Dual-Loop Controller with Screw Drive

Application Note

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002	2020-01-24	dg	Replaced 'spindle' with 'screw drive'.
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1 Introduction

This document describes the usage and setup of the dual-loop controller applied on an axis with screw drive. Axes with a screw drive often are equipped with two encoders. Typically the first feedback signal (*Encoder0*) is the position of the motor and the second feedback signal (*Encoder1*) is the position of the load. The *Triamec* dual-loop controller supports the control of such axes. Figure 1 shows a schematic setup for an axis with screw drive equipped with two encoders.

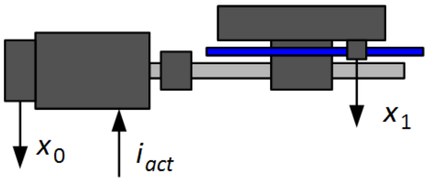

Figure 1: Schematic setup of an axis with screw drive with position output x_0 and x_1.

In a simplified approach the axis can be considered as a mass m_0 which represents the inertia of the motor and the screw[1] and a mass m_1 which represents the inertia of the linear axis. The two masses are coupled by the screw which can be considered as a weak damped mass spring system (Figure 2). This system can be described with two transfer functions: N_0 describes the transfer function between the current i_{act} and the position x_0. N_1 describes the transfer function between x_0 and x_1. The equations for the transfer functions are given in the appendix (section 5.1).

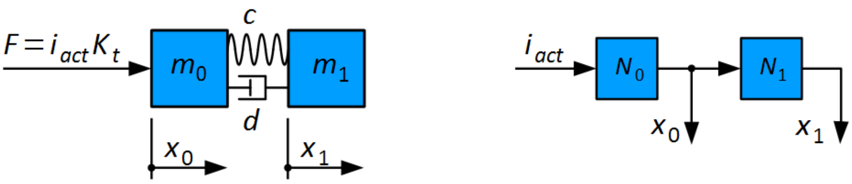

Figure 2: Damped mass-spring system and block diagram representation of a simplified axis with a screw drive.

1.1 Preconditions

The dual-loop controller is supported by the following hardware types:

- TSD80, TSD81, TSD85, TSD130, TSD350, TSD360, TSP710
- Depending on the application, option modules are needed to provide additional encoder inputs.

To operate the controller in dual-loop mode, the following conditions have to be fulfilled:

- The commutation of the motor is done with the signal of Encoder[0]. Therefore if commutation is used (which is the case if the motor type is not *DC*), Encoder[0] has to provide the position signal of the motor.
- The scale of the two encoders has to be the same. For example, if the scale of the load is linear and the scale of the motor is rotative, the Parameter Encoders.Encoder[0].Pitch has to be configured in such a way, that it matches the scale of Encoder[1] - or vice versa - by considering the gear ratio and the pitch of the drive screw.

1 Depending on the mechanical properties of the coupling and the screw some portions of the mass of the screw have to be assigned to the linear mass. It also has to be considered, that this portion of mass and the stiffness could depend on the position of the axis. Therefore it is recommended to do the Bode measurement at different positions.

- Depending on how the encoders are connected to the drive, the parameter General.Parameters.Encoder Topology has to be set accordingly. See also section 3 in [2].
- Parameter PositionController.MasterPositionSource can be used to select if the position and position error of Encoder[0] or Encoder[1] should be transmitted to the higher-level control system (e.g. Twincat).

2 Dual-Loop Position Controller Structure

To control axes with two encoders, Triamec drives are equipped with a dual-loop controller. Figure 3 shows the generic structure of the dual-loop controller with the following elements:

- P_0, P_1: Position controller 0 and position controller 1. Both controller provide a PIDT1 structure with up to 5 filters of second order.
- C_L: Current loop with the current controller and the electrical plant. This describes the transfer function between the commanded current i_{cmd} and the actual current i_{act}.
- M_0, M_1: Electromechanical transfer function between the actual current i_{act} and the measured position x_0 and x_1 respectively.

