LinMot®

How To: Force Control Loop Tuning

A guide to setting up the “Force Control” technology function

Classification: [x] Public
[ ] LinMot internal

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About This Document

The information used in this manual is based on the firmware:

- Firmware 6.9 Build 20201026

When using other versions, the scope of functions may differ!

Introduction

For accurate and stable force control there are a few points to consider:

- Measure as close as possible to the load on which you want to couple a controlled force!
- It is favorable to work against the intrinsic mass of the mechanical system when the force is applied vertically and not to superimpose the intrinsic mass of the force to be controlled.
- Select the measuring range of the sensor to suit the requirements of the application.
- Ensure that the sensor selected is rated to measure forces dynamically.
- Avoid unnecessarily large measuring ranges, as this reduces resolution.
- As a rule, the best accuracy of a sensor is always in the upper third of the measuring range.

Hypothetical use cases:

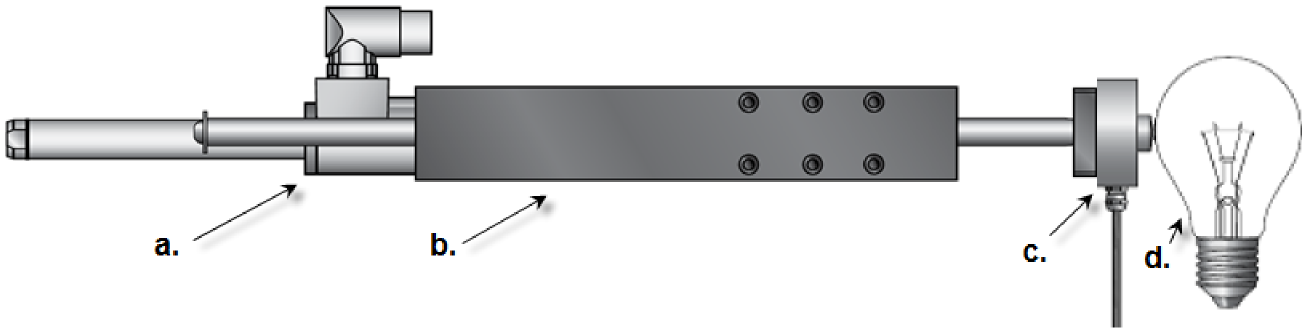

Figure 1: Hypothetical use case - feasible

Figure 1 shows a linear motor (a) in a guide (b). The force sensor (c) is mounted at the end of the guide and exerts a pressing force on an object (d).

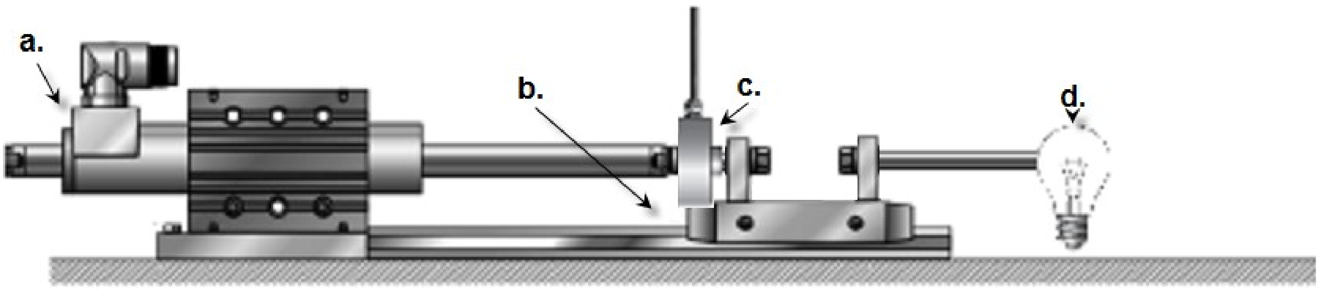

Figure 2: Hypothetical use case - avoid if possible

Figure 2 shows a linear motor (a) whose slider applies the pressing force through the force sensor (c) to a carriage (b), which in turn transmits the force to the object to be pressed (d).

Here, interference effects of the carriage are also measured and have a disturbing effect on the control process.

Such installation variants should be avoided.

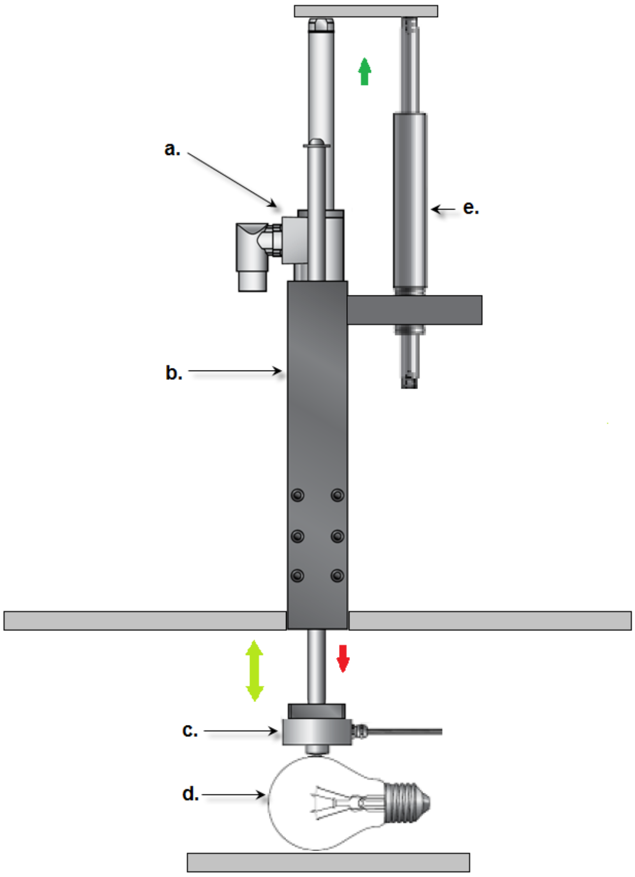

Figure 3: Hypothetical use case - feasible

In Figure 3, a linear motor (a) is used vertically in a guide (b) to exert a pressing force on an object (d) via a force sensor (c). The weight of the moving part of the motor and guide is compensated here by a spring (MagSpring, e). This means that no additional gravitational force is measured beyond the force to be controlled.

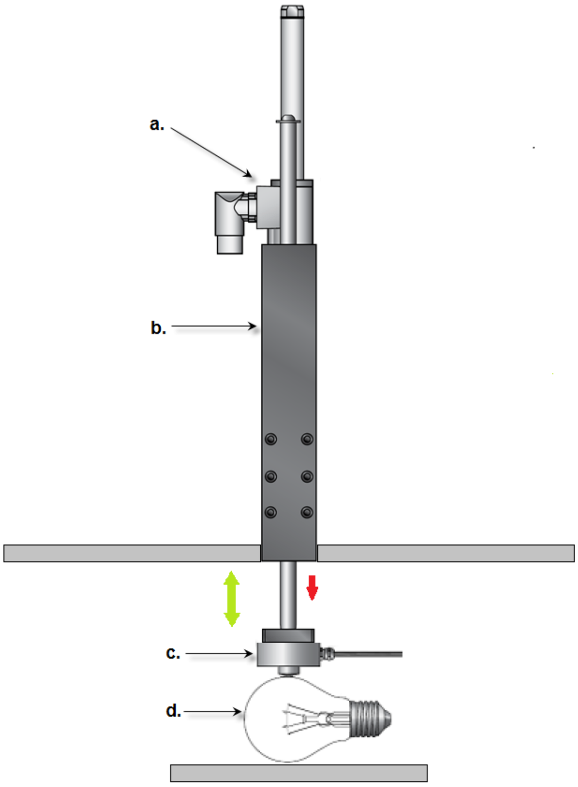

Figure 4: Hypothetical use case - avoid if possible

Figure 4 shows a vertical press application in which a linear motor (a) mounted vertically in a guide (b) applies a press force to an object (d) via a force sensor (c). Here, the weight of the moving part of the guide and motor is measured in addition to the force that is to be controlled. Depending on the required dynamics and accuracy, this can have a disruptive effect.

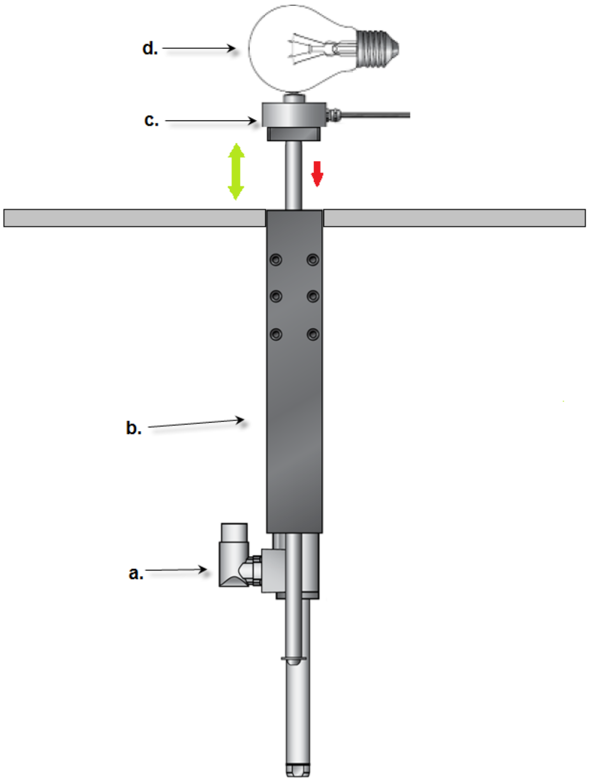

Figure 5: Hypothetical use case - feasible

Figure 5 also shows a vertical press application. Here, the linear motor (a) mounted in a guide (b) acts on the object (d) via the force sensor (c) against the weight of the moving components. In this configuration the force sensor measures only the force imparted to the object. The weight of the guide and motor are not measured and can be automatically compensated for as a type of offset force.

1 Device Requirements

The following drives offer the technology function "Force Control," though some models have functional differences in their PID controller structure and analogue input hardware. Depending on the process, this can restrict the control quality.

