1 Introduction

This document describes a custom HP Prime app, named 'Control systems'.

It is used to study the frequency and time domain responses of control systems consisting of a process and a controller. The app also calculates Root Locus Plots for unity feedback systems.

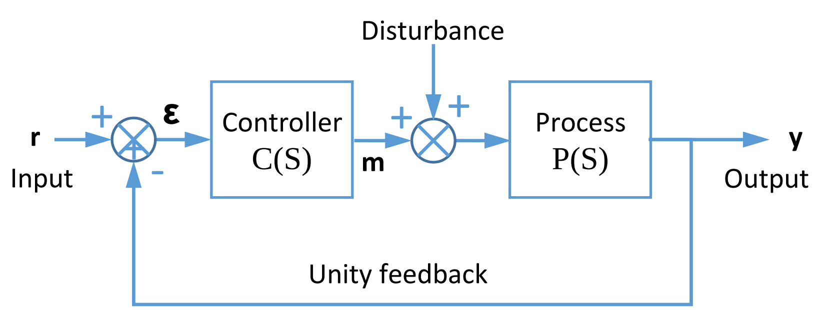
- In the frequency domain, open loop response with and without controller and resulting closed loop response (unity feedback loop) can be determined / compared.
- In the time domain, the app calculates the open loop and unity feedback loop response to reference changes as well as to disturbances (appearing between controller and process). It also calculates and visualizes the controller output. Input types: Dirac pulse, unit step and ramp.

Although the app type is 'Parametric', the app does not rely on the built in HP Prime parametric plot mechanism but on custom plotting routines, including custom mouse movement handling, key press detection and custom soft key menus to accomplish functionality that would not be possible otherwise. App parametric equations are only used in Numeric View. The app is entirely menu based (no need to type in commands).

Developer email: hataveme@gmail.com

2 Overview

The 'Control systems' app takes as input the transfer function of a process as well as the settings of a controller and produces several plots typically used to study relative and absolute stability etc. Results are available in numerical form as well.

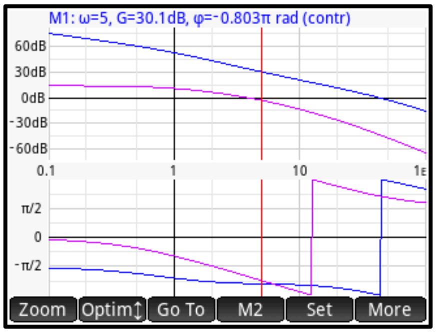


C(S) and P(S): transfer functions of controller and process, respectively

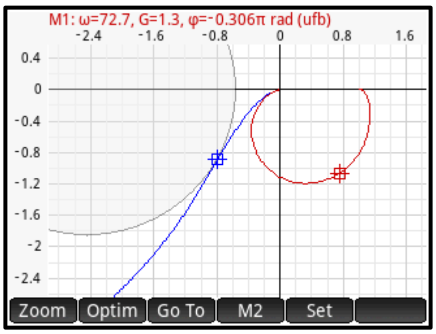
Plot types:

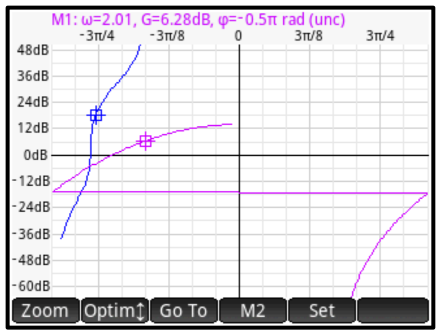
- Frequency domain: Nyquist, Nichols, Bode (magnitude + phase, magnitude only, phase only)
- Time domain: input, output, error signal, controller output
- Root Locus Plot

<u>Sample plots</u>



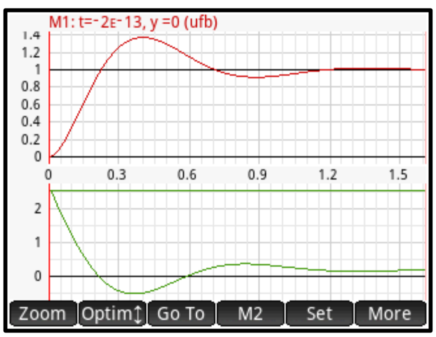
Bode plot



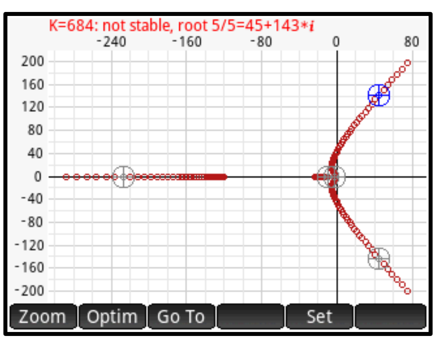


Nyquist and

Nichols plots



Time domain response plot

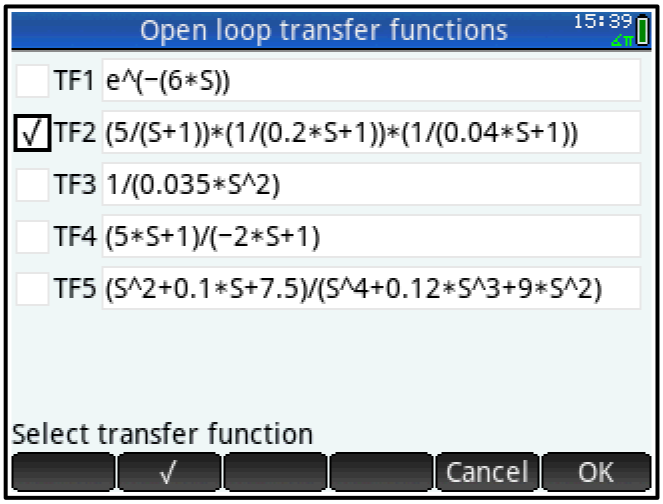


Root Locus plot

Note that the scales indicate <u>real</u> frequency (log scale) and magnitude (log or dB scale) units, instead of the logarithm of these values which would be the case if the standard HP Prime plot mechanism would be used.

3 Process transfer functions

When starting the app or pressing the Symb button, the HP Prime will <u>not</u> open the standard Symbolic View but will open the 'Process Transfer Function (open loop)' view.



You can enter a maximum of five Transfer functions (a transfer function is the Laplace transform of the time response of a process when a Dirac function is applied at its input at time = 0).

Select one process (radio buttons at the left) before pressing OK

⇒ Use S (capital S) as the symbol to denote the complex variable. Note that this will <u>not</u> refer to (real) HP Prime HOME variable S

⇒ A time delay is entered as a factor e^(-T*S) in the numerator, with T being a number representing the time delay

4 Angle measure

Press Shift Symb to open Symbolic Setup View and select the angle measure (standard HP Prime view).

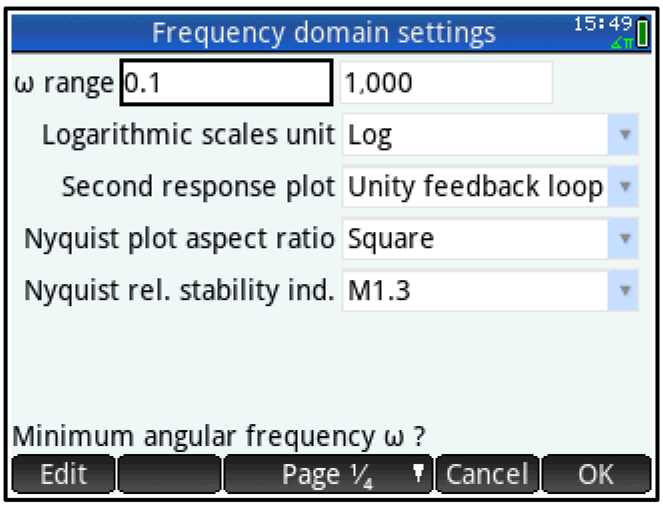
5 Plot Setup

Press Shift Plot to open the settings menu, which consists of 4 pages.

⇒ Note that the HP Prime will not open the standard Plot Setup View (which you won't need).

⇒ Alternatively, while a plot is displayed, you can directly access the relevant settings (frequency domain, time domain or root locus) by tapping the Set soft key.

5.1 Frequency domain settings (page 1)



Angular frequency range

Enter minimum and maximum frequency

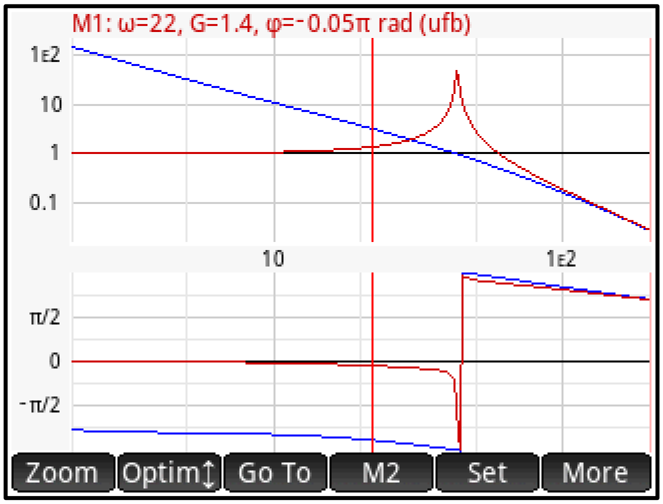
Logarithmic scales unit (for plot types with logarithmic magnitude scales)

- ***Log***: logarithmic scale
- ***dB***: decibel scale

Second response plot

- ***None***: single plot only, of the open loop frequency response (process with controller, if controller present). The plot is drawn in blue.
- ***W/h controller***: plots the open loop frequency response of the process ***without*** controller (only drawn if a controller present). The plot is drawn in purple.
- ***Unity feedback loop***: plots the closed loop frequency response (unity feedback loop). The plot is drawn in dark red.

This setting effects all frequency domain plot types. For instance, in the Bode plot, with "unity feedback loop" selected, this produces the following plot:



Function plotted in blue: open loop response

Function plotted in dark red: unity feedback loop response

Bode plot

Nyquist plot aspect ratio after optimizing

This setting will force a 'square' zoom (equal Real and Imaginary scales) each time the app optimizes the chart scales (Nyquist plot only).

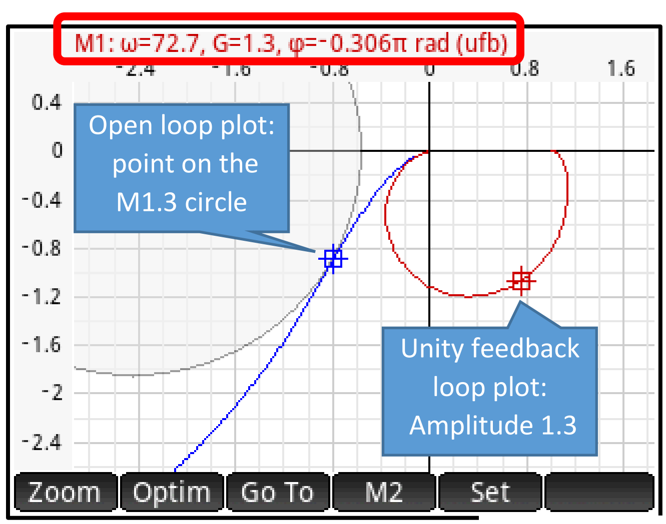
- ***Free***: no imposed aspect ratio
- ***Square***: real and imaginary axis use same scale

Note that chart scales are sometimes optimized automatically (e.g. always after you changed plot setup). You can also manually optimize chart scales.

Nyquist plot: show M1.3 and 'Deviation Ratio 1' circles

- ***None***: do not show any additional information
- ***M1.3***: show M1.3 circle (all points on the open loop plot resulting in a unity feedback loop amplitude ratio of 1.3)
- ***M1.3, DR1***: show M1.3 circle and 'Deviation Ratio 1' circle

A note on the 'Deviation Ratio 1' circle: when a disturbance signal is applied to the process, it depends on the angular frequency of that disturbance whether controlling the process (closed loop) will reduce the effect of that disturbance on the process output (compared with the uncontrolled, open loop process).

