between the motors. While the magnetic misalignment is caused by the limitations of the setup and can be reduced in other setups, the higher peak-to-peak differences during the move with Method 2 are caused by a higher bandwidth tuning of the position and velocity control loops of the drive than Method 1.

Table 6.2.: Test Results 100ms Move without Disturbance

	Method 1		**Method 2**	
	Axis 1	**Axis 2**	**Axis 1**	**Axis 2**
Current Positive Peak [A]	0.86	Combined with Axis 1	1.13	Combined with Axis 1
Current Negative Peak [A]	-0.6	Combined with Axis 1	-0.81	Combined with Axis 1
Velocity Feedback [Rev/s] Max.	27.33	26.79	28.56	28.19
Delay between Command and Feedback Velocity [ms]	6	6	0	0
Difference Command - Feedback Velocity Max. [Rev/s]	4.45	4.67	0.36	0.76
Difference Command - Feedback Velocity Min. [Rev/s]	-5.06	-5.19	-0.76	-1.21
Difference Axis 2 - Axis 1 Max. [Rev/s]	0.75	See Method 1 Axis 1	0.87	See Method 2 Axis 1
Difference Axis 2 - Axis 1 Min. [Rev/s]	-0.58	See Method 1 Axis 1	-1.11	See Method 2 Axis 1
Position Error [Rev] Max.	0.13	0.14	0.005	Not Measurable

In plots B and G in Figure 6.1, the commanded velocity and feedback velocity curves for the 50ms test moves of Method 1 and Method 2 are shown. It is possible to observe a larger difference between the commanded velocity and the feedback velocity with Method 1 than with Method 2. As shown in Tables 6.1, 6.2, and 6.3, both motors with Method 2 show minimal delays between commanded velocity and feedback velocity. With Method 2, the only delays measured between commanded and feedback velocity are 2ms for motor 1 and 2ms for motor 2 in the 200ms moves. For Method 1, all three test cases without disturbance presented delays of 4ms in the 50ms moves, increasing to 6ms and 8ms for the 100ms and 200ms moves respectively. This shows that Method 1 is less able to follow the velocity command signal.

To assess the ability of the methods to follow the command velocity, the difference between commanded velocity and feedback velocity for each of the axes was calculated and the results are shown in plots C and H in Figure 6.1. As shown in these plots, and quantified in Table 6.1, Method 1 shows higher dif-

ferences between the commanded and feedback velocity for both axes than both axes with Method 2. This difference between the commanded and feedback velocity allows concluding that Method 1 is less able to follow the velocity command signal. This assumption is further supported by analyzing the position errors as shown in plots E and J in Figure 6.1. As shown in Tables 6.1, 6.2, and 6.3, the position error of both axes with Method 1 is higher than the position error of both axes with Method 2. In the case of the 100ms moves, the maximum average position error of axis 1 over all three test moves with Method 1 is 30 times higher than the maximum average position error over the test moves with Method 2.

To evaluate the degree of synchronization between the two motors with each method, the difference between the captured velocity feedback of each motor is analyzed. The difference between the velocity feedback from both motors for both methods is shown in Graphics D and I in Figure 6.1. It can be seen from these figures that Method 2 yielded a slightly higher difference between the velocity feedback of motor 1 and 2 than Method 1, although the tuning of the drive in Method 2 is set to a significantly higher bandwidth than the drives in Method 1. So, tuning of the control loops have little effect on the difference in velocity between the motors, but since a drive tuned to higher bandwidth tends to correct velocity following error faster and more dynamically as shown by the profiles in Figures 6.1 D and I, Method 2 can keep the velocity following error significant lower as Method 1. The slightly higher difference in velocity feedback between axis 1 and 2 with Method 2 can be also confirmed for the 100ms and 200ms moves.

