High-performance robust control solutions

for advanced radio/optical telescopes

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Green Bank, West Virginia, USA. September 22nd, 2016

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CASE WESTERN RESERVE UNIVERSITY EST. 1826

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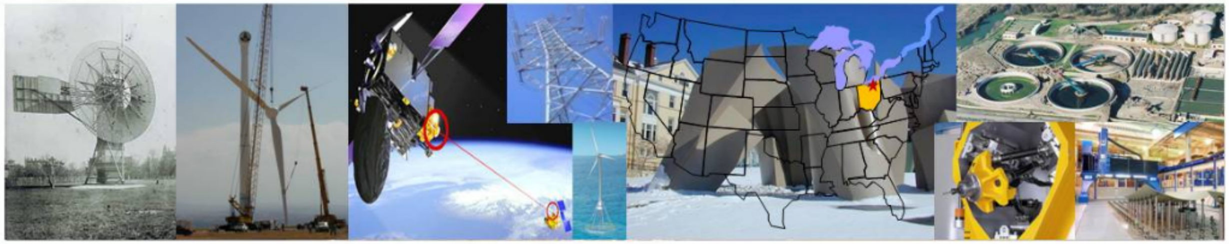

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http://cesc.case.edu

Control & Energy Systems Center (CESC)

Telescope control research projects

Back to CESC Home

Project 1: *High-performance control of multi-motor systems with cogging torque. Application to the Green Bank Telescope*

Abstract: This project develops: (1) a novel load-s
methodology, based on an iterative, self-tuning m
achieve high-performance control specifications i
affected by cogging torque, nonlinear characterist
speed specifications, including a reliable and eas
and (2) the implementation and experimental vali
controlling the azimuth (16 motors) and elevation
structure of the Green Bank Radio Telescope (GB
Observatory), West Virginia, US, the largest fully s
for low speed and very high precision tracking an
extending the frequency range of operation of the

Project 2: *Quantitative robust control n
performance active vibration control in
with model uncertainty. Application to t*

Abstract: In last few decades use of large flexible
applications like space robotics, space based tele

Green Bank Telescope (GBT), National Radio Astronomy Observatory (NRAO), WV, USA

Project 3: *High-Performance Quantitative Robust Switching Control for Optical Telescopes*

Abstract: This project introduces an innovative robust and nonlinear control design methodology for high-performance servo-systems in optical telescopes. The dynamics of optical telescopes typically vary according to azimuth and altitude angles, temperature, friction, speed and acceleration, leading to nonlinearities and plant parameter uncertainty. The methodology proposed in this project attenuates the effect of friction and combines robust Quantitative Feedback Theory (QFT) techniques with nonlinear switching strategies that achieve simultaneously the best characteristics of a set of very active robust controllers and very stable robust controllers. It is also proven that the nonlinear/switching controller is stable for any switching strategy and switching velocity, according to described frequency conditions based on common quadratic Lyapunov functions (CQLF) and the circle criterion.

Project 4: *Advanced nonlinear robust MIMO control systems for high precision tracking and pointing in large optical and radio telescopes. Application to the Giant Meterwave Radio Telescope*

Abstract: This project proposes (1) develop a new advanced nonlinear and robust multi-input multi-output control methodology to design high performance servo systems for extremely large telescopes and antennas, and (2) validate it experimentally in the GMRT, Giant Meterwave Radio Telescope, National Centre for Radio Astrophysics (NCRA), Tata Institute of Fundamental Research (TIFR), India. The facility has 30 fully steerable radio antennas, each of diameter 45 meters. GMRT operates in frequency range of 50 MHz to 1500 MHz. It is the largest radio telescope in Asia and largest in the world at this frequency range. The radio dishes of GMRT are made using SMART (Stretch Mesh Attached to Rope Trusses) concept. This allows construction of light weight, low cost dishes. But such structure also lowers the fundamental frequency of the dish making it more challenging to control under windy conditions.

Selection of publications

[1]. Garcia-Sanz,M., Ranka,T., Joshi,B.C. (2011). Advanced nonlinear robust controller design for high-performance servo-systems in large radar antennas. 63th National Aerospace & Electronics Conference, IEEE-NAECON, Dayton, Ohio, USA.

[2]. Garcia-Sanz,M., Ranka,T., Joshi,B.C. (2012). High-performance switching QFT control for large radio telescopes with saturation constraints. 64th National Aerospace & Electronics Conference, IEEE-NAECON, Dayton, Ohio, USA.

http://cesc.case.edu/OurTelescopeControlProjects.htm

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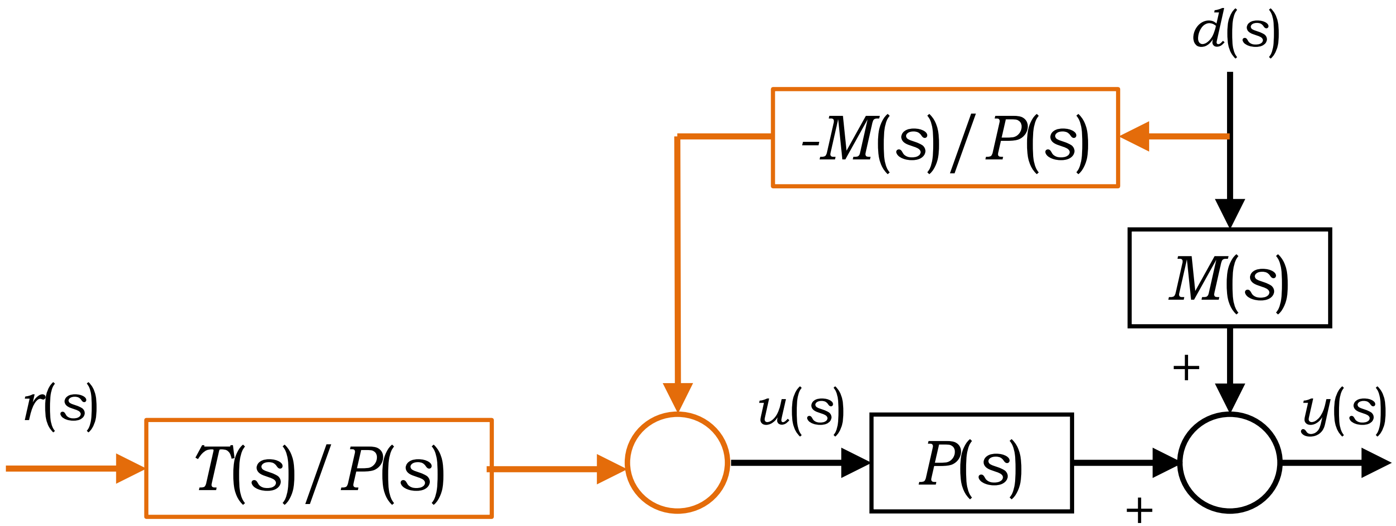
Why do we need feedback control?



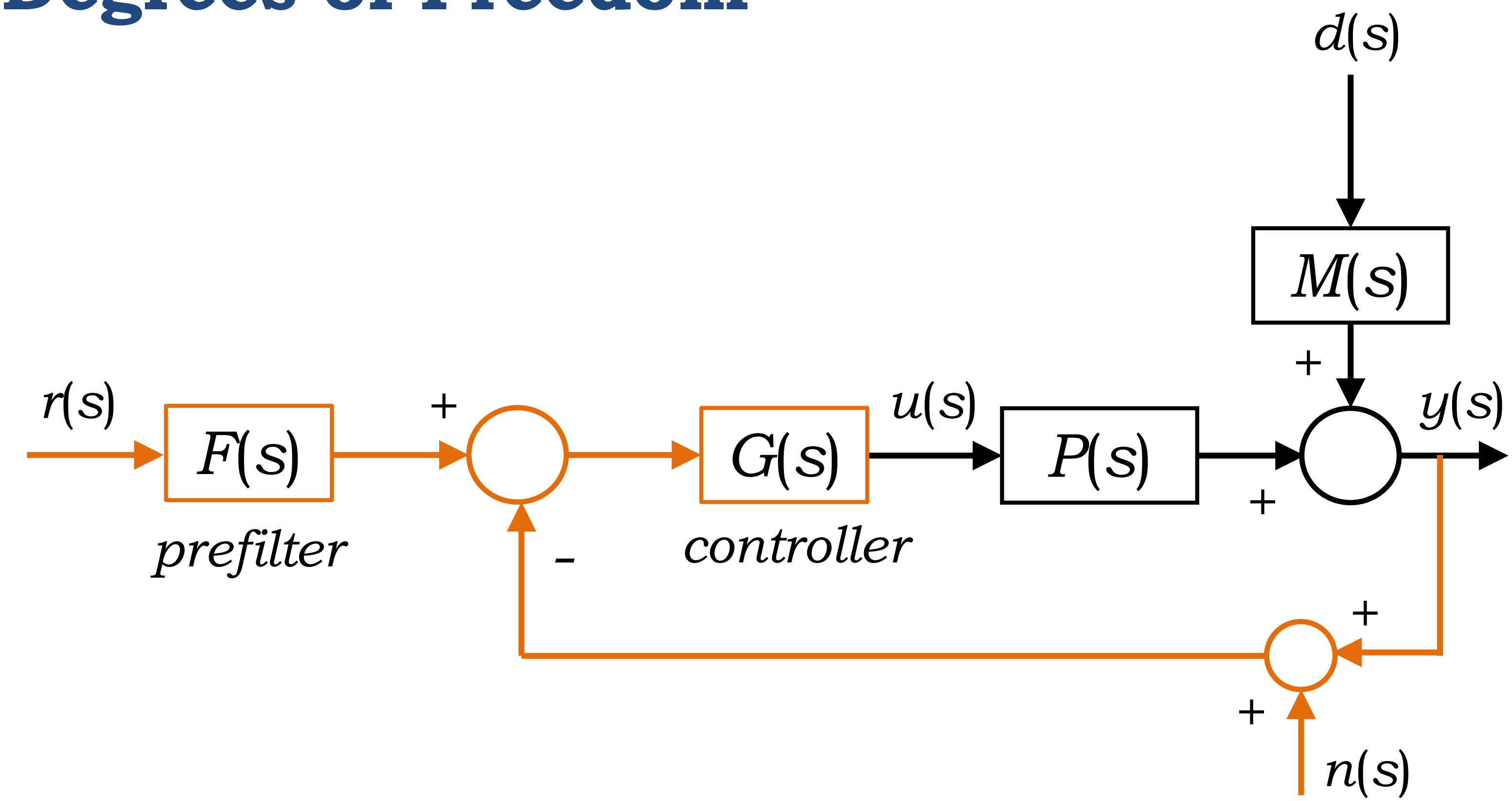
$y(s) = P(s)\ u(s) + M(s)\ d(s)$

with: $u(s) = -[M(s) / P(s)]\ d(s) + [T(s) / P(s)]\ r(s)$ THIS IS OPEN LOOP

$y(s) = T(s)\ r(s)$

We need feedback control because:
(a) *model uncertainty*, and (b) *unmeasured disturbances*

Feedback control.
2 Degrees of Freedom



$$y(s)=\frac{P(s)G(s)}{1+P(s)G(s)}F(s)\,r(s)+\frac{M(s)}{1+P(s)G(s)}d(s)-\frac{P(s)G(s)}{1+P(s)G(s)}n(s)$$

Control Engineering is about…

References, Trajectories

Control theory for demanding specifications

Sensors

Encoder AZ Motors
Encoder EL Motors
AZ and EL encoders
Quadrant detector
Accelerometers
Temp, etc.

Robust MIMO **QFT** Controllers

$$\begin{bmatrix} x(s) \\ y(s) \\ z(s) \\ \varphi(s) \\ \theta(s) \\ \psi(s) \end{bmatrix} = \begin{bmatrix} p_{11}(s) & p_{12}(s) & p_{13}(s) & p_{14}(s) & p_{15}(s) & p_{16}(s) \\ p_{21}(s) & p_{22}(s) & p_{23}(s) & p_{24}(s) & p_{25}(s) & p_{26}(s) \\ p_{31}(s) & p_{32}(s) & p_{33}(s) & p_{34}(s) & p_{35}(s) & p_{36}(s) \\ p_{41}(s) & p_{42}(s) & p_{43}(s) & p_{44}(s) & p_{45}(s) & p_{46}(s) \\ p_{51}(s) & p_{52}(s) & p_{53}(s) & p_{54}(s) & p_{55}(s) & p_{56}(s) \\ p_{61}(s) & p_{62}(s) & p_{63}(s) & p_{64}(s) & p_{65}(s) & p_{66}(s) \end{bmatrix} \begin{bmatrix} F_x(s) \\ F_y(s) \\ F_z(s) \\ T_\varphi(s) \\ T_\theta(s) \\ T_\psi(s) \end{bmatrix}$$

Real-time Computer

Actuators

Azimuth motors

Elevation motors

Sub-reflector parallel kinematics platform

Main dish surface actuators, etc.

Feedback

Telescope, Spacecraft or Wind Turbine or other…

*Understanding and modeling the **plant dynamics***

Disturbances

wind speed, gravity, azimuth trail, motor cogging, etc

- Stability
- Tracking
- Disturbance rejection
- Robustness
- Damping
- etc.

QFT Robust Control

Over the last 25 years we have worked on QFT (**Quantitative Feedback Theory**) robust control, including fundamental research and real-world applications with industry and space agencies.

Industrial projects where we have applied QFT Control solutions

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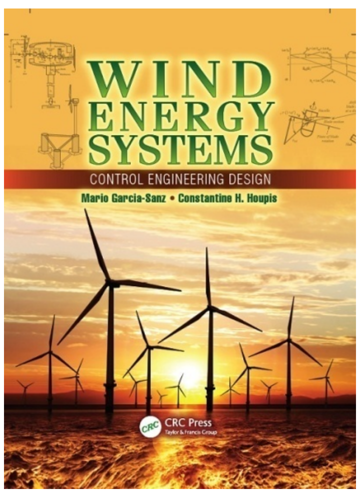
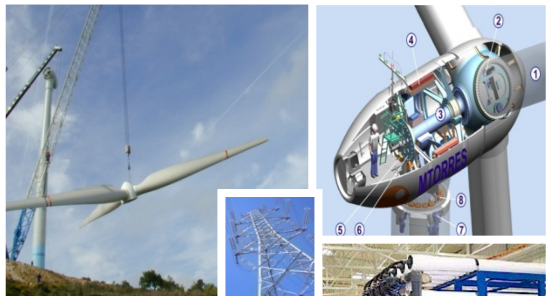
Prof. Mario Garcia-Sanz
Director

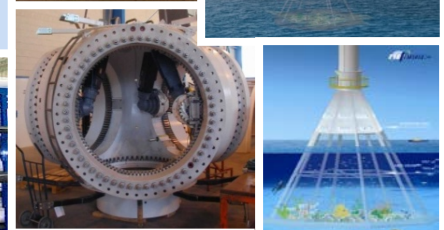


Wind Energy Systems: Control Engineering Design
Mario Garcia-Sanz and Constantine H. Houpis (2012)
CRC Press, Taylor & Francis.