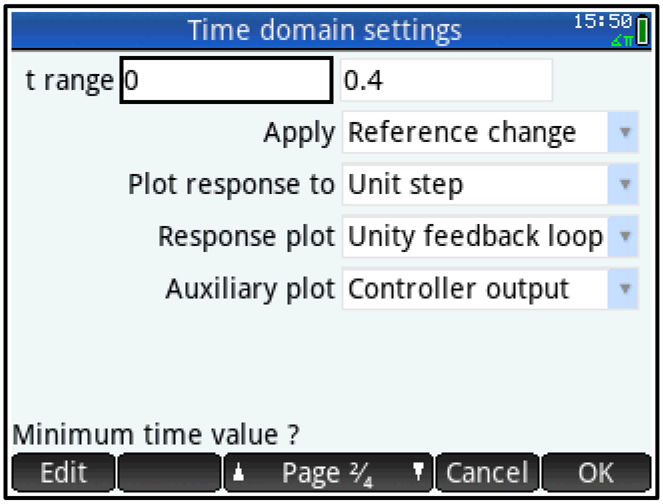


Nyquist plot

All points of the open loop plot:

- ➢ On the DR1 circle: controlling the process (closed loop) has no effect
- ➢ within the DR1 circle: controlling the process (closed loop) is harmful
- ➢ outside the DR1 circle: controlling the process (closed loop) is useful

5.2 Time domain settings (page 2)



Time range

Enter minimum and maximum time

Apply reference change or disturbance as input

- ***Reference change***: apply a reference change
- ***Disturbance***: apply a disturbance between controller output and process input

Note that the input will be plotted in <u>black</u> if it is a reference change, and in <u>dark yellow</u> if it is a disturbance.

Input signal: response to

- Dirac pulse
- Unit step
- Unit ramp

Response plot

Plots the process output for

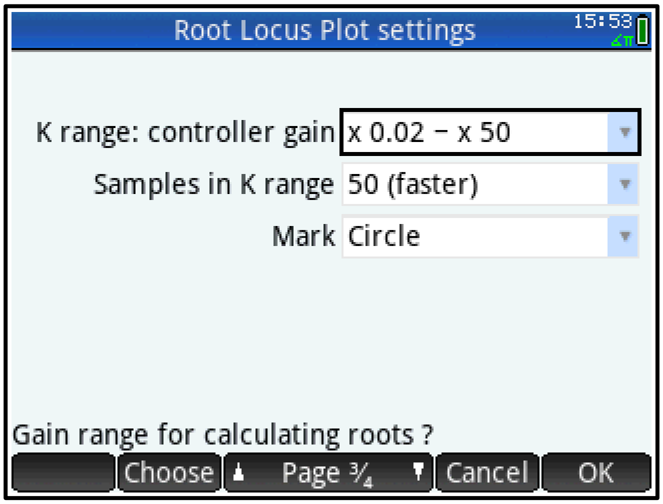
- Open loop
- Unity feedback loop

Note that process output is always plotted in <u>red</u> (for open loop as well as unity feedback loop response).

Auxiliary plot

- Error signal: show the error signal (controller input) on the optional second chart. This plot is drawn in <u>gray</u>
- Controller output: show controller output on the optional second chart. This plot is drawn in <u>green</u>

5.3 Root locus plot settings (page 3)



Gain range

Root locus plots take the controller open loop gain as a 'center point' (if no controller is present, then this center point gain will be 'one'). With the gain range setting, you define how wide the app needs to set the gain range for calculating roots. Options:

- Controller gain x 0.5 to 2
- Controller gain x 0.2 to 5
- Controller gain x 0.1 to 10
- Controller gain x 0.05 to 20
- Controller gain x 0.02 to 50
- Controller gain x 0.01 to 1 (gain < controller gain only)
- Controller gain x 1 to 100 (gain > controller gain only)

Note that gain is not increased linearly (adding a fixed step) but by applying a calculated factor, based on gain range and sample size (see next).

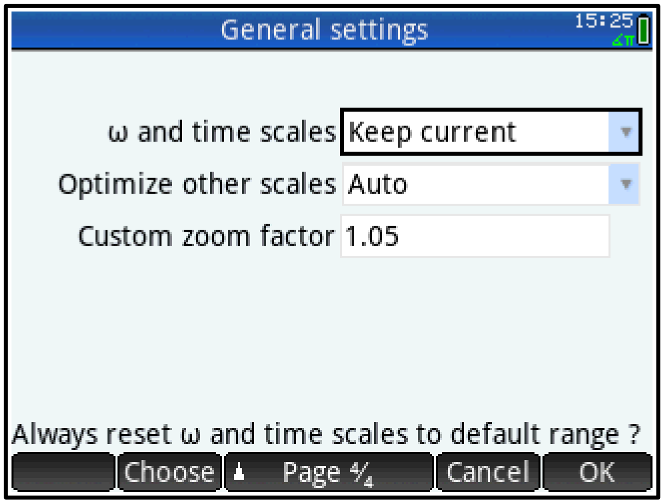
Sample size

Choose between 50, 100, 200, 500 or 1000 samples. The more samples, the slower the calculation.

Mark

- Dot
- Crosshair
- Circle

5.4 General settings (page 4)



Set ω and time scales

- ***Keep current***: do not change the angular frequency or time scales when re-plotting
- ***Default ω or t range***: reset the corresponding (ω or time) scale, the first time a plot is performed after
  - button Plot is pressed to start a new plot
  - button Symb is pressed to edit transfer functions or button Symb Setup is pressed
  - controller type is changed or controller settings are changed (View menu)
  - plot type is changed (View menu)

Note that this setting affects the Bode and time domain response plots only. It has no impact on Nyquist or Nichols plots because these plots (which do not have frequency or time scales) always use the ω or time ranges defined in plot setup to create a plot.

The first time a plot is performed after a Plot Setup (this menu), ω or time scales for that plot will **always** be reset to their defaults (irrespective of this setting).

Optimize other scales

- ***Manual***: scales are not optimized automatically when re-plotting
- ***Auto***: optimize other (non- ω or time) scales, the first time a plot is performed after
  - same actions as described under previous paragraph (‘Set ω and time scales’)
  - zooming, dragging, layout change (Bode and time domain response plots only)

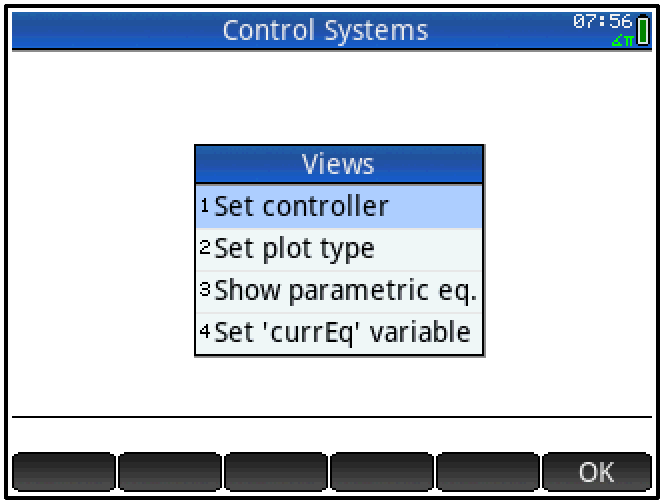
For Bode and time domain response plots, each time the ω or time range is reset to the default range, other scales are automatically optimized again as well.

Custom zoom factor

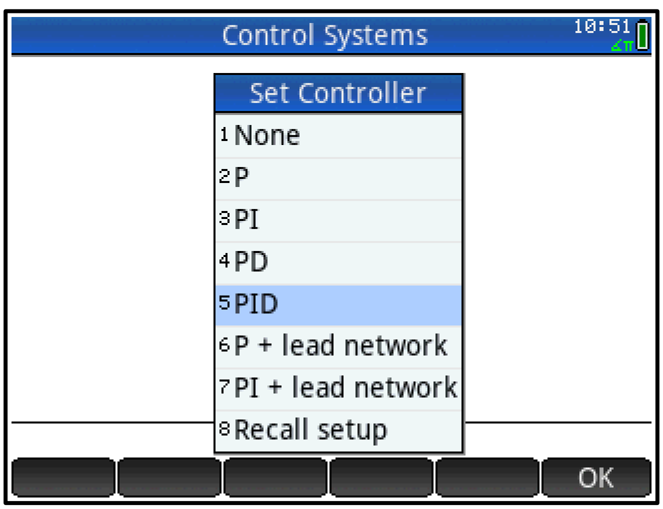
Enter a zoom factor between 1.05 and 10. This zoom factor will be applied when zooming in or out using the + or - buttons (only).

6 Selecting and setting up a controller

Press View. A custom Views Menu will open.



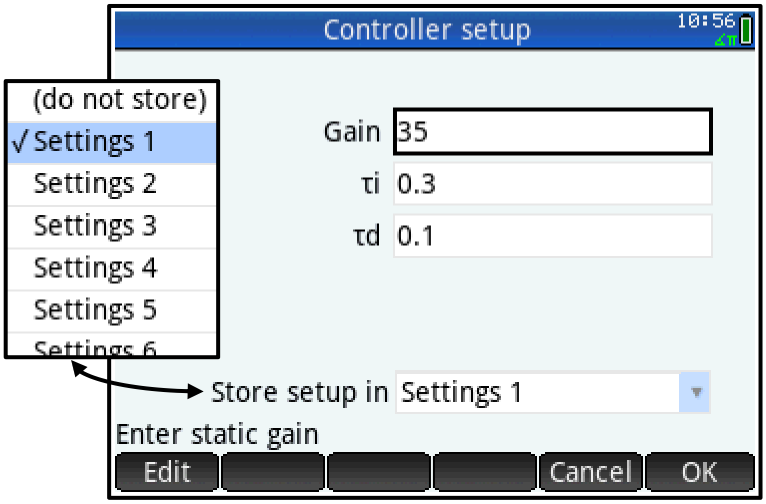
Select option 1 (Set controller) and either select a controller type or recall a previously stored controller setup.



6.1 Selecting a controller type

You can either decide not to use a controller at all (option 1), or to use a controller with proportional (P), integrating (I) or derivative (D) terms applied to the error signal (or a combination of these terms – options 2 to 5). The derivative term can be replaced by a lead network as well (see further), which will attenuate the controller's response for very high frequencies (options 6 and 7).

Example: select 'PID controller' in the 'Set controller' list. The controller setup screen will be displayed:



The currently active settings for static gain and integrator and differentiator time constants are displayed and can be changed.

You have the option to store this setup for later use (up to 9 setups can be saved) or you can select 'do not store' from the dropdown.

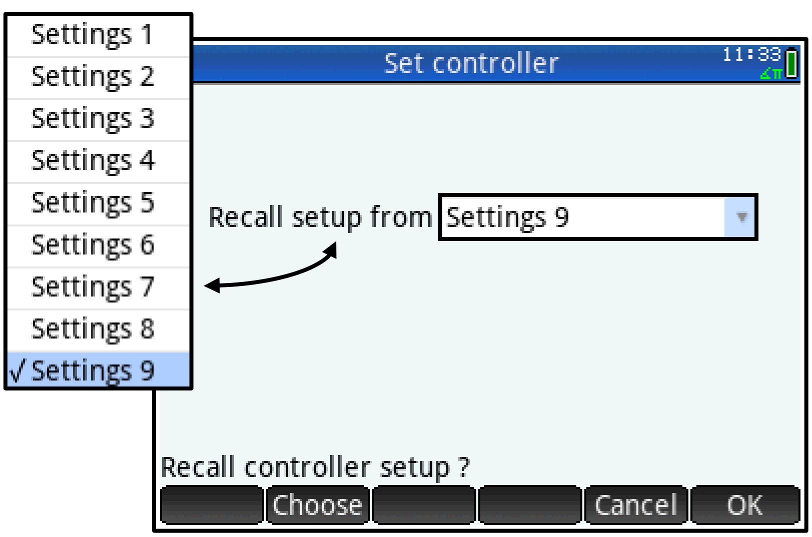
You can now change the static gain (proportional term) and the integrator and differentiator time constants.

The corresponding controller Transfer Function (which the app will construct) will then be:

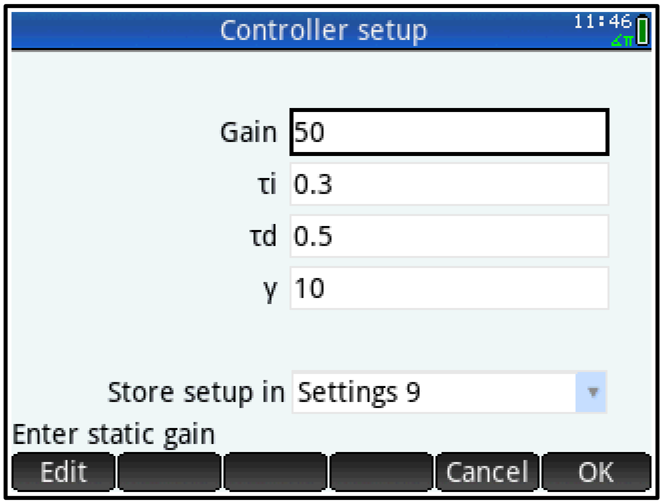
$$C(S) = GAIN * (1 + 1 / \tau_i S) * (1 + \tau_d S)$$

6.2 Recalling a previously stored controller setup

In the Views menu, select option 1 (Set controller) and then select option 8 (Recall setup) in the 'Set controller' list.



