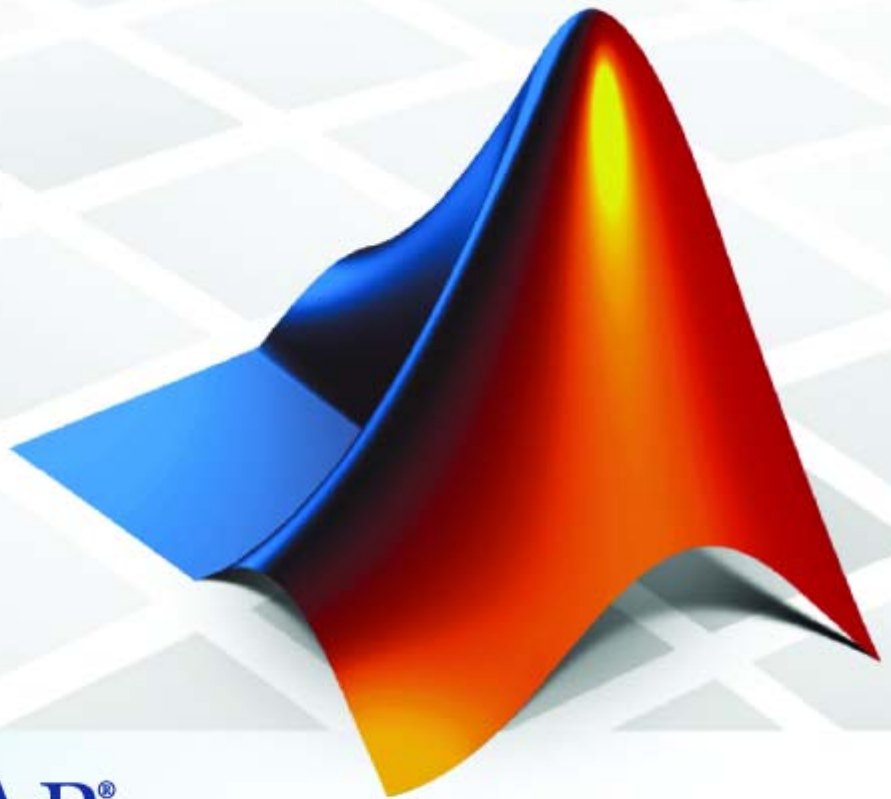


Getting Started with Simulink® Control Design 2



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Getting Started with Simulink Control Design

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Introduction

1

What Is Simulink Control Design?	1-2
Purpose of Linearization	1-3
Role of Linearization in Compensator Design	1-3
Using the GUI Versus Command-Line Functions	1-5
Using the Documentation	1-6
Expected Background	1-6
How to Use This Guide	1-6
Online Documentation	1-7
Using Examples and Demos	1-7
Related Products	1-7
Linearization Quick Start	1-8
Compensator Design Quick Start	1-10

Beginning a Project in Simulink Control Design

2

Creating or Opening a Simulink Model	2-2
Example Model: The Magnetic Ball System	2-2
Beginning a New Linearization Task	2-7

Specifying Operating Points

3

What Are Operating Points?	3-2
Equilibrium Operating Points	3-2
Simulink Model Operating Points	3-2
Why Are Operating Points Important?	3-6
Impact of Operating Points	3-6
Choosing an Operating Point for Accurate Linearization ..	3-7
Creating Operating Points in Simulink Control	
Design	3-9
Simulink Control Design Default Operating Point	3-9
Creating Operating Points from Specifications	3-9
Creating Operating Points from Known Values	3-14
Creating Operating Points from Simulation	3-17
Exporting and Saving Operating Points	3-20

Linearizing Models

4

What Is Linearization?	4-2
Linearization Background	4-2
Linearization of Simulink Models	4-3
Linearization Process Overview	4-3
Configuring Inputs and Outputs for the Linearized	
Model	4-5
What are Linearization Points?	4-5
Inserting Linearization Points	4-6
Removing Linearization Points	4-8
Performing Open-Loop Analysis	4-9
Inspecting Analysis I/Os	4-12
Linearizing the Model	4-15

Using the LTI Viewer	4-17
Analyzing the Results	4-19
Displaying Linearization Results	4-19
Validating the Linearization	4-21
Comparing the Results of Multiple Linearizations	4-25

Designing Compensators

5

What Is Compensator Design?	5-2
Beginning a Compensator Design Task	5-3
Picking Blocks to Tune	5-5
Selecting Closed-Loop Responses to Design	5-7
Selecting an Operating Point	5-10
Creating a SISO Design Task	5-13
Configuring Design Plots	5-14
Configuring Analysis Plots	5-16
Completing the Design	5-22
Storing and Retrieving Designs	5-26
Writing the Design to the Simulink Model	5-28

Saving and Exporting Your Work

6

Saving Projects	6-2
------------------------------	------------

Opening Previously Saved Projects	6-3
Exporting Results	6-4
Exporting Linearization Results	6-4
Exporting Compensator Designs	6-5
Exporting Operating Points	6-6
Exporting and Restoring Linearization I/O Settings	6-6

Examples

A

Linearization Example Using the Graphical Interface	A-2
------------------------------------------------------------------	------------

Index

Introduction

What Is Simulink Control Design?
(p. 1-2)

Introduction to the key features of Simulink® Control Design

Purpose of Linearization (p. 1-3)

Simplify system design and analysis using linearized models

Using the GUI Versus
Command-Line Functions (p. 1-5)

Compare features of the graphical and command-line interfaces

Using the Documentation (p. 1-6)

Expected background, how to use this guide, and other documentation sources

Linearization Quick Start (p. 1-8)

Brief outline of the linearization process using Simulink Control Design

Compensator Design Quick Start
(p. 1-10)

Brief outline of the compensator design process using Simulink Control Design

What Is Simulink Control Design?

Simulink® Control Design provides tools for linearization and compensator design for control systems and physical models in Simulink. Linearized Simulink models often simplify compensator design and system analysis. This is useful in many industries and applications, including

- Aerospace: flight control, guidance, navigation
- Automotive: cruise control, emissions control, transmission
- Equipment manufacturing: motors, disk drives, servos

Simulink Control Design works with the Simulink linearization engine and the SISO Design Tool in Control System Toolbox. Use Simulink Control Design to

- Compute operating points of Simulink models using specifications or simulation.
- Extract linear models from Simulink models.
- Tune compensator blocks in Simulink models with either single or multi-loop configurations.

Simulink Control Design provides a graphical user interface (GUI) for performing linearization and compensator design for Simulink models. This chapter introduces a Quick Start guide for using this GUI. The remaining chapters give more details on the linearization and compensator design tasks.

Purpose of Linearization

Many common control system analysis and design methodologies require linear, time-invariant models. However, control systems and physical models created with Simulink are often nonlinear and time-varying. Linearization is the approximation of a nonlinear system as a linear system, based on the assumption that the system is almost linear within a certain range of operation. With a linearized model you can

- Use the Control System Toolbox LTI Viewer to display and analyze the dynamic behaviors of a model.
- Use the compensator design tools in Control System Toolbox, Robust Control Toolbox, and Model Predictive Control Toolbox to tune control systems.
- Express a model as a transfer function, state space model, or zero-pole-gain model.
- Determine the response of a model to arbitrary input signals.

A linearized model can provide a good approximation to a nonlinear system when created and used carefully. Factors affecting the accuracy of the approximation addressed in Chapter 2, “Beginning a Project in Simulink Control Design” are

- Choice of operating points. See Chapter 3, “Specifying Operating Points”.
- Understanding the equations for the linearized model. See “What Is Linearization?” on page 4-2.
- Controlling the effect of feedback loops. See “What Is Open-Loop Analysis?” on page 4-9.

Role of Linearization in Compensator Design

Linearized models are especially important for designing compensators. Most compensator design methodologies, such as Bode plots, require a linear plant model. Since most real-world plant models are nonlinear, you must typically linearize the system before you design the compensators for it. As a result, the design of good compensators relies on a good linearization.

Although compensator design with Simulink Control Design automates the process and linearizes the model for you, it is still important to understand the fundamentals of creating an accurate linear model. Additionally, you should always check that the compensator you designed for the linearized system also works for the nonlinear system. Typically, the compensator works well for the nonlinear system as long as the system does not vary widely from the operating point.

Using the GUI Versus Command-Line Functions

The Simulink Control Design GUI provides a graphical environment for control system linearization and design. With the graphical environment, you can easily inspect and analyze operating points and results of linearization. In addition, you can save and restore settings as well as export results to the MATLAB® workspace.

You can also linearize models using the command-line functions. With the functions, you can automate many of your linearization tasks and perform *batch linearization*, such as linearization of a system at several different values of a parameter. There are no Simulink Control Design functions specifically intended for designing compensators.

Using the Documentation

- “Expected Background” on page 1-6
- “How to Use This Guide” on page 1-6
- “Online Documentation” on page 1-7
- “Using Examples and Demos” on page 1-7
- “Related Products” on page 1-7

Expected Background

Users should be familiar with control systems design and analysis, and have experience creating Simulink models. Familiarity with Control System Toolbox is also desirable.

How to Use This Guide

To quickly get started linearizing models with Simulink Control Design, read “Linearization Quick Start” on page 1-8 for a brief overview of the linearization process.

To quickly get started designing compensators with Simulink Control Design, read “Compensator Design Quick Start” on page 1-10 for a brief overview of the compensator design process.

If you are new to linearization, read “What Are Operating Points?” on page 3-2 and “What Is Linearization?” on page 4-2. These sections introduce linearization concepts that are important for accurate creation and use of linearized models.

All users should read Chapter 4, “Linearizing Models” and Chapter 5, “Designing Compensators”, which describe features and use of the Simulink Control Design GUI.

To automate the linearization process, or perform batch linearization, continue with “Linearizing Models Using Functions” in the *Simulink Control Design User’s Guide*.

Online Documentation

Further documentation is available online or in the Help browser, including the function and block references: “Functions — Alphabetical List” and “Blocks — Alphabetical List”.

Using Examples and Demos

The Simulink Control Design documentation uses several examples. You can access these examples by typing

```
demo
```

at the MATLAB prompt and selecting **Simulink Control Design** under the **Simulink** node. You can also access the examples by clicking the **Demos** tab in the Help browser.

Related Products

The MathWorks provides several products that are especially relevant to the kinds of tasks you can perform with Simulink Control Design. For more information about these products, visit the MathWorks Web site at <http://www.mathworks.com/products/simcontrol/>.

Linearization Quick Start

To quickly get started linearizing models with Simulink Control Design, follow these steps. The documentation gives additional information for each step in the process and describes the advanced functionality of the product.

- 1** Create or open a Simulink model and decide which portion of the model you need to linearize. See “Creating or Opening a Simulink Model” on page 2-2 for more information.
- 2** Open a linearization task for this model in the Control and Estimation Tools Manager by selecting **Tools > Control Design > Linear Analysis** from the model window. See “Beginning a New Linearization Task” on page 2-7 for more information.
- 3** Select inputs and outputs for the linearized model by inserting linearization points on the model diagram. To do this, right-click a signal line and select **Linearization Points**, and then select either **Input Point** or **Output Point** depending on whether you want the signal to be an input or output for the linearized model. To remove the effect of feedback loops from the linearized model, you can artificially open a loop by right-clicking the signal line and selecting **Linearization Points > Open Loop**. See “Configuring Inputs and Outputs for the Linearized Model” on page 4-5 for more information.
- 4** Specify the operating point for the linearized model in the **Operating Points** node of the Control and Estimation Tools Manager. To compute a steady-state operating point from state specifications, click the **Compute Operating Points** tab and enter the specifications into the table, then click **Compute Operating Points**. See Chapter 3, “Specifying Operating Points” for more information and for methods of specifying alternative operating points.
- 5** Linearize the model by first clicking the **Operating Points** tab within the **Linearization Task** node and then selecting the appropriate operating point from the list. To compute the linearized model, click the **Linearize Model** button. See “Linearizing the Model” on page 4-15 for more information.

- 6** Analyze the results with the **Linearization Result** pane and the **Linearization Inspector** pane within the **Model** node. Create plots of the results with the **Custom Views** node. See “Analyzing the Results” on page 4-19 for more information.
- 7** Export the linearized model to the MATLAB workspace by right-clicking the **Model** node and selecting **Export**. See Chapter 6, “Saving and Exporting Your Work”, for more information.

Compensator Design Quick Start

To quickly get started designing compensators with Simulink Control Design, follow these steps. The documentation gives additional information for each step in the process and describes the advanced functionality of the product.

- 1** Create or open a Simulink model. See “Creating or Opening a Simulink Model” on page 2-2 for more information.
- 2** Open a compensator design task for this model by selecting **Tools > Control Design > Compensator Design** from the model window. The compensator design task opens in the Control and Estimation Tools Manager. See “Beginning a Compensator Design Task” on page 5-3 for more information.
- 3** Within the **Tunable Blocks** pane of the **Simulink Compensator Design Task** node, click the **Add Blocks** button to select the blocks in your model whose parameters you want to tune. These are typically the compensators in your model. See “Picking Blocks to Tune” on page 5-5 for more information.
- 4** Within the **Closed-Loop Signals** pane, select the closed-loop system(s) whose response(s) you want to design. A closed-loop system is defined by an input point, such as a reference or disturbance signal, and an output point, such as a measured output or actuator signal.

To define the closed-loop signals, insert linearization input and output points on the model diagram. Right-click a signal line and select **Linearization Points**, and then select either **Input Point** or **Output Point** depending on whether you want the signal to be an input or output for the closed-loop system. See “Selecting Closed-Loop Responses to Design” on page 5-7 for more information.

- 5** Within the **Operating Point** pane, select the operating point to linearize the model about when designing the compensators. To create a new operating point, click the **New Operating Point** button. See Chapter 3, “Specifying Operating Points” for more information and for methods of specifying operating points.
- 6** Click the **Tune Blocks** button to open the Design Configuration Wizard which guides you through the selection and configuration of the open- and

closed-loop systems you want to tune, and the design and analysis plots you want to use for this task. See “Creating a SISO Design Task” on page 5-13 for more information.

7 After completing the Design Configuration Wizard, a **SISO Design Task** node is created in the Control and Estimation Tools Manager. The **SISO Design Task** includes several tools for tuning the response of SISO systems:

- A graphical editing environment in the SISO Design Tool window that contains the design plots you configured in the Design Configuration Wizard
- An LTI Viewer window where you can view the time and frequency analysis plots that you configured in the Design Configuration Wizard
- A compensator editor where you can directly edit the block mask parameters or the poles and zeros of compensators in your system
- A tool that automatically generates compensators using PID, internal model control (IMC), or linear-quadratic-Gaussian (LQG) methods (uses Control System Toolbox)
- A response optimization tool that automatically tunes the system to satisfy design requirements (available when you have the product Simulink Response Optimization)

See “Completing the Design” on page 5-22 for more information on designing compensators with the **SISO Design Task** node.

8 From the **SISO Design Task** node, click the **Design** node under the **Design History** node. Then click the **Update Simulink Block Parameters** button to write your tuned parameter values back to the Simulink model. See “Writing the Design to the Simulink Model” on page 5-28 for more information.

Beginning a Project in Simulink Control Design

This chapter introduces a Simulink model of a magnetic ball system that the remaining sections use to illustrate the features of Simulink Control Design. A linearization task is created for the model in the Control and Estimation Tools Manager, a graphical environment that manages the Simulink Control Design linearization and compensator design projects. The key features of a project in the Control and Estimation Tools Manager are also presented.

Creating or Opening a Simulink Model (p. 2-2)

Opening the Simulink model of the magnetic ball example

Beginning a New Linearization Task (p. 2-7)

Introduction to the features of the Control and Estimation Tools Manager GUI

Creating or Opening a Simulink Model

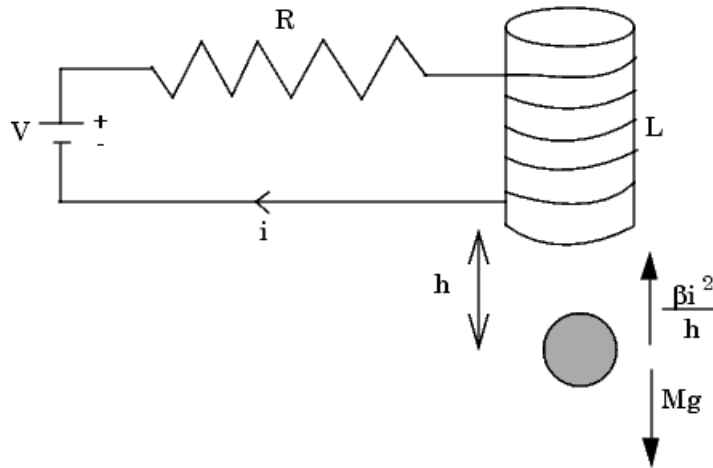
The first step in the linearization or compensator design process is to create or open a Simulink model of your system. The model can have any number of inputs and outputs (including none), and any number of states. The model can include user-defined blocks or S-functions. Your model can involve multiple compensators in addition to the plant, multiple feedback loops, and any number of subsystems.

Example Model: The Magnetic Ball System

This section introduces an example model, the magnetic ball system, that the remaining sections and chapters use to illustrate the process of linearizing a model or designing a compensator with Simulink Control Design.

Magnetic Ball System

The electronic circuit in the following figure consists of a voltage source, a resistor, and an inductor in the form of a tightly wound coil. An iron ball beneath the inductor experiences a gravitational force as well as an induced magnetic force (from the inductor) that opposes the gravitational force.



Model Equations

A differential equation for the force balance on the ball is given by

$$M \frac{d^2 h}{dt^2} = Mg - \frac{\beta i^2}{h}$$

where M is the mass of the ball, h is the height (position) of the ball, g is the acceleration due to gravity, i is the current, and β is a constant related to the magnetic force experienced by the ball. This equation describes the height, h , of the ball due to the unbalanced forces acting upon it.

The current in the circuit also varies with time and is given by the following differential equation

$$L \frac{di}{dt} = V - iR$$

where L is the inductance of the coil, V is the voltage in the circuit, and R is the resistance of the circuit.

The system of equations has three states:

$$h, \frac{dh}{dt}, i$$

The system also has one input (V), and one output (h). It is a nonlinear system due to the term in the equation involving the square of i and the inverse of h .

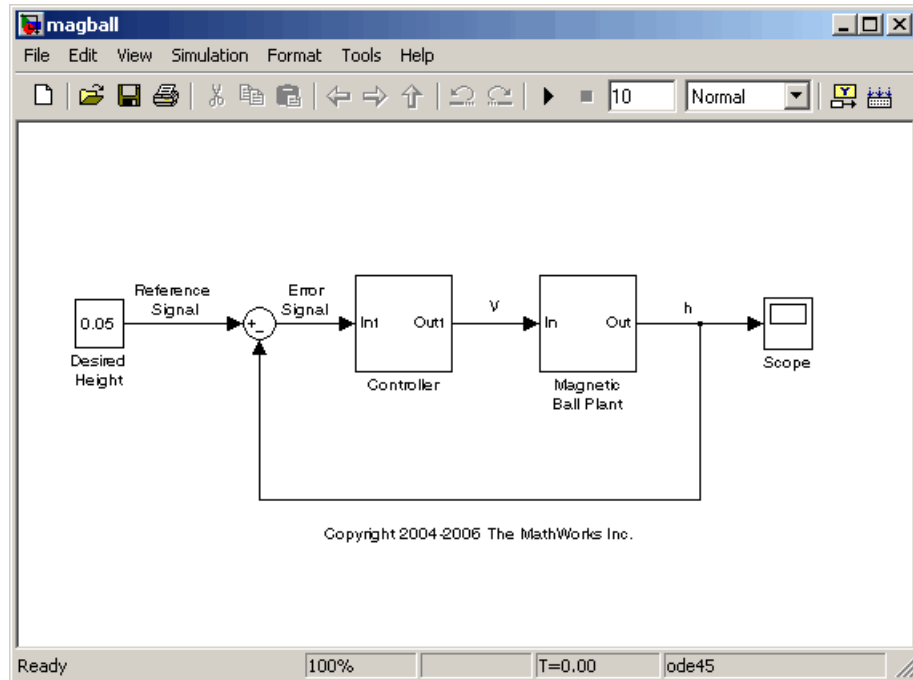
Due to its nonlinearity, you cannot analyze this system using methods for linear-time-invariant (LTI) systems such as step response plots, bode diagrams, and root-locus plots. However, you can linearize the model with Simulink Control Design to approximate the nonlinear system as an LTI system. Linearization also occurs automatically when designing a compensator with Simulink Control Design. This linearized system can then use the LTI Viewer for display and analysis and the SISO Design Tool for compensator design. Refer to “Purpose of Linearization” on page 1-3 for a discussion of the uses of linearized models and “Linearization of Simulink Models” on page 4-3 for a discussion of the linearization process.

