Saimaa University of Applied Sciences
Technology Lappeenranta
Mechanical Engineering and Production Technology

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Position Control of Cartesian Robot

Thesis 2019

Abstract

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Industrial robots have been a key factor that helps manufacturing businesses stay competitive and advance in the market. Cartesian robots are one of the material handling solutions which are widely used in industrial environment solving labor issues as well as improving productivity. In certain applications, it is critical to achieve high outcome of position accuracy while being dynamically operated.

The purpose of this thesis was to investigate technologies included in motion control system and certain factors that affects position accuracy aspect in Cartesian robots.

An experiment was carried out with a Cartesian robot ordered from Festo to validate the discussed theories. The test was done in Saimaa University of Applied Sciences laboratory. Data for this study was gathered from actual experiments, books, internet sources and online training programs.

Due to unproper commissioning, faults encountered during the testing phase as well as time limit of the project, the experiment failed to yield reasonable results. However, the mentioned issues can be avoided for future work.

Keywords: Cartesian robot, control system, brushed DC motor, AC motor, servo, PID, motion profile, Industrial Ethernet, Fieldbus, Profinet, Isochronous Real-time, PLC, variable-frequency drive, rotary encoder

Terminology

AC – Alternating Current

BLDC – Brushless Direct current

CNC – Computer Numerical Control

DC – Direct Current

IRT – Isochronous real-time

PID – Proportional-integral-derivative

PLC – Programmable Logic Controller

PMDC – Permanent magnet direct current

PPR – Pulses per revolution

PWD – Pulse Width Modulation

RT – Real-time

VFD – Variable frequency drive

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1 Introduction

1.1 Overview of thesis topic

Automation in material handling tasks plays vital roles in solving challenges. Multi-axis robots are widely seen in industrial environment for several reasons such as eliminating human labor issues, increasing production output and helping businesses in many ways. One of the most traditional and universal applications is a computer numerical control machine (CNC machine) which is automated control of machining tools including lathes, milling machines and 3D printing machines. For wider scale operations, it can be witnessed in pharmaceutical industries, electronics assembly industries, automobile assembly lines, smart warehouses, etc. The use of the technology is vast and various. Different types of applications require certain level of excellence in performance in term of motion control. In this research, investigation was done on a three-dimensional gantry system (or so-called Cartesian robot). Several factors should be taken into consideration when a Cartesian robot is configured such as control system, motion profiles, types of actuators, efficiency of power transmission, performance of network, etc. The goal of the thesis was to discuss mentioned aspects and validate theoretical calculations applied into a specified real-world system.

1.2 System background information

Festo is a multinational tech company which is well-known for its engineering solution and service in automation process and factory. A gantry system with specified dimensions and specifications was ordered from the company as to be tested in practical experiment. From Festo’s website, a Cartesian robot can be ordered according to customized specifications: Sub-components and integrated technologies can be selected from third parties, which usually are other major electronic device manufacturers. Systematically, the Cartesian robot architecture comprises of a controller performing as a brain of the system, drivers which control the motion of axes and a specific network type acting as a communication link between the devices. On top of that, sensor technology monitoring physical aspects of the system, for example position of axis, is often integrated. The hardware components comprised of a controller S7 1500 series, Sinamics G120 drives and Profinet, which were solutions from Siemens. Rotary incremental encoders, which were mounted at output loads sending feedback signals to the drives, were universal industrial incremental encoders from Hengstler. Software used was TIA Portal version 15.

1.3 Constraints

Regarding motion control technology, there are different modes to take into consideration. Put it more specified, there are mainly three separate modes including position control, speed control and torque control. In practicality, they are usually adapted altogether or as a combination of two of them.

In the actual test, only position control was executed. On top of that, the position control of vertical Z axis was neglected as it was driven by a rather simple form of pneumatic actuator and there were only two destinations to be reached which were two endpoints of the stroke.

The time limit of the thesis played an important role in the results of the experiment as tests need to be done many times with different data sets each time until a final optimum solution can be found.

2 Theoretical background

2.1 Industrial Robot: Classification and Application

The function of an industrial robot is to increase production speed, work tirelessly and perform tasks impossible for human labor. In manufacturing world, automated tasks are vast and various, thus the general term robot is broken down into more detailed sub-categories with their own unique capabilities and features. The differences between robot types are mainly about the architectures, which is adapted in different areas of applications. Technically, there are four types of robots which include Cartesian, Articulated, SCARA and Delta robot.

A Cartesian robot is an industrial robot with three principal axes of control which are X, Y and Z and they are rectangular to each other. The X and Y axes make planar surface parallel to the ground while the Z axis is responsible for vertical motion. The actuators mounted to each axis are responsible for driving the axes correspondingly. Typically, an electrical motor combined with a set of other mechanical devices including gearboxes, couplings, pulleys, belts, etc., makes the traversing movement of an axis. Some gantry systems require two motors mounted at base axis as it demands more torque to overcome systems' weights. Such a configuration usually takes more effort from programmers as both electrical motors (drives) must be synchronized, meaning that they are operated at same kinematic values in synchronized timeframe which include distance, velocity, acceleration/deceleration and jerk. Depending on certain factors some applications are closed-loop feedback control systems while others are open. Closed-loop mechanism offers greater results in accuracy whether it is speed, position or both. There are multiple ways of configuring Cartesian robot mechanically. More often, how the gantry robot is configured is shown on the left side of Figure 1 with two fixed parallel profiles (beam of steel or aluminum profile) supporting the system weight. It can be configured with only one base axis as shown on the right side of the figure.

Figure 1. Different configurations of Cartesian robot. Festo.

An Articulated robot is designed in a more complex structure with sets of rotary joints, ranging from 4 to 7 joints driven by servo motors. The architecture is built on the principle of a human arm. As said, it is capable of supporting multiple degrees of freedom and the flexibility is clear. Several examples of Articulated robot utilization are in tasks such as: welding, material handling, painting, etc.

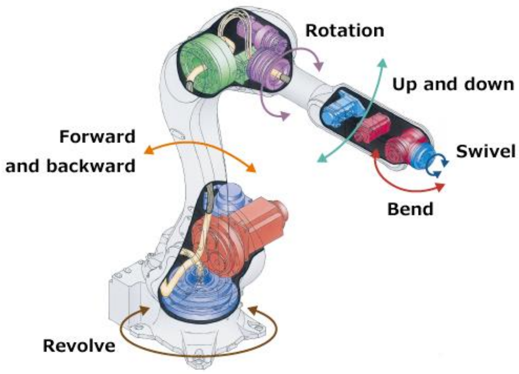


Figure 2. Structure of Articulated robot. Kawasaki 2018.

SCARA robot of which the acronym stands for selective-compliance-articulated robot arms, is used to improve the speed and repeatability on small assembly applications. The robots work along vertical axes by rotating on the same plane. Delta robots support six degrees of freedom as it comprises of 3 arms connected to universal joints at the base. As the execution is fast and precise, the robot is used for picking and placing of negligible-mass objects. The similarities between SCARA and Delta robot are that they are applied in handling tasks of low-weight loads requiring precision and speed as in pharmaceutical industry, electronics industry and food industry. There are a few differences between them such that Delta robot is faster though the maximum capacity is expected to be from 0,3 to 9 kg, which is less compared to the range between 0,5 to 20 kg of SCARA. (Owen-Hill 2019.)

Figure 3. Delta robot and SCARA robot architectures. Fanuc.

When it comes to decision of choosing which types of robot would fit the most, machine builders usually take into consideration the capabilities and costs associated with different robot types. An articulated robot makes the most use of itself in medium-load applications (up to 2 tons maximum load), usually in manufacturing industries and car assembly lines. Delta robot and SCARA robot offer higher precision in small and repeatable tasks as well as simpler implementation at competitive cost. Cartesian robot only outweighs the previous two when application demands higher load whereas accuracy remains in the same range. (Directindustry 2019.)

2.2 Motion Actuators: Characteristics of Electrical Drives

Actuators which are responsible for traversing motion of axes can be in different forms, be it pneumatically, electrically or hydraulically. Figure 4 shows pros and cons of usage of different types of actuators. A typical way to configure actuators for a robotic system is to implement electrical motors due to precision in motion control, power efficiency and proper ranges of torque and speed values.

Features\types	Electrical	Hydraulic	Pneumatic
Working Principle	Electricity. Application of magnetic fields to a ferrous core and thereby inducing motion.	By changes of pressure in High Quality Oil Base with Additives, Water Based Solutions, and Synthetic liquids.	Use a compressible gas as the medium for energy transmission.
Basic System	Solid State Logic, Power Amplifiers, DC motors (brushed and brushless, low inertia, geared and direct drive, permanent magnet) or AC motors, Gear Boxes, Ball Nuts, Coolers.	Pump, Sump, Regulators, Filters, Heat Exchangers, Servo Valves, Motors, Actuators, Accumulators	Compressor, intersta-ge Coolers, Pressure Controls, Filter, Dryers, Mufflers, valves, Actua-tors, Snubbers.
Efficiency	Over 90 % for Large Systems	Seldom over 60 %	Seldom over 30 %
Advantages	Energy easily stored and re-supplied. Control flexibility of the mechani-cal system. Easy to install and clean. Lower cost.	Very quick movements with great force. Low noise level.	Cleaner and nonflam-mable. Easy installation, operation and mainte-nance. Lower cost. Light weight.
Disadvantages	Produce very small torques compared to their size and weight.	Susceptibility to Contami-nation, High Temperature Sensitivity due to viscosity changes	Less force capability than hydraulic actuators. Lower force and speed.
Principal Appli-cations	The most common choice with a huge number of applications in the robotic industry.	Nuclear and underwater applications, remote operated vehicles	Walking machines and haptic systems

Figure 4. Comparison between different forms of actuators. Desarrollo 2014.

Rotary electrical machines are differentiated based on their operating principles, power source types and the ways they are mechanically configured. As indicated in Figure 5, electrical motors are firstly discriminated by their power input types which is either direct current (DC) or alternating current (AC). While every electrical motor consists of two parts including a stator and a rotor, the working principles vary. DC motors operate under principle of electromagnetism whereas AC motors follow electromagnetic induction principle.

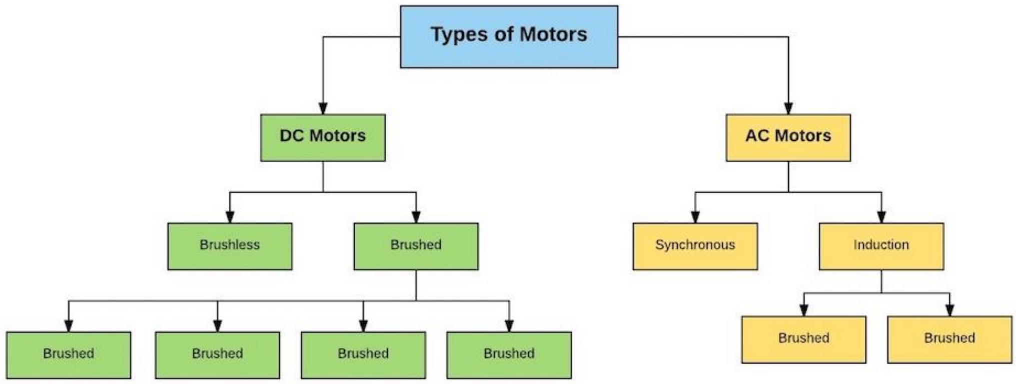


Figure 5. Types of electrical motors. Sahota 2017.

In a brushed DC motor, a rotary part consists a set of copper coils which carry electromagnets. These electromagnets are created by direct current flowing through the coils which are connected to DC power source by a pair of commutator rings. A stator of an DC motor consists of permanent magnets which provide permanent magnet field. According Lorentz’s law of electromagnetic force, magnetic forces are induced with opposite directions in two opposite sections of a coil located on the sides of the stator’s polarities, which rotates the rotor. After every half of a revolution, direction of the current flowing in the coils reverses as the commutator rings change physical contacts to the opposite brushes as shown in Figure 6.

