MATLAB / Simulink Lab Course

Simulink Control Design

Objectives & Preparation "Simulink Control Design"

- Which MathWorks products are covered?
  - ⇨ Simulink Control Design

- What skills are learnt?
  - ⇨ Search for operating points of Simulink models
  - ⇨ Linearize the system around operating points
  - ⇨ Estimate the frequency response of the system
  - ⇨ Tune controllers with the Simulink Control Design
  - ⇨ Verify the model and the controlled closed-loop system

- How to prepare for the session?
  - ⇨ Simulink Control Design documentation:
    - https://de.mathworks.com/help/slcontrol/
  - ⇨ Tutorials for each section of this session:
    - https://de.mathworks.com/help/slcontrol/getting-started-with-simulink-control-design.html

Outline

1. Introduction
2. Operating Points
3. Linearization
4. Frequency Response Estimation
5. Control Design
6. Model Verification

1. Introduction

Introduction

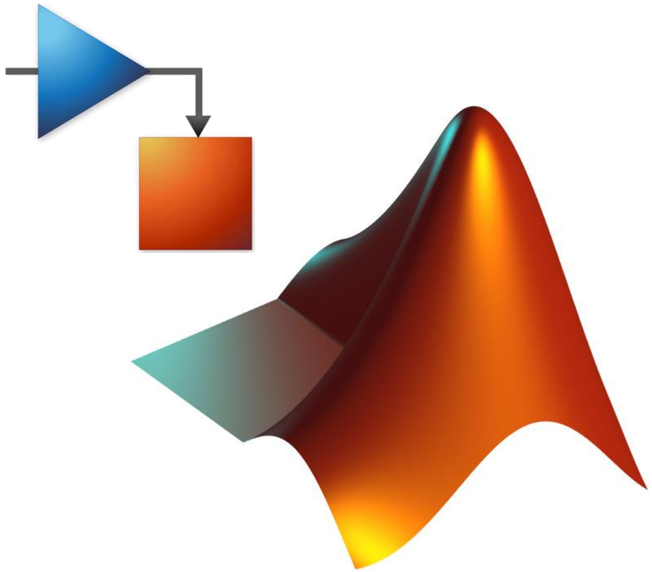
- Similar to MATLAB's Control System Toolbox, **Simulink Control Design** is a useful tool for **analysis and design of dynamic (control) systems**, which are modeled in Simulink.
- While the Control System Toolbox describes linear systems only, Simulink Control Design is additionally capable of working with **nonlinear systems**.
- The functionalities of the Simulink Control Design toolbox presented here include:
  - Nonintrusive computation of operating points (trimming) of Simulink models
  - Exact linearization of nonlinear Simulink models
  - Simulation-based computation of frequency responses
  - Graphical and automated tuning of PID controllers and arbitrary controller layouts.
  - Numerical optimization of compensators to meet time-domain or frequency-domain requirements.
- Other toolboxes that are helpful for control design using Simulink include the Simulink Design Optimization (SDO) toolbox, the Simulink Design Verifier and the Robust Control Toolbox. They are not covered by this lab course. Visit the MATLAB lecture or refer to the MATLAB help to learn more!

Introduction

- The following list of steps puts the features of the toolbox and the sections of this course into the context of actual control system development:

1. Build a Simulink model of the plant (Suppose this model is nonlinear.)	Session: Simulink Fundamentals
2. Determine (relevant) operating points of the plant	Section 2: Operating Points
3. Linearize the plant at those operating points (and possibly verify the linearization)	Sections 3 & 4: Linearization, FRE
4. Design a linear controller, based on the linearized plant model	Section 5: Control Design
5. Verify that the linear controller performs as desired with the nonlinear plant	Section 6: Model Verification

2. Operating Points

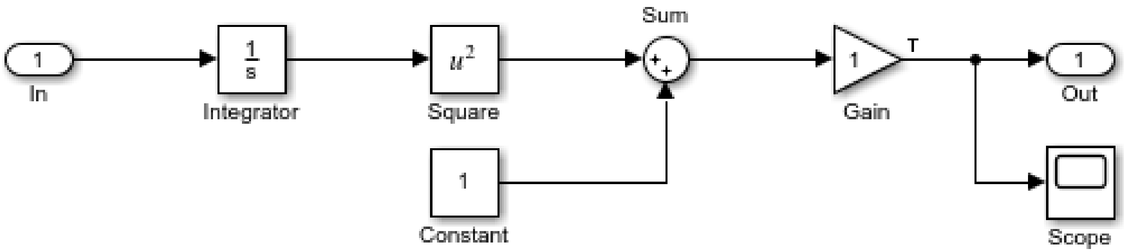


Operating Points

- An operating point is the state of a dynamic system at a specific point in time.
- A steady-state operating point, also called equilibrium or trim condition, is an operating point at which (some) state variables do not change over time.
- After an operating point has been found, the system can be linearized (see section 3), so that linear control theory can be applied.
- Simulink itself provides a function that finds operating points, named `trim`. The Simulink Control Design toolbox, however, brings substantial advantages:
    - A Graphical User Interface (GUI)
    - Multiple optimization methods
    - Constraints on state, input, and output variables using upper and lower bounds
    - Steady-state operating points for models with discrete states
    - Model reference support

Operating Points

- The operating point of a Simulink model consists of the model initial states and root-level input signals. In the case of the following model, this is
  - The inport In1
  - The state of the Integrator block



- States are introduced by blocks like integrators, transfer function-, state space-, PID-, or zero-pole-gain-blocks (or their discrete-time counterparts).

- Inputs are represented by inports.

- Outputs are represented by outports or by "Trim Output Constraints": any signal in a model can be specified a Trim Output Constraint by *Right Click → Linear Analysis Points → Trim Output Constraint*. The signal arrow is the accompanied by the letter "T". 

Operating Points

- You can find steady-state operating points from user specifications or after specific simulation times. While the first method is optimization-based ("trimming"), the latter method is simulation-based and also referred to as "**simulation snapshot**."

Optimization-based search

Use this approach

- when you know some of the **operating point states** and **model input or output signal levels**.

This approach produces poor results:

- When you specify initial guesses far away from the desired operating point.
- When you specify incompatible input, output, or state constraints at equilibrium.

Simulation-based search

Use this approach

- when the **simulation time is sufficiently short** for the model to reach steady state.

This approach produces poor results:

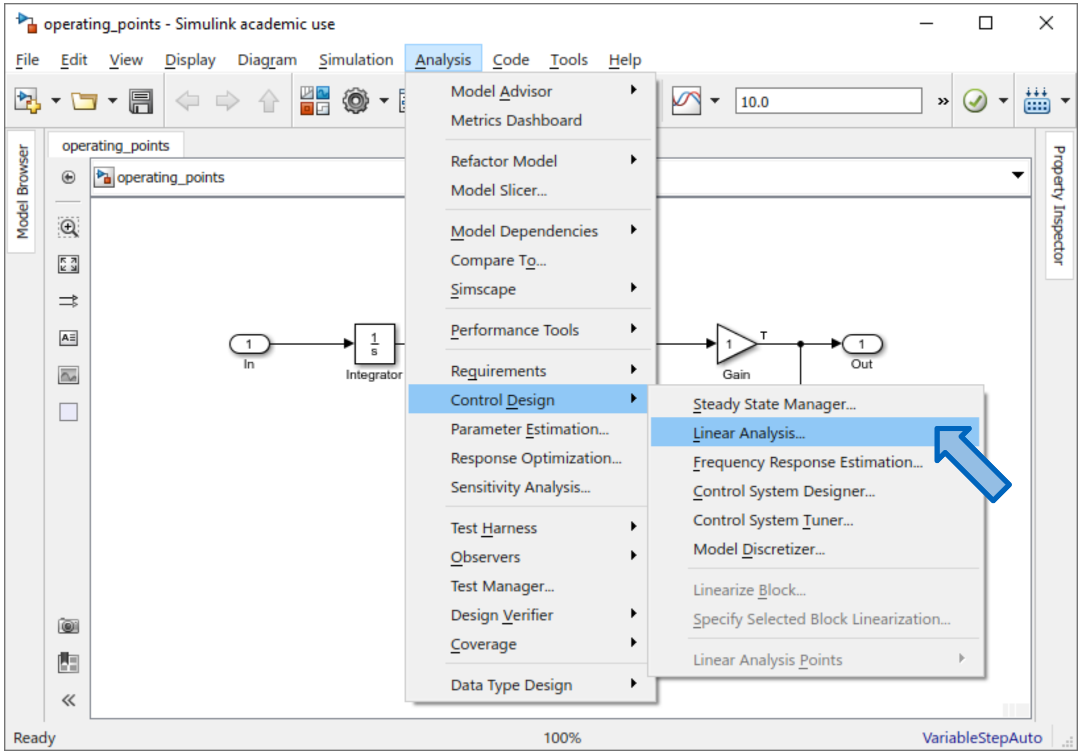
- If the model takes too long to reach steady state.
- When you specify initial conditions that do not cause the model to reach true equilibrium.

Both approaches can be combined: First a simulation snapshot, then an optimization.

Operating Points

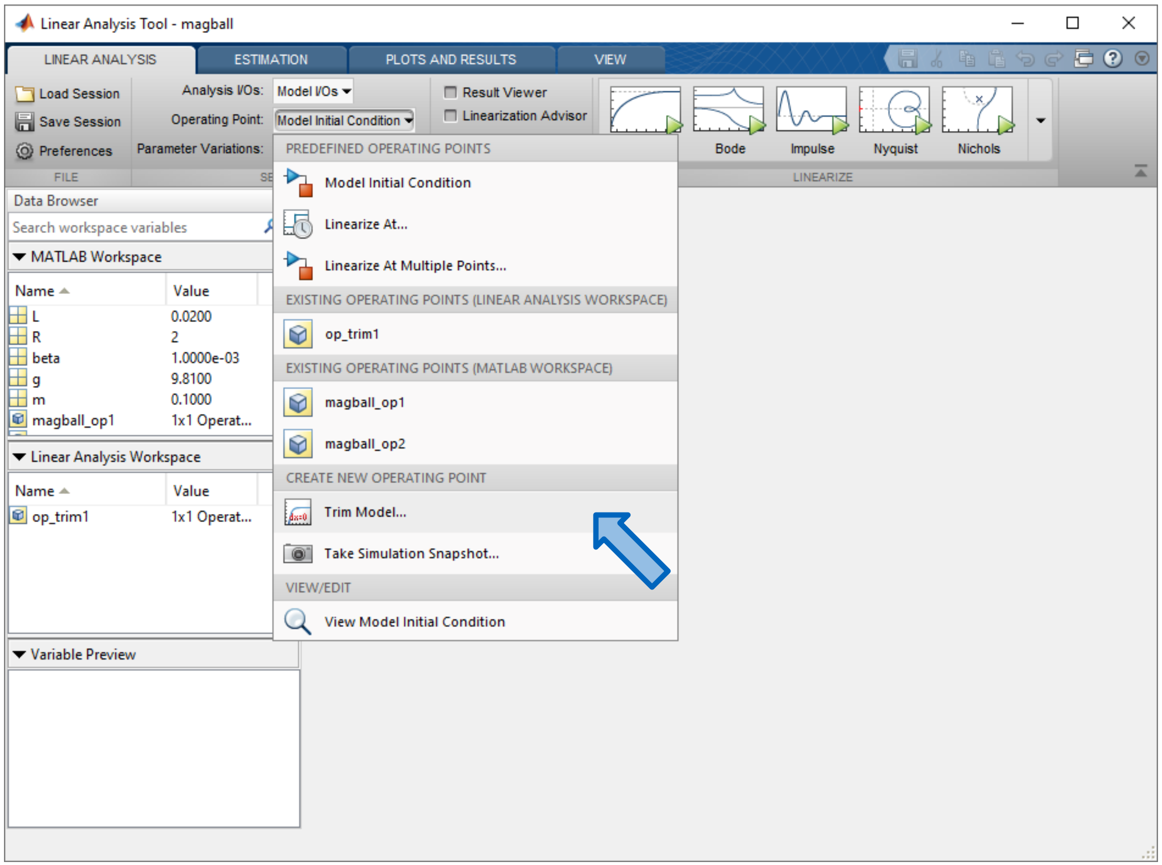
- Three different search methods for steady-state operating points are presented here:
  1. Optimization-based search for steady-state operating points from state specifications (trimming)
  2. Simulation-based search for steady-state operating points (simulation snapshot)
  3. Initialization of optimization-based search using simulation snapshots