Opening the Model

To open the model for the magnetic ball example, type

```
magball
```

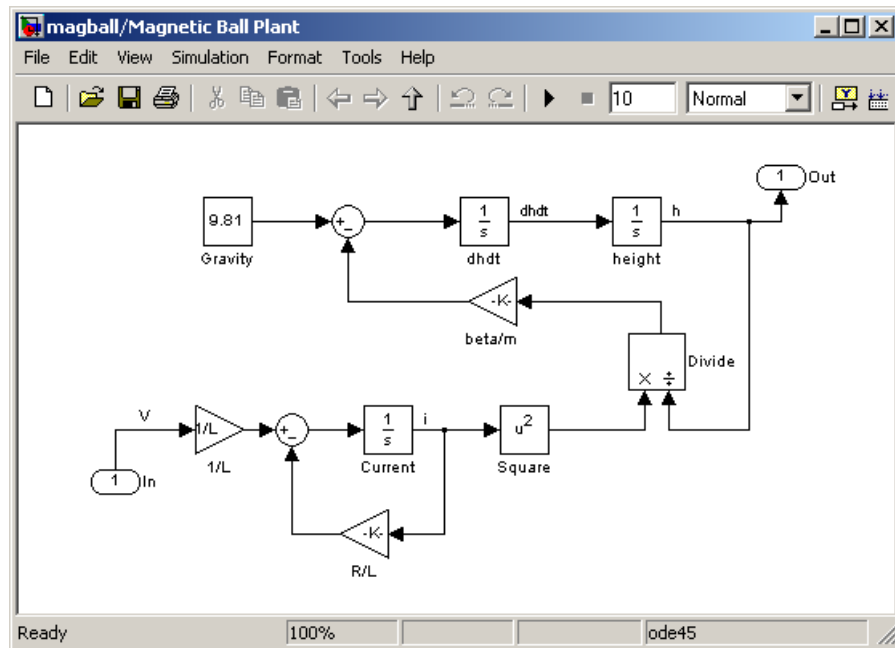
at the MATLAB prompt. The magnetic ball system opens in Simulink as shown in this figure.



The magball model consists of

- The magnetic ball system itself, within the subsystem labeled Magnetic Ball Plant.
- A Controller subsystem that controls the height of the ball by balancing the forces acting on it.
- A reference signal that sets the desired height of the ball.
- A Scope block that displays the height of the ball as a function of time.

Double-click a block to view its contents. The Controller block contains a zero-pole-gain model. The Magnetic Ball Plant block is shown in this figure.



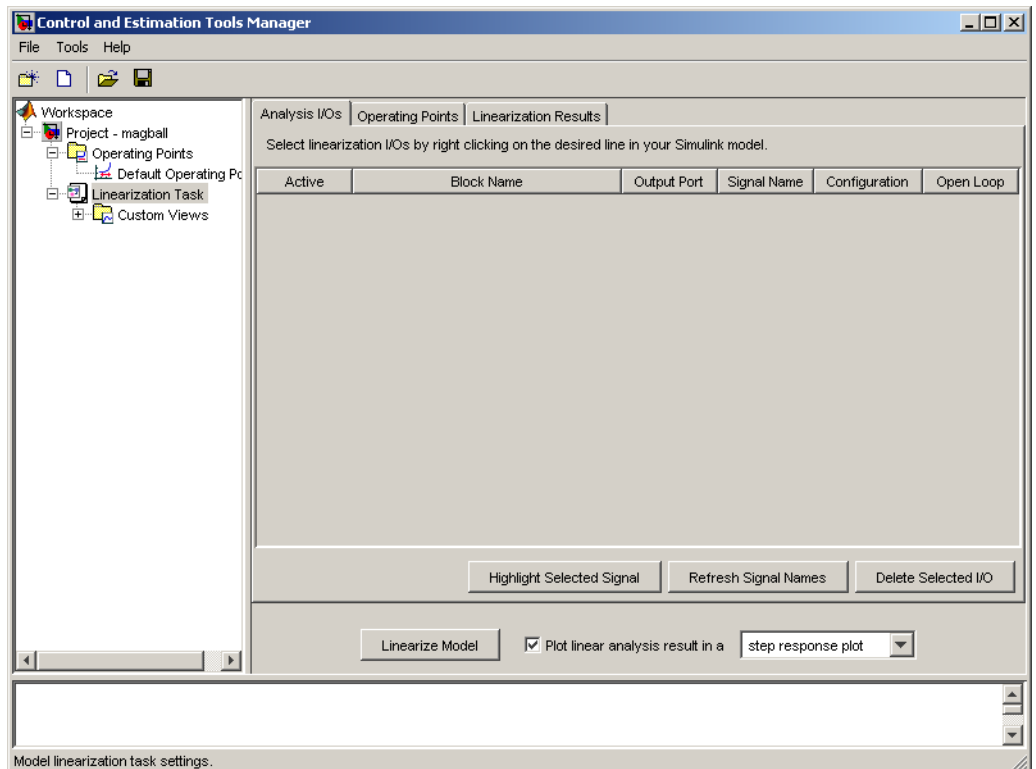
The input to the Magnetic Ball Plant system, which is also the output of the Controller subsystem, is the voltage, V . The output is the height of the ball, h . The system contains three states within the three integrators: height, dh/dt , and Current.

Values of the parameters are given as $M=0.1$ kg, $g=9.81$ m/s², $R=2$ Ohm, $L=0.02$ H, and $\beta=0.001$.

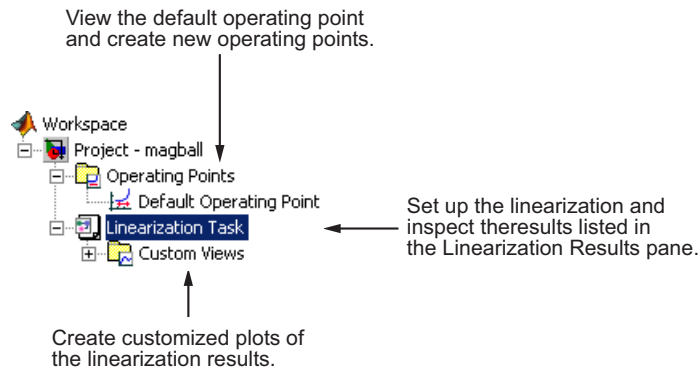
Beginning a New Linearization Task

The Control and Estimation Tools Manager provides a graphical environment for performing, and managing, control and estimation tasks such as linearization and compensator design. Within this environment you can create projects which can include several tasks, including tasks from Simulink Parameter Estimation and Model Predictive Control Toolbox, when they are installed.

To open a new project within the Control and Estimation Tools Manager for linearization of the magball model, select **Tools > Control Design > Linear Analysis** from the magball11 window. The Control and Estimation Tools Manager opens and creates a new linearization task, as shown in the following figure.



The left pane of the Control and Estimation Tools Manager shows the project tree, which contains all your current projects. At this stage you should have just one project, **Project - magball**. Select a node within the tree to display its contents in the pane on the right.



- For information on the **Operating Points** node or the **Operating Points** pane within the **Linearization Task** node, refer to Chapter 3, “Specifying Operating Points”.
- For information on the **Analysis I/Os** pane within the **Linearization Task** node, refer to “Configuring Inputs and Outputs for the Linearized Model” on page 4-5.
- For information on the **Linearization Results** pane within the **Linearization Task** node and inspecting linearization results, refer to “Analyzing the Results” on page 4-19.
- For information on **Custom Views**, refer to “Analyzing the Results” on page 4-19.

Specifying Operating Points

What Are Operating Points? (p. 3-2)	Definitions and descriptions of the operating point of a dynamic system, including equilibrium, steady state, and operating points
Why Are Operating Points Important? (p. 3-6)	Explanation of the significance of the operating point of a dynamic system
Creating Operating Points in Simulink Control Design (p. 3-9)	Creating operating points using multiple techniques in Simulink Control Design
Exporting and Saving Operating Points (p. 3-20)	Saving operating points for future use

What Are Operating Points?

The *operating point* of a dynamic system defines its overall *state* at a given time. For example, in a model of a car engine, variables such as engine speed, throttle angle, engine temperature, and surrounding atmospheric conditions typically describe the operating point. It is important to specify the operating point accurately because it affects the system's behavior. For example, the behavior of a car engine can vary greatly when it operates at high or low elevations.

This section contains the following topics:

- “Equilibrium Operating Points” on page 3-2
- “Simulink Model Operating Points” on page 3-2

Equilibrium Operating Points

An *equilibrium operating point* remains steady and constant with time; all states in the model are at equilibrium. It is also known as a *steady state* or *trimmed operating point*. For example, a car operating on cruise control on a flat road maintains a constant speed. Its operating point is steady, or at equilibrium.

A hanging pendulum provides an example of a stable equilibrium operating point. When the pendulum hangs straight down, its position does not change with time because it is at an equilibrium position. When its position deviates slightly from this position, it always returns to the equilibrium; small changes in the operating point do not cause the system to leave the region of good approximation around the equilibrium value.

A pendulum that points upward provides an example of an unstable equilibrium operating point. As long as the pendulum points *exactly* upward, it is steady at this equilibrium state. However, when the pendulum deviates slightly from this state, it swings downward and the operating point leaves the region around the equilibrium value.

Simulink Model Operating Points

This section includes the following topics:

- “Operating Point Versus Simulink Full-Model Operating Point” on page 3-3
- “Example of a Simulink Model Operating Point” on page 3-4

Operating Point Versus Simulink Full-Model Operating Point

The Simulink full model operating point includes information from all of the blocks in a Simulink model. When you use Simulink Control Design or the MATLAB command line to create operating points for a model, you are actually creating an *operating point object* (what is referred to as the operating point). The operating point is a subset of the Simulink full-model operating point.

The following table shows the different types of blocks that make up a full-model operating point and which types are included in the operating point.

Makeup of Simulink Full-Model Operating Point

Block Types	Example of Blocks	Included in Operating Point?
Blocks with double value states and root level inport blocks	Integrator, State Space, Transfer Function, Inport	Yes
Blocks with internal state representation that impacts block outputs	Backlash, Memory, Stateflow	No
Source blocks with outputs specified by block dialog parameters	Constant, Step	No

The operating point includes only the block information most commonly redefined by users. This information provides you with three places to make changes to the parameters of these common blocks in your model:

- Directly in the Simulink Control Design Control and Estimation Tools Manager GUI
- At the MATLAB command line

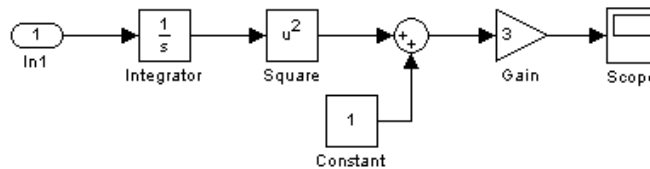
- In the Simulink model

If you want to make changes to any block not included in the operating point, you must make the changes directly in the Simulink model.

Example of a Simulink Model Operating Point

The following figure shows a simple Simulink model that has one block with state (the integrator block) and therefore one state, x_1 . This state depends on the initial conditions set in the integrator block. The value of this state and the input from the inport block define the operating point in Simulink Control Design.

The square block output is derived from just the initial condition of the integrator block while the gain block has its output derived from both the initial condition of the integrator block and output of the constant block. The derivative dx/dt of the integrator block state is defined by the output level of the root inport block.

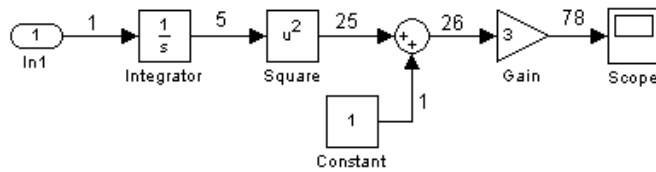


The state, x_1 , defines the signal levels at the input and output of every block in the model by propagating through the blocks in the model as follows.

- 1 The integrator block initial condition of $x_0 = 5$ sets the state $x_1 = 5$.
- 2 The state, x_1 , propagates in the direction of the arrows through the blocks in the model, defining input and output signals on each block, as described in the following table.

Block	Input Signal Level	Block Operation	Output Signal Level
Square	5	squares	25
Sum	25 from square, 1 from constant	sums	26
Gain	26	multiplies by 3	78

The following figure shows these input and output signal levels for each block.



Why Are Operating Points Important?

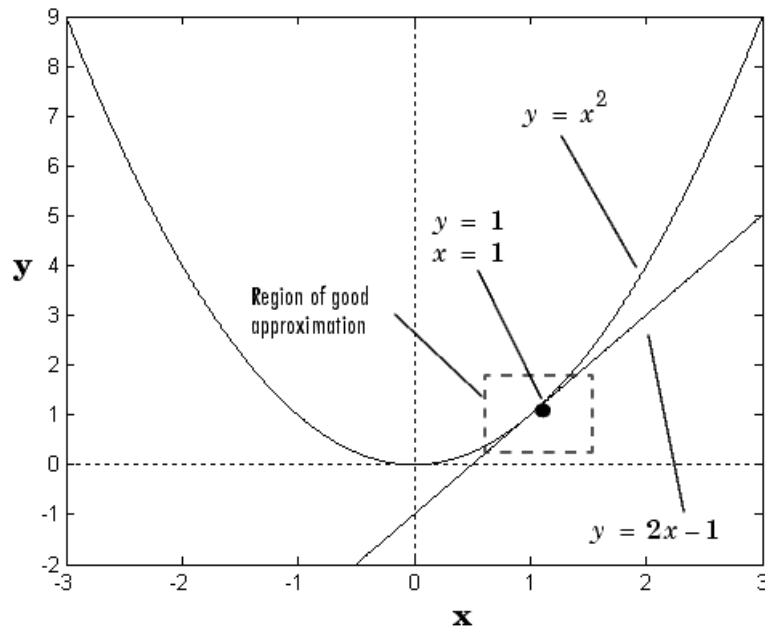
- “Impact of Operating Points” on page 3-6
- “Choosing an Operating Point for Accurate Linearization” on page 3-7

Impact of Operating Points

A linearized model is an approximation that is valid in a region around the operating point of the system where the linearization took place. Near the operating point the approximation is good, while far away it may be poor. A linearized model of a car being operated at 3000 ft. is very accurate at elevations close to 3000 ft. but less accurate as the car travels higher or lower.

Example of a Linear Approximation of a Function

The following figure shows a nonlinear function, $y = x^2$, and a linear function, $y = 2x - 1$. The linear function is an approximation to the nonlinear function about the operating point $x=1, y=1$. Near this operating point, the approximation is good. Away from this operating point, the approximation is poor. The precise boundaries of this region are often somewhat arbitrary. The following figure shows a possible region of good approximation for the linearization of $y = x^2$.



Choosing an Operating Point for Accurate Linearization

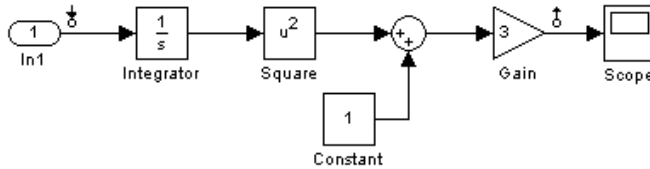
Your choice of operating point is important when you:

- Linearize a Simulink model. The choice of operating point determines the accuracy of the linear approximation.
- Designing compensators with Simulink Control Design. A Simulink Compensator Design Task uses linearization when analyzing a Simulink model.

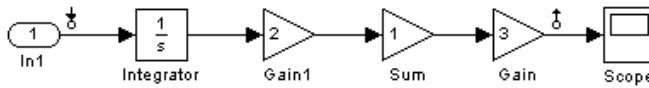
Tip Choose an operating point that is very close to the expected operating values of the system. One option is to use an equilibrium operating point, described in “Equilibrium Operating Points” on page 3-2.

Example of Linearization Results About Two Different Operating Points

A model can have two entirely different linearizations when the linearization is performed about different operating points. The following model can be linearized using Simulink Control Design.



The linearization result for this model is shown in the following figure.



When this linearization is performed about two different operating points, two different linearization results occur as shown in the following table.

Operating Point	Linearization Result
Initial Condition = 5, State x1 = 5	30/s
Initial Condition = 0, State x1 = 0	0

Note The operating point consists of values for *all* the states in the model, although only those states between the linearization points are linearized. The whole model contributes to the operating point values of the states, inputs, and outputs of the portion of the model you are linearizing.

Creating Operating Points in Simulink Control Design

- “Simulink Control Design Default Operating Point” on page 3-9
- “Creating Operating Points from Specifications” on page 3-9
- “Creating Operating Points from Known Values” on page 3-14
- “Creating Operating Points from Simulation” on page 3-17

Simulink Control Design Default Operating Point

A default operating point is automatically created and stored in a node in the project tree every time you open the Control and Estimation Tools Manager. Simulink Control Design always retrieves the default operating point of the model unless you indicated otherwise. The default operating point consists of a snapshot of initial condition variables in the Simulink model. Initial condition variables are a special set of variables that can be set in the Simulink model. These variable include initial conditions for blocks with state, such as the integrator or state space blocks, and output values of root level inport blocks. For more information on setting these variables, see “Importing and Exporting Simulation Data” in the Simulink User’s Guide.

By clicking on the **Default Operating Point** node, you can view these values and modify them for use in a linearization. The output levels for blocks like a constant block remain defined in the model.

Creating Operating Points from Specifications

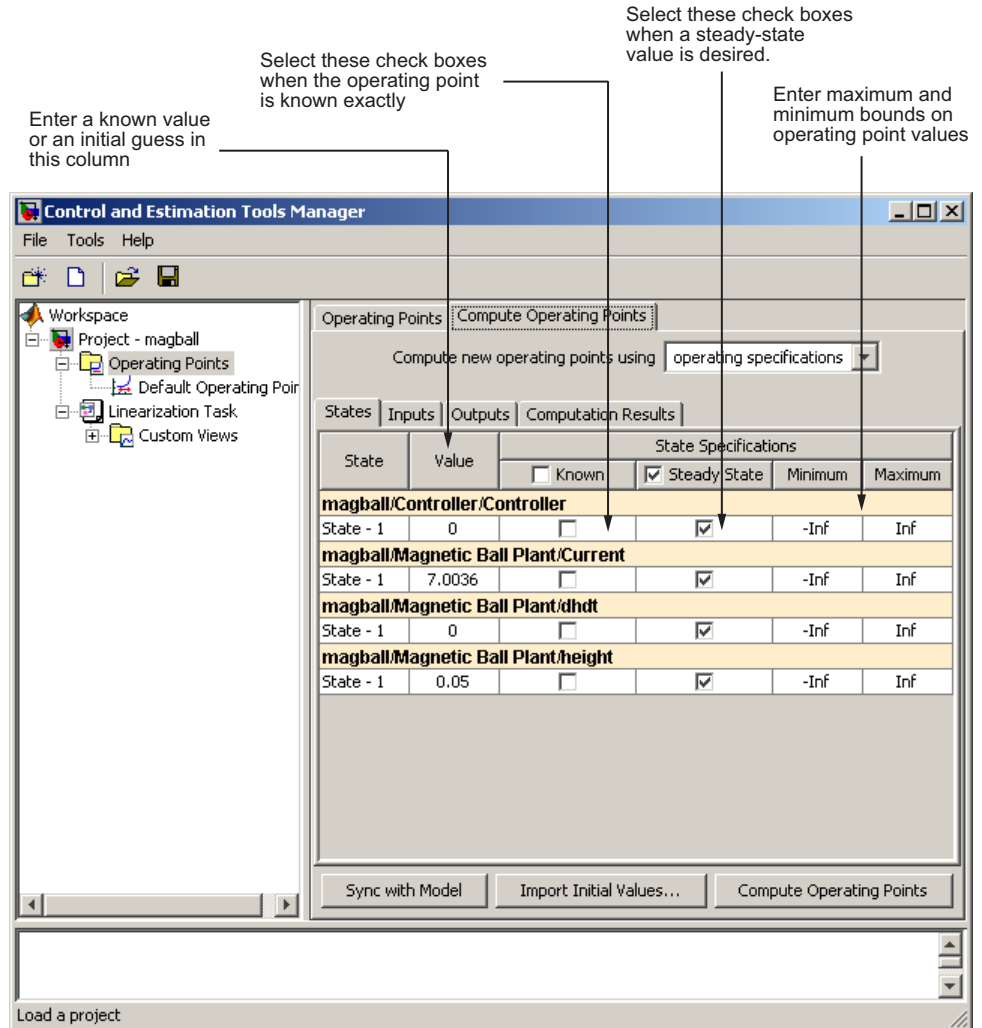
This section continues the magball example from “Beginning a New Linearization Task” on page 2-7. At this stage in the example, a linearization task has already been created for the model.

You can use Simulink Control Design to compute the operating point from specifications when you only know partial or implicit information. Typical operating point specifications search for steady state or equilibrium operating points.

1 Create a new operating point by either:

- Selecting the **Operating Points** node and then clicking the **Compute Operating Points** tab

- Clicking the **New Operating Point** button on the **Operating Points** pane of the **Linearization Task** node
- 2** From the **Compute new operating points using** list, select operating specifications. The Control and Estimation Tools Manager window should now resemble the following figure.



- 3** Enter operating point specifications in the table, such as any known values or constraints on signal values. Switch between states, inputs, and outputs using the tabs on the left.

A suitable set of specifications for the magball model is shown in the following figure. This model does not contain any root-level input or output ports and, as a result, the **Inputs** and **Outputs** panes are empty. You can still constrain the output signal of any block by adding an **Output Constraint** linearization point to the model. See “Constraining Outputs” in the *Simulink Control Design User’s Guide* for information about adding an output constraint to the specifications for an operating point.