Example: recall the controller setup previously stored in settings 9. The controller setup screen will be displayed:



According to this example, a 'PI+lead network' controller setup was stored in settings 9. This is essentially a PID controller with a correction (based on the value for γ) applied to the higher frequency range.

You can now change the static gain (proportional term), the integrator and differentiator time constants and the lead compensation factor γ.

The corresponding controller Transfer Function (which the app will construct) will be:

$$C(S) = GAIN * (1 + 1 / \tau_i S) * (1 + \tau_d S) / (1 + (\tau_d / \gamma) S)$$

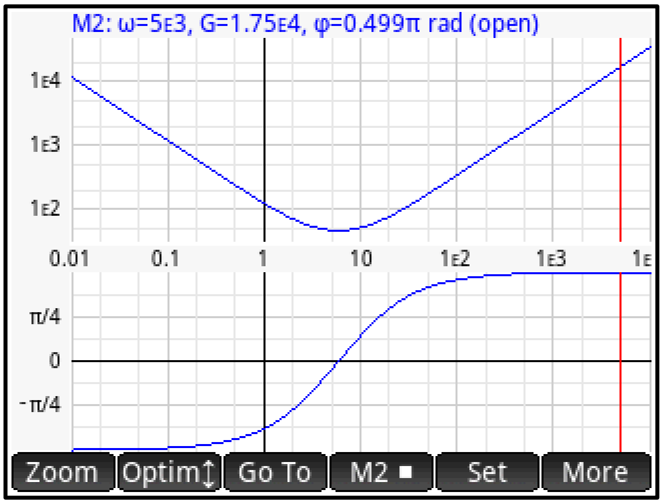
For γ = 1, this controller will behave like a PI-type controller. If γ is infinity, then the controller will behave like a PID controller. Typically, γ ranges from 2 to 20.

For a given γ, the amplitude in the high frequency range will slowly approach γ times the static gain (GAIN * γ), and this for frequencies higher then γ / τd, instead of going to infinity as would be the case for a pure PID controller. The phase angle will approach zero for very high frequencies, instead of +90° (pure PID controller).

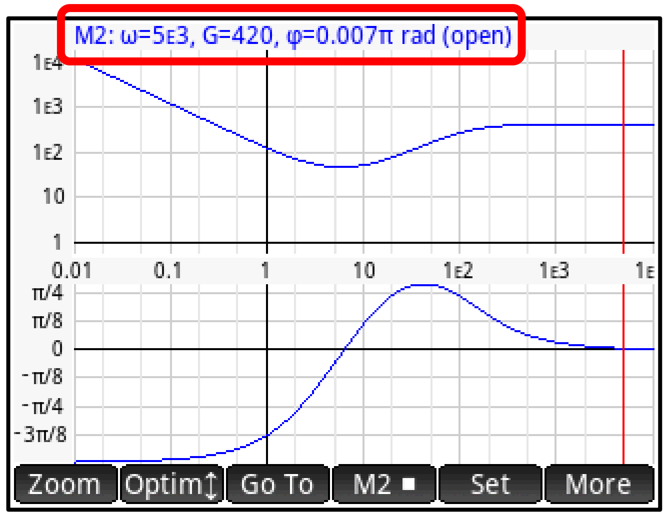
- The lower γ, the lower the maximum phase lead. This maximum phase lead will also be obtained for a lower frequency.

The Bode diagrams below show amplitude and phase characteristics for two controllers with same values for gain, integrator and differentiator constants (resp. 35, 0.3 and 0.1). The left Bode diagram represents a pure PID controller, whereas the right plot represents a PI controller with lead compensation (γ = 12).

The right Bode diagram clearly shows that for ω = 5000 rad/s (marker 2), the indicated gain is 420, which is 35 * 12 = gain * γ and the phase angle is almost 0°. The maximum phase lead (0.293 π rad) is reached for ω = 39 rad/s.



PID controller



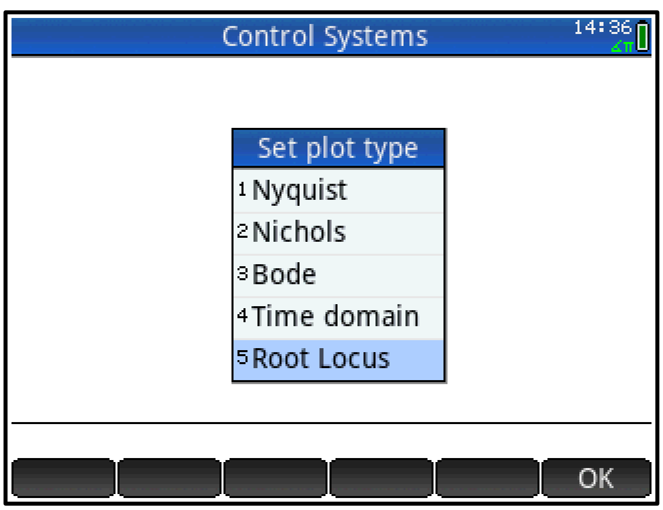
PI controller with lead compensation

Note: in order to obtain these plots, set the process transfer function to ‘1 * 1’.

7 Selecting a plot type

Press View to open the custom Views Menu and select option 2 (Set plot type).

Then, choose the desired plot type from the menu.



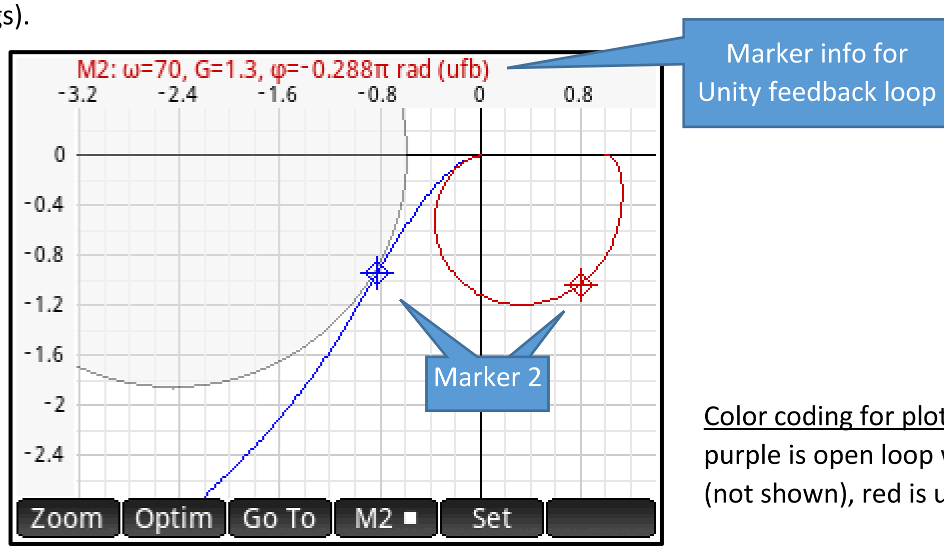
Note: associated functionality (zooming etc.) will be discussed globally in a next section.

8 Frequency and time domain plots

8.1 Plot types

Nyquist plot

This is a polar plot, with linear scales, of the transfer function C(jω) * P(jω). In the sample screenshot below, the plot for the transfer function of the unity feedback loop is also shown, as is the M1.3 circle (see section about settings).

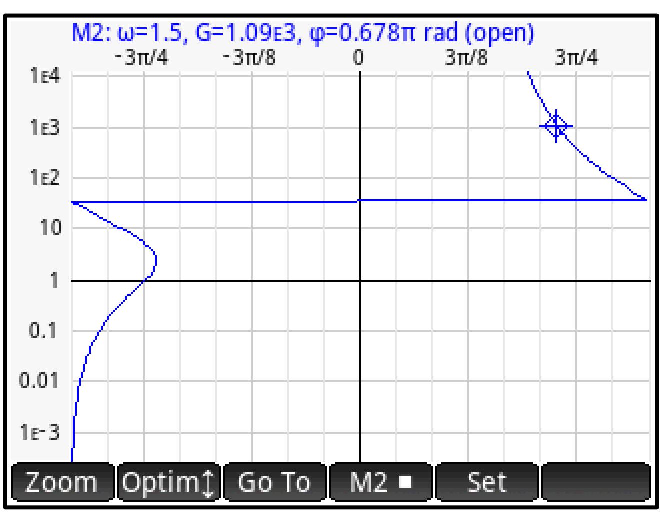


<u>Color coding for plots:</u> blue is open loop, purple is open loop with inactive controller (not shown), red is unity feedback loop

Nichols plot

This is a magnitude / phase angle plot of the transfer function C(jω) * P(jω). The magnitude (vertical scale) is logarithmic.

In the sample screenshot below, no secondary response plot is selected (see section about settings).

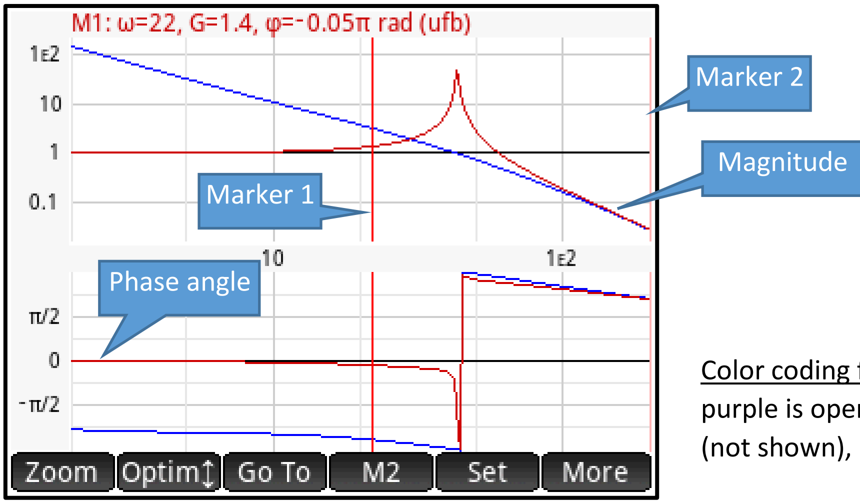


<u>Color coding for plots:</u> blue is open loop, purple is open loop with inactive controller (not shown), red is unity feedback loop (not shown)

Bode plot

This is a frequency domain response plot for a given transfer function.

Magnitude (logarithmic or dB scale) and phase angle are plotted on separate charts.

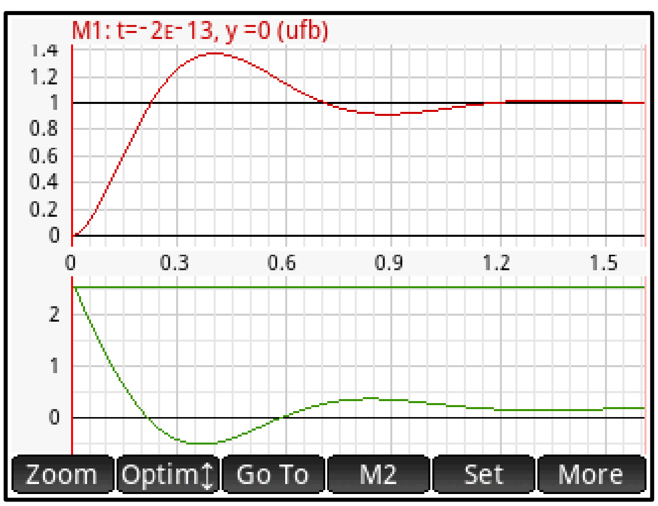


Color coding for plots: blue is open loop, purple is open loop with inactive controller (not shown), red is unity feedback loop

Time domain response plot

As mentioned before, you can choose between reference input change and disturbance, and the change can be a Dirac pulse, a unit step or a unit ramp.

In the examples below, the unity feedback response plot is shown, together with (lower chart) the controller output (you can also visualize the error signal).