Table 6.3.: Test Results 200ms Move without Disturbance

	Method 1		**Method 2**	
	Axis 1	**Axis 2**	**Axis 1**	**Axis 2**
Current Positive Peak [A]	0.6	Combined with Axis 1	0.72	Combined with Axis 1
Current Negative Peak [A]	-0.37	Combined with Axis 1	-0.35	Combined with Axis 1
Velocity Feedback [Rev/s] Max.	31.38	31.21	31.21	31.6
Delay between Command and Feedback Velocity [ms]	8	8	2	2
Difference Command - Feedback Velocity Max. [Rev/s]	2.81	2.88	0.06	0.43
Difference Command - Feedback Velocity Min. [Rev/s]	-3.16	-3.27	-0.53	-0.75
Difference Axis 2 - Axis 1 Max. [Rev/s]	0.37	See Method 1 Axis 1	0.52	See Method 2 Axis 1
Difference Axis 2 - Axis 1 Min. [Rev/s]	-0.17	See Method 1 Axis 1	-0.67	See Method 2 Axis 1
Position Error [Rev] Max.	0.16	0.16	0.003	Not Measurable

6.2. Tests with Disturbance

In this Section, the test results for the test cases (50ms, 100ms, 200ms move time) with disturbance applied as outlined in Section 5.3 are presented. As described in Section 5.3, the disturbance was applied

using the torque trim feature of the drives. The load disturbance was electronically applied via torque trim at halfway through each move with the torque trim set to 50 percent of the motor rated torque. Similar to Section 6.1, the test results of the 50ms test moves are presented in Figure 6.3. In Tables 6.4, 6.5, and 6.6, data comparing the results from the tests with 50ms, 100ms, and 200ms moves with applied disturbance are summarized.

As stated above, the disturbance was applied to each axis halfway through each move. Comparing the positive current peak feedback of the moves with and without disturbance, it can be stated that there is only a minimal difference between the with and without disturbance test cases. The positive motor current peaks for the test cases with and without disturbance have a maximum difference of 0.02A. Based on the motor current equation shown in Section 6.1, the results of the total motor current calculations for both methods for the 50ms test moves with applied disturbance are shown in plots A and F in Figure 6.3. The combined positive peak motor current with Method 1 is 1.01A, and the negative motor current peak is -0.82 A. Compared to the motor currents shown in Figure 6.1 (Method 1: Positive Peak Current: 1.01 A, Negative Peak Current: -0.78 A, Method 2: Positive Peak Current: 1.54 A, Negative Peak Current: -1.22 A) for the test 50ms moves without disturbance, a significant difference in motor currents between test cases with and without disturbance cannot be identified. The positive peak motor current of both motors with Method 2 reaches 1.52A, with a negative peak of -1.21A. It can be stated that Method 1 shows lower motor currents throughout the three test cases with disturbance than Method 2, as in the test cases without applied disturbance. The lower motor currents of Method 1 can be explained by the same reason as for the without disturbance test cases. Method 1 is not able to follow the velocity and position command signals as closely as Method 2. As for the test cases without disturbance, Method 2 yields lower velocity following errors in the disturbance test cases than Method 1, which results in higher energy usage and higher developed motor torque. This significant lower velocity following errors of Method 2 compared to Method 1 is a result of the higher bandwidth of the position and velocity control loops in the drive with Method 2 than Method 1.

Similar to Section 6.1, the captured oscilloscope trends of 100ms moves for each method with disturbance applied at 50ms, which is halfway through the move, is shown in Figure 6.4 (Note: This is a single move overview and not an average of all three test moves per test case). Comparing the current shown in Figure 6.4.a for Method 1 with the current for Method 2 shown in Figure 6.4.b, a significant difference at