Control Applications

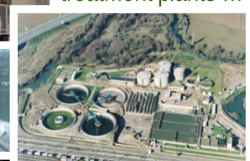
Energy: Multi-megawatt wind turbines, Variable-speed multi-pole synchronous generators, Off-shore systems, Desalination systems, Waves energy conversion …



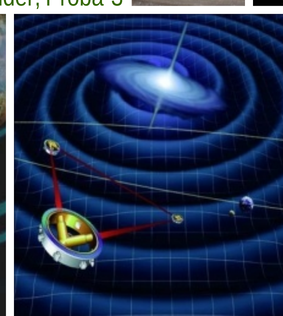


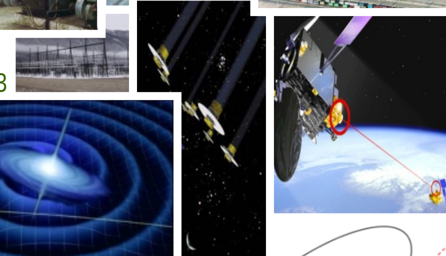
Industrial : Robotics, Grid, Furnaces, Heating systems, Paper converting machines, Automatic manufacturing machines, PKM …

Environmental: Waste-water treatment plants …

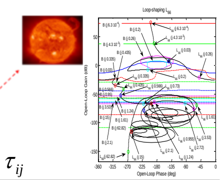


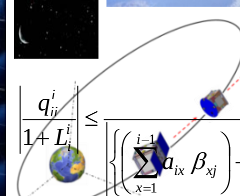
Spacecraft : with flexible appendages, flying in formation, Darwin mission, Lisa-pathfinder, Proba-3





QFT Robust Control for MIMO, non-linear, distributed, nmp …





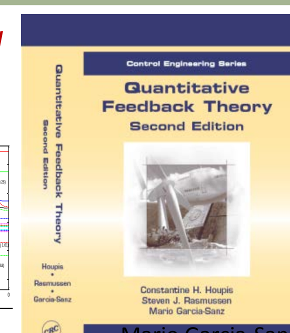
$$\left|\frac{q_{ij}^i}{1+L_i^i}\right| \le \frac{\tau_{ij}}{\left|\left[\left(\sum_{x=1}^{i-1} a_{ix}\beta_{xj}\right)+\beta_{ij}-\sum_{k=i+1}^{n}\left(p_{ik}^{*i}+g_{ik}\right)\tau_{kj}\right]_{ij}\right|_{max}}$$

Fundamental research

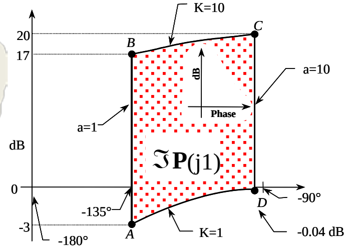
*To gain knowledge on multi-input-multi-output systems, nonlinear plants, distributed parameter systems, non-minimum phase, time delay and/or uncertainty, etc., and to develop new methodologies to design **quantitative robust controllers** to improve the **efficiency** and **reliability** of such systems*

Applied reseach

*To develop advanced solutions with industrial partners, for practical control engineering problems in **Energy Systems**, Multi-megawatt Wind Turbines, Formation Flying **Spacecraft**, Satellites with Flexible Appendages , **Power** Systems, **Water** Treatment Plants, etc.*



Plant Model + Uncertainty



Performance Specifications (P.S.)

Robustness

Performance

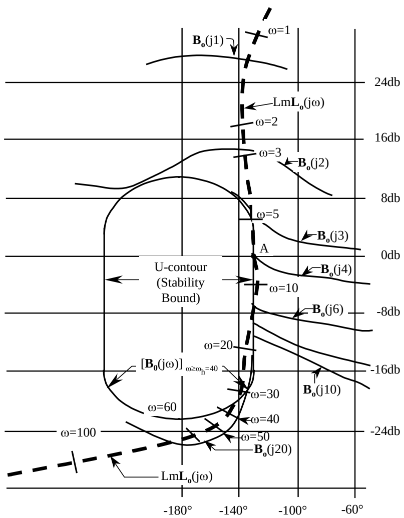
QFT Controller Design

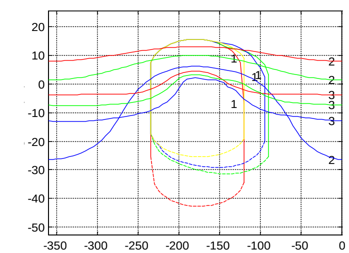
Bounds

LoopShaping

L_0

Transparency of the technique

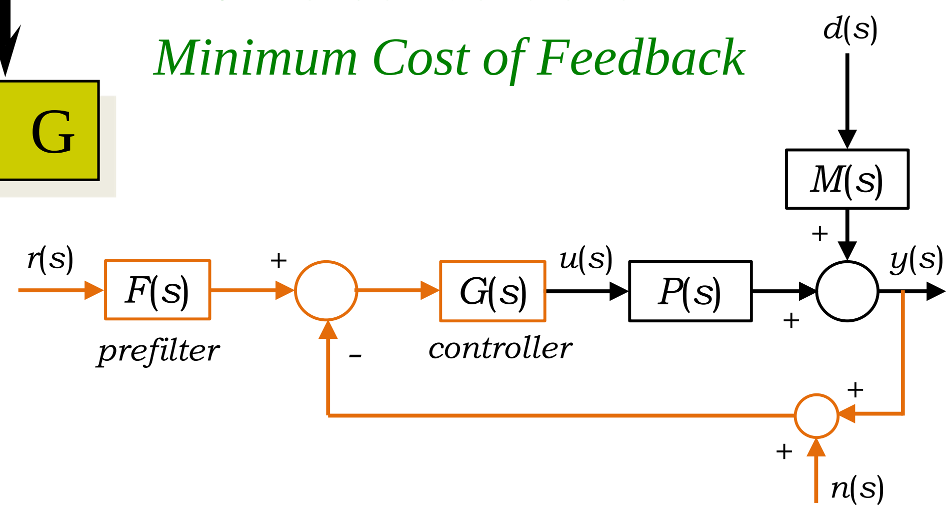




Minimum Order Controller

Minimum Cost of Feedback

F , G



QFT. A successful robust control theory for real-world applications:

- Stable and Unstable Systems,
- SISO and MIMO Plants,
- Analog and Discrete Systems,
- Linear and Non-linear Plants,
- Constant and variable parameters,
- Minimum and Non-minimum Phase,
- Cascade Control Systems, etc.

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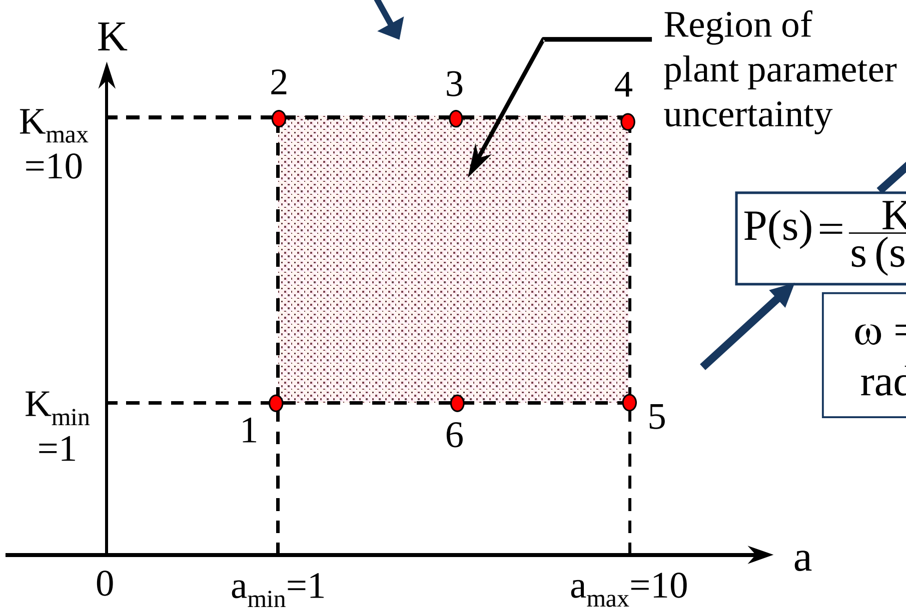
Model with Uncertainty: QFT-Templates

Plant Template obtained by mapping points of uncertainty region into points on to the N.C.

Model →

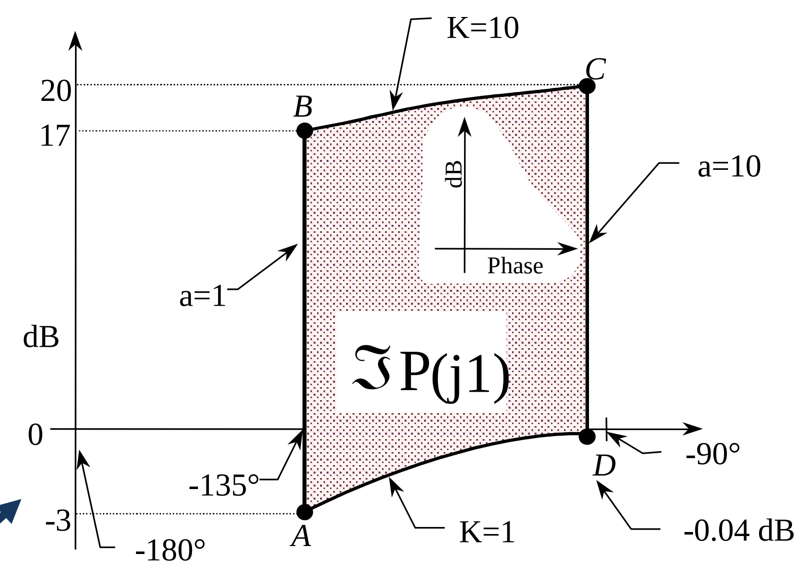
$$P(s) = \frac{K\,a}{s\,(s+a)}$$

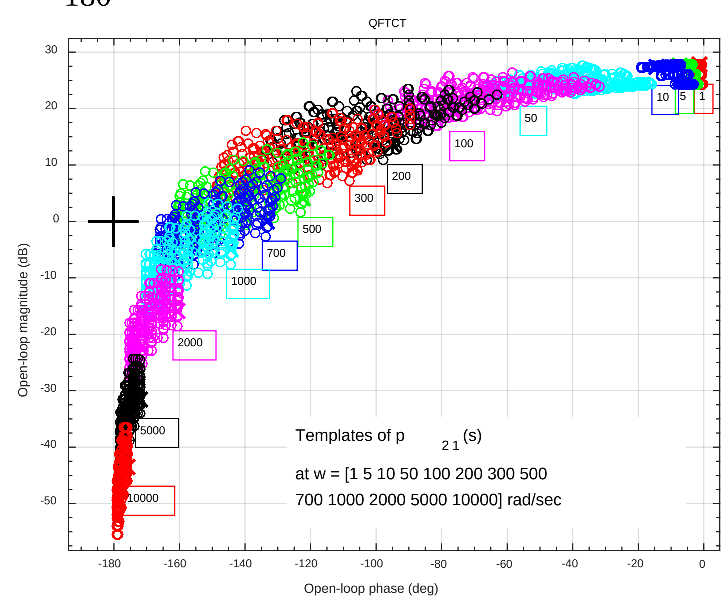
Parameter Uncertainty



$$P(s) = \frac{K\,a}{s\,(s+a)}$$

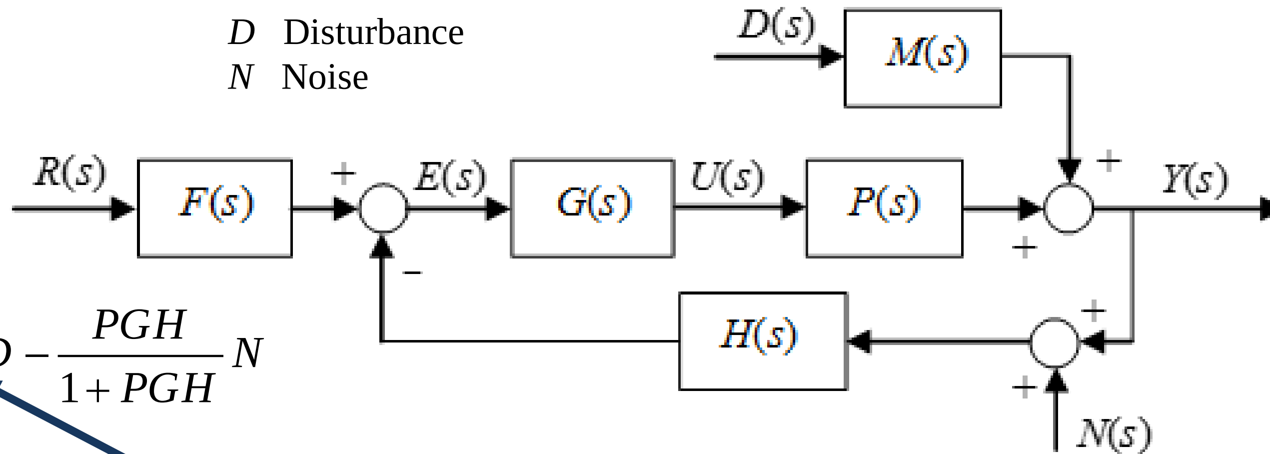
ω = 1 rad/s





Control Specifications

R Reference
D Disturbance
N Noise



$$Y = \frac{PG}{1+PGH} F R + \frac{M}{1+PGH} D - \frac{PGH}{1+PGH} N$$

$$E = \frac{1}{1+PGH} F R - \frac{H\,M}{1+PGH} D - \frac{H}{1+PGH} N$$

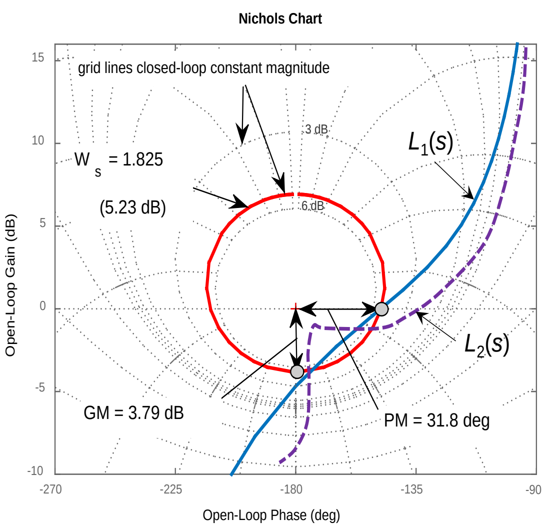
$$U = \frac{G}{1+PGH} F R - \frac{GH}{1+PGH} (M\,D + N)$$

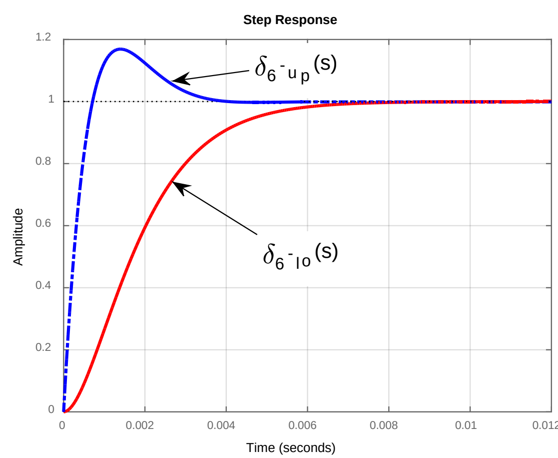
Specifications in terms of T.F.