Responses to a reference change

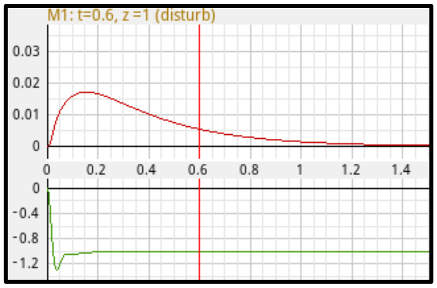
Color coding for plots

Upper chart:

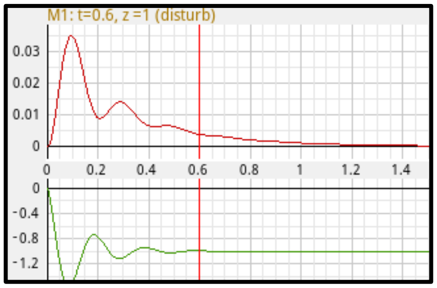
- Black: reference change as input
- Dark yellow: disturbance as input (not shown)
- Red: output

Lower chart

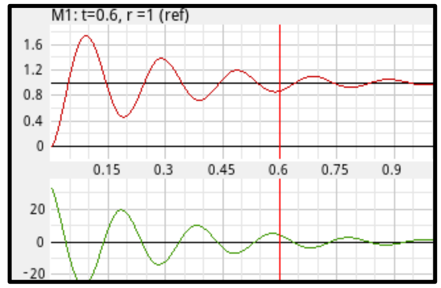
- Gray: error signal (not shown)
- Green: controller output



Responses to a disturbance



Responses to a disturbance: underdamped



Responses to a reference change: underdamped

Note: time domain response plots are based on the calculation of an Inverse Laplace Transform. Standard HP Prime function 'invlaplace' is used for that, but it is not always capable to perform the calculation. If it fails, you will receive an error message.

8.2 Markers

All frequency and time domain plots have two markers, labeled marker 1 (M1) and marker 2 (M2). Markers are associated with a set angular frequency (ω) or, for time domain response plots, with a set time.

- Bode plots and time domain response plots display these markers as two vertical lines. The active marker (if within the visible frequency range) is shown in a bright red color. The inactive marker is shown in a very light red color. Marker 1 is always positioned to the left of marker 2.
- Nyquist and Nichols plots display the markers as a cross hair with a square around it. For marker 2, this square is tilted 45 degrees. In order not to overload the screen, only the active marker (M1 or M2) will be visible (if two plots are currently shown, then each plot will have its active marker).

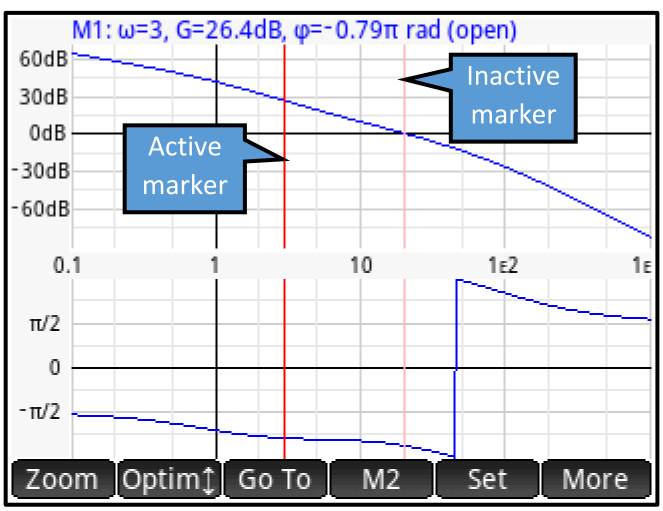
  If the status line (see further) currently displays the <u>change</u> in magnitude and phase between the two marker positions for a plot, then the two markers (M1 and M2) for that plot are shown instead.

The status line on top of the chart displays more info about the active marker / about the markers.

Selecting the active marker

Tap the **M2** button to alternate between marker 1 and 2. If marker 2 is active, a square dot will be shown to the right of the soft key 'M2' label.

For Bode plots and time domain response plots (only), you can also activate a marker by tapping on a marker and holding for a second. The marker position will not move.

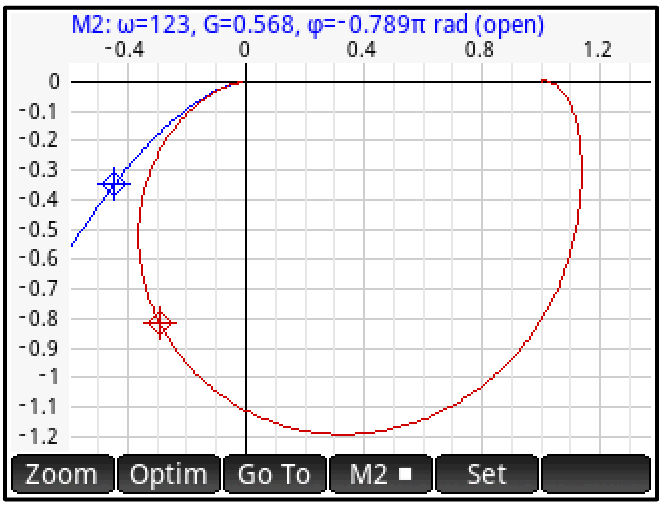


Bode plot with marker 1 active

Moving the markers

To move a marker, you can

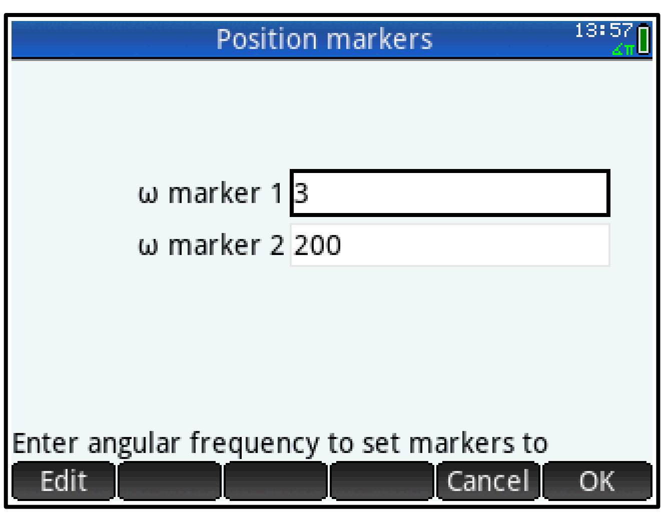
- Tap the screen. This will move the active marker. If this would move the active marker beyond the other marker (M1 is always positioned left of M2), the other marker will become active and will be moved instead
- Press the left ◀ or right ▶ arrow keys to decrease or increase the set angular frequency (or time) for the active marker, moving that marker
- Press and hold the left ◀ or right ▶ arrow keys: after half a second, the active marker position will start moving left or right at a constant speed. This speed will increase with a factor ten after another 1.5 seconds
- Press Shift and then press the left ◀ or right ▶ arrow keys to move the active marker to the left or right border of the chart (Bode plots and time domain response plots) or to the outer ends of the plot (Nyquist and Nichols plots)



Nyquist plot. Marker 2 is active and is shown for the two plots currently displayed

- Tap the Go To soft key and enter an angular frequency or time (time domain response plots) to set markers.

  Tap OK



Note that, as M1 is always positioned left of M2, a marker will never be able to move beyond the position of the other marker.

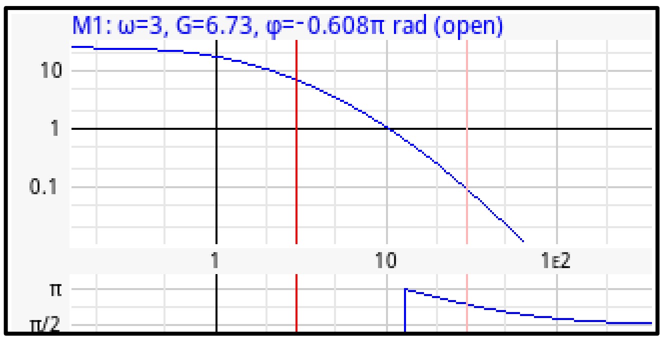
8.3 The status line

On top of the screen, a status line displays more information about the (active) marker(s).

Information that can be viewed:

Frequency domain response plots:

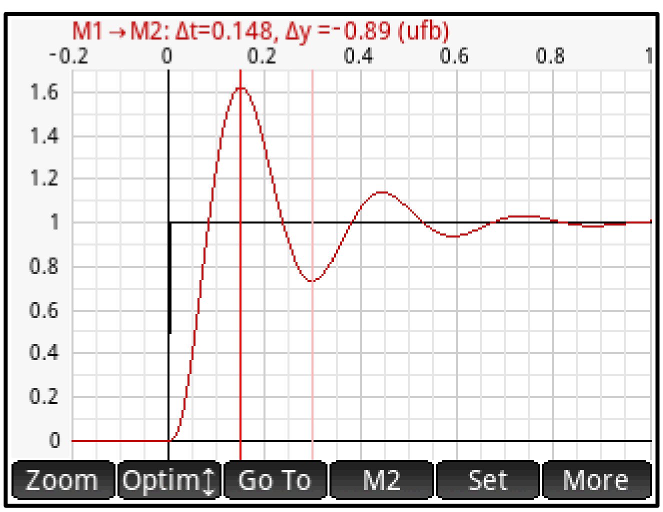
- Magnitude and phase angle for a single plot (e.g. open loop plot), for the angular frequency at the active marker position
- Magnitude change (ratio) and phase angle change (difference) between the two plots currently shown (if applicable), for the angular frequency at the active marker position
- Magnitude change (ratio) and phase angle change (difference) for a plot, between the angular frequencies at marker 1 and marker 2



Marker 1: positioned at ω = 3; magnitude (G) and phase angle (φ) for open loop response (blue) displayed in selected units (dB and Radians, respectively)

Time domain response plot:

- Magnitude of the input (reference change or disturbance) at a point in time indicated by the active marker position
- Magnitude of the output at a point in time indicated by the active marker position
- Magnitude of the controller output / error signal (depending on Plot Setup) at a point in time indicated by the active marker position
- Magnitude change (difference) between two points in time as indicated by the two markers

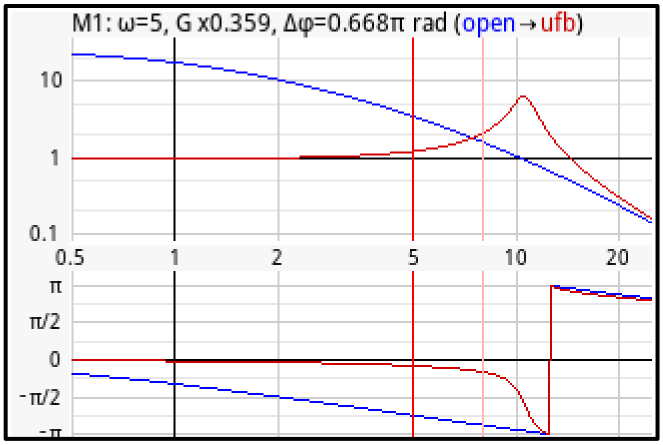


Markers positioned at first and second output top (red) : time difference is 0.148 seconds, change in magnitude = -89

Cycling through the information

To show information about the active marker: press the up arrow ▲ key repeatedly.

- Frequency domain response plots: this first shows magnitude and phase for plot 1, and then, if currently two plots are displayed, for plot 2 (each time in the color of the plot). Finally, magnitude change (ratio) and phase angle change (difference) is displayed going from plot 1 to plot 2 (in black)



Marker 1: positioned at ω = 5; magnitude change (G x refers to a ratio, log scale) and phase angle change (Δφ) from open loop response to unity feedback loop response is displayed in selected units (log scale and Radians, respectively)

- Time domain response plots: this cycles through input magnitude, then output magnitude, and then error signal magnitude or controller output magnitude (depending on Plot Setup)

To show the change in magnitude (and, frequency domain plots only: phase angle) between the two marker positions M1 and M2: press the down arrow ▼ key repeatedly.