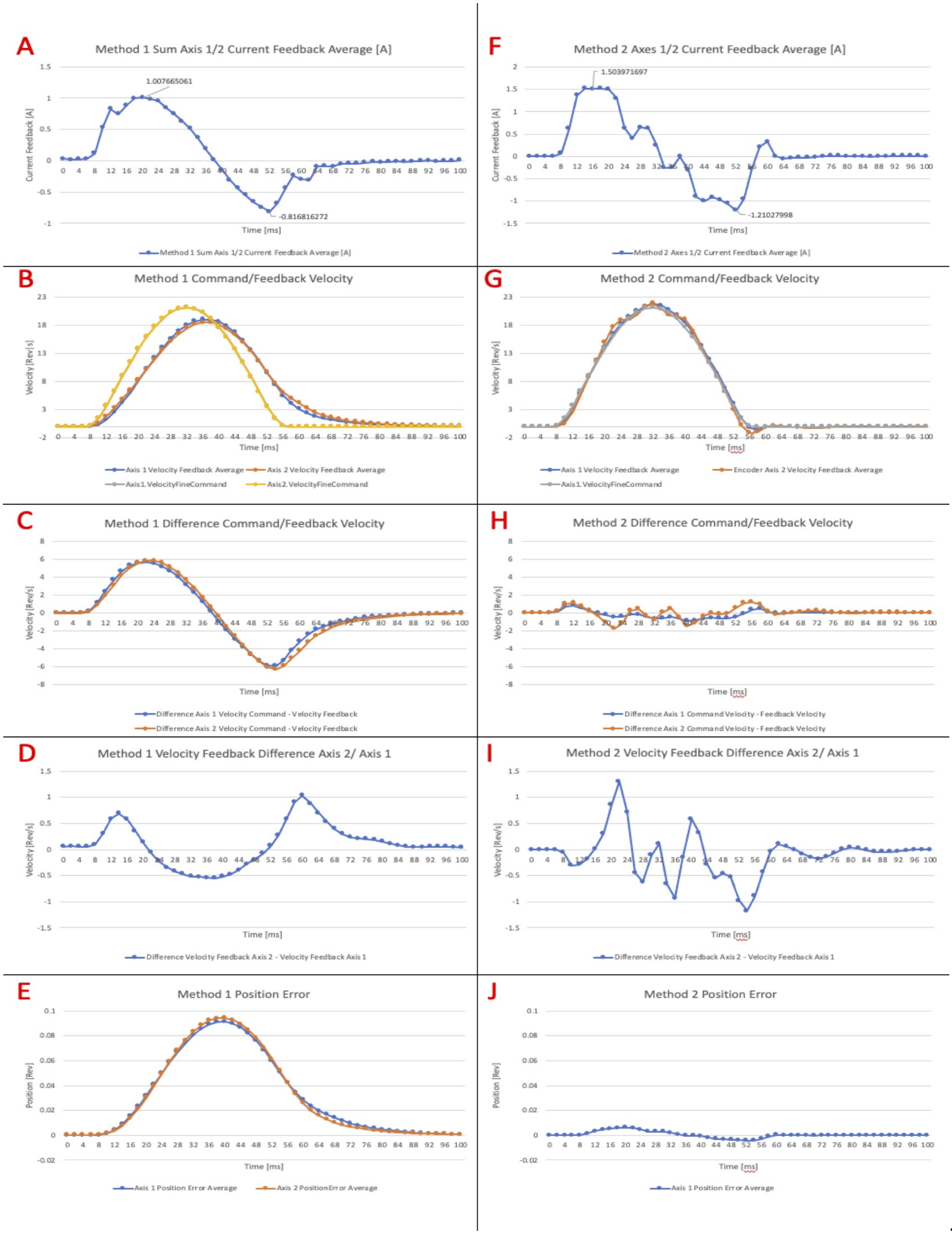


Figure 6.3.: Overview of Test Results 50ms Move with Disturbance. (a-e) Method 1, (f-j) Method 2

Table 6.4.: Test Results 50ms Move with Disturbance

	Method 1		Method 2	
	Axis 1	**Axis 2**	**Axis 1**	**Axis 2**
Current Positive Peak [A]	1.01	Combined with Axis 1	1.52	Combined with Axis 1
Current Negative Peak [A]	-0.82	Combined with Axis 1	-1.21	Combined with Axis 1
Velocity Feedback [Rev/s] Max.	19.01	18.46	21.75	21.86
Delay between Command and Feedback Velocity [ms]	4	4	0	0
Difference Command - Feedback Velocity Max. [Rev/s]	5.66	5.8	0.79	1.21
Difference Command - Feedback Velocity Min. [Rev/s]	-5.94	-6.3	-0.88	-1.75
Difference Axis 2 - Axis 1 Max. [Rev/s]	1.04	See Method 1 Axis 1	1.3	See Method 2 Axis 1
Difference Axis 2 - Axis 1 Min. [Rev/s]	-0.55	See Method 1 Axis 1	-1.18	See Method 2 Axis 1
Position Error [Rev] Max.	0.09	0.09	0.006	Not Measurable

the beginning of the move can be identified. As described in Section 6.1 for the tests without disturbance, the motor current signals with Method 2 show an unbalanced behavior at the beginning of the move. With

