Tutorial of implemented FMBS tool

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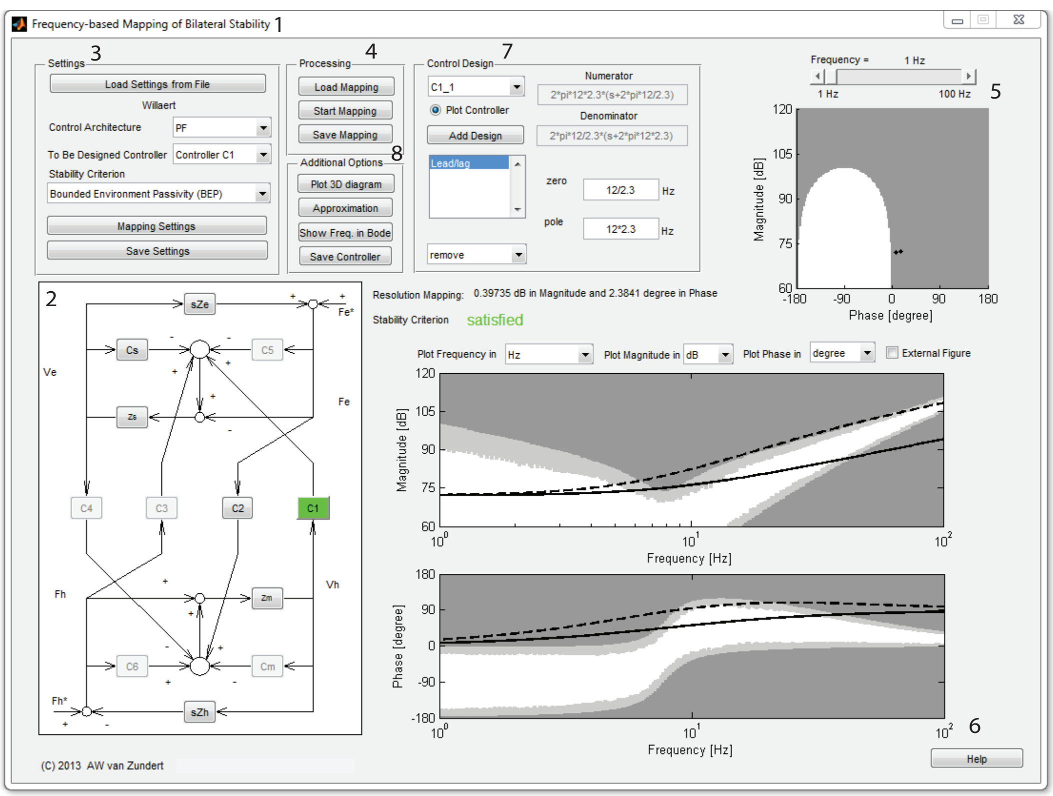

Figure 1: The FMBS tool consisting of the Frequency-based Mapping of Bilateral Stability method. The numbers indicate the elements discussed in the different paragraphs.

1 Guideline for the FMBS tool

The FMBS tool is developed to simplify the control optimisation of controllers in bilaterally controlled teleoperation systems using the Frequency-based Mapping of Bilateral Stability (FMBS) method. This tool is created using Matlab R2012b in Windows 7 64-bit. A tool description can be found in the paper: 'Stability-based loop shaping of bilateral controllers - implementation and practical validation' in the third section. The FMBS tool has been made available at:

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http://cstwiki.wtb.tue.nl/index.php?title=FMBS_tool
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Here some specifications of the FMBS tool:

- The FMBS tool can only be used for Linear Time-Invariant (LTI) bilateral control architectures.
- Only LTI and Single-Input Single-Output (SISO) system models can be implemented.
- The system models can only be implemented a continuous transfer function representation.
- Only frequency-based stability requirements can be used in this tool.
- Due to discretisation there is a limited range visible in frequency, magnitude and phase. Furthermore, between discretisation points no guarantees can be given for all system dynamics, controllers and stability criteria.

Below a short roadmap is developed for the optimisation of bilateral controllers using the FMBS tool:

1. Choose the desired control architecture in the 'Settings' panel (See Section 3).
2. Define the system dynamics using the bilateral control architecture scheme (See Section 2).
3. Choose the stability criterion in the 'Settings' panel for which the bilateral controlled teleoperation system should be satisfied.
4. Specify the resolution of the stability mapping and the range for which the stability mapping is desired, via the 'Mapping Settings'.
5. Choose the to-be designed controller in the 'Settings' panel.
6. Save settings, such that the system dynamics, controllers and all stability mapping settings can be loaded in a later session.
7. Start the stability mapping via the 'Processing' panel (See Section 4).
8. Check in the magnitude-phase stability diagram (See Section 5) for every frequency and in the Bode diagram (See Section 6) whether the stability mapping is accurate enough. If multiple unstable regions occur in the magnitude-phase stability diagrams the multiple-rectangular stability-mapping method can be chosen in the 'Mapping Settings'. Furthermore, check whether the number of discretisation points and the range in magnitude, phase and frequency are as desired. For this step some additional options can be used (See Section 8).
9. If the stability mapping is not accurate enough some parameters should be changed and the stability should be mapped again.