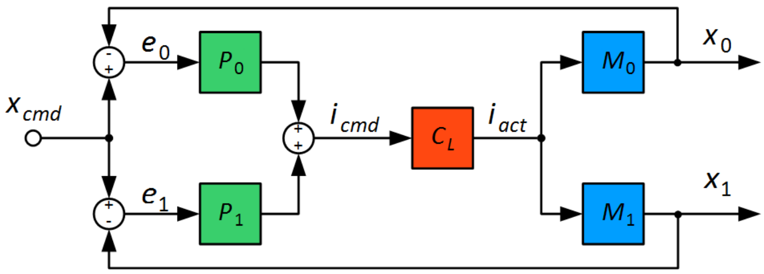

Figure 3: Generic structure of the dual-loop position controller.

The transfer functions of the dual-loop controller can be described with the following equations:

$$\frac{x_0}{x_{cmd}}=\frac{(P_0+P_1)C_L M_0}{1+C_L(P_0 M_0+P_1 M_1)}; \qquad \frac{x_1}{x_{cmd}}=\frac{(P_0+P_1)C_L M_1}{1+C_L(P_0 M_0+P_1 M_1)}. \tag{1}$$

Both transfer functions have the same denominator and the numerator is only different regarding the electromechanical transfer function M_0 and M_1.

3 Representation in Bode Tuning Tool

To ease the tuning of the two position controllers P_0 and P_1 with the bode tool, the controller structure displayed in Figure 3 is rearranged by considering the structure of the axis displayed in Figure 2. With this, the controller loop can be displayed as a cascaded controller with an inner controller loop A and an outer controller loop B as show in Figure 4.

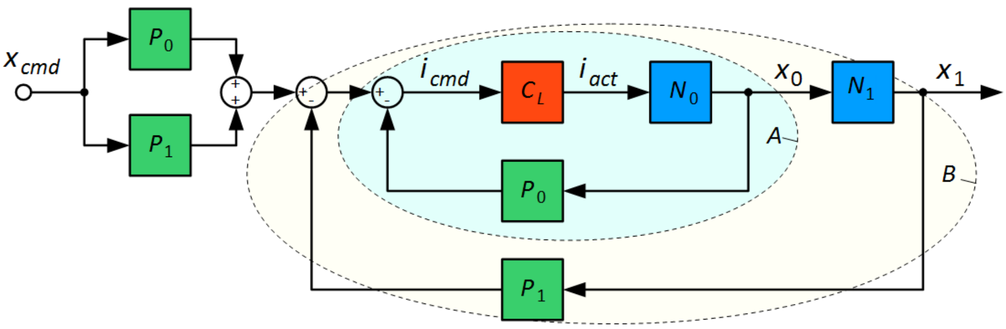

Figure 4: Cascaded display of the dual-loop controller with inner loop A and outer loop B.

In contrast to Figure 3, in Figure 4 the controllers P_0 and P_1 are moved to the feedback path and are added as prefilters to maintain the transfer function. The transfer functions M_0 and M_1 from Figure 3 can be expressed as

$$M_0 = N_0 \quad ; \qquad M_1 = N_0 N_1 \ . \tag{2}$$

With this representation it is possible to first tune the inner controller loop and afterwards the outer loop (with consideration of the closed inner loop).

3.1 Inner Loop

The stability of the inner controller loop is *not* affected by the configuration of the outer controller loop. Therefore, the inner loop can be configured as **Single Loop**. The following setup is required to configure the inner controller loop:

- If Encoder[0] is used for the inner loop, select **Position 0** from the **Select Controller** panel (else if Encoder[1] is used, select **Position 1** – not recommended for the inner loop).
- Make sure, **Single Loop** is selected in the **Select Controller** panel (Figure 5).

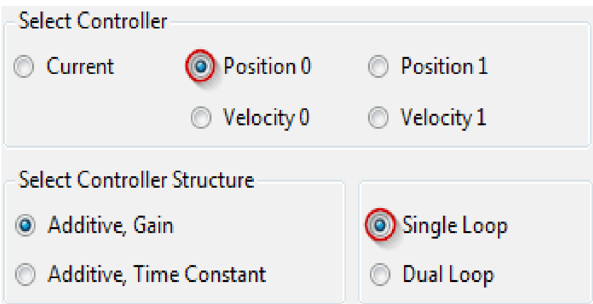

Figure 5: Setup for the tuning of the inner controller loop.

If **Position 0** and **Single Loop** is selected as shown in Figure 5, the following transfer functions are displayed in the bode plot:

$$F_o = P_0 C_L N_0 \quad , \qquad F_c = \frac{P_0 C_L N_0}{1 + P_0 C_L N_0} \tag{3}$$

where F_o is the open loop transfer function and F_c is the closed loop transfer function (with consideration of the prefilter) of the inner loop.