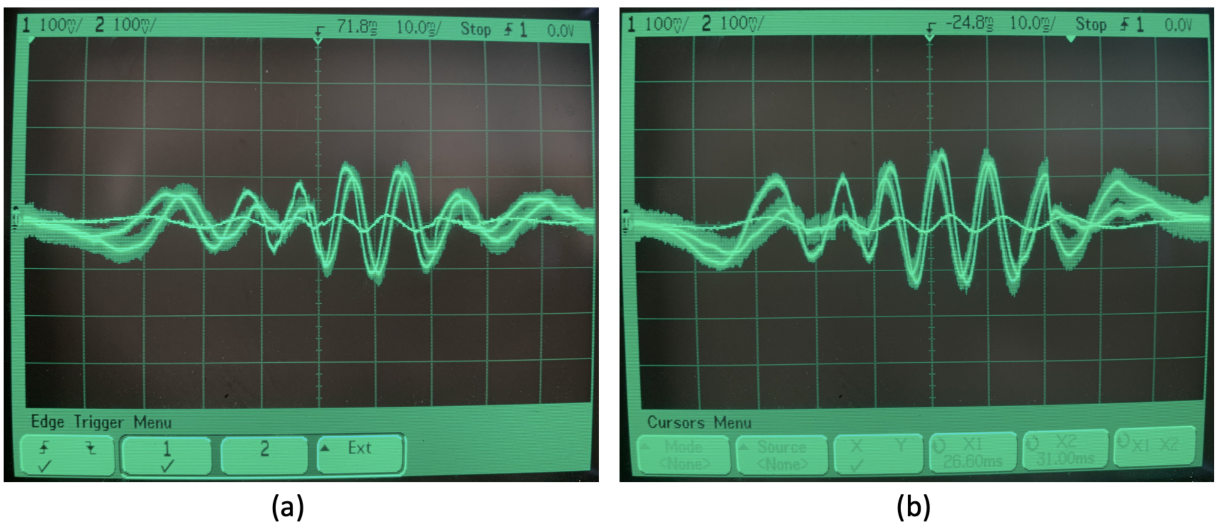


Figure 6.4.: Oscilloscope Motor Current with Disturbance

Method 1, this behavior is not be seen for all test cases with applied disturbance. The oscilloscope picture confirms for the disturbance tests a higher peak-to-peak difference with Method 2 than with Method 1 as in the test cases without disturbance. The unbalanced behavior at the beginning of the move with Method 2 is likely due to the slight magnetic misalignment of the motors and the compliance of the belt between the two motors. Analyzing the motor currents shown in Figure 6.4 regarding the impact of the applied disturbance in the middle of the move, it can be stated that a significant difference to the test cases without disturbance cannot be identified. Both methods resulted in good disturbance rejection.

Table 6.5.: Test Results 100ms Move with Disturbance

	Method 1		Method 2	
	Axis 1	**Axis 2**	**Axis 1**	**Axis 2**
Current Positive Peak [A]	0.86	Combined with Axis 1	1.13	Combined with Axis 1
Current Negative Peak [A]	-0.63	Combined with Axis 1	-0.8	Combined with Axis 1
Velocity Feedback [Rev/s] Max.	27.3	26.77	28.53	27.94
Delay between Command and Feedback Velocity [ms]	6	6	0	0
Difference Command - Feedback Velocity Max. [Rev/s]	4.47	4.63	0.34	0.62
Difference Command - Feedback Velocity Min. [Rev/s]	-5.08	-5.23	-0.77	-1.21
Difference Axis 2 - Axis 1 Max. [Rev/s]	0.81	See Method 1 Axis 1	0.85	See Method 2 Axis 1
Difference Axis 2 - Axis 1 Min. [Rev/s]	-0.57	See Method 1 Axis 1	-0.91	See Method 2 Axis 1
Position Error [Rev] Max.	0.13	0.13	0.004	Not Measurable

Comparing the velocity command and velocity feedback data from Method 1 with disturbance and without disturbance, a significant difference for all test cases cannot be identified. The same was observed with Method 2. Thus, the velocity following errors are relatively unchanged with and without disturbance for both methods. In regards to the magnitude and timing of the velocity feedback, both methods behave almost identically during the tests with disturbance and the tests without disturbance. Method 1 shows a delay between commanded velocity and feedback velocity while disturbance is applied. The measured delay between the commanded and feedback velocity is 4ms, 6ms, and 8ms for the 50ms, 100ms, and 200ms moves respectively. Method 1 shows in the tests with disturbance the same delays as in the tests without disturbance. Method 2 shows no delay between commanded and feedback velocity in all three test cases with applied disturbance. The delay between commanded velocity and feedback velocity is higher with Method 1 as shown in Figure 6.3.c compared with Method 2 as shown in Figure 6.3.h, which is the same behavior observed with the tests without disturbance. As in the test cases without disturbance, Method 2 yields a slightly higher difference between the velocity feedback of motor 1 and 2 than Method 1. The calculated difference between the velocity feedback of motor 1 and 2 for each method are shown in plots D and I in Figure 6.3. As stated in Section 6.1 for the test cases without applied disturbance, the test results for the test cases with disturbance confirm that the significant higher tuned bandwidth of the drive with Method 2 has little effect on the difference in velocity between the two motors.