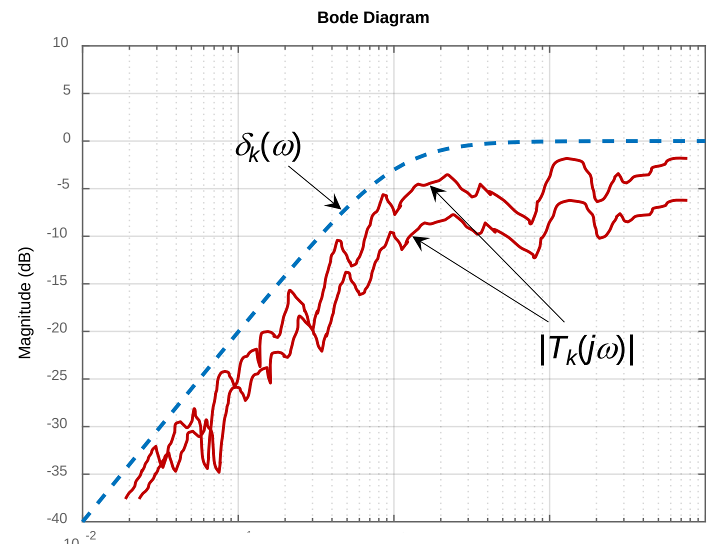
$$\left|\frac{Y(s)}{D(s)}\right| = \left|T_k(s)\right| = \left|\frac{M(s)}{1+P(s)G(s)}\right| \le \delta_k(\omega), \;\; \omega \in \Omega_k$$

$$\delta_{6\_lo}(\omega) < \left|F(s)\,\frac{P(s)G(s)}{1+P(s)G(s)}\right| \le \delta_{6\_up}(\omega)$$

$\omega \in [.....]$ rad/sec







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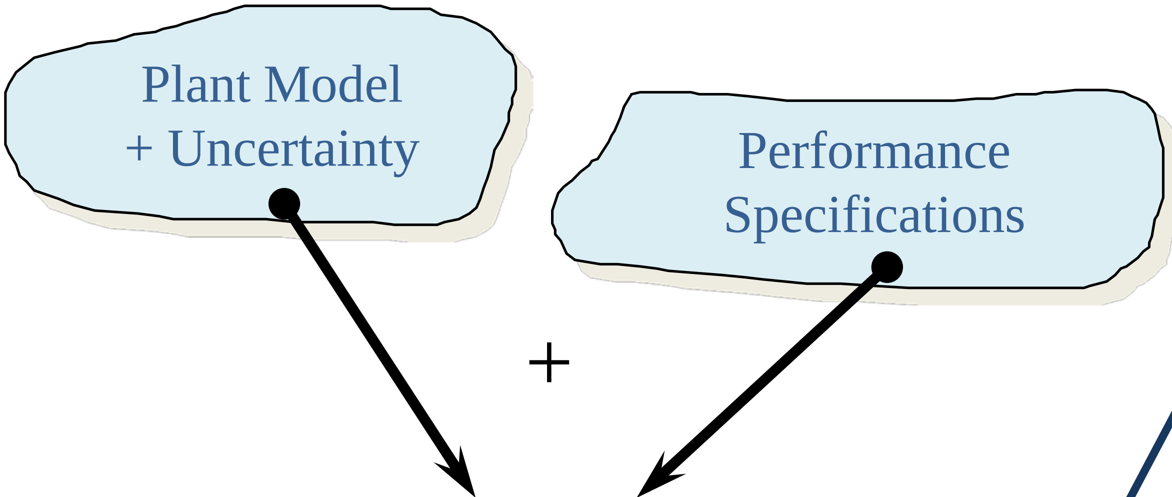
QFT-Bounds



Bound Quadratic Inequality

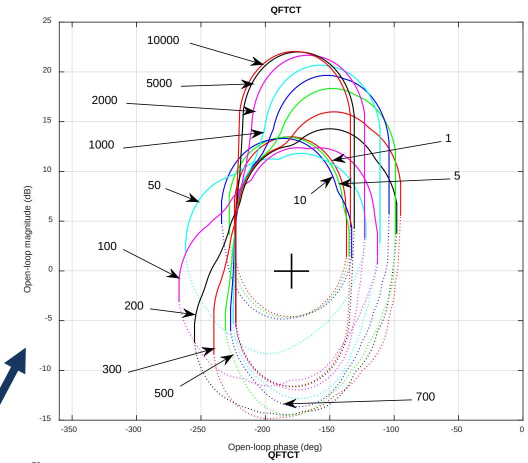
$$p^2 \cdot \left(1-\frac{1}{\delta_1^2}\right) \cdot g^2 + 2 \cdot p \cdot \cos(\phi+\theta) \cdot g + 1 \geq 0$$

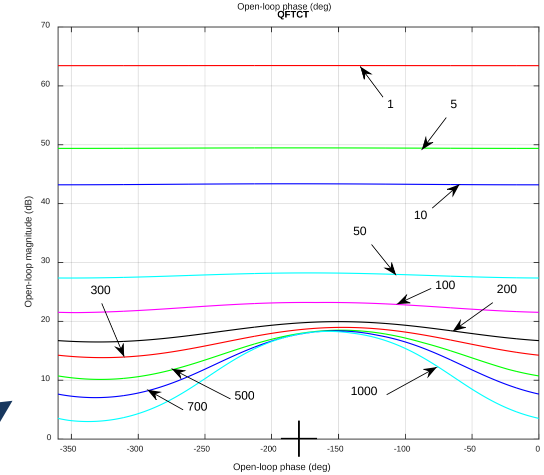
$$p^2 \cdot g^2 + 2 \cdot p \cdot \cos(\phi+\theta) \cdot g + \left(1-\frac{1}{\delta_2^2}\right) \geq 0$$

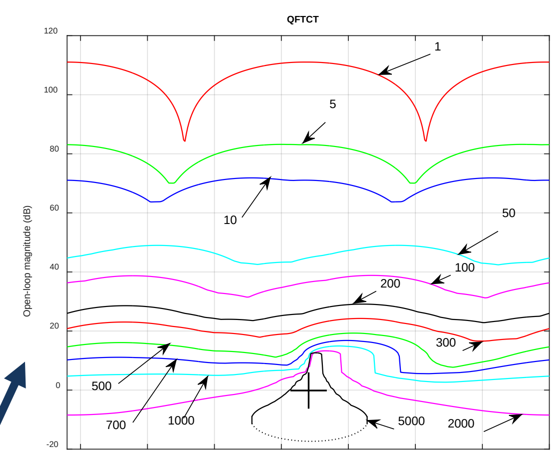
$$p^2 \cdot g^2 + 2 \cdot p \cdot \cos(\phi+\theta) \cdot g + \left(1-\frac{p^2}{\delta_3^2}\right) \geq 0$$

$$\left(p^2 - \frac{1}{\delta_4^2}\right) \cdot g^2 + 2 \cdot p \cdot \cos(\phi+\theta) \cdot g + 1 \geq 0$$

$$p_e^2 p_d^2 \left(1-\frac{1}{\delta_5^2}\right) \cdot g^2 + 2 p_e p_d \left(p_e \cos(\phi+\theta_d) - \frac{p_d}{\delta_5^2} \cos(\phi+\theta_e)\right) \cdot g + \left(p_e^2 - \frac{p_d^2}{\delta_5^2}\right) \geq 0$$







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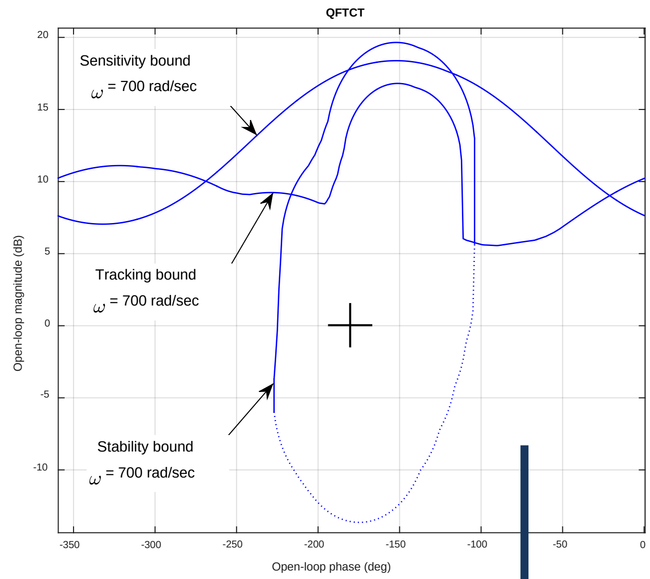
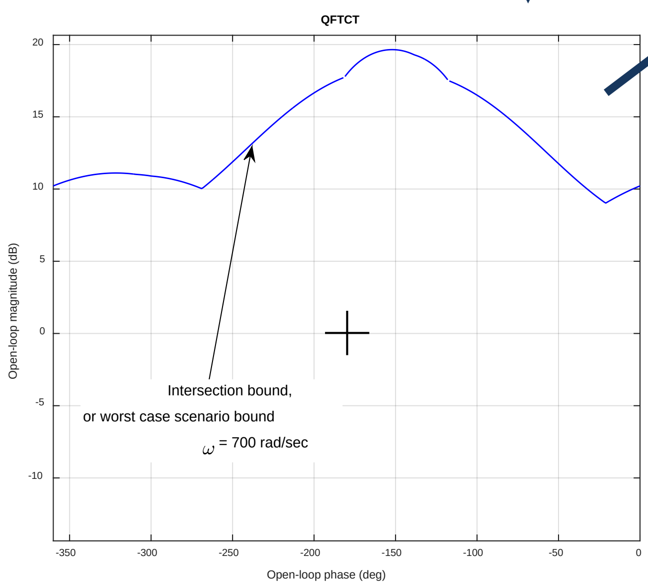
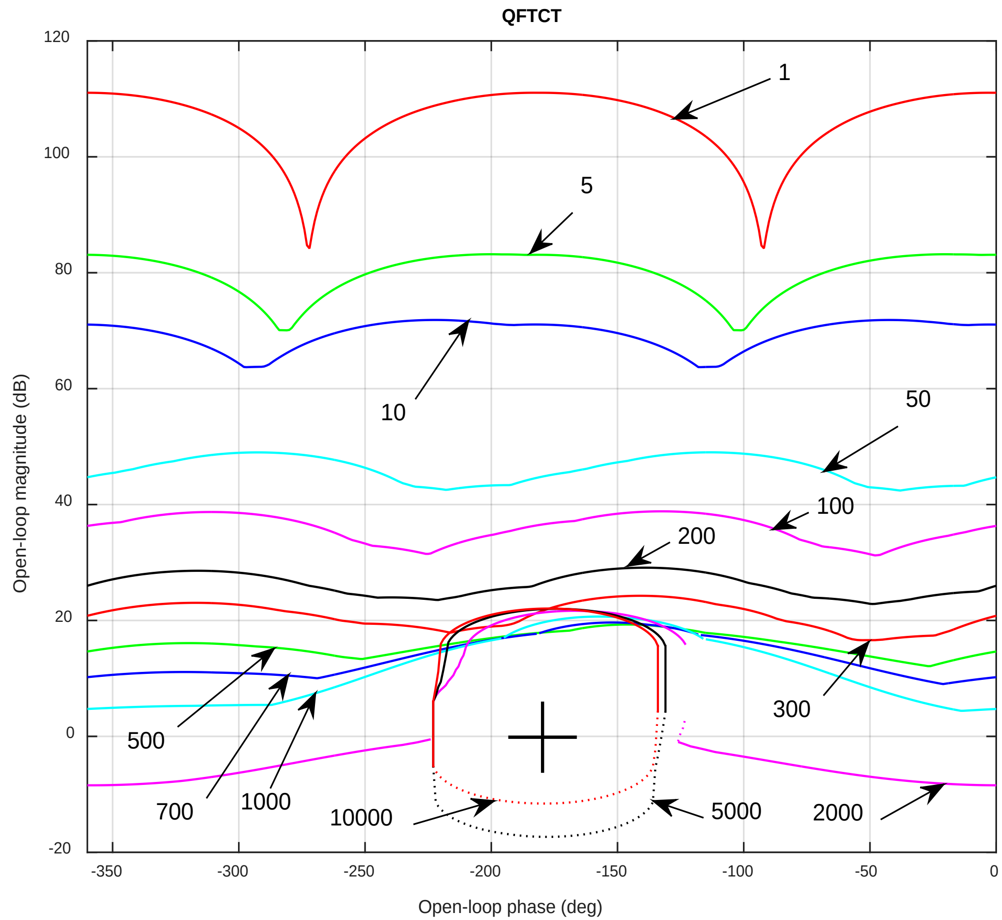
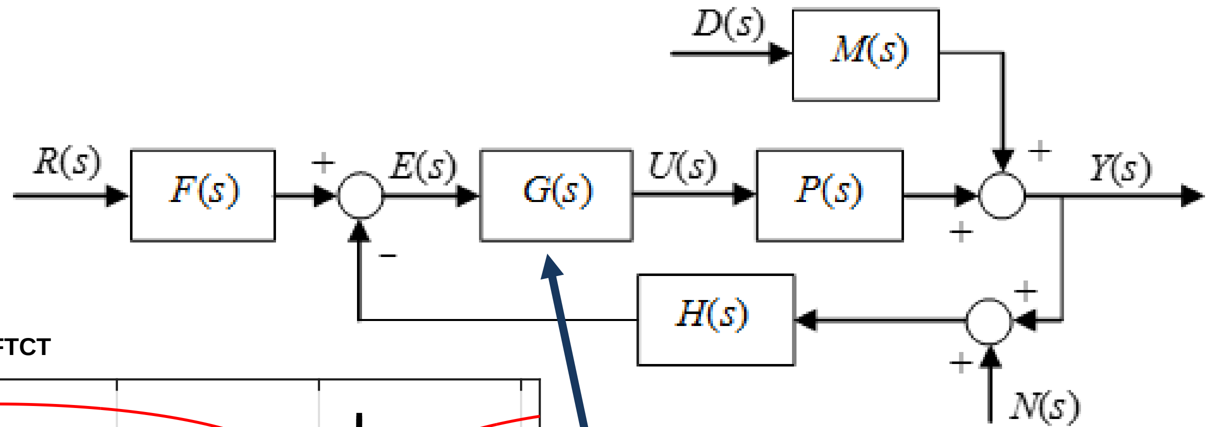
QFT-Bounds

