Control System Toolbox 5

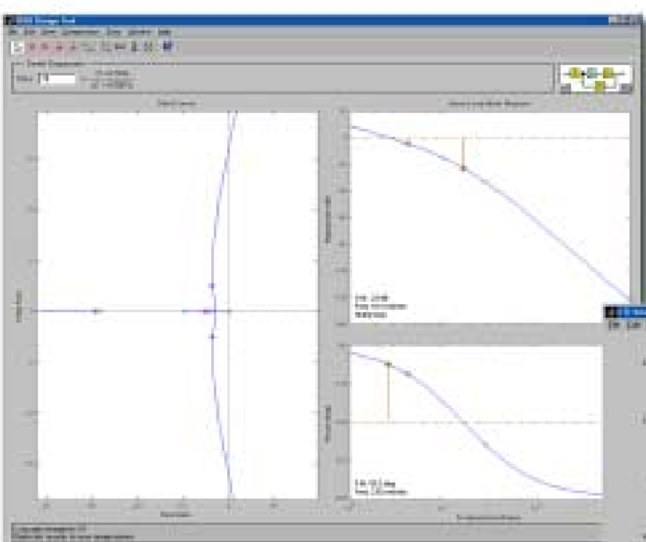
for designing and analyzing automatic control systems

The Control System Toolbox builds on the foundation of MATLAB® to provide specialized tools for control system engineering. The toolbox is a collection of algorithms, written primarily as M-files, that implement common control system design, analysis, and modeling techniques.

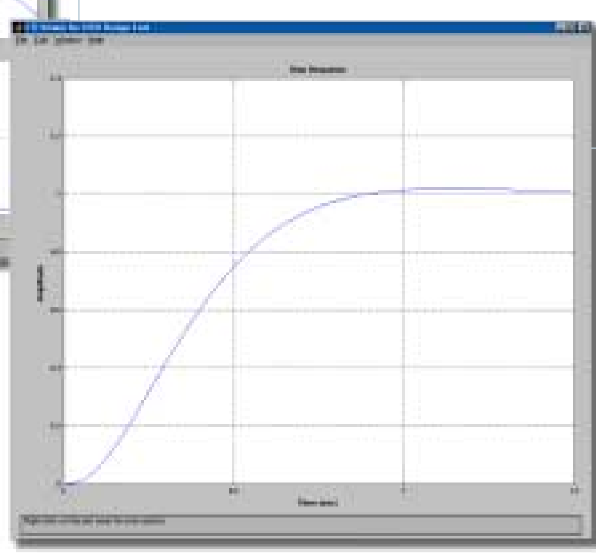
The Control System Toolbox is a core toolbox for the analysis, design, and tuning of feedback control systems. Its broad range of capabilities encompasses both classical and modern control design methods, including root locus, pole placement, and LQG regulator design. Convenient graphical user interfaces (GUIs) simplify typical control engineering tasks.