- All of them – and also many other functionalities presented in the following sections – can be accessed through the Linear Analysis Tool.



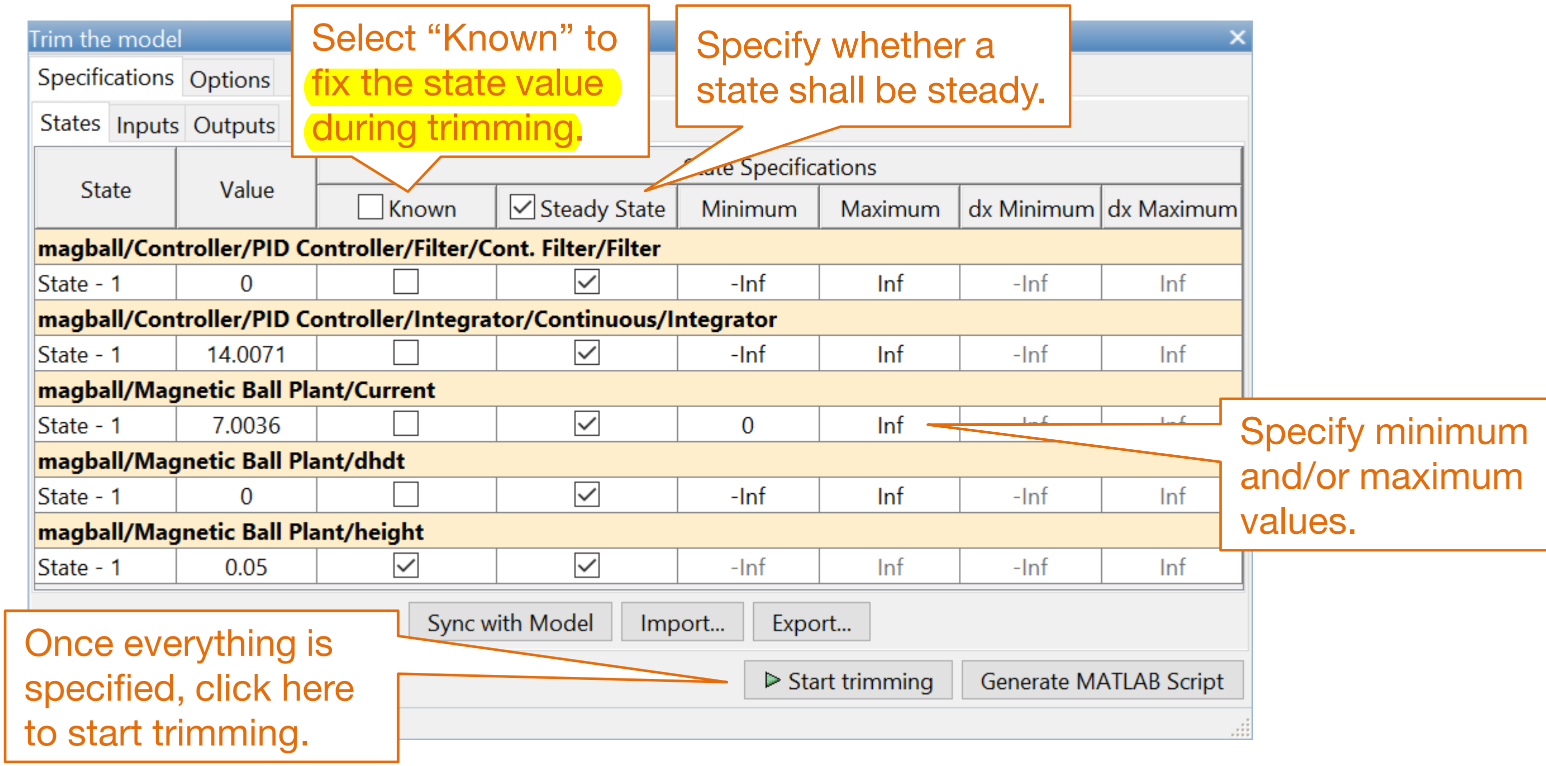
Operating Points – Optimization-based Search

- On the Linear Analysis Tool GUI, choose "Trim Model…" from the "Operating Point" dropdown menu to open a dialog box for operating point search.



Operating Points – Optimization-based Search

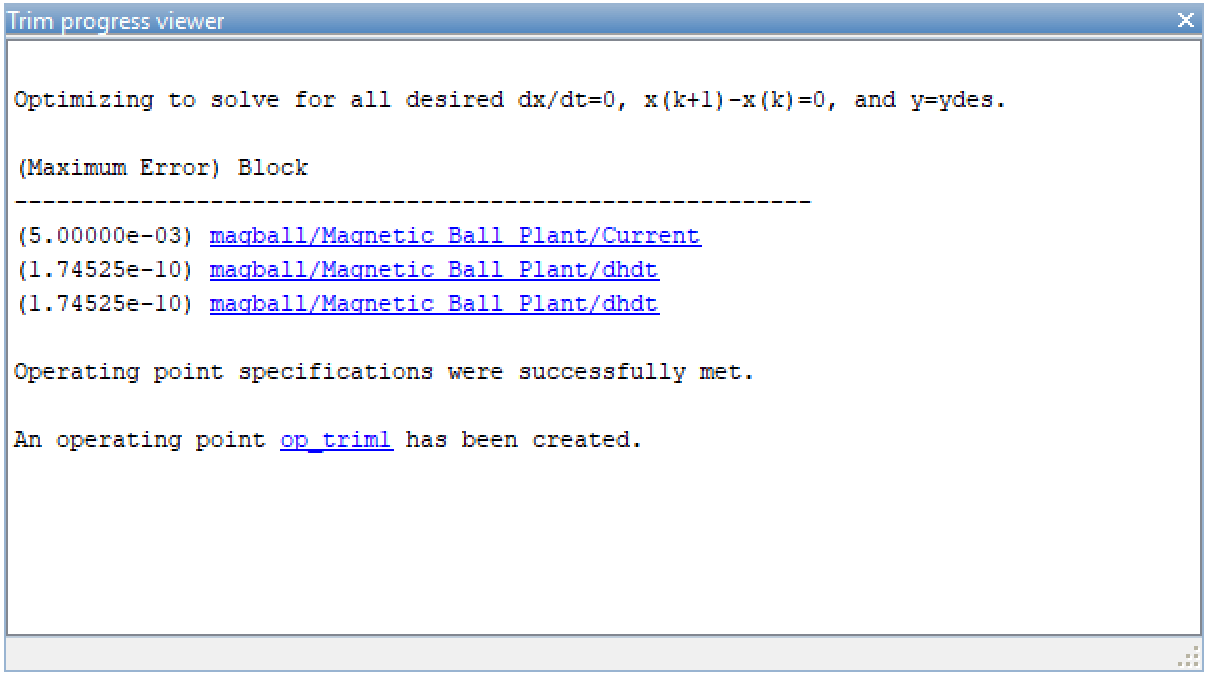
- By default, the list of states is shown. You can specify the system states and trim.



- Alternatively, you can select the “Outputs” tab and specify the outputs for trimming. In this case, you would usually specify one or more outputs as “Known” and enter their known value in the “Value” column.

Operating Points – Optimization-based Search

- During trimming, a new window shows the current progress (“Trim progress viewer”).



Operating Points – Optimization-based Search

- After successful trimming, a new operating point is added to the Linear Analysis Tool workspace (not the MATLAB workspace).
- Double-click the new operating point to see its details.

▾ Linear Analysis Workspace

Name ▴	Value
op_trim1	1x1 OperatingReport

Edit: op_trim1

Optimizer Output | Details

State | Input | Output

State	Desired Value	Actual Value	Desired dx	ual dx
magball/Controller/PID Controller/Filter/Cont. Filter/Filter				
State - 1	[-Inf , Inf]	0	0	0
magball/Controller/PID Controller/Integrator/Continuous/Integrator				
State - 1	[-Inf , Inf]	14.0071	0	0
magball/Magnetic Ball Plant/Current				
State - 1	[0 , Inf]	7.0036	0	4.2064e-11
magball/Magneti Ball Plant/dhdt				
State - 1	[-Inf , Inf]	0	0	-1.7453e-10
magball/M ic Ball Plant/height				
State - 1	0.05	0.05	0	0

Initialize model...