10. Do step 5,7,8 and 9 again for all controllers, that can be tuned, in the control architecture. See which of the controllers can be optimised best and optimise this controller first using the 'Control Design' panel (See Section 7).
11. Update the designed controller in the bilateral control architecture scheme.
12. Do step 5,7,8,9,10 and 11 for all controllers that can be optimised until the optimal combination of controllers is achieved.

2 The bilateral control architecture scheme

In Figure 2 the bilateral control architecture scheme is visualised. In the FMBS tool this scheme is located at the bottom left and is used for the implementation of the system dynamics and controllers.

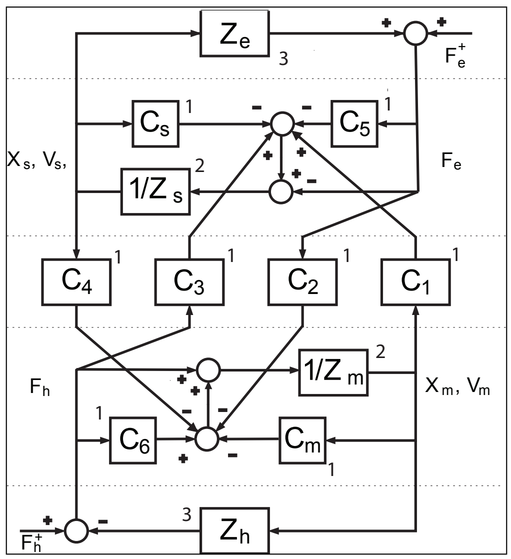


Figure 2: General bilateral control architecture scheme adapted from Lawrence [1, 3] with position X_m, X_s or velocity V_m, V_s for the master and slave, respectively. The master and slave dynamics are represented by Z_m and Z_s, respectively. Note that $Z(s) = \frac{F}{V}$ and $sZ(s) = \frac{F}{X}$, where F is force. All eight C_i elements, with $i \in 1, ..., 6, s, m$ represent the controllers. The human operator and environment models are indicated with Z_h and Z_e, respectively. The reacting forces of the human operator and environment are F_h and F_e respectively, where the superscript + indicates an exogenous force. For clarity, the dependency on the Laplace operator s is omitted.

By clicking on a block in this scheme a pop-up appears in this the corresponding model can be declared. Below for three types of blocks the pop-up menus are described, corresponding to the numbers in Figure 2.

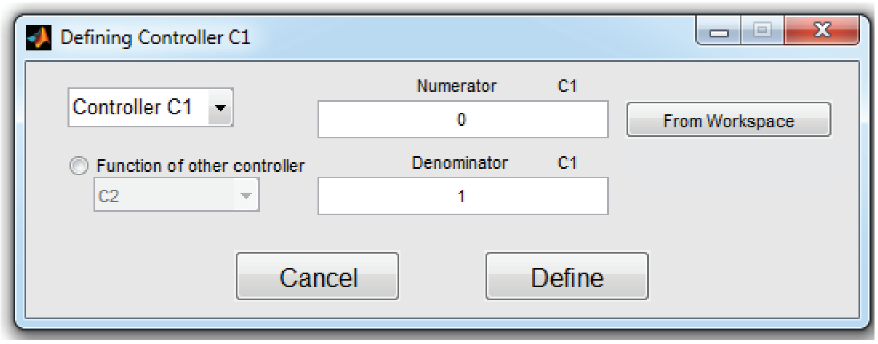


Figure 3: Pop-up menu for the declaration of controller $C_1(j\omega)$. The values that are visible are the default settings.

1. Clicking on these blocks results in a pop-up menu in which the corresponding controller can be declared (see Figure 3). In this pop-up menu the corresponding control element can be declared by giving the numerator and the denominator. Furthermore, a controller can be selected from the workspace as a transfer function. If the controller is a function of another controller, and thus should change proportionally with that other controller, this can be implemented by checking the 'Function of other controller' box. In this case the controller can be defined as a function of the selected controller. By default all controllers are defined as 0.

2. Clicking on these blocks results in a pop-up menu in which the corresponding master or slave dynamics can be declared (see Figure 4). There is a certain freedom in the declaration of these dynamics. The dynamics can either be defined as a transfer function $1/Z = V/F$ or as an impedance $Z = F/V$ with F the reacting force and V the velocity. Furthermore, the dynamics can be defined with respect to velocity $V = sX$ or with respect to position X.

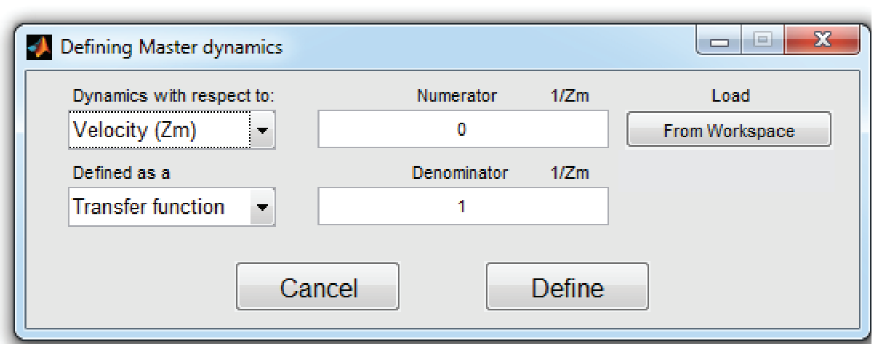


Figure 4: Pop-up menu for the declaration of the master model $1/Zm$. The values that are visible are the default settings.