- Frequency domain response plots): this first shows magnitude change (ratio) and phase angle change (difference) for plot 1, and then, if currently two plots are displayed, for plot 2
- Time domain response plots: this alternatively shows magnitude change for input and output plot (always as a difference, not a ratio)

8.4 Zooming

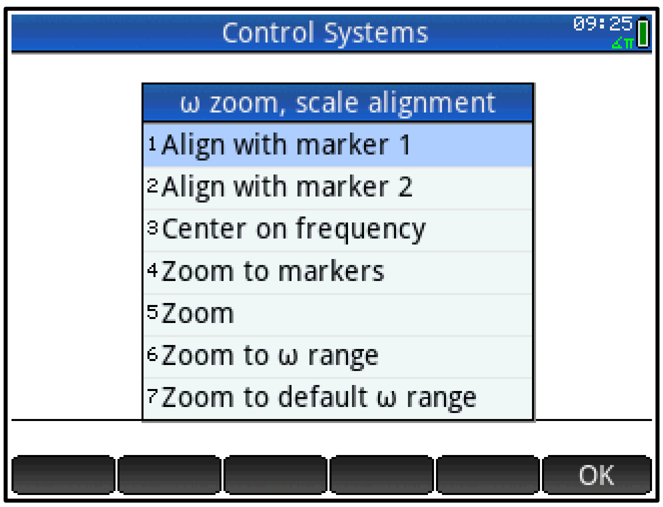
Bode plots and time domain plots

Zooming is performed by either

- Performing a two-finger pinch zoom gesture (the zoom is animated by shrinking / stretching the graphic object representing the plot)
- Pressing the + or – key. This will zoom in or out using a custom zoom factor as entered in plot Setup.
- Tapping the Zoom soft key

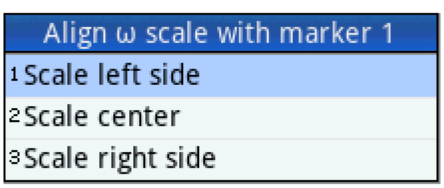
Zooming is always performed horizontally (Bode plot: ω zoom, time domain: time zoom).

We will use the Bode plot to describe the zoom menu options, but the time domain response plot zoom works in the same way. When tapping the Zoom soft key, the zoom menu opens:



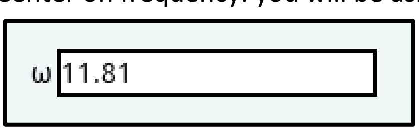
Zooming options available:

- Align the plot with marker 1 or marker 2, but do not change the scale

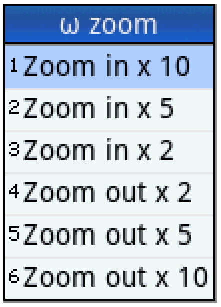


You will be presented three options: align the left side of the scale, the right side or the center of the plot with the current position (angular frequency ω) of the selected marker

- Center on frequency: you will be asked to enter an angular frequency (ω) to center the plot



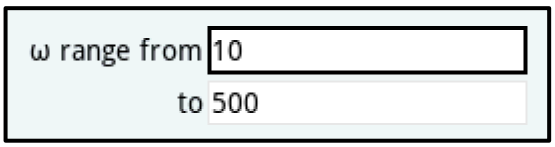
- Zoom to markers: rescale such that the current position of markers 1 and 2 (angular frequency ω) will coincide with the left and right border of the plot, respectively
- Zoom:



Select the desired zoom factor from the submenu.

You can either zoom in or zoom out by a factor of 2, 5 or 10

- Zoom to ω range: enter an angular frequency range to zoom to

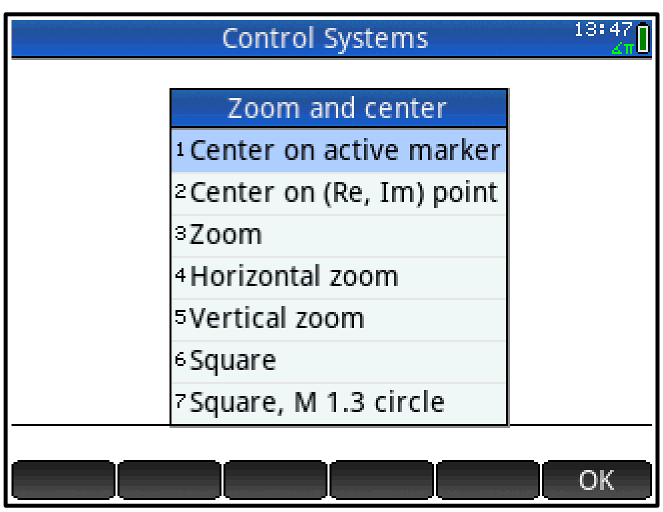


- Zoom to default ω range: plot according to the ω range defined in Plot Setup

Nyquist plots

Zooming is performed by either

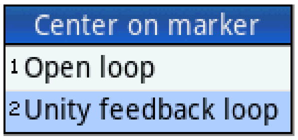
- Performing a two-finger pinch zoom gesture (the zoom is animated by shrinking / stretching the graphic object representing the plot). If the zoom gesture is performed diagonally, the same zoom factor is used in the two dimensions. You can also zoom horizontally or vertically by performing a horizontal or vertical zoom gesture.
- Pressing the + or – key. This will zoom in or out using a custom zoom factor as entered in plot Setup.
- Tapping the Zoom soft key. This opens the zoom menu for Nyquist plots:



Zooming options available:

- Center on active marker

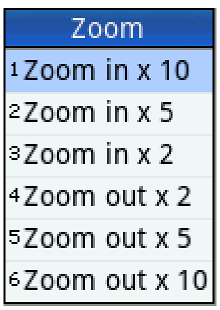
  If two plots are currently displayed, this will center on the active marker for the plot selected in the status line.



Only when the app cannot decide (when the status line is currently displaying magnitude and phase angle difference between the two plots), you will be asked to choose a plot

- Center on (Re, Im) point: enter the coordinates of a point on the complex plane

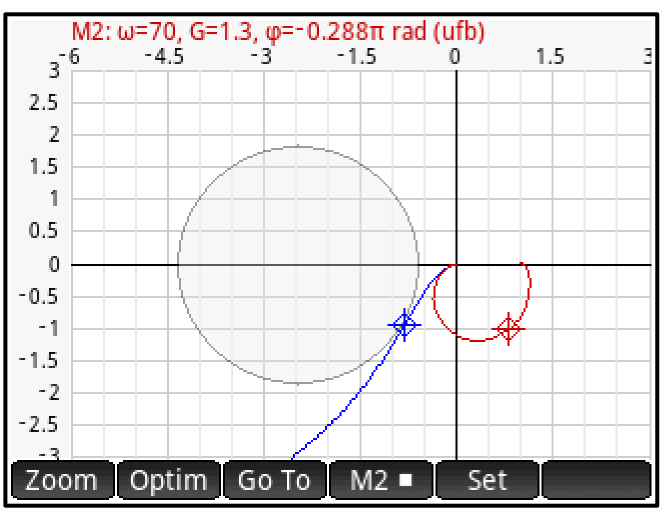
- Zoom, horizontal zoom, vertical zoom:



Select the desired zoom factor from the submenu.

You can either zoom in or zoom out by a factor of 2, 5 or 10

- Square: makes the horizontal and vertical scales equal
- Square, M1.3 circle: makes the horizontal and vertical scales equal and centers the plot around the M1.3 circle



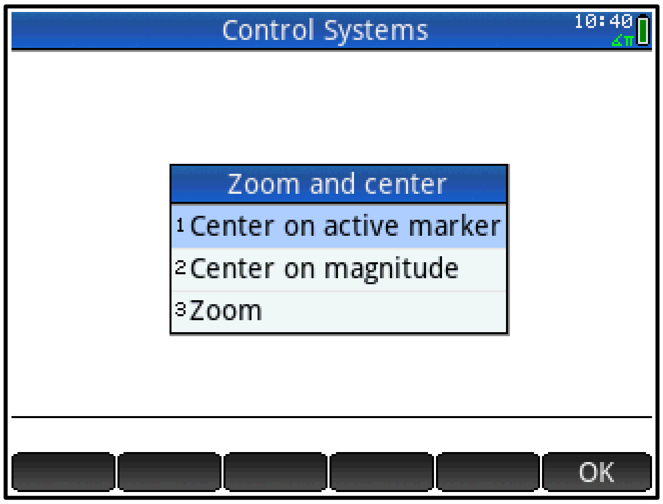
Nyquist plot, centered around the M1.3 circle. Marker 2 is active and shown for the two plots (open loop and unity feedback loop)

Nichols plots

Zooming is always performed vertically (the horizontal scale is fixed and runs from -π to π radians, in the selected angle unit).

Zooming is performed by either

- Performing a two-finger pinch zoom gesture (the zoom is animated by shrinking / stretching the graphic object representing the plot)
- Pressing the + or – key. This will zoom in or out using a custom zoom factor as entered in plot Setup.
- Tapping the Zoom soft key. This opens the zoom menu for Nichols plots:

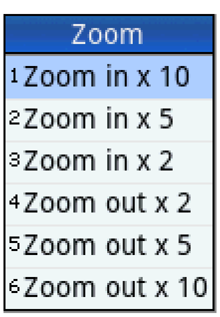


Zooming options available:

- Center on active marker (as with Nyquist plots, if two plots are currently displayed, this will center on the active marker for the plot selected in the status line)

- Center on magnitude: enter a magnitude to center the plot vertically

- Zoom (this will perform a vertical zoom only)



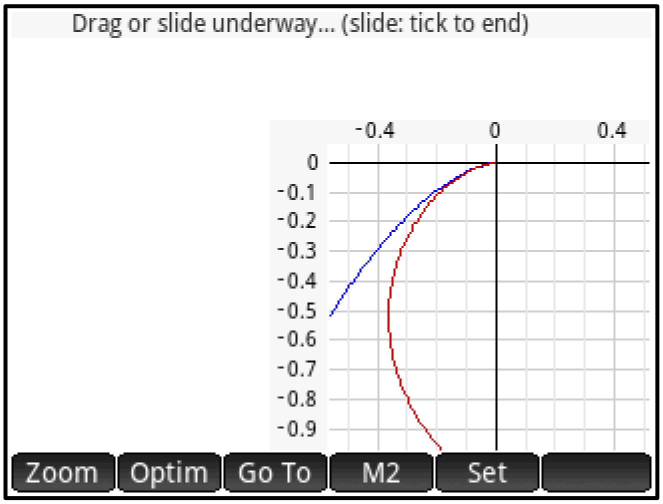
Select the desired zoom factor from the submenu.

You can either zoom in or zoom out by a factor of 2, 5 or 10

8.5 Scrolling

Place a finger on the screen and either

- drag the plot in the desired direction
- slide your finger. End the slide and re-plot by tapping the screen



Animation during dragging or sliding

Bode plot and time domain response plot: animated scrolling is always performed horizontally (Bode plot: ω zoom, time domain plot: time scroll).

Nichols plot: scrolling is performed vertically, as the horizontal scale is fixed and runs from -π to π radians, in the selected angle unit.

8.6 Optimizing

Optimizing adjusts the chart scales in such a way that the plot(s) fit(s) best on the charts.

- Bode plots and time domain response plot: this optimizes the vertical scale, based on the ω or time scale range displayed horizontally
- Nyquist plots: this optimizes the horizontal and vertical scales, based on the ω range selected for plotting
- Nichols plots: this optimizes the vertical scale, based on the ω range selected for plotting (the horizontal scale is fixed and runs from -π to π radians, in the selected angle unit).

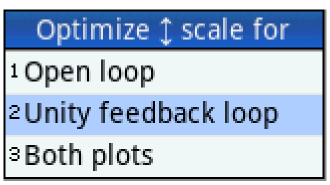
Optimizing is either performed automatically (if enabled in Plot Settings – general settings) or manually.

To optimize the plots manually: tap the **Optim↕** softkey (or, for Nyquist plots, the **Optim** softkey).

If manually optimizing and currently two plots are shown, a popup will ask you to select the plot(s) to optimize for.

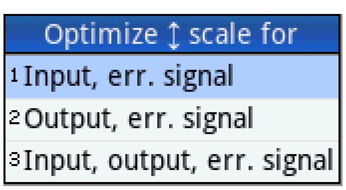
- Frequency domain plots (Bode, Nyquist, Nichols)

  If currently <u>two</u> plots are being shown, you will be asked whether to optimize for the open loop plot, the secondary plot (as selected in Plot Setup) or both plots.



- Time domain response plots

  You will be asked whether to optimize for the input plot, the process output plot or for both plots. The auxiliary plot (error signal or controller output, depending on Plot Setup) will always be optimized at that time.



8.7 Changing chart layout

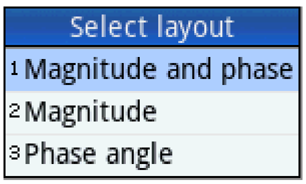
Bode plots and time domain plots normally draw two charts: an upper chart and a lower chart. What is actually plot is can be selected in Plot Setup, but it comes down to:

- Bode plots: upper chart shows magnitude plots, whereas lower chart shows phase angle plots
- Time domain plots: upper chart plots reference change or disturbance, together with process output, whereas lower chart plots either error signal or controller output

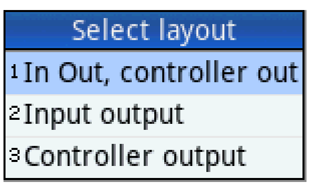
However, you can enlarge the upper or the lower plot to occupy the whole screen.