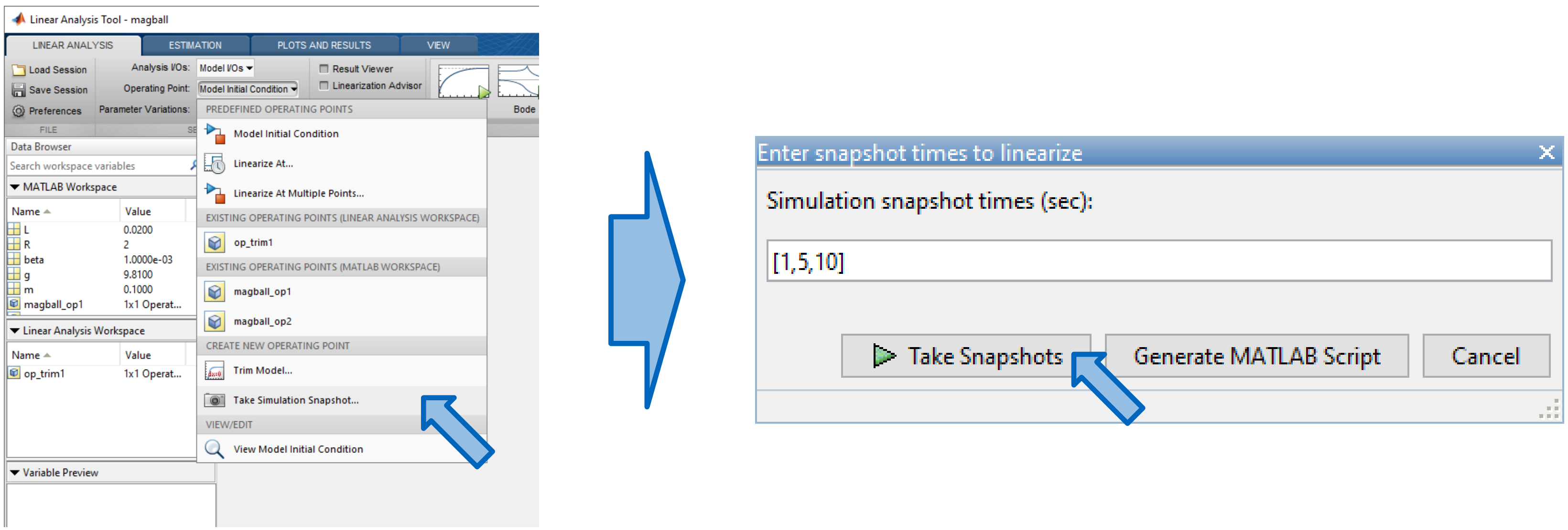
Two state derivatives are not exactly zero, but sufficiently small.

A minimum value of zero had been specified for this state.

This state had been specified as “known.”

Operating Points – Simulation-based Search

- To initialize a steady-state operating point search using simulation snapshot, select “Take Simulation Snapshot…” from the “Operating Point” dropdown menu.

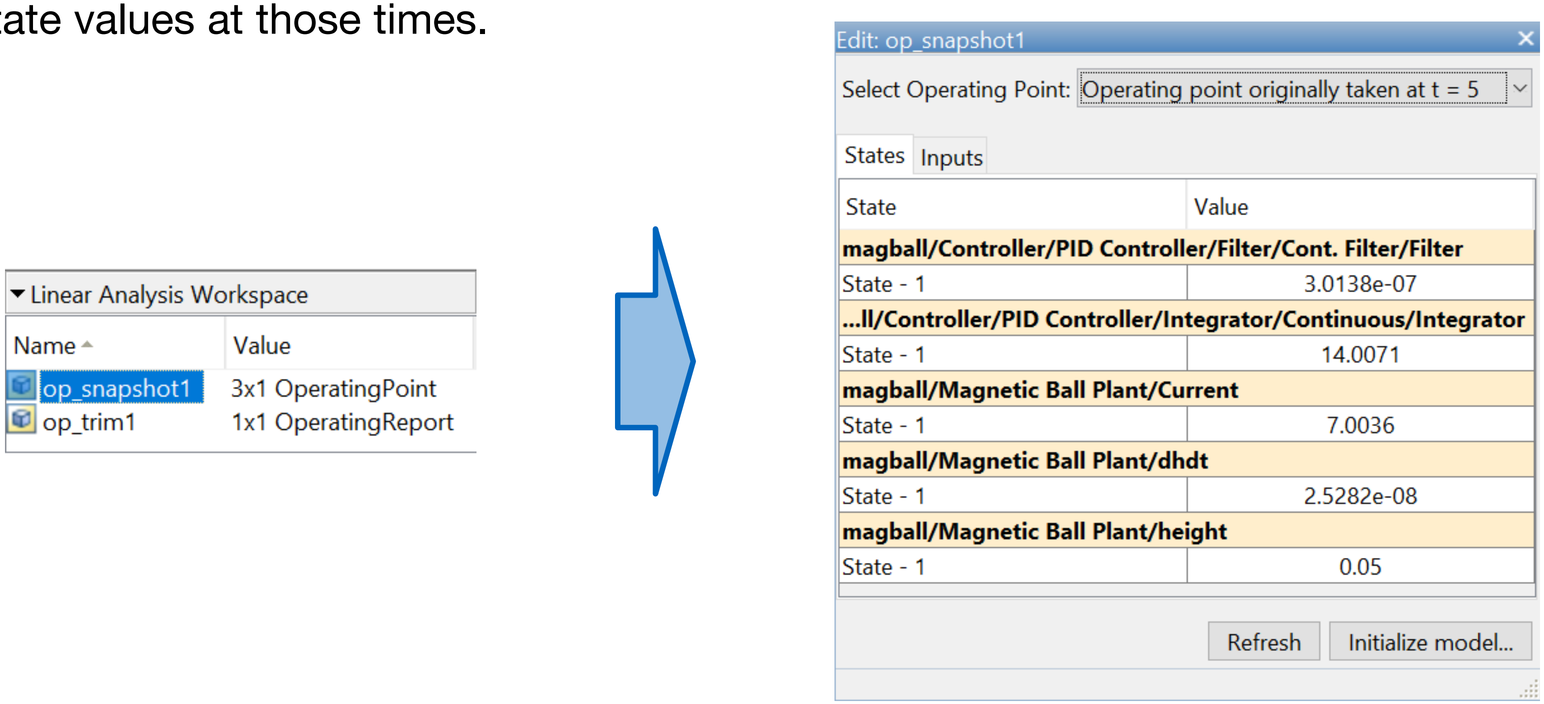


- A new window opens that prompts you to choose one or more simulation snapshot times.

- Click “Take Snapshots” to take snapshots at the specified times.

Operating Points – Simulation-based Search

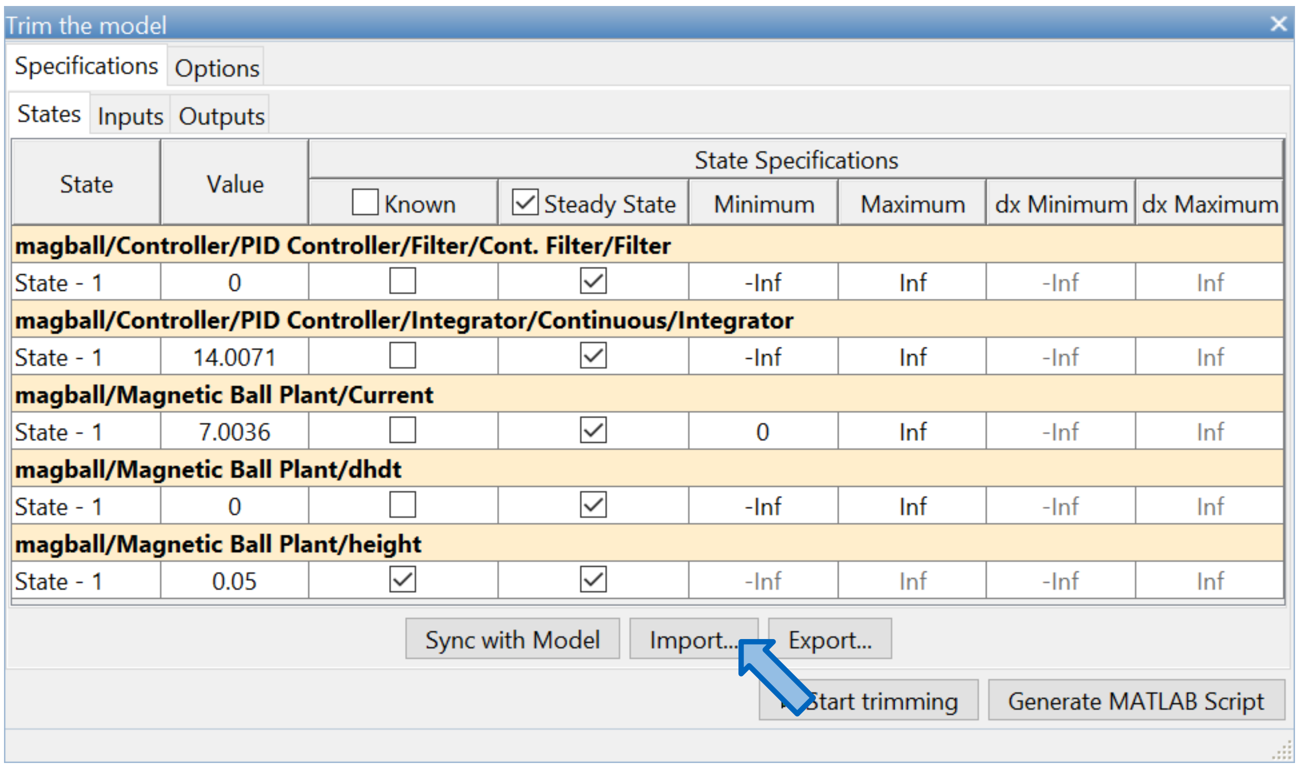
- The snapshots will then appear in the Linear Analysis Tool workspace. They contain all state values at those times.



- The generated snapshots can be used to initialize the optimization-based search (see next slide). However, for this purpose, generate only a single snapshot at a specific time (instead of a vector as shown in the last slide).

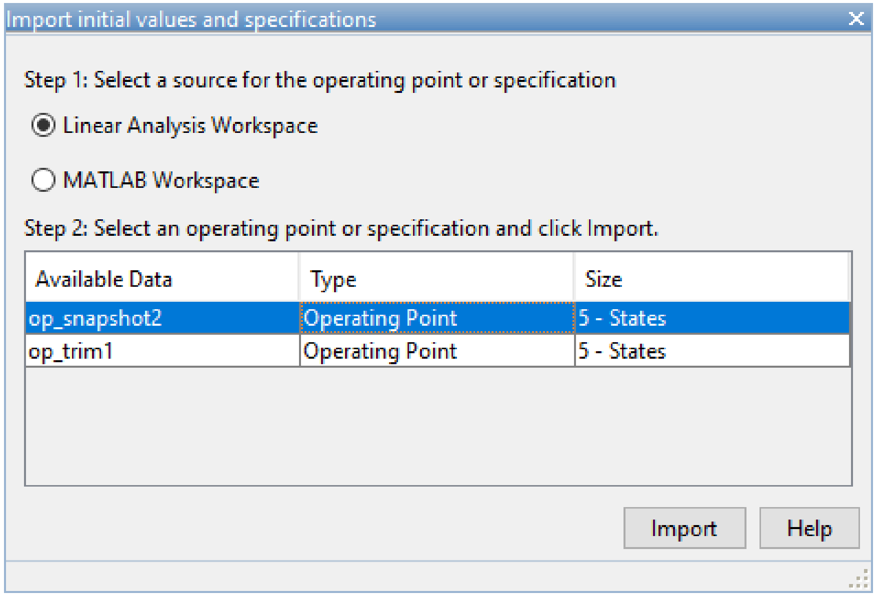
Operating Points – Initialize Optimization-based Search with Snapshots

- To initialize the optimization-based search with a snapshot, select “Trim Model…” from the “Operating Points” drop down menu as before.
- However, this time, click “Import…”



Operating Points – Initialize Optimization-based Search with Snapshots

- Select the snapshot you have just created and click "Import."