Drives with closed loop force control	A/D	Analog inputs
B1100-VF	10 Bit	1x 0-10V & 1x -10…10V
B1100-GP	10 Bit	1x 0-10V & 1x -10…10V
C11X0	10 Bit	1x 0-10V & 1x -10…10V
C12X0	12 Bit	1x 0-10V & 1x -10…10V
C14X0	12 Bit	1x 0-10V & 1x -10…10V
E11X0	12 Bit	1 x 0-10V
E12X0	12 Bit	1x 0-10V & 1x -10…10V
E14X0	12 Bit	1x 0-10V & 1x -10…10V

Table 1: Overview of supported drives and their basic functions

X: Available, -: not available

The following drives with the fieldbus variants listed support motion commands of the technology function "Force Control" via the fieldbus:

Drives	Fieldbus
B1100-GP	CANOpen DeviceNet, LinRS
C11X0-	Profinet, EtherCAT, CANOpen, LinRS
C12X0-	Profinet, EtherCAT, Powerlink, Ethernet/IP, CC-Link, Sercos III (FSP_IO), LinUDP
C14X0-	Profinet, EtherCAT, Powerlink, Ethernet/IP, Sercos III (FSP_IO), LinUDP
E11X0-	CANOpen, Profibus DP, DeviceNet, LinRS
E12X0-	Profinet, EtherCAT, Powerlink, Ethernet/IP, Sercos III (FSP_IO), Profibus DP, LinUDP, CANOpen, LinRS
E14X0-	Profinet, EtherCAT, Powerlink, Ethernet/IP, Sercos III (FSP_IO), Profibus DP, LinUDP, CANOpen, LinRS

Table 2: Drives and fieldbuses for using the "force control" operation commands

Force control functionality requires the purchase of the “Force Control” technology function, which is sold separately. If this is to be ordered after the drive, the device serial number must be specified, as the activation license is linked to the serial number.

Details on how to activate the technology function can be found in the associated manual Technology Function "Closed Loop Force Control" (0185-1096-E).

Attention: The technology function "Force Control" must be ordered separately and is not automatically available!

The values of Table 1 refer to firmware 6.9 Build 20201026 and may differ when using other firmware versions.

1.1 Functional Scope of the Drives

As listed in table 1, different drives have different capabilities. Depending on the application requirements, this may be relevant.

The resolution of the A/D converter determines the possible resolution and control accuracy in conjunction with the sensor and its measuring range.

The analog inputs on the drive dictate the type of force sensor and measurement amplifier that should be used, as well as the possible controller resolution.

The controller structure determines the possibility to control the desired setpoint.

The available filter(s) allow signal filtering.

Pre-control parameters allow compensation of known and constant variables.

The "Speed Limiter" functionality is useful for certain applications.

1.1.1 Control Accuracy / Resolution

Within the drive, the resolution of the possible setpoint specification is 0.1N.
However, the achievable resolution of the measurement signal is also important. As a work of experience one can say that one can regulate to 10 times the measuring resolution or more exactly.

Example 1:
Measuring amplifier signall 0-10V -> 0-100N
A/D 12Bit = 0.00244140625 V / Bit
=> 0.0244140625 N as the smallest possible resolution

Therefore, 0.2N controller accuracy should be achievable.

Example 2:
Measuring amplifier signal -10…10V -> -50…50N
A/D 12Bit = 0.0048828125 V / Bit
=> 100N / 20V * 0.0048828125 V/Bit -> 0.0244140625 N/Bit as the smallest possible resolution

Therefore, 0.2N controller accuracy should be achievable.

1.1.2 Analog Inputs

Depending on the drive, a single 0-10V or an additional -10...10V input is available.
Depending on the used transmitter the necessary connection can be made.

A direct connection of a measuring bridge is not possible!
A measuring transducer suitable for the measuring cell is always necessary.

1.1.3 Control Structure

The controller structure determines how complex the controlled system may be in order to be able to compensate for disturbances.
Each control function can be considered as an adjustable degree of freedom for disturbance compensation.

A controller structure with PID can therefore offer a further degree of freedom for compensation as compared to a PI controller.

However, experience has shown that a pure I controller is sufficient for force control.

1.1.4 Filter

Filters are used for signal smoothing and stabilization in case disturbances make the signal very unsteady, which can cause additional load on the control loop. However, active filters limit the dynamics of the system, so the use of filter time constants must be considered with respect to the desired application.

The filters are essentially used to filter/stabilize the measured quantity, not to compensate for EMC effects.

1.1.5 Feed-Forward

Feed-Forward parameters are used to directly compensate for known and constant disturbance variables. This takes pressure off of the control loop and, depending on the application, can make the system more stable and controllable.

1.1.6 Speed Limiter

The "Speed Limiter" is an additional function that was introduced for the following rotary applications:
- Screwing
- Closing
- Turning to torque

If in the listed processes for any reason the mechanical load / counterforce / counter torque is omitted, the force controller would provide full drive power within a very short time, potentially leading to runaway motion.
To be able to avoid possible damage in such situations, the speed of movement can be monitored and/or limited during force control.
This can also be used to trigger an error message and/or quick shutdown.

1.2 Prerequisite Sensor / Measuring Amplifier

The required analog input must be freely available for the drive used. Depending on the sensor, a 0-10V input or differential -10...10V input is available.

The sensor must be connected to the input through the required measuring amplifier. Since analog signals are involved, it is recommended to pay attention to EMC and additional shielding to the measurement hardware if necessary.

2 Electrical Connection

The following connection variants assume that the drive is generally wired and ready for operation according to its Installation Guide.

The connection of the supply voltages, motor cables, etc. are not considered here, but are to be created for a correct function!

Attention: Make sure that the installation is EMC-compliant! Sporadically triggered disturbances can cause damage to the mechanical system or the force sensor!

2.1 Connection Signal Conditioner / Sensor 0-10V

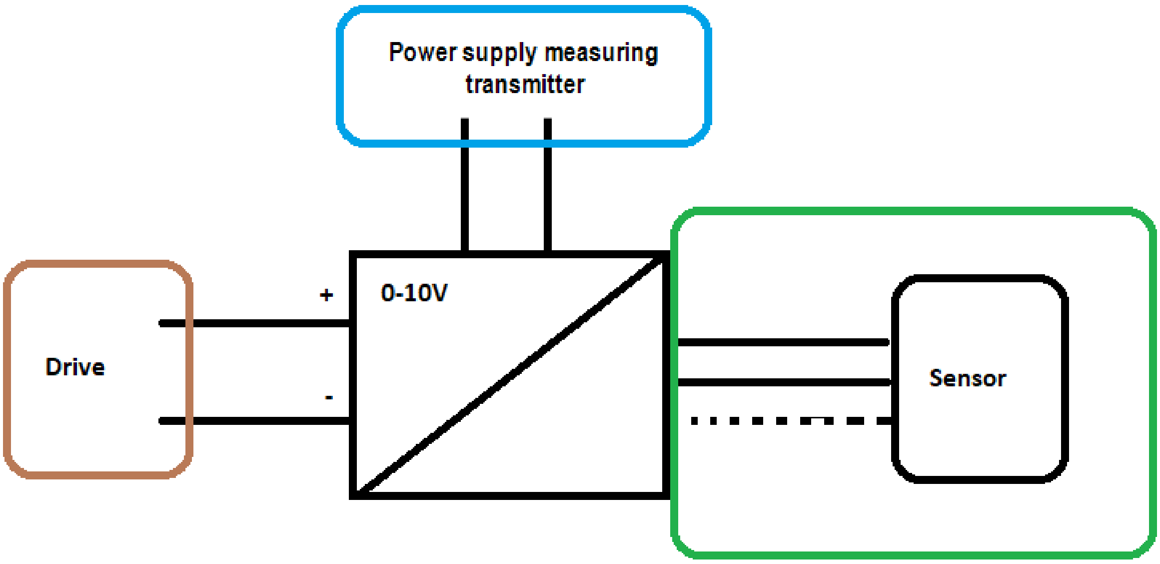

Figure 6: Schematic diagram 0-10V measuring device

The schematic diagram of a 0-10V measuring device shows the signal conditioner, which is coupled to the analog input "0-10V" and the drive ground "GND" at the drive (brown area).

The signal conditioner itself requires a separate power supply, which must be done according to the signal conditioner manufacturer's specifications (blue area).

The sensor that detects the physical quantity must also be connected according to the specifications of the sensor and signal conditioner manufacturer (green area).

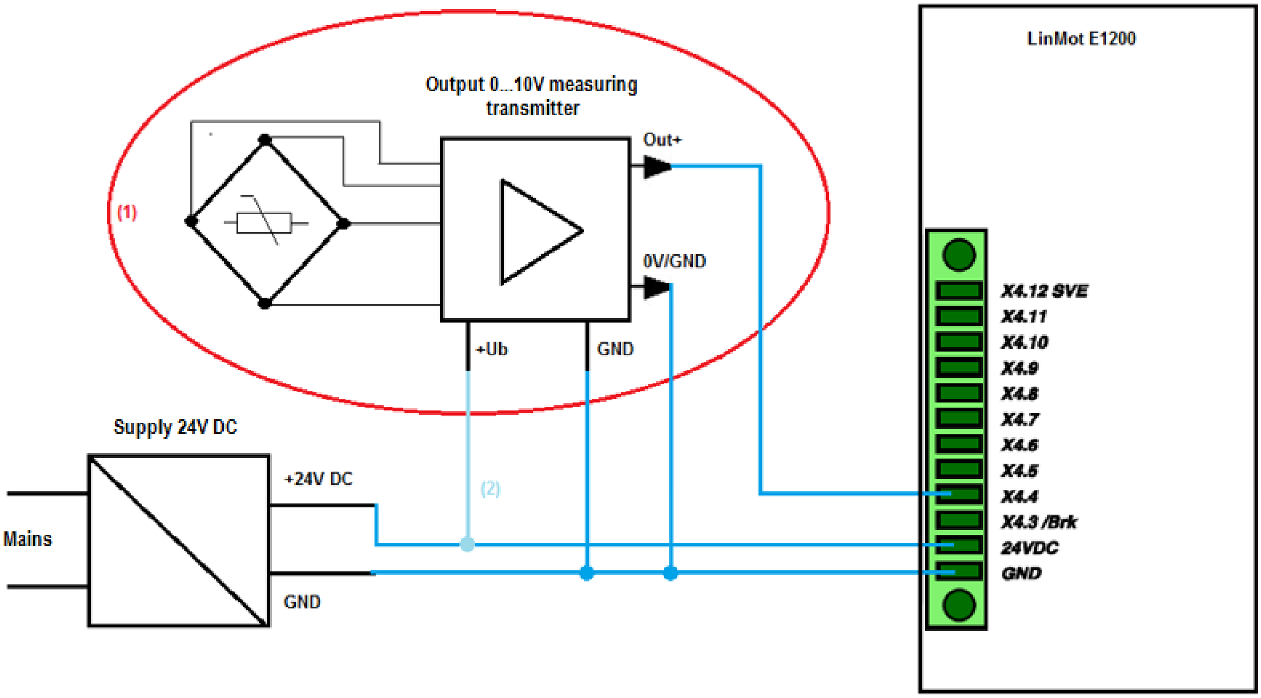

Figure 7: Example connection of a signal conditioner to E12X0 Drive

Figure 7 shows schematically the connection of a force sensor and its signal conditioner ((1), marked red) to a drive (here type E1200) and its logic supply.