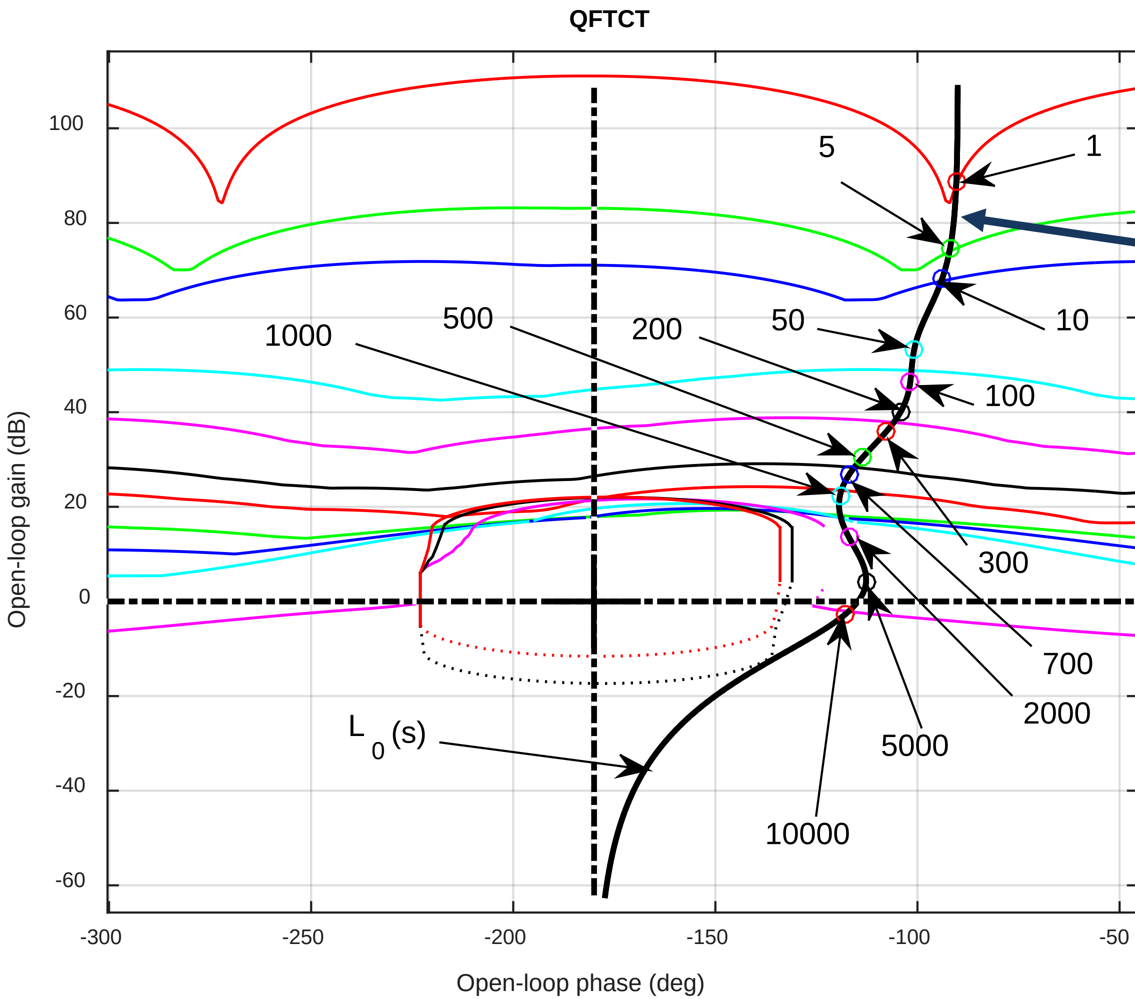

QFTCT
Sensitivity bound
ω = 700 rad/sec
Tracking bound
ω = 700 rad/sec
Stability bound
ω = 700 rad/sec
Open-loop magnitude (dB)
Open-loop phase (deg)
20
15
10
5
0
-5
-10
-350
-300
-250
-200
-150
-100
-50
0


QFTCT
Intersection bound,
or worst case scenario bound
ω = 700 rad/sec
Open-loop magnitude (dB)
Open-loop phase (deg)
20
15
10
5
0
-5
-10
-350
-300
-250
-200
-150
-100
-50
0


QFTCT
1
5
10
50
100
200
300
500
700
1000
10000
5000
2000
Open-loop magnitude (dB)
Open-loop phase (deg)
120
100
80
60
40
20
0
-20
-350
-300
-250
-200
-150
-100
-50
0

Designing G(s)
or Loop Shaping $L_o(s)$

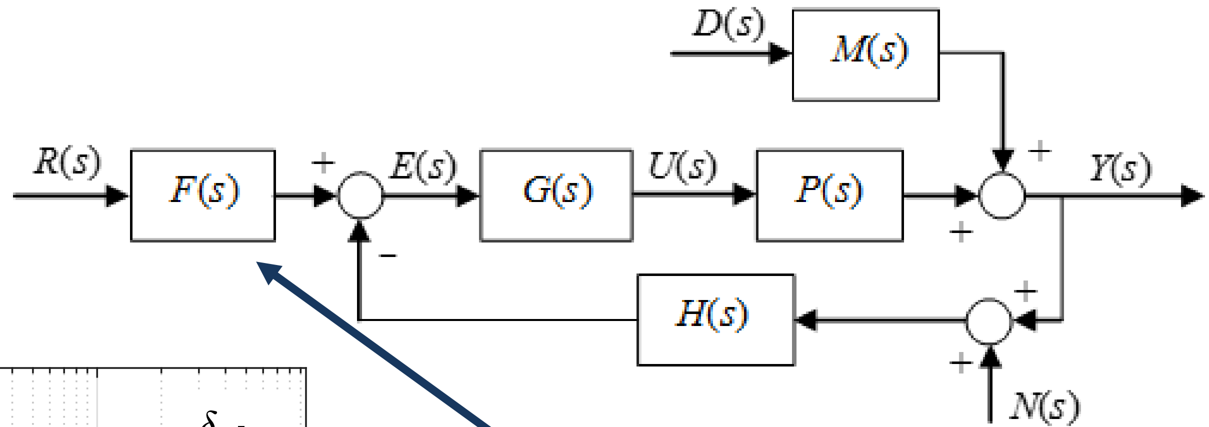


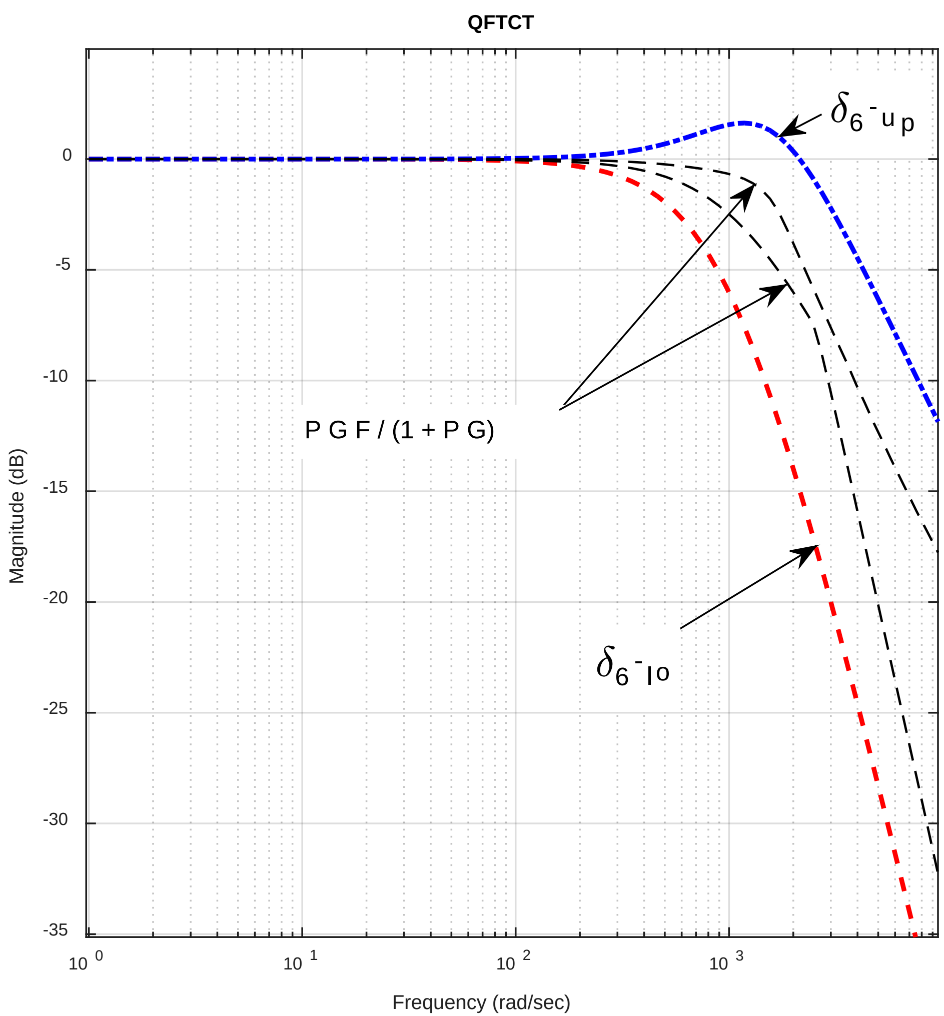


$$L_0(s) = P_0(s)G(s)$$

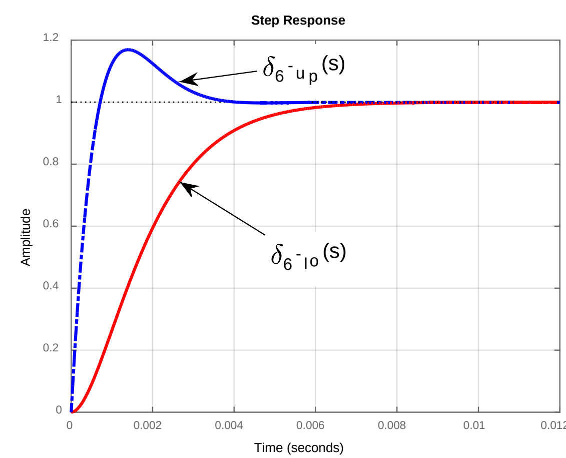
$$G(s) = \frac{1100\left(\frac{s}{55}+1\right)\left(\frac{s}{1700}+1\right)}{s\left(\frac{s}{25000}+1\right)}$$

Designing F(s)





$$F(s) = \frac{1}{\left(\dfrac{s}{1100} + 1\right)}$$



QFT Control Toolbox

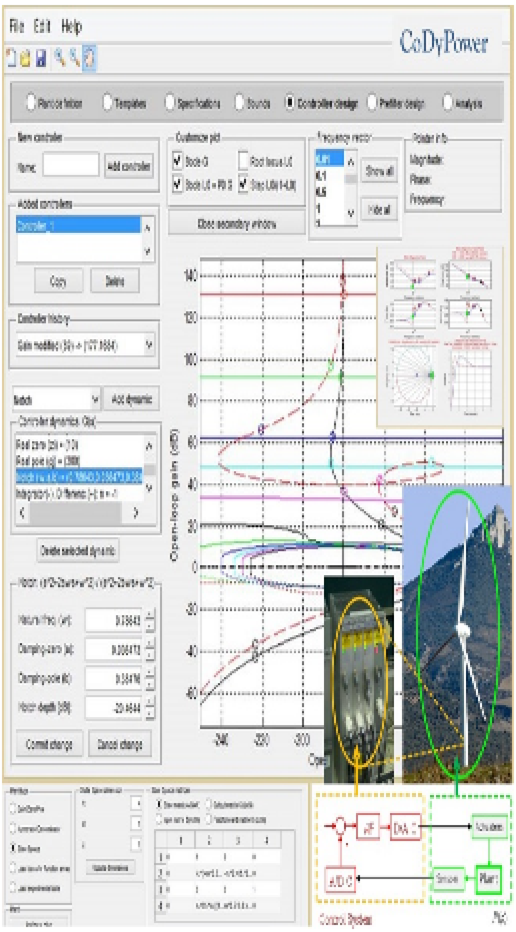
http://codypower.com

Professional
version 11.20 2016

CoDyPower LLC

QFT Control Toolbox for Matlab

Back CDP Home



QFTCT - professional

to design quantitative robust control systems

The QFT Control Toolbox, or QFTCT, is the professional, interactive and user-friendly toolbox for Matlab of CoDyPower LLC, © 2016.

It applies the Quantitative Feedback Theory (QFT) to the design of automatic robust control systems. The software has been developed by Prof. Mario Garcia-Sanz.

Over the years, the toolbox has been widely applied by industry, space agencies, research centers and universities to design control solutions and servo-systems.

The toolbox (1) deals with plants with model uncertainty, (2) is able to work with multi-objective performance specifications, (3) keeps the engineering understanding of the design in the frequency domain, and (4) gives solutions from simple PID regulators to more advanced control strategies when necessary.

References: Click here to see projects and publications.

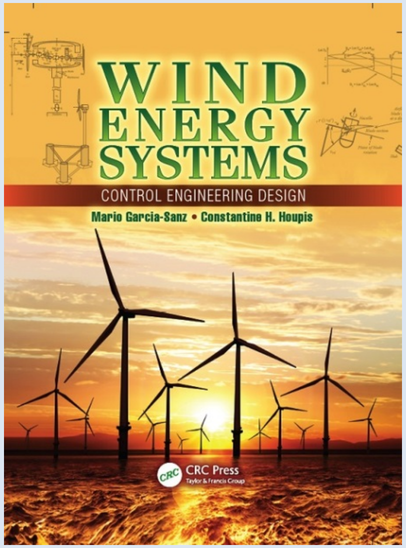
Screenshots of the toolbox: Click here to see details.

Technical support: Click here for support.

The professional version of the QFTCT includes algorithms to deal with high order plants and a large number of parameters with uncertainty. It also allows the designer to work with external mFiles to describe any plant dynamics, including structural uncertainty and also experimental data. It also gives the option of include additional plants, different from the system plant, and the possibility of define special performance specifications involving these additional plants.

How to adquire the toolbox:
For those interested on purchasing a license of the professional QFT Control Toolbox for Matlab, please Click here.

For additional information, please email:
sales@codypower.com



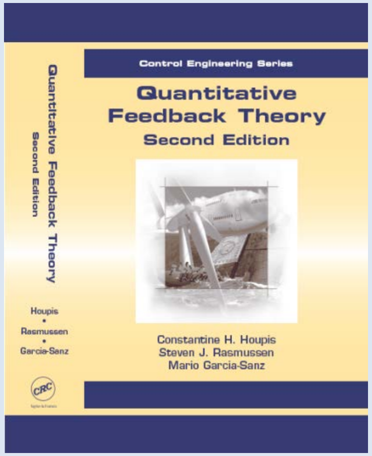
Wind Energy Systems: Control Engineering Design

Mario García-Sanz and Constantine H. Houpis (2012), CRC Press, Taylor & Francis.

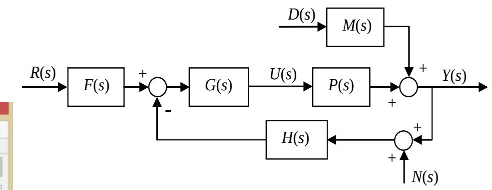
Bestselling book!!!!