- The state values in the "Trim the model…" window are now the values from the snapshot.
- You can now continue with the optimization-based trimming as described above.
- Instead of using the GUI, you can also write MATLAB code that performs all those same steps automatically. MATLAB code can also be generated from the GUI. Refer to the MATLAB help (function `findop`, Linear Analysis Tool) for more information.

3. Linearization

Linearization

- Simulink itself provides the function `linmod` for model linearization. Again, the Simulink Control Design toolbox brings several advantages, including GUIs and more flexibility.

- It is possible to either compute an exact linearization, or to make a frequency response estimation. Exact linearization is covered in this section. Refer to section 4 for frequency response estimation.

Exact linearization

- Is faster, because it does not require simulation of the Simulink model.

- Returns a parametric (state-space).

- Should be used in most cases.

Frequency Response Estimation

Use this approach

- to validate exact linearization accuracy.

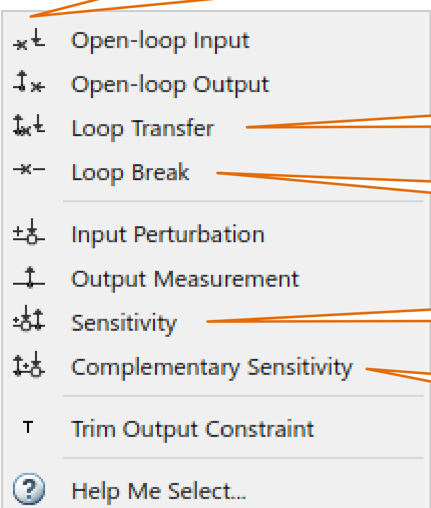
- when the Simulink model contains discontinuities or non-periodic event-based dynamics.

- to study the impact of amplitude size on frequency response.

Linearization

- Before actual linearization, the portion of the model to be linearized has to be specified. This can be done in several ways:
  - In the model, by adding inports, outports, and/or by specifying additional linear analysis points. Note that these points are saved with the model! *Right click on a signal → Linear Analysis Points*

These symbols illustrate how the selected signal will be treated during linearization. They are combinations of loop break, input, output and additive disturbance.



Use to compute open-loop transfer function around the loop.

Use in case of nested loops to ignore the effect of certain loops.

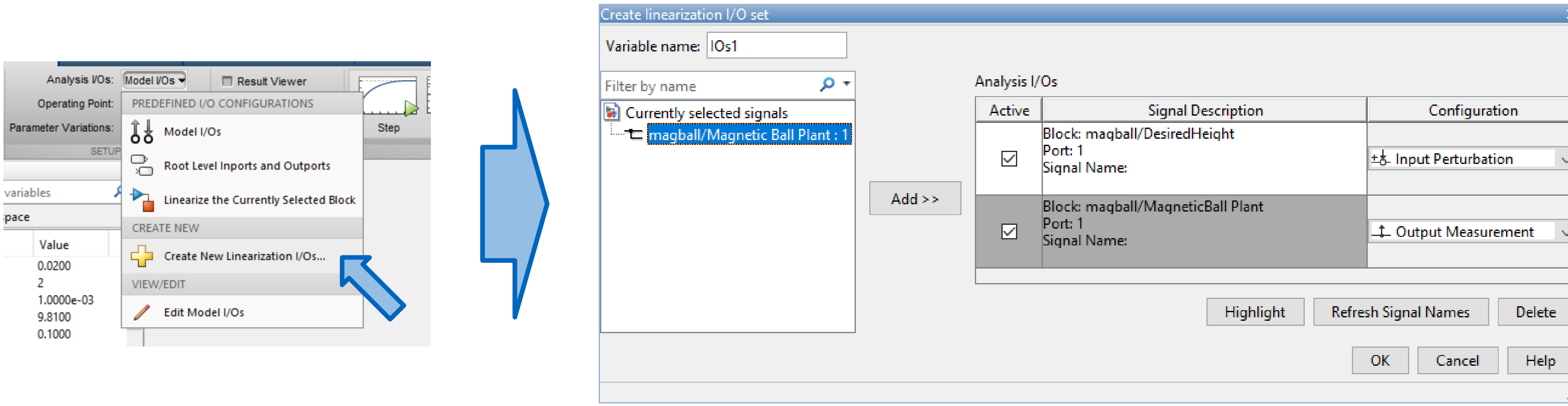
Use to compute sensitivity function for additive disturbance.

Use to compute closed-loop transfer function around the loop.

  - Using the Linear Analysis Tool GUI (details on the next slide)
  - Using the MATLAB command `linio` (refer to MATLAB help)

Linearization

- To specify linear analysis points in the GUI, select “Create New Linearization I/Os…” from the “Analysis I/Os” dropdown menu. The “Create linearization I/O set” window opens.



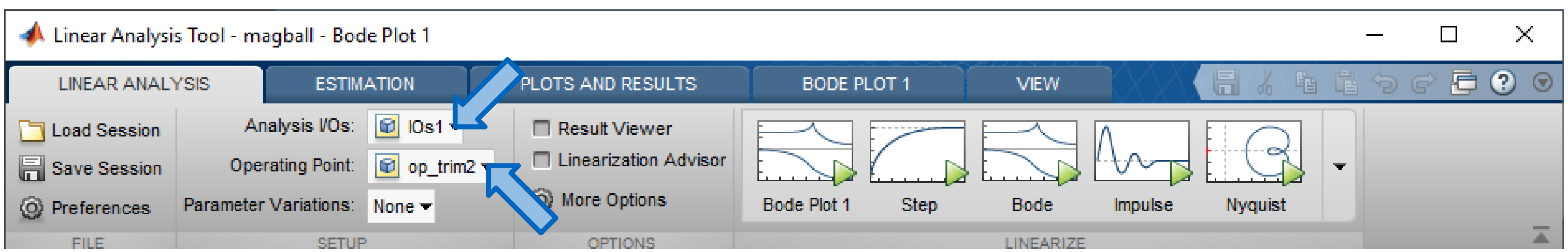
1. Now, select a signal in the Simulink model (simple left click)
2. It appears in the window. Click “Add >>” to add the signal.
3. Repeat steps 1 and 2 to add further signals, if needed.
4. Use the dropdown menu for specification (same options as above)
5. Click OK to save the I/O set.

Linearization

- Having defined the operating point as well as the input/output set to linearize, actual linearization can be accomplished with the following steps.

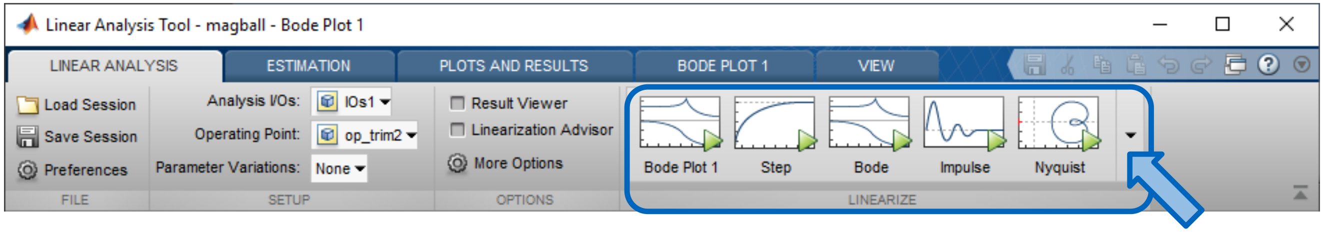
1. In the GUI, select the linearization inputs/outputs set. You can choose, for example, the set you have previously created, the root level in- and outports, or a selected block.

2. Select an operating point or simulation snapshot. Again, you can choose between predefined operating points, such as the model initial condition, and those operating points you have previously created.



Linearization

3. With the proper I/O set and the operating point selected, click on one of the plot symbols to linearize.



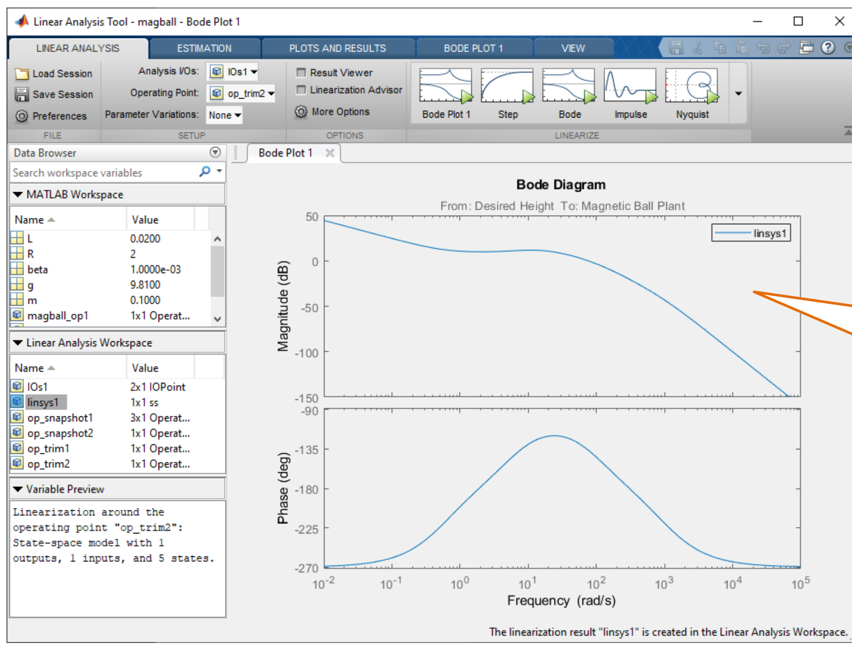
- The linearized model will appear in the GUI workspace and the plot will show on the GUI.

Use "drag and drop" to copy variables from one workspace to another.

The I/O set

The linear system

The operating point

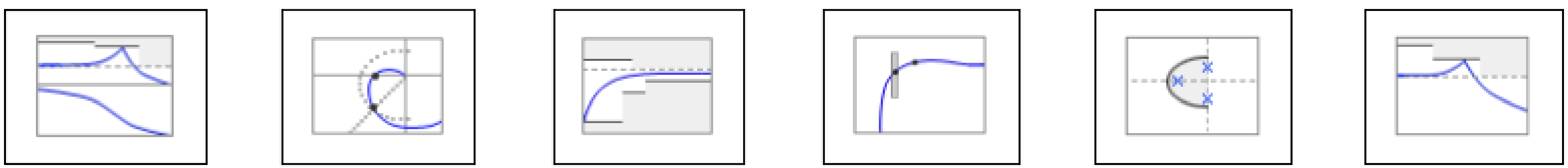


The plot. It can be used for (initial) analysis of the linearized system.

Linearization – Visualization During Simulation

- Linear system characteristics can also be visualized during simulation. They are computed at specified snapshot times, or upon activation by an external trigger.