Regarding the measured position errors for each method with disturbance, it was observed that no significant difference occurred in comparison to the test results without disturbance. The measured position errors for each method are shown in plots E and J in Figure 6.3. In the case of the 100ms moves, the maximum average position error of axis 1 over all three test moves with Method 1 is 30 times higher than

Table 6.6.: Test Results 200ms Move with Disturbance

	Method 1		Method 2	
	Axis 1	**Axis 2**	**Axis 1**	**Axis 2**
Current Positive Peak [A]	0.59	Combined with Axis 1	0.69	Combined with Axis 1
Current Negative Peak [A]	-0.37	Combined with Axis 1	-0.39	Combined with Axis 1
Velocity Feedback [Rev/s] Max.	31.37	31.21	32.07	31.72
Delay between Command and Feedback Velocity [ms]	8	8	0	0
Difference Command - Feedback Velocity Max. [Rev/s]	2.83	2.88	0.07	0.39
Difference Command - Feedback Velocity Min. [Rev/s]	-3.16	-3.24	-0.55	-0.66
Difference Axis 2 - Axis 1 Max. [Rev/s]	0.36	See Method 1 Axis 1	0.45	See Method 2 Axis 1
Difference Axis 2 - Axis 1 Min. [Rev/s]	-0.16	See Method 1 Axis 1	-0.78	See Method 2 Axis 1
Position Error [Rev] Max.	0.16	0.16	0.002	Not Measurable

the average position error over the test moves with Method 2. This ratio is the same as for the no disturbance tests.

7. Discussion, Conclusion and Future Outlook

The conclusions regarding the six test cases presented in Chapter 6, are discussed in this chapter. The summary of the conclusions can be found in Table 7.1. The test results for each method were analyzed with respect to the following three points:

1. Ability to follow the command signals
2. Ability to control synchronized motions between axes
3. Ability to evenly share loads between the two axes

Regarding the first point, it can be stated that Method 2 can follow the command signals closer than Method 1. Comparing the velocity feedback values in all test cases, Method 2 shows a lower velocity following error between the command velocity signal and the velocity feedback signal. Additionally, Method 2 can reach the peak commanded velocity in all test cases by achieving higher acceleration values. This ability of Method 2 to follow the commanded velocity closer is shown in 30 to 40 times lower differences between the maximum commanded velocity and feedback velocity in comparison to Method 1. This ability of Method 2 to follow more closely the command signals is also shown in lower position errors in all test cases. Method 2 shows 15 to 80 times lower position errors than Method 1. The reason for higher position and velocity following errors with Method 1 can be mainly attributed to a lower control loop bandwidth than Method 2. Following the setup procedure for Method 1, the control loops as described in Section 3.3 are tuned to a lower bandwidth than the control loop settings with Method 2. The lower bandwidth of the control loops with Method 1 results in longer response times to the command signals and less aggressive adaptions to velocity and position error signals. The setup procedure of Method 2 results in a higher tuned drive with higher control loop bandwidth. The higher tuned drive with Method 2 can react more aggressively to velocity and position errors and can follow the commanded signals more closely, keeping the velocity and position following error low.

Regarding the second point, the ability of the two load sharing methods to control synchronized motions between the axes is analyzed based on the velocity feedback differences between the two axes. In

Table 7.1.: Methods Comparison Summary

Criteria	**Method 1 (two drives, two motors)**	**Method 2 (one drive, two motors)**
Delay between command and feedback velocity	High	Low
Position Following Error	High	Low
Velocity Following Error	High	Low
Speed synchronization between motor (difference between motor speed 1 and 2)	Good	Good
Load sharing between motors	Even	Even

all test cases, the two Methods present a very similar behavior with Method 2 showing slightly higher differences in velocity between the two axes compared to Method 1. It can be concluded that the two Methods can synchronize between the axes in nearly the same way, with slightly better performance than Method 1.