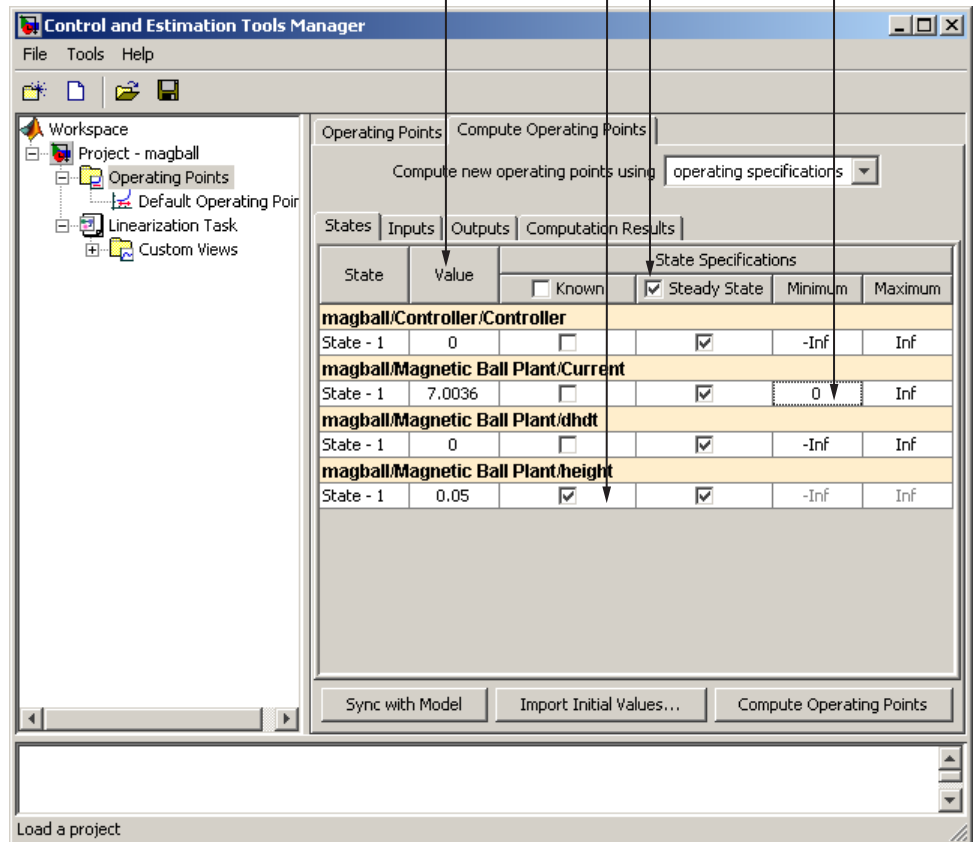
3 Specifying Operating Points

The height of the ball is known exactly (same as the reference signal height).

The ball height is 0.05 (same as the reference signal value). For a steady ball, use initial guess of 0 for dhdt. For the remaining states, choose arbitrary initial guesses.

A steady-state operating point is desired.

Use a minimum value of zero for the current (by convention current is positive when flowing clockwise around the circuit).



The screenshot shows the Control and Estimation Tools Manager window. The 'Operating Points' tab is active, displaying a table of state specifications. The table has columns for State, Value, Known, Steady State, Minimum, and Maximum. The states listed are:

State	Value	Known	Steady State	Minimum	Maximum
magball/Controller/Controller					
State - 1	0	<input type="checkbox"/>	<input checked="" type="checkbox"/>	-Inf	Inf
magball/Magnetic Ball Plant/Current					
State - 1	7.0036	<input type="checkbox"/>	<input checked="" type="checkbox"/>	0	Inf
magball/Magnetic Ball Plant/dhdt					
State - 1	0	<input type="checkbox"/>	<input checked="" type="checkbox"/>	-Inf	Inf
magball/Magnetic Ball Plant/height					
State - 1	0.05	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	-Inf	Inf

Buttons at the bottom include 'Sync with Model', 'Import Initial Values...', and 'Compute Operating Points'.

When you add states, inputs, or outputs to the model, or remove them from the model, click the **Sync with Model** button to update the operating point table to reflect these changes.

- 4 Click **Compute Operating Points**. Simulink Control Design finds an operating point that closely matches the specifications and adds the new operating point, labeled **Operating Point**, to the **Operating Points** node.

Some specifications, even values specified as **Known**, may not be met exactly. Select the operating point in the project tree to view its contents and assess the results.

Actual dx values are small, because a steady-state value was found.

The screenshot shows the 'Control and Estimation Tools Manager' interface. On the left, the 'Workspace' pane shows a project tree for 'Project - magball' with 'Operating Points' expanded to show 'Default Operating Point' and 'Operating Point'. The 'Operating Point' is selected. The main pane displays a table with columns: State, Desired Value, Actual Value, Desired dx, and Actual dx. The table is organized into sections for different components: 'magball/Controller/Controller', 'magball/Magnetic Ball Plant/Current', 'magball/Magnetic Ball Plant/dhdt', and 'magball/Magnetic Ball Plant/height'. A message at the bottom states: 'An operating point called Operating Point has been added to the node Operating Points.'

State	Desired Value	Actual Value	Desired dx	Actual dx
magball/Controller/Controller				
State - 1	[-Inf , Inf]	-14.0071	0	0
magball/Magnetic Ball Plant/Current				
State - 1	[-Inf , Inf]	7.0036	0	3.4106e-013
magball/Magnetic Ball Plant/dhdt				
State - 1	[-Inf , Inf]	0	0	-1.7764e-015
magball/Magnetic Ball Plant/height				
State - 1	0.05	0.05	0	0

For information on options that you can set when finding operating points from partial specifications, see “Changing Optimization Settings” in the *Simulink Control Design User’s Guide*.

Note Inputs and outputs for the operating point are not the same as the linearization input and output points, or analysis I/Os, used to define the inputs and outputs of the linearized model. Instead, operating-point inputs and outputs define the full operating point of a Simulink model, along with any additional, user-defined output constraints.

Creating Operating Points from Known Values

This section continues the magball example from “Creating Operating Points from Specifications” on page 3-9. At this stage in the example, a linearization task has already been created for the model, and a steady state operating point has been computed from specifications.

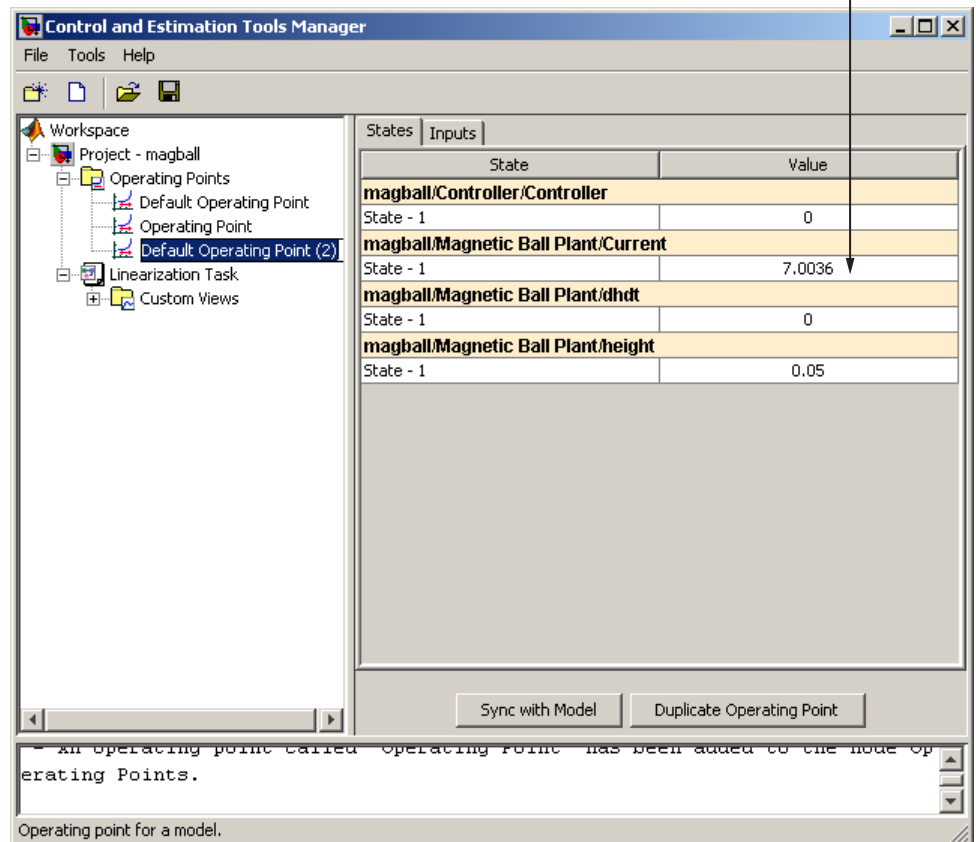
When you know the values of *all* states and inputs at the operating point, you can create a new operating point in the Control and Estimation Tools Manager and manually edit the operating point values:

- 1 Select the **Operating Points** node in the left pane and then click the **Operating Points** tab in the right pane.
- 2 Click the **New** button in the bottom-right corner to create a new operating point under the **Operating Points** node. This new operating point is labeled **Default Operating Point (2)**.

3 View the details of **Default Operating Point (2)** (shown in the following figure) by either:

- Selecting it under the **Operating Points** node in the project tree
- Selecting it in the **Operating Points** pane of the **Linearization Task** node, and then clicking **View**

Enter known values of states and inputs at the operating point.



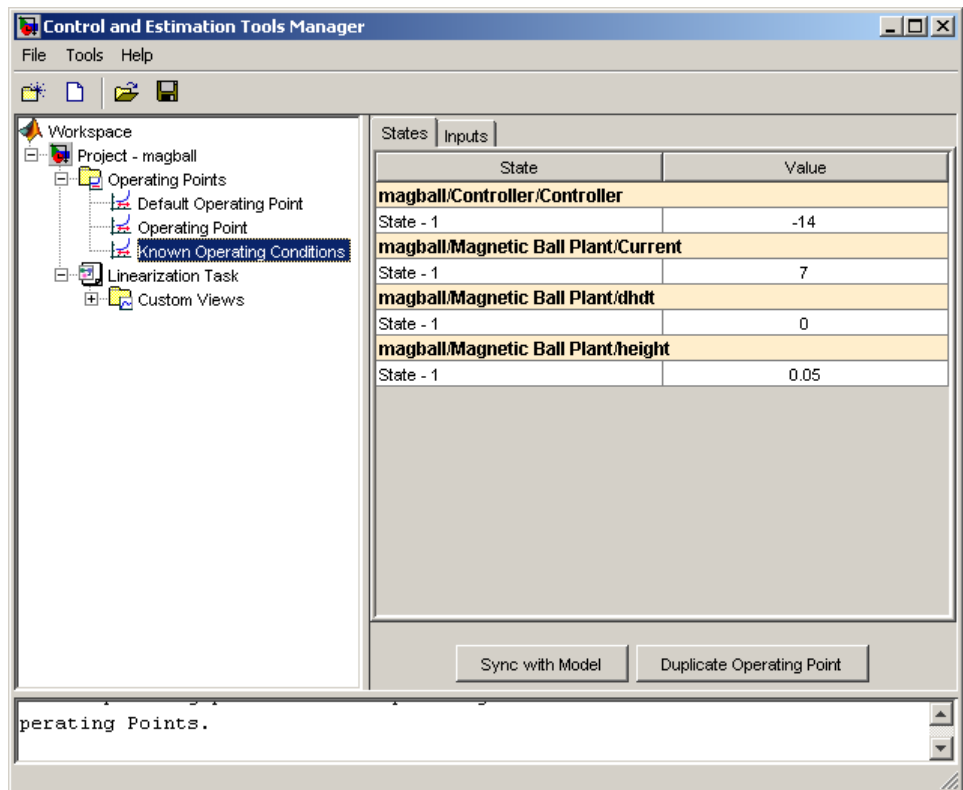
4 Edit the operating point by entering new values in the table. Switch between state and input values using the tabs on the left.

Change the value of **State-1** of **Controller** to -14 and the value of **Current** to 7. The model does not contain any root-level input ports, and, as a result, the **Inputs** pane is empty.

When you add states, inputs, or outputs to the model, or remove them from the model, click the **Sync with Model** button to update the operating point table to reflect these changes.

- 5 Rename the operating point by right-clicking **Default Operating Point (2)** under the **Operating Points** node, selecting **Rename**, and entering a new name in the dialog box.

For example, label this operating condition **Known Operating Conditions**. The pane should now resemble the following figure.



Creating Operating Points from Simulation

You can use Simulink Control Design to create an operating point from a simulation of your model at the following simulation points:

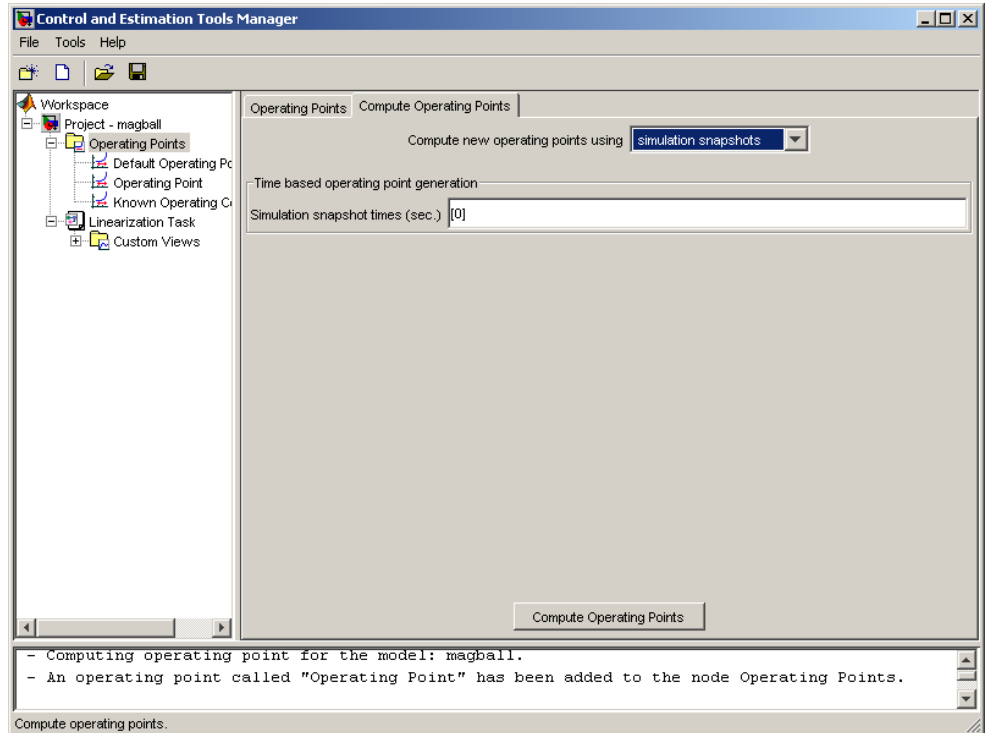
- Specified simulation times, such as when the simulation reaches a steady state solution (see example in this section).
- Events during a specified simulation interval (see “Creating Operating Points at Simulation Events” in the *Simulink Control Design User’s Guide*).

This section continues the magball example from “Creating Operating Points from Known Values” on page 3-14. At this stage in the example, a linearization task has already been created for the model, a steady state operating point has been computed from specifications, and a completely known operating point has been specified.

To create operating points at specified simulation times:

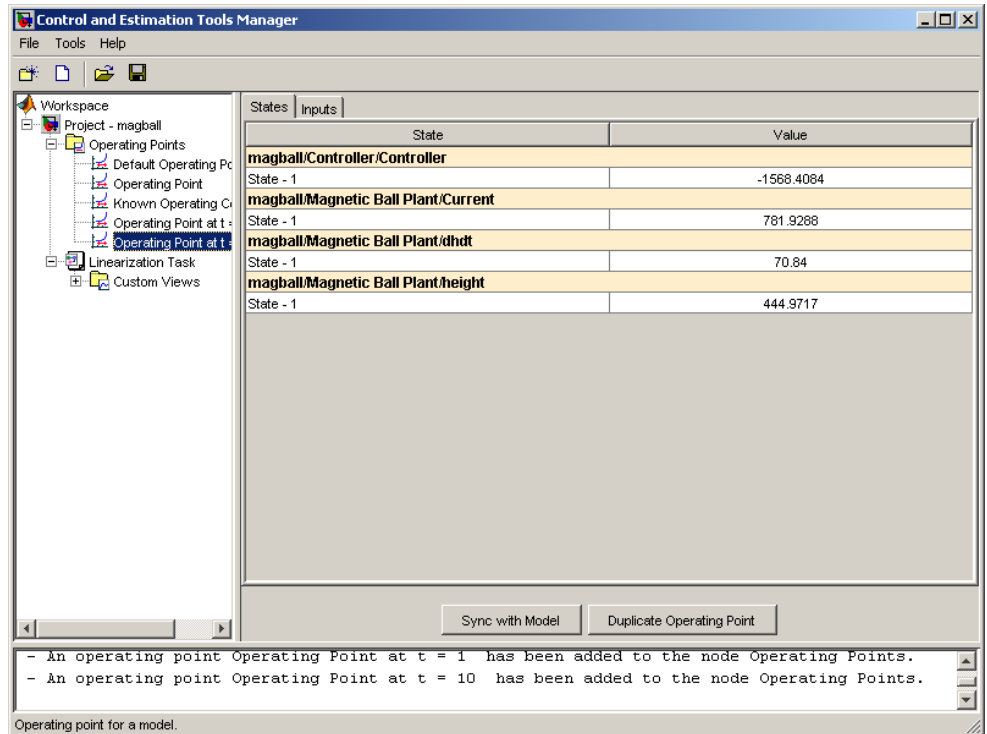
- 1 Create a new operating point from simulation by either:
 - Selecting the **Operating Points** node in the project tree, and then clicking the **Compute Operating Points** tab
 - Clicking the **New Operating Point** button on the **Operating Points** pane of the **Linearization Task** node

- From the **Compute new operating points using** list, select **simulation snapshots**. The window should now resemble the following figure.



- Enter a vector of times in the **Simulation snapshot times (sec)** field. Enter `[1, 10]` to compute operating points at $t=1$ and $t=10$.
- Click **Compute Operating Points**. Simulink Control Design simulates the model, extracts operating points, labeled **Operating Point at $t=1$** and **Operating Point at $t=10$** , and adds them to the **Operating Points**

node in the project tree. Select an operating point to view its contents, and assess the results as shown in this figure.



When you add states, inputs, or outputs to the model, or remove them from the model, click the **Sync with Model** button to update the operating point table to reflect these changes.

Exporting and Saving Operating Points

You can export and save operating points that you created with Simulink Control Design and then use them in a future Simulink Control Design task, with command-line functions, or to initialize a Simulink model for simulation. This section continues the magball example. At this stage in the example, several operating points have been created.

In “Creating Operating Points from Specifications” on page 3-9 you computed an operating point from specifications. To export it to the MATLAB workspace:

- 1** Under the **Operating Points** node in the Control and Estimation Tools Manager, right-click the operating point labeled **Operating Point** that you computed from specifications. Select **Export to Workspace**.
- 2** In the Export to Workspace dialog box
 - a** Select **Base Workspace** to export the operating point to the MATLAB workspace.
 - b** Enter `Operating_Point` for the **Variable Name** parameter.
 - c** Click **OK** to export the operating point and close the dialog box.

After you have exported the operating point to the MATLAB workspace, you can save it in a MAT-file for later use. To save the operating point `Operating_Point` in a file named `magball_operating_points.mat`, enter the following command:

```
save magball_operating_point Operating_Point
```


Linearizing Models

What Is Linearization? (p. 4-2)

Factors affecting linearization of Simulink models and an overview of the linearization process

Configuring Inputs and Outputs for the Linearized Model (p. 4-5)

Selecting and inspecting linearization points, and performing open-loop analysis

Linearizing the Model (p. 4-15)

Running the linearization

Analyzing the Results (p. 4-19)

Inspecting the linearization results and displaying the results in the LTI Viewer.

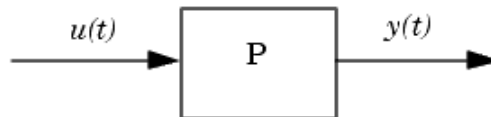
What Is Linearization?

- “Linearization Background” on page 4-2
- “Linearization of Simulink Models” on page 4-3
- “Linearization Process Overview” on page 4-3

Linearization Background

A linearized model is an approximation to a nonlinear system, which is valid in a small region around the operating point of the system. Engineers often use linearization in the design and analysis of control systems and physical models.

The following figure shows a visual representation of a nonlinear system as a block diagram. The diagram consists of an external input signal, $u(t)$, a measured output signal, $y(t)$, and the nonlinear system that describes the system’s states and its dynamic behavior, P .



You can also express a nonlinear system in terms of the state space equations

$$\dot{x}(t) = f(x(t), u(t), t)$$

$$y(t) = g(x(t), u(t), t)$$

where $x(t)$ represents the system’s states, $u(t)$ represents the inputs, and $y(t)$ represents the outputs. In these equations, the variables vary continuously with time. Discrete-time and multi-rate models are discussed in “Linearization of Discrete-Time Models” in the online documentation. A

linear time-invariant approximation to this nonlinear system is valid in a region around the operating point at $t=t_0$, $x(t_0)=x_0$, and $u(t_0)=u_0$. If the values of the system's states, $x(t)$ and inputs, $u(t)$ are close enough to the operating point, the system will behave approximately linearly.

Linearization of Simulink Models

Simulink uses a series of connected *blocks* to model physical systems and control systems. Input and output signals connect the blocks, which represent mathematical operations. The nonlinear system, P, in the previous figure, represents a series of connected Simulink blocks.

Simulink linearizes both continuous and discrete-time nonlinear systems by computing the state-space matrices of the linearized model, A , B , C , and D , using one of the linearization algorithms described in “Understanding and Controlling Results of Linearized Models” in the *Simulink Control Design User's Guide*.