Since most industrial signal conditioners are designed for 24V DC supply, the signal conditioner and the drive can both be supplied by the same 24V supply.

Attention: Observe the permissible supply voltage of the signal conditioner according to its installation instructions. If it is not compatible with the 24V DC supply typical for LinMot Drives, the connection must be made in a suitable form.

2.2 Connection Signal Conditioner / Sensor -10...10V

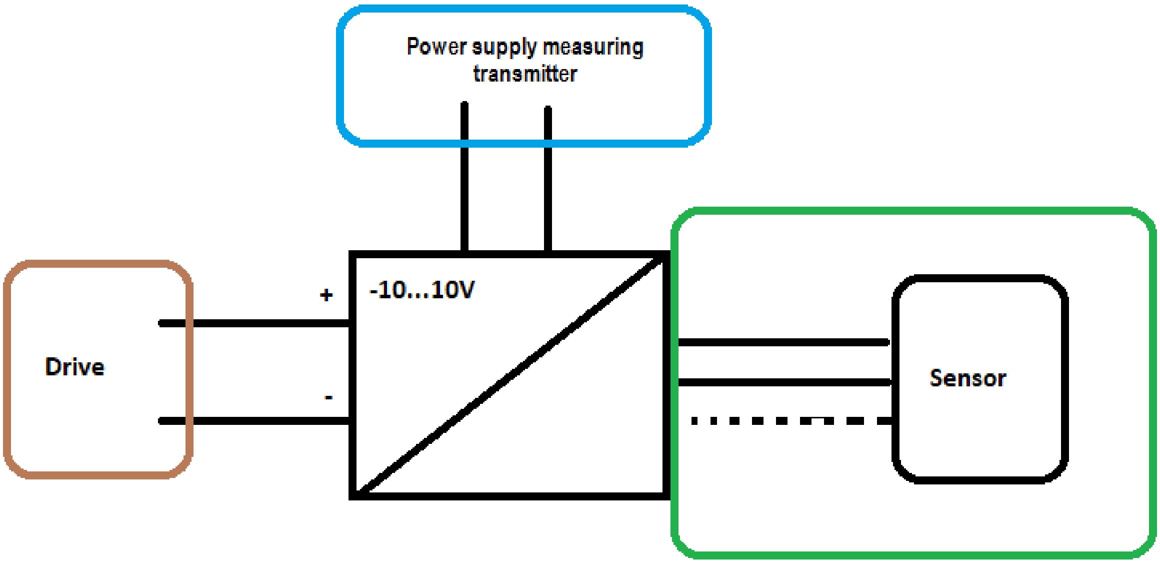

Figure 8: Schematic diagram -10-10V measuring device

The schematic diagram of a -10...10V measuring device shows the signal conditioner, which is coupled to the analog input "-10...10V" and the drive ground "GND" at the drive (brown area).

The signal conditioner itself requires a separate power supply, which must be done according to the signal conditioner manufacturer's specifications (blue area).

The sensor that detects the physical quantity must also be connected according to the specifications of the sensor and signal conditioner manufacturer (green area).

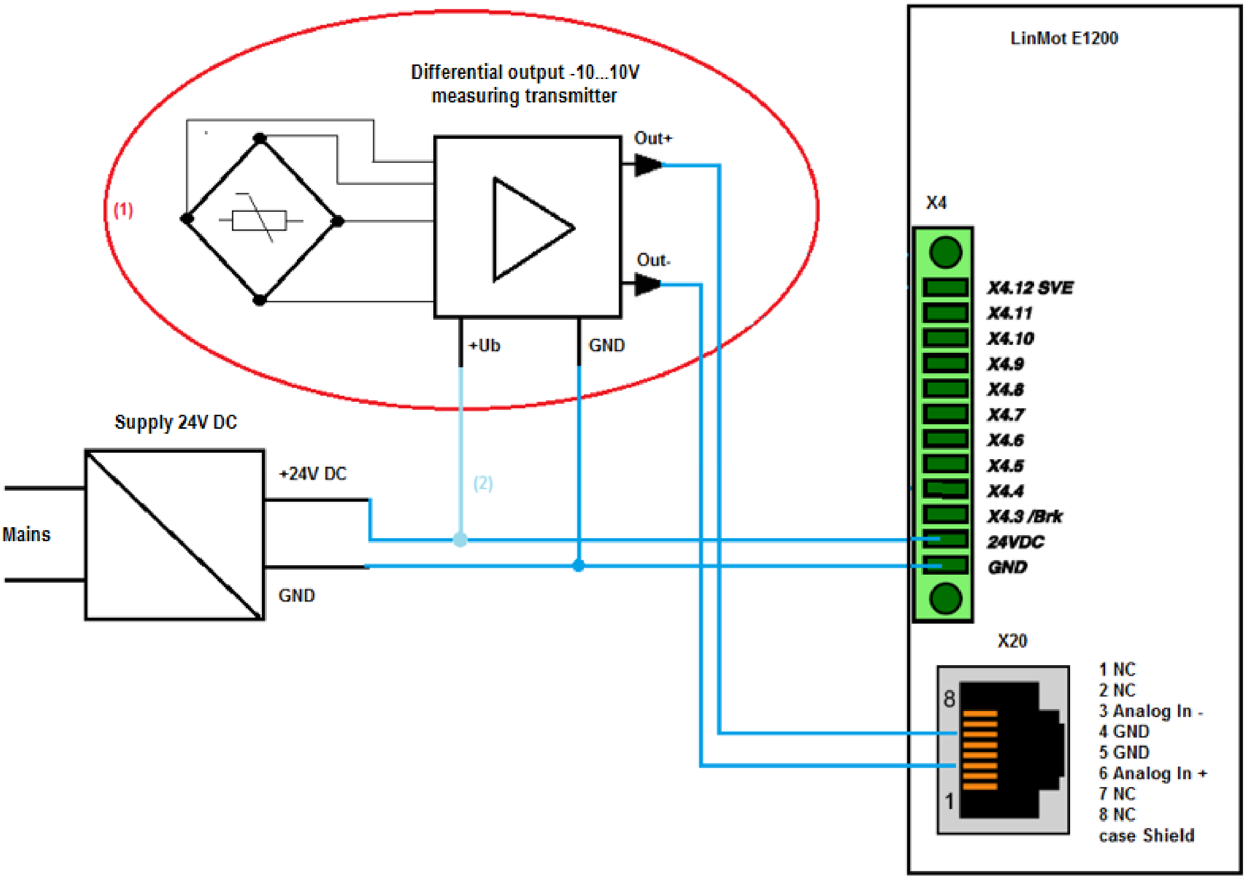

Figure 9: Example connection of a signal conditioner to E12X0 drive

Figure 9 shows schematically the connection of a force sensor and its signal conditioner ((1), marked red) to a drive (here type E1200) and its logic supply.

Since most industrial signal conditioners are designed for 24V DC supply, the signal conditioner and the drive can both be supplied by the same 24V supply.

Attention: Observe the permissible supply voltage of the signal conditioner according to its installation instructions. If it is not compatible with the 24V DC supply typical for LinMot Drives, the connection must be made in a suitable form.

3 Setting the Signal Conditioner / Sensor

Depending on the sensor / signal conditioner used, this must be set. Consult the instructions of the sensor / signal conditioner manufacturer here!

4 Configuration of the Analog Input

To be able to use an external measuring signal, the input channel must be configured after the electrical connection has been made.

Depending on the drive used, certain parameters may not be available (see Table 1).