3.2 Outer Loop

The stability of the outer loop depends on the setup of the inner loop. Therefore the inner loop has to be setup first and may be adjusted iteratively to match the needs of the outer loop. The following setup is required to configure the outer controller loop:

- If Encoder[1] is used for the outer loop, select **Position 1** from the **Select Controller** panel (else if Encoder[0] is used, select **Position 0** which is not recommended for the outer loop).
- Make sure, **Dual Loop** is selected in the **Select Controller** panel (Figure 6). With this, the *Bode* plots of the outer loop consider the closed inner loop.

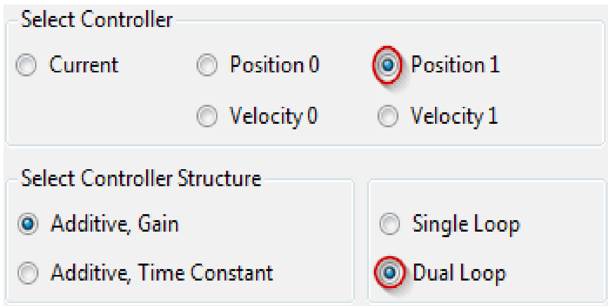

Figure 6: Setup for the tuning of the outer controller loop.

If **Position 1** and **Dual Loop** is selected as shown in Figure 6, the following transfer functions are displayed in the bode plot:

$$G_o = \frac{P_1 C_L N_0 N_1}{1+P_0 C_L N_0} \quad , \qquad G_c = \frac{(P_0+P_1) C_L N_0 N_1}{1+P_0 C_L N_0 + P_1 C_L N_0 N_1} \tag{4}$$

where G_o is the open loop transfer function and G_c is the closed loop transfer function of the outer loop.

Important When switching between inner loop and outer loop always both radio buttons have to be altered. **Position 0** ↔ **Position 1**; **Single Loop** ↔ **Dual Loop**

3.3 Inner Loop with Closed Outer Loop

Finally also the transfer functions H_o and H_c between x_{cmd} and x_0 with closed outer loop can be examined with the following setup:

- If Encoder[0] is used for the inner loop, select **Position 0** from the **Select Controller** panel.
- Make sure, **Dual Loop** is selected in the **Select Controller** panel.

In this case the following transfer functions are displayed in the bode plot:

$$H_o = \frac{P_0 C_L N_0}{1+P_1 C_L N_0 N_1} \quad , \qquad H_c = \frac{(P_0+P_1) C_L N_0}{1+P_0 C_L N_0 + P_1 C_L N_0 N_1} \tag{5}$$

Consider that the outer closed loop transfer function is only different by the N_1 transfer function in the numerator

$$H_c = \frac{G_c}{N_1} \quad . \tag{6}$$

Therefore, if G_c is stable and the numerator of N_1 has no zeros located in the right complex half plane, also H_c is expected to be stable.

4 Bode Tuning Best Practice

The dual-loop structure displayed in Figure 3 offers variety of parameters to configure the controller. Beside the the eight parameters for the two PIDT1 controllers also five filters of second orders are available for each controller which adds additional 20 parameters. This allows a wide degree of freedom of how to configure the controller. This chapter illustrates one possible approach of how to set the parameters.

In this section it is assumed that the configuration of the drive is already set with valid parameters and the current controller is tuned. See [1] for more information of how to setup the registers and also regarding the basics of *Bode* measurement and tuning. As the transfer function of a screw drive depends on the position of the axis, it is recommended to do the Bode measurement at several locations.

4.1 Inner Loop

The aim for the inner controller loop is to add damping to the system with sufficient stability margins. Essentially, only **Kd** and **T1** and eventually filters needs to be set. The integrator gain **Ki** must be set to zero to avoid interference with the integrator of the outer loop.
The inner loop can be configured by executing the following steps:

- Activate **Position 0** in the **Select Controller** panel and **Single Loop** in the **Select Controller Structure** panel (Figure 7).
- Set the controller parameter **T1** to an initial value of about 0.0005s. This value may has to be adjusted in later optimization of the controller. Reducing the value will increase the damping at higher frequencies but also amplify the gain at higher frequencies. As a rule of thumb the value should finally be set according to the following approximation

$$T_1 \approx \frac{0.05}{f_{gc}} \quad , \tag{7}$$

  where f_{gc} is the gain crossover frequency at which the open loop gain of the tuned outer controller crosses 0dB (see section 4.2). Therefore the initial value of 0.0005 would corresponds to an assumed gain crossover frequency of 100Hz.
- In the Nyquist view the differential gain **Kd** can now be adjusted so that the open loop transfer function touches but does not exceeds the the circle labeled with 1.3 (Figure 7).