- In the Simulink Library Browser, under *Simulink Control Design/Linear Analysis Plots*, you can find the following blocks:



Bode Plot | Gain and Phase Margin Plot | Linear Step Response Plot | Nichols Plot | Pole-Zero Plot | Singular Value Plot

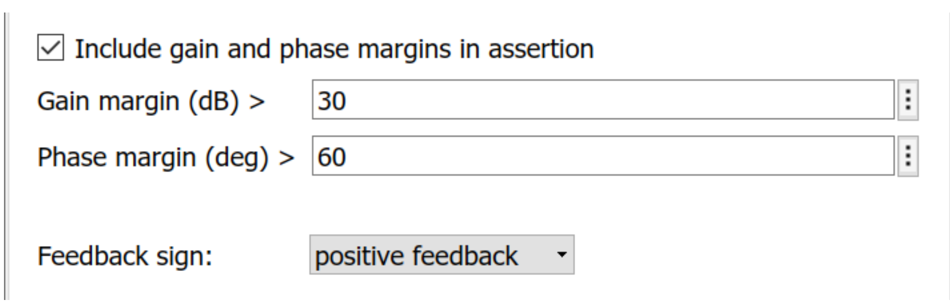
- Place one or more of these blocks in the model to be analyzed.

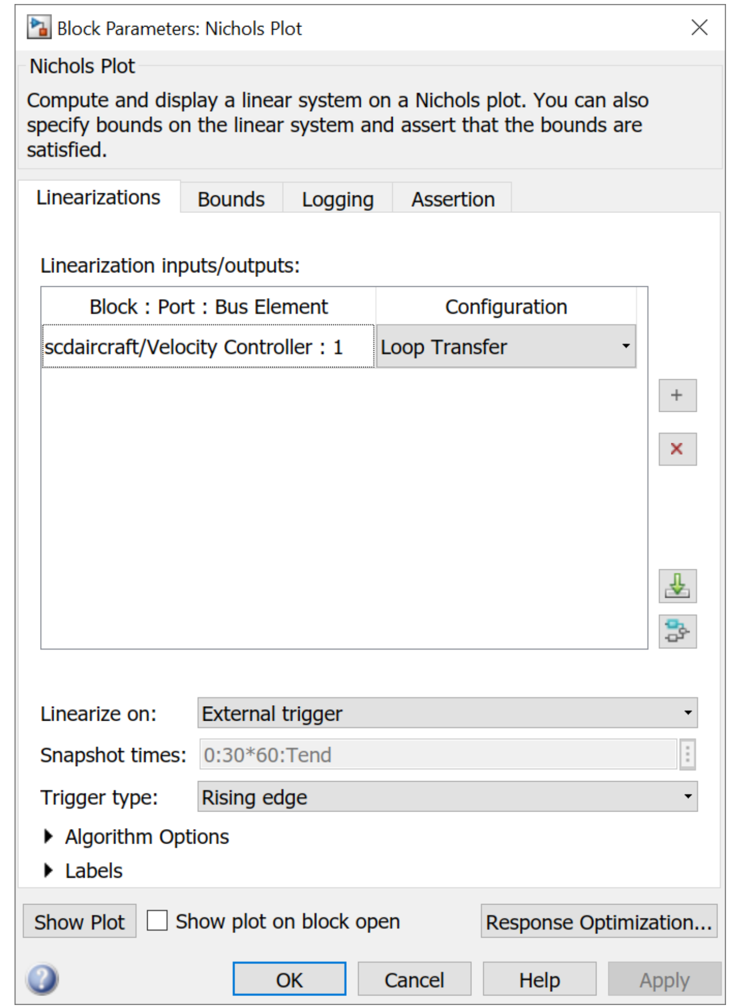
- To configure a block, open it with a double-click.

- You will see four tabs: “Linearizations”, “Bounds”, “Logging” and “Assertion”

Linearization – Visualization During Simulation

- On the “Linearizations” tab, you can specify the input/output set. To do this, click the “+” symbol to open an additional window. Then proceed like with the Linear Analysis Tool. (Select a signal in the Simulink model, click “<<“ and specify configuration in drop down menu.)
- You can also choose whether to linearize on snapshots (and specify the snapshot times), or on an external trigger (the block will then have an inport).
- On the “Logging” tab, you can choose to save the results to the MATLAB workspace.
- An example for the “Bounds” tab:





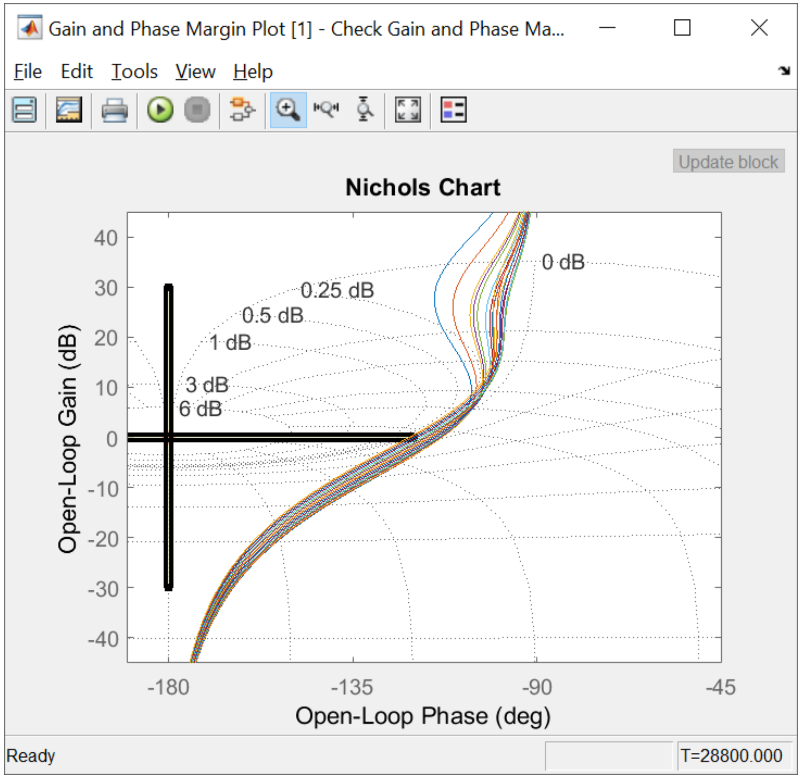
Linearization – Visualization During Simulation

- On the tab “Bounds,” you can define bounds that are visualized on the plots and that can be used for assertion.
  It is often useful to define bounds from design requirements.

- On the tab “Assertion,” you can enable assertion of the bounds. You can also choose
  - to output the assertion signal,
  - to stop the simulation when assertion fails or
  - to make a custom callback when assertion fails.

- To view the plot, click “Show Plot.” Show Plot

- On the right, you can see an example of a gain and phase margin plot, with linearizations at different simulation snapshot times.



4. Frequency Response Estimation

Frequency Response Estimation

- As indicated above, frequency response estimation can be seen as an alternative to exact linearization. It is especially useful
  - to validate exact linearization accuracy,
  - when the Simulink model contains discontinuities or non-periodic event-based dynamics and
  - to study the impact of amplitude size on frequency response.
- The frequency response of a stable system describes the amplitude change and phase shift as a function of frequency (think of the Bode diagram…).
- Just like exact linearization, frequency response estimation requires an input/output set.
- An estimation signal (chirp, sinestream or random) is then injected at the specified input.
- The resulting signal at the specified output is observed
- The estimation is then $G(s) \approx \dfrac{\text{fast Fourier transform of output signal}}{\text{fast Fourier transform of input signal}}$

Frequency Response Estimation

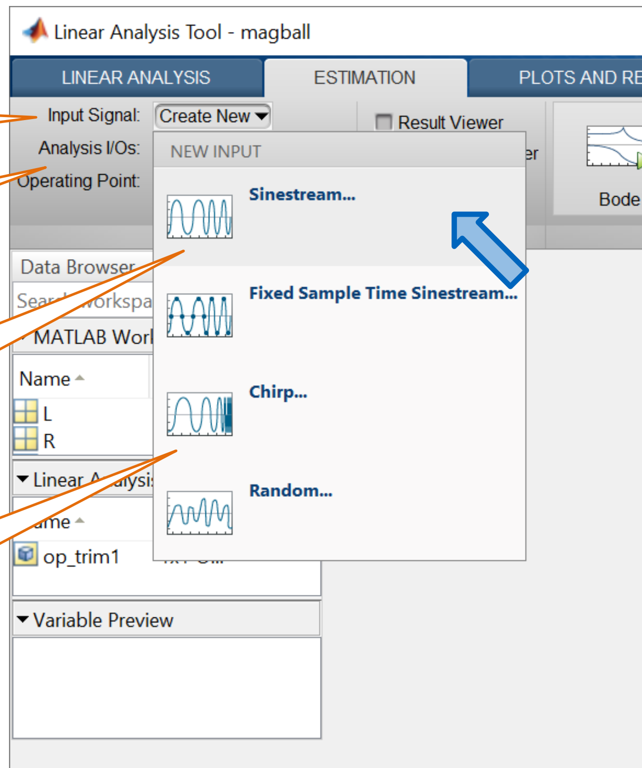
- Frequency response estimation can be done using the Linear Analysis Tool. Select the “Estimation” tab.
- From the “Input Signal” dropdown menu, select “Sinestream…” The “Create sinestream input” dialog box appears (see next slide).

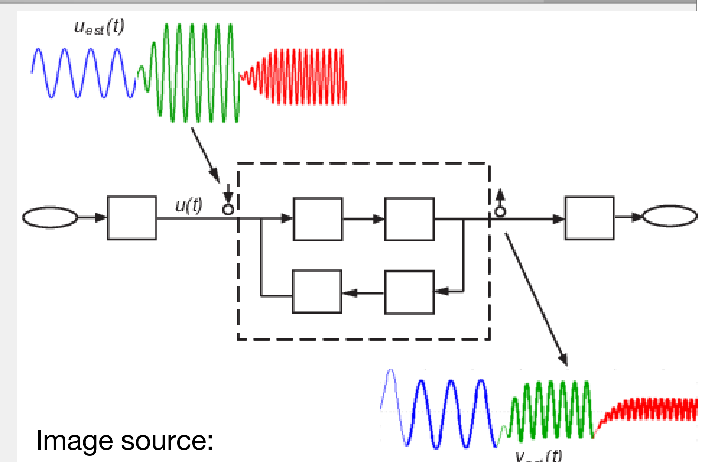
Signal that is injected for estimation.

Same as for linearization.