4.1 Selecting the Input Channel

To select the input channel, select the heading in the parameter tree:

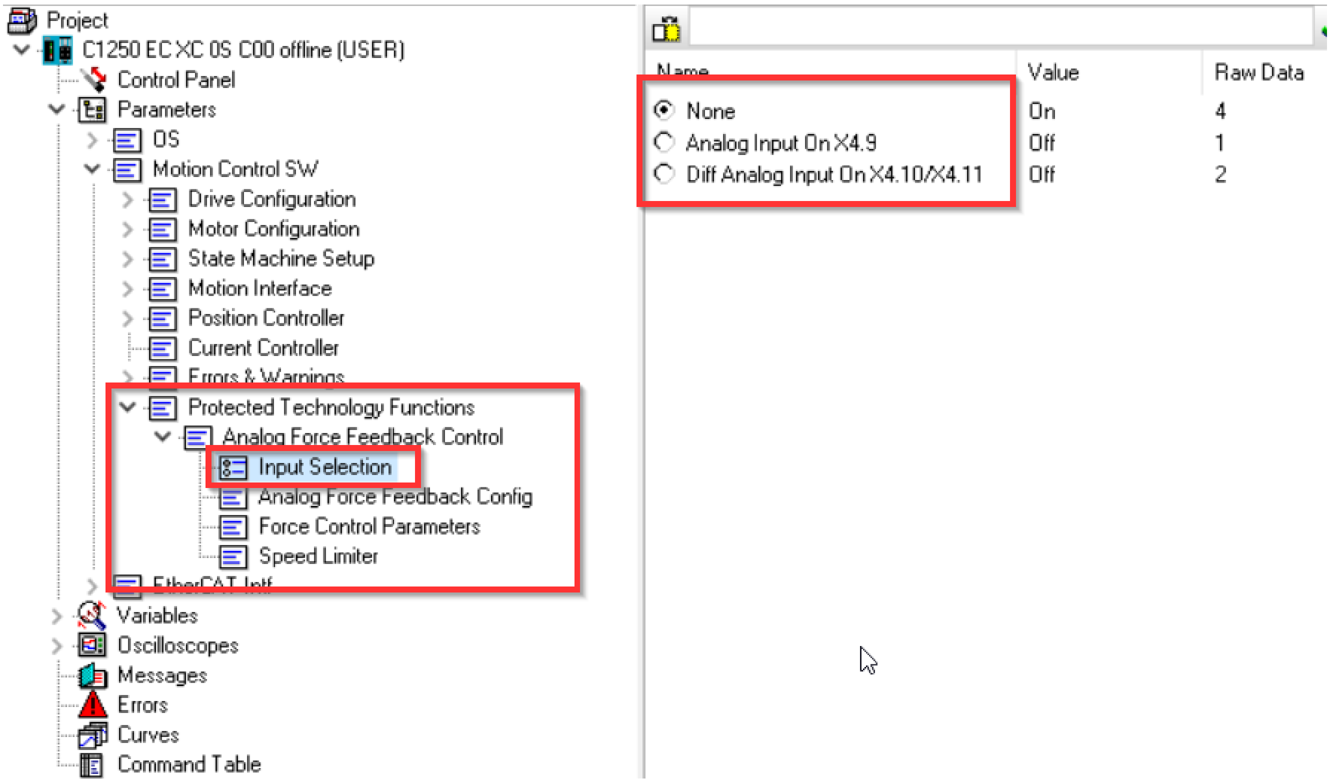

Figure 10: Input parameterization - select input channel

Select the input channel used here.

4.2 Configuring the Measuring Range

To configure the measuring range, select this heading in the parameter tree:

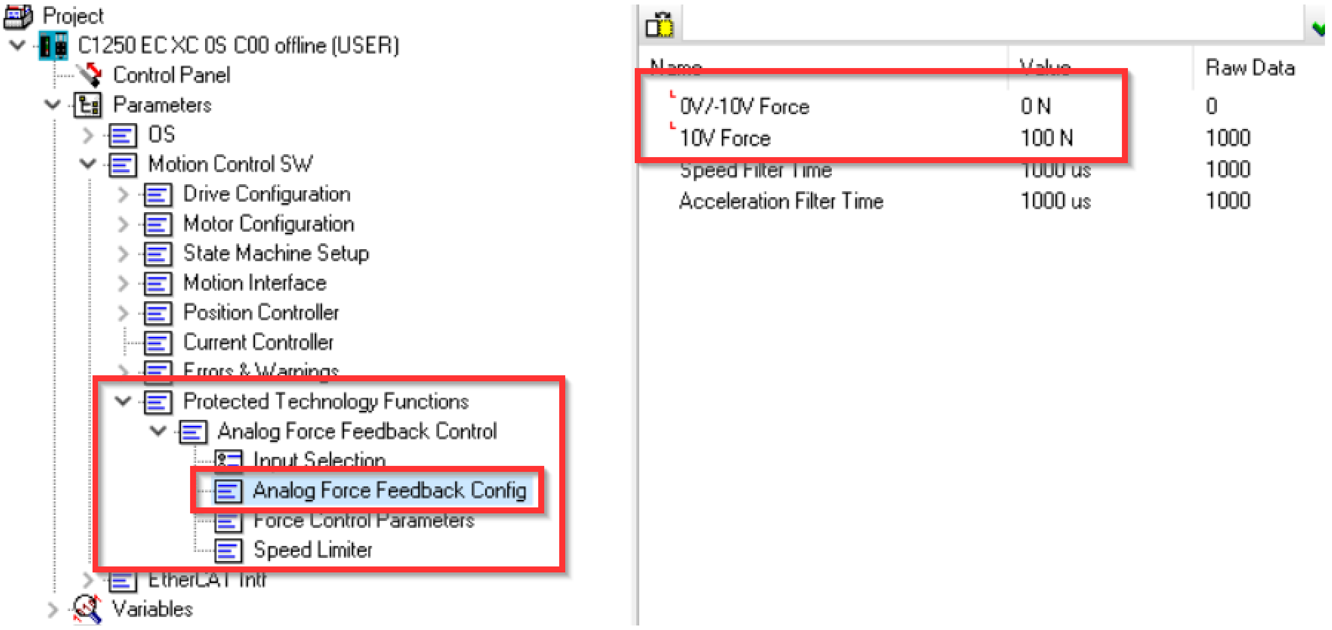

Figure 11: Input parameterization - measuring range

Now enter here the measuring range that has been assigned in your signal conditioner for the analog signal.

For the parameter "0V/-10V Force":

- At 0-10V   Measuring range starts at 0V
- At -10...10V   Measuring range starts at -10V

4.3 Configuring the Filters

To configure the filters, select this category in the parameter tree:

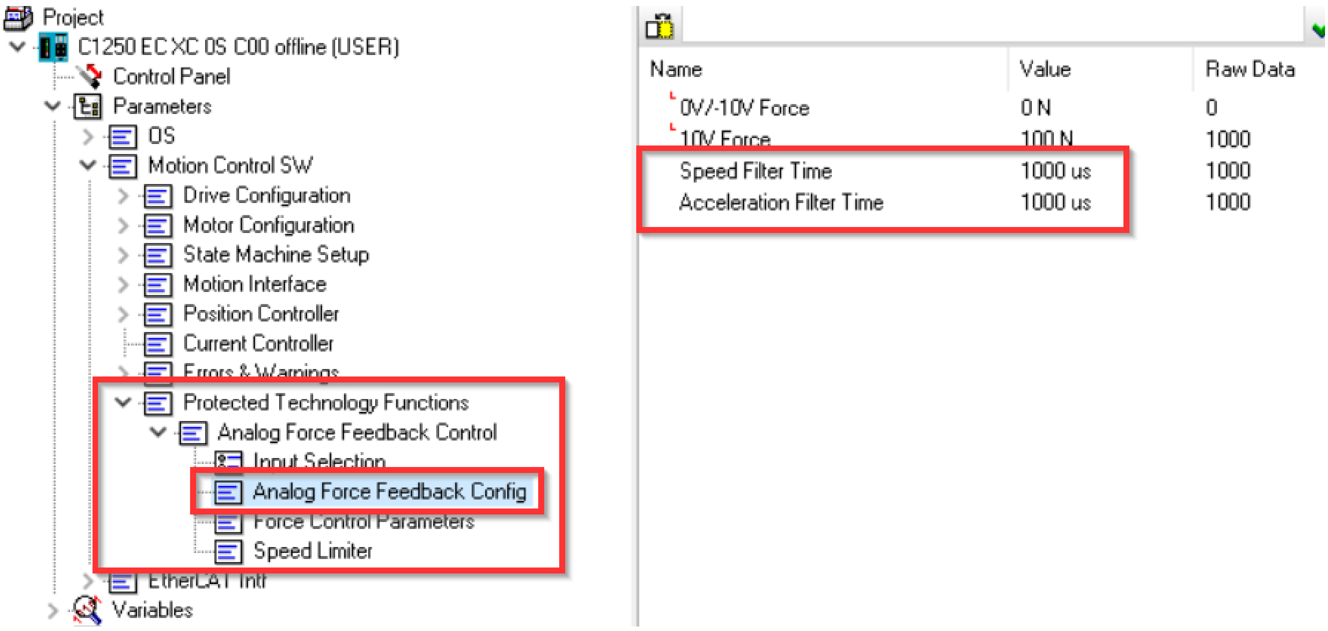

Figure 12: Input parameterization - setting filters

Attention: These filters are not available on every drive type! See table 1.

Here you can adjust the filter time "Speed Filter Time" if required. This filter time is used in the determination of the force change rate for the D portion of the control loop.

The "Acceleration Filter Time" is used in the determination of the actual acceleration, which serves as the input variable of the FF Acceleration prefilter.

The actual speed used has its "Speed Filter Time" (UPID 13A8/13BC) in position controller set A or B and can be adjusted there.

Hint: As a rule, nothing needs to be changed here. An increase dampens the prefilter influence, and a decrease increases the prefilter influence on the control loop.

5 Procedure for Adjusting the Force Control Loop

The Feed-Forward parameters listed here are not available on every drive.
For details, refer to table 1.

As a rule, it is not necessary to use these pre-control parameters. However, they are useful when tuning with other parameters proves difficult.

It is recommended to leave them at the default values and start by setting the control loop.

5.1 Determination of the "FF Friction" Feed-Forward Parameter

This feed-forward parameter is used to compensate for dry friction forces. The value of this parameter is added to the output of the PI/PID network when the motor moves (the sign changes depending on the direction of movement).

The corresponding value for this parameter can be calculated if the motor type and the value of the dry friction force are known. This compensates for the influence of dry friction outside of the PI/PID control loop.