3. Clicking on these blocks results in a pop-menu in which the corresponding human operator and environment dynamics can be declared. This pop-up menu is similar to that of 4. However, these dynamics can only be implemented as an impedance $Z = F/V$.

3 The 'Settings' panel

This panel is located in the left upper corner in the FMBS tool. Figure 5 shows this panel. In this panel the design specifications can be defined. Below every item in this panel is explained.

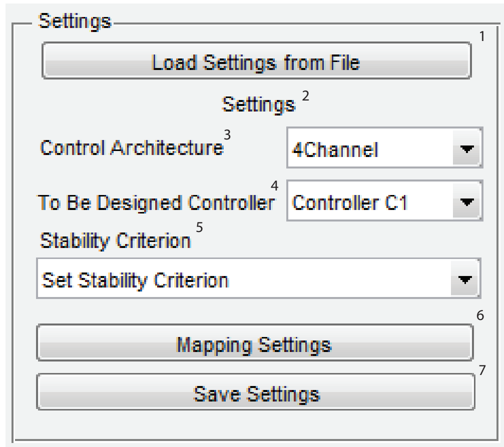


Figure 5: The 'Settings' panel. The default settings are visualised and the numbers are not in the original panel.

1. By pressing this button a previously saved session can be loaded. Only settings saved with the FMBS tool can be loaded. Furthermore, after loading all settings and the stability mapping are both overwritten.

2. This indicates the name of the current session. The default name is 'Settings'.

3. Using this drop-down menu the to-be used bilateral control architecture can be selected. The possible control architectures that can be used are: '4Channel' (default), Position-Error ('PERR')[7, 8, 2], Shared Compliance Control ('SCC') [7, 8] and Position-Force ('PF')[6, 7, 8] control architecture. If a control architecture is selected for which some controllers are not used, these controllers are faded out in the bilateral controlled architecture scheme.

   Note that the choice for an architecture is not necessary since the other control architectures are identical to the '4Channel' architecture for specific settings for some controllers. However, it can be useful to keep a good overview during the design procedure.

4. In this drop-down menu the to-be designed controller can be selected. This is the controller for which the stability information will be evaluated and mapped on magnitude-phase stability diagrams for every frequency and on a Bode diagram. By default 'Controller C1' is selected. The selected controller is coloured green in the bilateral control architecture scheme.

5. In this menu the to-be used stability criterion can be selected. Note that for the FMBS method only the frequency-based stability requirements are included [1]. For all stability criteria it is required to compute the hybrid matrix given in (1), where F_h is the human reaction force, F_e the environment reaction force, V_s the velocity of the slave and V_m the velocity of the master. Note that this matrix is computed with respect to velocity. This hybrid matrix consists of four hybrid elements $h_{i,j}(j\omega)$, with $i, j \in 1, 2$, given in (2) [9]. For clarity the dependence on $j\omega$ is omitted. Note that the hybrid elements are a function of

the master and slave dynamics and the eight controllers in the bilateral control architecture depicted in Figure 2.

$$\begin{bmatrix} F_h \\ V_s \end{bmatrix} = \begin{bmatrix} h_{11}(j\omega) & h_{12}(j\omega) \\ h_{21}(j\omega) & h_{22}(j\omega) \end{bmatrix} \begin{bmatrix} V_m \\ F_e \end{bmatrix} \tag{1}$$

$$\begin{aligned} h_{11} =& \frac{1}{j\omega}\frac{(j\omega Z_s + C_s)(j\omega Z_m + C_m) + C_1C_4}{h_{den}} \\ h_{12} =& \frac{-(j\omega Z_s + C_s)C_2 + C_4(1 + C_5)}{h_{den}} \\ h_{21} =& \frac{(j\omega Z_m + C_m)C_3 + C_1(1 + C_6)}{h_{den}} \\ h_{22} =& j\omega\frac{(1 + C_5)(1 + C_6) - C_2C_3}{h_{den}} \end{aligned} \tag{2}$$

with

$$h_{den} = (j\omega Z_s + C_s)(1 + C_6) - C_3C_4 \tag{3}$$

The following frequency-based stability requirements are available in the FMBS tool:

- the 'Bounded Environment Passivity (BEP)' criterion given by (4) [6]. Here $Z_e(j\omega)$ is the environment impedance.

$$\Re\left(h_{11}(j\omega) - \frac{h_{12}(j\omega)h_{21}(j\omega)Z_e(j\omega)}{1 + h_{22}Z_e(j\omega)}\right) \geq 0, \quad \forall\omega \tag{4}$$

- the 'Llewellyn's Absolute Stability Theorem (LAST)' given by (5) [5].