Several adjacent sine waves of varying frequency

A sine wave with continuously changing frequency





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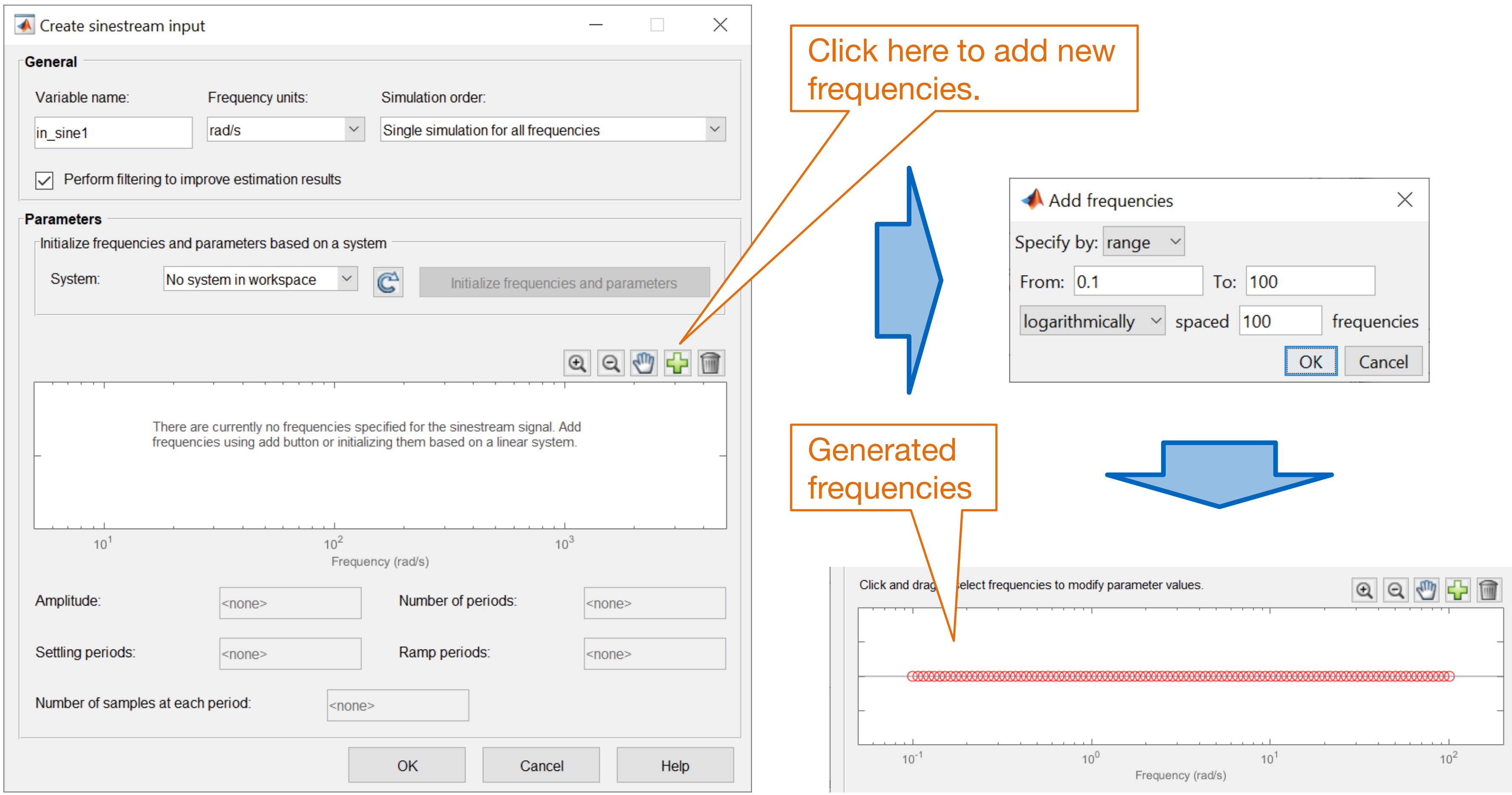
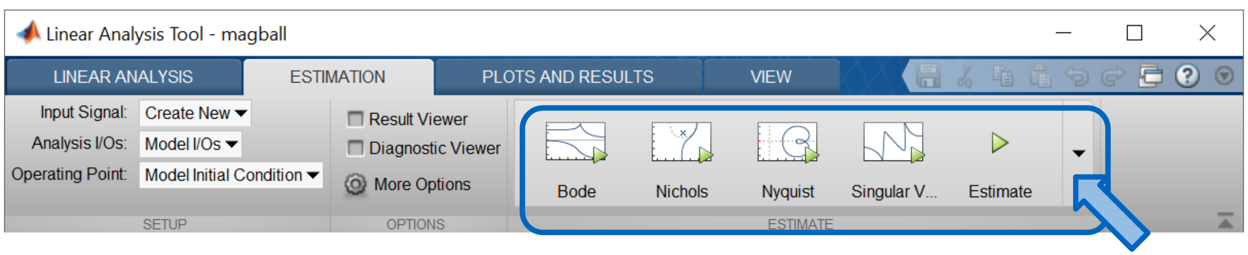
Frequency Response Estimation

- How to proceed on the “Create sinestream input” dialog box:



Frequency Response Estimation

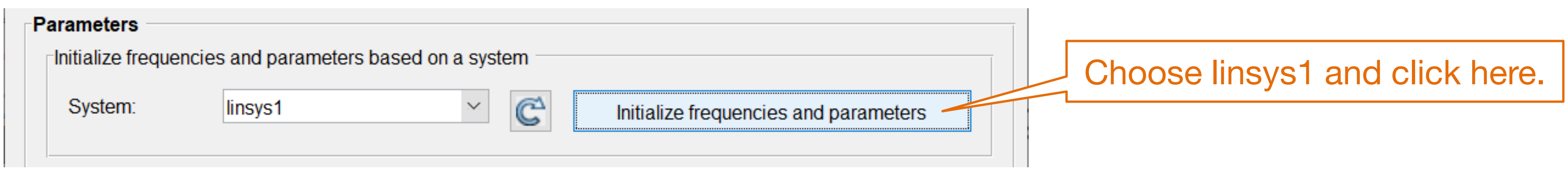
- The next step is to select all frequencies created (the red circles). You can do this like you would select multiple files on your desktop: left-click and hold, draw a rectangle around all red circles and then release the mouse button.
- The boxes below the diagram become active. In the “Amplitude” box, enter 1.
- Click “OK” to create the signal.
- Back on the Linear Analysis Tool, click on one of the plot symbols to start the estimation.



- The estimation model will appear in the Linear Analysis Tool workspace and the plot will show on the GUI.
- Again, you can also use MATLAB code (`freqest`) or generate MATLAB code from the GUI.

Frequency Response Estimation

- Frequency response estimation is also a useful tool for verification of an exact linearization.
- Suppose you have linearized a system with the Linear Analysis Tool.
  The resulting linear system is called “linsys1”. There is a Bode plot called “Bode Plot 1”
- You can, again, create a sinestream input. This time, however, you can initialize the frequencies of the signal based on the dynamics of the linear system linsys1.



- To plot the frequency response estimation on top of the existing Bode diagram of linsys1, click on the “Bode Plot 1” button (instead of the “Bode” button).
- Ideally, the frequency response (= Bode plot) of the estimated model matches that of the linearized model linsys1.

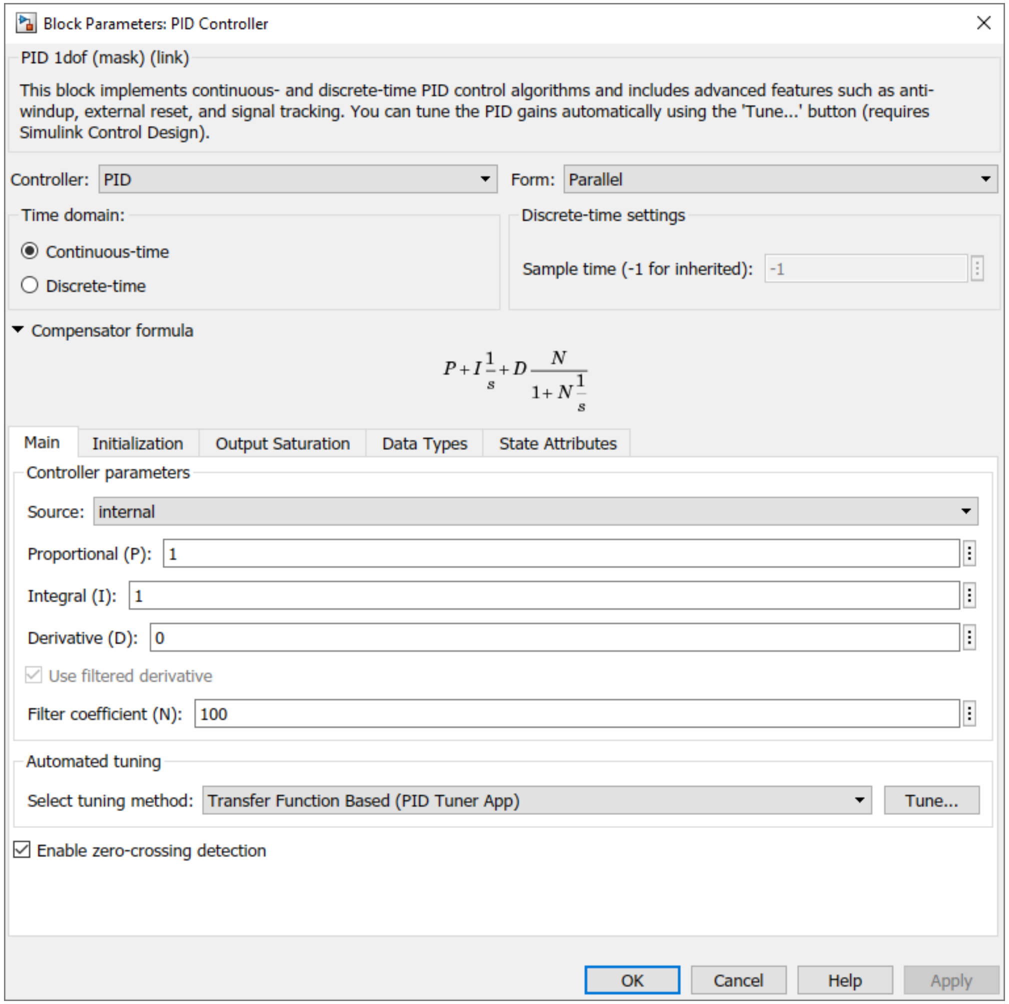
5. Control Design

Control Design

- Suppose you have determined operating points of the plant under consideration, linearized the plant and verified the linearization.
- You could now take the linearized state-space model and apply the control design methods of the Simulink Control System toolbox (which you already know).
- You can also use the PID Tuner or the SISO Design Tool from within the Simulink environment (this section).
- Moreover, with the Robust Control Toolbox, you could perform control system tuning using the functions `controlSystemTuner` and `systune` (see MATLAB help).