KEY FEATURES

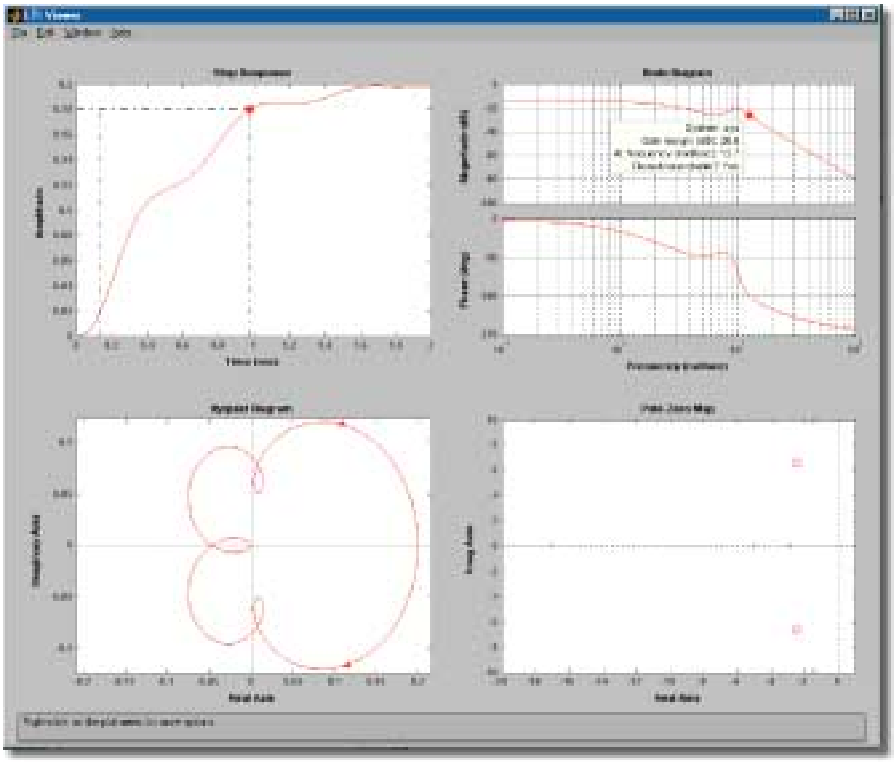
- LTI Viewer, an interactive GUI for analyzing and comparing linear-time-invariant (LTI) systems
- SISO Design Tool, an interactive GUI for analyzing and tuning single-input/single-output (SISO) feedback control systems
- GUI suite for setting preferences and properties, giving you complete control over the visualization of time and frequency plots
- Specialized data structures, called LTI objects, for concisely representing transfer function, state-space, zero/pole/gain, and frequency response data model formats
- Support for multi-input/multi-output (MIMO) systems, continuous-time and sampled-data systems, and systems with time delays
- Functions and operators for connecting LTI models with complex block diagrams (series, parallel, and feedback connections)
- Support for a variety of discrete-to-continuous conversion methods
- Functions for plotting the time and frequency responses of systems and comparing several systems with a single command
- Tools for classical and modern control design techniques, including root locus, loop shaping, pole placement, and LQR/LQG regulation



With the SISO Design GUI, you can tune gains and design compensators using root locus and loop shaping techniques. The compensator parameters can be changed graphically by interacting with the root locus and Bode diagrams. When you modify the compensator gain or dynamics, the open- and closed-loop response plots update automatically, providing useful guidance in the tuning process.



A linked LTI Viewer displays open- and closed-loop response plots.



With the LTI Viewer, you can easily graph the responses of one or several systems—all in one window. Step and impulse plots, pole/zero plots, and all frequency-domain responses (Bode, Nyquist, Nichols, and singular values) are available in the LTI Viewer. The LTI Viewer allows you to display important response characteristics, such as stability margins on the plots using data markers.

With the Control System Toolbox, you can model linear-time-invariant (LTI) systems in transfer function, zero/pole/gain, or state-space form. You can manipulate both continuous-time and discrete-time systems and convert between various model representations. You can compute and graph time responses, frequency responses, and root loci. Other functions let you perform pole placement, optimal control, and estimation. The Control System Toolbox is open and extensible, allowing you to create custom M-files to suit your particular application.

Building Models

The Control System Toolbox supports four linear model representations: state-space models (SS), transfer functions (TF), zero/pole/gain (ZPK) models, and frequency response data (FRD) models.

LTI objects are provided for each model type. In addition to model data, LTI objects can store the sample time of discrete-time systems, time delays, input and output names, notes about the model, and more. Using LTI objects, you can manipulate models as single entities and combine them using matrix-like operations.

In the following example, `sys1` and `sys2` are linear models being combined with a simple command-line operation:

```
>> sys1 + sys2
% parallel connection of
systems sys1 and sys2
```

You can also manipulate and analyze entire collections of linear models at the same time using LTI model arrays.

Model Characteristics

The Control System Toolbox contains commands to query model characteristics such as the I/O dimensions, poles, zeros, and DC gain. These commands apply to both continuous- and discrete-time models.

Interconnecting Linear Models

You can easily connect LTI models in parallel, series, or feedback mode. You can also use these basic interconnections in combination to derive models of complex block diagrams.