$$2\Re(h_{11})(j\omega)\Re(h_{22}(j\omega)) - \Re(h_{12}(j\omega)h_{21}(j\omega)) - |h_{12}(j\omega)h_{21}(j\omega)| > 0, \quad \forall\omega \tag{5}$$

- the 'Nyquist Criterion for infinite environment stiffness (SIES)' given by (6) [?].

$$\Im\left(\frac{h_{11}(j\omega)h_{22}(j\omega) - h_{12}(j\omega)h_{21}(j\omega)}{j\omega h_{11}(j\omega)}\right) < 0, \quad \forall\omega \tag{6}$$

- the 'Raisbeck's Passivity Theorem (RPT)' given by (8) [4].

$$4\Re(h_{11}(j\omega))\Re(h_{22}(j\omega)) - (\Re(h_{12}(j\omega)) + \Re(h_{21}(j\omega)))^2 - \tag{7}$$

$$(\Im(h_{12}(j\omega)) + \Im(h_{21}(j\omega)))^2 > 0, \quad \forall\omega \tag{8}$$

- a 'Own Stability Criterion (OSC)' can be defined. This could be necessary if the desired frequency-based stability requirement is not incorporated in the FMBS tool. For using this a function file should be included in the directory where the FMBS folder is located and then in the folder 'StabilityCriteria' containing the user-defined stability criterion. This function should have as an input $[\{C_1, C_2, C_3, C_4, C_5, C_6, C_s, C_m\}, \{Z_e, Z_h, Z_s, Z_m\}, s]$ where every element can be either a three dimensional matrix (consisting of the magnitude, phase and frequency of the to-be designed controller selected in the 'Settings' panel) or a scalar and $s = j\omega$. The output of the function can be either a scalar or a vector that has a 1's and/or 0's for when the criterion is satisfied or not, respectively. Here an the function is included for the 'Bounded Environment Passivity' criterion:

```
function stabProp = BoundedEnvironmentPassivity(C,Z,s)
        % with C1 = C{1}; C2 = C{2}; C3 = C{3}; C4 = C{4};
        %      C5 = C{5}; C6 = C{6}; Cs = C{7}; Cm = C{8};
        %      Ze = Z{1}; Zh = Z{2}; Zs = Z{3}; Zm = Z{4};
        %      s = j\omega

        [h11 h12 h21 h22] = extractHybrid(Z,C,s);

        Ze = Z{1};

        bepCrit = real(h11 - (h12.*h21.*Ze)./(1+h22.*Ze));
        stabProp = bepCrit >= 0;

end
```

6. By pressing this button a pop-up menu appears. This pop-up menu is visualised in Figure 6. In this menu the desired discretisation settings, that should be used for the stability mapping, can be defined. The range, number of points in this range and the units in which the settings should be interpreted can be defined. In the main screen of the FMBS tool (Figure 1) the resolution that will be used is visualised for magnitude and phase. This resolution is computed by (9) and (10) respectively. Here $M(\omega)$ indicates the magnitude, $\phi(\omega)$ the phase, max the maximum value, min the minimum value and n_i the number of points used in i, where $i \in \{M(\omega), \phi(\omega)\}$.

$$Res_{M(\omega)} = \frac{M_{max}(\omega) - M_{min}(\omega)}{n_{M(\omega)}} \tag{9}$$

$$Res_{\phi(\omega)} = \frac{\phi_{max}(\omega) - \phi_{min}(\omega)}{n_{\phi(\omega)}} \tag{10}$$

   Since the points for frequency are distributed logarithmically no constant resolution is present. This resolution defines a bound on the to-be used system dynamics and controllers. If the to-be used stability criterion (selected in the 'Settings' panel) changes from stability to instability to stability (or reversed) in a range smaller than the resolution no stability can be guaranteed. Hereby assuming that the stability criterion is smooth with respect to frequency.

   For frequency, the available units are in (Hz) and in (rad/s). For magnitude only dB units can be used and for phase the settings can be defined in $(degrees)$ or in (rad).

   In this pop-up menu also the stability-mapping method that should be used can be specified. Section 4 describes the two stability-mapping methods that can be used. By default the single-rectangular stability-mapping method is used. By selecting the checkbox: 'Use multiple-rectangular stability-mapping method' the multiple-rectangular stability-mapping method can be used.

   The 'Reset' button, resets all parameters in the 'Mapping Settings' pop-up menu to the values that are already defined. The 'Initialize' button, resets all these parameters to the default values.

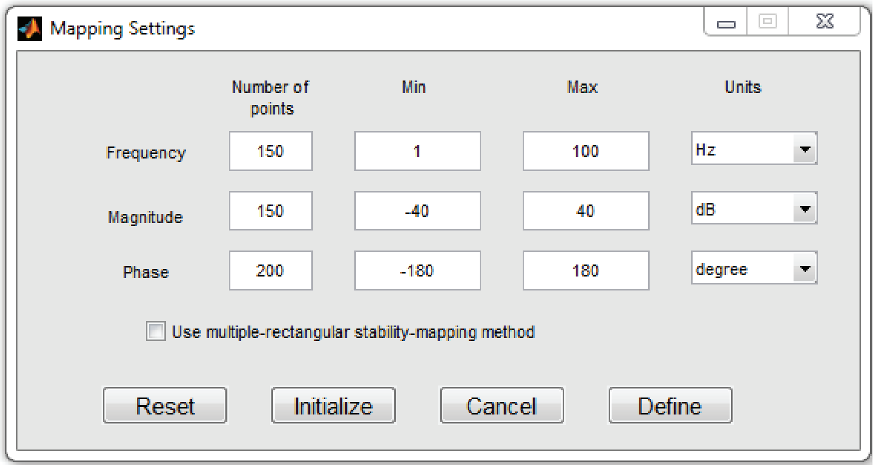


Figure 6: The 'Mapping Settings' pop-up menu. The values that are visible are the default settings.