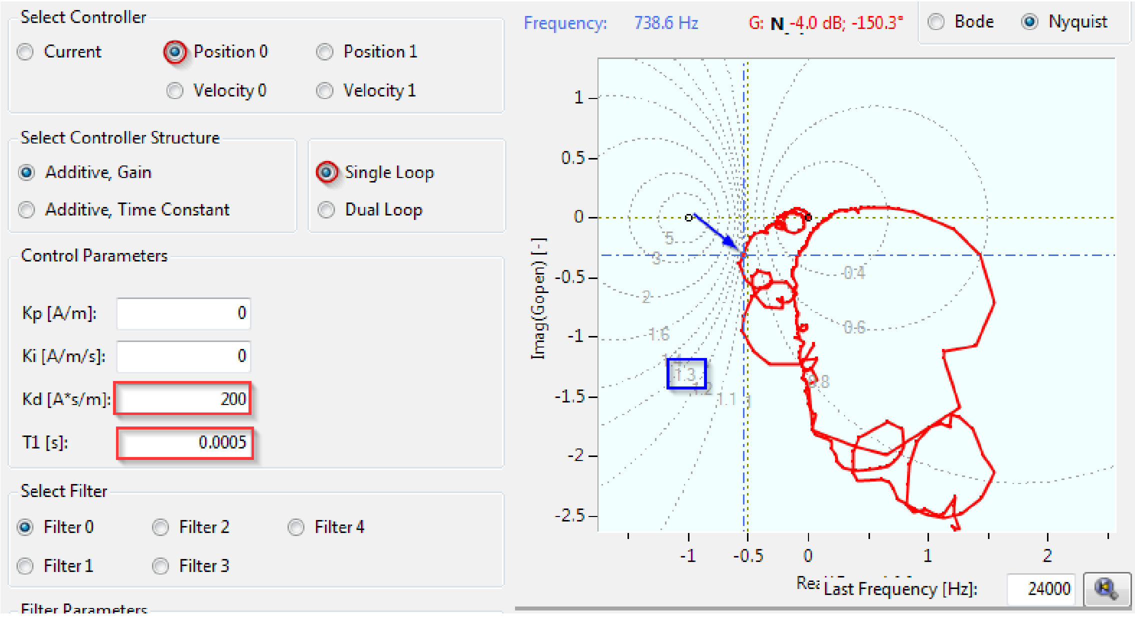

Figure 7: Tuning of inner controller loop.

4.2 Outer Loop

The goal for the outer controller loop is to get a stiff system with sufficient stability margins. Thanks to the damping of the inner loop no additional damping of the outer loop should be required in most cases. Therefore **Kd** and **T1** are mostly set to zero.

The outer loop can be configured by executing the following steps:

- Activate **Position 1** in the **Select Controller** panel and **Dual Loop** in the **Select Controller Structure** panel and set Kr = 1 and Tn = 0 and activate the **Bode** plot view (Figure 8).
- In the bode plot choose a gain crossover frequency f_{gc} as displayed in Figure 8 with sufficient phase margin (A) and sufficient attenuation at higher frequencies (B).