To obtain correct compensation, the value of this parameter is calculated as follows: Dry friction force [N] divided by the motor force constant [N/A].

$$FF\ Friction = \frac{Dry\ friction\ force\ [N]}{Motor\ force\ constant\ [N/A]}$$

The motor force constant can be found in the motor data sheet, or in the parameter tree:

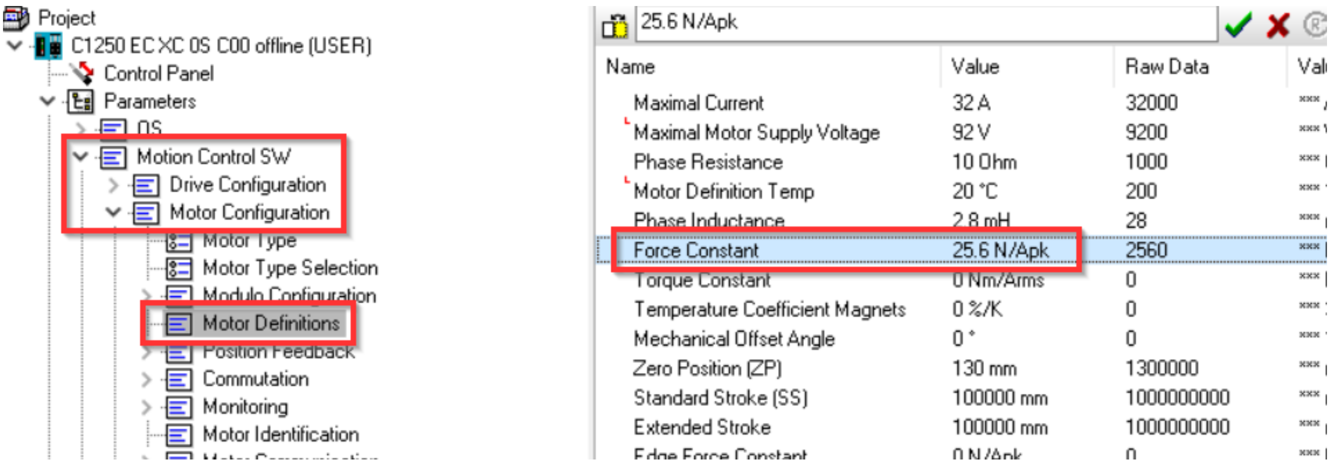

Figure 13: FF Friction – motor force constant

Attention: This filter can cause the system to oscillate at very small speed changes! Be sure to set the "FF Friction Deadband" value to prevent this!

5.2 Determining the "FF Acceleration" Feed-Forward Parameter

This feed-forward parameter is used for compensation of forces caused by acceleration of motor and load mass. The value of this parameter multiplied by the value of the actual acceleration is added to the output of the PID network.

The corresponding value for this parameter can be calculated if the motor type and mass are known. Thus inertia can be compensated for and does not have to be handled by the actual control loop.

To obtain correct compensation, the value of this parameter is determined as follows:
Total mass of the load [kg] divided by the force constant of the motor [N/A].

$$FF\ Acceleration = \frac{Moving\ load\ mass\ [Kg]}{Motor\ force\ constant\ \left[\frac{N}{A}\right]}$$

5.3 "FF Friction Deadband" parameter

"FF Friction Deadband" is an additional parameter used to define a deadband for the effect of the feed forward control "FF Friction".

If the parameter is "0", every movement with a sign change will send the specified FF Friction current to the motor.
This may have an unfavorable effect and cause the control loop to oscillate. To avoid this, this parameter can be used to define a dead band so that very slight fluctuations in movement are ignored when calculating the friction feed-forward.

Do not make the deadband too small. Select a value at least slightly larger than the fluctuation range of the velocity at standstill.

You can measure this with the drive’s oscilloscope and read it with the Min/Max function as a "Peak to Peak" value:

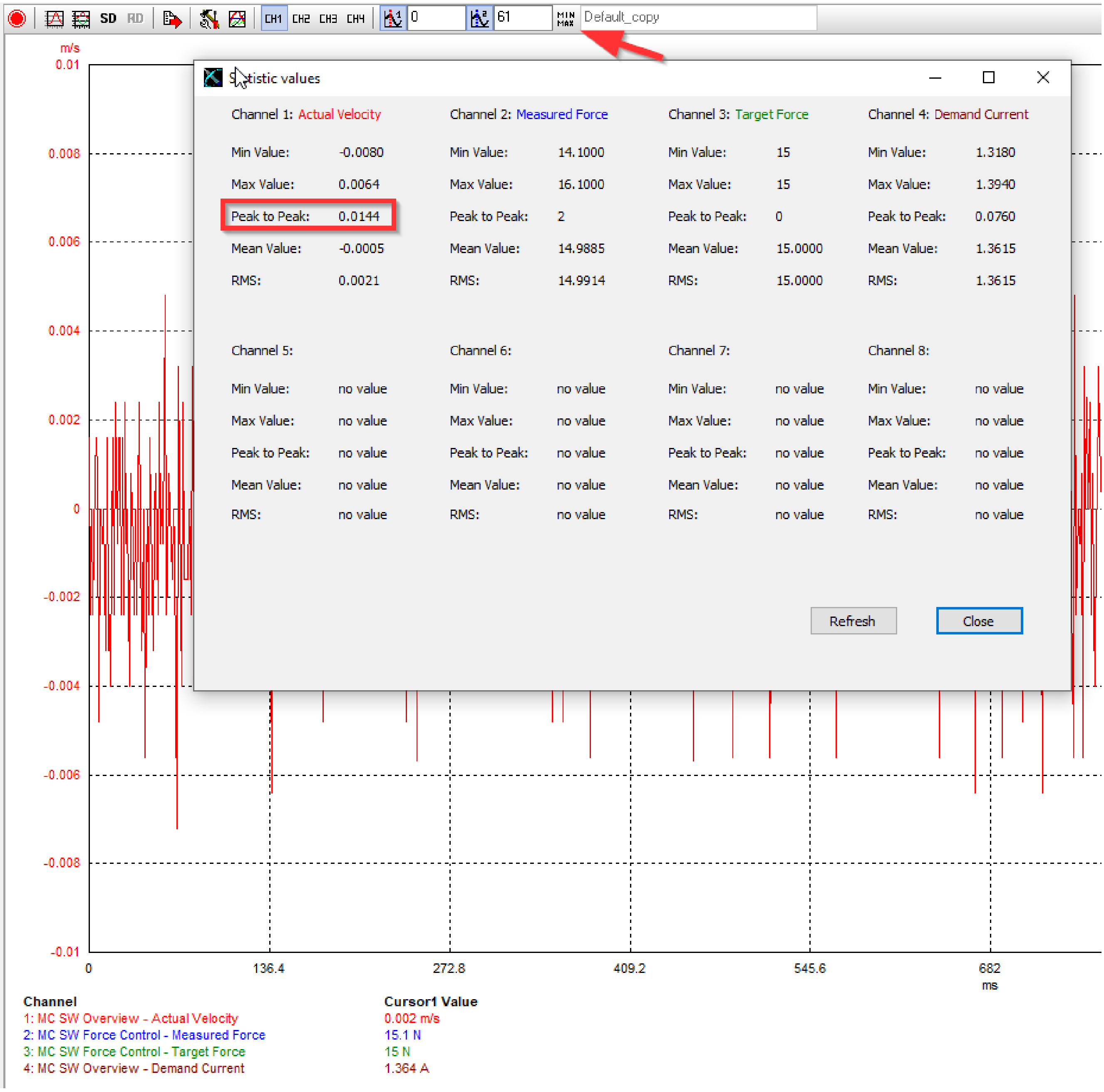

Figure 14: Determine the velocity fluctuation for the "FF Friction Deadband".

Here a fluctuation in the range of 0.0144m/s can be seen. Therefore a dead band of at least 0.02m/s should be applied to minimize the noise of the position sensor.

5.4 Current Limit

The force controller has its own current limit, which is set by default to the permissible maximum value of the drive's power stage during commissioning. One can limit the maximum possible force by reducing this value. This should be used to protect load cells in particular (by limiting the force on the load cell), and also to limit limit peaks.

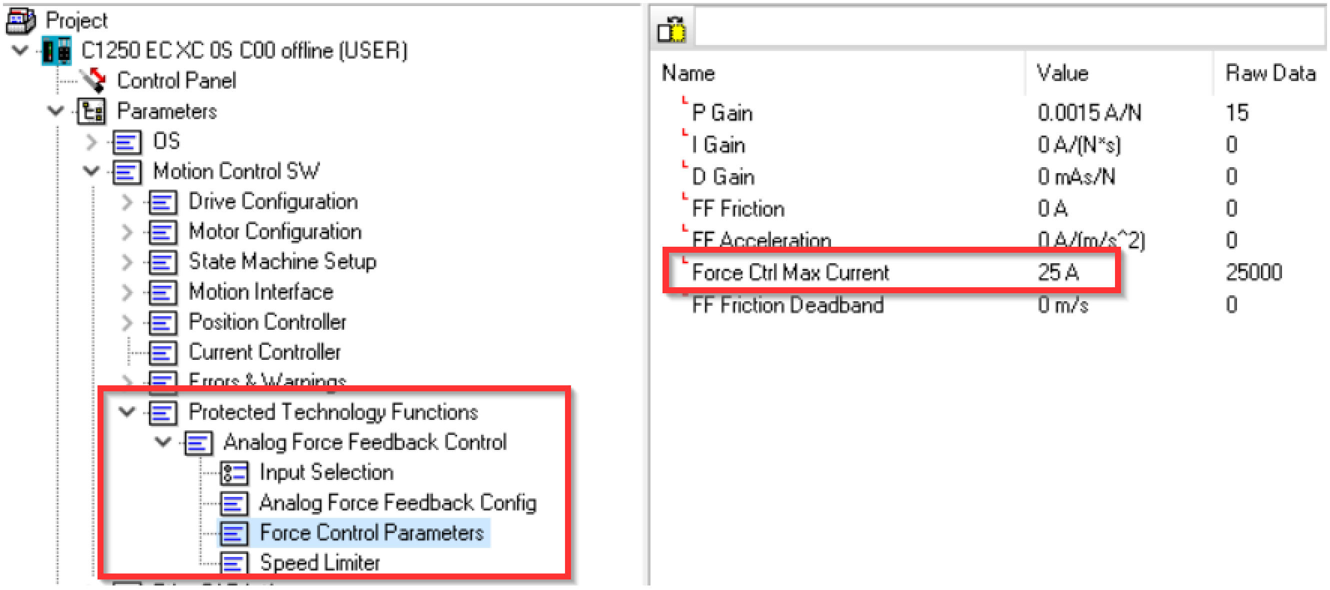

Figure 15: Current limit in the force control loop

The motor's force constant can be used to determine a possible current limit for the force controller. The force constant can be found here:

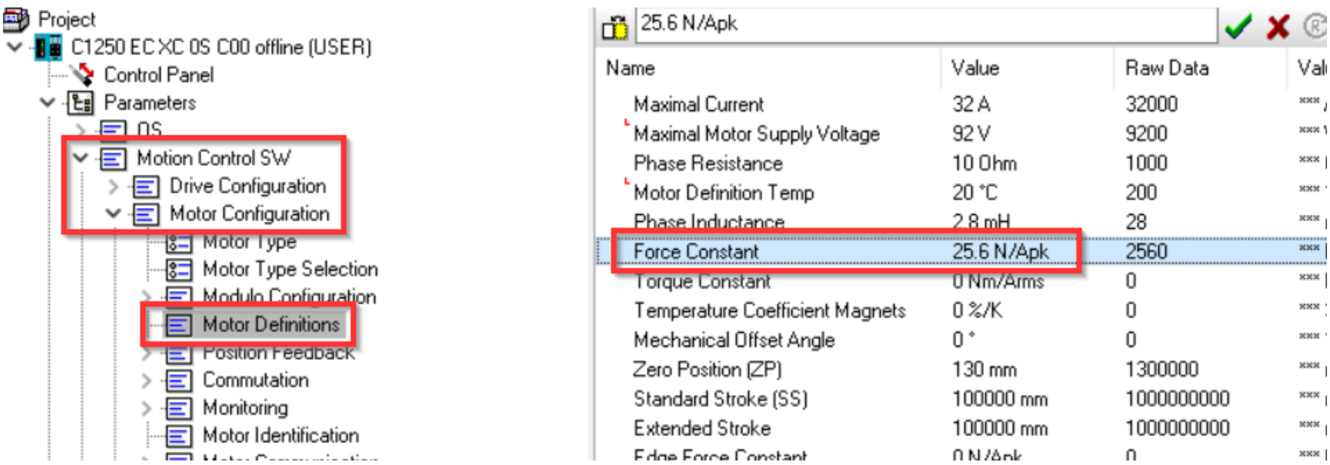

Figure 16: Empirical controller setting - motor force constant

Then divide the force sensor's maximum force by the force constant to get the current limit.

Example:
Measuring system measures force from 0 - 150N
Force constant = 25.6N/A

$$\text{Force control Max Current} = \frac{150N}{25.6N/A} = 5.85A$$

Once you have determined and entered the force limit, switch the drive active.

The axis should be referenced and mechanically coupled on a test object in order to be able to apply and measure a force during testing.

Attention: Make sure that there is mechanical contact with no air gap to avoid jumps and shocks to the sensor!

Attention: The calculated current limit may be too low to fully utilize the measuring range due to tolerances and temperature drift. In this case, increase the current limit until the end of the measuring range is reached!

Check whether the direction of action of the measurement is correct in relation to the direction of movement of the motor. To do this, you can display the measured force in the "Control Panel".

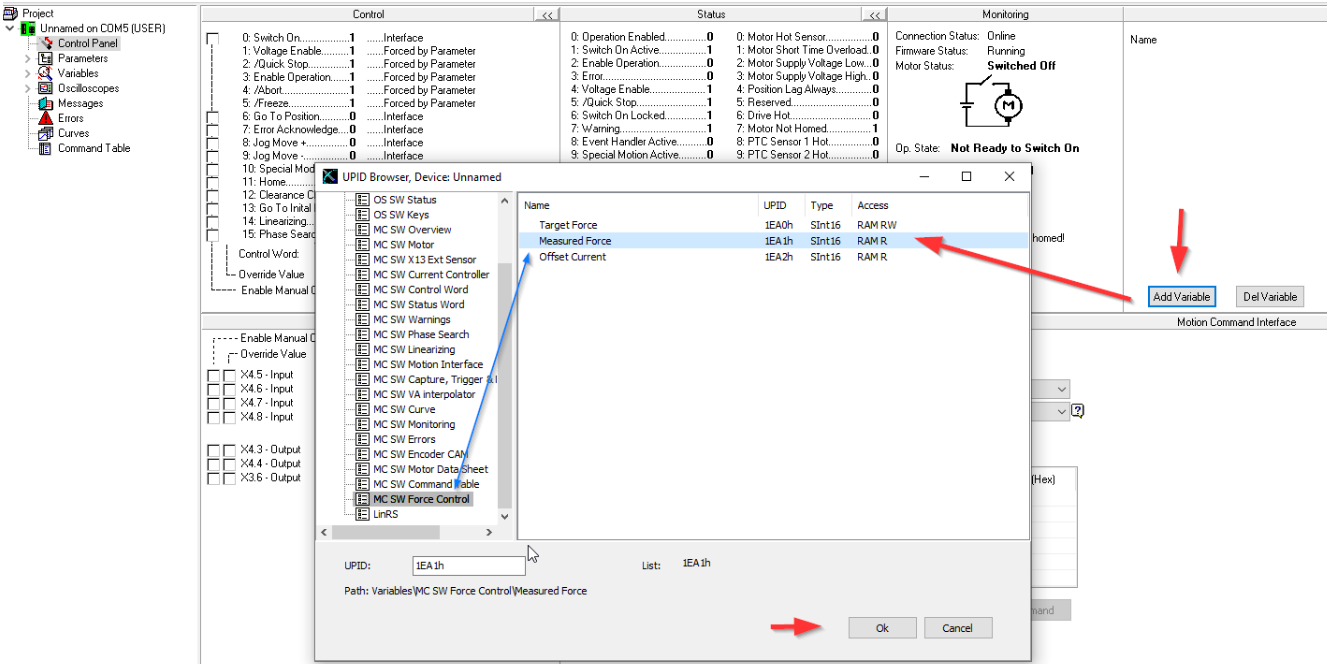

Figure 17: LinMot Talk "Control Panel" - monitor additional variable values

Using the "Motion Command Interface", you can then perform small movements with the +1/-1mm button so that the motor exerts a force via the measuring cell.

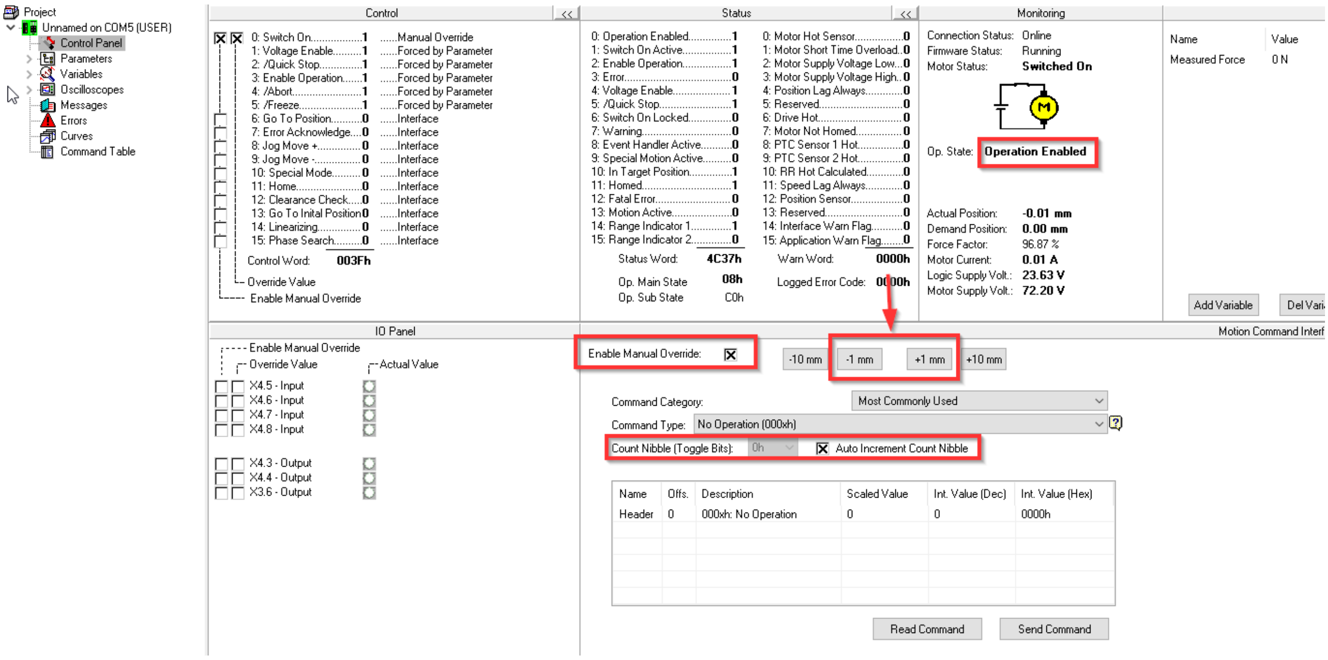

Figure 18: LinMot Talk "Control Panel" - manually position motor and observe force increase

If you are moving in the positive direction, you should notice a positive increase in force.

5.5 Speed Filter

Normally, the "Speed Filters" do not need to be adjusted. Leave the values at the default settings.

5.6 Speed Limiter

In general, the "Speed Limiter" should be defined to avoid a runaway of the motor in case of a "force break" (sensor loses force contact).

The value of the speed limit will depend on the process. In the case of force control commands, the drive first moves in a position-controlled manner until a force limit is reached. On this limit the drive changes from the position controller to the force controller.

It is then possible, for example, to use the speed at this switchover point as the limit, or even to apply a smaller value, since the speed generally decreases when the target force is reached.

5.7 Empirical Setting of the Force Control Loop for Static Control

To be able to set the force controller empirically, the mechanics and measurement technology must first be installed and commissioned. In particular, the direction of action of the force sensor in relation to the positive direction of movement must be checked.

For rotary motors, set the unit system in the “Motor Wizard” to "Rotary" so that you find Nm instead of N in the force control parameters.

Once the drive has been configured, you can start commissioning the force controller.
To do this, the mechanics must first be brought into a state that force control is possible when the drive is active. The sensor should therefore have mechanical contact with the load and provide a measured value.

By default, the LinMot drive operates in position-controlled mode and only changes to the force-controlled mode by means of special force control commands.

The initial default setting is a D component of 0, an I component of 0 and a P component of 0.0015.
Depending on the motor used, the peak force should be limited with the "Force Control Max Current" so that the upper measuring range limit of the sensor used is not exceeded.

Do not set the feed-forward values yet; first test whether the desired control can be realized directly.

Attention: Force sensors can be irreparably damaged by mechanical overload! Observe the maximum permissible force values.