Analysis and Design

Some tasks lend themselves to graphical manipulation, while others benefit from the flexibility of the command line. The Control System Toolbox is designed to accommodate both approaches, providing both GUIs and a complete set of command-line functions for model analysis and design.

Analyzing Models Graphically Using the LTI Viewer

The Control System Toolbox LTI Viewer is a GUI that simplifies the analysis of linear, time-invariant systems. You use the LTI Viewer to view and compare the response plots of several linear models at the same time. You can generate time and frequency response plots to inspect key response parameters, such as rise time, maximum overshoot, and stability margins. Using mouse-driven interactions you can select input and output channels from MIMO systems.

The LTI Viewer can display up to seven different plot types simultaneously, including step, impulse, Bode (magnitude and phase or magnitude only), Nyquist, Nichols, sigma, and pole/zero.

Using right-click menu options, you can access several LTI Viewer controls and options, including:

- **Plot Type**—changes the plot type
- **Systems**—selects or deselects any of the models loaded in the LTI Viewer
- **Characteristics**—displays key response characteristics and parameters
- **Zoom**—zooms in and out of plot regions
- **Grid**—adds grids to your plots
- **Properties**—opens the Property Editor, where you can customize plot attributes

In addition to right-click menus, all response plots include data markers. These allow you to scan the plot data, identify key data, and determine the source system for a given plot.

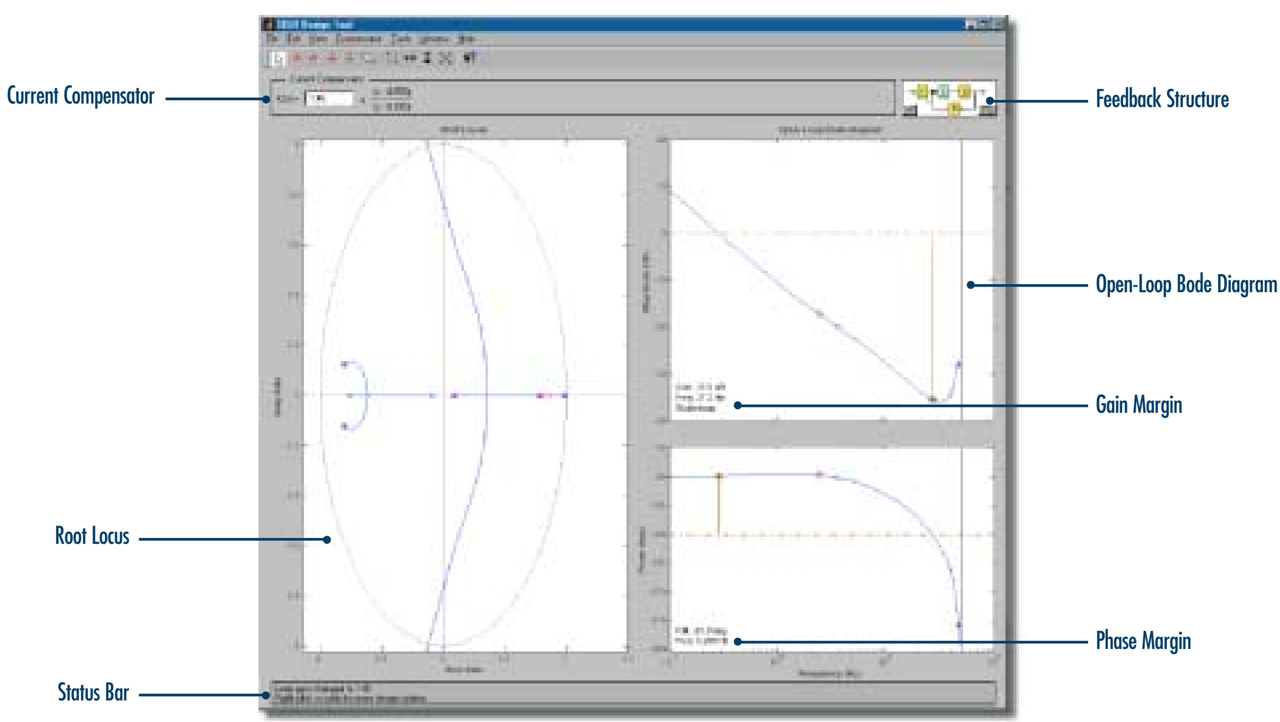
Analyzing Models Using the Command Line

The LTI Viewer is suitable for a wide range of applications where a GUI-driven environment is desirable. For situations that require programming, customized plots, or the inclusion of data unrelated to your LTI models, the Control System Toolbox provides command-line functions that implement the basic plots for time- and frequency-domain analysis used in control system engineering. These functions apply to any kind of linear model (continuous or discrete, SISO or MIMO,) or to arrays of models.