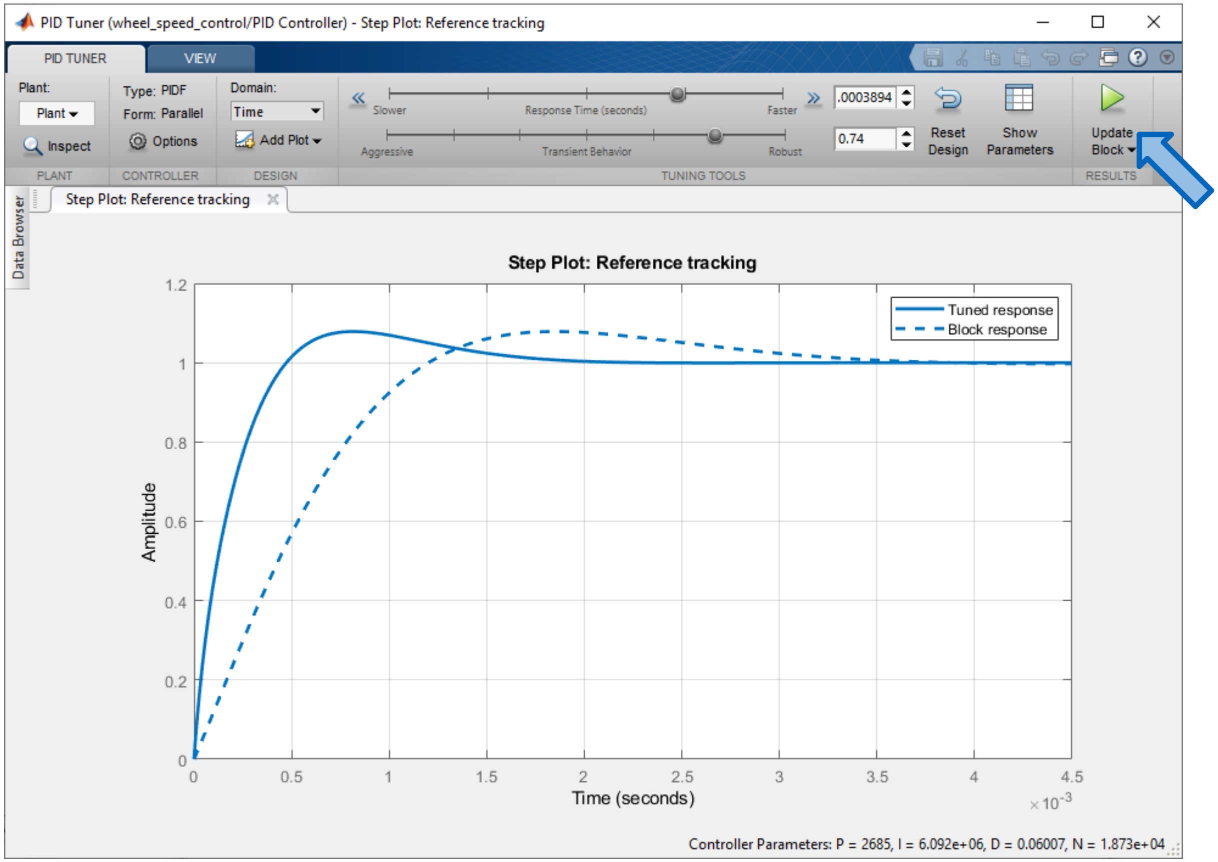
Control Design – PID Tuner

- To use the PID Tuner from within Simulink for control design, you need to use either the PID Controller or the PID Controller (2DOF) block in your model.
- Open the block dialog (double-click), then click “Tune…” to open the PID Tuner.
- When opening the PID Tuner, the software computes a linearized plant model as seen by the controller (using the current operating point).



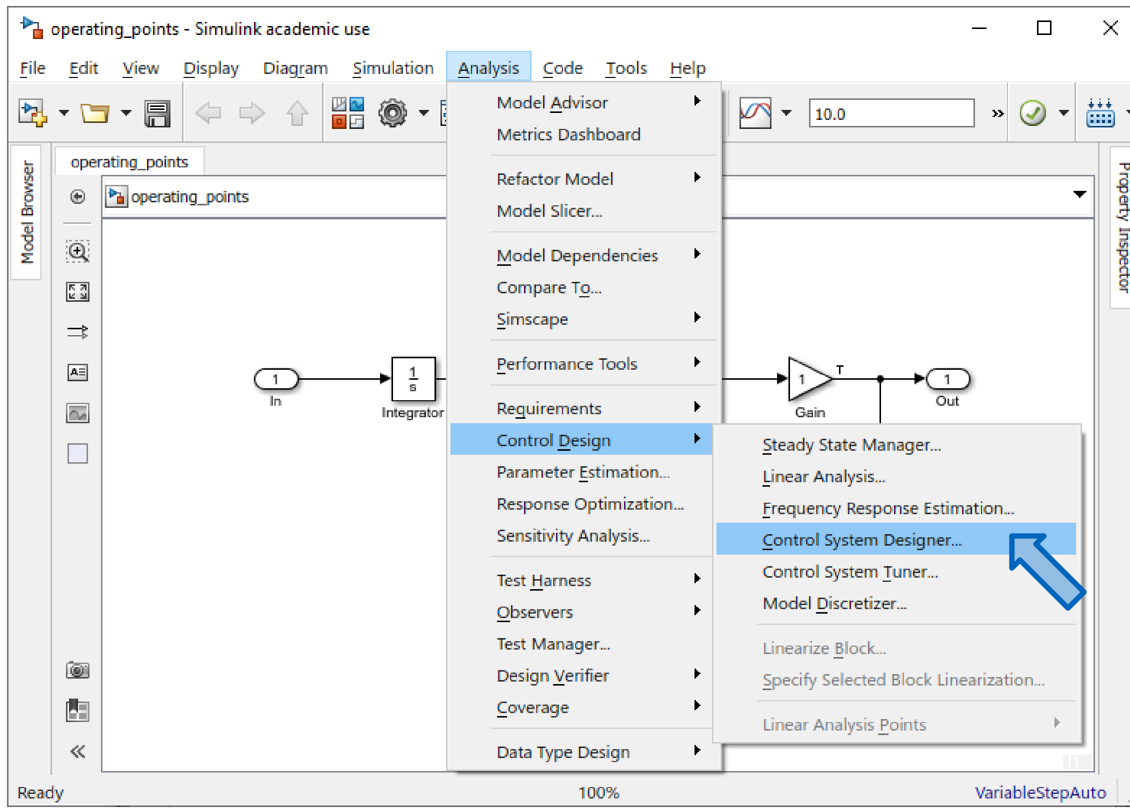
Control Design – PID Tuner

- Once the desired result is obtained, click “Update Block” to automatically adjust the block settings according to your tuning result.



Control Design – SISO Loop Tuning

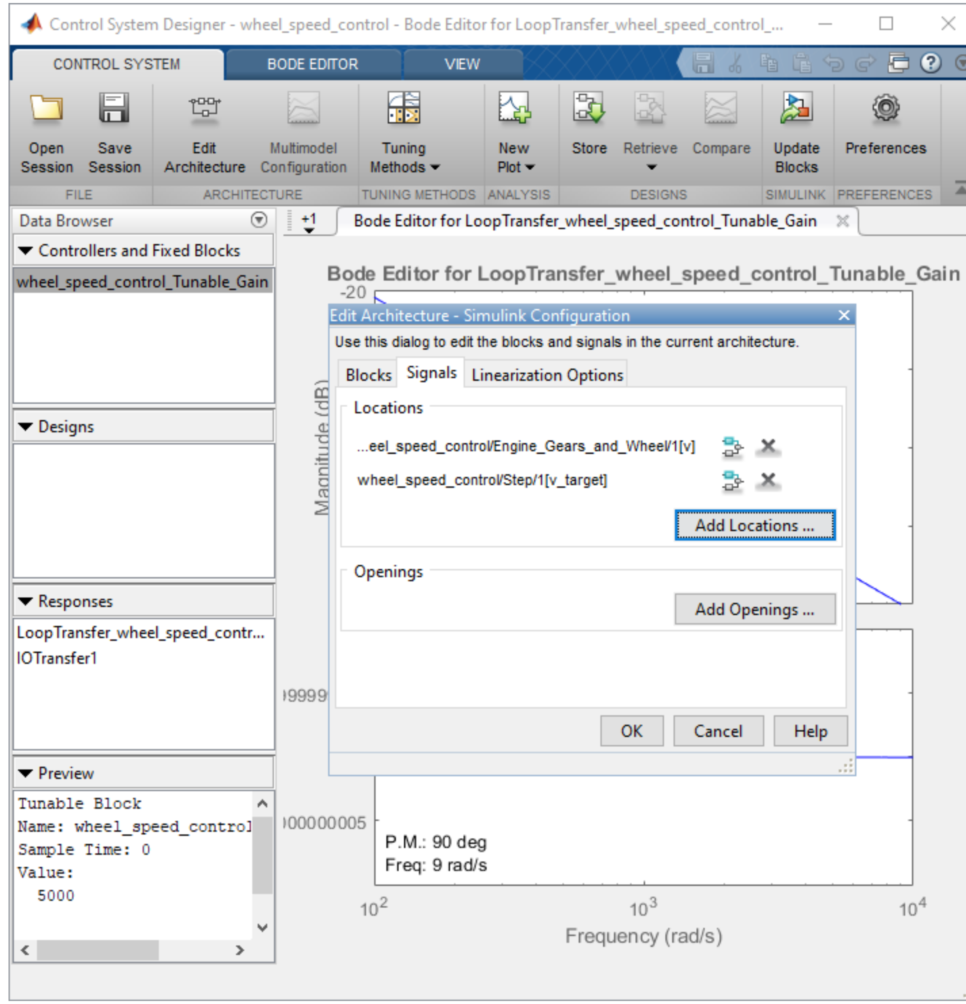
- The SISO Design Tool as well can be used from within the Simulink environment. Note that it only works with tunable blocks in the model:
  - Gain
  - LTI System
  - Discrete Filter
  - PID Controller
  - State-space blocks
  - Zero-pole blocks
  - Transfer function blocks



- The first step is to open the Control and Estimation Tools Manager by proceeding as shown on the right (select “Control System Designer…”).

Control Design – SISO Loop Tuning

- In the Control System Designer, add the tunable blocks under “Edit Architecture” > “Blocks”.
- Under “Signals”, add the Simulink signals that you want to use for tuning your controller (linearization).
- Further options for the linearization of the system, such as operating points, can be configured.
- Various graphical tuning methods and analysis plots are available (see next slide).