In general, start by setting the P gain value to 0, and the D gain value to 0. For the FF parameters, set each to 0.

For linear motors (using linear units) you can then use 0.5 A/(N*s) as the step size for the I component. For rotary motors (using rotary units) you can use 50 to 100 A/(Nm*s) as the step size.

Use the oscilloscope to observe the control behavior.

Use the following oscilloscope settings:

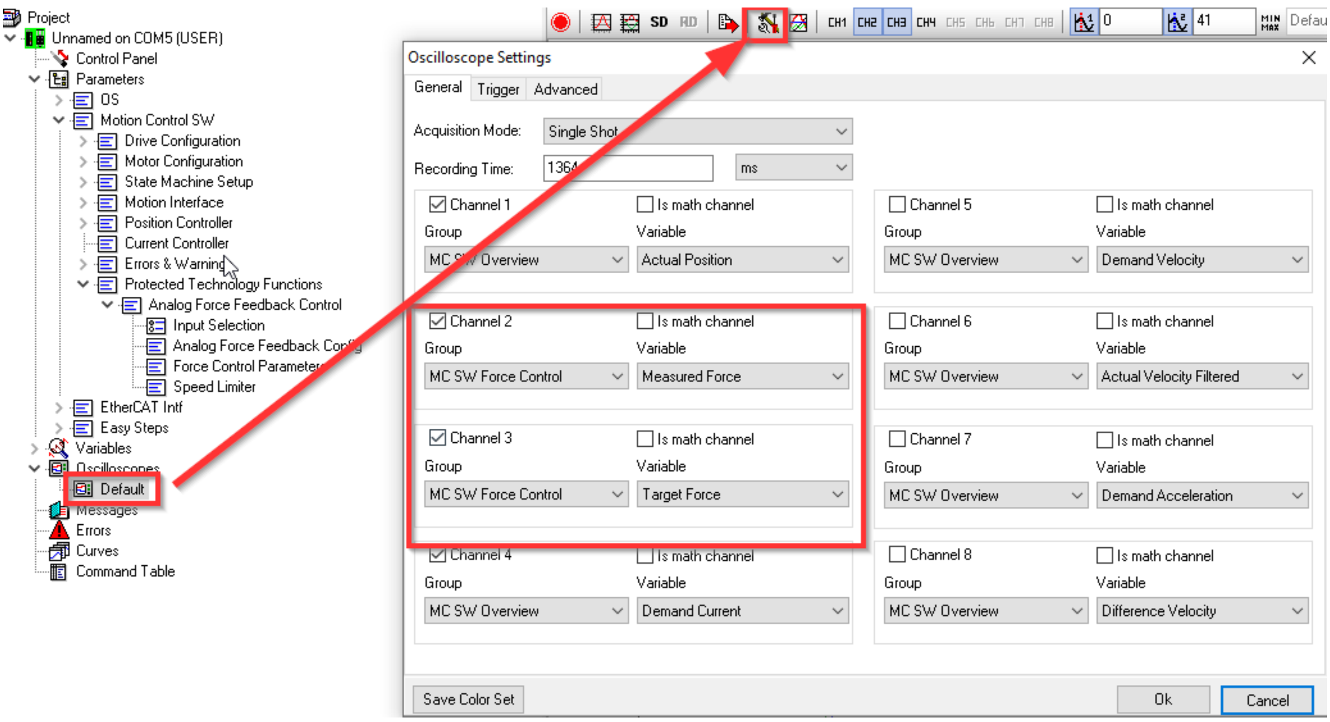

Figure 19: Oscilloscope recording channels for force controller

To start a recording when the force setpoint changes:

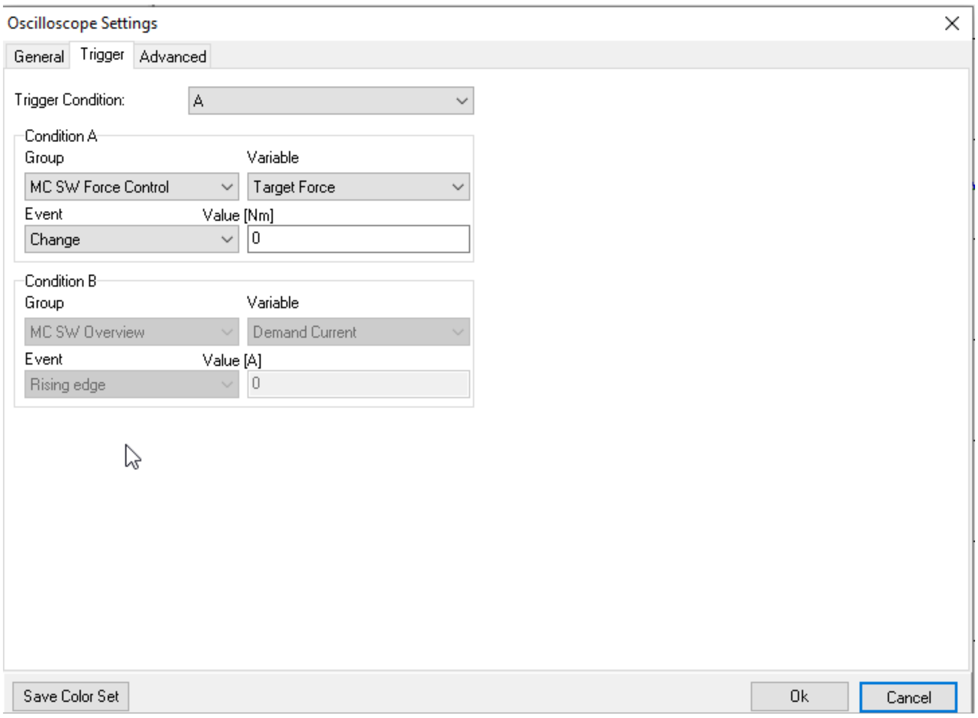

Figure 20: Oscilloscope trigger settings for force controller

To see the start jump as well, set a pre-trigger:

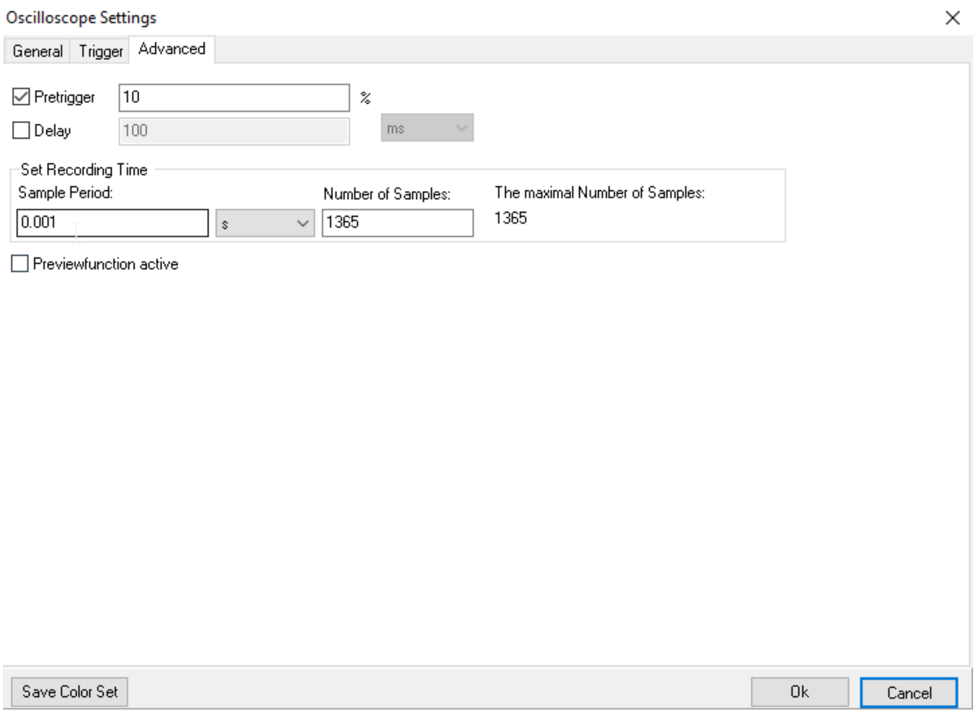

Figure 21: Oscilloscope pre-trigger for force controller

It is recommended to define two force values for the initial testing. You can initially select 1/10 of the measuring range as the lower force value and e.g. ½ or 2/3 of the measuring range as the upper force value.

Example:
Measuring range 0-100N
Lower force value: 100N / 10 = 10N
Upper force value: 100N * 2/3 = 66N

You can then turn on the drive, perform homing, if necessary, and if necessary, bring the mechanics into the operating range where there is a force closure, meaning the sensor is providing a reading.

Then activate the oscilloscope, which waits for the trigger event to create a recording.

To be able to adjust the controller, you must alternately specify different target forces to observe the effect of setpoint changes on the control loop behavior.

In the "Control Panel" of LinMot Talk you can select the move command "382xh: Force Ctrl Change Target Force" and then specify the target force for adjustment there.