7. All settings, including the defined system dynamics (see Section 2), can be saved under a specified name. By default this name is the name visible at 2 in Figure 5.

4 The 'Processing' panel

This panel is located at the top center in the FMBS tool. Figure 7 shows this panel. In this panel the stability mapping can be handled. Below every item in this panel is explained.

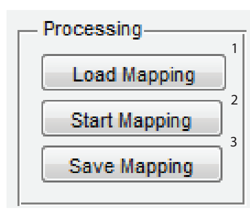


Figure 7: The 'Processing' panel. The numbers are not in the original panel.

1. By pressing this button a previously saved session can be loaded. Only settings saved with the FMBS tool can be loaded. Furthermore, after loading the stability mapping is overwritten. Note that the settings should be loaded separately before a mapping can be loaded.

2. By pressing this button the stability mapping is started. Below in the bottom center of the FMBS tool the progress of the stability mapping is visualised. During the stability mapping all data generated during previous mappings are overwritten.

   - At first the declared dynamics are extracted: All system dynamics and controllers are discretised and saved in three dimensional matrices (dependent on magnitude, phase and frequency of the controller selected in the 'Settings' panel), for every element respectively. For analysis purposes, the system dynamics are defined with respect to velocity and as an impedance.
   - Second, the stability criterion (selected in the 'Settings' panel) is evaluated for the specified controller (selected in the 'Settings' panel and defined in the bilateral control architecture scheme). The controller is evaluated for the range and number of points in

frequency, both specified in the 'Mapping Settings'. It is visualised in the main screen of the FMBS method (Figure 1) whether the stability criterion is satisfied or not. Furthermore, the range of frequencies for which the stability criterion is not satisfied is visualised.

- Third the stability criterion (selected in the 'Settings' panel) is evaluated, using the three-dimensional matrices for the controllers and the system dynamics. To reduce the computation time, the stability evaluation is performed using matrix multiplications. Due to this approach the maximum number of discretisation points is limited by the physical memory of the used computer. Now the three-dimensional magnitude-phase-frequency stability grid is available where every stable magnitude-phase-frequency grid point is 1 and every unstable grid point is 0.
- Then, the stability information for the three-dimensional stability grid is mapped on a Bode diagram (described in Section 6). The stability mapping is performed by approximating the (un)stable regions on the magnitude-phase stability diagrams for every frequency (described in Section 5).

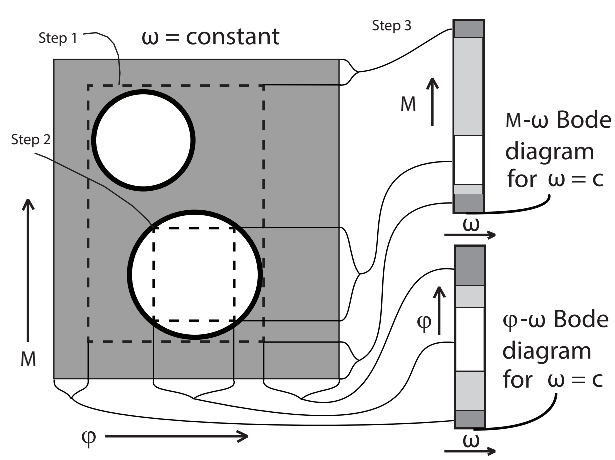
  This mapping can be performed using two different mappings. This was selected in the 'Mapping Settings' pop-up menu. Either the single-rectangular stability-mapping method or the multiple-rectangular stability-mapping method can be used.

  Both stability mappings consists of three steps (for every frequency):

Step 1 find the unstable regions in the considered magnitude-phase for constant frequency diagram by approximating all unstable points;

Step 2 find the largest unstable region with only unstable points;

Step 3 map the approximated unstable region on a Bode diagram.



(a) Magnitude-phase stability diagram (left) for constant frequency with multiple unstable regions mapped onto a Bode diagram (right) using the single-rectangular stability-mapping method.

(b) Magnitude-phase stability diagram for constant frequency with multiple unstable regions mapped onto a Bode diagram (right) using the multiple-rectangular stability-mapping method.

Figure 8: A conceptual example of the approximation of unstable regions in the magnitude-phase stability diagram for constant frequency.

Note that it can be that the to-be approximated regions can comprise the stable regions instead of the unstable regions. The method is explained for approximation of unstable regions. The difference between the two methods is that for the approximation of stable regions the mapping is reversed. Section 6 discusses the consequence of this reversed stability mapping in the Bode diagram.