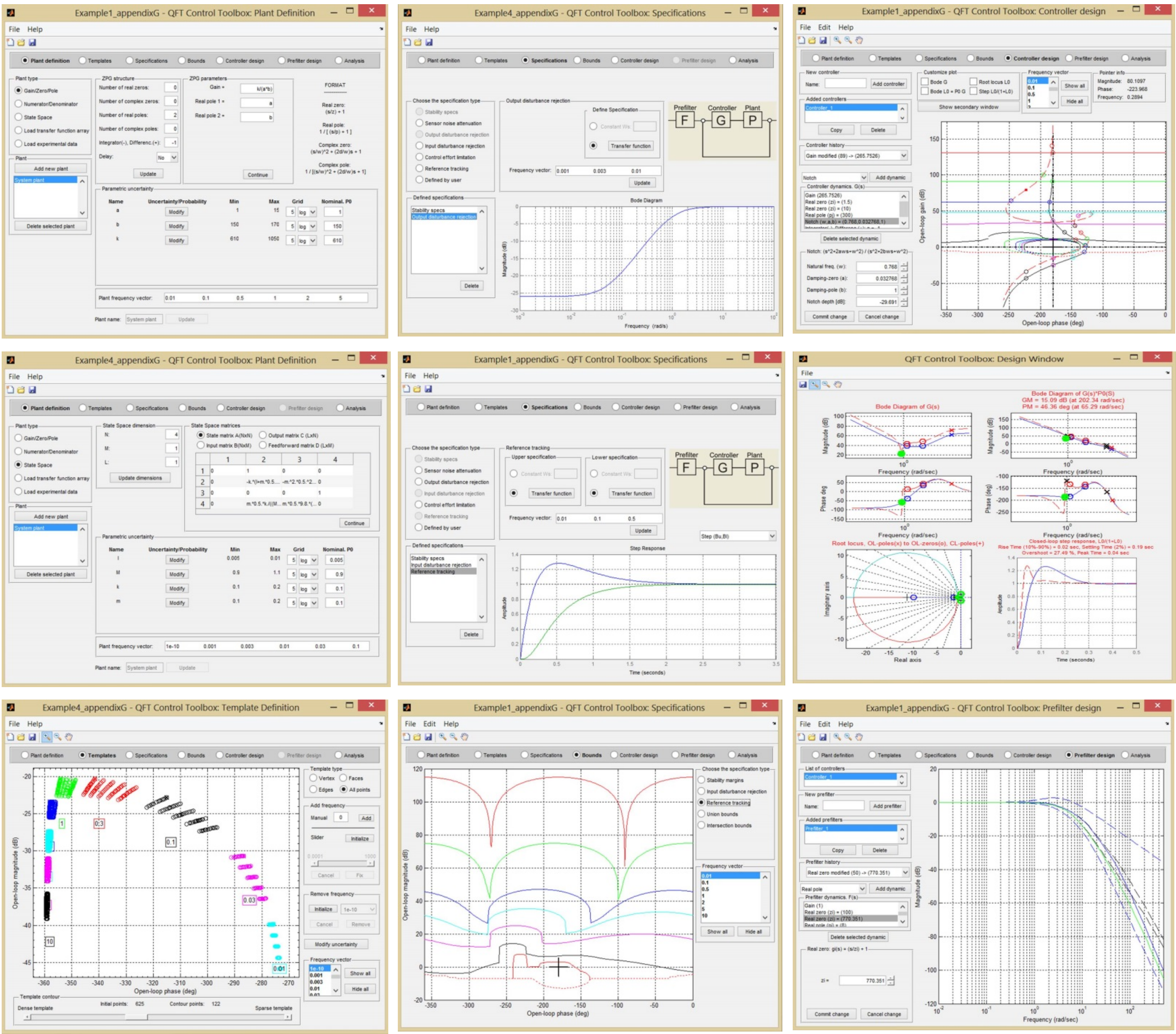
Quantitative Feedback Theory. Fundamentals and applications

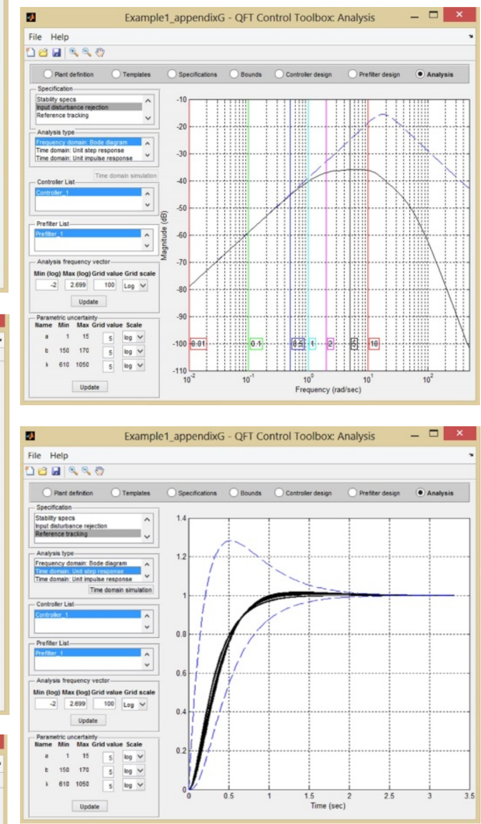
C.H. Houpis, S.J. Rasmussen and M. García-Sanz (2006), 2nd edition, CRC Press, *Taylor & Francis.*



The QFT Control Toolbox (QFTCT) --Screenshots--







Mario Garcia-Sanz, "***The QFT Control Toolbox (QFTCT) for Matlab***", Professional version 11.20, 2016,
http://codypower.com

applied control technology consortium

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http://www.actc-control.com/enews/web/enews1608.asp#Item3

Enabling Your Engineers to Solve Your Control Problems through Technology Transfer

E-News August 2016 Edition

The Importance of Simulation by Professor Mike J Grimble

If on some future occasion I am to be sent to a desert island and can take only one control technique with me then it will have to be the very trustworthy simulation capability. PID control would of course be helpful on the sandy beaches but simulation is probably the most important tool for the control engineer. In years gone by this was certainly not the case and in fact only 30 years ago simulation facilities were what might be described as primitive. However, in recent years simulation has become a valuable tool, certainly for those employed in advanced control systems design.

Quantitative Feedback Theory

The subject of Quantitative Feedback Theory (QFT) sounds highly theoretical but in fact it provides one of the most practical robust control design methods available. It is true that it has been used by a rather limited community of researchers but it is now becoming a much more accessible and valuable method, mainly because the availability of good design software.

Professor Mario Garcia-Sanz who is now at Case Western Reserve University, has developed a very easy to use design package particularly designed for multivariable systems. In the early days of QFT it was only really suitable for single-input single-output design but over the year's various software tools and design methodologies have been developed, which provide practical multivariable control solutions. One of the most successful packages and a text book were produced by Professor Constantine Hopes and Dr Steve Rasmussen. These both worked at the Air Force Institute of Technology in Ohio, USA in fact Professor Garcia-Sanz also worked with these researchers at various times (see Quantitative Feedback Theory: Fundamentals and Applications, Second Edition by Constantine H. Houpis, Steven J. Rasmussen, Mario Garcia-Sanz).

The main advantage of QFT is that it provides a robust control design tool and the robustness is meaningful. That is, there are a number of control design methods which provide some form of robustness, sometimes of only a theoretical nature. However, QFT really does allow the engineer to understand the robustness margins that are being achieved. In the early days a Nichols chart was used and a rather laborious process was needed to establish the boundaries of uncertainty which then allowed the robust control design to be achieved. In recent years the computer aided design packages make the whole process much faster and more efficient. Moreover, the type of experience need by the engineer is to have a good instinct for frequency domain control design. Classically trained control engineers often have very good instincts in this respect and hence the design method is very accessible.

Contents

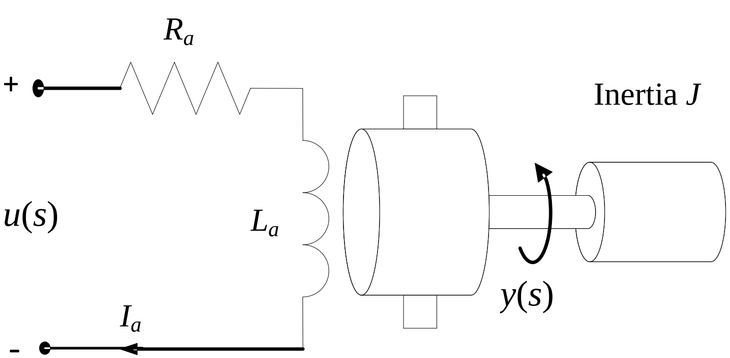
Example

A DC motor

Objective: Control the shaft angle $y(s)$ by changing the voltage $u(s)$

$$\frac{y(s)}{u(s)} = P(s) = \frac{K_m}{s(J\,s+D)(L_a\,s+R_a)} = \frac{k}{s(s+a)(s+b)}$$

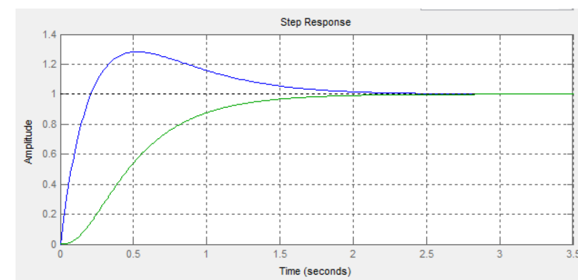
$610 \le k \le 1050$; $1 \le a \le 15$; $150 \le b \le 170$.