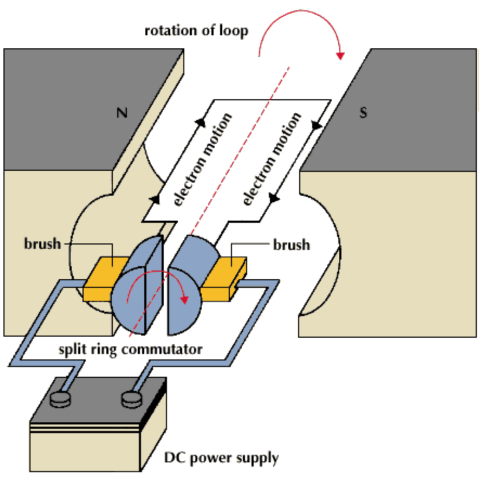


Figure 6. Simplified configuration of a brushed DC motor. Garche 2008.

There are four types of brushed DC motors such as permanent magnet, shunt-wound, series-wound and compound-wound. The fundamental difference between the four types lies in the ways stationary parts are configured. A permanent magnet DC (PMDC) motor uses permanent magnets to produce the magnetic field. The torque is limited to the permanent magnets' capability, which limits the range of applications. However, a permanent magnet brushed DC motor has good speed control capability as it responds quickly to changes in voltage. In a shunt-wound brushed DC motor, magnetic polarities are created by windings which are connected in parallel with the windings of the rotor. It is excellent at controlling speed. The motor type provides constant torque at low speed range while the torque is decreased at high speeds. Series-wound motors have field windings in series with the rotor. The motor type is usually applied in high torque applications such as cranes and winches. Series-wound brushed DC motors have poor speed torque characteristic, meaning that speed value is inversely proportional to the torque. This can be dangerous in some applications that when loads are removed instantly, the speed will sharply increase. A compound wound brushed DC motor is a combination of both the shunt-wound and series-wound motors in terms of hardware configuration and performance characteristics. It has high torque at low speeds as seen with the series-wound brushed DC motors and excellent speed control capability as with the shunt-wound brushed DC motors. The motor type is greatly suitable for industrial and automotive applications. However, this is the most expensive type of brushed DC motors. (Mouton 2008.)

Brushless DC (BLDC) motors do not use brushes. The configuration of a brushless DC motor is different from a brushed DC motor that a rotary part is a permanent magnet while a stator consists of coils. Thus, this is one benefit of a brushless DC motor that there is no physical contact between mechanical parts, which means there are less wear parts compared to a brushed DC motor which requires less maintenance. With a BLDC motor, rotation is done by changing direction of the magnetic fields generated by stationary coils. The speed of the rotation is adjusted by changing the voltage to the coils. As a BLDC motor has to know the position of the rotor in order to give pulses to the correct coils, there is a sensing encoder that detects the position and a controller that sends signals to the motor accordingly. Due to good controllability and long operating life, BLDC motors are used in devices that run continuously such as washing machines, air conditioners and other consumer electronics. A stepper motor is a BLDC motor that operates in discrete steps, meaning that it is a synchronous brushless motor where a full rotation is made up by a number of equal steps. The rotor is a permanent magnet or soft iron surrounded by the stator which comprises of electromagnets which form the stationary part of the motor. Every time an input DC voltage is applied in sequence, a stepper motor rotates one step at a time. The distance between each step is called step angle. The range of steps per revolution is wide, started from 12 to 400, which means the range of step angle of 30 to 0,9 degree. Being operated under the same principle, stepper motors are emphasized in position control aspect while BLDC motors are focused more on continuous running applications.

On the other hand, the majority of high-power motors use AC power source and work in completely different way as compared to DC motors. There are two types of AC motors including asynchronous motors and synchronous motors. Firstly, an asynchronous AC motor (or so-called induction motor) operates under the principle of electromagnetic induction. When the stator winding receives the supply, magnetic flux is produced due to the flow of current in the coil. The rotor consists of short-circuited coils. According to Faraday's law of electromagnetic induction, when the flux cut through the coil in the rotor, the current will start flowing through the coil of the rotor. Consequently, another flux is generated in the rotational part. The flux produced by the rotor will be lagging after the stator's magnetic field. The difference between the two rotating speeds is called a slip. With a synchronous AC motor, the rotation of the rotor is synchronized with the frequency of the supply current. This is possible as the rotor winding is injected with DC supply, which creates poles at the rotor that perform as a magnetic locking between the stator and the rotor magnetic fields. AC motors share with BLDC motors several advantages over brushed DC motors such as cost effectiveness, long-lasting characteristic, quietness and minimum need of maintenance. However, an AC motor could only rotate at a fixed speed associated with the frequency of the alternating current unless a variable-frequency drive is adapted, which increases the cost of the system. Also, the weight of AC motors is another disadvantage due to the coil windings.

2.3 Variable-frequency Drive

There are several ways of naming an electrical device that controls an induction motor, be it variable-frequency drive (VFD), AC Drive or inverter. The function of an inverter is to manipulate 3-phased induction motor speed and torque by adjusting input frequency of alternating current and voltage.

The structure of an inverter comprises of several major components which include: Rectifier, DC bus, inverter and a control circuit. AC power is converted to DC power through rectifier, then the power is sent through DC bus in order to be stored and delivered to the next phase. The DC bus consists of capacitors and inductors to smooth against ripples. Inverter which includes electronic switches such as: transistors, thyristors, IGBT, etc., receives DC power and converts it to AC which is delivered to the induction motor. The technique being used is pulse width modulation as to control output frequency for controlling the speed of motor. Last but not least, control circuit performs as an interface which receives feedback signals from motor like current, speed reference and give back ratio of voltage to frequency to control motor speed. (Sourav 2019.)

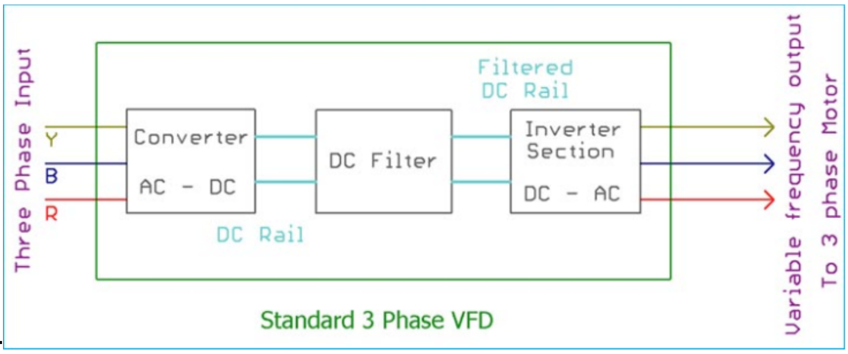


Figure 7. Structure of an inverter. Sourav 2019.

2.4 Power Transmission Technology

As discussed in previous section, electrical drives hold several advantages over other forms of actuators. However, one major drawback of electrical motors is low produced torque compared to their own sizes and weights. There is a set of solutions to overcome the disadvantage by adapting transmission technologies such as gearboxes, belt drives and chain drives.

A gearbox is a mechanical component that consists a series of integrated gears covered by a housing. The function of a gearbox is to alter torque and speed between an input supply and an output load. Based on orientation of axes, gearboxes are differentiated to three categories including parallel axes, intersecting axes and non-parallel (non-intersecting) axes. In a parallel-axes-typed gearbox, an input shaft and an output shaft are parallel. Examples of this type of gearbox are spur gear, rack, helical gear and internal gear. They provide high transmission efficiency. With a system of intersecting shafts, for example bevel gear, the drive shaft and the load shaft form right angle of orientations. The last type of gearing system includes worm gear and screw gear that the shafts are neither parallel nor intersecting each other. This is the least efficient type of gearbox due to sliding contacts. The application of gearbox is vast and various. Sometimes a gearbox can be used as a combination with belt drives or chain drives for optimization.

Figure 8. Configurations of different types of gearboxes. Marcep Inc 2017.

Another transmission technology that is widely used in industrial environment is belt drives. The system consists of a driven pulley, a driving pulley and a belt. Mechanical power or rotary motion is transmitted from the driving pulley to the driven pulley due to frictional grip between the belt and the pulleys' surfaces. Belt drives have several benefits including transmission efficiency at high speeds, low cost of operating and maintenance, life-long running and smooth operation. Yet, loss of power usually occurs due to slip between pulleys and belt. On top of that, there is always creep in this type of drive as different sections of the belt encounter expansion and contraction in the same time due to the difference in pulleys' diameters.

Lastly, chain drives are usually preferred in industrial applications such as moving of heavy materials, hydraulic lift truck fork operation, hoists, etc. They transfer power through the use of a linked chain and sprockets. Chain drives do not slip or creep compared to belt drives. Besides, the technology is highly efficient in transfer a large amount of torque within a limited space. Chain drives require frequent lubrication. The drive type can cause vibration and noise.

2.5 Closed-loop Control Mechanism: PID Controller

Control system with feedback loop is commonly adapted in many industries. Depending on the applications the models of the mechanism vary accordingly. Overall, controllers give set point values of engineering parameters to system output, sensing technology records real time values and sends back to controllers in form of electrical signals. The controllers measure differences between real time values and set point values (error values) and adjust the system in the way that errors are less likely to happen overtime and the values are minimized as much as possible. This is done with specific built-in mathematical functions inside the controllers. As mentioned above, closed-loop feedback models are unique with their own applications. Figure 9 shows one example of a model in speed control of DC motor:

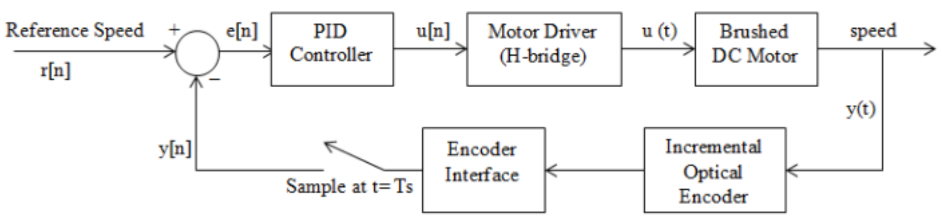


Figure 9. Speed Control model of a DC motor. Joshi 2016.

An open-loop system operates in the way that electrical supply is sent to a motor from a drive to actuate motion without receiving any feedback information from the output load. Such mechanism is associated with motors without any integrated sensors regardless of power source types. Stepper motor is the most favorable candidate among other open-loop drives in term of motion control. In real-world tasks, disturbances play large roles in causing hassles to the systems which yield output values that are totally unrelated to set point values. Thus, servo technology with its feedback feature is commonly seen in industrial environment. A sensing technology, which is a rotary encoder, is integrated at the end of a rotary shaft to form a closed-loop mechanism. Information of the rotor such as speed and position are interpreted and sent back to the motor drive. Based on the values it gets combined with pre-defined motion profiles, the drive adjusts the current and voltage accordingly.

Proportional-integral-derivative (PID) is the control algorithm that is used by most motion control applications. The proportional component of the PID controller determines a linear relationship between system's error and the output. The ratio between the change of the output and the change of the input is called proportional gain whereas the inverse ratio of the two parameters is defined as proportional band. The integral controller is different from the proportional controller that proportional controller needs constant error while the integral peer accumulates previous errors overtime. The purpose is to eliminate the offset that results from the proportional control. Derivative control is adapted to limit overshoot and dampen system oscillations. It determines the output based on the rate of change of the error. As different applications have their own specific behavior requirements, there is barely an absolute guideline for tuning PID controller. Two of the most popular methods are Ziegler-Nichols method and Cohen-Coon method. In Ziegler-Nichols method, the I and D terms are set to zero. After that, proportional gain is increased until the system achieves a stable oscillation point. The ultimate gain is used in conjunction with the period of the oscillation in order to determine the proportional gain, integral time and derivative time. Cohen-Coon method starts with already settled process and then conducts a step change test to determine the process gain, dead time and time constant. (Collins 2017.)