Linearization Process Overview

The main steps to linearize a model using the Simulink Control Design GUI are as follows:

- 1** Create or open a model. See “Creating or Opening a Simulink Model” on page 2-2.
- 2** Create a new linearization task on the Control and Estimation Tools Manager. See “Beginning a New Linearization Task” on page 2-7.
- 3** Specify an operating point for the model. See Chapter 3, “Specifying Operating Points”.
- 4** Insert linearization input and output points in the model. See “Configuring Inputs and Outputs for the Linearized Model” on page 4-5.
- 5** Linearize the model. See “Linearizing the Model” on page 4-15.
- 6** Inspect and validate the linearization. See “Analyzing the Results” on page 4-19.

- 7 Save your project and export the results to the MATLAB Workspace. See Chapter 6, “Saving and Exporting Your Work”.

The first three steps in this process were completed in the previous chapters. This chapter continues the magball model example to give a detailed discussion of the remaining steps.

You can also use the Simulink Control Design command-line functions to linearize a model. “Linearizing Models Using Functions” in the *Simulink Control Design User’s Guide* gives detailed information on these functions. For a discussion of the advantages and disadvantages of the GUI versus the command-line interface, refer to “Using the GUI Versus Command-Line Functions” on page 1-5.

Configuring Inputs and Outputs for the Linearized Model

- “What are Linearization Points?” on page 4-5
- “Inserting Linearization Points” on page 4-6
- “Removing Linearization Points” on page 4-8
- “Performing Open-Loop Analysis” on page 4-9
- “Inspecting Analysis I/Os” on page 4-12

What are Linearization Points?

Before linearizing the model, you must first configure the model diagram. This involves selecting input and output linearization points (also called analysis I/Os), and then, if necessary, inserting open-loop points for performing open-loop analysis. You can inspect the selected linearization points using the **Analysis I/Os** pane within the **Linearization Task** node of the Control and Estimation Tools Manager.

A linearization input point defines an input to the linearized model while a linearization output point defines an output of the linearized model. Additionally, when the linearized models are computed using numerical perturbation, an input point is the point on the diagram where the small perturbation to the input signal is introduced and an output point is the point on the diagram where the small perturbation to the output signal is measured. Linearization input and output points are not the same as *operating points* which define the state of the model at the point of linearization.

The region between the input and output points defines the portion of the model that you want to linearize, unless a feedback loop feeds the output signal back into another section of the model. In some cases you might want to remove the effect of a feedback signal. For example, you might want to linearize only the plant model within in a feedback control loop. When such a feedback loop is present, you can remove the effect of the loop without manually breaking signal lines by inserting an open-loop point. Instructions for inserting open-loop points are in “Performing Open-Loop Analysis” on page 4-9.

You can use Simulink Control Design to linearize the whole model, or any blocks or subsystems within the model. To define the system you are linearizing, place linearization points before and after it in the model diagram.

When you want to linearize a model that contains references to other models using the Model block, you must use the numerical perturbation linearization algorithm. The numerical perturbation algorithm numerically perturbs the whole model and does not use linearization input and output points. See “Numerical-Perturbation Linearization” in the *Simulink Control Design User’s Guide* for more information.

Note Linearization input and output points should not be confused with Simulink Inport and Outport blocks. Input and output points define linear analysis inputs and outputs, while Inport and Outport blocks define the operating point of the system.

Inserting Linearization Points

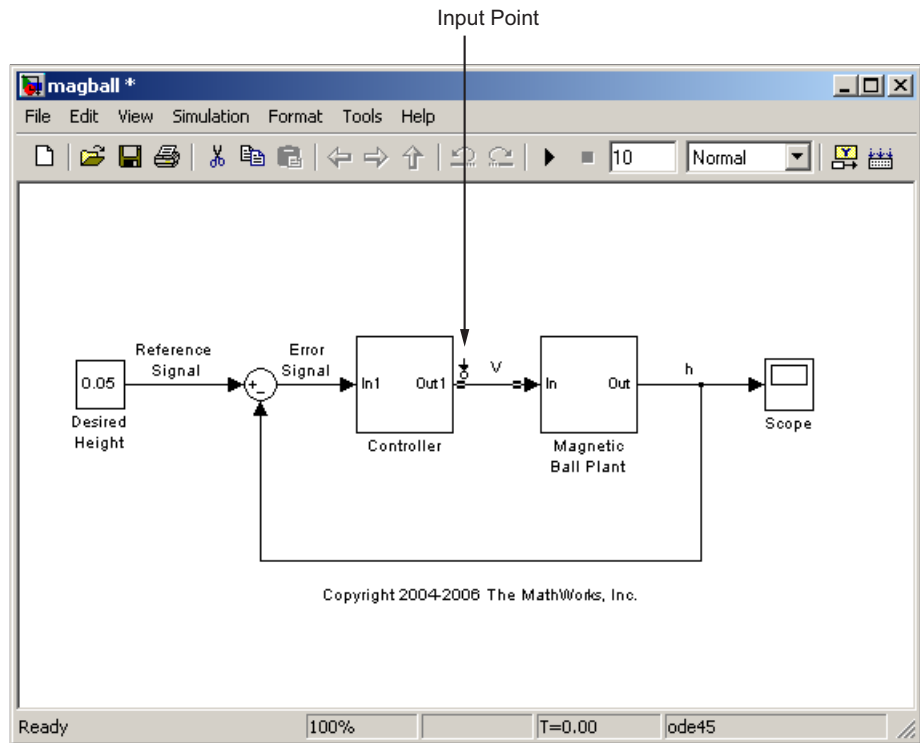
This section continues the magball example from “Creating Operating Points from Simulation” on page 3-17. At this stage in the example, a linearization task has been created and operating points have been specified.

For a definition of linearization points, also known as analysis I/Os, see “What are Linearization Points?” on page 4-5.

In the magnetic ball model, the nonlinearities are all contained within the Magnetic Ball Plant. To linearize this subsystem:

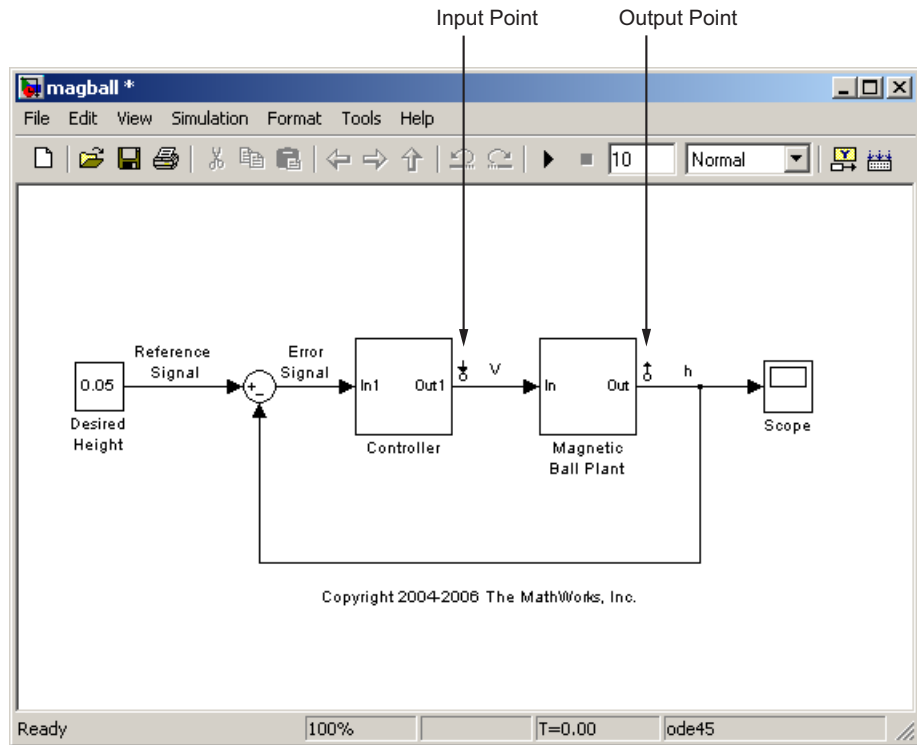
- 1 Select the **Linearization Task** node within the Control and Estimation Tools Manager.
- 2 On the magball model diagram, position the mouse on the signal line between the Magnetic Ball Plant and the Controller. Right-click and select **Linearization Points > Input Point** from the menu.

The model diagram now contains a small arrow pointing toward a circle just above the signal line between the Controller and the Magnetic Ball Plant, as in the following figure. This symbol indicates an input point for linearization has been placed there.



- 3 Right-click the signal line after the Magnetic Ball Plant and select **Linearization Points > Output Point** from the menu.

A small arrow pointing away from a circle on the signal line appears after the Magnetic Ball Plant indicating an output point for linearization has been placed there. The diagram should now look like that in the following figure.



Note All linearization points are referenced to the output port of the block the signal line originates from. For example, placing a linearization point anywhere on the feedback loop in the figure above will result in a linearization point at the output of the Magnetic Ball Plant block.

To remove a linearization point from the model, see “Removing Linearization Points” on page 4-8. To inspect the linearization points in the Control and Estimation Tools Manager, see “Inspecting Analysis I/Os” on page 4-12.

Removing Linearization Points

To remove a linearization point from a signal line in your model, repeat the same process as for inserting a linearization point. For example, to remove

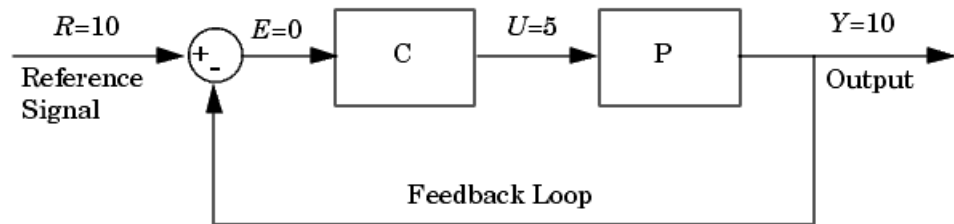
an input point, right-click the signal line containing the input point and select **Linearization Points > Input Point** from the menu. The input point disappears from the diagram.

Performing Open-Loop Analysis

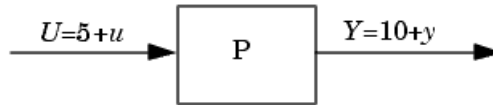
Due to the presence of feedback loops in a model, the input and output points might not completely define the portion of the model you want to linearize. In these cases, to remove the effect of signals feeding back into the portion of the model you are linearizing, you might choose to insert an open-loop point. “What Is Open-Loop Analysis?” on page 4-9 discusses the concepts behind open-loop analysis. “Inserting Loop Openings” on page 4-11 continues the magball example by inserting open-loop linearization points in the magball model. “Open-Loop Analysis Using Functions” in the online documentation gives methods for assigning open-loop points in Simulink models using functions.

What Is Open-Loop Analysis?

Many control systems contain feedback loops. An example of such a system is shown in this figure.

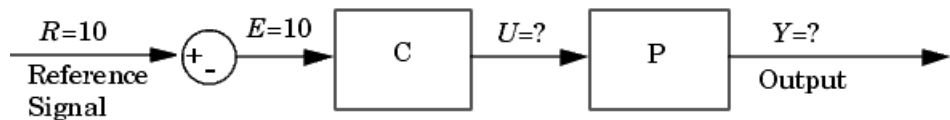


The model represented in this figure is at equilibrium. Consider linearizing the plant, P, about this equilibrium operating point by changing the input signal, U , by a small amount, u , and measuring the change in the output signal, y . The portion of the system that you want to linearize is shown in the following figure.



However, due to the presence of the feedback loop, the change in the output signal will feed back into the controller, C , and then into the plant. This affects the behavior of the system you are linearizing. In fact, if C and P were linear, the linearized model between U and Y would be $\frac{P(s)}{1+C(s)P(s)}$ rather than $P(s)$.

You could manually remove the feedback signal from the model in an attempt to resolve this issue. However, as shown in the following figure, this changes the operating point of the system since the error signal, E , is now equal to the reference signal, R . Linearizing about this new operating point would change the linearization results. Of course, this only makes a difference for nonlinear models. When the model is already linear, it has the same form regardless of the operating point.



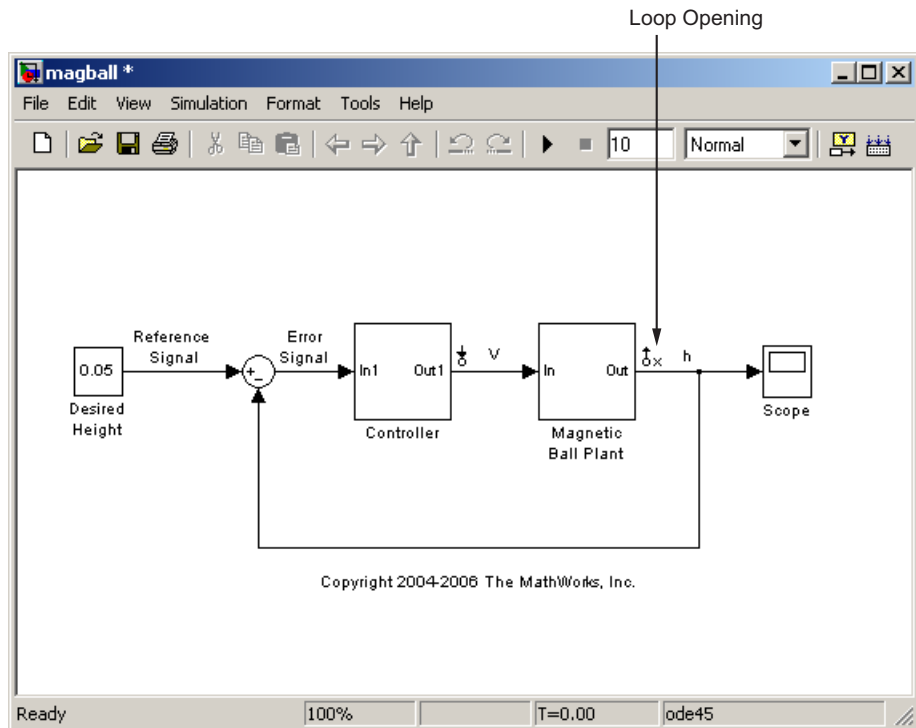
When linearizing Simulink models, use the Simulink Control Design capability to label an input or output point as open loop. Doing so ensures that the output signal is not fed back into the model but keeps the operating point the same. In other words, in the linear case, you would compute $P(s)$

rather than $\frac{P(s)}{1+C(s)P(s)}$. For more information, see “Performing Open-Loop Analysis” on page 4-9.

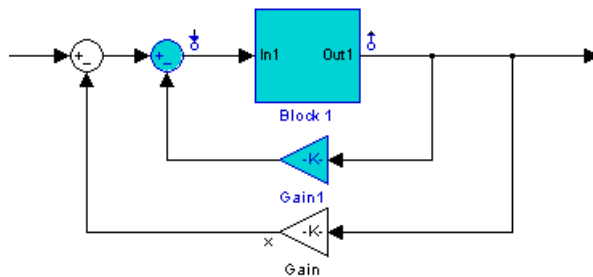
Inserting Loop Openings

This section continues the example from “Inserting Linearization Points” on page 4-6. At this stage in the example, a linearization task has already been created for the model, operating points have been specified, and linearization input and output points have been inserted.

To linearize only the Magnetic Ball Plant, right-click the signal line containing the output point and select **Linearization Points > Open Loop**. This inserts a small x next to the output point in the diagram, representing a loop opening.



Note You do not need to place a loop opening in the same place as an input or output point. For example, in the following figure the highlighted blocks are included in the linearization. The loop opening is placed after the gain on the outer feedback loop, which removes the effect of this loop from the linearization. Placing a loop opening at the same place as the output point would have removed the effect of the inner loop from the linearization as well.



Inspecting Analysis I/Os

This section continues the example from “Inserting Loop Openings” on page 4-11. At this stage in the example, a linearization task has already been created for the model, operating points have been specified, linearization input and output points have been inserted, and loop openings have been created.

To view the linearization points, click the **Analysis I/Os** tab in the **Linearization Task** node in the Control and Estimation Tools Manager, as shown in the following figure. Use this pane to inspect and make changes to your linearization points.

Make points active or inactive.
Points that are inactive will not
be used in the linearization.

Change the type of
a linearization point

Add or remove
loop openings

Control and Estimation Tools Manager

File Tools Help

Workspace

- Project - magball
 - Operating Point
 - Default Ope
 - Operating F
 - Known Ope
 - Operating F
 - Operating F
 - Linearization Ta
 - Custom View

Analysis I/Os | Operating Points | Linearization Results

Select linearization I/Os by right clicking on the desired line in your Simulink model.

Active	Block Name	Output Port	Signal Name	Configuration	Open Loop
<input checked="" type="checkbox"/>	magball/Controller	1		Input	<input type="checkbox"/>
<input checked="" type="checkbox"/>	magball/Magnetic Ball Plant	1	Operating F	Output	<input checked="" type="checkbox"/>

Highlight Selected Signal Refresh Signal Names Delete Selected I/O

Linearize Model Plot linear analysis result in a step response plot

- An operating point Operating Point at t = 10 has been added to the node
Operating Points.

Model linearization task settings.

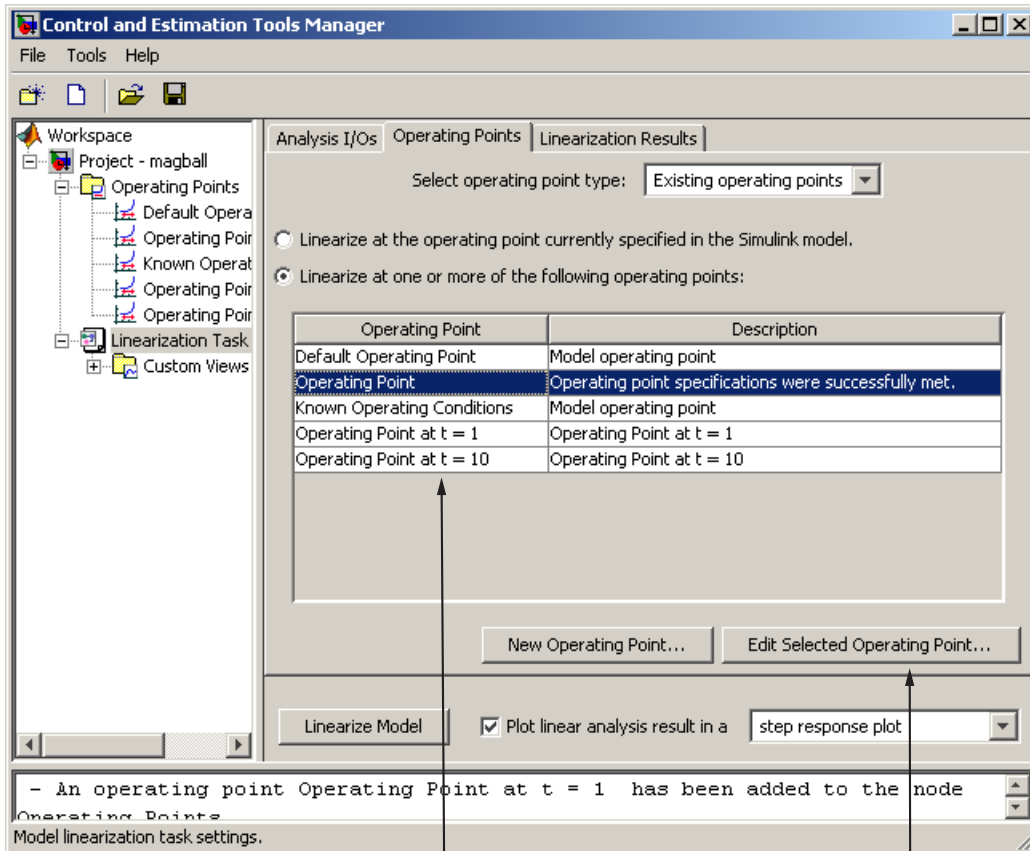
Note You cannot make changes to the **Analysis I/Os** or perform open-loop analysis when you select Numerical Perturbation as the **Linearization Algorithm** in the Linearization Task Options window (accessed by selecting **Tools > Options** from the Control and Estimation Tools Manager window). See “Changing Linearization Settings and Algorithms” in the online *Simulink Control Design User’s Guide* for information.

Linearizing the Model

This section continues the example from “Inspecting Analysis I/Os” on page 4-12. At this stage in the example, a linearization task has been created, operating points have been specified, and linearization points have been inserted.

In this step of the linearization task, you linearize the model using one of the operating points the you created in the project workspace. For information about additional linearization option, see “Linearizing Models in the Control and Estimation Tools Manager” in the *Simulink Control Design User’s Guide*.

Click the **Operating Points** tab in the **Linearization Task** node to select one or more operating points for the linearization. To linearize the magnetic ball model around the operating point computed from partial specifications, first select the **Linearize at one or more of the following operating points** option button. Then, select **Operating Point** in the list, as shown in the following figure.