Control Design – SISO Loop Tuning

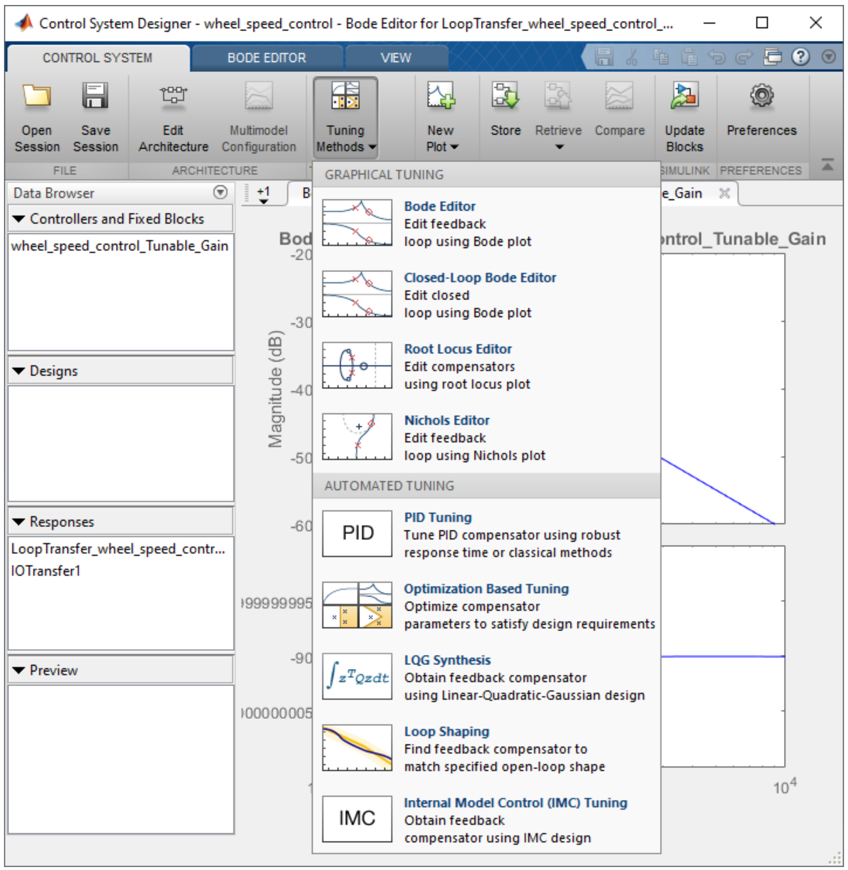
- Graphical **tuning methods** are interactive plots, which are used to tune the response of the system using either open-loop or closed-loop design methods. With the tuning methods, you add, remove and modify controller poles, zeros and gains:
  - Bode Editor, Close-Loop Bode Editor
  - Root Locus Editor
  - Nichols Editor

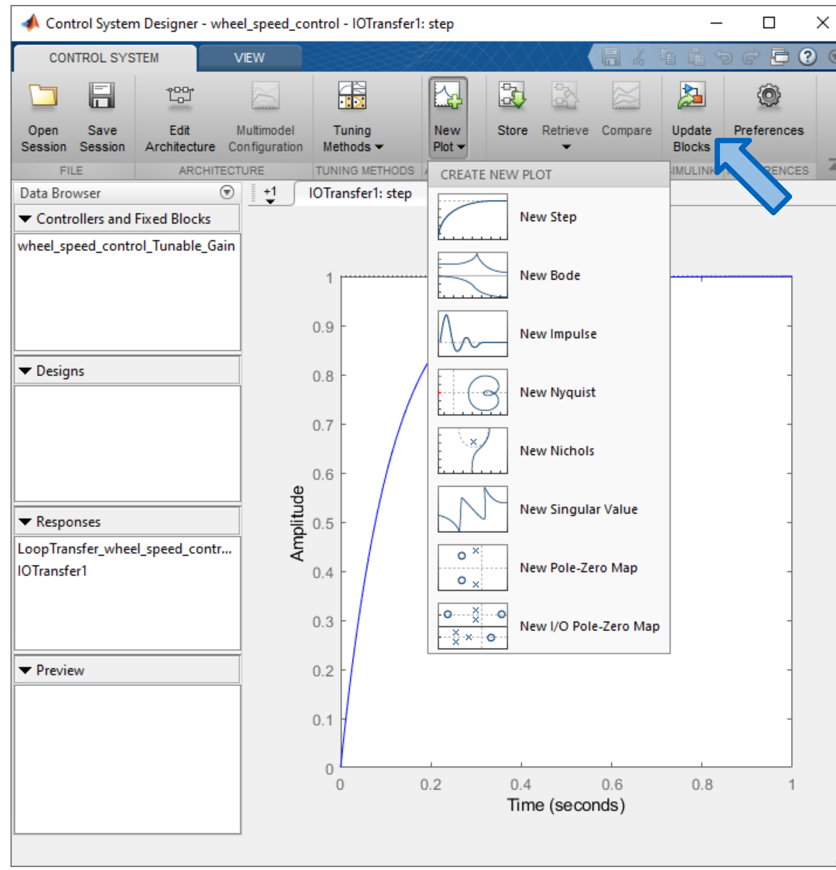
- Additional **plots** allow to analyze the response or dynamics of a closed-loop system in the model. Analysis plots cannot directly be edited, however, will automatically update to reflect the effects of any changes you make in the tuned parameters:
  - Step, Bode, Impulse, Nyquist, Nichols, Singular Value, Pole-Zero Map, I/O Pole-Zero Map

- Additionally, further **automated tuning methods** are available:
  - PID Tuning
  - Optimization Based Tuning
  - LQG Synthesis
  - Loop Shaping
  - Internal Model Control (IMC) Tuning

Control Design – SISO Loop Tuning

- Once you have obtained the final design, simply click on “Update Simulink Block Parameters” to automatically adjust the block settings according to your design.



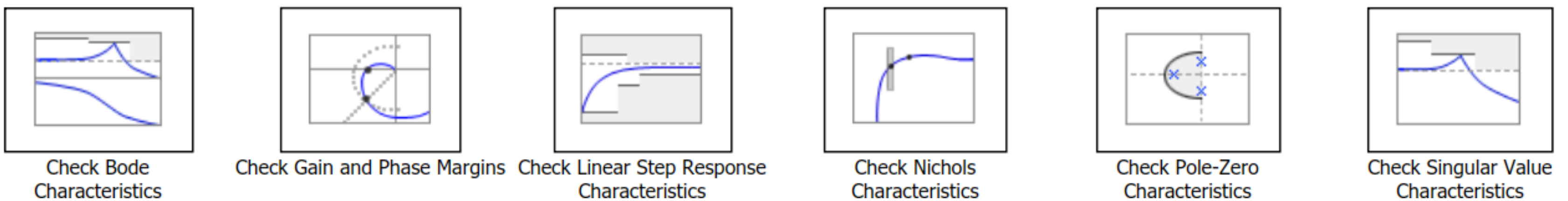


6. Model Verification

Model Verification

- Model verification can be useful to ensure that a (nonlinear) closed control loop that you have previously designed with linear methods behaves like required.

- Blocks for model verification concerning linear analysis can be found in the Simulink Library Browser, under *Simulink Control Design/Model Verification*.

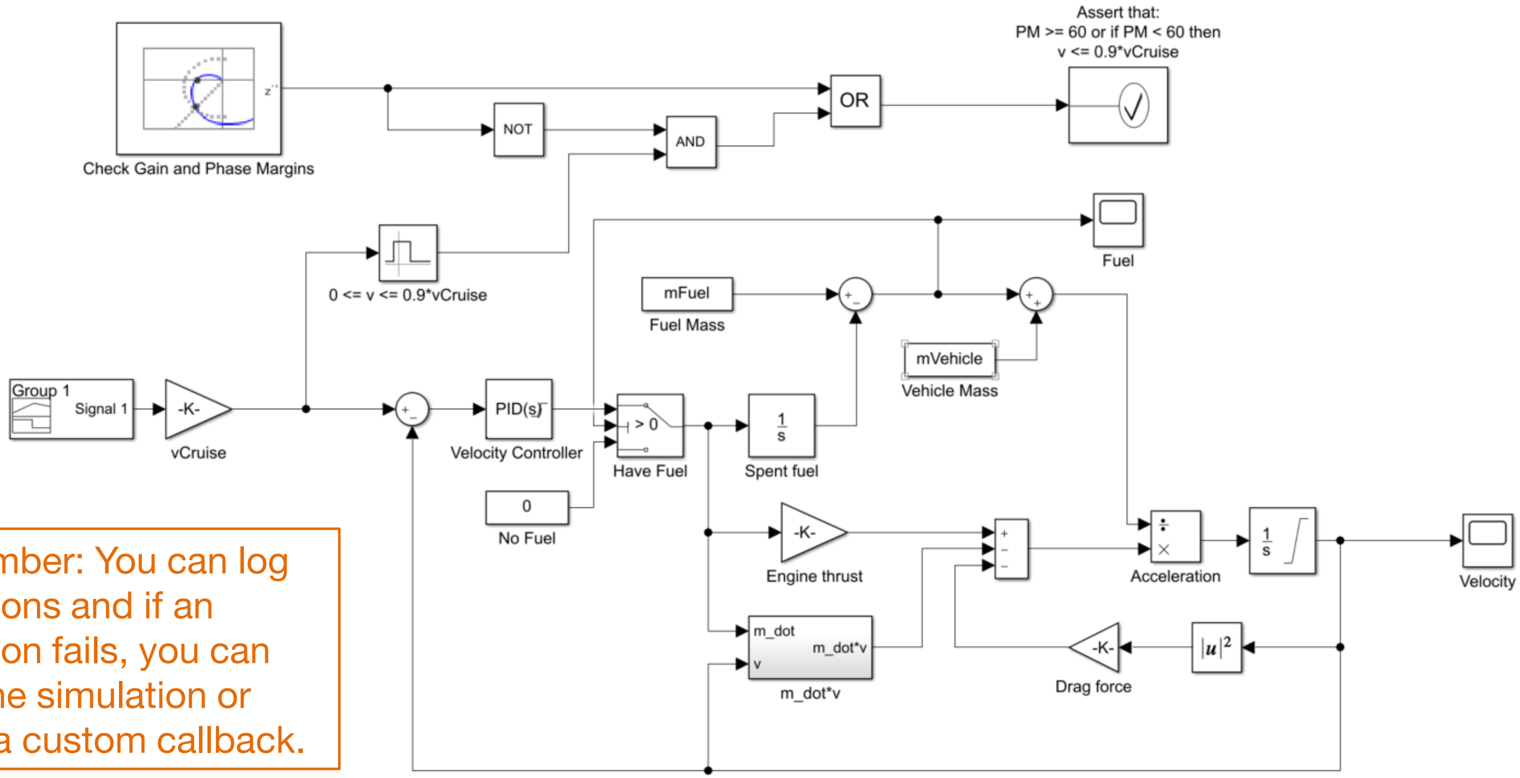


- These blocks are similar to the Linear Analysis Plot blocks (those for visualization during simulation – see section 3), but have different default settings.

- Most notably, these blocks have default bounds and assertion settings.

Model Verification

- Other blocks for model verification (other than linear analysis) can be found in the Simulink Library Browser under *Simulink/Model Verification*. You can combine these blocks with those from the Simulink Control Design toolbox to model most if not all requirements.



Remember: You can log assertions and if an assertion fails, you can stop the simulation or make a custom callback.