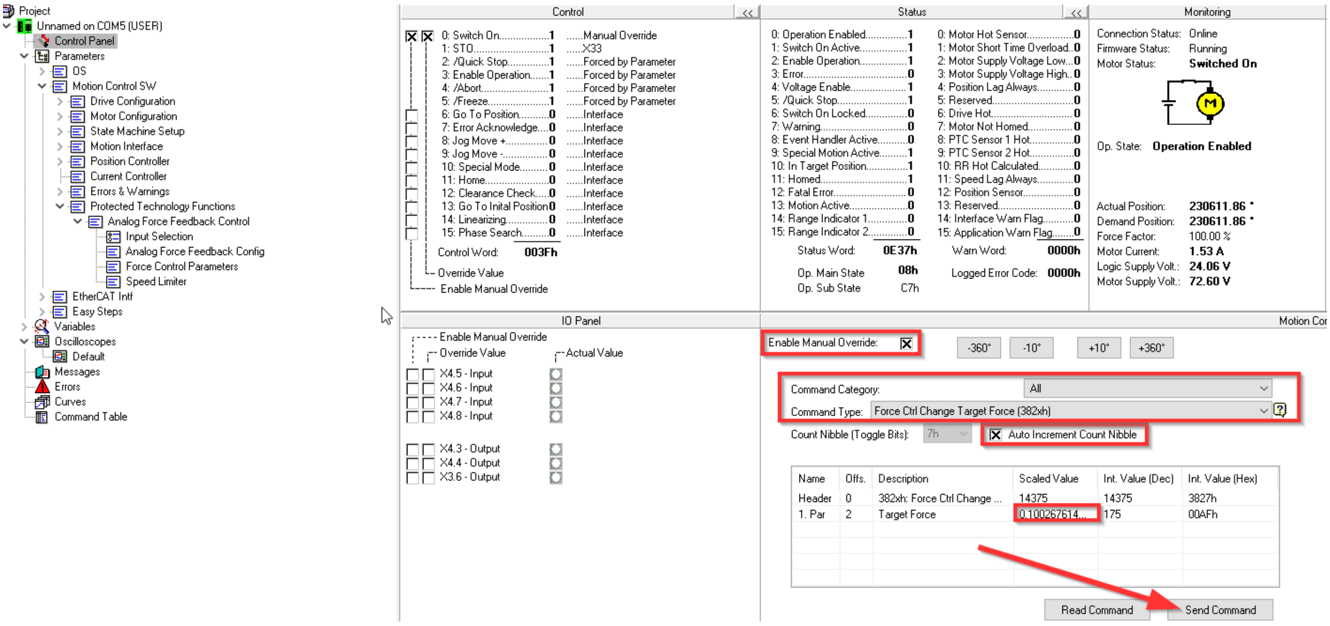

Figure 22: Force regulator setting - "Control Panel"

<u>Setup can proceed as follows:</u>

1. activate the oscilloscope ("Waiting for Trigger")
2. preset lower force value
3. examine the oscilloscope to see to what extent and at what speed the setpoint value is reached
4. increase I-portion by one step (0.5 linear or 50/100 rotary) if necessary
5. activate oscilloscope again ("Waiting for Trigger")
6. preset upper force value
7. examine the oscilloscope to see to what extent and at what speed the setpoint value is reached
8. if necessary, increase I-portion by one step (0.5 linear or 50/100 rotary)
9. if result is still not satisfactory, repeat procedure from step 1

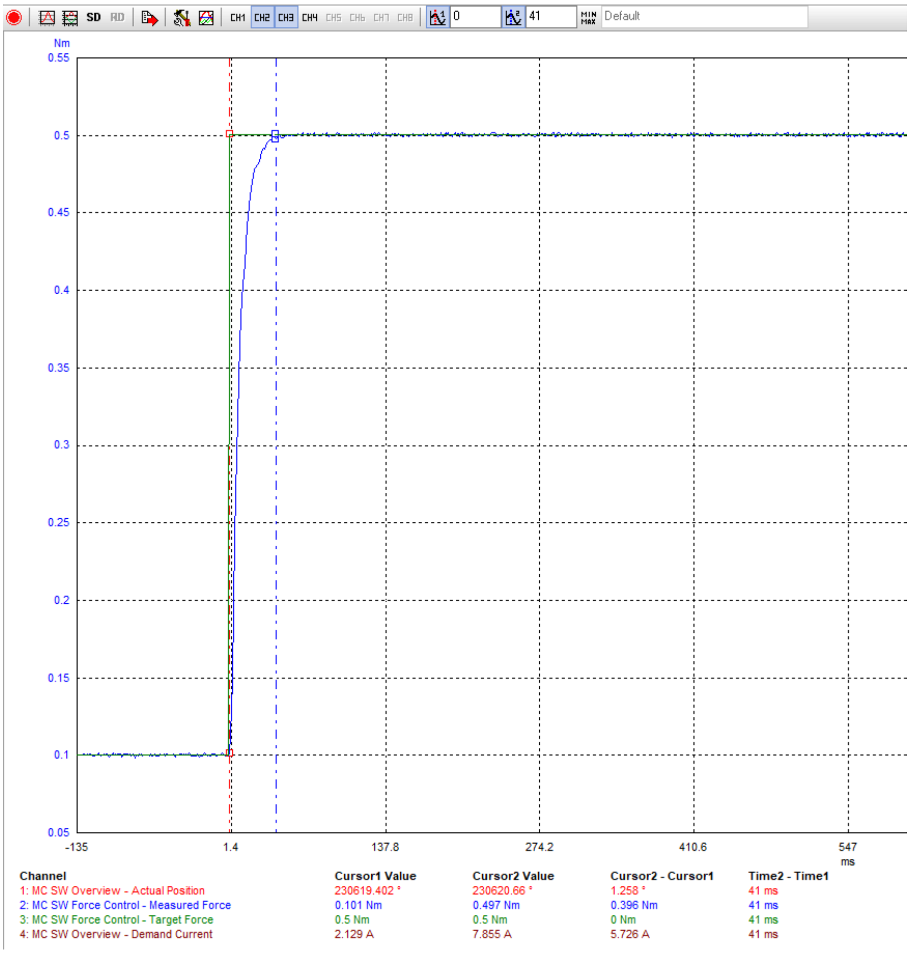

Figure 23: Force control - possible setting result

The result of the adjustment could look like the graph shown in Figure 23. The ultimate goal is to reach the setpoint value while maintaining a reasonable settling time. Here a setpoint of 0.5Nm has been reached within 41ms.

For rotary motors, a value above 1000 for the **I** component is normal. For linear motors it is usually below 100. If the achievable result with pure **I**-gain is not sufficient, you can now increase the D-gain in small steps. Here it is important to only make small steps in the order of magnitude of the given scaling factor, otherwise the system can start to oscillate, which in turn can lead to damage to the sensor!

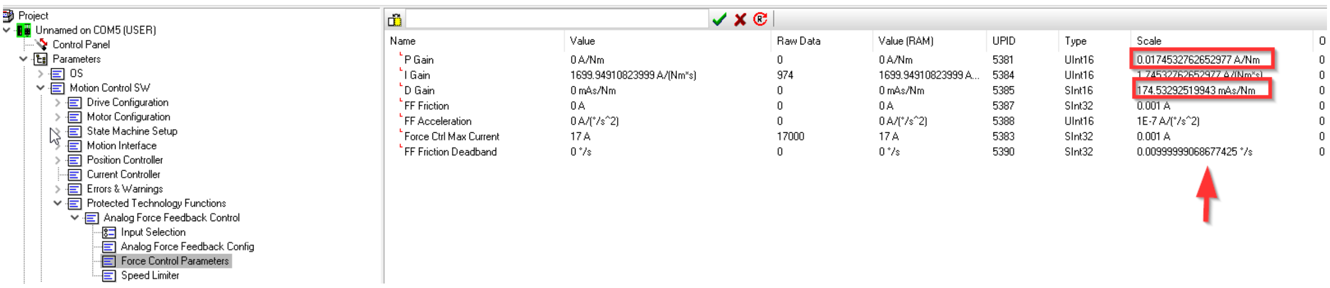

Figure 24: Force control - finding parameter scaling values

If gradually increasing the D component is not satisfactory, you can then use the same procedure to increase the P component in increments of the scale value.

⚠ **Attention:** Force sensors can be irreparably damaged by mechanical overload! Observe the maximum permissible force values and avoid oscillation of the control loop.

6 Using the “Force Control” technology function on I/O devices

In general, the “Force Control” technology function is operated by means of motion commands. These are available on all drives. The commands can be used via command table / digital trigger or also via fieldbus from a PLC.

Details on the available commands can be found in the manual Technology Function "Closed Loop Force Control" and in the manual "Motion Control Software Manual"

7 Using the “Force Control” Technology Function on Devices with Drive Profiles

Drive that are integrated as a native axis in certain PLCs no longer function as a pure I/O device. Instead, they operate as a servo axis as defined by the controller, meaning that the controller’s motion commands are used instead of those from LinMot’s libraries. Therefore, the motion commands of the technology function “Force Control” can no longer be used.

However, certain profiles on corresponding fieldbuses offer force or torque operation modes.

The following table shows the devices with drive profiles and fieldbuses that can also use the “Force Control” technology function.

Drive-Type	Profile	Fieldbus	Typical PLC
C1150-DS	DS402	EtherCAT	Omron NJ / TRIO
C1250-DS	DS402	EtherCAT	Omron NJ / TRIO
C1450-DS	DS402	EtherCAT	Omron NJ / TRIO
E1250-DS	DS402	EtherCAT	Omron NJ / TRIO
E1450-DS	DS402	EtherCAT	Omron NJ / TRIO
C1250-PD	ProfiDrive	ProfiNet	Siemens
C1450-PD	ProfiDrive	ProfiNet	Siemens
E1250-PD	ProfiDrive	ProfiNet	Siemens
E1450-PD	ProfiDrive	ProfiNet	Siemens

Table 3: Force control by means of drive profiles

7.1 Use of Force Control on Profile DS402

When using the DS402 drive profile, it is recommended to use the PDO "Cyclic Position Velocity Torque Mode 0x1604" if position-controlled or force-controlled operation is required, or "Cyclic Torque Mode 0x1606" if the drive operates exclusively in force mode.

Here it must be additionally noted that these two PDOs are controlled via the "Mode of Operation". Thus it is possible to distinguish between "Open Loop" and "Closed Loop" Force Control. "Open Loop" is just a simple setting of the motor’s current, while "Closed Loop" uses the technology function “Force Control” and controls the motor’s current dynamically based on measured force.

Details about the modes and the integration of the PDO can be found in the interface manual EtherCAT CiA402 und im gerätespezifischen Kapitel in der Application Note SPS Inbetriebnahme.
and in the corresponding chapter of the application note PLC Commissioning or contact LinMot technical support.

7.2 Use of Force Control on Profile ProfiDrive

The ProfiDrive profile does not directly support the force control function. To use the function nevertheless, please consult the chapter "Drive Profile Siemens TIA" in the application note PLC Commissioning.

8 Document Version

Version	Date	Author	Description
1V0	25.02.2021	mr	Initial version

Note:
The information in this documentation reflects the stage of development at the time of press and is therefore without obligation. NTI AG reserves itself the right to make changes at any time and without notice to reflect further technical advance or product improvement.

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