List of operating points
available in project workspace

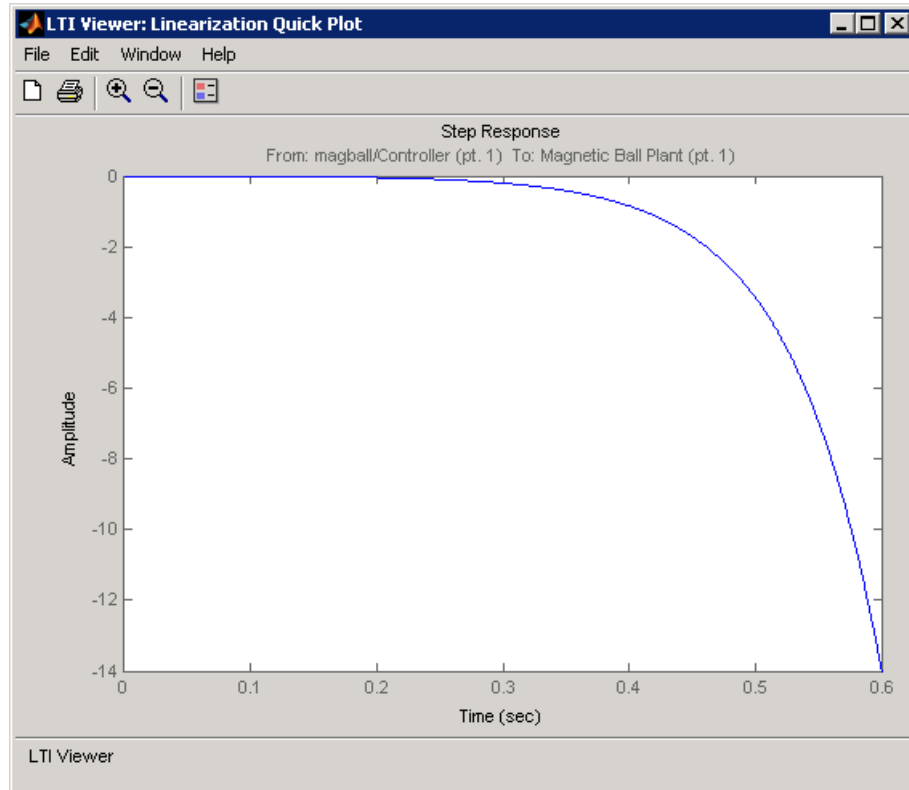
View and edit details of the
selected operating point

To compute the linearized model:

- 1 In the menu to the right of the **Linearize Model** button, select from one of the nine options for displaying the results of the linearization. Clear the check box next to this menu when you do not want to display the results.

- Click the **Linearize Model** button at the bottom of the pane. Simulink Control Design computes the linearized model and displays it in the LTI Viewer.

The following figure shows the step response for the linearized magball model.



Using the LTI Viewer

To add characteristics such as settling time or peak response to your plot, right-click anywhere in the plot area and select an option from the menu. Add data markers by clicking the point you want to mark. In addition, you can display up to six plots at one time. To change the number of plots, select **Edit > Plot Configurations**. Export the linearized model to the workspace

by selecting **File > Export**. For more information, see “LTI Viewer” in the Getting Started with Control System Toolbox documentation.

Analyzing the Results

- To display and remove linearization results, refer to “Displaying Linearization Results” on page 4-19
- To inspect and validate the linearization results, refer to “Validating the Linearization” on page 4-21.
- To display and configure plots of the results, refer to “Comparing the Results of Multiple Linearizations” on page 4-25.
- For methods on simulating the linearized model for comparison with the original model, refer to “Comparing the Linearized and Original Models” in the online documentation.

Displaying Linearization Results

This section continues the magball example from “Linearizing the Model” on page 4-15. At this stage in the example, a linearization task has been created, operating points have been specified, linearization points have been inserted, and a linearized model has been computed.

To display the **Linearization Result** pane, as shown in the following figure, select the **Model** node in the project tree. To delete the linearization result, right-click **Model** and select **Delete** from the menu. The **Linearization Result** pane displays a mathematical representation of the linearized model. By default it appears as a state space system and it displays the state space matrices. However, within the pane you can choose to view the model as a zero-pole-gain system or as a transfer function. You can also export the model to the MATLAB workspace.

4 Linearizing Models

Switch between results based on different operating points

Workspace

Project - magball

- Operating Poi
 - Default O
 - Operating
 - Known Op
 - Operating
 - Operating
- Linearization
 - Model
 - Custom V

Select model from linearization: Default Operating Point

Linearization Result | Linearization Inspector

Linearization Result:

- To plot the response of this result click on the node labeled Custom Views.
- To export the result click on the Export To Workspace button below.

a =

	x1	x2	x3
x1	-100	0	0
x2	-2.801	0	196.2
x3	0	1	0

b =

	magball/Cont
x1	50
x2	0

Display linear model as: State Space

Export to Workspace...

- LTI viewer is ready...

- A linearization result Model has been added to the current Task.

Linearization analysis result.

View the operating points used in the analysis by clicking the + to the left of the Model node

Linearization Result gives the state-space matrices of the linearized model

Export the linearized model to the workspace

Validating the Linearization

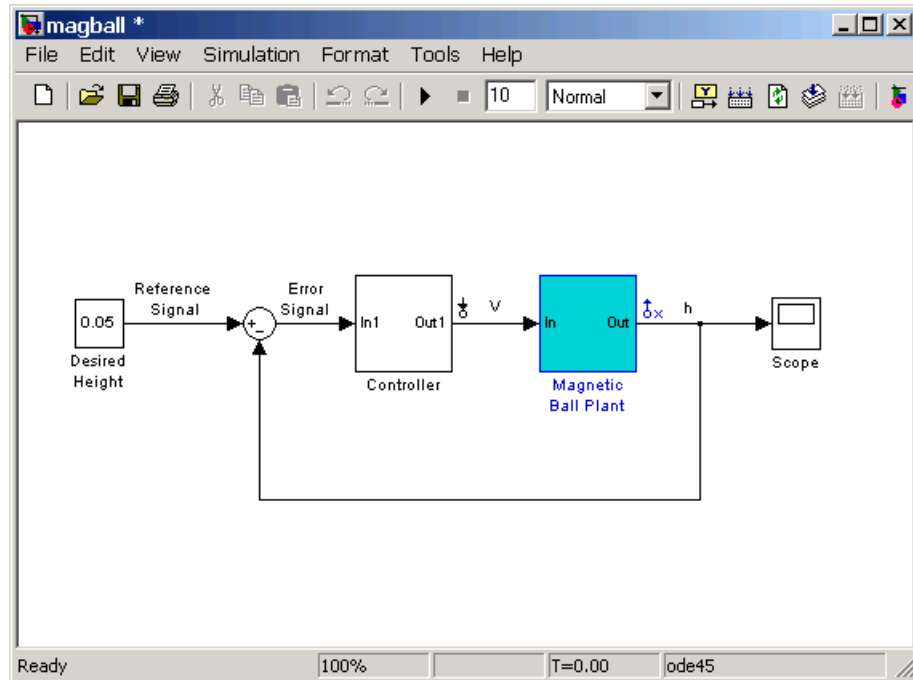
You can validate a linearization in Simulink Control Design using the following techniques:

- “Highlighting Blocks in the Linearization” on page 4-21
- “Inspecting the Linearization Block by Block” on page 4-22

Highlighting Blocks in the Linearization

This section continues the magball example from “Displaying Linearization Results” on page 4-19. At this stage in the example, a linearization task has been created, operating points have been created, linearization points have been inserted, and a linearized model has been computed.

To verify that the correct portion of the model was linearized, you can highlight the blocks in the model that were used in the linearization. To do this, right-click the **Model** node and select **Highlight Blocks in Linearization**. The following figure shows that the Magnetic Ball Plant block, including all blocks within it, was used in the linearization.



To remove the highlighting, right-click the **Model** node and select **Remove Highlighting**.

Note You cannot use the **Highlight Blocks in Linearization** or **Remove Highlighting** option for models that are linearized with numerical-perturbation linearization (when Numerical perturbation is selected as the **Linearization Algorithm** parameter in the Linearization Task Options window).

Inspecting the Linearization Block by Block

This section continues the example from “Validating the Linearization” on page 4-21. At this stage in the example, a linearization task has been created, operating points have been created, linearization points have been inserted, and a linearized model has been computed.

The **Linearization Task** includes a **Linearization Inspector** in which you can inspect the results of the linearization block by block. This is useful when you want to verify that a block of interest, such as a block with a sharp discontinuity, linearized as expected. To inspect the linearization of a block, click the **Linearization Inspector** tab within the **Model** node. This pane displays the linearization matrices of the individual blocks in the linearization path, that is, the blocks between the input and output points.

This figure shows the results of the magnetic ball model in the **Linearization Inspector** pane with **Magnetic Ball Plant** highlighted.

Select a block to inspect.

State-space matrices A, B, C, and D are displayed along with the sample times, and whether the block is in the linearization path.

Linearization Result Linearization Inspector

Select model from linearization: Default Operating Point

Subsystem Blocks

- height
- 1/L
- Current**
- Square
- Divide
- Gravity
- R/L
- Sum
- beta/m
- Sum1
- dhd

A	0.0
B	1.0
C	1.0
D	0.0
InLinearizationPath	Yes
SampleTimes	0.0

Show Block Plot block: step response plot

Linearization analysis result.

- A linearization result Model has been added to the current Task.

Plot results of this block linearization.

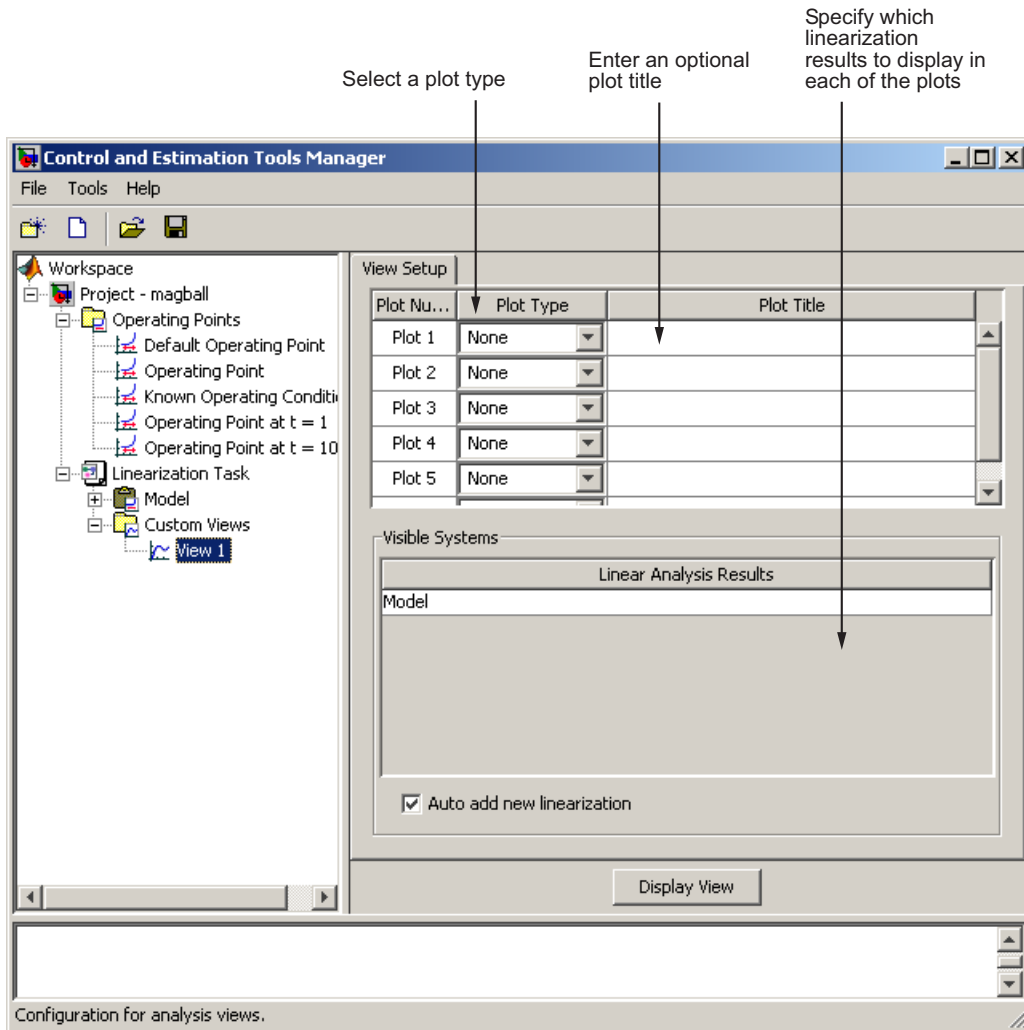
Sample time is zero for continuous systems, nonzero for discrete systems.

Note The **Linearization Inspector** pane does not exist for models that are linearized with numerical-perturbation linearization (when Numerical perturbation is selected as the **Linearization Algorithm** parameter in the Linearization Task Options window) as there are no individual block linearizations to inspect.

Comparing the Results of Multiple Linearizations

This section continues the magball example from “Inspecting the Linearization Block by Block” on page 4-22. At this stage in the example, a linearization task has been created, operating points have been created, linearization points have been inserted, and a linearized model has been computed and inspected.

The LTI Viewer automatically displays a **Linearization Quick Plot** of the linearization results after the linearization. To create additional, customized plots, especially for comparing multiple linearizations, right-click the **Custom Views** node under the **Linearization Task** node and select **Add View**. A new view, **View1**, is added to the **Custom Views** node. Select the **View1** node to display the **View Setup** pane and set up this view.



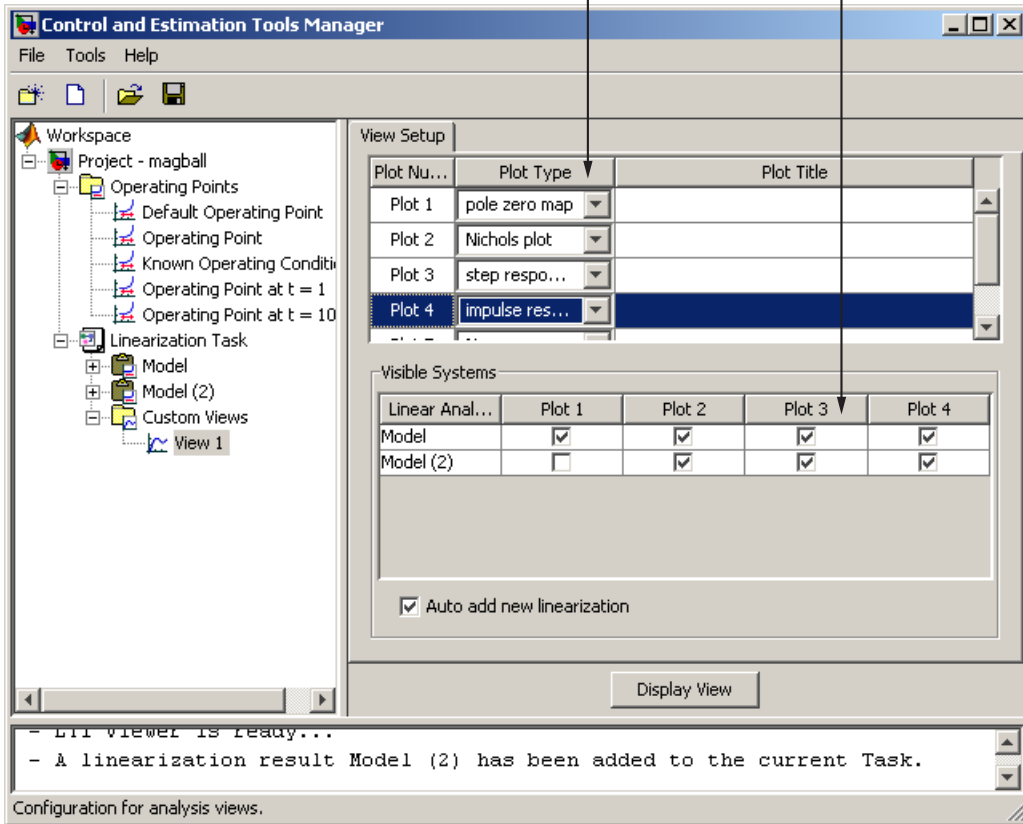
Example

Before configuring the **View Setup** pane for the magnetic ball system, run another linearization of this model using the operating point labeled **Known Operating Conditions**, that you computed in “Creating Operating Points from Known Values” on page 3-14. This adds **Model (2)** to the **Linearization Task** node.

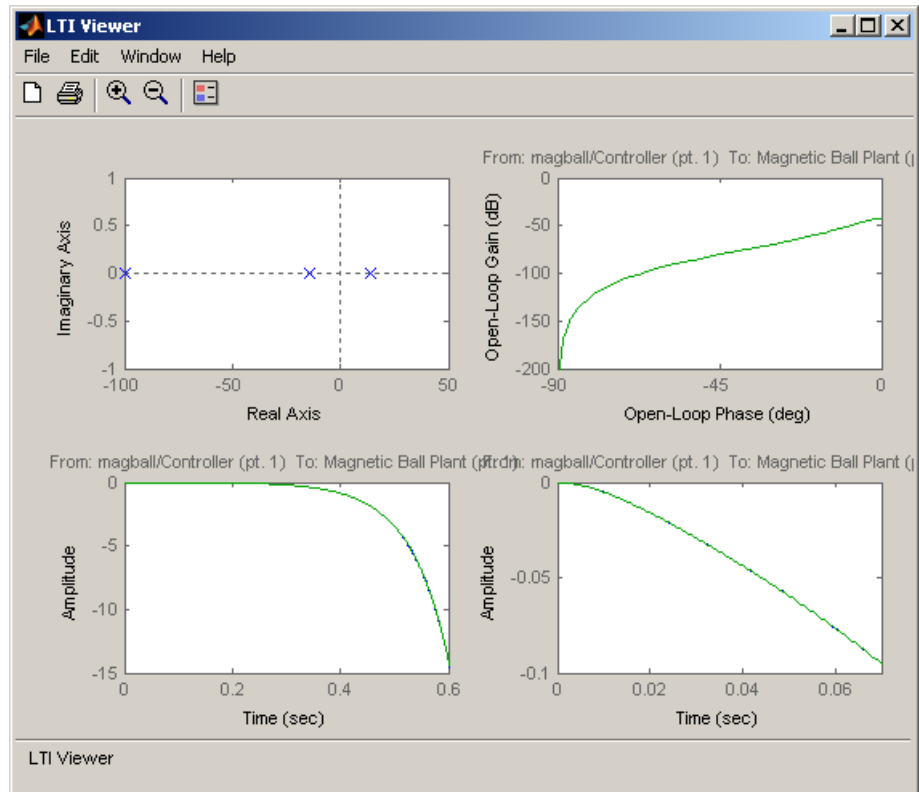
Configure **View Setup** as shown in the following figure:

Select plot types
pole zero map,
Nichols plot, step
response, and
impulse response

Display Model in
plots 1, 3, and 4.
Display Model (2)
in plots 2, 3, and 4.



Click **Display View** to display the LTI Viewer, as shown in the following figure:



Before proceeding to Chapter 5, “Designing Compensators”, close the Control and Estimation Tools Manager and the magball model. You do not need to save any projects or any changes to the model.

Designing Compensators

What Is Compensator Design?
(p. 5-2)

Description of concepts and methodologies for compensator design

Beginning a Compensator Design Task (p. 5-3)

Creating a Compensator Design Task in the Control and Estimation Tools Manager

Picking Blocks to Tune (p. 5-5)

Selecting the compensator blocks that you want to tune in your design

Selecting Closed-Loop Responses to Design (p. 5-7)

Specifying the closed-loop responses whose behavior you want to design or control

Selecting an Operating Point (p. 5-10)

Choosing an operating point that the model is linearized about during the compensator design

Creating a SISO Design Task (p. 5-13)

Setting up the SISO Design Tool plots that you will use to tune the response of the model

Completing the Design (p. 5-22)

Finishing the compensator design using graphical, automated, and direct methods

What Is Compensator Design?

Compensator design is the process of designing compensators for a control system so that the system behaves in a desired way. Compensators in Simulink models are represented by blocks such as Transfer function, Zero-Pole-Gain, and PID blocks. These blocks can act as feedback controllers, pre-filters, feedforward controllers, sensors, etc. Compensator design for Simulink models can be as simple as adjusting gains in a one of these blocks, or as complicated as adding, deleting, or moving poles and zeros in multiple compensators over multiple feedback loops.

Compensator design methodologies often make use of tools such as Bode diagrams, root-locus diagrams, or response plots. These tools require that the plant model is linear; however, most real-world systems are nonlinear. Simulink Control Design simplifies the task of designing compensators for Simulink models by automatically linearizing the model before creating a SISO Design Task in which you can edit and design the compensators using a variety of tools.