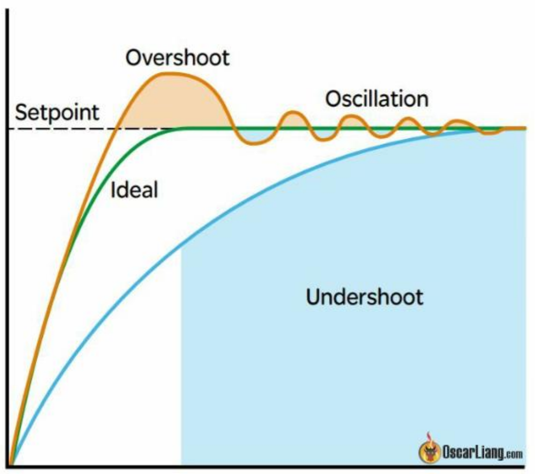


Figure 10. Example of oscillation in a PID tuning application. Liang 2018.

Regarding to motion control application, closed-loop control system with integrated PID controller outweighs traditional open-loop counterpart. Although a stepper motor is still idea for certain applications such as 3D printers, textile machines, printing presses, etc., those requires low speed torque in general and it might be cheaper due to simple implementation and programming, a stepper motor cannot avoid step loss which is responsible for low position accuracy and low stability. Higher dynamic applications usually demand closed-loop mechanism.

2.6 Sensing Technology: Rotary Encoder

A rotary encoder plays an important role in a closed-loop motion control system which can be mounted either at the back of a motor shaft to form a servo motor or at an output load. There are two types of rotary encoders such as absolute encoder and incremental encoder. An absolute encoder converts angular position of shaft to electrical signals whereas an incremental encoder provides information of the shaft including position, speed and distance. Both types are similar in the way information is interpreted into electrical signal that when motor is running, a beam of light is shed into a rotating circular disk with a number of hollow marks.

Signals are generated when the beam passes through those marks entering photosensor. (Khan 2015.)

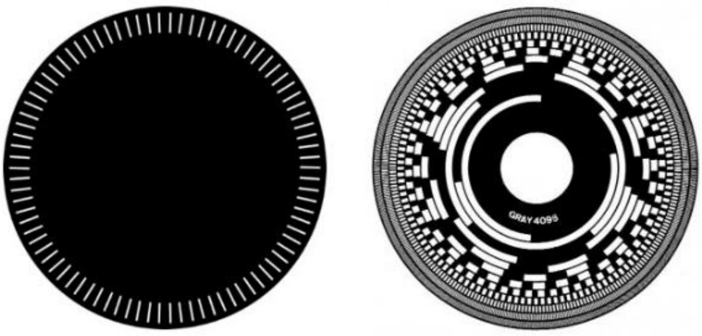


Figure 11. Configuration of incremental encoder (left) and absolute encoder (right). Khan 2015.

Incremental encoder provides a specified amount of pulses in one rotation of the encoder. The output can be either single line of pulses with an A channel or two lines of pulses including A and B channels that are offset in order to determine direction of rotation. For some encoders with a zero mark, there can be a third channel Z or N which gives a pulse every revolution. (Hengstler.)

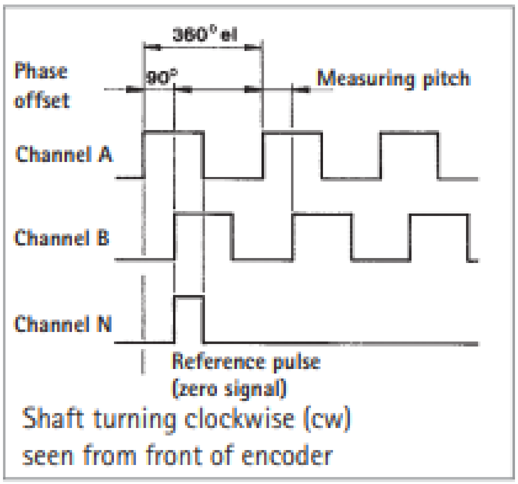


Figure 12. Signal output of an incremental encoder. Hengstler.

One useful method which can be utilized with an incremental encoder is to double or quadruple the resolution based on the subsequent circuitry as shown in Figure 10. For example, a channel provides 1000 pulses per revolution (PPR) can be quadrupled to 4000 resolution feedback output.

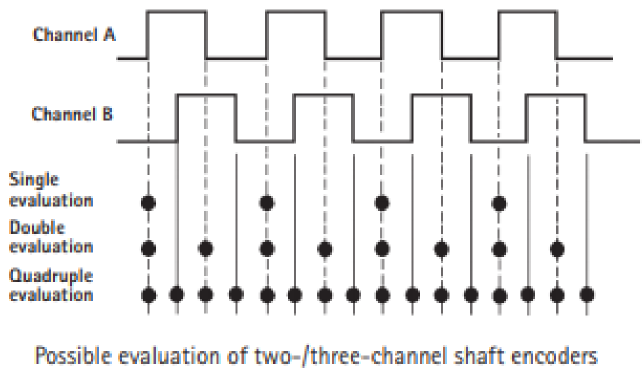


Figure 13. Quadrupling technique of incremental encoder. Hengstler.

On the other hand, absolute encoder operates in different mechanism. According to Smoot (2018), an absolute encoder tells exactly the position of rotating shaft due to pre-assigned codes of a disc. This is a reason that information of position is not lost when power is shut down. Rather different from pulses generated in incremental encoder, resolutions of absolute encoder are interpreted in terms of bits associated to the number of unique data words over one revolution. Furthermore, an absolute encoder offers two modes of operation: single-turn and multi-turn. Single-turn encoder provides data of position over one revolution which is repeated after every revolution whereas multi-turn encoder provides additional ¨turns¨ counters measuring number of revolutions.

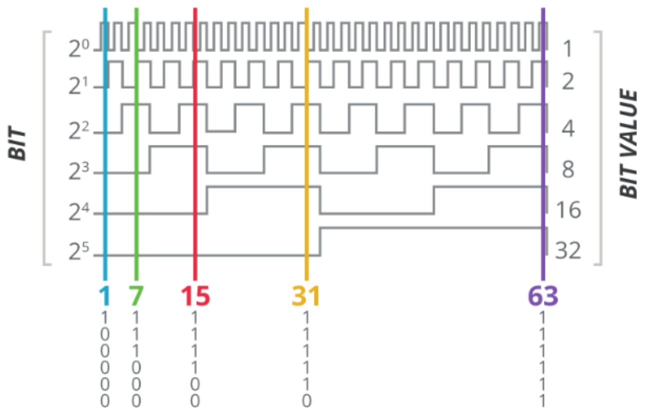


Figure 14. Digital interpretation of position in absolute encoder. Smoot 2018.

While incremental encoder is simple built thus cheaper, absolute encoder is more essential in some applications. An absolute encoder remains information of shaft position when power is off while an incremental encoder loses the information.

Re-homing procedure in case of incremental encoder usage can be time consuming and impossible sometimes, for example with a robotic arm. (Smoot 2018.)

2.7 Motion Control Profiles

While it is important to have an optimal oscillation and reduce overshooting phenomenon for a servo-based motion control system, how the motion profiles are graphically depicted play large roles in affecting the system performance. A point-to-point traversing profile is one of the most basic moves that is used in almost every motion control application. A load is accelerated to a constant velocity until deceleration happens to stop the load at an end point. This can be depicted as a triangular or trapezoidal motion profile as shown in Figure 15. The triangular profile is used in such cases that travelling between two points happens in shortest amount of time. The system accelerates quickly to the maximum velocity and then immediately decelerates to zero. This is applied in basic pick-and-place applications. On the other hand, a trapezoidal motion profile is adapted in systems where the maximum velocity is expected to stay constant for certain amount of time. The trapezoidal motion type can be witnessed in CNC applications such as machine tools and printers.

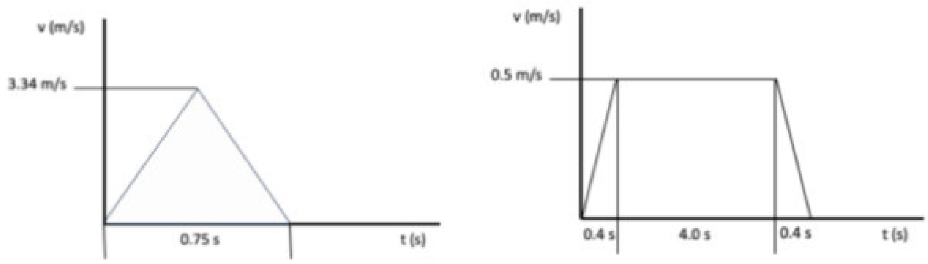


Figure 15. Triangular and trapezoidal motion profiles. Collins 2019.

When it comes to system dimensioning, there are four engineering parameters that form a motion profile which consists of distance, velocity, acceleration/deceleration and jerk. From a mathematical point of view, the later functions are the derivative of the previous ones, for example velocity is a derivative function of distance while acceleration is the derivative of velocity and so on. Acceleration is the rate of change in velocity while jerk is the rate at which acceleration is increasing or decreasing. In a trapezoidal profile, acceleration jumps constantly from zero to constant value, which causes theoretically infinite jerk. This is undesirable as jerk causes vibration which affects position accuracy, settling time and cycle time (Collins 2017). One method to reduce jerk is to change motion profile from a trapezoidal shape to an s-curve profile. In an s-curve moving profile, acceleration and deceleration form a trapezoidal shape as shown in Figure 16. The method smooths motion at critical points rather than making them change suddenly and abruptly.

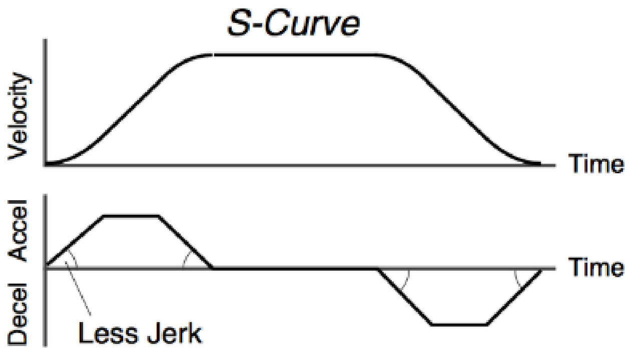


Figure 16. S-curve move profile. Collins 2017.

2.8 Programmable Logic Controller (PLC)

A programmable logic controller (PLC) is a form of microprocessor-based controller designed for industrial usage (Bolton 2009, p. 3). A PLC uses a programmable memory to store user-oriented instructions and to implement functions such as logic, sequencing, timing, counting and arithmetic in order to control machines and processes (IEC 2003, p. 7). The structure of a PLC consists of a power supply, a central processing unit (CPU), input/output cards, memory and a rack that supports whole modules.

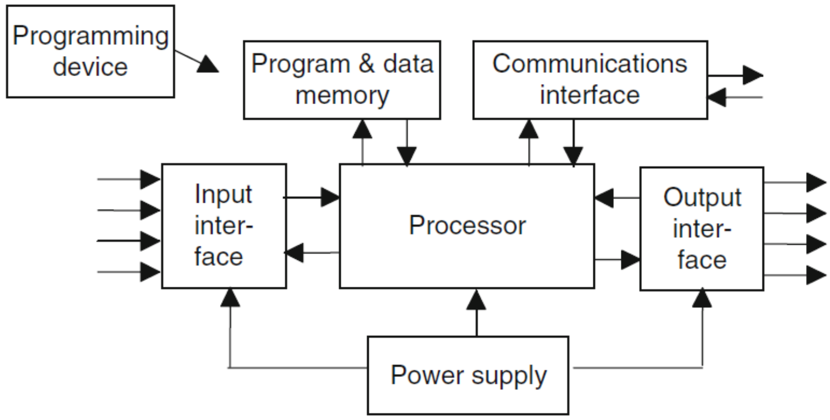


Figure 17. Structure of a PLC. Farisi 2017.