The approximation steps above are rectangular. Since the unstable regions are typically not rectangular, there is some conservatism due to the rectangular approximation. This conservatism is defined by the difference between the approximation in step 1 and 2. The difference between the two stability-mapping methods is explained below.

Single-rectangular stability-mapping method

This method uses only one rectangle for step 1 and step 2 in the magnitude. Due to phase wrapping, this method incorporates approximation of multiple regions in the phase range. However, this could result in a lot of additional conservatism as can be seen in Figure 8(a).

Multiple-rectangular stability-mapping method

This method deals with the approximation of multiple unstable regions in the magnitude-phase stability diagram for constant frequency (Figure 8(b)). This stability-mapping method could have a reduced amount of conservatism on the Bode diagrams. Additionally to the steps above, this method comprises an initial identification step for multiple unstable regions. For this identification, a binary image technique [**?**] is used: connected component labelling. This technique labels every unstable region, such that every unstable region can be approximated with a single rectangle.

Note that the approximation of multiple unstable regions has an effect on the interpretation of the stability mappings on the Bode diagram. This will be explained in Section 6.

This stability-mapping method has a higher computation time than the single-rectangular stability-mapping method.

- After the stability mapping on the Bode diagram (Section 6) of the controller (selected in nr. 4 in Figure 5), the specified (initial) controller is plotted in the Bode diagram as a line and in the magnitude-phase stability diagram for constant frequency (described in Section 5) as a dot.

5 The 'magnitude-phase stability diagram for constant frequency'

Here the magnitude-phase stability diagrams for every discretised frequency can be visualised (See Figure 9). Below, every item, numbered in this diagram, is explained.

1. This is the magnitude-phase plot for a constant frequency ($15.84Hz$) that is a result of the stability mapping, described in Section 4. The dark grey region consists of points for magnitude, phase and frequency of the to-be designed controller (selected in the 'Settings' panel) that satisfy the stability criterion (selected in the 'Settings' panel). The white region consists of points that do not satisfy the stability criterion.

2. This is a slider that enables the selection of a magnitude-phase stability diagram for a specific frequency. Frequency is the parameter along the slider. On the left and right of the slider the minimum and maximum frequency is given for which the magnitude-phase stability diagrams can be visualised. These are the limits defined in the 'Mapping Settings'. Note that using

the arrows on both sides of the slider, there are only 100 plots available. However, by moving the cursor all evaluated frequencies (defined in the 'Mapping Settings') can be selected.

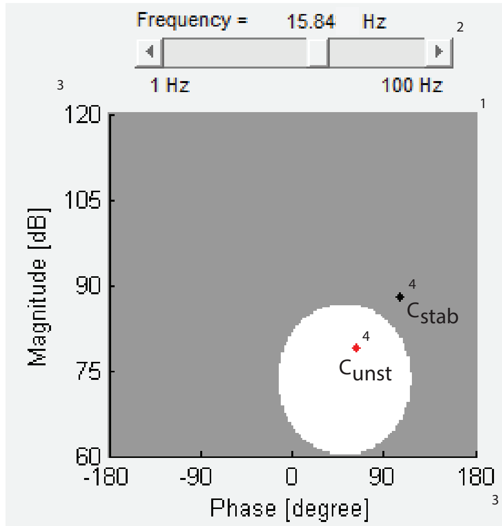


Figure 9: The magnitude-phase stability diagram for a frequency of $\omega = 15.84Hz$ containing an unstable (C_{unst}, red dot) and stable (C_{stab} black dot) controller. Note that the C_{unst}, C_{stab} and the numbers are both not visible in the original diagram.

3. The axis depends on the defined range in the 'Mapping Settings'. The range is visualised in four linear increments and in the units specified in the 'Mapping Settings'.

4. The to-be designed controller (selected in the 'Settings' panel and defined in the bilateral control architecture scheme) is visualised in this diagram for one frequency. A black dot (C_{stab}) corresponds to a controller that satisfies the stability criterion (selected in the 'Settings' panel) and a red dot (C_{unst}) corresponds to a controller that does not satisfy the stability criterion.

In Section 8 additional options are described in which the approximation rectangles (see Section 4) of the regions in the magnitude-phase stability diagrams can be visualised.

6 The 'Bode diagram with stability mapping'

Here the Bode diagram with stability mapping is visualised (See Figure 10), that is a result of the stability mapping described in Section 4. Below, every item, numbered in this diagram, is explained.

1. This is Bode diagram that is a result of the stability mapping, described in Section 4. There are two important aspects that should be considered for the interpretation of the stability mapping on the Bode diagram.