Regarding the third point, since it is not possible to monitor the current feedback for both motors with Method 2, the conclusions about the ability of the methods to share the load evenly between the axes are based on the visual comparison of the oscilloscope results of the motor currents. As described in Section 5.2.1, the motor current is directly related to the developed torque of a motor. By comparing the motor currents with each other, it can be analyzed if the motors are developing similar torque and therefore share the load evenly. When analyzing the motor current readings on the oscilloscope for the two Methods, the following points are identified:

1. The control bandwidth in Method 2 is tuned higher, causing higher peak currents
2. Method 2 shows uneven motor currents, especially during acceleration. The uneven motor currents are most likely caused by the compliance of the system. With Method 2, the motors reach higher acceleration values compared to Method 1, causing that motor 2 shows delayed motion reactions. The delayed motion reaction of motor 2 with Method 2 causes higher differences in speed between the two motors at the start of the move, and a higher discrepancy in motor current between the two motors
3. From the scope signals, both Methods present similar load sharing once the highest effect of compliance has passed (around the middle of the move)
4. The difference in velocity between the motors for both Methods is very similar.

Based on the above mentioned points, it can be concluded that Method 1 and 2 present similar abilities to evenly share torque between the motors, taking into account that Method 2 was developed for rigidly coupled systems and the uneven motor currents at the beginning of the move are caused by compliance in the system. The tuning procedure of Method 1 results in a lower bandwidth of the control loops. Consequently,

the position reference signal is not accurately followed, resulting in a large distortion of the motion profile shape and extending the move time significantly. Thus, higher machine rates are only possible with Method 2.

As previously mentioned, the tuning process of Method 1 results in lower control loop bandwidth that causes higher position and velocity following errors compared to Method 2. To reduce the position and velocity following errors with Method 1, the tuning procedure could be enhanced. Regarding future tests, other test setups to further compare the efficiency of the two load sharing techniques can be beneficial. The test setup was limited in two main aspects:

- Flexible (compliant) mechanical coupling between motors
- Limited ability to fine tune magnetic motor alignment

The flexible coupling of the two motors with a belt in the test setup for this thesis impacts the synchronization of the motors. A setup with a rigid coupling between the motors would minimize the effects of unsynchronized motors and allow for a better understanding of the ability of the two load sharing techniques to evenly share loads. The limitations of the test setup to fine tune the magnetic alignment of the motors caused a slight misalignment during the tests. This misalignment between the motors increases the likelihood of unsynchronized motions between the motors. Reducing the misalignment further improves the ability to compare the level of load sharing between the motors. An additional recommendation for future tests can be made regarding the type of oscilloscope. Due to limitations regarding available equipment, the oscilloscope used for this thesis did not allow to electronically export of the current data of the motors for further analysis. Using a more advanced oscilloscope would allow for further analysis of the motor currents and the level of load sharing between the motors. When considering additional tests, it can be also of interest to test the two Methods for systems with more than two motors. It can be of interest to test larger setups to test the boundaries of the two methods in regards to their ability to control an increasing amount of motors. To do that, a practical test setup that allows increasing the number of motors involved while providing a stable coupling between the motors must be developed.

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A. Ladder Program Method 1

Ladder program written to command test moves for Method 1.

R03_Motion - Ladder Diagram **Page 1**
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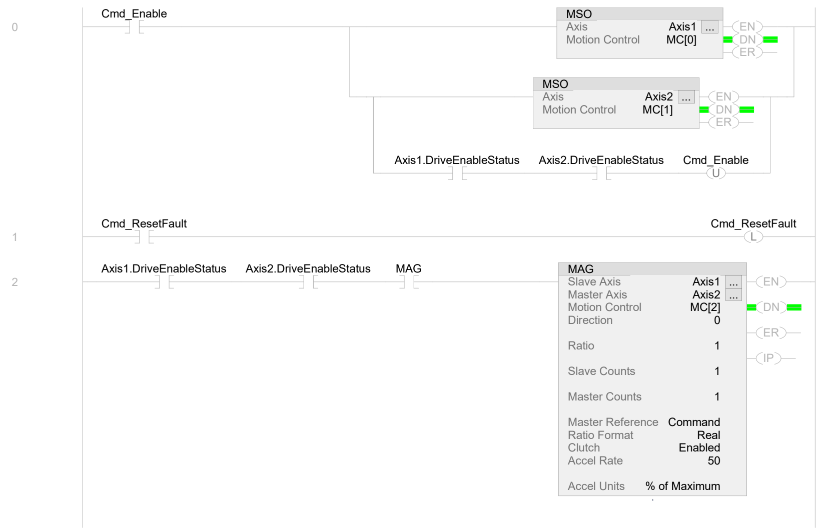