Press the More soft key and select a layout from the submenu that will open.

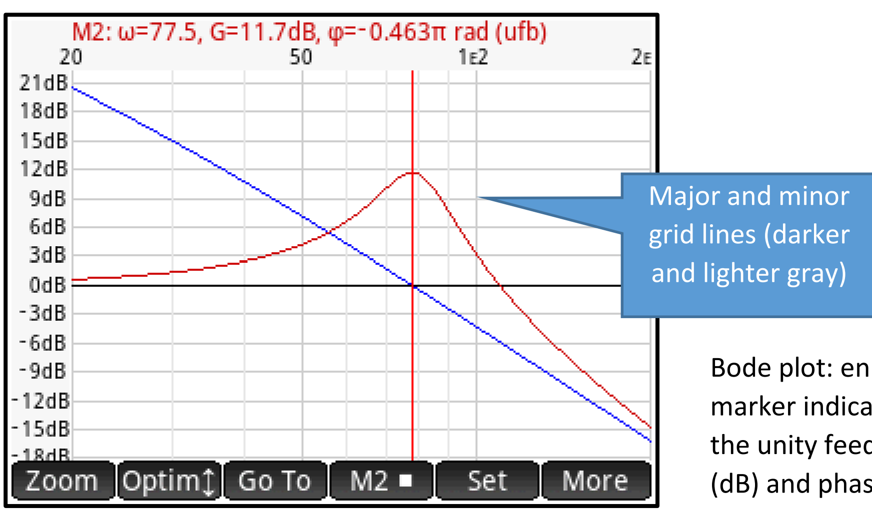
- Bode plot: select one of these options:



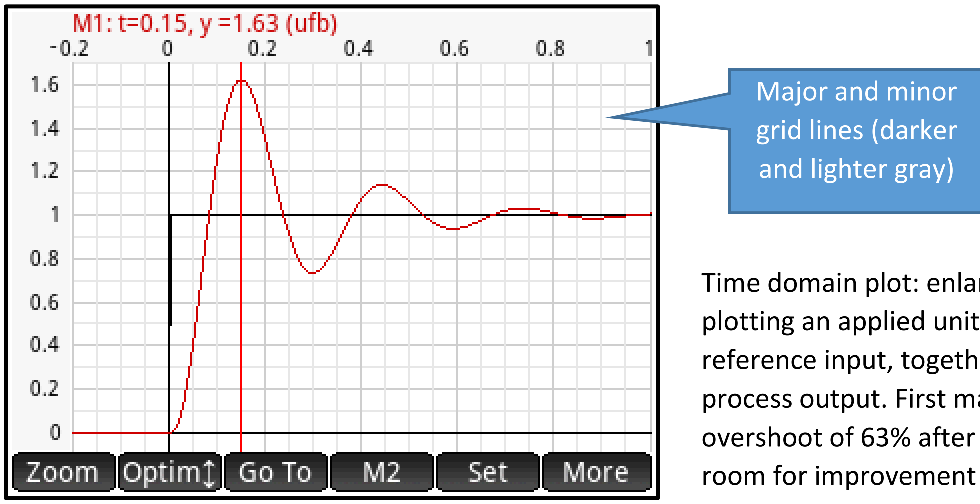
- Time domain plot currently plotting disturbance and process output on the upper chart and controller output on the lower chart: select from



Alternatively, you can also press Shift and then press the up ▲ arrow key to toggle between two-chart display and the enlarged upper chart. Or press Shift and then press the down ▼ arrow key to toggle between two-chart display and the enlarged lower chart.



Bode plot: enlarged magnitude plot, second marker indicating the resonance frequency of the unity feedback response with magnitude (dB) and phase angle in radians

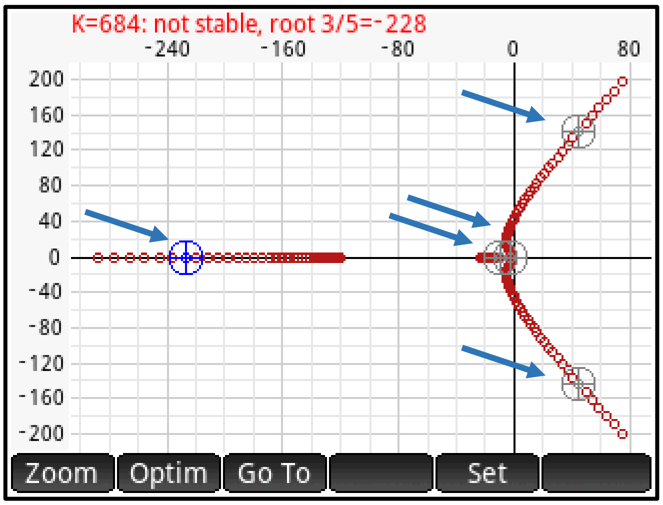


Time domain plot: enlarged upper chart, plotting an applied unit step (in black) at the reference input, together with the resulting process output. First marker indicating an overshoot of 63% after 0.15 seconds. So, some room for improvement here !

9 Root Locus Plots

This is a scatter plot, in the complex plane, of the roots of the unity feedback loop characteristic equation, for a given range of open loop gain values, centered around the controller gain (see Plot Setup).

Roots are indicated by small circles in a dark red color (instead of circles, you can also select a crosshair or a dot marker).



Root locus plot. Characteristic equation for unity feedback loop has 5 roots (for open loop gain equal to 684).

Note: characteristic equation for unity feedback loop equals D(s) + K * N(s) with
- N(s): numerator of open loop transfer function
- D(s): denominator of open loop transfer function

9.1 Highlighting roots

The root locus plot allows you to highlight all the roots for a selectable open loop gain value and it will display information about these roots in the status line.

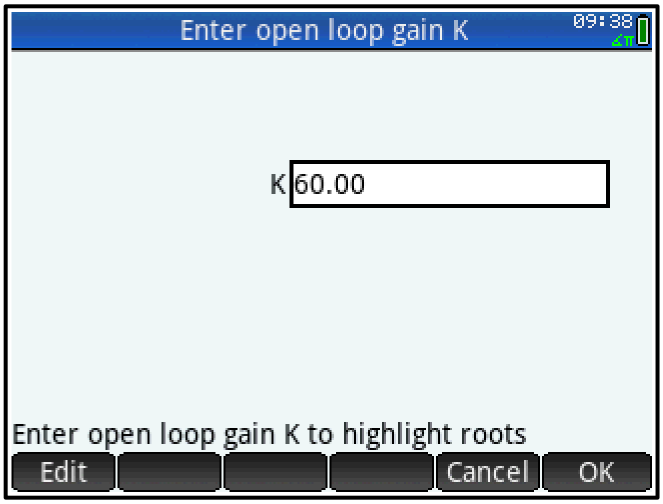
Highlighted roots are shown with a large dark gray circle, with a crosshair inside, around them. For one of the highlighted roots this large circle is shown in blue and more information about this root is displayed in the status line.

Viewing roots for a specific open loop gain

To change the selected open loop gain, you can

- Tap the screen, close to a root. This will select the open loop gain for that root and highlight all the roots for this open loop gain. The tapped root will be highlighted in blue, indicating that information about that root will be displayed in the status line
- Press the left ◀ or right ▶ arrow keys to decrease or increase the open loop gain
- Press and hold the left ◀ or right ▶ arrow keys: after half a second, the selected open loop gain will start decreasing or increasing at a constant speed. This speed will further increase after another 1.5 seconds

- Press Shift and then press the left ◀ arrow key to set the open loop gain to the lowest value in the open loop gain range, as selected in Plot Setup
  - ⇒ If the currently selected open loop gain is greater than the ‘center position’ (which is the controller gain, see Plot Setup) then this center position will be selected instead
- Press Shift and then press the left ▶ arrow key to set the open loop gain to the highest value in the open loop gain range, as selected in Plot Setup
  - ⇒ If the currently selected open loop gain is less than the ‘center position’ (which is the controller gain, see Plot Setup) then this center position will be selected instead
- Tap the Go To soft key and the desired open loop gain. Then, tap OK



Note that you can select any open loop gain value – this includes gain values outside the K-range selected for the plot .

9.2 The status line

The status line contains information about the selected root. More specifically, it displays

- the open loop gain (‘K’)
- the number of roots (characteristic equation of the unity feedback loop) and the selected root (s / n)
- the value of the root (either real or complex)
- whether the system is stable (all roots having a negative real part) or not stable. If stable, the status line is green, if not it will turn red

Cycling through the roots for a selected open loop gain

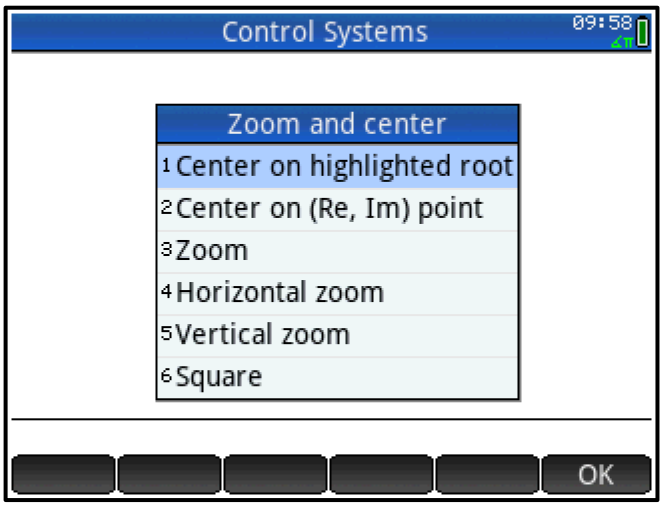
- Tap the screen, close to a root (note: this may change the selected open loop gain)
- Press the up ▲ or down ▼ arrow keys

The selected root will be highlighted in blue and information about it will be displayed in the status line.

9.3 Zooming

Zooming is performed by either

- Performing a two-finger pinch zoom gesture (the zoom is animated by shrinking / stretching the graphic object representing the plot). If the zoom gesture is performed diagonally, the same zoom factor is used in the two dimensions. You can also zoom horizontally or vertically by performing a horizontal or vertical zoom gesture.
- Pressing the + or – key. This will zoom in or out using a custom zoom factor as entered in plot Setup.
- Tapping the Zoom soft key. This opens the zoom menu for Root Locus plots:

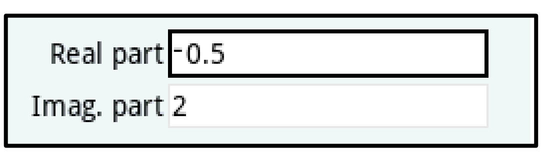


Zooming options available:

- Center on highlighted root

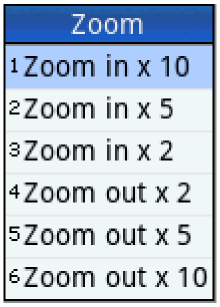
  The root currently highlighted in blue will be put in the middle of the chart. Scales will not change

- Center on (Re, Im) point: enter the coordinates of a point on the complex plane



The selected point will be placed in the middle of the chart. Scales will not change

- Zoom, horizontal zoom, vertical zoom:



Select the desired zoom factor from the submenu.

You can either zoom in or zoom out by a factor of 2, 5 or 10

- Square: makes the horizontal and vertical scales equal

9.4 Scrolling

Place a finger on the screen and either

- drag the plot in the desired direction
- slide your finger. End the slide and re-plot by tapping the screen

Scrolling is animated by moving the graphic object representing the plot in the indicated direction before replotting occurs.

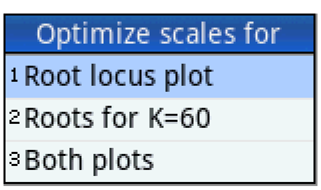
9.5 Optimizing

Optimizing adjusts the chart scales in such a way that the plot fits best on the chart.

Optimizing is either performed automatically (if enabled in Plot Settings – general settings) or manually.

To optimize the plots manually: tap the Optim softkey.

If manually optimizing, you can choose how to optimize the plot:



The second option will optimize the plot, only considering the highlighted roots (the roots for the selected open loop gain value).

10 Active keys

When a plot is currently displayed, the number of active keys is limited.

An active key means that a key press is detected by the program, resulting in a specific action.