Regarding PLC programming, John and Tiegelkamp (2001, p.12) indicates: “IEC 61131-3 sees itself as a guideline for PLC programming, no as a rigid set of rules. The enormous number of details defined means that programming systems can only be expected to implement part but not all of the standard. PLC manufacturers have to document this amount: if they want to conform to the standard they have to prove in which parts they do or do not fulfill the standard”. This guideline plays a vital role on the PLC market and its development, as it considerably shortens the time to market for PLC manufacturers as well as eliminating the need for system specialists and training personnel, helping PLC programmers more flexibility and capability to work with multiple PLC systems simultaneously.

2.9 Data communication

Network devices are capable of communicating to each other relying on network protocols. Network protocols comprise sets of established rules that govern how data is formatted and transferred regardless of the differences in their underlying infrastructures, designs or standards. There have been several network protocols that are designed specifically for industrial applications due to higher demand in performance. Typically, the differences between these industrial networks to an office ethernet are higher delivering time of data package, guaranteed mechanism for data collision avoidance and better protection class of physical layers as they get exposed to hazardous environment.

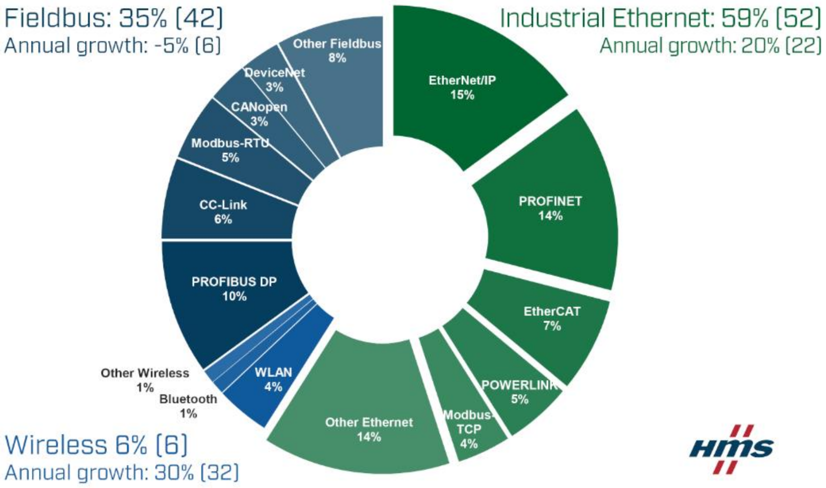


Figure 18. Industrial network market share in 2019. HMS Networks AB 2019.

According to HMS Networks report, two of the most dominant industrial networks are Industrial Ethernet and Fieldbus. In 2019, Industrial Ethernet accounts for more than half of industrial market shares which is 60%, followed closely by fieldbus making up to 35%. In can be noticed that in 2018, the shares ratio between the two were 52% over 42%, indicating that Industrial Ethernet has been outgrowing fieldbus with growth rate of 20% compared to -5% of fieldbus. While the most popular candidate of fieldbus is PROFIBUS which contributes to 10% of the market share, Ethernet mainly consists of EtherNet/IP, PROFINET and EtherCAT with the number of 15%, 14% and 7% respectively. Besides, a steep growth can be seen from wireless network which is 30%. (HMS Networks 2019).

Fieldbus is a mean of communicating between industrial input devices (sensors, switches, etc.) and output devices (actuators, valves, drives, etc.) without connecting every single device back to programmable logic controller, meaning that multiple devices to connect simultaneously. Profibus is the most successful fieldbus technology with speeds up to 12 Mbps and supports up to 126 addresses.

Ethernet communications typically are non-deterministic with a reaction time of around 100 ms. Industrial Ethernet protocols utilized Media Access Control (MAC) layer to achieve deterministic responses and very low latency (Texas Instrument, 2018). When it comes to motion control applications, Ethernet-based protocols are mostly preferred due to their mechanism and competitive performance with lowest cycle times. As clearly seen in Figure 16, the three most dominant candidates of industrial Ethernet support their own unique competitiveness to the market. The comparison is made in two bandwidths 100Mbit/s and 1Gbit/s. With bandwidth of 100 Mbit/s, EtherCAT claims the winning position with lowest cycle time of 1.35 µs whereas Profinet and Isochronous Real-time (IRT) and EtherNet/IP operate at 3 µs. In contrast at 1 Gbit/s bandwidth, Profinet (IRT) and EtherNet/IP run at lowest available cycle time of 0,6 µs while EtherCAT achieves 0,85 µs. J. (Robert, Georges, Rondeau, Divoux 2006-2012, p. 754.)

Protocol	*FastEthernet* (100 Mb/s)	*GigaEthernet* (1 Gb/s)
EtherCat	1.35 μs	0.85 μs
Profinet IRT	3 μs	0.6 μs
Modbus/TCP	1 μs (*hub*)	
EtherNet/IP	3 μs	0.6 μs

Figure 19. Comparison of cycle time between Ethernet-based protocols. Robert, Georges, Rondeau, Divoux 2006-2012, p. 754.

3 Project Implementation

3.1 Basic Positioner and position control features

Sinamics G120 inverter which is equipped with control unit CU 250S-2 supports function ¨basic positioner¨ (EPOS), which controls position of an axis. The term telegram is used for cyclic data exchange between a PLC and Sinamics drives. The function basic positioner uses telegram 111.

Receive data

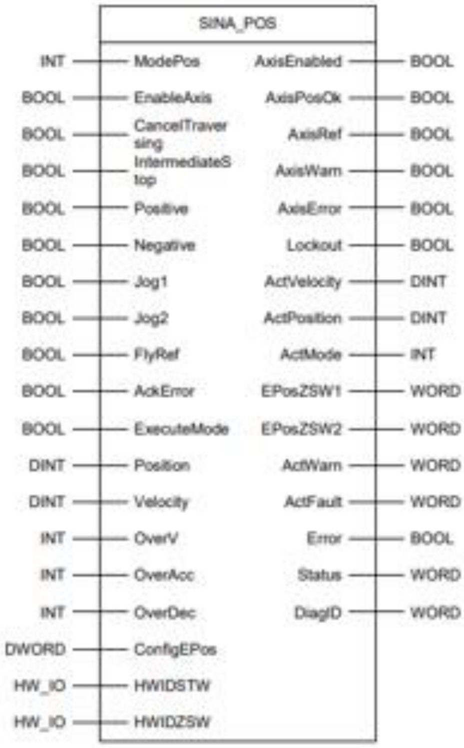
PZD Number	Reference	Description	Units
1	STW1	Main control word	BOOL
2	SATZANW	Traversing block selection	BOOL
3	POS_STW	EPOS control word	BOOL
4	STW2	Control word 2	BOOL
5	OVERRIDE	EPOS velocity override	Percentage - 16384 DEC or 4000 HEX = 100% of velocity setpoint
6 7	MDI_TARPOS	Position setpoint	LU
8 9	MDI_VELOCITY	Velocity setpoint	1000 LU/min
10	MDI_ACC	Acceleration override	Percentage - 16384 DEC or 4000 HEX = 100% of p2572
11	MDI_DEC	Deceleration override	Percentage - 16384 DEC or 4000 HEX = 100% of p2573
12	USER	User definanble	INT/WORD

Send data

PZD Number	Reference	Description	Units
1	ZSW1	Main status word	BOOL
2	POS_ZSW1	EPOS status word	BOOL
3	POS_ZSW2	EPOS status word 2	BOOL
4	ZSW2	Status word 2	BOOL
5	MELDW	Drive status	BOOL
6 7	XIST_A	Actual position	LU
8 9	NIST_B	Actual speed	Percentage - 40000000 HEX or 1073741824 DEC = 100% of p2000
10	FAULT_CODE	Fault code	INT
11	WARN_CODE	Alarm code	INT
12	USER	User definanble	INT/WORD

Figure 20. Data assignment of telegram 111. Siemens AG 2017.

On the PLC side, there are already-made function blocks associated with telegram 111 and they can be found from DriveLib. For position control, function block Sina_Pos (FB 284) is used to cyclically control Sinamics drive with telegram 111. (Siemens AG, 2017).



Name	Type	Start value	Function
ModePos	INT	0	Operating mode: 1: Positioning, relative 2: Positioning, absolute 3: Positioning as setup 4: Homing – reference point approach 5: Homing – reference point definition 6: Traversing block 7: Jog mode 8: Jog mode, incremental
EnableAxis	BOOL	FALSE	Start/stop the drive
CancelTraversing	BOOL	TRUE	FALSE: discard active positioning job TRUE: do not discard
IntermediateStop	BOOL	TRUE	FALSE: active move command is interrupted TRUE: no intermediate stop
Positive	BOOL	FALSE	positive direction
Negative	BOOL	FALSE	negative direction
Jog1	BOOL	FALSE	Jog mode, signal source 1
Jog2	BOOL	FALSE	Jog mode, signal source 2
FlyRef	BOOL	FALSE	FALSE: disable Homing on the fly TRUE: enable Homing on the fly
AckError	BOOL	FALSE	Acknowledgment of errors
ExecuteMode	BOOL	FALSE	Enable positioning job or setpoint transfer
Position	DINT	0	Position setpoint value in Length Unit (see Section Path unit LU)
Velocity	DINT	0	Speed setpoint value in Length Unit/min (see Section Path unit LU)
OverV	INT	100	Velocity override 0 – 199%
OverAcc	INT	100	Acceleration override 0 – 100%
OverDec	INT	100	Deceleration override 0 – 100%
ConfigEPos	DWORD	16#00000003	The following bits of the control word of the drive are pre-assigned: Bit 1: OFF2 Bit 2: OFF3
HWIDSTW	HW_IO	0	Hardware ID setpoint value (see Section Telegram slot)
HWIDZSW	HW_IO	0	Hardware ID actual value (see section Telegram slot)

Figure 21. Function bock ¨Sina_Pos¨ (FB 284) with block parameters. Siemens AG 2017.

3.2 Engineering calculations and specifications

The system was defined and built by Festo. From the manufacturer’s catalog, axis X and axis Y were identical in feed constant which was 58 mm per output load revolution. Both axes had the same mechanical specifications of diameter of shafts, tooth belts and gear box ratios. The only differences were stroke lengths and load carried by each axis, though they barely affected system performance noticeably in term of position control. As Basic Positioner feature was enabled, which means instead of interpreting position measurements in standard unit like m or mm, it can be shown in a customized unit which is Length Unit (LU). For example, 1 LU can be defined as 1 mm or 1 µm depending on system capability as well as how precise users want to interpret them (more often the goal is to find the smallest unit). In order to decide correctly how small the unit, other system aspects were studied and calculated.

From the catalog, the maximum frequency of the incremental encoders is 300 kHz, number of PPR is 1000 pulses which is quadrupled electronically to 4000 pulses. Firstly, the maximum speed of load amounted to encoders can be found by formula:

$$n_{max} = \frac{f_{max} * 60}{PPR}$$

- n_{max} : maximum revolution/minute
- f_{max} : maximum frequency
- 60 second/minute
- PPR : pulse per revolution

Thus, the maximum speed the encoders can bear is 4500 rpm. This value is under limit set by the manufacturer as shown in Figure 22.