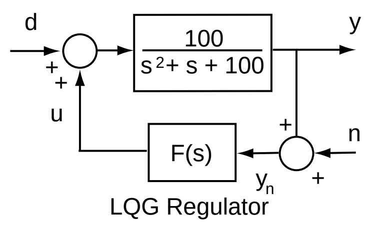
Designing Compensators Using SISO Design Tool

The Control System Toolbox SISO Design Tool is a GUI that lets you analyze and tune SISO feedback control systems. Using the SISO Design Tool, you can graphically tune the compensator gain and dynamics using a mix of root locus and loop shaping techniques. For example, you can use the root locus view to stabilize the feedback loop and enforce some minimum damping, and use the Bode diagrams to adjust the bandwidth, check the gain and phase margins, or add a notch filter for disturbance rejection.

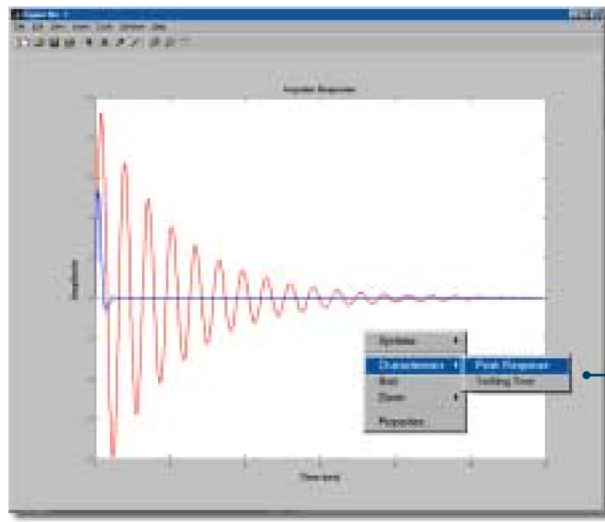
The SISO Design Tool is designed to work closely with the LTI Viewer, allowing you to rapidly iterate on your design and immediately see the results in the LTI Viewer. When you make a change in the compensator, the



The SISO Design GUI can be used for both continuous- and discrete-time plants. Here, the root locus and Bode diagrams are shown for a discrete-time plant.



This example illustrates the design of a simple LQG regulator. The code excerpt below shows how the controller is designed and how the closed-loop system is created. The impulse-response plot shows a comparison between the open-loop system (red) and the closed-loop system (blue).



Right-click menus simplify customizations of plots and GUIs

```
G = ss(tf(100,[1 1 100]))             % state-space plant model
Klqr = lqry(G,10,1)                   % design feedback gain matrix
Kest = kalman(G(:,[1 1]),1, 0.01)     % Kalman estimator design
F = lqgreg(Kest, Klqr)                % combine regulator and estimator
clsys = feedback(G,F,+1)              % form closed-loop system
impulse(G, 'r', clsys, 'b')           % generate and plot impulse response
```

LTI Viewer associated with your SISO Design Tool automatically updates the response plots that you have chosen.