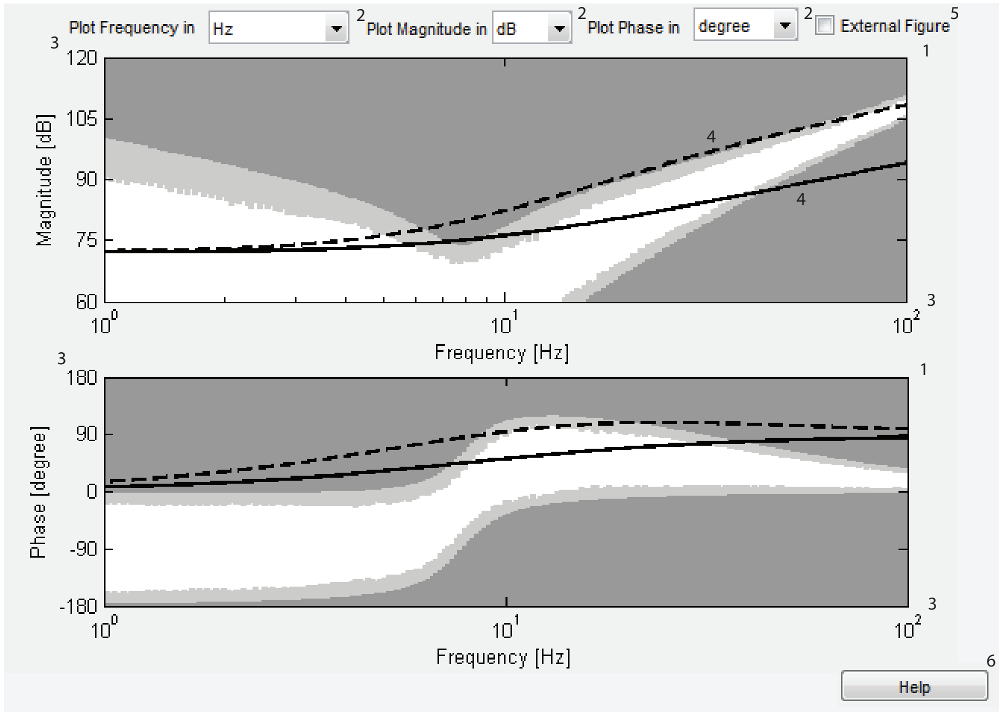


Figure 10: The Bode diagram containing a stability mapping and an unstable (solid line) and stable (dashed line) controller. The numbers are not in the original diagram.

(a) It is important to consider the sort mapping that is used: 'normal' or 'reversed'.

'normal' In the stability mapping, the unstable regions are approximated by a rectangle. In this case the Bode diagram with stability mapping of a controller can be interpreted like this: If in the Bode diagram the controller lies in the dark grey area for one of the two Bode plots, the used stability criterion is satisfied. Only if the controller lies in the white area for both Bode plots is the used stability criterion not satisfied.

'reversed' In the reversed stability mapping the stable regions are approximated by a rectangle. The interpretation of the stability mapping on the Bode diagram is also reversed: If in the stability mapping on the Bode diagram the controller lies in the white area for one of the two Bode plots, the used stability criterion is not satisfied. Only if the controller lies in the dark grey area for both Bode plots is the used stability criterion satisfied. If a reversed mapping is applied, this is indicated at the specific frequency by a red circle indicator at the top of the Bode-magnitude plot and the Bode-phase plot. Note that these red circles are not visualised in Figure 10.

For both mappings it holds that if the controller lies in the light grey area it is unknown whether the stability criterion is satisfied or not. If stability cannot be evaluated using the stability mapping on the Bode diagram it is necessary to evaluate the magnitude-phase stability diagrams, described in Section 5.

For every frequency another magnitude-phase stability diagram is evaluated. Hence, it could be that for a specified range of frequencies both sorts of stability mappings can occur.

(b) If the multiple-rectangular stability-mapping method is used it should be made sure which unstable area in the stability mapping on one Bode plot corresponds to which unstable area in the stability mapping on the other Bode plot. This can be evaluated using the magnitude-phase stability diagrams for constant frequency.

2. In these drop-down menus the units of the Bode diagrams can be changed. Initially the units are defined as in the 'Mapping Settings' is defined. If the units are changed, the diagrams are updated instantly.

3. The axis depends on the defined range in the 'Mapping Settings'. The range is visualised in four linear increments for magnitude and phase, and a logarithmic scale for frequencies. The units that are visible are specified in the 'Mapping Settings'.

4. The to-be designed controller (selected in the 'Settings' panel and defined in the bilateral control architecture scheme) is visualised in this diagram for one frequency. A solid line corresponds to a controller specified in the bilateral control architecture scheme before the stability mapping. A dashed line corresponds to the first controller that is designed using the 'Control Design' panel, described in Section 7, a dashed-dotted line for the second and a dotted line for the third. For any additional controllers not specific line sort has been defined.

5. By selecting this checkbox the Bode diagram and the magnitude-stability diagram are plotted in an external figure. Every change in either figure generates another external figure, respectively.

In Section 8 additional options are described. In this 'Additional Options' panel the frequency on which the magnitude-phase stability diagram is visible can be indicated in the Bode diagram.

7 The 'Control Design' panel

This panel is located in the top center of the FMBS tool. Figure 11 shows this panel. Below every item in this panel is explained. Initially only the items numbered with 1, 2, 3, 5 and 7 are visible. This 'Control Design' panel is adapted from another graphical tool: 'Shapeit' [10].

1. By pressing this button a pop-up menu appears. In this menu one can choose between defining a complete new controller, altering the controller implemented in the bilateral control architecture scheme from Section 2, or loading a controller that has been saved in previous sections. These three possibilities are elaborated below.