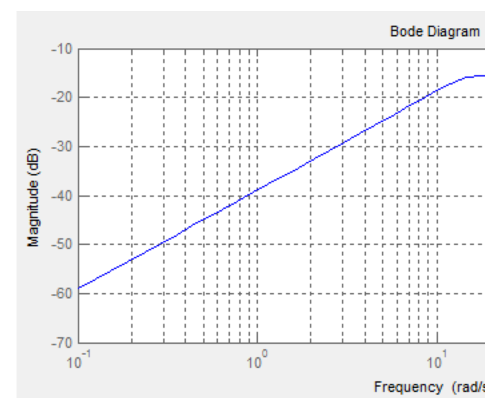
Required control specifications

1. Stability

2. Reference tracking



3. Disturbance rejection



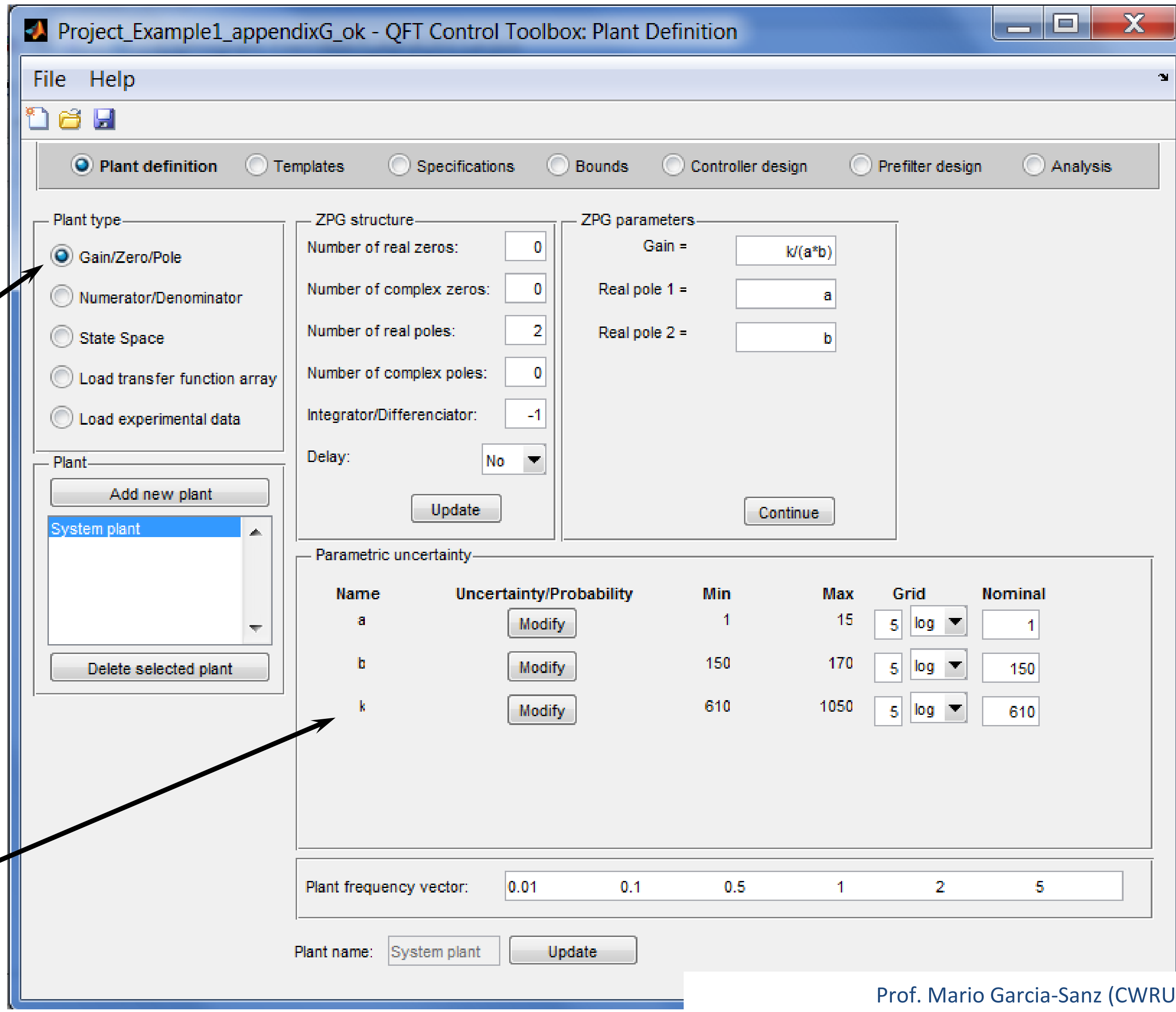
The QFT Control Toolbox

an interactive Matlab CAD toolbox for Quantitative Feedback Theory

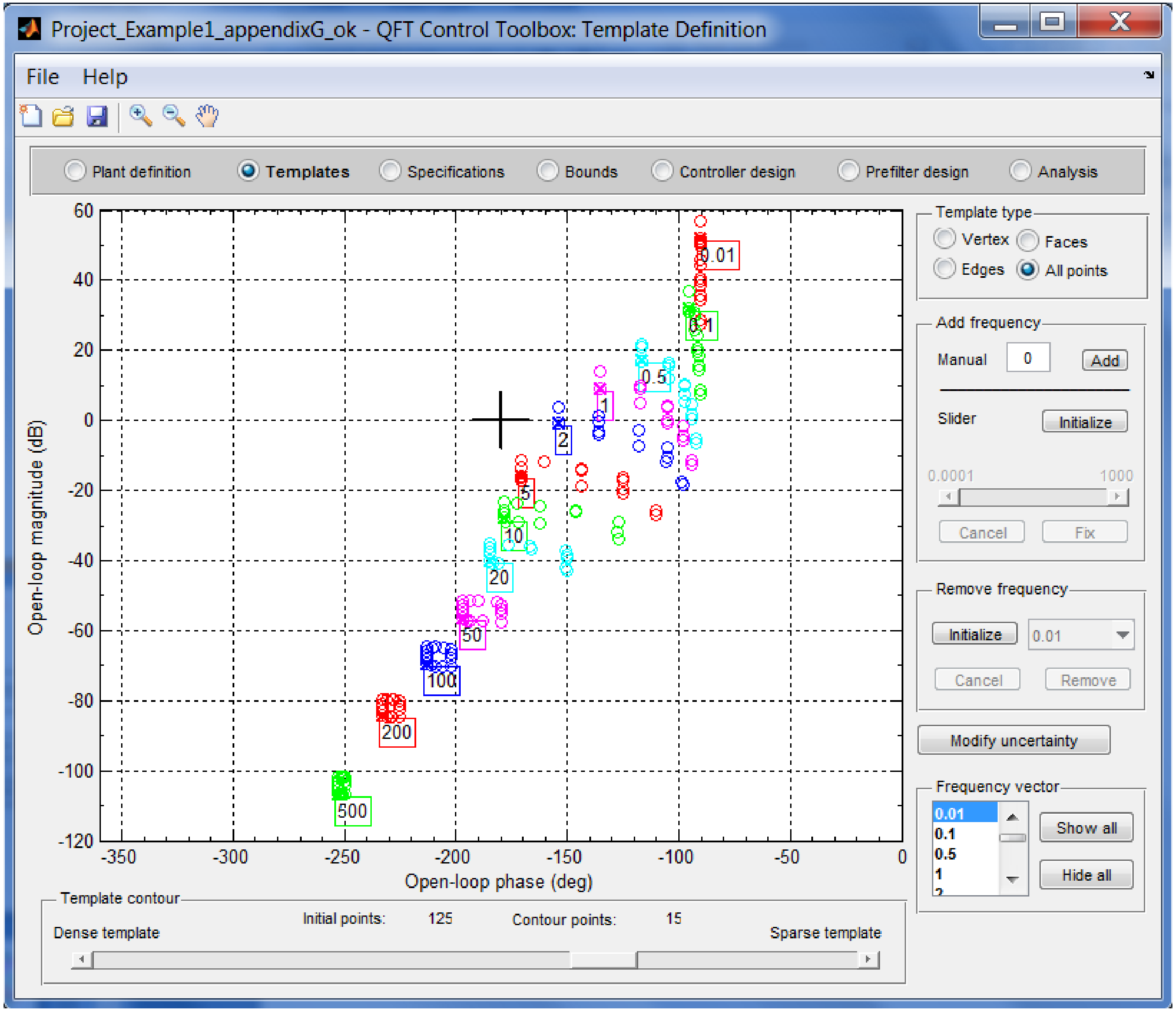
Plant Definition

$$\frac{y(s)}{u(s)} = \frac{k}{s(s+a)(s+b)}$$

$$610 \le k \le 1050$$
$$1 \le a \le 15$$
$$150 \le b \le 170$$



Templates



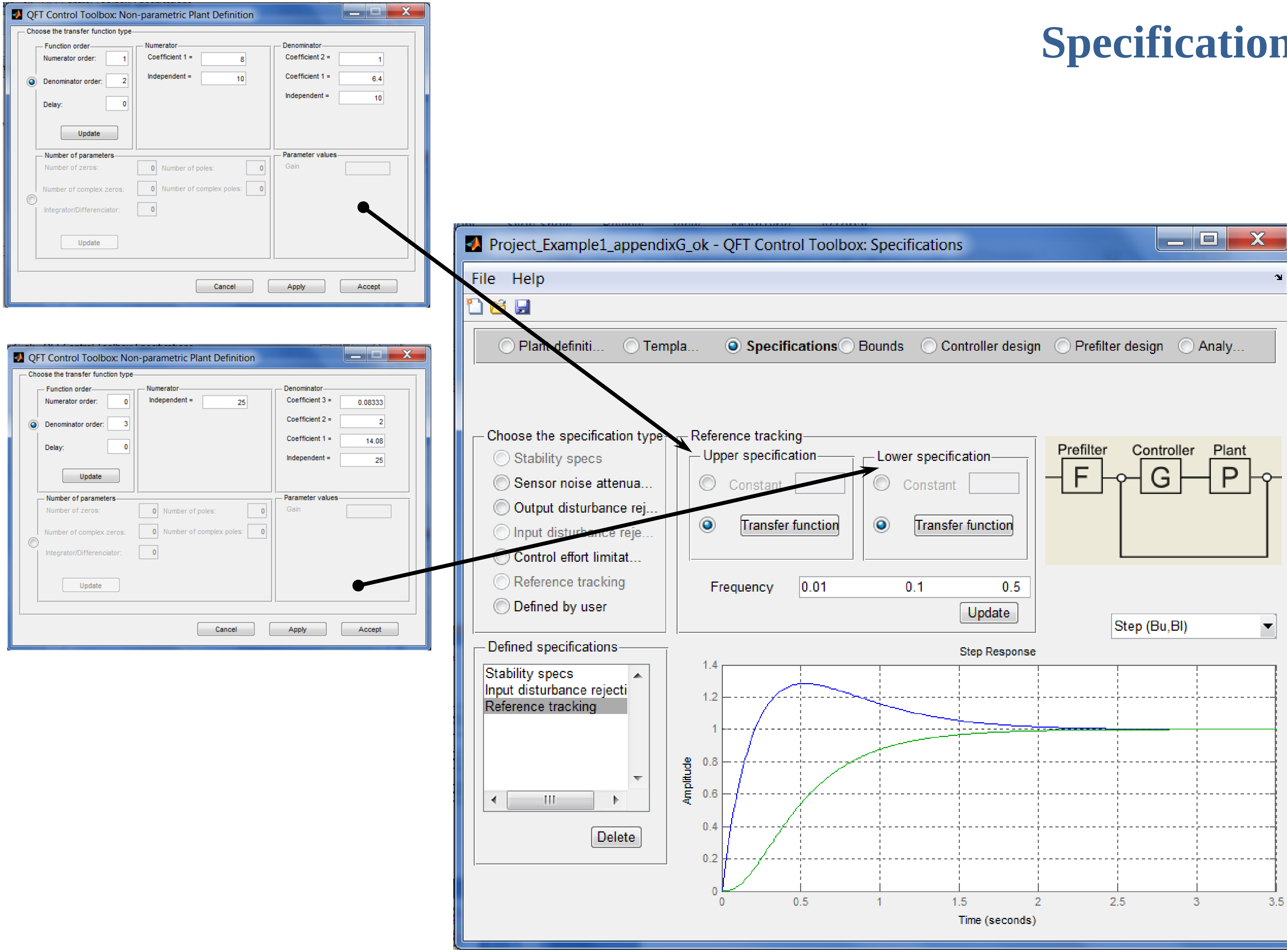
$$\frac{y(s)}{u(s)} = \frac{k}{s(s+a)(s+b)}$$

$$610 \le k \le 1050$$
$$1 \le a \le 15$$
$$150 \le b \le 170$$

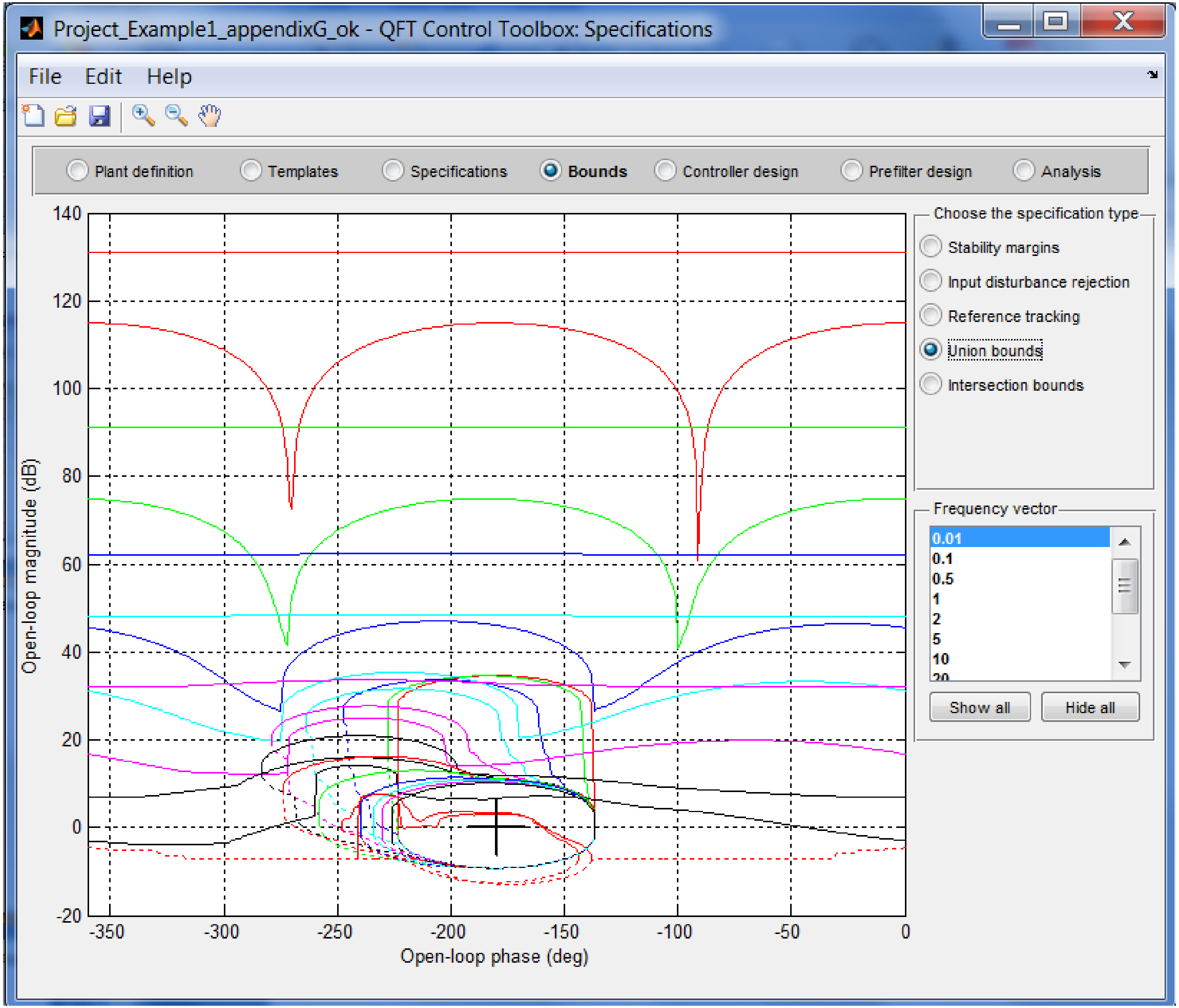
s ≈ j ω

ω = [0.01 0.1 0.5 1 2 5 10 20 50 100 200 500] rad/sec

Specifications



Bounds


Project_Example1_appendixG_ok - QFT Control Toolbox: Specifications
File
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Controller design
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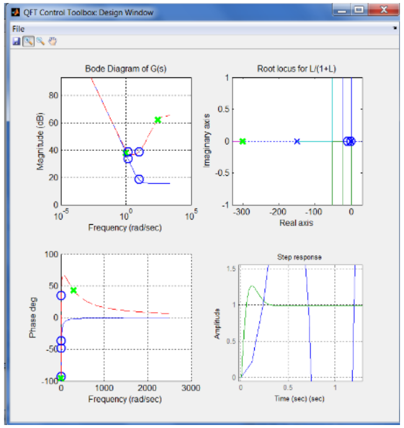
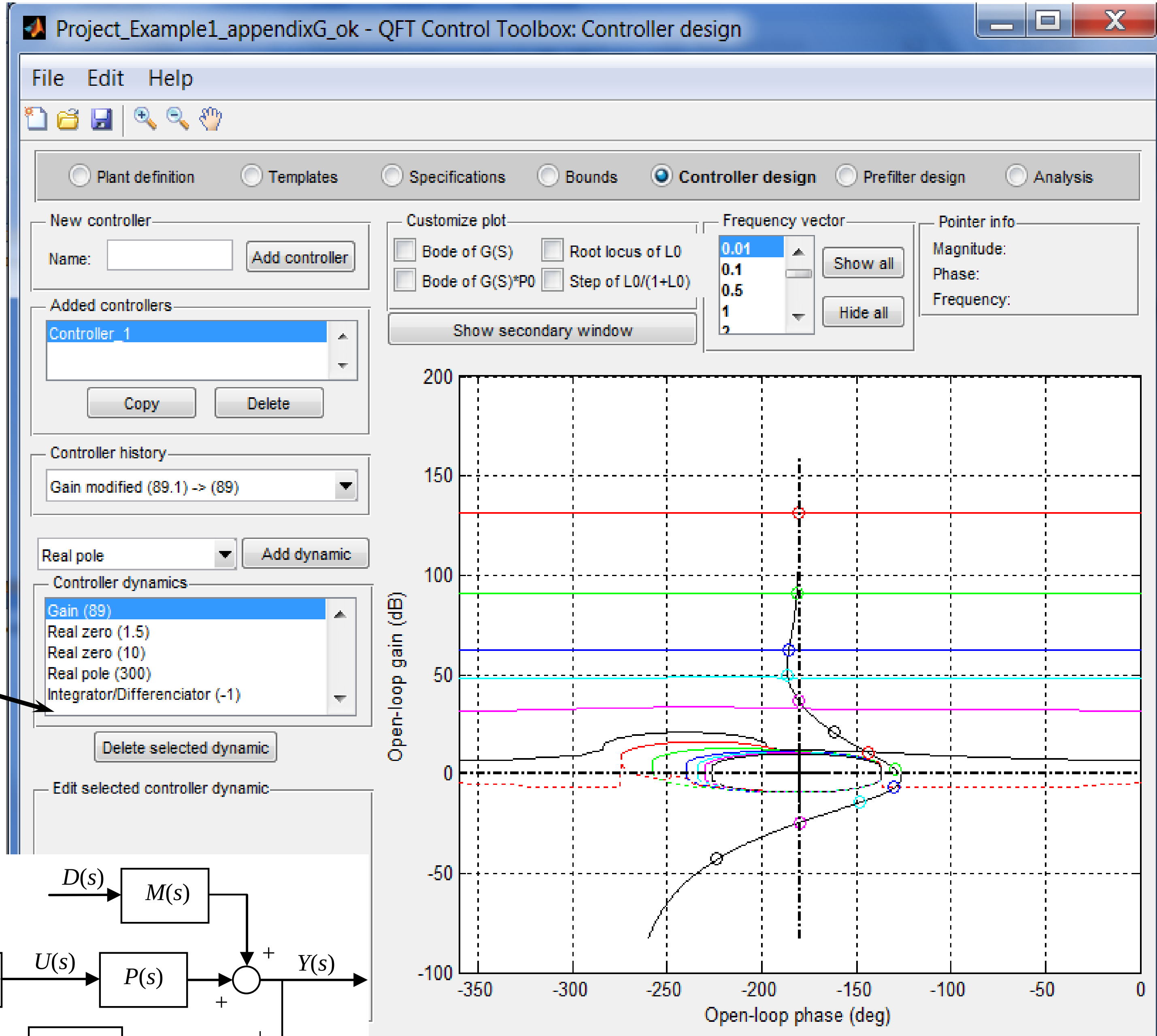
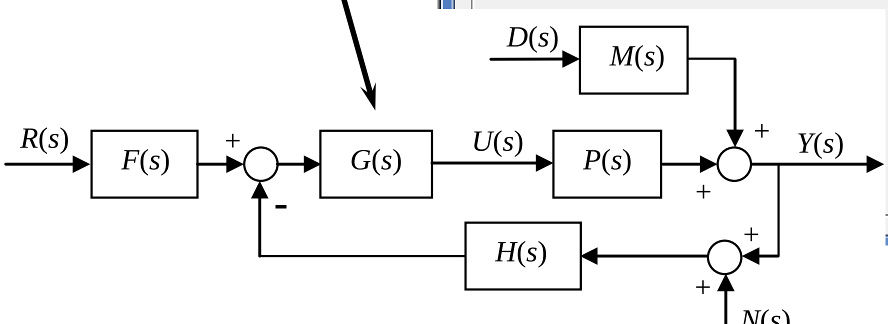
Analysis
Choose the specification type
Stability margins
Input disturbance rejection
Reference tracking
Union bounds
Intersection bounds
Frequency vector
0.01
0.1
0.5
1
2
5
10
Show all
Hide all
Open-loop magnitude (dB)
Open-loop phase (deg)
140
120
100
80
60
40
20
0
-20
-350
-300
-250
-200
-150
-100
-50
0