The SISO Design Tool:

- Integrates most Control System Toolbox functionality into a single GUI
- Dynamically links time, frequency, and pole/zero views, offering complementary insights into the design objectives and issues
- Provides graphical insight into design tradeoffs
- Helps manage complexity and design iterations

Pull-down and right-click menus give you the flexibility to perform control design tasks with one mouse-click. In particular, you can:

- Drop compensator poles and zeros in the root locus or Bode diagram views
- Add lead/lag networks and notch filters
- Graphically tune compensator parameters with the mouse
- Inspect closed-loop responses (using the LTI Viewer)
- Adjust phase and gain margins
- Convert models between discrete- and continuous-time

Designing Compensators Using the Command Line

In addition to the SISO Design Tool, the Control System Toolbox provides a set of commands that you can use for a broader range of control applications, including:

- Functions for classical SISO design (damping data, root locus, and gain and phase margins)
- Functions for modern MIMO design (pole placement, LQR/LQG methods, and Kalman filtering)

[Linear-Quadratic-Gaussian (LQG) control is a modern state-space technique for designing optimal dynamic regulators. It enables you to trade off regulation performance and control effort and take into account process disturbances and measurement noise.]

Setting Plot Preferences and Properties

The Control System Toolbox provides three GUIs that give you complete control over the visualization of time and frequency plots generated by the toolbox:

- **Toolbox Preferences**—global options that you can save from session to session
- **Tool Preferences**—options set for a particular instance of the LTI Viewer or SISO Design Tool
- **Plot Properties**—options for customizing a given response plot

Documentation and Demonstrations

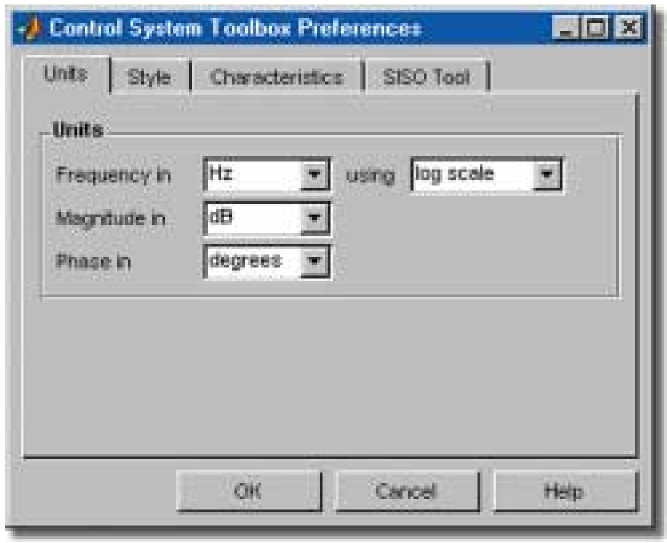
The Control System Toolbox provides extensive online documentation, including *Getting Started,* an introduction and tutorial for new users, and complete reference chapters for the toolbox GUIs and functions.

The Control System Toolbox also provides an extensive suite of demonstrations, including tutorial demos (Getting Started, Model Analysis, Do's and Don'ts); interactive demos (RLC circuit, stability margins, discretization); and detailed case studies of six applications (DC motor, feedback amplifier, disk drive, jet autopilot, steel mill, and process control).

Related Products

The MathWorks provides several products that are especially relevant to the tasks that you can perform with the Control System Toolbox. These include:

- **Simulink**®—a comprehensive environment for modeling, simulating, and analyzing dynamic systems in a block diagram format



The Control System Toolbox Preferences dialog box allows you to specify options that are saved from session to session. The LTI Viewer and SISO Design GUIs have preference dialog boxes for setting plot options within these GUIs. Finally, individual response plots have property editors for further customization.

- **Nonlinear Control Design Blockset**—an optimization-based approach to control system design that tunes parameters based on user-defined, time-domain performance constraints
- **System Identification Toolbox**—tools for building linear models of dynamic systems from measured input/output data
- **Fuzzy Logic Toolbox**—tools for developing fuzzy logic algorithms
- **Robust Control Toolbox**—tools for the modeling, analysis, and design of "robust" multivariable feedback control systems using H_∞ techniques
- **μ-Analysis and Synthesis Toolbox**—computational algorithms for the structured singular value, μ, applicable to robustness and performance analysis for systems with modeling and parameter uncertainties
- **Linear Matrix Inequality Toolbox**—convex optimization algorithms for solving linear matrix inequalities (LMI), with application to robust control, multi-objective control, and gain scheduling
- **Model Predictive Control Toolbox**—a complete set of tools for implementing model predictive control strategies ■