Compensator design in the Control and Estimation Tools Manager involves the following steps:

- 1** “Picking Blocks to Tune” on page 5-5
- 2** “Selecting Closed-Loop Responses to Design” on page 5-7
- 3** “Selecting an Operating Point” on page 5-10
- 4** “Creating a SISO Design Task” on page 5-13
- 5** “Completing the Design” on page 5-22

Beginning a Compensator Design Task

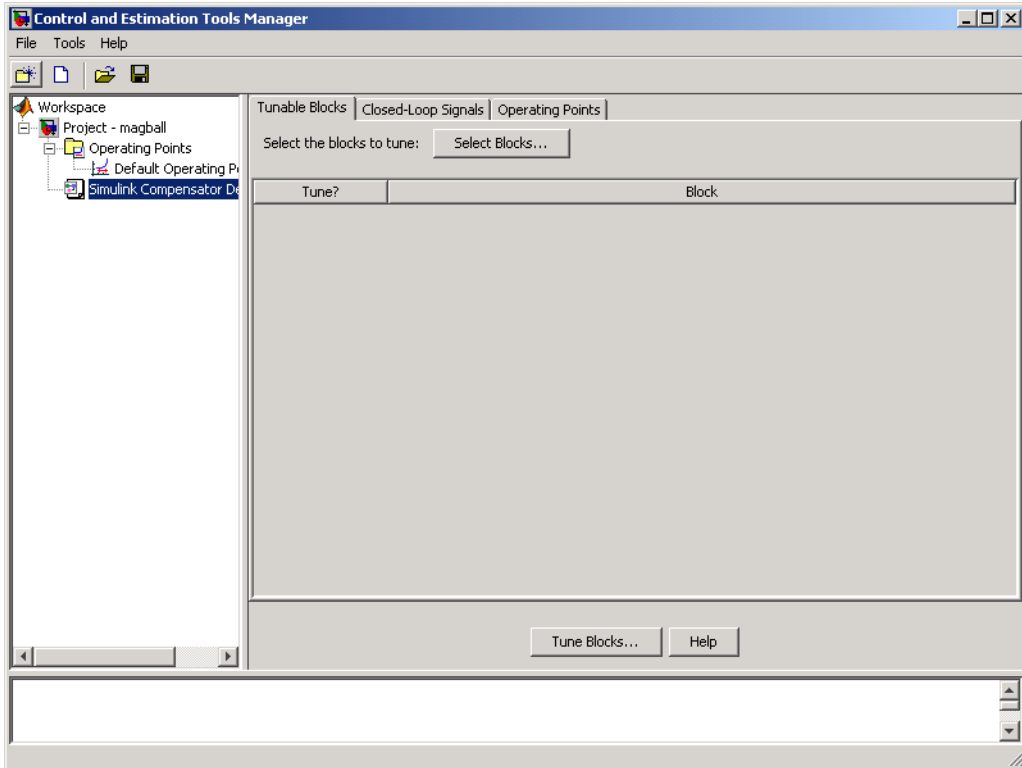
This chapter continues the magball example from “Example Model: The Magnetic Ball System” on page 2-2.

Before you begin this compensator design example, close the Control and Estimation Tools Manager and the magball model, if you have them open, to make sure you are working with a fresh version of the magball model. You do not need to save any projects or any changes to the model.

To begin a new compensator design task for the magball model:

- 1** Enter `magball` at the MATLAB command line to open the magball model.
- 2** Select **Tools > Control Design > Compensator Design** from the `magball` window.

The Control and Estimation Tools Manager opens and creates a new compensator design task, as shown in the following figure.



The project tree in the left pane of the Control and Estimation Tools Manager now shows a **Simulink Compensator Design Task** node as part of **Project - magball** in addition to the **Operating Points** node. You can select a node within the tree to display its contents in the right pane.

- For information on the **Tunable Blocks** pane within the **Simulink Compensator Design Task** node, refer to “Picking Blocks to Tune” on page 5-5.
- For information on the **Closed-Loop Signals** pane within the **Simulink Compensator Design Task** node, refer to “Selecting Closed-Loop Responses to Design” on page 5-7.
- For information on the **Operating Points** node or the **Operating Points** pane within the **Simulink Compensator Design Task** node, refer to “Selecting an Operating Point” on page 5-10.

Picking Blocks to Tune

This section continues the magball example from “Beginning a Compensator Design Task” on page 5-3. At this stage in the example, a compensator design task has been created.

In this step of the compensator design task, you will select the tunable blocks in your model. The tunable blocks are those that you will tune in the SISO Design Tool to achieve the desired response of your system. They are typically the compensators in the system.

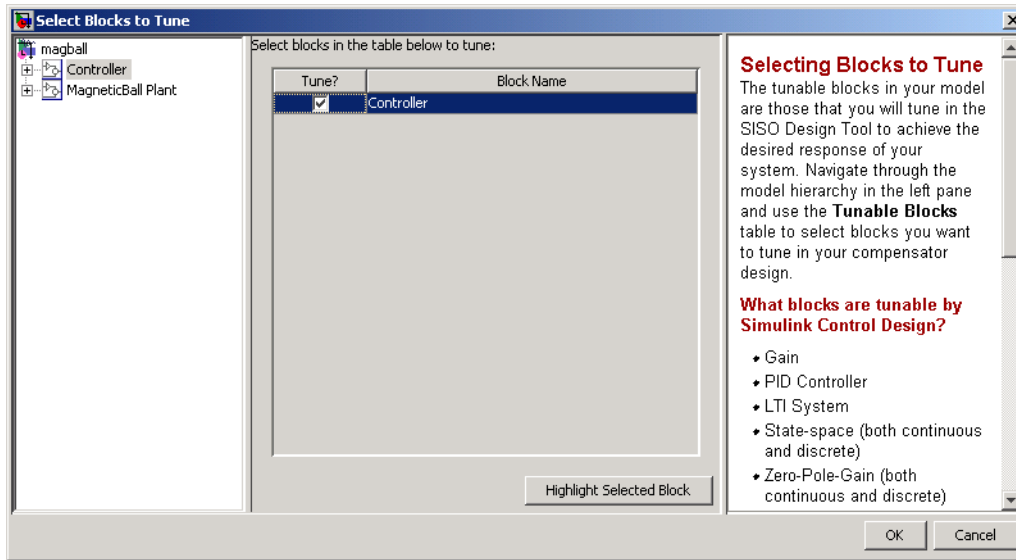
Blocks that are tunable in a Simulink Compensator Design Task include

- Gain
- PID
- LTI
- State-space (both continuous and discrete)
- Zero-Pole-Gain (both continuous and discrete)
- Transfer function (both continuous and discrete)

For the complete list of tunable blocks, see “What Blocks Are Tunable by Simulink Control Design?” in the *Simulink Control Design User’s Guide*.

This example will tune the compensator block called Controller inside the Controller subsystem. To add this as a tunable block for the magball model:

- 1** Select the **Simulink Compensator Design Task** node.
- 2** Within the **Tunable Blocks** pane, click the **Select Blocks** button. This opens the Select Blocks to Tune dialog box.
- 3** Select the Controller subsystem in the left pane to display that subsystem’s tunable blocks within the center pane. Within the center pane, select the check box next to the Controller block’s name.



4 Click **OK** to apply your selections, and close the dialog box.

Selecting Closed-Loop Responses to Design

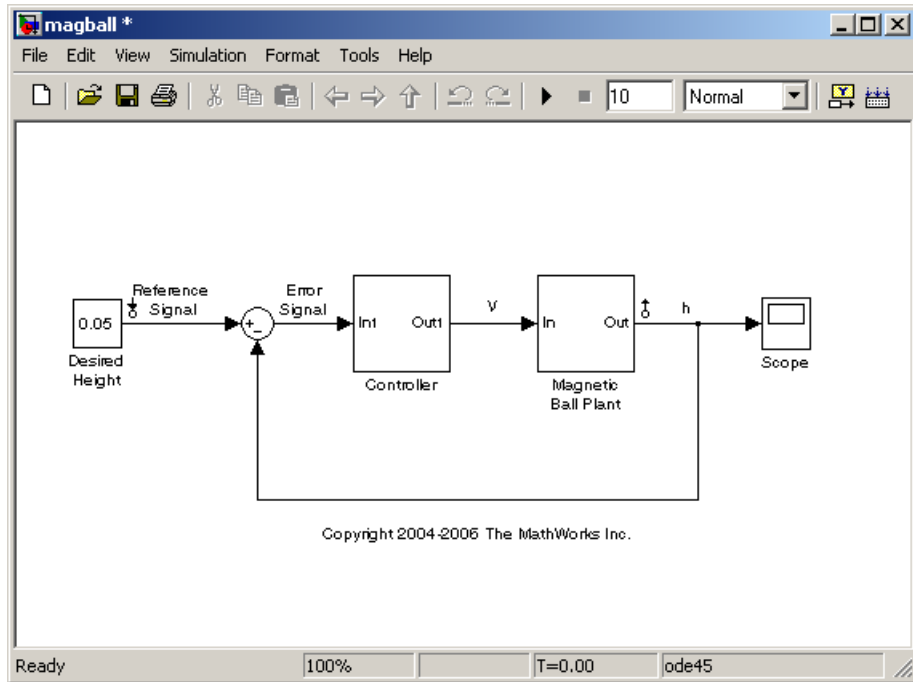
This section continues the magball example from “Picking Blocks to Tune” on page 5-5. At this stage in the example a compensator design task has been created, and tunable blocks have been selected.

In this step of the compensator design task, you will select the closed loops whose responses you want to design in your model. A closed-loop system is defined by an input point, such as a reference or disturbance signal, and an output point, such as a measured output or actuator signal. The **Simulink Compensator Design Task** uses linearization points on the signal lines of the model to determine the closed-loop systems. For more information on linearization points, see “Configuring Inputs and Outputs for the Linearized Model” on page 4-5.

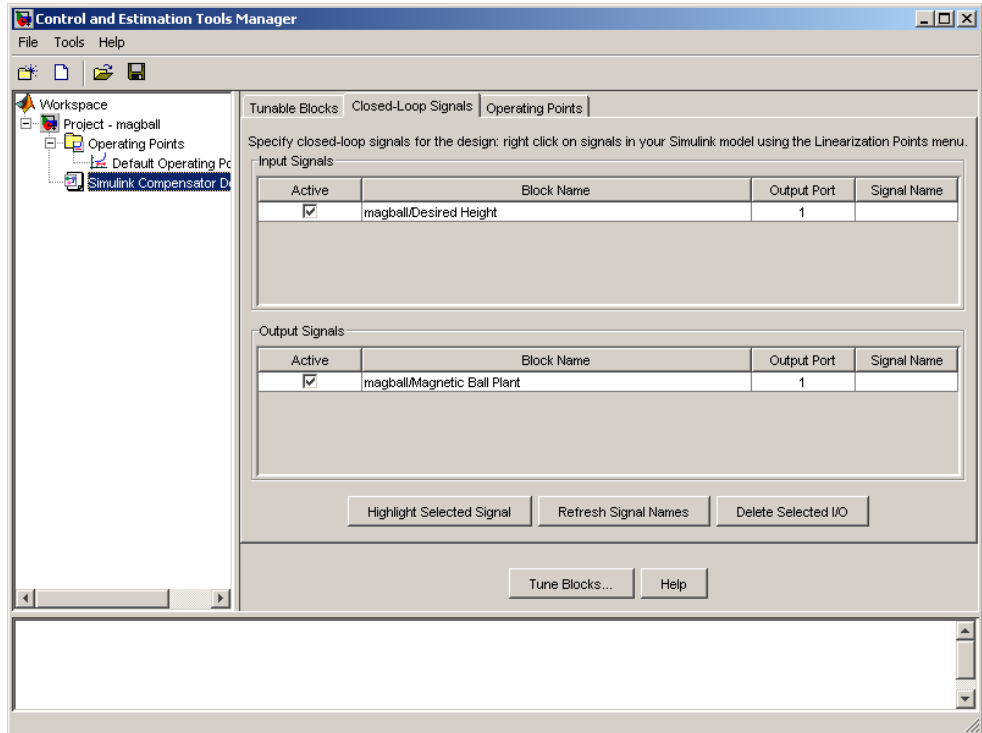
In this example you will design the response of the closed-loop system from the reference signal to the output of the plant model. To set up linearization points to define this closed-loop system, perform the following steps:

- 1** On the magball model diagram, position the mouse on the Reference signal between the Desired Height block and the Sum block. Right-click and select **Linearization Points > Input Point** from the menu to add an input point.
- 2** Position the mouse on the signal line at the output of the Magnetic Ball Plant block. Right-click and select **Linearization Points > Output Point** from the menu to add an output point.

The magball model should now appear as follows:



Within the Control and Estimation Tools Manager, click the **Closed-Loop Signals** tab of the **Simulink Compensator Design Task** node to view the input and output points in the model.



Within this pane you can view the input and output signals in the model and use the **Active** column to select the ones you want to use to define closed-loop systems for compensator design.

Selecting an Operating Point

This section continues the magball example from “Selecting Closed-Loop Responses to Design” on page 5-7. At this stage in the example, a compensator design task has been created, tunable blocks have been selected, and closed-loop signals have been selected.

In this step of the compensator design task, you will select the operating point that you want to use in the compensator design. Simulink Control Design uses the operating point when it linearizes the model before creating a SISO Design Task.

Note A compensator designed for the linearized model is likely to control the behavior of the nonlinear model only in a small region around the operating point that the model was linearized at. Therefore it is important that the linearization of the model is accurate and the selection of the operating point about which the system is linearized is an important step in the compensator design process.

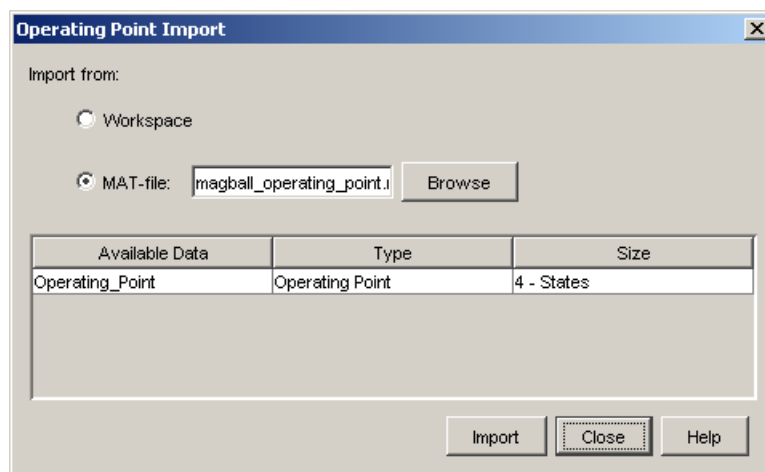
In Chapter 3, “Specifying Operating Points”, you created operating points for this model, exported one to the MATLAB workspace, and saved it in a MAT-file. This example imports the operating point that you saved. If you did not already compute and save an operating point for the magball model, you can import an operating point that was installed along with the Simulink Control Design demos.

To import an operating point for compensator design, perform the following steps:

- 1** Select the **Operating Points** node in the Control and Estimation Tools Manager.
- 2** Click the **Import** button, in the bottom-right corner of the Control and Estimation Tools Manager.
- 3** In the Operating Point Import dialog box, select **MAT-file** as the location to import from.

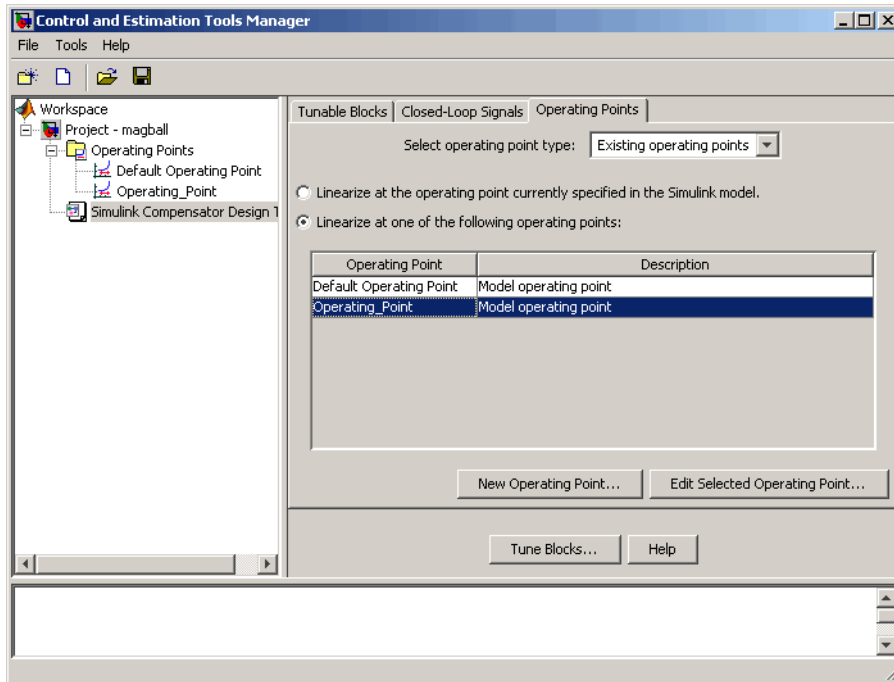
- 4 Click **Browse** and locate the file `magball_operating_point.mat` that you previously saved. If you did not previously save an operating point, browse to `matlabroot/toolbox/slcontrol/slctrldemos/magball_operating_point.mat`.
- 5 Click **Open** to return to the Operating Point Import dialog box.

The Operating Point Import dialog box now shows all the operating points available within the selected MAT-file. In this case just a single operating point is contained in the MAT-file.



- 6 Select this operating point and click **Import** to import it into the Control and Estimation Tools Manager.

Click the **Operating Points** tab in the **Simulink Compensator Design Task** node to select an operating point for the compensator design. For this example, you should use the operating point that you just imported, called **Operating_Point**. To specify this operating point, first select the **Linearize at one of the following operating points** option button. Then select **Operating_Point** in the list, as shown in the following figure.



For information on performing compensator design at specified simulation times and events, see “Linearizing at an Operating Point” in the *Simulink Control Design User’s Guide*.

Creating a SISO Design Task

- “Configuring Design Plots” on page 5-14
- “Configuring Analysis Plots” on page 5-16

This section continues the magball example from “Selecting an Operating Point” on page 5-10. At this stage in the example, a compensator design task has been created, and tunable blocks, closed-loop signals, and an operating point have been selected.

In this step of the compensator design task, you will create and configure a **SISO Design Task** in the Control and Estimation Tools Manager. The **SISO Design Task** includes several tools for tuning the response of SISO systems:

- A graphical editing environment in the SISO Design Tool window that contains design plots such as root-locus, and Bode diagrams
- An LTI Viewer window where you can view time and frequency analysis plots of the system
- A compensator editor where you can directly edit the block mask parameters or the poles and zeros of compensators in your system
- A tool that automatically generates compensators using PID, internal model control (IMC), or linear-quadratic-Gaussian (LQG) methods (uses Control System Toolbox)
- A response optimization tool that automatically tunes the system to satisfy design requirements (available when you have the product Simulink Response Optimization)

The Design Configuration Wizard guides you through the selection of the open- and closed-loop systems you want to design and the configuration of the design and analysis plots you want to use in the **SISO Design Task**. To launch the wizard, click the **Tune Blocks** button in the Simulink Compensator Design Task node. The wizard opens in a separate window.

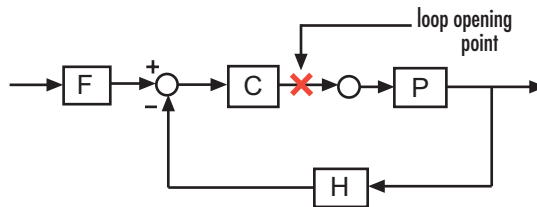
The first page of the wizard provides an overview of the design configuration process and lists some issues to consider when selecting design and analysis plots. Click **Next** to continue to step 1 of the design configuration process on the second page of the wizard.

Configuring Design Plots

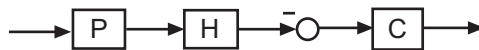
In step 1, select the open- and closed-loop systems that you want to design in your model, and up to six corresponding design plots you want to use.

Open-loop design allows you to design the response of a closed feedback loop in your model by artificially opening the loop and designing the response of this *open-loop* system. The open-loop design plots use rules of linear control theory to determine the dynamics of the closed-loop system from those of the open-loop system. Open-loop design is typically used to tune compensators that lie inside feedback loops.

Simulink Control Design creates a set of default open-loop systems for your model, shown in the lower half of the wizard. To create these open-loop systems, Simulink Control Design artificially opens the feedback loop at the output signal of each tunable block (at the X in the following figure) and unwraps the closed-loop system to create the corresponding open-loop system.



The unwrapped open-loop system would appear as shown in the following figure. This is the system shown in the open-loop design plots.



Note that elements that are outside the feedback loop, such as the prefilter **F**, are not seen in the open-loop system.

In this example, you will tune the response of **Open Loop 1** which is defined by a loop opening at the output of the Controller block. This open-loop system contains the plant model and the controller. To design this system, select Open Loop 1 from the menu next to **Plot 1** in the wizard.

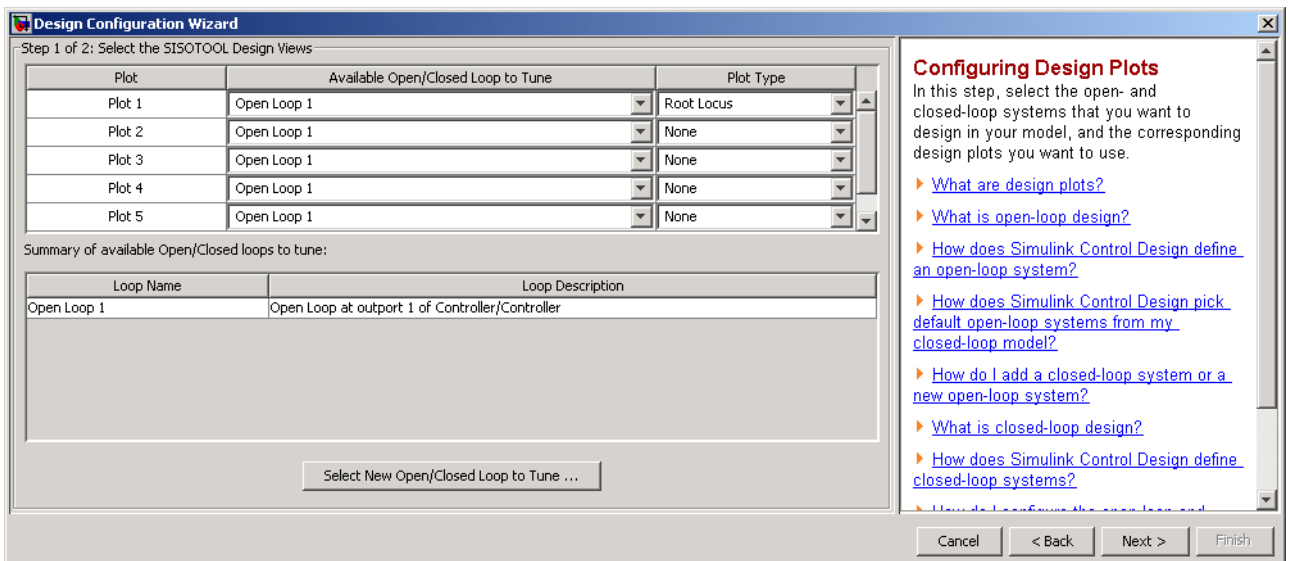
Next, select a design plot to use for this open-loop system. Design plots are interactive plots within the SISO Design Tool. You can use them to graphically tune parameters and manually move, add, or remove poles and zeros of the tunable blocks to tune and design the dynamics of open- and closed-loop systems in your model.