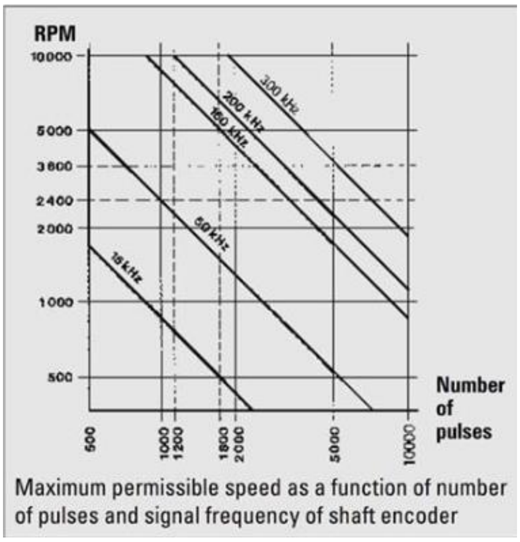
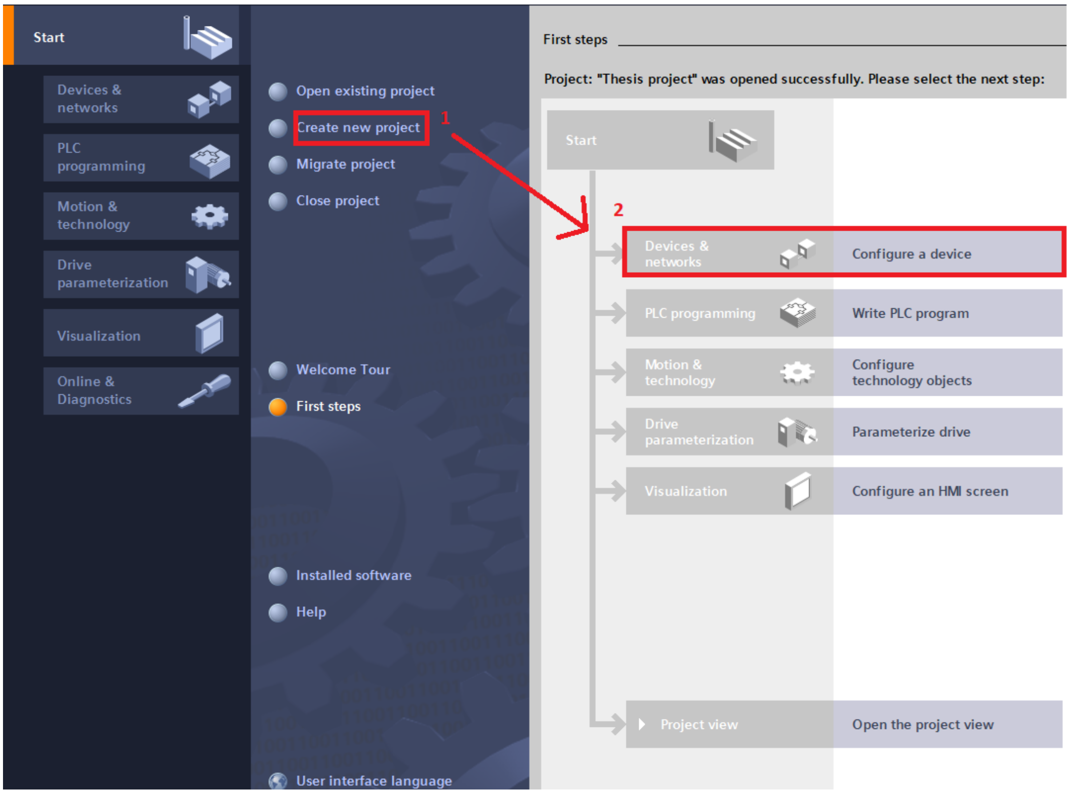


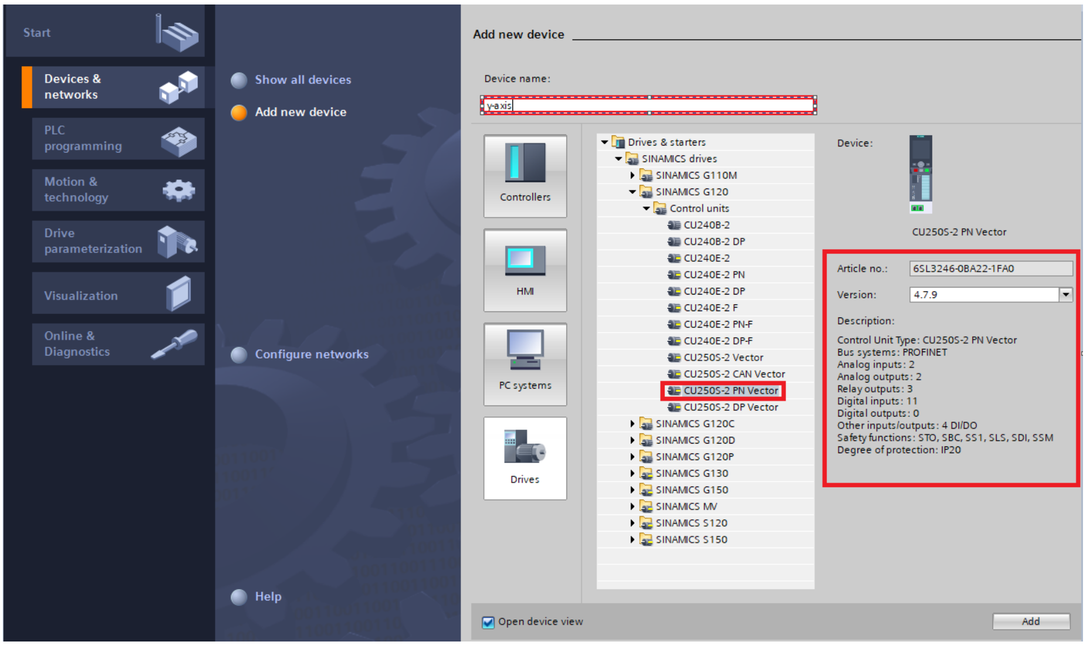
Figure 22. Graph of functional speed. Hengstler.

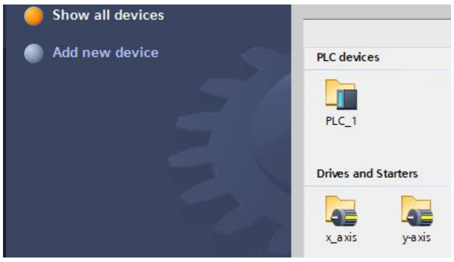
Secondly, as one revolution is divided into 4000 pulses, meaning that each pulse accounts for $\frac{360°}{4000} = 0{,}09°$. Combined with the fact that every revolution the output load makes, the axis traverses 58 mm. Hence, every pulse that is received by variable-frequency inverter, the axis traverses $\frac{0{,}09° * 58\ mm}{360°} = 0{,}0145\ \text{mm}$. This is the smallest distance the system can control and measure. 1 LU was decided to be equal to 0,1 mm or 10 mm was equal to 100 LU.

3.3 Configurations and execution

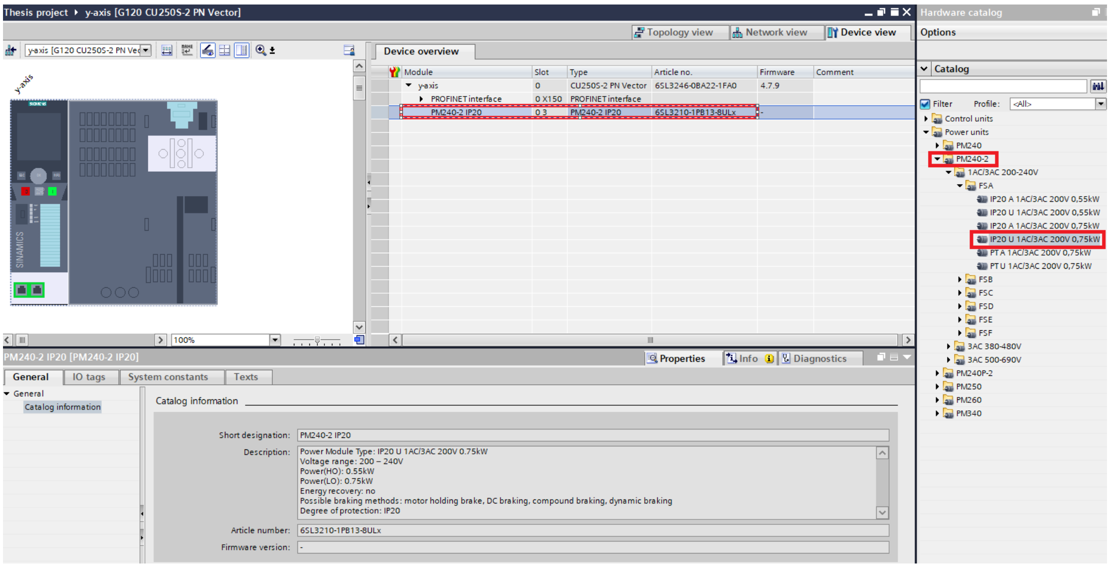
Since the project was commissioned once, this section shows step by step the tutorial of commissioning the project.



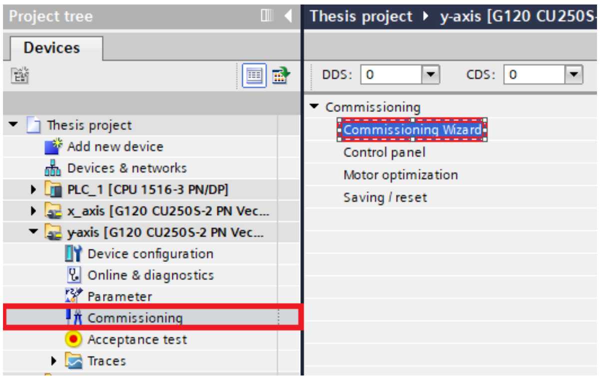




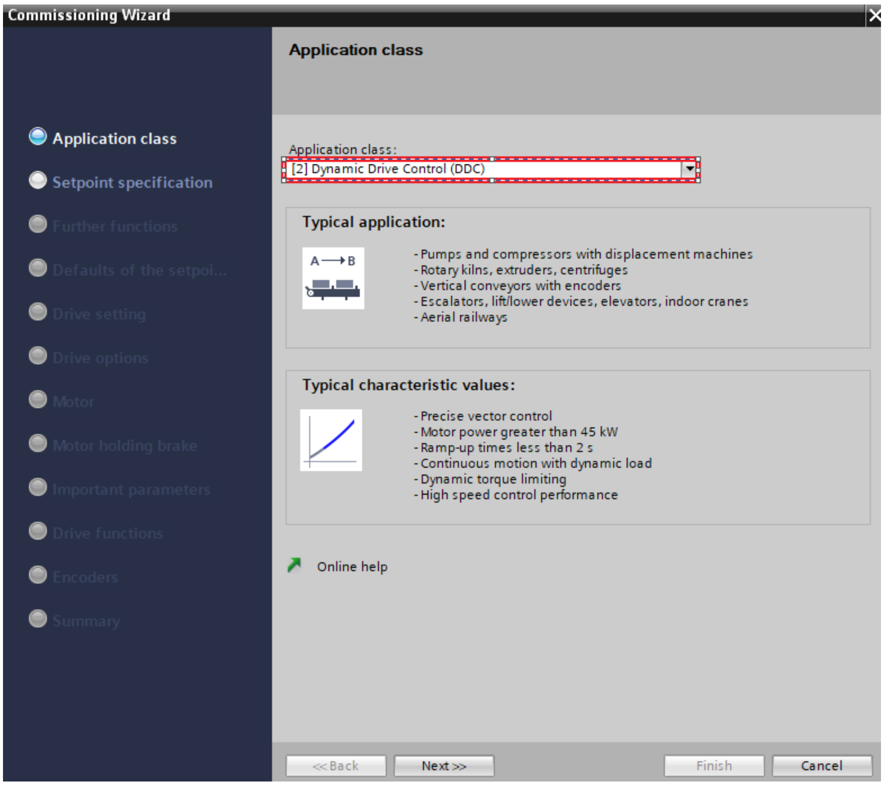
The system should include one CPU and two inverters.