Logix Designer

R03_Motion - Ladder Diagram **Page 2**
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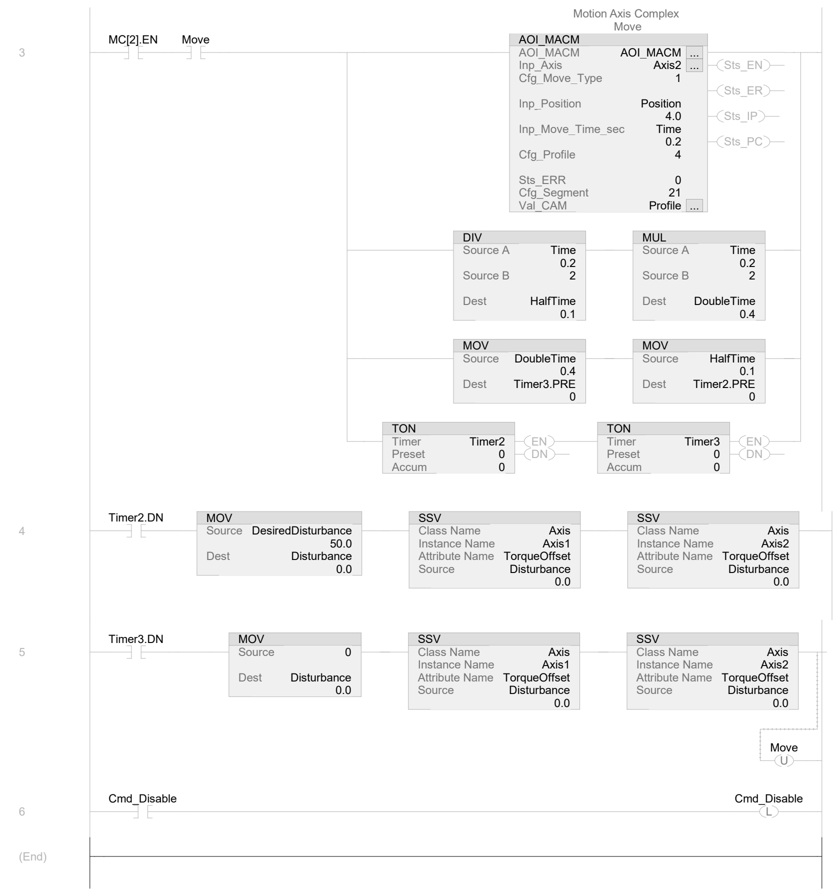

Logix Designer

B. Ladder Program Method 2

Ladder program written to command test moves for Method 2.