These are the active keys and the corresponding actions:

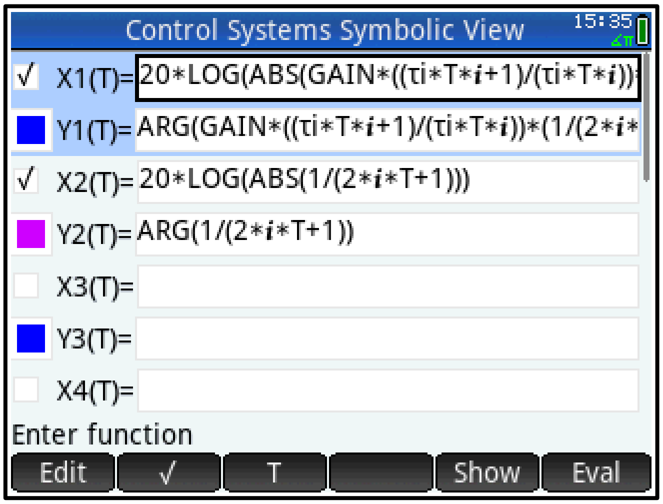
- Apps, App Info, Home, Home Settings: standard global view is displayed
- Symb Setup, Num Setup: standard app view is displayed
- Plot Setup: control systems app settings are displayed (instead of standard app plot setup view)
- Symb: display transfer functions (instead of standard app parametric equations view)
- Plot: launch interactive plotting routine (instead of standard app plot view)
- Num: standard app view is displayed, except when Root Locus Plot is currently selected as plot type: pressing Num will then display a matrix with information about the calculated roots
- Arrow keys ▲ ▼ ◀ ▶ : custom functionality (as explained above)
- + and - keys : zoom in ands out
- Shift: toggles Shift status (while in interactive plotting mode)
- View: displays custom Views menu
- Esc: exits interactive plot and returns to Home View (to abort plotting while the plot is being drawn: keep holding down the Esc key until you return to the Home screen)

The ON key exits interactive plotting as well, but this is a HP Prime system function, so this key is not handled by the 'control systems' app.

All other keys have no function at all, except that pressing any key resets the Key Shift status.

11 Show parametric equations

From the Home view, Press View to open the custom Views Menu and select option 3 (Show parametric Eq.) to open the standard HP Prime Symbolic View showing the parametric equations set by the 'control systems' app.



Equations shown here are not used for plotting. Their only use is to provide data for display in numerical View.

These equations are shown for your information only because they are set by the app, based on the controller settings and process transfer function entered.

Note that Root Locus plots do not use parametric equations.

11.1 Frequency domain response plots (Nyquist, Nichols, Bode)

In all equations, all instances of complex variable 'S' in the Transfer Functions are replaced with expression '*i* * T' (*i* refers to the imaginary unit, T refers to the real variable T used as independent variable in the parametric equations).

- X1(T): and Y1(T): equations for open loop transfer function
- X2(T) and Y2(T): equations for transfer function for the second plot (if selected in Plot Setup)

Please refer to next section (Numerical view) for the definition of these equations

11.2 Time domain response plots

- X1(T): input value (reference change or disturbance, depending on Plot Setup)
- Y1(T): process output value
- X2(T): error signal value
- Y2(T): controller output value

12 Numerical view

Press Shift Num to open Numeric Setup View and set numerical range etc. (standard HP Prime view).

Note: if the set plot type is Root Locus, then the settings in Numeric Setup View will have no effect.

12.1 Frequency and time domain plots

Press Num to open Numerical View (standard HP Prime view).

Information displayed in the respective table columns:

Plot type	T	X1	Y1	X2	Y2
Nyquist	ω	Transfer function - real part, plot 1	Transfer function - imag. Part, plot 1	Transfer function - real part, plot 2	Transfer function - imag. Part, plot 2
Nichols	ω	Phase angle plot 1	Magnitude plot 1 (value or dB)	Phase angle plot 2	Magnitude plot 2 (value or dB)
Bode	ω	Magnitude plot 1 (value or dB)	Phase angle plot 1	Magnitude plot 2 (value or dB)	Phase angle plot 2
Time domain	time	Input value	Process output value	Error signal value	Controller output value

ω: angular frequency

Note: for frequency domain plots, columns X2, Y2 are set to ‘0’ if currently no secondary plot is selected (see ‘Second response plot’ in Plot Setup)

12.2 Root locus plots

Press Num to view a read-only matrix with information about all roots calculated as per settings in Plot Setup.

The matrix contains all roots of the characteristic equation of the unity feedback loop transfer function, for a given range of open loop gain values, centered around the controller gain.

Information displayed in the respective table columns:

(no label)	1	2	3
Root sequence number	K-value (gain)	Real part of root	Imag. Part of root

Note that there will be as many entries for a given K value as there are roots.

13 Retrieving equations

The Control Systems App calculates a set of equations as a base for plotting, based on the transfer functions and controller settings entered, the type of plot (frequency domain, time domain or root locus) and the current settings.

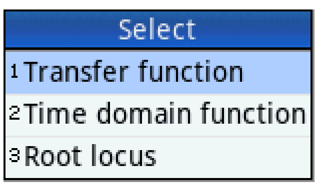
You can retrieve these equations, either to a special variable ‘currEq’ (current equation) or to the home screen.

13.1 Storing an equation in variable ‘currEq’

From the Home view, Press View to open the custom Views Menu and select option 4 (Set ‘currEq’ variable).

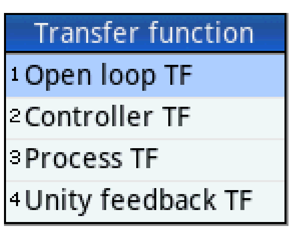
Note that it is not possible to return a value to Home View from the Views menu.

Select which type of equation you want to retrieve:



Then, select the equation you want. It will be stored in variable ‘currEq’

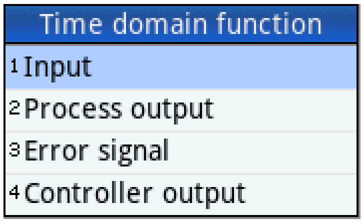
1. Transfer functions (frequency domain):



The equations returned will be functions of *i* * T (imaginary unit x Home variable T, with T representing angular frequency)

Note: the open loop transfer function is the combined transfer function of controller and process

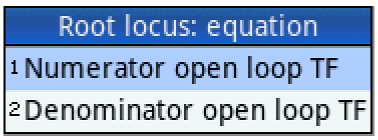
2. Time domain equations (inverse Laplace Transforms):



The equations returned will be functions of Home variable T, representing time

Note: the input can either be a reference change or a disturbance (as defined in Plot Setup)

3. Root Locus Plot equations



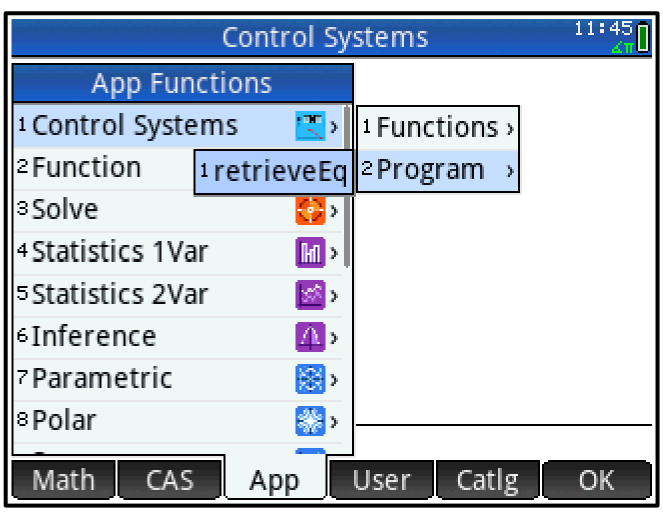
The equations returned will be functions of CAS variable s

Note: the characteristic equation for a unity feedback loop equals D(s) + K * N(s) with

- N(s): numerator of open loop transfer function
- D(s): denominator of open loop transfer function

13.2 Returning an equation to Home View

Execute app program 'retrieveEq' (either type the program name or select it from the Control Systems App program catalog, as shown).



You will be guided through the same menu options as described in previous section.

The selected equation will be returned to Home View and it will be stored in variable 'currEq'.

14 Utility "Grid"

Use: draws a horizontal and vertical grid (either logarithmic, in dB or linear) on the HP Prime screen or any of the graphic objects (G0 to G9).

The program is called by the 'control systems' app, but it is an independent program that is available for general use.

To draw a grid, use this syntax:

```
DrawGrid(graphicObject, range, pixelRange, horizontalScaleSettings, verticalScaleSettings);
```

With

GraphicObject: one of the graphic objects G0 to G9 (G0 represents the screen)

Range: {Xlow, Xhigh, Ylow, Yhigh}

→ a list indicating lowest and highest values to be displayed in the grid. For linear scales, this corresponds to minimum and maximum values in Cartesian (user) coordinates.
Note: lowest values correspond to the lower left corner of grid

PixelRange: {Xlow, Xrange, Ylow, Yrange}

→ a list indicating starting pixel and number of pixels to be used for the grid, in the horizontal (X) and vertical (Y) dimension.
Note: Xlow and Ylow correspond to the upper left of the grid

horizontalScaleSettings: { [scaleType, [printLabels, [labelsInGrid, [lineUnits, [scaleAsFraction, [log1only, [unitSymbol, [multSymbol, [color, [majorColor]]]]]]]]] }

verticalScaleSettings: same list format as horizontalScaleSettings

With

Par. No	Parameter name	Description
1	scaleType	0 = logarithmic, 1 = dB (decibel), 2 = linear Note: If scaleType is not present (empty list), the (vertical or horizontal) grid will not be drawn.
2	printLabels	0 = no value labels, 1 = print value labels. *Default if parameter is not present*: print labels
3	labelsInGrid	0 = labels are printed outside the grid area, 1 = print labels within grid area. Note: label spacing is automatically determined. *Default if parameter is not present*: outside

4	lineUnits	Minimum grid line spacing. Note that spacing will automatically increase (to the lowest possible multiple of lineUnits) if the grid would become too dense. This parameter is used for dB and linear scales only, it is ignored for logarithmic (non-dB) scales – refer to the 'log1only' parameter for logarithmic scales. *Default if parameter is not present*: 3 dB for dB scale, automatic grid lines for linear scale. You may also refer to the default by entering value -1 for this parameter.
5	scaleAsFraction	0 = print regular value labels, 1 = print value labels as fractions, e.g. display ½ instead of 0.5 (only used for linear scales). *Default if parameter is not present*: regular labels
6	log1only	Only used for logarithmic scales. 0 = draw grid lines for 1 EXP n to 9 EXP n. 1 = draw grid lines for 1 EXP n only (n: integer). Note that grid lines are only drawn when the value range (scale) permits it. *Default if parameter is not present*: draw grid lines for 1…9 EXP n
7	unitSymbol	Linear scales only. Unit symbol to be printed after the value label. *Default if parameter is not present*: empty string
8	multSymbol	Linear scales only. Symbol to be printed as part of the value label. Especially useful with 'scale as fraction' display. For instance, with multSymbol = "π", value 3/2 will be printed as 3π/2. *Default if parameter is not present*: empty string
9	gridLineColor	Grid line color as an RGB value. *Default if parameter is not present:* RGB(230, 230, 230) (light gray). You may also refer to the default by entering value -1 for this parameter
10	majorGridLineColor	Major grid line color as an RGB value. *Default if parameter is not present:* RGB(200, 200, 200) (darker gray). You may also refer to the default by entering value -1 for this parameter.