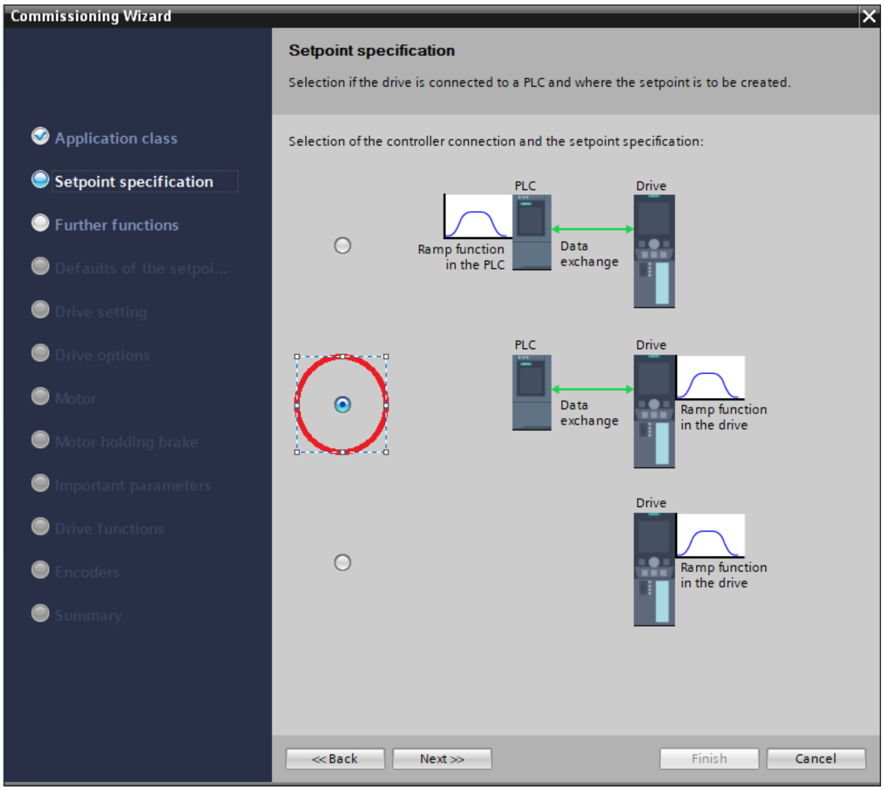


Then power unit is assigned to control units with correct device name.

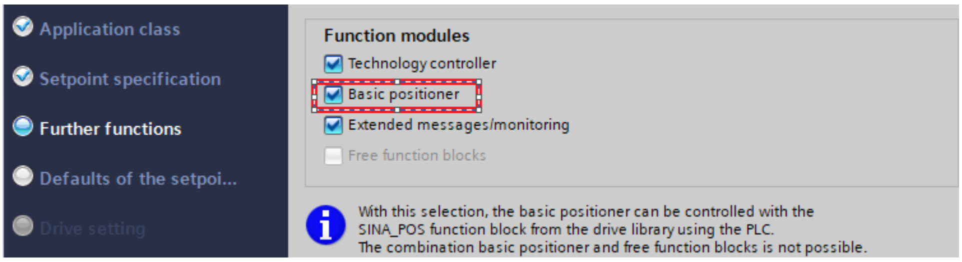


After that, the system is commissioned by commissioning wizard. Options and modes have to be selected according to the pictures listed below.

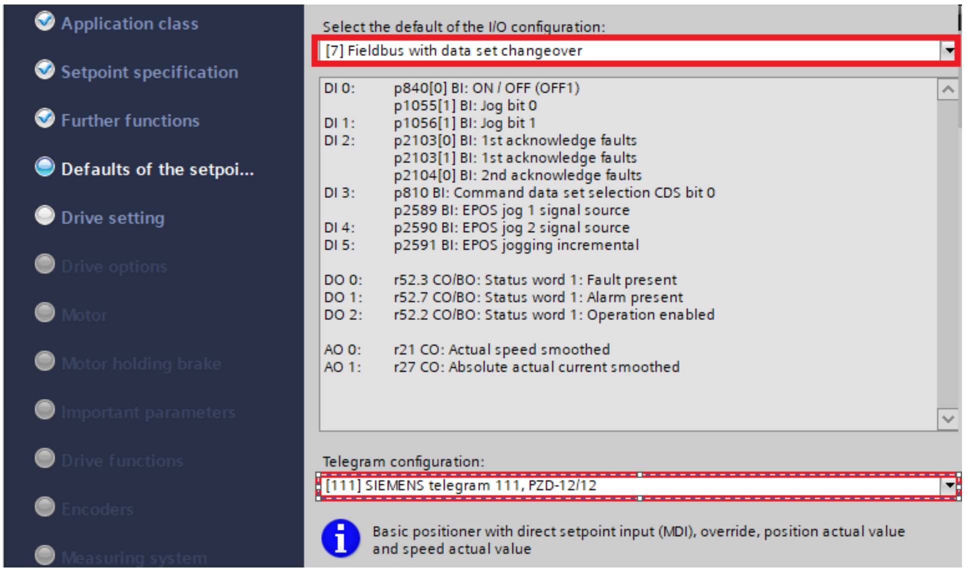




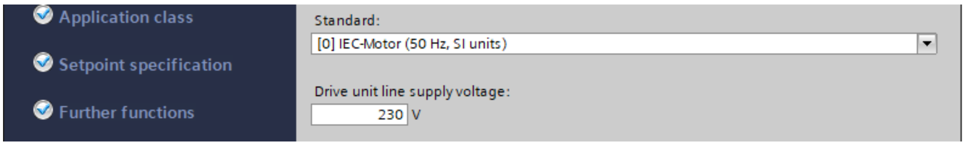
Ramping characteristics are defined in the drive.



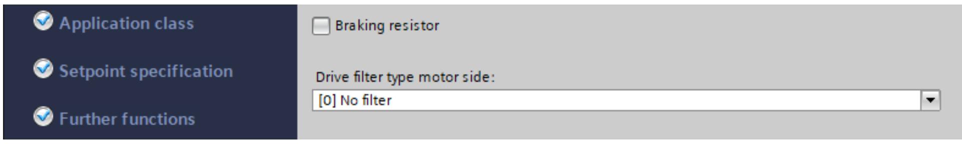
Basic positioner has to be selected in this phase in order to activate telegram 111.

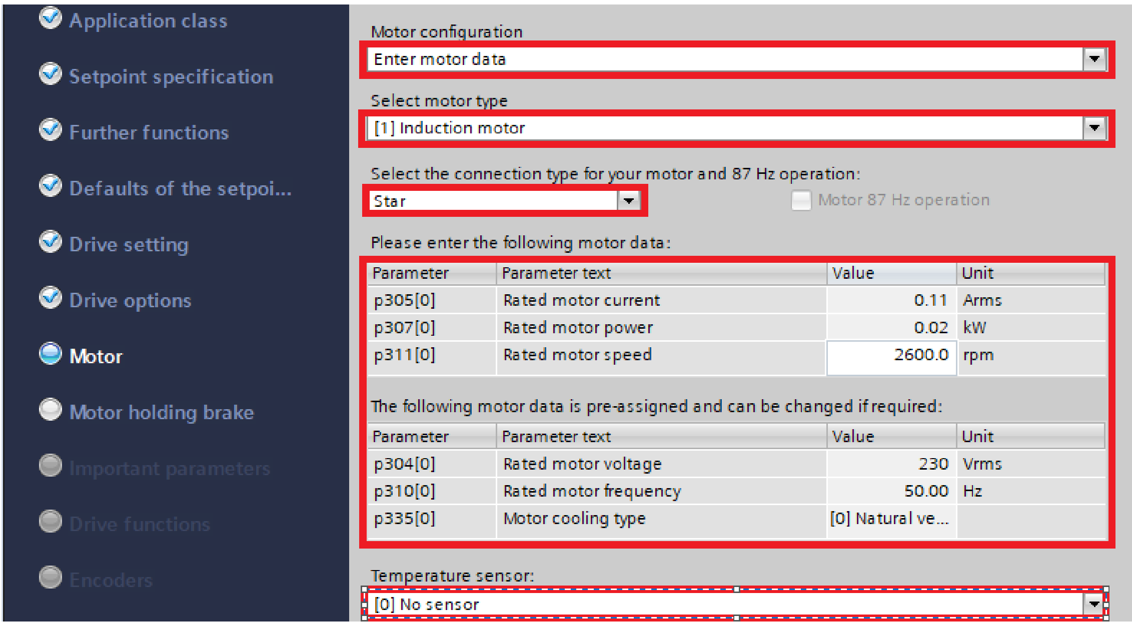


Fieldbus with data set changeover means either command data are sent from PLC or I/O terminals of the drive.

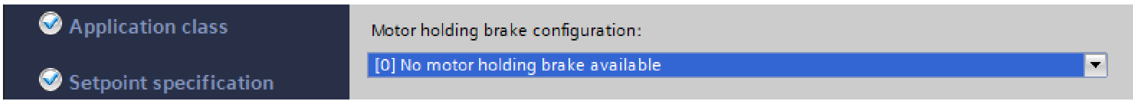


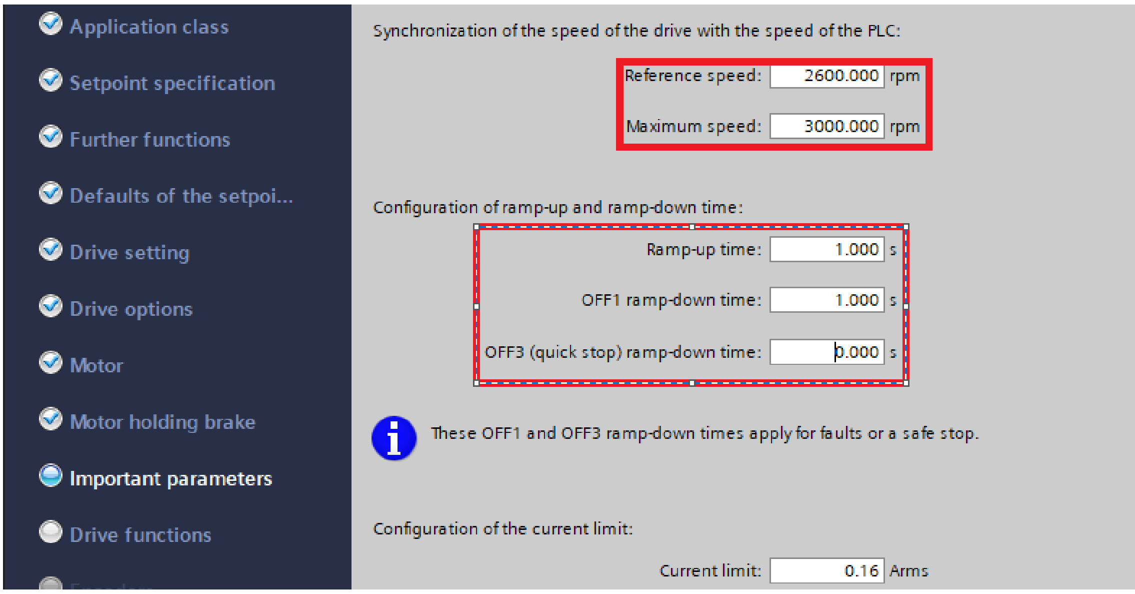
Information of supply voltage of the induction motor.