R03_Motion1 - Ladder Diagram **Page 1**
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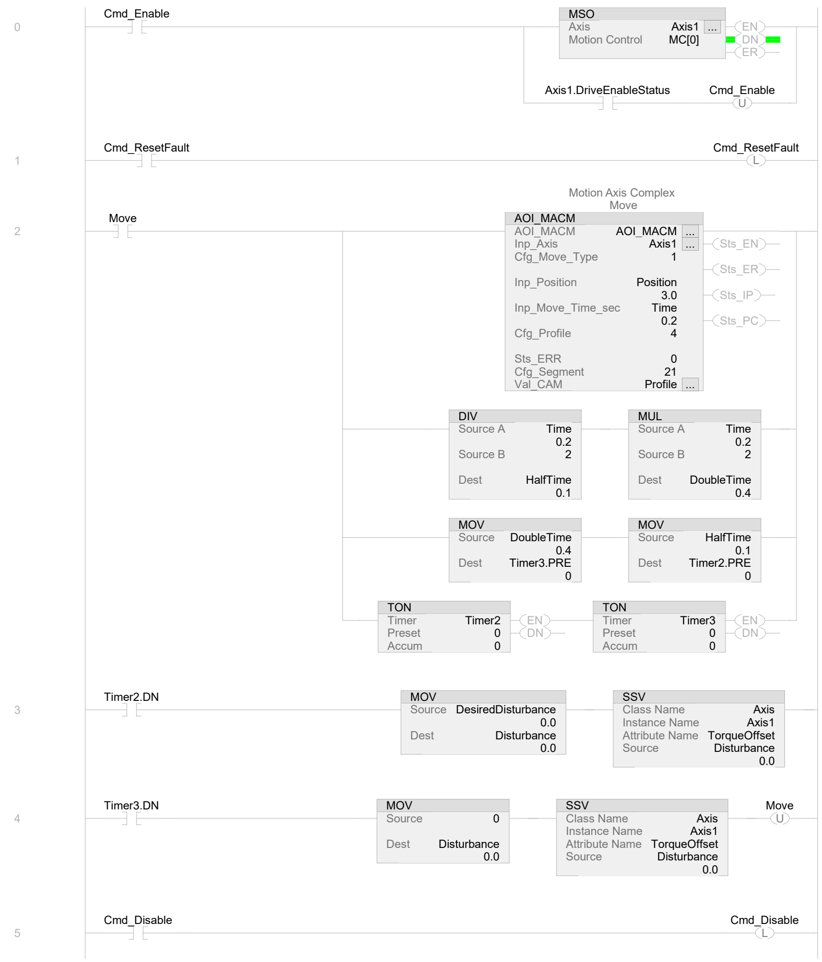

R03_Motion1 - Ladder Diagram **Page 2**
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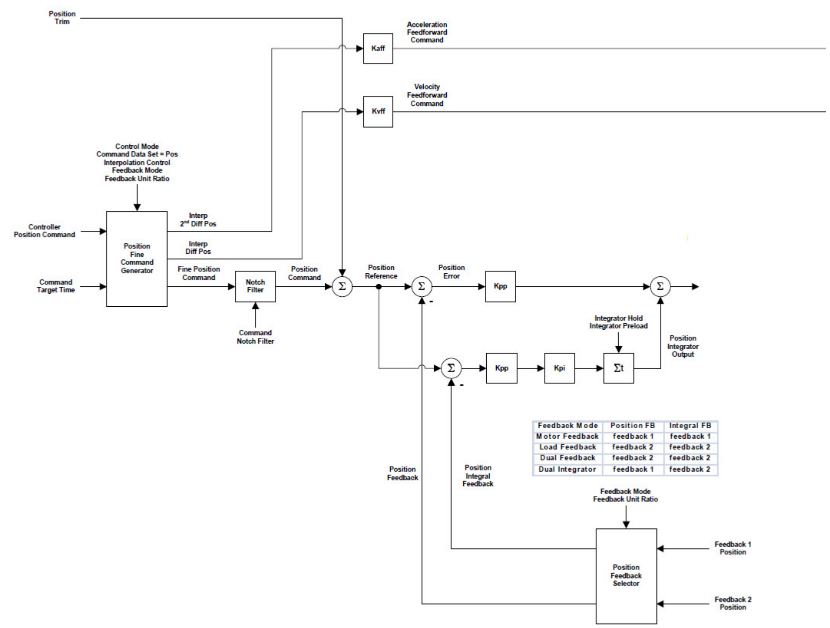
C. Drive Loops

Rockwell Automation drive position loop.


Position Trim
Acceleration Feedforward Command
Kaff
Velocity Feedforward Command
Kvff
Control Mode
Command Data Set = Pos
Interpolation Control
Feedback Mode
Feedback Unit Ratio
Controller Position Command
Command Target Time
Position Fine Command Generator
Interp 2nd Diff Pos
Interp Diff Pos
Fine Position Command
Notch Filter
Command Notch Filter
Position Command
Σ
Position Reference
Position Error
Kpp
Integrator Hold
Integrator Preload
Kpi
Σt
Position Integrator Output
Feedback Mode | Position FB | Integral FB
Motor Feedback | feedback 1 | feedback 1
Load Feedback | feedback 2 | feedback 2
Dual Feedback | feedback 2 | feedback 2
Dual Integrator | feedback 1 | feedback 2
Position Feedback
Position Integral Feedback
Feedback Mode
Feedback Unit Ratio
Position Feedback Selector
Feedback 1 Position
Feedback 2 Position