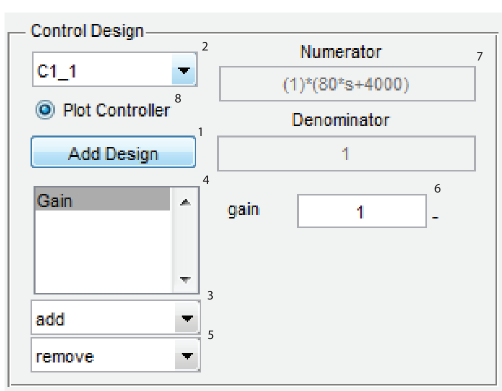


Figure 11: The 'Control Design' panel. The numbers are not in the original panel.

- Complete New Controller: By choosing for this option a pop-up screen appears. This screen is similar to Figure 3. However, this controller cannot be a function of another controller. In this pop-up screen the numerator and denominator of a transfer function can be defined and a transfer function can be loaded from the workspace. This controller can only be changed by altering the numerator and denominator and not by using the standard component-adding feature described in 4.
- Alter Current Controller: By choosing this option a pop-up screen appears in which solely the name of the newly defined controller can be defined.
- Load Existing Controller: By choosing for this option a previously saved controller (see Section 8) can be added. Note that using this function only controllers can be added that are previously saved by the FMBS tool.

After adding a controller, all defined controllers become visible in 2.

2. Several designs can be created for the to-be designed controller selected in the 'Settings' panel. In this drop-down menu all the defined control designs can be selected.By selecting this box the designed controller can be plotted in or deleted from the Bode diagram (Section 6), the magnitude-phase stability diagram (Section 5) and the three-dimensional stability magnitude-phase-frequency grid (Section 8).

   The original controller is visualised by a solid line. The first control design is a dashed line. The second control design is a dashed-dotted line and the third control design is visualised by a dotted line. For any additional controllers not specific line sort has been defined.

3. Using this drop-down menu several components can be added to the original controller. The following control components can be used: a 'Gain' K, an 'Integrator' C_{Int} defined by (11), a 'Lead/Lag' $C_{Lead/Lag}$ defined by (12), a 'Low pass 1st order' C_{lp1} defined by (13), a 'Low pass 2nd order' C_{lp2} defined by (14), a 'Notch' C_{Notch} defined by (15) and a 'PD' C_{PD} defined by (16). Here f_1 defines the zeros, f_2 the poles, β_1 and β_2 the damping of the zeros and poles, respectively.

$$C_{Int} = \frac{s + f_1}{s} \tag{11}$$

$$C_{Lead/Lag} = \frac{f_2(s + f_1)}{f_1(s + f_2)} \tag{12}$$

$$C_{lp1} = \frac{f_2}{s + f_2} \tag{13}$$

$$C_{lp2} = \frac{f_2^2}{s^2 + \beta_2 f_2 + f_2^2} \tag{14}$$

$$C_{Notch} = \frac{f_2^2(s^2 + \beta_1 f_1 + f_1^2)}{f_1^2(s^2 + \beta_2 f_2 + f_2^2)} \tag{15}$$

$$C_{PD} = P + Ds \tag{16}$$

   with s is the Laplace varable.

4. Here all added components are listed.

5. Using this drop-down menu a control design (listed in 2) can be deleted, using the first option. Using the second option a control component can be deleted (listed in 4). Note that

the original controller defined in the bilateral control architecture scheme (Section 2) cannot be deleted or altered.

6. Here the parameters for the control components can be added. For example the zeros, poles and damping parameters. By selecting a specific component, the specific parameters can be defined accordingly.

7. Here the defined controller can be seen. If at 1 a 'Complete New Controller' is added, the numerator and denominator can be changed. However, if a 'Alter Current Controller' design is added, the corresponding components are visualised and only the parameters f_1, f_2, β_1, β_2, P and D can be changed.

8. By selecting this box the designed controller can be plotted in or deleted from the Bode diagram (Section 6), the magnitude-phase stability diagram (Section 5) and the three-dimensional stability magnitude-phase-frequency grid (Section 8).

8 The 'Additional Options' panel

This panel is located below the 'Processing' panel. Figure 12 shows this panel. Below the numbered items are explained.

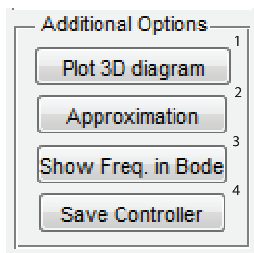


Figure 12: The 'Additional Options' panel. The numbers are not in the original panel.

1. By clicking on this button the three-dimensional stability magnitude-phase-frequency grid is be visualised in an external figure. In this diagram only the border between the stable and unstable regions are visualised.

2. By clicking on this button the approximation rectangles are visualised in the magnitude-phase stability diagram for constant frequency.

3. By clicking on this button the frequency for which the magnitude-phase stability diagram is visualised is indicated in the Bode diagram.

4. By clicking on this button one of the added control designs can be saved. The complete control design can be saved, such that it can be loaded for later analysis using the FMBS tool. Furthermore, the controller can be saved as a transfer function.

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