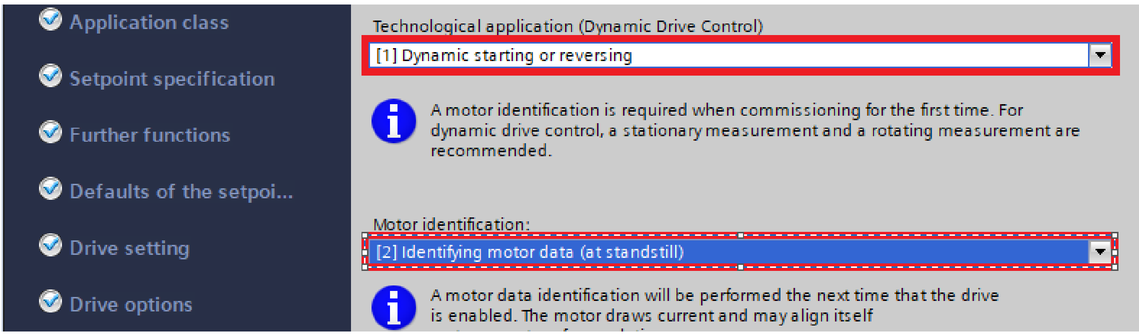


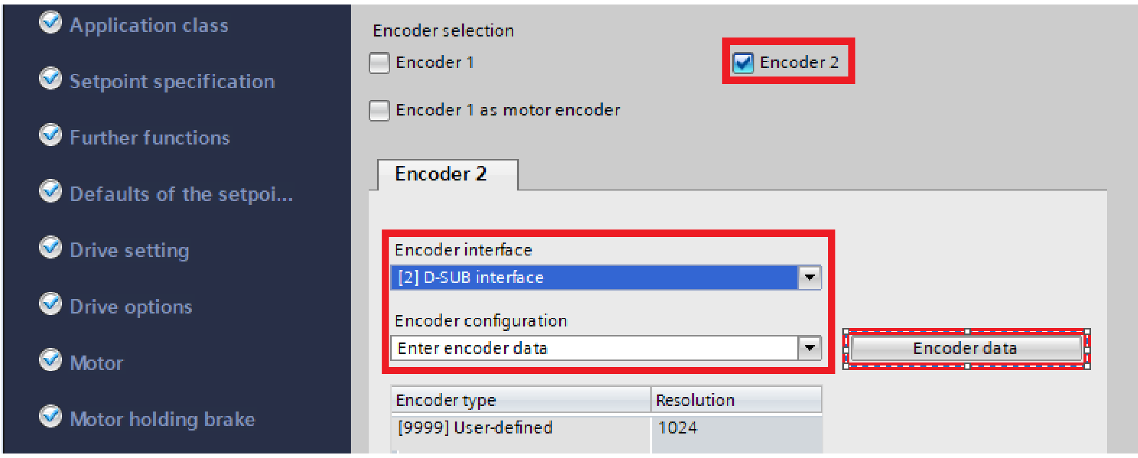
Reference values are input from motor’s plate.



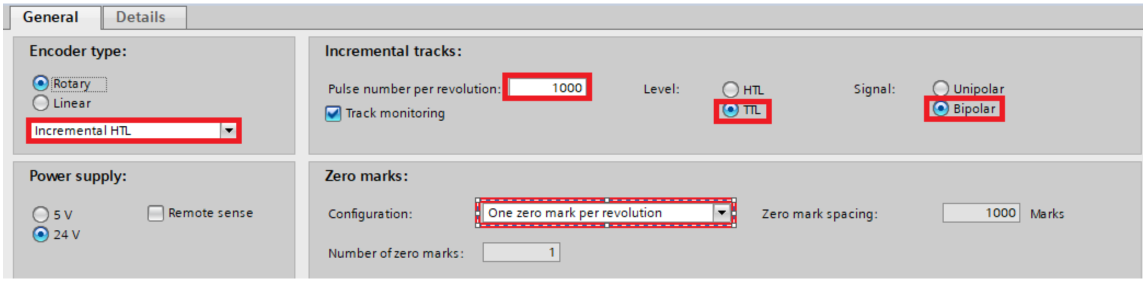


Ramping time is initially decided to be 1 second.

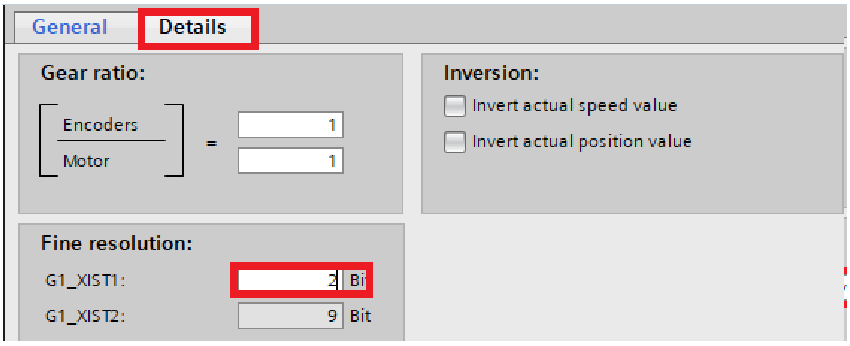




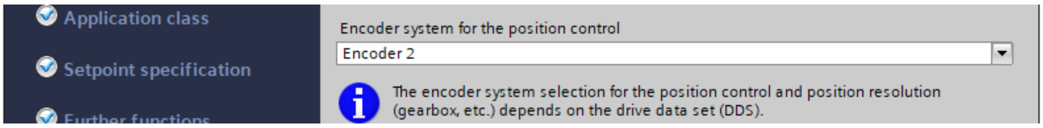
Encoder 2 box is selected as the encoder is mounted at output load and in opposite direction with the motor.

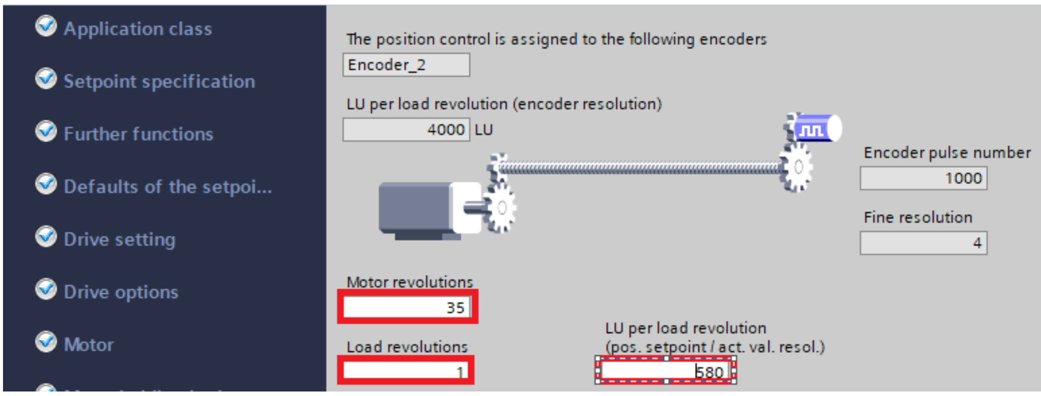


Information of incremental encoder.



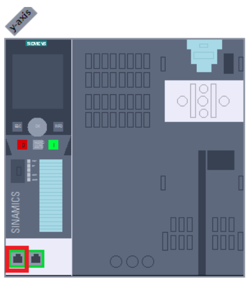
The gear ratio section tells the ratio between the revolution of encoder and motor when the encoder is mounted at the end of the motor or the ratio between revolution of encoder and output load. It is the second case in the project which is 1:1. Also, the fine resolution tells how much it can break it down from the original pulse of the encoders. As explained above, for incremental encoder, it is only possible to quadruple the resolution which is multiplication of 4, or 2^2. The parameter G1_X1ST1 indicating the multiplication.



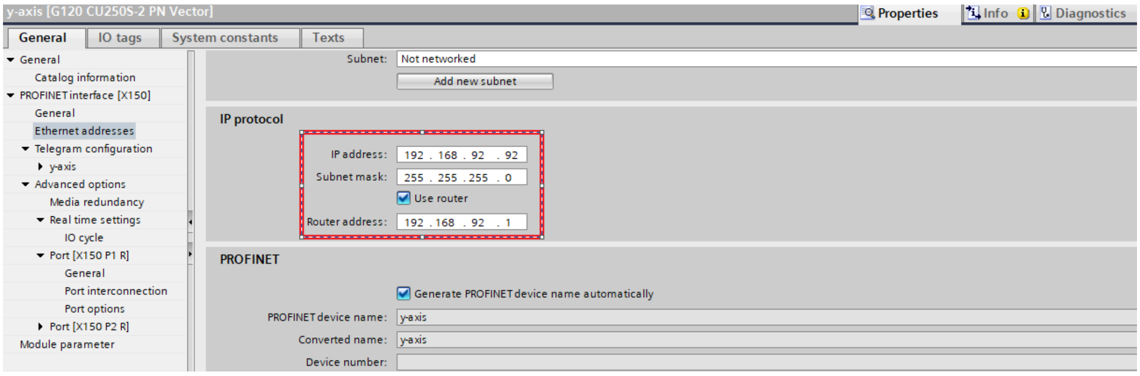


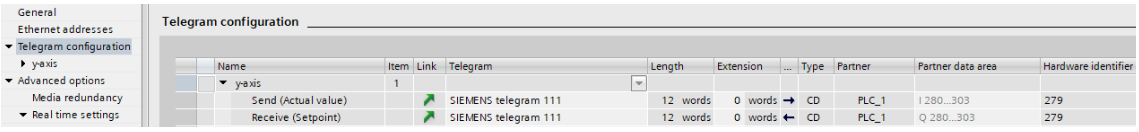
As explained and calculated above, 0,1 mm is equal to 1LU and the feed rate of the system is 58 mm per revolution. Thus, LU per load revolution is 580. Also, a gearbox was adapted to the system with the ratio of 35 to 1.

After this point, the inverters should be assigned addresses and configured in the network.

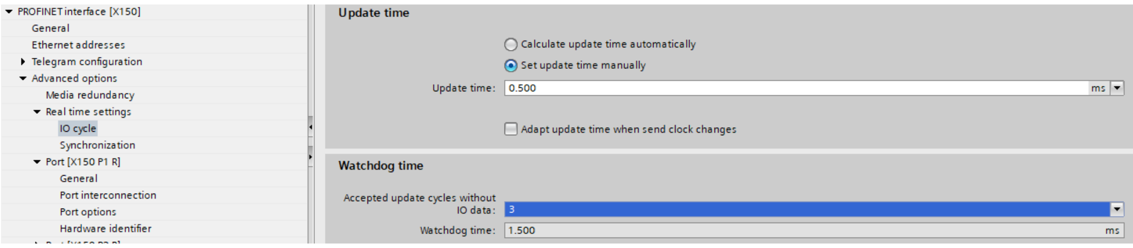


Data will be transferred through port 1 of each drive.





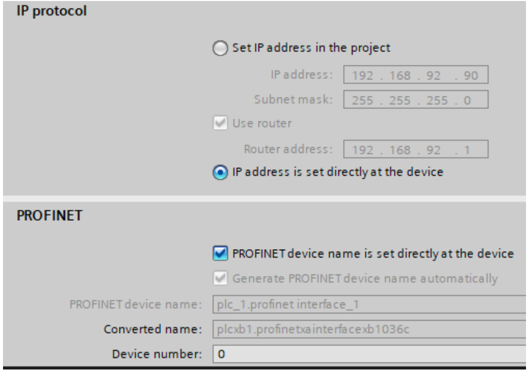
As Basic Positioner function is switched on from commissioning phase, telegram 111 is automatically assigned.

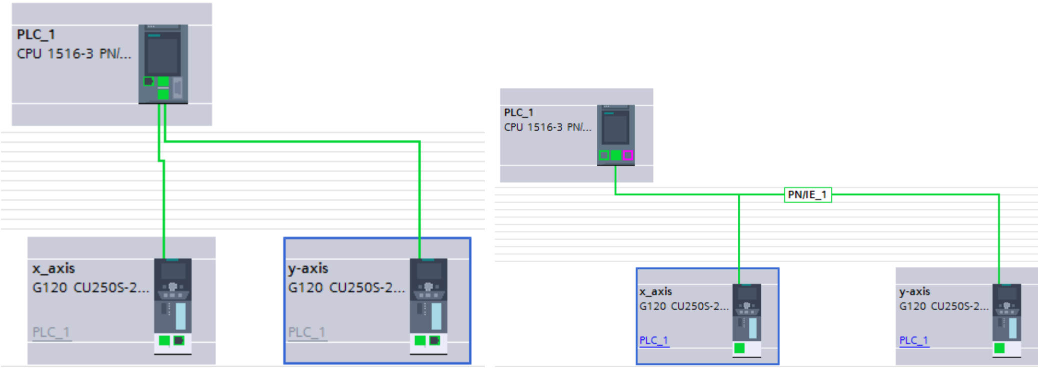


The communication is Real-time so update time can be set up at the minimum value of 0.5, followed by automatic updated watchdog time.