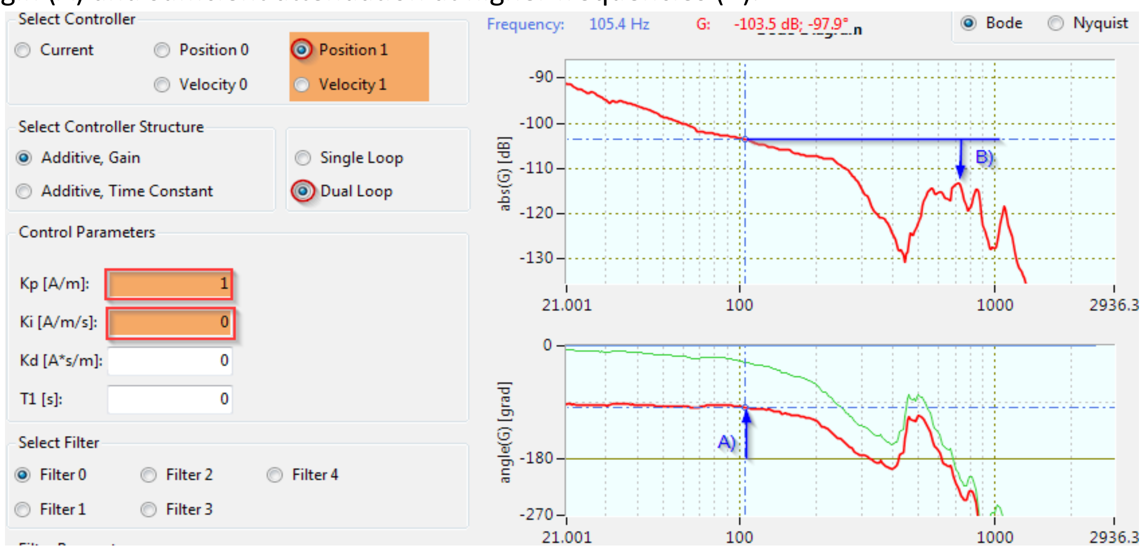

Figure 8: Tuning of outer loop: A) phase margin; B) attenuation at higher frequencies.

- In the example displayed in Figure 8 f_{gc} is chosen at 105Hz where the open loop gain G_{gc} is -103.5dB (with **Kp** = 1). With G_{gc} the controller gain can be calculated with equation (8) which yields **Kp** = 150000. With this **Kp**, the open loop gain in the bode display should now cross 0dB at f_{gc} (Figure 9).

$$Kp \approx 10^{\frac{-G_{gc}}{20}} \quad . \tag{8}$$

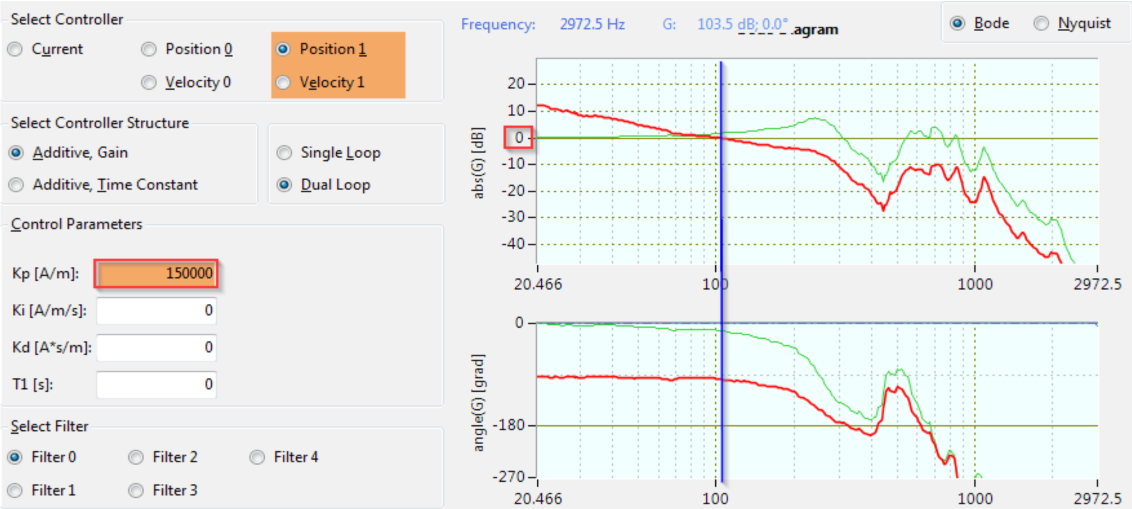

Figure 9: Gain crossover frequency with tuned Kp.

- Now the integrator gain **Ki** can be adjusted in the **Nyquist** view so that the open loop transfer function touches but not exceeds the the circle labeled with 1.3 (Figure 10). This may requires also to adjust the proportional gain **Kp**. The following equation can be used to calculate an initial value for **Ki**.

$$Ki \approx 100\, K_p \tag{9}$$

- It may be required to further optimize the controller by adjust the inner and outer loop iteratively and maybe also to add some filters.