Sample Commands

General

`ctrlpref`	Set Control System Toolbox preferences

Creating Linear Models

`tf`	Create a transfer function model
`zpk`	Create a zero/pole/gain model
`ss, dss`	Create a state-space model
`frd`	Create a frequency response data model
`set`	Set/modify properties of LTI models

Data Extraction

`tfdata`	Extract numerator(s) and denominator(s)
`zpkdata`	Extract zero/pole/gain data
`ssdata`	Extract state-space matrices
`get`	Access values of LTI model properties

Conversions

`ss`	Conversion to state-space
`zpk`	Conversion to zero/pole/gain
`tf`	Conversion to transfer function
`frd`	Conversion to frequency data
`c2d`	Continuous-to-discrete conversion
`d2c`	Discrete-to-continuous conversion
`d2d`	Resample discrete-time model

System Interconnections

`append`	Group LTI systems by appending inputs and outputs
`parallel`	Generalized parallel connection
`series`	Generalized series connection
`feedback`	Feedback connection of two systems
`lft`	Generalized feedback inter-connection
`connect`	Derive state-space model from block diagram description

Model Dynamics

`pole`	System poles
`zero`	System (transmission) zeros
`pzmap`	Pole-zero map
`damp`	Natural frequency and damping of system poles
`dcgain`	DC (low frequency) gain
`norm`	Norms of LTI systems
`covar`	Covariance of response to white noise

Time-Domain Analysis

`ltiview`	Response analysis GUI (LTI Viewer)
`step`	Step response
`impulse`	Impulse response
`initial`	Response of state-space system with given initial state
`lsim`	Response to arbitrary inputs

Frequency-Domain Analysis

`ltiview`	Response analysis GUI (LTI Viewer)
`bode`	Bode diagrams of the frequency response
`sigma`	Singular value frequency plot
`nyquist`	Nyquist plot
`nichols`	Nichols plot
`margin`	Gain and phase margins
`allmargin`	All crossover frequencies and related gain/phase margins
`freqresp`	Frequency response over a frequency grid

Classical Design

`sisotool`	SISO design GUI (root locus and loop shaping techniques)
`rlocus`	Evans root locus

Pole Placement

`place`	MIMO pole placement
`estim`	Form estimator given estimator gain
`reg`	Form regulator given state-feedback and estimator gains

LQR/LQG Design

`lqr, dlqr`	Linear-quadratic (LQ) state-feedback regulator
`lqry`	LQ regulator with output weighting
`lqrd`	Discrete LQ regulator for continuous plant
`kalman`	Kalman estimator
`kalmd`	Discrete Kalman estimator for continuous plant

State-Space Models

`rss, drss`	Random stable state-space models
`ss2ss`	State coordinate transformation
`ctrb, obsv`	Controllability and observability matrices
`gram`	Controllability and observability gramians
`minreal`	Minimal realization and pole/zero cancellation
`ssbal`	Diagonal balancing of state-space realizations
`balreal`	Gramian-based input/output balancing
`modred`	Model state reduction

Time Delays

`totaldelay`	Total delay between each input/output pair
`delay2z`	Replace delays by poles at z=0 or FRD phase shift
`pade`	Pade approximation of time delays

Matrix Equation Solvers

`lyap`	Solve continuous Lyapunov equations
`dlyap`	Solve discrete Lyapunov equations
`care`	Solve continuous algebraic Riccati equations
`dare`	Solve discrete algebraic Riccati equations

For demos, application examples, tutorials, user stories, and pricing:

- Visit **www.mathworks.com**
- Contact The MathWorks directly

US & Canada	508-647-7000
Benelux	+31 (0)182 53 76 44
France	+33 (0)1 41 14 67 14
Germany	+49 (0)89 995901 0
Spain	+34 93 362 13 00
Switzerland	+41 (0)31 954 20 20
UK	+44 (0)1223 423 200

Visit **www.mathworks.com** to obtain contact information for authorized MathWorks representatives in countries throughout Asia Pacific, Latin America, the Middle East, Africa, and the rest of Europe.

The MathWorks Tel: 508.647.7000 info@mathworks.com www.mathworks.com

9318v02 10/00