After this point, the PLC can be configured according to specifications of real modules.

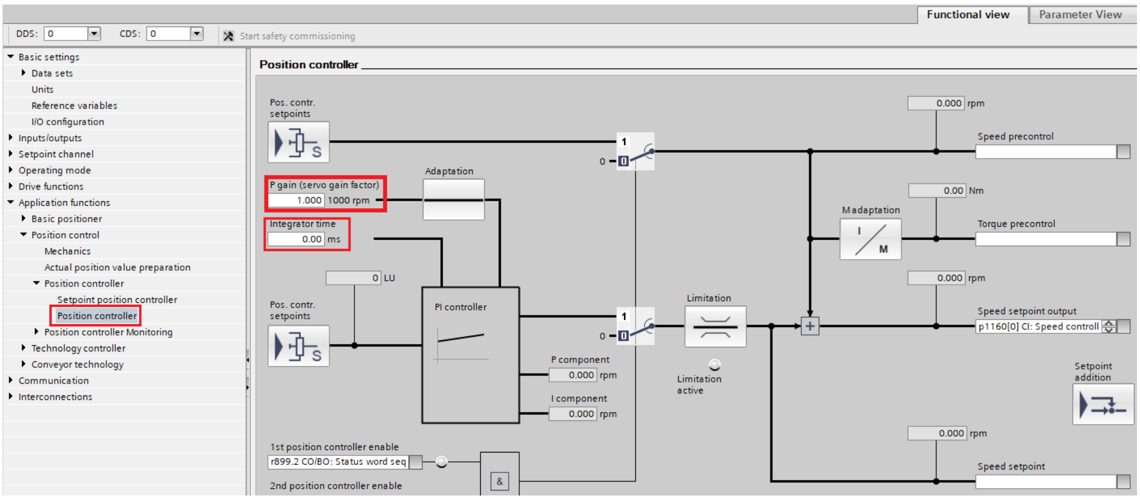
PLC_1	0	1			CPU 1516-3 PN/DP	6ES7 516-3AN01-0AB0	V2.5
PROFINET interface_1	0	1 X1			PROFINET interface		
PROFINET interface_2	0	1 X2			PROFINET interface		
DP interface_1	0	1 X3			DP interface		
DI 32x24VDC HF_1	0	2	0...3		DI 32x24VDC HF	6ES7 521-1BL00-0AB0	V2.1
DQ 32x24VDC/0.5A HF_1	0	3		0...3	DQ 32x24VDC/0.5...	6ES7 522-1BL01-0AB0	V1.0
AI 8xU/I/RTD/TC ST_1	0	4	4...19		AI 8xU/I/RTD/TC ST	6ES7 531-7KF00-0AB0	V2.1
AQ 4xU/I ST_1	0	5		4...11	AQ 4xU/I ST	6ES7 532-5HD00-0AB0	V2.1





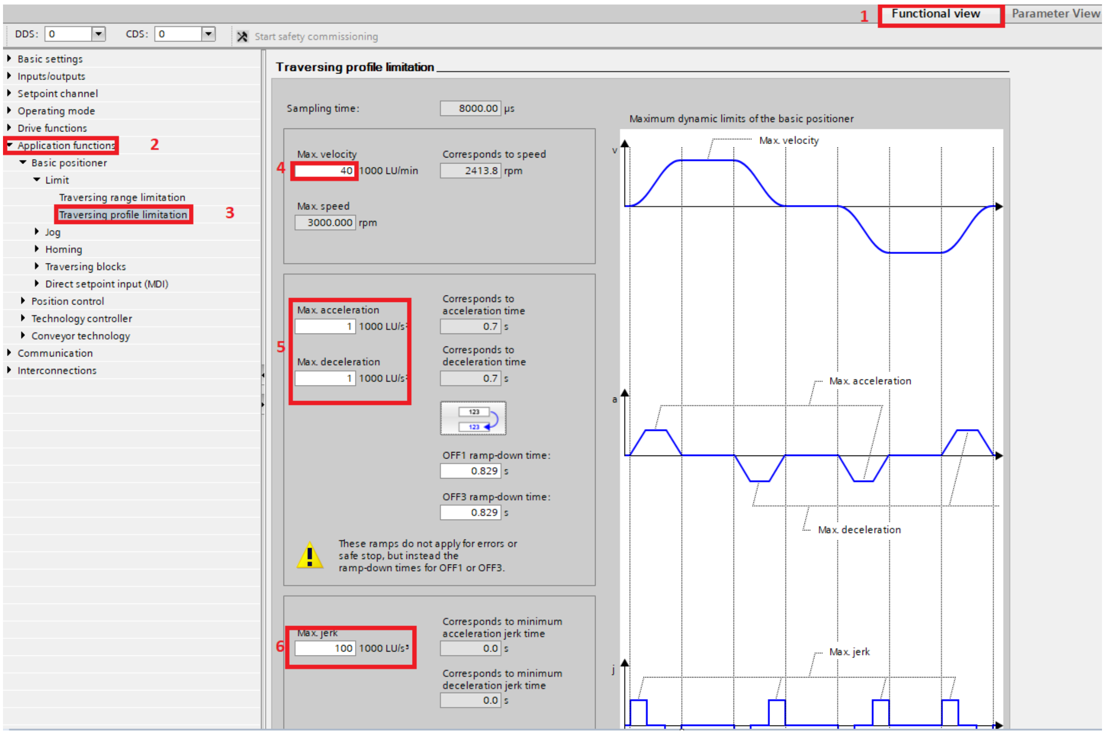
Topology view (on the left) and network view of network system.

At this point, PID tuning can be made for optimization of speed control.

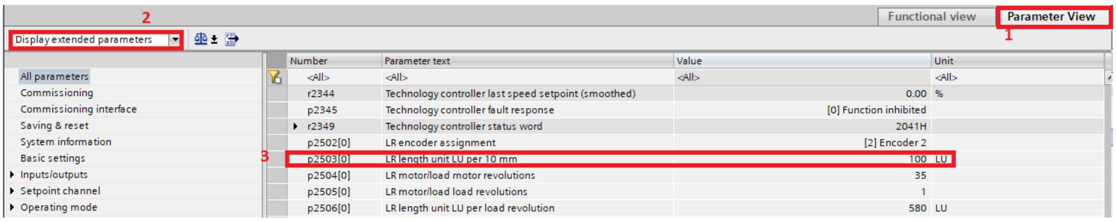


The P gain value can be increased until rotational speed achives reasonable results.

After the network configuration is done, further changes in motion control parameters as well as the designed program have to be implemented.



As in basic positioner mode, the user can define the traversing profile of axes which includes velocity, acceleration and jerk. The parameters are chosen according to reference speed and common sense.



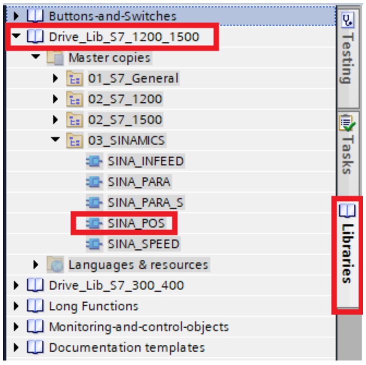
10 mm is assigned to be 10000 LU in default, so the user should re-define the parameter according to own specification.

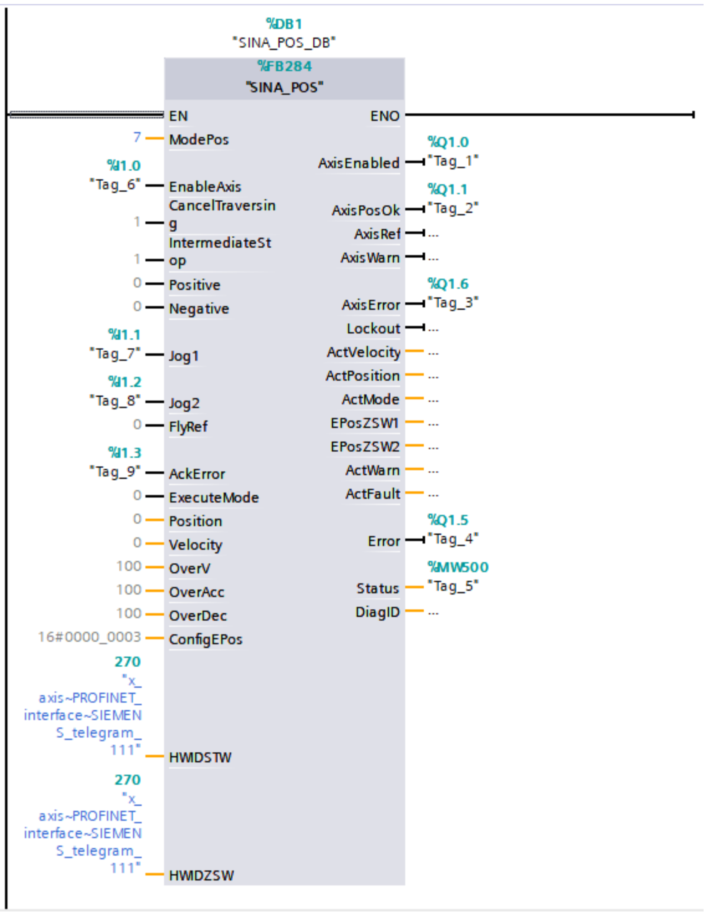
p2585	EPOS jog 1 setpoint velocity	-100	1000 LU/min
p2586	EPOS jog 2 setpoint velocity	100	1000 LU/min
p2587	EPOS jog 1 traversing distance	1000	LU
p2588	EPOS jog 2 traversing distance	1000	LU

p2605	EPOS search for reference approach velocity reference cam	50	1000 LU/min
p2606	EPOS search for reference reference cam maximum distance	2147482647	LU
p2607	EPOS search for reference reference cam present	1	
p2608	EPOS search for reference approach velocity zero mark	50	1000 LU/min
p2609	EPOS search for reference max distance ref cam and zero mai	20000	LU
p2610	EPOS search for ref. tol. bandwidth for distance to zero mark	2147482647	LU
p2611	EPOS search for reference approach velocity reference point	50	1000 LU/min

A programming block was created in PLC in order to control data received and transmitted from drives.

The ¨SINA_POS¨ block was called from Drive_Lib_S7_1200_1500 in libraries





For jogging of x-axis only, mode number 7 was chosen, HWIDSTW and HWIDZSW were assigned to telegram slot of x-axis. Other digital input signals which control the drive were also assigned.

4 Results

The experiment failed at the commissioning stage. Most of the issues were related to Basic Positioner feature such as: failure of giving command from master control (PC) to the drives, the actual engineering results did not match with parameters commissioned in the converters, the encoders measured exactly the position yet converters failed to give a correct command to output loads.

As there were many parameters which interrelated to each other and due to project time limit, exact causes for each problem could not able to be found. On the other hand, the network was configured correctly with precise devices' addresses and specifications of network transmission.

5 Future Work

Due to the complication of the project, it is suggested to follow other motion control projects with tightly related system configurations and features for time saving purpose. On top of that, some of the components were not state of the art including the inverters and the incremental encoders. The encoders used in the project were universal industrial encoders with 1000 PPR which theoretically guaranteed linear movement accuracy of 0,1 mm as proved above. Encoders with higher number of pulses of at least 5 times more can be integrated in order to achieve accuracy which is competitive in the market level. The control unit CU250S is not able to offer IRT communication, which can be replaced by a later version of the drive.

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