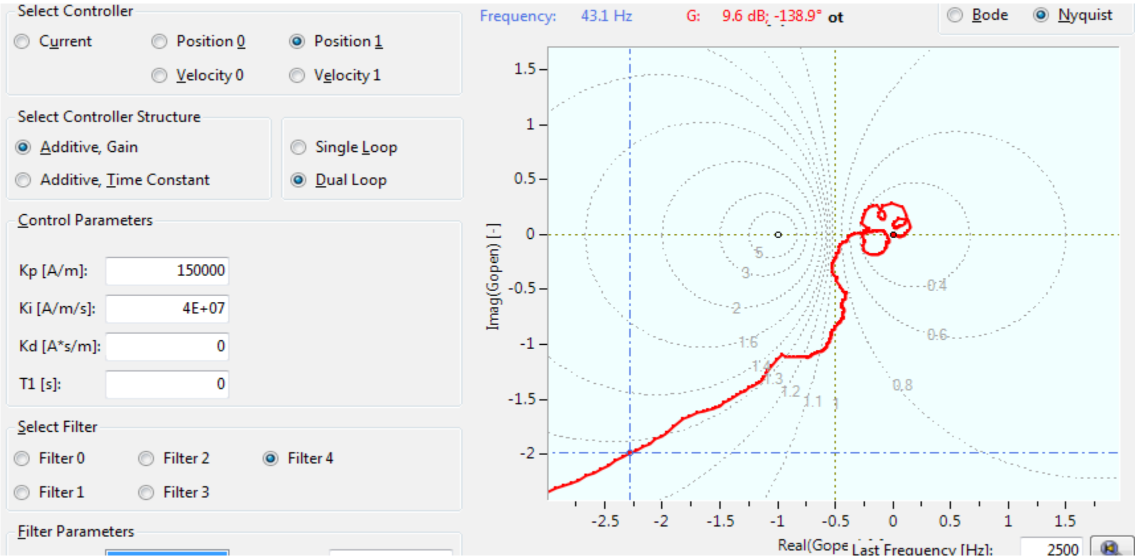

Figure 10: Nyquist view of the tuned outer controller loop.

4.3 Verification

Finally the stability of the inner controller loop with closed outer loop can be verified. It is expected, that the inner loop is stable if the tuning is executed as described above, but it is recommended to verified, if the stability margins are sufficient.

- Activate **Position 0** in the **Select Controller** panel and **Dual Loop** in the **Select Controller Structure** panel and activate the **Bode** plot view (Figure 11).
- Verify if the open loop transfer function does not exceed the 1.4 circle and if the critical point [-1, 0j] is located at the left of the curve when following the curve from low frequency to high frequency.

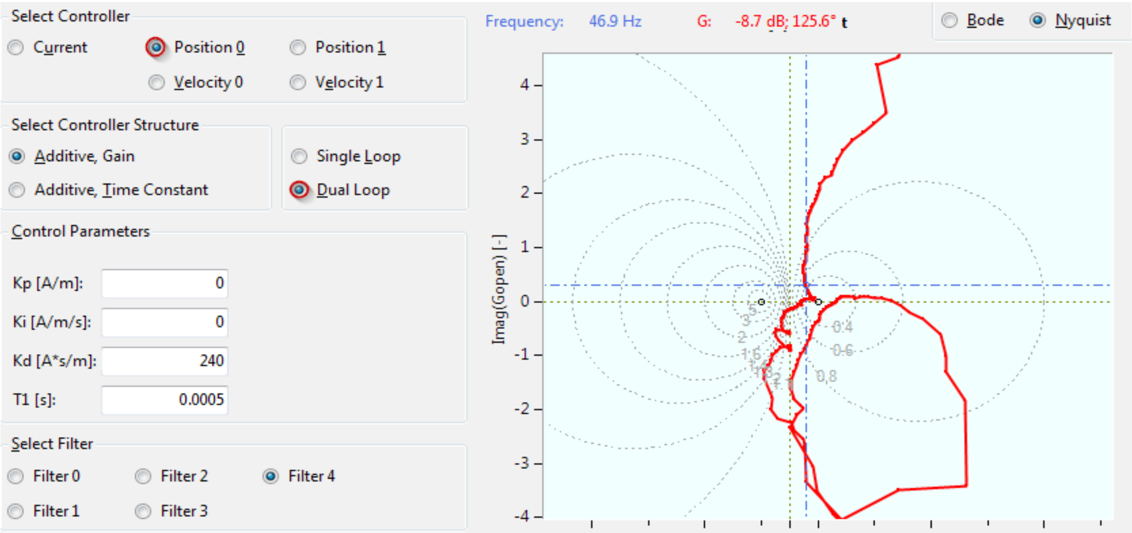

Figure 11: Nyquist plot of the inner controller with closed outer controller loop.