Note: as mentioned above, if *horizontalScaleSettings* or *verticalScaleSettings* is an empty list, the corresponding (vertical or horizontal) grid will not be drawn

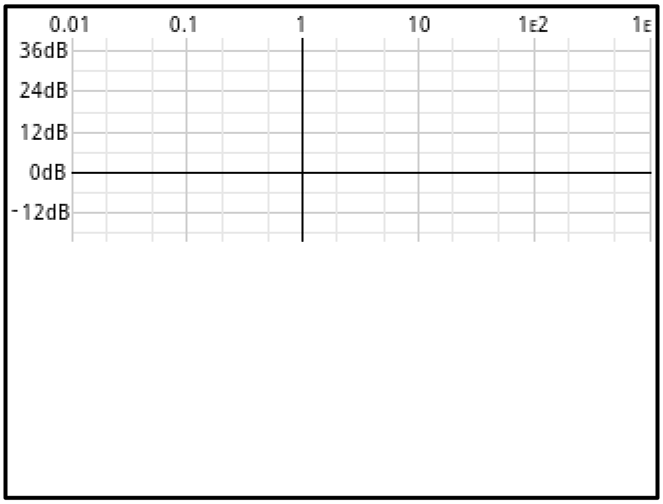
Example 1:

```
RECT();

DrawGrid(G0, {0.01, 1000, 0.1, 100}, {30, 290, 13, 102}, {0}, {1} );

WAIT();
```

Will display the following grid:



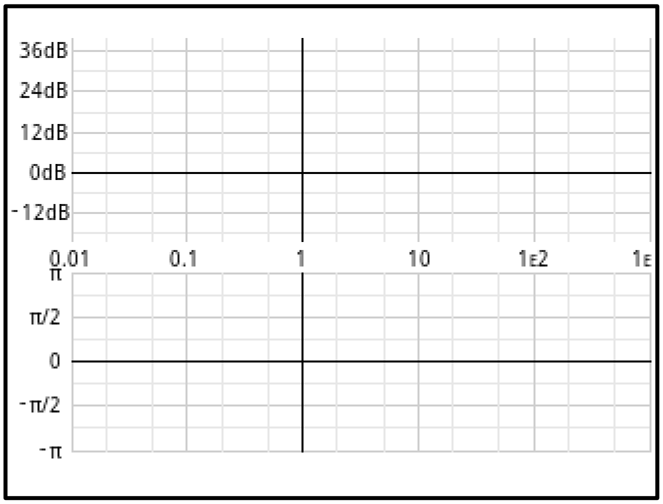
Notes:

1. The horizontal scale (from 0.01 to 1000) is logarithmic, whereas the vertical scale (from 0.1 to 100) is in dB (1 dB = 20 LOG(value), as requested by the last two parameters {0} and {1}
2. Horizontal scale: the labels indicate the real values, not the logarithm of the values. When appropriate, scientific format is used
3. Horizontal scale: note that vertical grid lines for 0.02, 0.05, 0.2, 0.5, 2, 5, 20, 50, … are also drawn. If the scale permits it, even more grid lines will be drawn (1…9 EXP n)
4. Vertical scale: calibrated in dB. The lowest value (0.1) corresponds to -20 dB. As the (default) minimum scale unit of 3 dB would result in a very dense grid, labels are printed every 12 dB. So, the lowest label shown is the label for -12 dB
5. Major grid lines (having a label) are drawn a little darker, to clearly indicate which line a label belongs to

Example 2:

```
RECT();
DrawGrid(G0, {0.01, 1000, 0.1, 100}, {30, 290, 13, 102}, {0, 0}, {1} );
DrawGrid(G0, {0.01, 1000, -1, 1}, {30, 290, 130, 90}, {0, 1}, {2, 1, 0, 1/8, 1, 0, "", "π"} );
WAIT();
```

Will display the following grid



This leaves some room for a status line at the top and a softkey line at the bottom.

Note that the second grid has a linear scale, calibrated in fractions of PI. The minimum grid line spacing is specified as 1/8, but it is automatically set to ¼ because of the scale given.

Also note that, as the two grids share the same horizontal scale, labels are only drawn once.

Please check out the 'control systems' app to see a practical implementation.

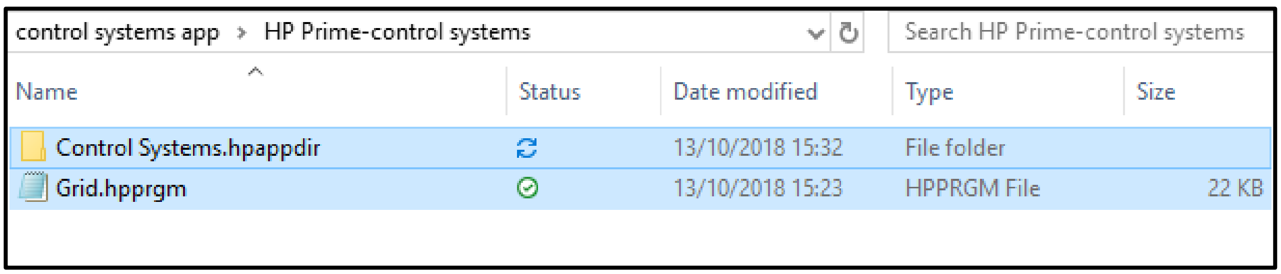
15 Installation

Before you start: make sure your calculator is ON, connected to your computer via USB and visible in the HP connectivity kit.

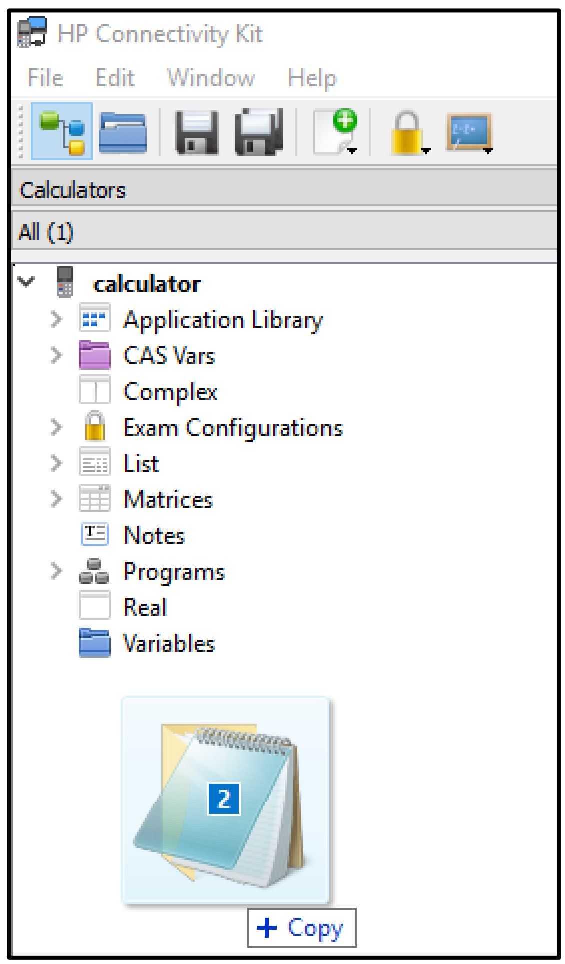
⇒ If the HP connectivity kit is not yet installed on your computer, you will need to install it first. Please refer to HP's documentation.

<u>Installation procedure:</u>

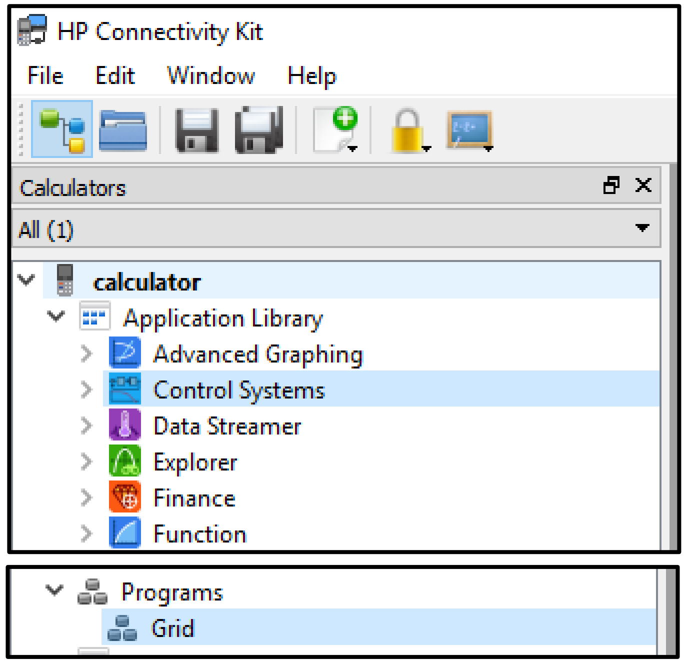
1. Unzip compressed folder "HP Prime-control systems.zip" and select the two items in File Explorer as indicated in the figure below.



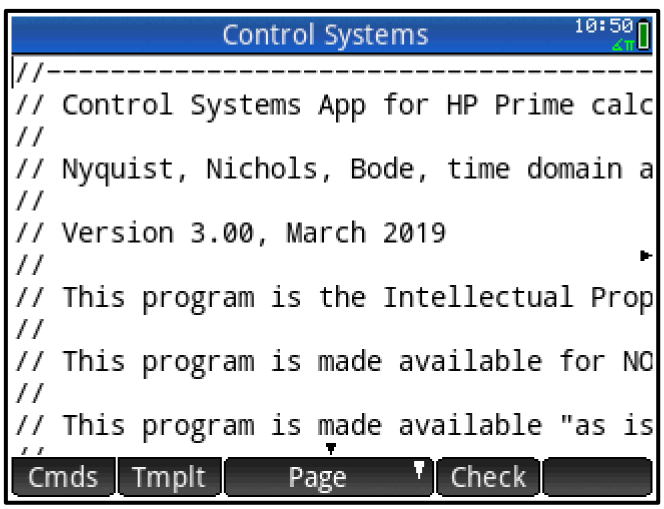
2. In the HP connectivity kit, make sure the 'Calculators' window is displayed. Then, drag the two items you selected earlier to the free space below the content tree.



3. Check that
   - the ‘Control Systems’ app is present in the Application Library
   - the Grid program is present in the ‘Programs’ section of the content tree

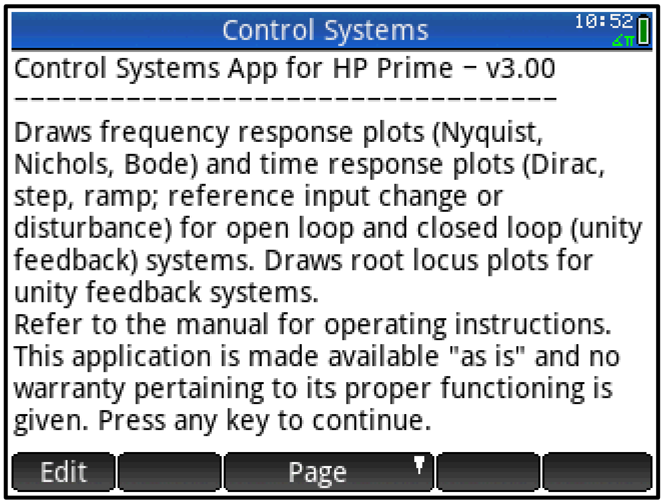


4. Open the program catalog, select the Control Systems App and tap Edit
   Verify that you see the screen below:

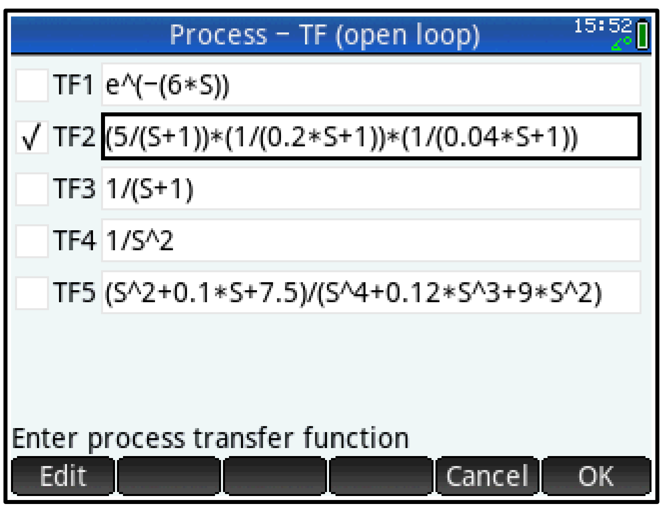


⇒ If this step is not performed (after installation), the App may not start correctly.

5. Press the Apps button. Select the Control Systems App (it could be at the bottom) and press Start



6. Press Enter. You should now see the app (custom) Symbolic View, where you can enter Transfer Functions (see section about Process transfer functions).



The Control Systems app is now up and running.

16 Known issues

16.1 View menu does not disappear

When pressing the View button while a program is still running, the View menu is only displayed when program execution stops. This is typically the case when you press the View button while a Bode plot is being drawn.

If you don't wait until the View menu appears before making a selection (by pressing a numeric button), this key stroke is sent to the command line and the View menu does not disappear.

To correct this situation:

1. Power OFF the calculator and then power ON again
2. Press and hold the On Key while pressing the Symb key

The calculator performs a soft reset and the View menu will disappear.

16.2 Plotting becomes slow

After some time, plotting a Bode diagram can become a little slow.

If this happens, perform a soft reset (procedure explained earlier in this section).