The available design plots are

- Open-loop design plots: root locus, Nichols, open-loop Bode
 - Use these plots to tune blocks that act as feedback elements.
- Closed-loop design plots: closed-loop Bode
 - Use this plot to tune blocks that act as feedforward or prefilter elements.

You can also use the design plots to specify requirements for stability, performance, or both to use in using optimization-based automated tuning.

For this example, select Root Locus from the menu next to **Plot 1** to use this plot type as the design plot for **Open Loop 1**. Step 1 of the wizard should now look similar to the following figure.



Click **Next** to proceed to step 2 of the wizard.

Configuring Analysis Plots

In this step, select the closed-loop responses that you want to view while designing your model, and the corresponding analysis plots you want to use to view them.

Analysis plots are plots that show the responses or dynamics of a closed or open loop systems or tunable blocks in your model. Although you cannot directly edit the analysis plots by graphically moving gains, poles, zeros, etc., changes that you make in the design plots, compensator editor, or automated design tools will affect the responses in the analysis plots. Possible analysis plots include

- Step response
- Impulse response
- Bode and Bode magnitude
- Nyquist
- Nichols
- Pole/Zero

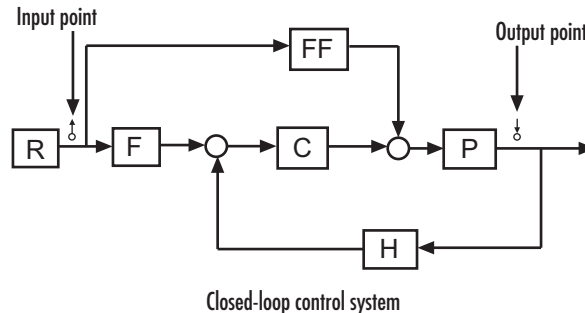
You can use analysis plots to

- Analyze closed-loop, open-loop, and tuned block responses in your control system.
- Define stability and performance requirements for optimization-based automated tuning.

For this example, select Step from the menu for **Plot 1** to create a step response analysis plot.

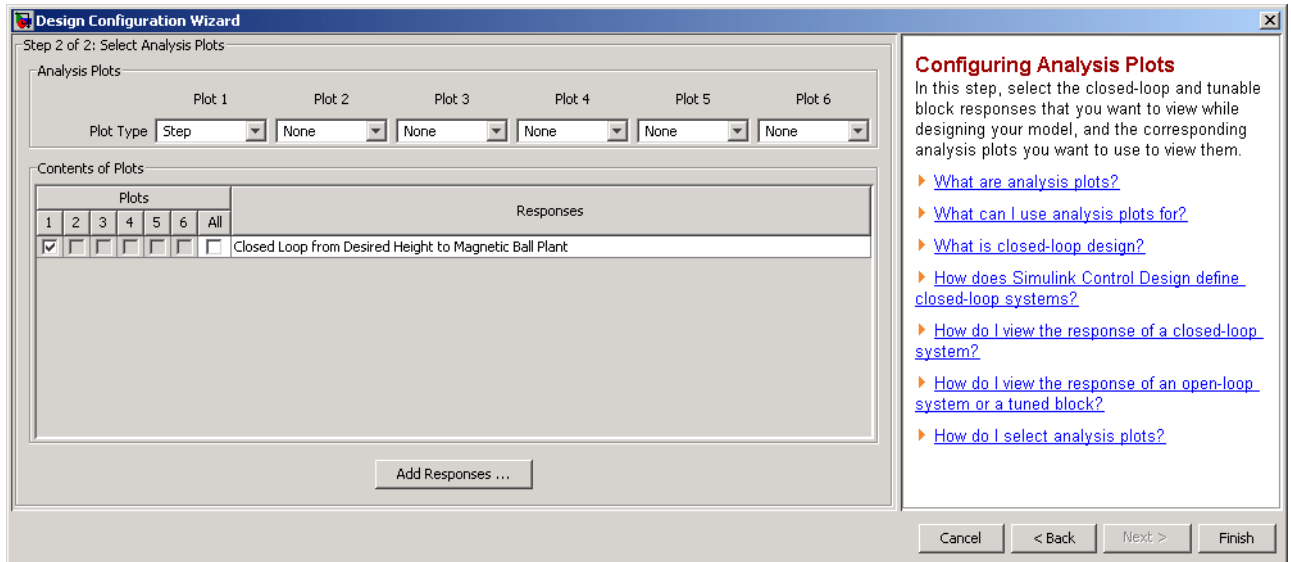
Next, select the closed-loop system that you want to display in this plot. A closed-loop system is a system that has not had any feedback loops opened for open-loop design. It typically defines the system whose response you want to control and it lies between the input and output signals of interest, for example between a reference signal and the plant output signal.

Simulink Control Design uses linearization input and output points that you place on signal lines in your model to define closed-loop systems. The closed-loop system includes all blocks in the path between the input and the output.

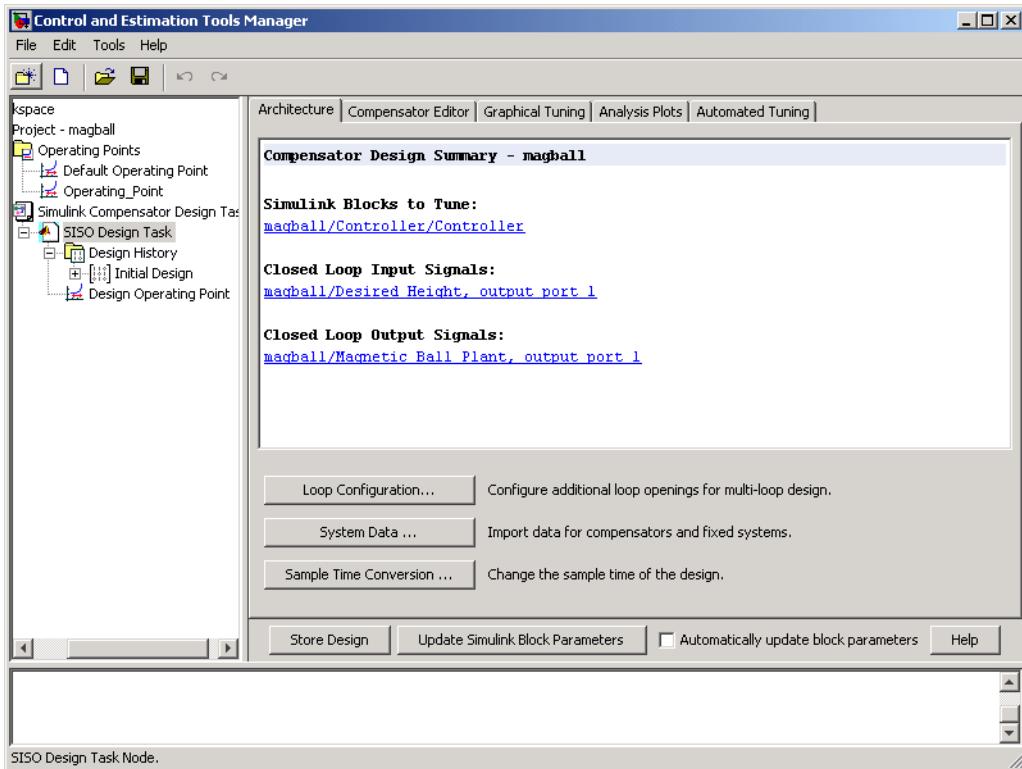


Simulink Control Design automatically displays a list of up to four closed-loop systems in your model, based on the input and output points on the signal lines. In this example, only one closed-loop system appears in the wizard, the closed-loop from the Desired Height signal to the output of the Magnetic Ball Plant Model, because the system only has one input and one output point. You can add additional closed-loop responses, as well as open-loop and tunable block responses. To add a new response, click the **Add Responses** button and complete the Select a New Response to Analyze dialog box.

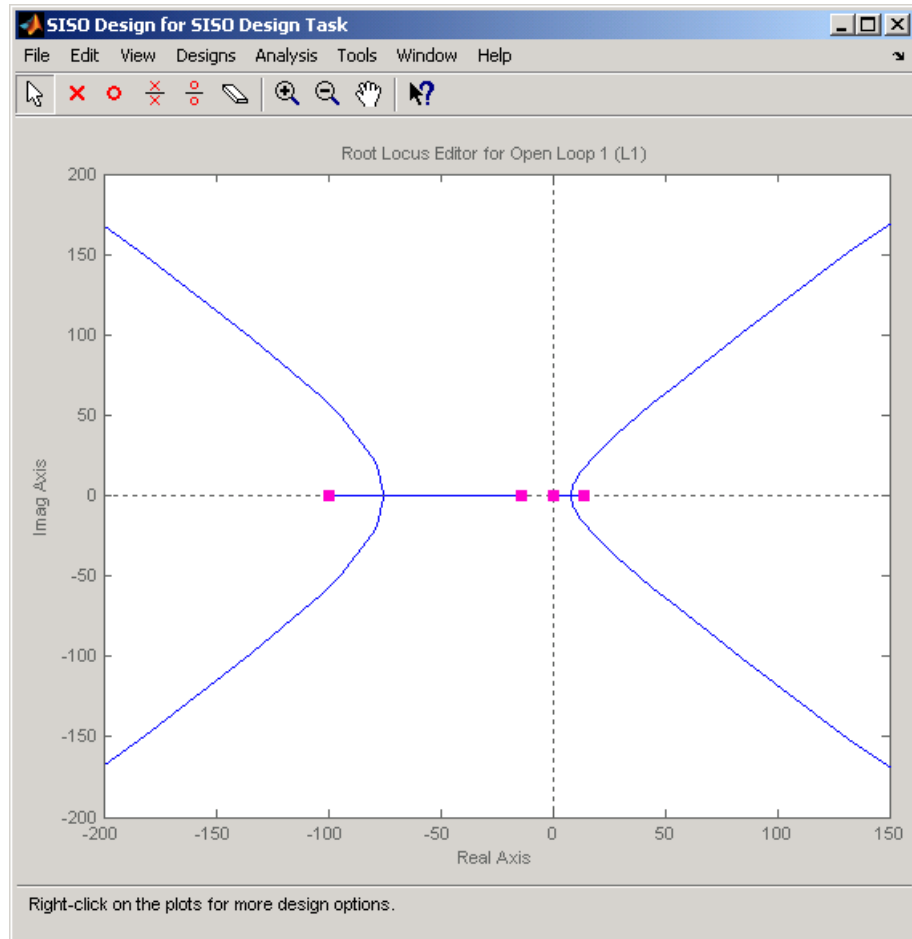
To display the current closed-loop system in the step response plot of **Plot 1**, select the check box under **Plot 1** to the left of the closed-loop system. Step 2 of the wizard should now look similar to the following figure.



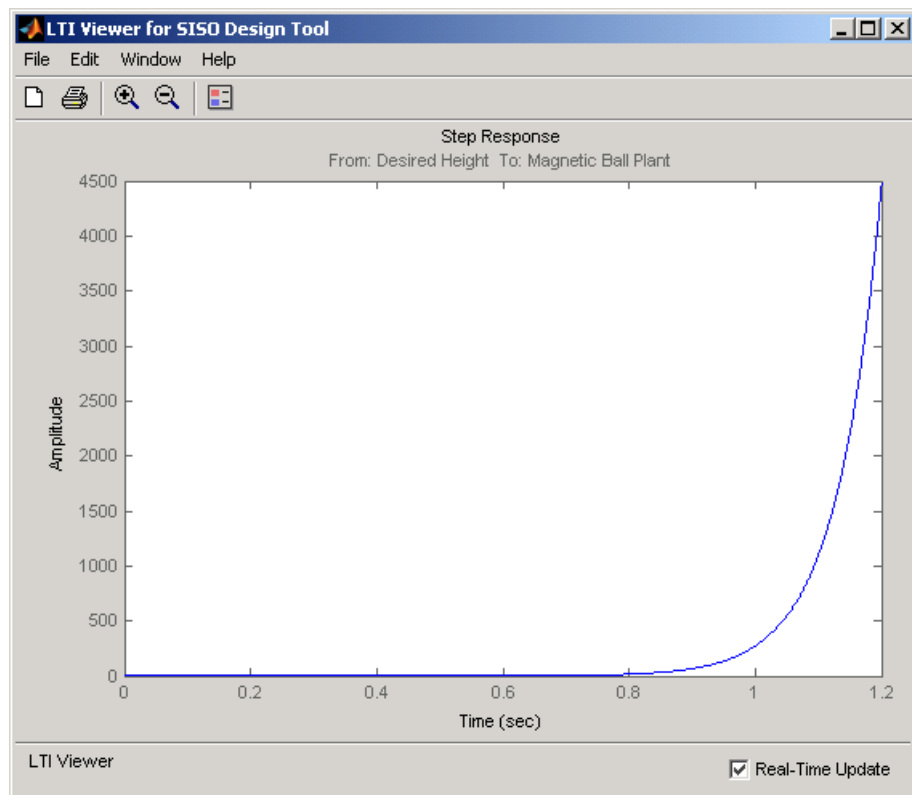
Click **Finish** to complete the wizard and create the **SISO Design Task** underneath the **Simulink Compensator Design Task** node within the Control and Estimation Tools Manager, as shown in the following figure.



The **SISO Design Task** also includes the design plots you configured in the Design Configuration Wizard. They appear within the SISO Design Tool window, as shown in the following figure.



In addition, the **SISO Design Task** also includes the analysis plots you configured in the Design Configuration Wizard. They appear within the LTI Viewer window, as shown in the following figure.



Completing the Design

- “Storing and Retrieving Designs” on page 5-26
- “Writing the Design to the Simulink Model” on page 5-28

This section continues the magball example from “Creating a SISO Design Task” on page 5-13. At this stage in the example, a compensator design task has been created, tunable blocks, closed-loop signals, and an operating point have been selected, design and analysis plots have been created, and a **SISO Design Task** node has been created in the Control and Estimation Tools Manager.

In this step of the compensator design task, you will complete the design of the compensator in the magball model, using the **SISO Design Task** node. For a more detailed discussion of the **SISO Design Task** node, refer to the Control System Toolbox documentation.

The **SISO Design Task** node contains five panes with various tools for designing the compensators in your system.

- **Architecture:**
 - Configure loops for multi-loop design by opening signals to remove the effects of other feedback loops.
 - Import compensators into your system.
 - Convert the sample time of the system or switch between different sample times to design different compensators.
- **Compensator Editor:**
 - Directly edit the poles, zeros, and gains of the compensator.
 - Add or remove poles and zeros to the compensators.
- **Graphical Tuning:**
 - Configure design plots in the SISO Design Tool.
 - Use design plots to graphically manipulate the response of the system.
- **Analysis Plots:**
 - Configure analysis plots in the LTI Viewer.

- Use analysis plots to view the response of open- or closed-loop systems.
- **Automated Tuning:** Design compensators using one of several automated methods.
 - Automatically generate compensators using PID, internal model control (IMC), or linear-quadratic-Gaussian (LQG) methods (uses Control System Toolbox).
 - Use a response optimization tool that automatically tunes the system to satisfy design requirements (available when you have the Simulink Response Optimization product).

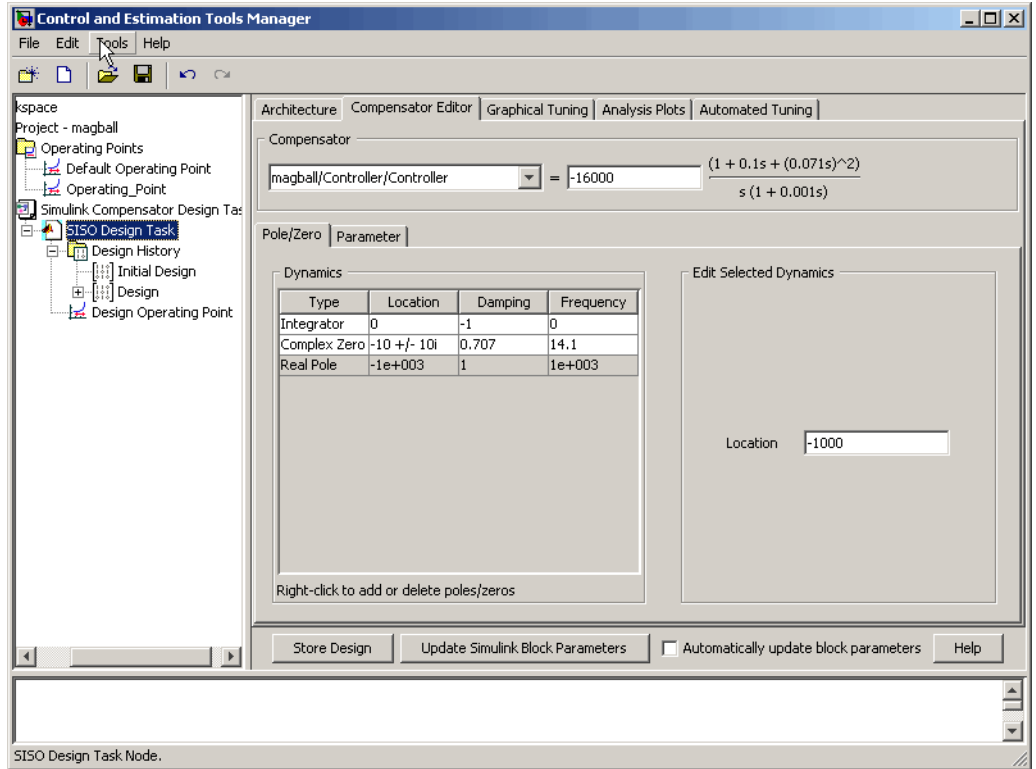
You can use any of these design methods, or a combination of methods, to design the compensators for your system. A suitable final design for the Controller of the magball model is:

- Gain: -16000
- Integrator at the origin
- Complex zeros at $-10 \pm 10i$
- Real pole at -1000

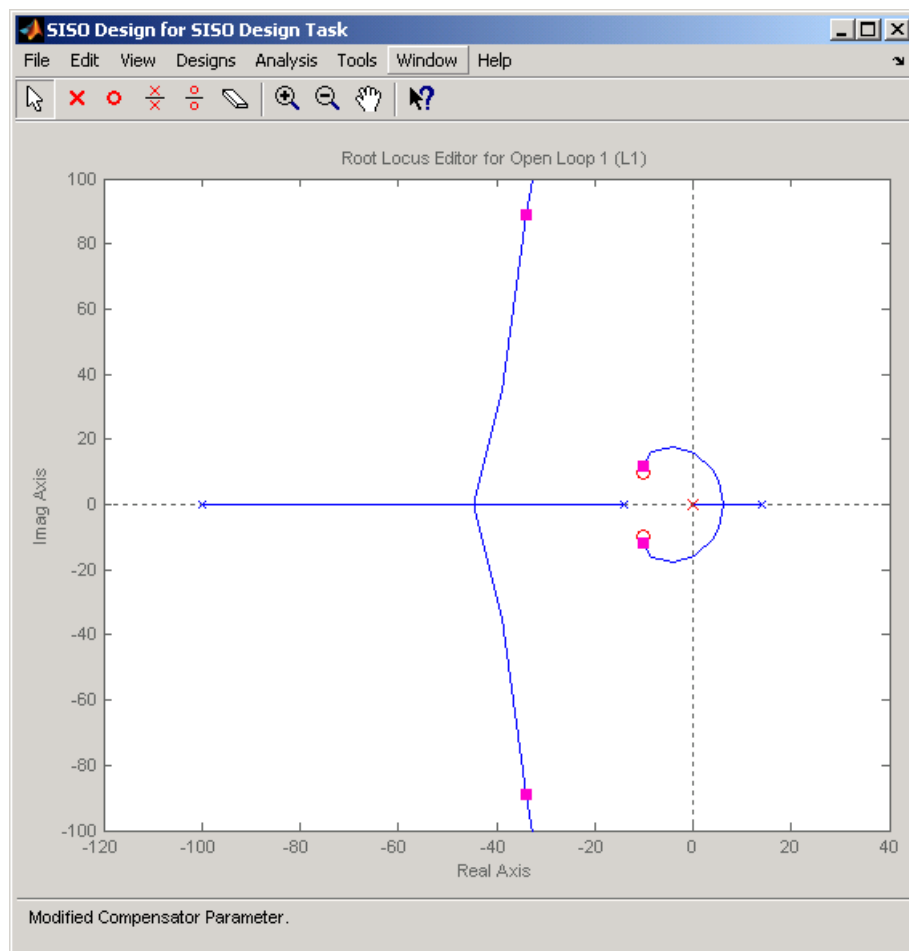
You can use the **Compensator Editor** in the **SISO Design Task** node to specify these settings. The initial design contains an integrator at the origin. Specify the remaining settings as follows:

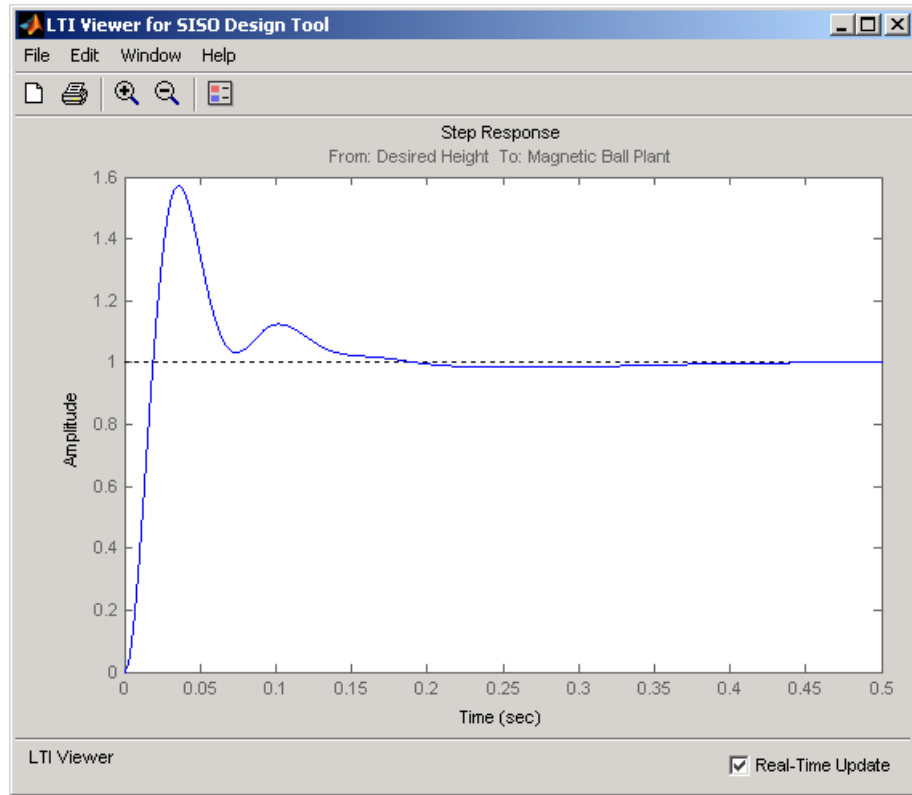
- Gain — Enter -16000 in the text box to the right of the equal sign in the **Compensator** area.
- Complex zeros — In the **Dynamics** table, right-click and then select **Add Pole/Zero > Complex Zero**. Select the new complex zero in the **Dynamics** table. In the **Edit Selected Dynamics** table:
 - Enter -10 in the **Real Part** field.
 - Enter 10 in the **Imaginary Part** field.
- Real pole — In the **Dynamics** table, right-click and then select **Add Pole/Zero > Real Pole**. Select the new real pole in the **Dynamics** table. In the **Edit Selected Dynamics** table:
 - Enter -1000 in the **Location** field.

The Control and Estimation Tools Manager should now appear as follows:



With these settings, the root-locus diagram and step-response plot should look similar to the following figure.





Storing and Retrieving Designs

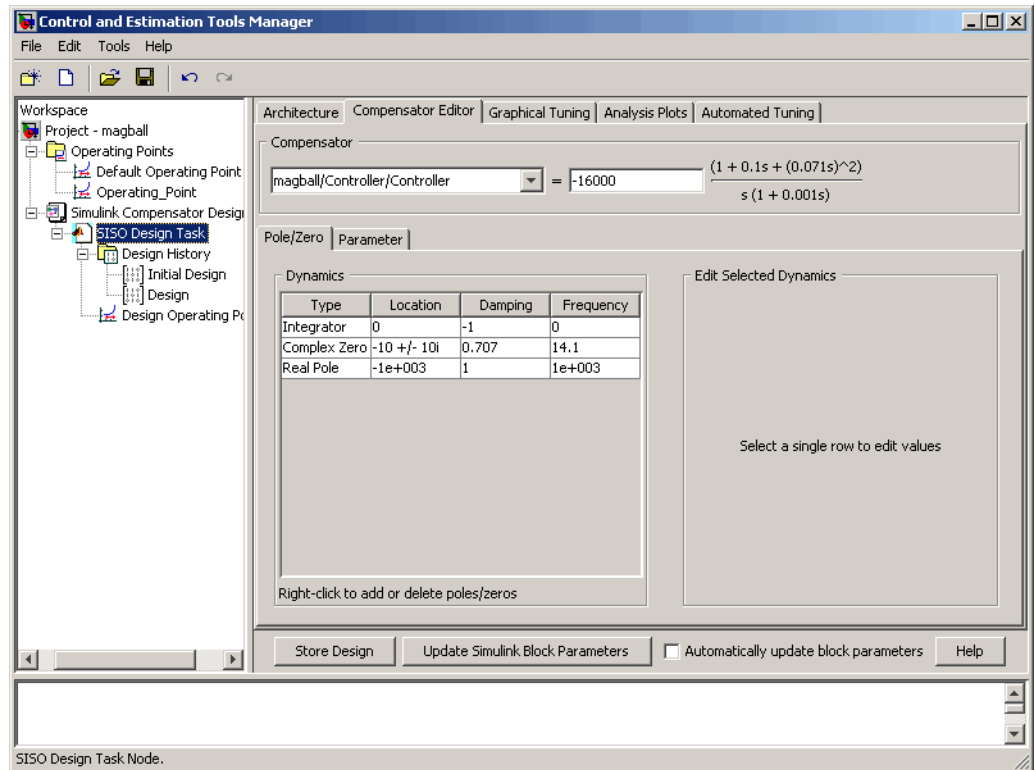
When you design a compensator within a **Simulink Compensator Design Task**, you can store the current design. You can retrieve the stored design at any time. This storage and retrieval capability lets you continue designing and still be able to return to a previously saved version of the design.

This section continues the example from “Completing the Design” on page 5-22. At this stage in the example, a compensator has been designed to control the system. To store the design within the **SISO Design Task** node, perform the following steps:

- 1 Select the **SISO Design Task** node in the Control and Estimation Tools Manager.

2 Underneath the **SISO Design Task** panes, click the **Store Design** button.

Clicking this button adds the current design to the **Design History** node as shown in the following figure. The default name for the design is **Design**.



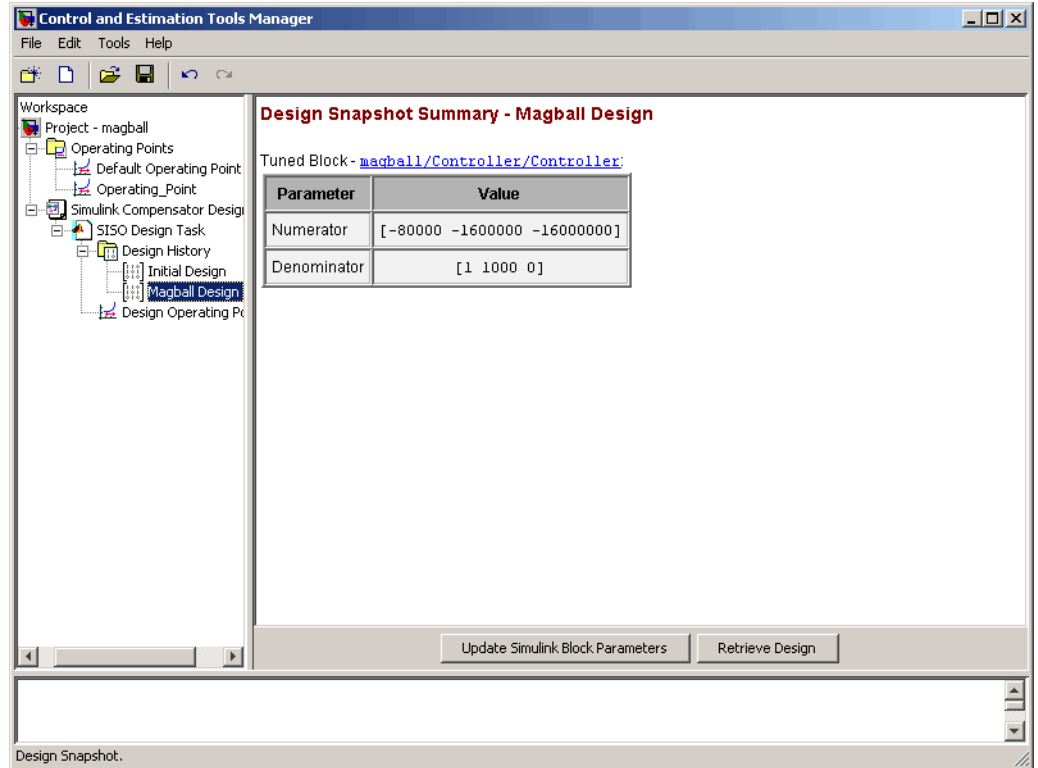
To rename the design to something more descriptive:

1 Right-click the **Design** node underneath the **Design History** node.

2 Select **Rename** from the right-click menu.

3 Enter a name for your design. For this example, call the design **Magball Design**.

The Control and Estimation Tools Manager should now appear as follows:



Note After you store a compensator design, you can continue to refine it. If you make undesired changes, you can retrieve the stored design by selecting it in the **Design History** node and then clicking the **Retrieve Design** button.

Writing the Design to the Simulink Model

When designing a compensator within a **Simulink Compensator Design Task** node, you can write the compensator design to the Simulink model. This is useful when

- You want to see how the current design performs in the full nonlinear model.

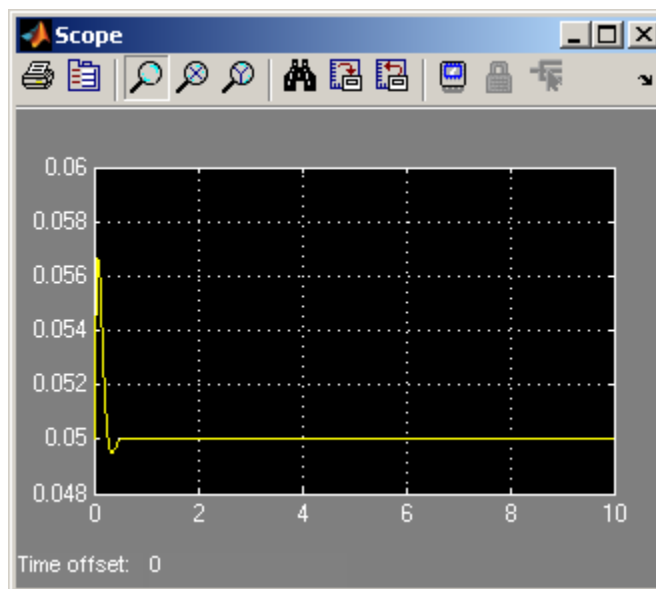
- You have completed the design and you want to update the model with the newly designed parameters.

This section continues the example from “Storing and Retrieving Designs” on page 5-26. At this stage in the example a compensator has been designed to control the system and the design has been stored within the **SISO Design Task** node. To write the stored design to the magball model, perform the following steps:

- 1** Select the **Magball Design** node under the **Design History** node in the Control and Estimation Tools Manager.
- 2** Click the **Update Simulink Block Parameters** button.

You can now simulate the magball model containing the newly designed Controller block. For more information on simulating models, see “Running Simulations” in the Simulink documentation.

After simulation, the Scope block of the magball model should look similar to the following figure.



As you can see, the system is now stable and the height of the magnetic ball settles at the desired height of 0.05 m.

Saving and Exporting Your Work

Saving Projects (p. 6-2)

Saving projects in the Control and Estimation Tools Manager

Opening Previously Saved Projects (p. 6-3)

Loading projects in the Control and Estimation Tools Manager

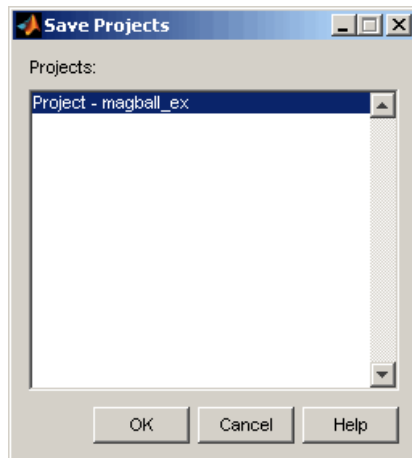
Exporting Results (p. 6-4)

Exporting the results to the MATLAB workspace

Saving Projects

A Control and Estimation Tools Manager project can consist of multiple tasks such as linearization, compensator design, and operating points tasks as well as tasks from Simulink Parameter Estimation and Model Predictive Control Toolbox. Each task contains data, objects, and results for the analysis of a particular model.

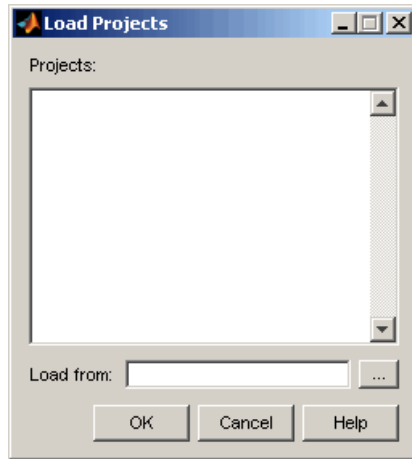
- 1 To save a project as a MAT-file, select **File > Save** from the Control and Estimation Tools Manager window.



- 2 In the Save Projects dialog box, select one or more projects you want to save. You can save multiple projects in one file. Click **OK**, and browse to the folder where you want to save the project. Enter the project name, and click **Save**.

Opening Previously Saved Projects

- 1 To open previously saved projects, select **File > Load** from the Control and Estimation Tools Manager window. This opens the Load Projects dialog box.



- 2 Choose a project-file by either browsing for the directory and file, or typing the full path and filename in the **Load from** field. Project files are always MAT-files. After you specify the file, the projects contained in this file appear in the list. Select one or more projects in the list, and then click **OK**. When a file contains multiple projects, you can choose to load them all or just a few.

Exporting Results

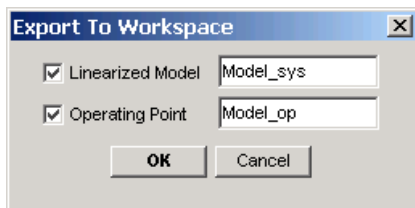
Using command-line functions, you can export operating points, compensator designs, and results of a linearization to the MATLAB workspace for further analysis. You can also export and restore linearization I/O settings.

This section includes the following topics:

- “Exporting Linearization Results” on page 6-4
- “Exporting Compensator Designs” on page 6-5
- “Exporting Operating Points” on page 6-6
- “Exporting and Restoring Linearization I/O Settings” on page 6-6

Exporting Linearization Results

To export linearization results and the corresponding operating points, right-click the results node, **Model**, under the **Linearization Task** node and select **Export** from the menu. In the Export To Workspace dialog box, choose new names for the linearized model and operating point, or accept the defaults, and then click **OK**.



The MATLAB workspace now contains two new objects, `Model_op` and `Model_sys`. To see this, type

```
who
```

at the MATLAB prompt. This returns

```
Your variables are:
```

```
L           Model_sys  beta           m
```

Model_op R g

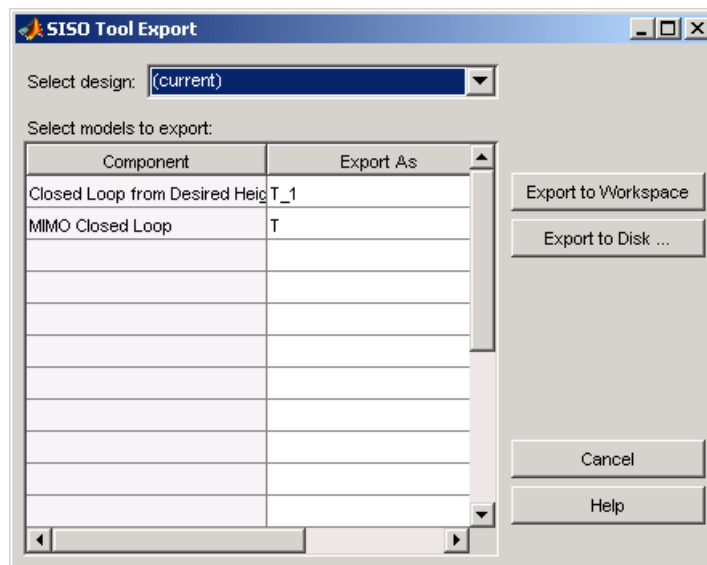
Alternatively, you can export the results to the MATLAB workspace by selecting **File > Export** from the LTI Viewer window or by clicking the **Export to Workspace** button at the bottom of the **Linearization Summary** pane within the **Model** node.

By right-clicking the results node, **Model**, you can also delete results.

Exporting Compensator Designs

To export a compensator design to the MATLAB workspace:

- 1 Select **File > Export** from the SISO Design Tool window.
- 2 In the SISO Tool Export dialog box, use the **Select design** list to choose the design you want to export.
- 3 In the list, select the compensators to export, and then click either **Export to Workspace** or **Export to Disk**.



Exporting Operating Points

After creating operating points using Simulink Control Design, you can use the Export To Workspace dialog box to export them for use outside of the Control and Estimation Tools Manager. You can use the exported operating point to perform analysis at the MATLAB command line or to initialize a model for simulation.

- 1 Under **Select destination workspace**, select either
 - **Base workspace** to export the operating point to the MATLAB workspace where you can use it with Simulink Control Design command-line functions
 - **Model workspace** to export the operating point to the Model workspace where you can save it with the model for future use.
- 2 Enter a name for the exported operating point.
- 3 Select **Use the operating point to initialize model** when you want to use the operating point values as initial conditions for the states and inputs in the model. The initial values are automatically set in the **Data Import/Export** pane of the Configuration Parameters dialog box. Simulink uses these initial conditions when simulating the model.

Exporting and Restoring Linearization I/O Settings

To export linearization I/O settings to the MATLAB workspace, use the `getlinio` function. You can save these settings using the `save` function. Use them in a later session by reloading them with the `load` function. Upload them to the model diagram with the `setlinio` function.

For more information, see the function reference pages for `getlinio` and `setlinio`.

Examples

Use this list to find examples in the documentation.

Linearization Example Using the Graphical Interface

“Example Model: The Magnetic Ball System” on page 2-2

A

analysis I/Os. *See* input and output points

C

compensator design

- analysis plots 5-16
- beginning a task 5-3
- closed-loop responses 5-7
- creating a SISO Design Task 5-13
- design methods 5-22
- design plots 5-14
- exporting 6-5
- open-loop systems 5-14
- operating points 5-10
- overview 5-2
- quick start guide 1-10
- retrieving designs 5-26
- storing designs 5-26
- tunable blocks 5-5
- writing to Simulink model 5-28

compensator design tasks

- opening 6-3
- saving 6-2

Control and Estimation Tools Manager

- compensator design task 5-3
- opening 2-7
- overview 2-8
- SISO Design Task 5-13

E

equilibrium operating points 3-2

- computing 3-9

equilibrium states

- computing 3-9

I

inport and outport blocks

difference from input and output points 4-6

input and output points

- inspecting with GUI 4-12
- purpose 4-5
- removing 4-8
- specifying 4-6

input points. *See* input and output points

L

linearization

- accurate 3-7
- beginning a new project 2-7
- benefits of command-line functions 1-5
- benefits of GUI 1-5
- custom plots 4-25
- displaying results 4-19
- factors affecting 1-3
- highlighting blocks 4-21
- inspecting 4-22
- operating points 3-6 to 3-7
- overview 4-3
- purpose of 1-3
- quick start guide 1-8
- removing results 4-19
- results 4-19
- role in compensator design 1-3
- using GUI 4-15
- validating results 4-21

linearization method

- for nonlinear models 4-2
- for Simulink models 4-3

linearization points

- adding 4-6
- deleting 4-8
- removing 4-8
- selecting 4-6

linearization results

- custom plots 4-25
- exporting 6-4

- in LTI viewer 4-17
- inspecting 4-22
- linearization tasks
 - opening 6-3
 - saving 6-2
- loop opening
 - purpose 4-9

M

- magnetic ball
 - equations 2-3
 - example 2-2
 - Simulink model 2-4

O

- open-loop analysis 4-9
- operating points
 - choosing 3-7
 - computing equilibrium 3-9
 - computing from specifications 3-9
 - creating 3-9
 - default operating point 3-9
 - definition 3-2
 - equilibrium 3-2
 - exporting 6-6
 - extracted from simulation times 3-17
 - impact 3-6
 - importance 3-6
 - saving and exporting 3-20

- Simulink model 3-2
 - specifying with completely known values 3-14
 - specifying with GUI 3-1
 - steady state 3-2
 - trimming 3-9
- output points. *See* input and output points

P

- project
 - linearization 2-7

R

- retrieving compensator designs 5-26

S

- Simulink Control Design 1-2
- Simulink model operating points 3-2
- SISO Design Task
 - creating 5-13
- steady state operating points 3-2
 - computing 3-9
- storing compensator designs 5-26

T

- trimming
 - operating points 3-9