4.4 Test in Time Domain

To verify the tuning of the controller in time domain, it is recommended to use the signal generator to measure and analyze the step response.

To analyze the dynamic behavior of the axis the Axis Module can be used to generate jerk restricted moves with the internal path-planner.

See also [1] for more information of how to setup the scope for the measurement.

5 Appendix

5.1 Simplified Transfer Functions of an Axis with Screw Drive

In a simplified theoretical approach the axis can be considered as a mass m_0 which represents the inertia of the motor and a mass m_1 which represents the inertia of the liner axis. The two masses are coupled by the screw which can be considered as a weak damped mass spring system (Figure 2). Based on this approach the transfer function of the axis can be described with the following equations:

$$N_0 = \frac{x_0}{i_{act}} = \frac{K_t}{m_0 + m_1} \cdot \frac{\frac{m_0 + m_1}{m_1} s^2 + 2 D \omega_0 s + \omega_0^2}{s^2 + 2 D \omega_0 s + \omega_0^2} \ ,$$

$$N_0 N_1 = \frac{x_1}{i_{act}} = \frac{K_t}{m_0 + m_1} \cdot \frac{2 D \omega_0 s + \omega_0^2}{s^2 + 2 D \omega_0 s + \omega_0^2} \ , \qquad (10)$$

$$N_1 = \frac{x_1}{x_0} = \frac{d s + c}{s^2 + d s + c} \ ,$$

$$\text{with} \quad \omega_0^2 = c \frac{m_1 + m_2}{m_1 m_2} \quad \text{and} \quad D = \frac{d}{2 \omega_0} \frac{m_1 + m_2}{m_1 m_2} = \frac{d \omega_0}{2 c} \ .$$

Theoretically this transfer functions could be used to evaluate the controller parameters for example by using robust controller theory or pole placement. But this simplified representation of the screw drive does often not sufficiently match with the real system, as for example higher eigenmodes, dead-time and nonlinearities like friction and backlash are not considered. Therefore in practice the bode tuning approach has turned out as more practicable and is therefore described in this document.

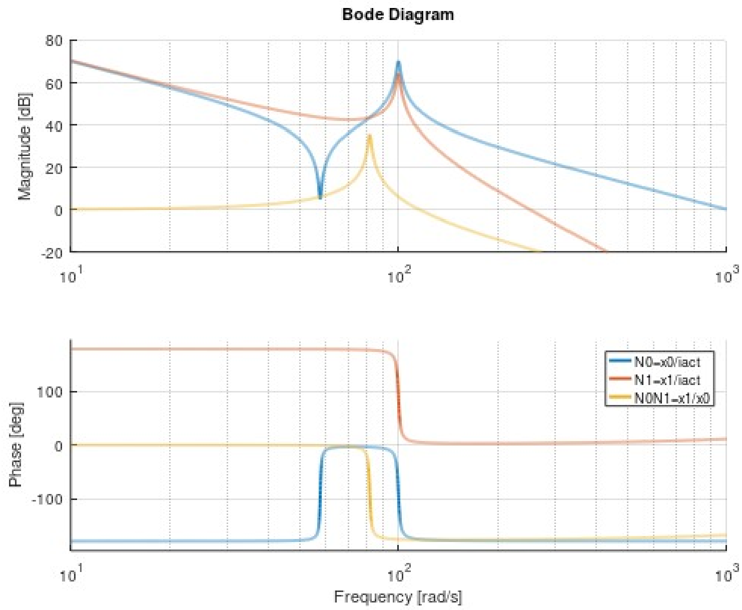

Figure 12: Transfer function of damped two mass-sping system.

5.2 Comparison with a Common Controller used in the Industry

Figure 13 shows a popular controller structure used in the industry for axes with screw drive. This section shows that the transfer function of this structure can be rebuild with the *Triamec* dual-loop controller and that the *Triamec* dual-loop controller is a more general form of this controller.