Loop-shaping



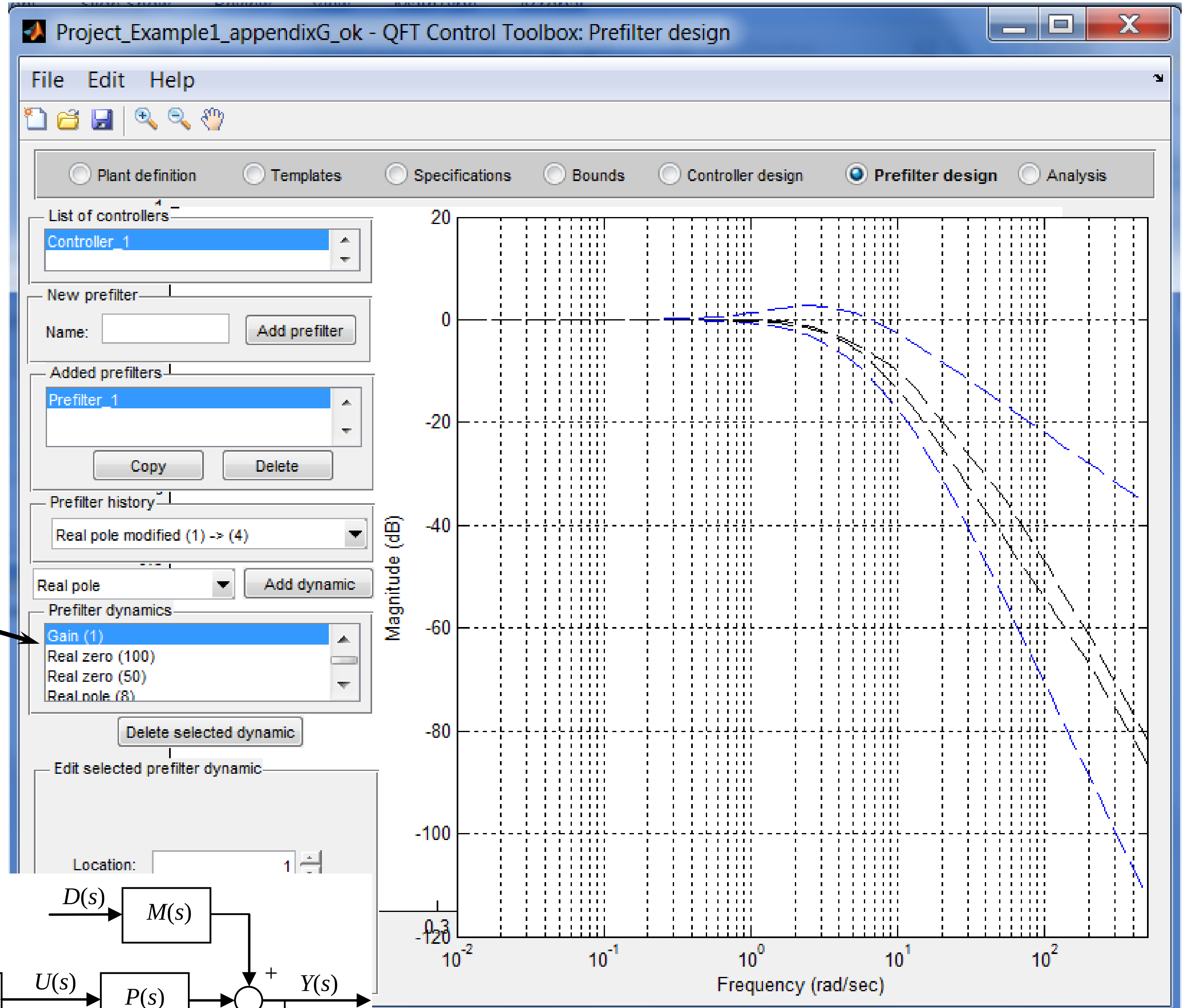
$$G(s)=\frac{89\left(\frac{s}{10}+1\right)\left(\frac{s}{1.5}+1\right)}{s\left(\frac{s}{300}+1\right)}$$

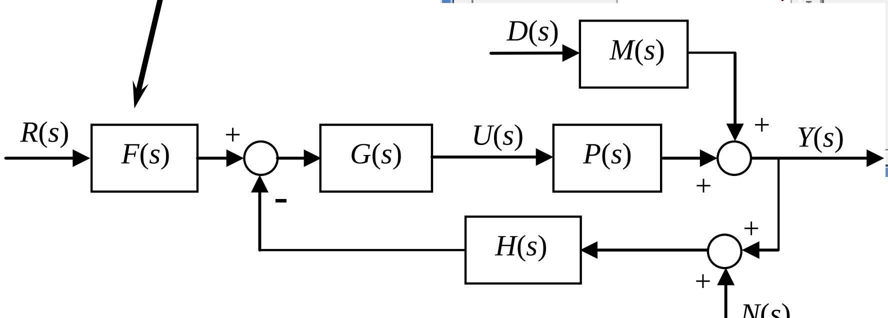




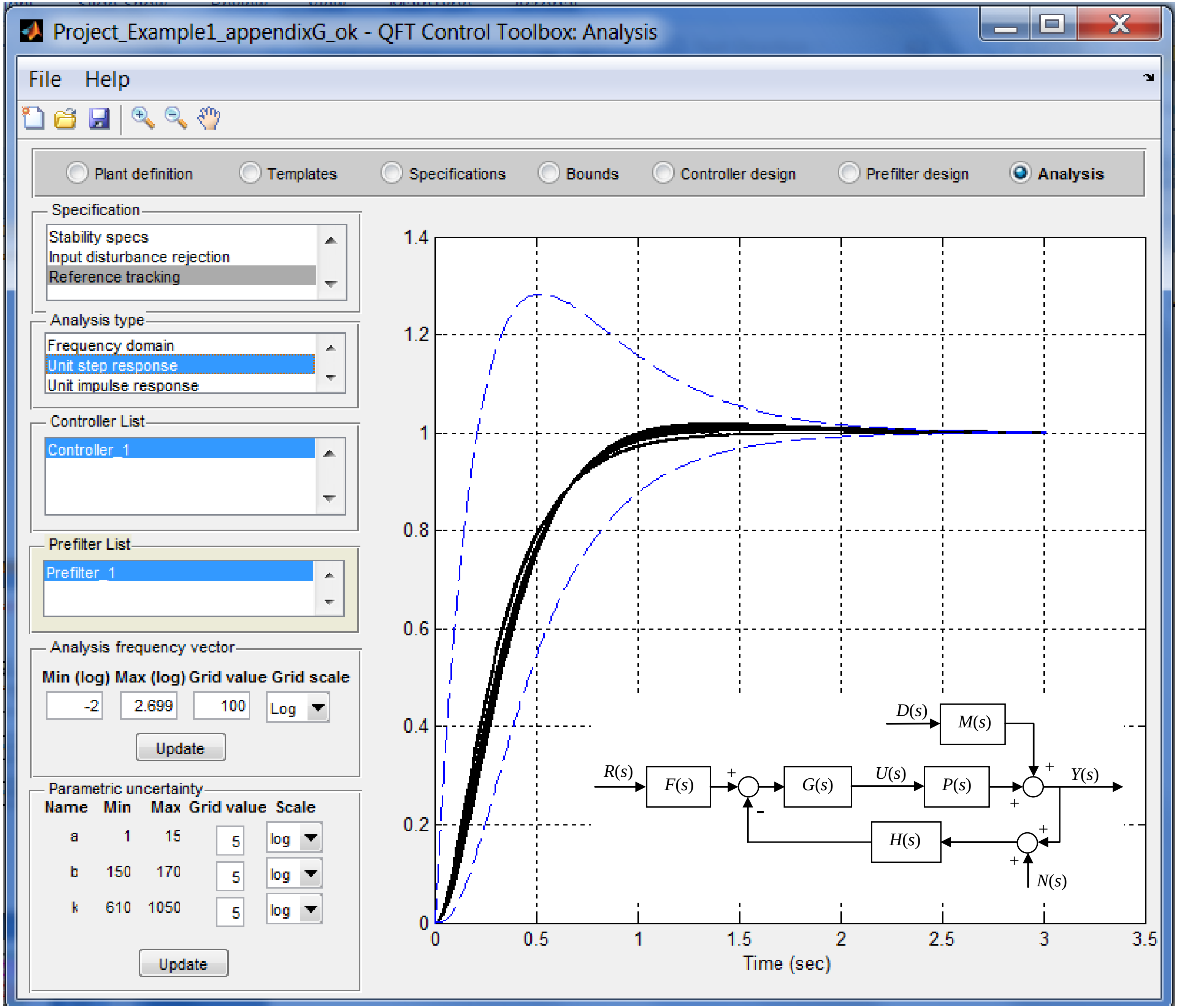
Prefilter

$$F(s)=\frac{\left(\frac{s}{50}+1\right)\left(\frac{s}{100}+1\right)}{\left(\frac{s}{4}+1\right)\left(\frac{s}{8}+1\right)}$$





Analysis



Project_Example1_appendixG_ok - QFT Control Toolbox: Analysis
File Help
Plant definition
Templates
Specifications
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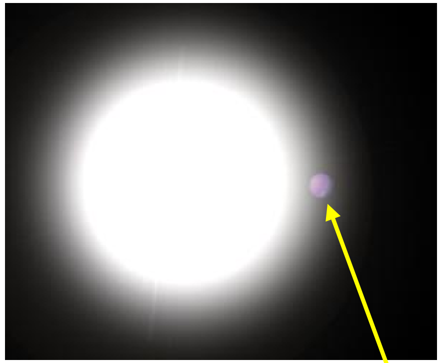
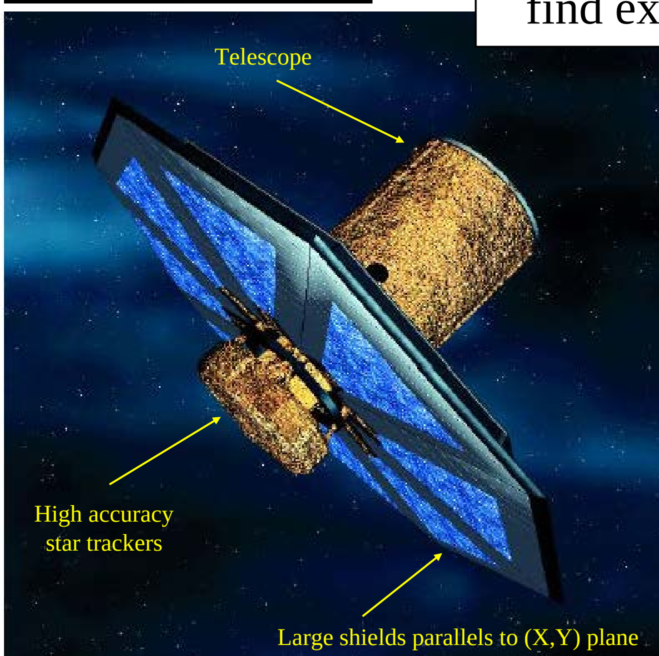
Controller design
Prefilter design
Analysis
Specification
Stability specs
Input disturbance rejection
Reference tracking
Analysis type
Frequency domain
Unit step response
Unit impulse response
Controller List
Controller_1
Prefilter List
Prefilter_1
Analysis frequency vector
Min (log) Max (log) Grid value Grid scale
-2
2.699
100
Log
Update
Parametric uncertainty
Name Min Max Grid value Scale
a 1 15 5 log
b 150 170 5 log
k 610 1050 5 log
Update
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 0.5 1 1.5 2 2.5 3 3.5
Time (sec)
D(s)
M(s)
R(s)
F(s)
G(s)
U(s)
P(s)
Y(s)
H(s)
N(s)

Project. *MIMO QFT control for a Space Telescope with large flimsy appendages. The Darwin mission*



Interferometry to find exo-planets.



Non-diagonal MIMO QFT Controller Design for a Darwin-type Spacecraft with large flimsy appendages.

ESA-ESTEC, Noordwijk (Holland)

Project 2005-2011
Principal Investigator: Mario García-Sanz

Ref: M. Garcia-Sanz, I. Eguinoa, M. Barreras, S. Bennani

"Non-diagonal MIMO QFT Controller Design for Darwin-type Spacecraft with large flimsy appendages".

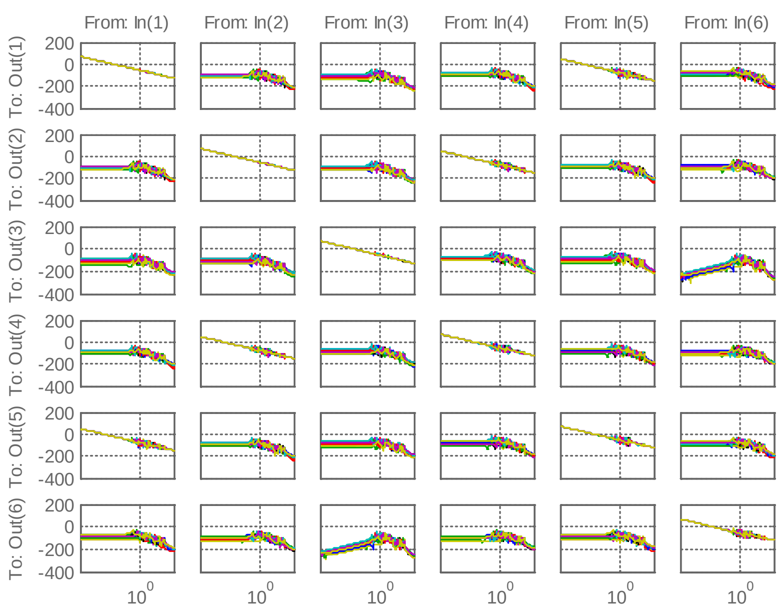
International Journal of Dynamic Systems, Measurement and Control, ASME, USA. Vol. 130, January 2008.