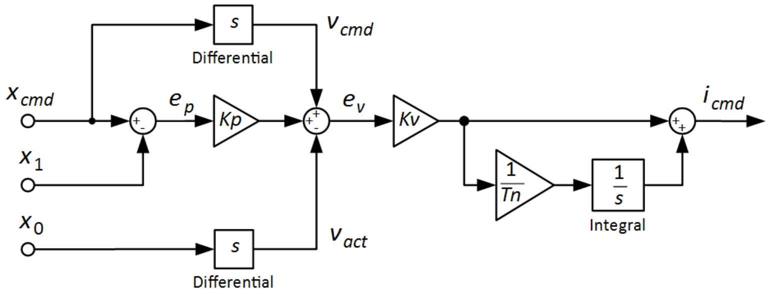

Figure 13: Cascaded multiplicative controller structure.

By rearranging the block diagram, the multiplicative structure can be modified into two additive controllers without changing the transfer function of the controller (Figure 14 left).

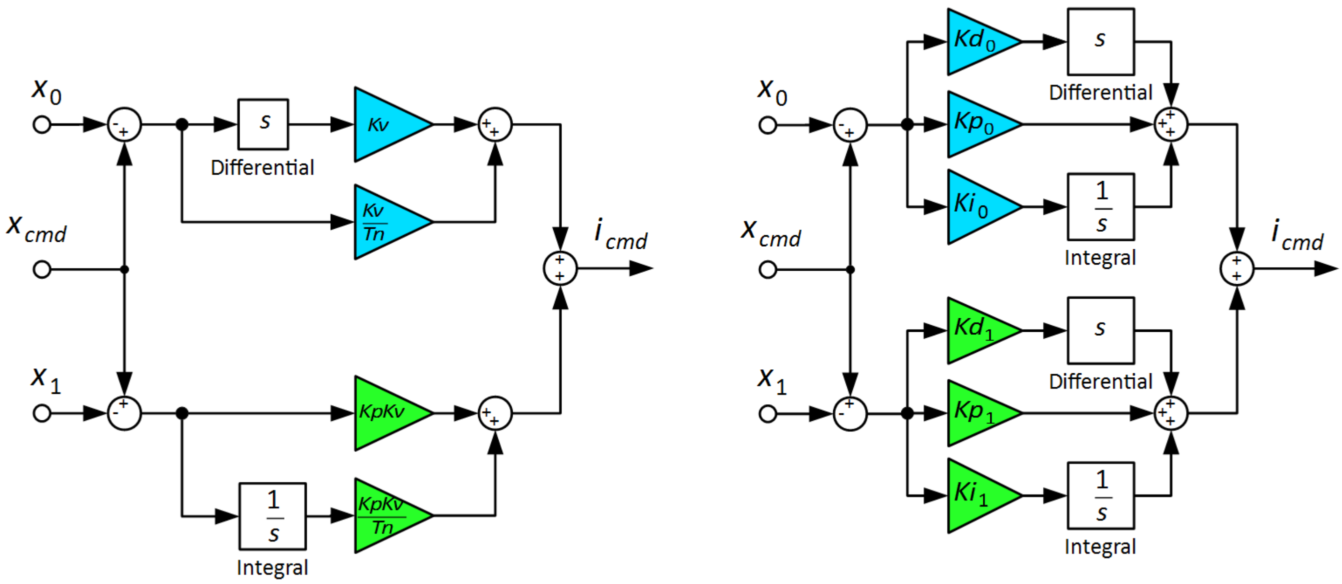

Figure 14: Comparison between the modified additive controller structure (left) with the Triamec dual-loop controller structure(right).

By comparing the modified structure with the Triamec dual-loop controller (Figure 14 right) on can derive the parametrization of the dual-loop controller to achieve the same transfer function of the controller.

Controller 0:

$$Kp_0 = \frac{Kv}{Tn} \quad , \quad Kd_0 = Kv \quad , \quad Ki_0 = 0 \tag{11}$$

Controller 1:

$$Kp_1 = KpKv \quad , \quad Kd_1 = 0 \quad , \quad Ki_1 = \frac{KpKv}{Tn} \tag{12}$$

References

[1] “Drive Setup Guide, TSD, TSP360 and TSP710”, SW_TSD-TSP360-TSP710-Setup-Guide_EP002.pdf, Triamec Motion AG, 2019

[2] “Encoder configuration for the TSD drive series”, AN107_Encoder_EP009.pdf, Triamec Motion AG, 2019