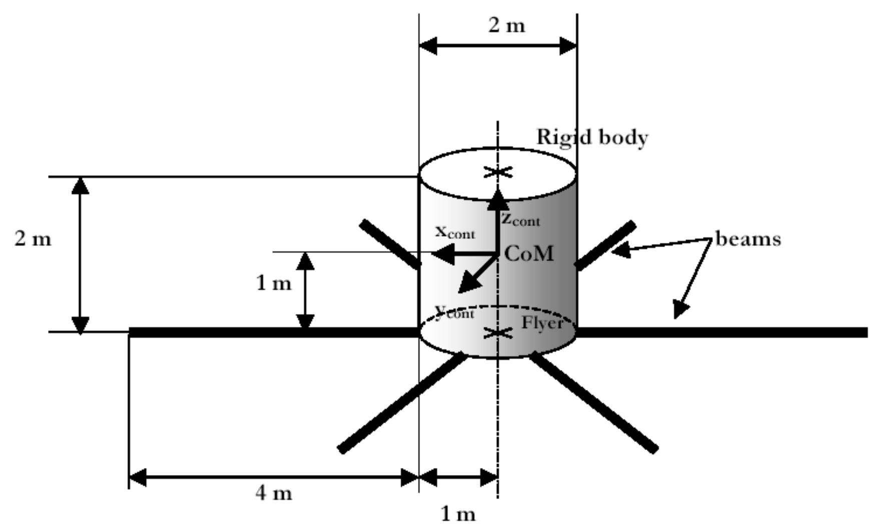
Darwin Flyer 6DOF Dynamics with flexible modes

Position → $x(s), y(s), z(s)$; Attitude → $\varphi(s), \theta(s), \psi(s)$; Force → $F_x(s), F_y(s), F_z(s)$; Torque → $T_\varphi(s), T_\theta(s), T_\psi(s)$

$$\begin{bmatrix} x(s) \\ y(s) \\ z(s) \\ \varphi(s) \\ \theta(s) \\ \psi(s) \end{bmatrix} = \begin{bmatrix} p_{11}(s) & p_{12}(s) & p_{13}(s) & p_{14}(s) & p_{15}(s) & p_{16}(s) \\ p_{21}(s) & p_{22}(s) & p_{23}(s) & p_{24}(s) & p_{25}(s) & p_{26}(s) \\ p_{31}(s) & p_{32}(s) & p_{33}(s) & p_{34}(s) & p_{35}(s) & p_{36}(s) \\ p_{41}(s) & p_{42}(s) & p_{43}(s) & p_{44}(s) & p_{45}(s) & p_{46}(s) \\ p_{51}(s) & p_{52}(s) & p_{53}(s) & p_{54}(s) & p_{55}(s) & p_{56}(s) \\ p_{61}(s) & p_{62}(s) & p_{63}(s) & p_{64}(s) & p_{65}(s) & p_{66}(s) \end{bmatrix} \begin{bmatrix} F_x(s) \\ F_y(s) \\ F_z(s) \\ T_\varphi(s) \\ T_\theta(s) \\ T_\psi(s) \end{bmatrix}$$

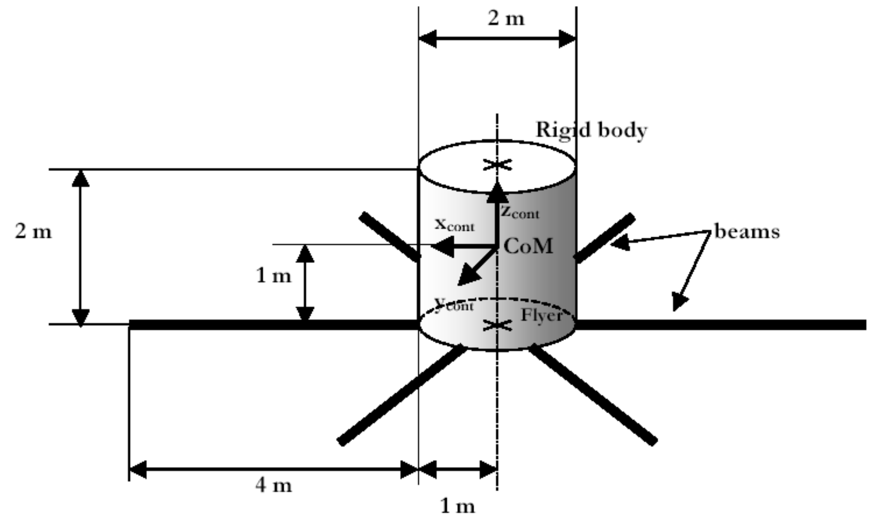
where every $p_{ij}(s)$, i, j = 1, 2, … 6, is a 50 order Laplace transfer function with uncertainty.





Spec. 6DOF: 3D Position: 1 μm
3D Attitud: 25 mas

Satellite Description



- <u>Satellite dimensions</u>
  - body mass : 500 kg
  - cylinder with Zcont as revolution axis. 2 m diameter and 2 m height
  - beam mass : 7 kg * 6 beams = 42 kg
  - length of simple beam : 4 m

- <u>Flexible modes</u>
  - Validated with finite elements methods
  - 1st flexible mode has been considered for each beam and along its X and Y axes

Parameter	Uncertainty range
Frequency	[0.05 , 0.5] Hz
Damping	[0.1 , 1] %
Mass	5 %
Inertia	1 %

SYSTEM DYNAMICS UNCERTAINTY
The satellite parameters vary within a certain range of uncertainty

Satellite Modeling

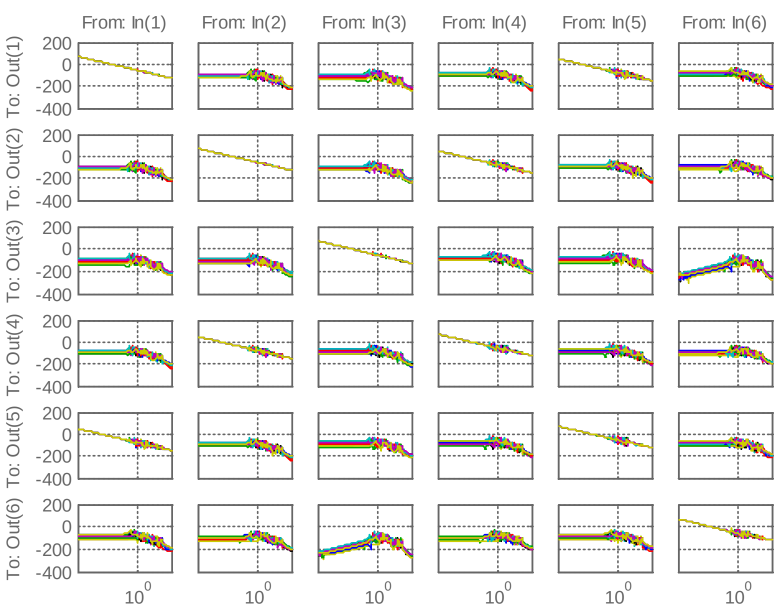
Darwin Flyer 6DOF Dynamics with flexible modes

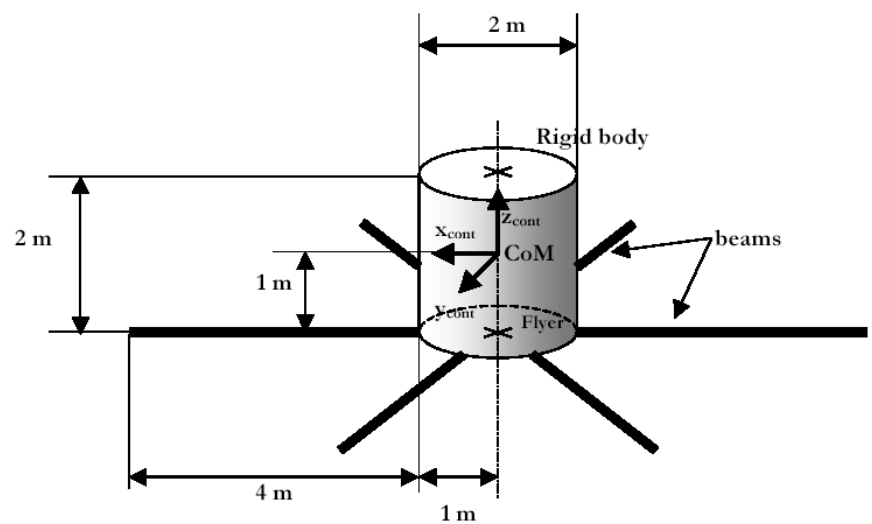
Position, Attitude = P(s) · Force, Torque:

$$\begin{bmatrix} x(s) \\ y(s) \\ z(s) \\ \varphi(s) \\ \theta(s) \\ \psi(s) \end{bmatrix} = \begin{bmatrix} p_{11}(s) & p_{12}(s) & p_{13}(s) & p_{14}(s) & p_{15}(s) & p_{16}(s) \\ p_{21}(s) & p_{22}(s) & p_{23}(s) & p_{24}(s) & p_{25}(s) & p_{26}(s) \\ p_{31}(s) & p_{32}(s) & p_{33}(s) & p_{34}(s) & p_{35}(s) & p_{36}(s) \\ p_{41}(s) & p_{42}(s) & p_{43}(s) & p_{44}(s) & p_{45}(s) & p_{46}(s) \\ p_{51}(s) & p_{52}(s) & p_{53}(s) & p_{54}(s) & p_{55}(s) & p_{56}(s) \\ p_{61}(s) & p_{62}(s) & p_{63}(s) & p_{64}(s) & p_{65}(s) & p_{66}(s) \end{bmatrix} \begin{bmatrix} F_x(s) \\ F_y(s) \\ F_z(s) \\ T_\varphi(s) \\ T_\theta(s) \\ T_\psi(s) \end{bmatrix}$$

Position: $x(s)$, $y(s)$, $z(s)$; Attitude: $\varphi(s)$, $\theta(s)$, $\psi(s)$; Force: $F_x(s)$, $F_y(s)$, $F_z(s)$; Torque: $T_\varphi(s)$, $T_\theta(s)$, $T_\psi(s)$

where every $p_{ij}(s)$, i, j = 1, 2, … 6, is a 50 order Laplace transfer function with uncertainty.



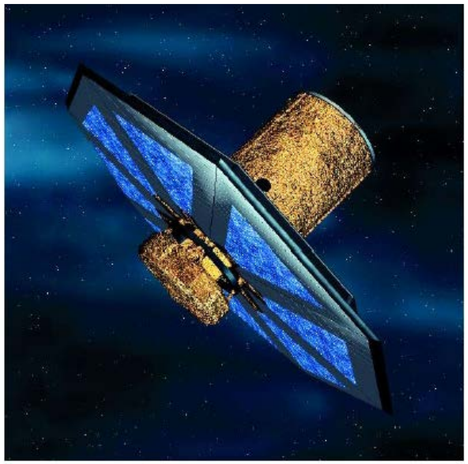


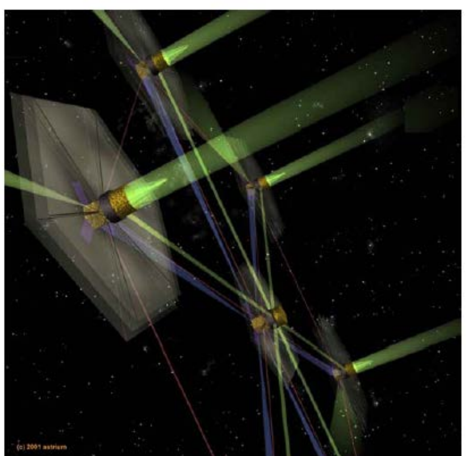
Spec. 6DOF: 3D Position: 1 µm

3D Attitud: 25 mas

Specificacions

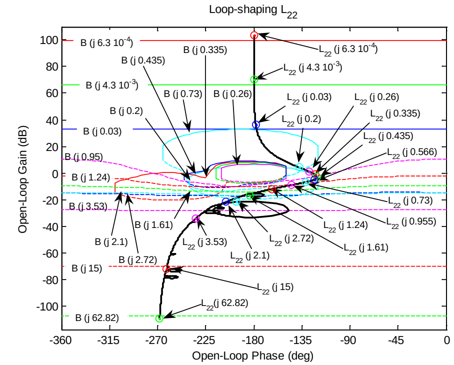
Darwin-type Flyer Requirements



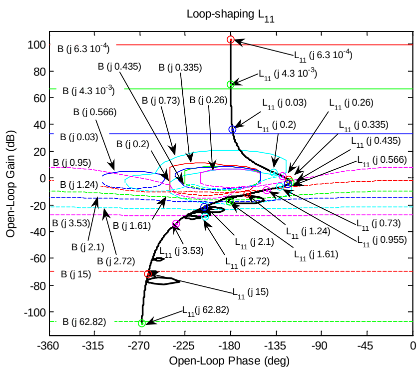


	Objective	Numerical Requirement
Astronomical Requirements	Position accuracy	Maximum absolute value: 1 μm for all axes
		Standard deviation: 0.33 μm for all axes
	Pointing accuracy	Maximum absolute value: 25.5 mas for all axes (3 σ)
		Standard deviation: 8.5 mas for all axes (1 σ)
Engineering Requirements	Bandwidth	~ 0.01 Hz for all axes
	Saturation limits	Maximum force: 150 μN Maximum torque: 150 μNm
	Rejection of high frequency noises (from measurement and actuation)	High roll-off after the bandwidth
Control Requirements	Stability margins	$\max_{\omega} \lvert \boldsymbol{T}(j\omega) \rvert < 2$ $\max_{\omega} \lvert \boldsymbol{S}(j\omega) \rvert < 2$
	Loop interaction	Minimum
	Rejection of flexible modes	Maximum
	Controller complexity and order	Minimum

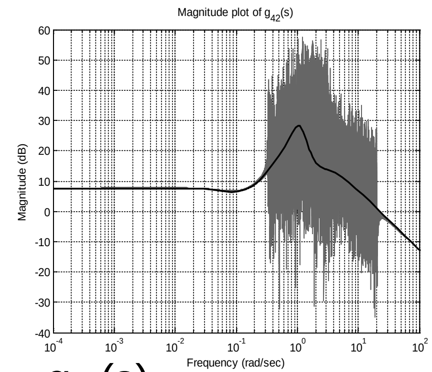
DESIGN



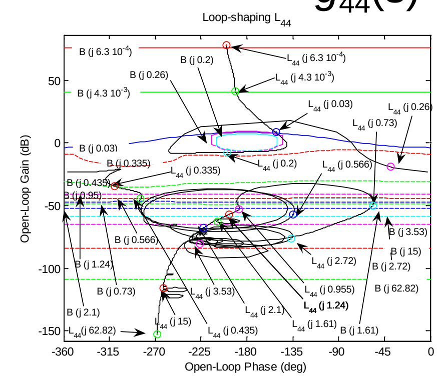
$g_{22}(s)$



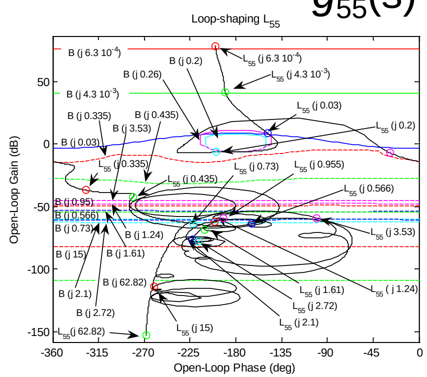
$g_{11}(s)$



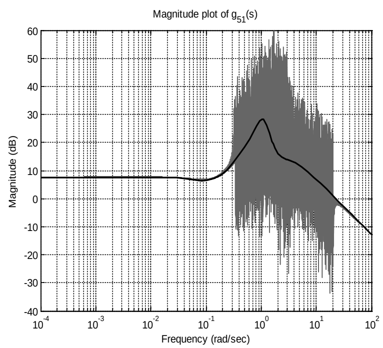
$g_{42}(s)$



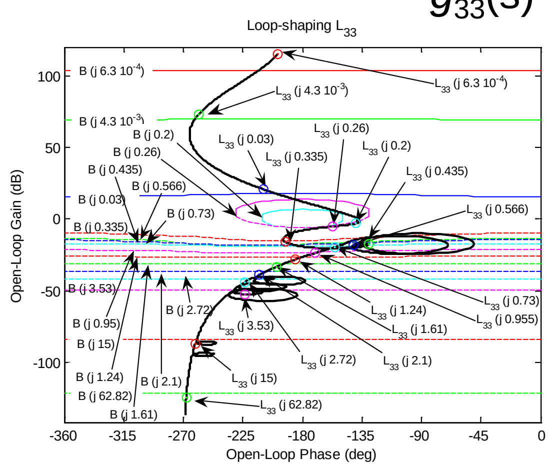
$g_{44}(s)$



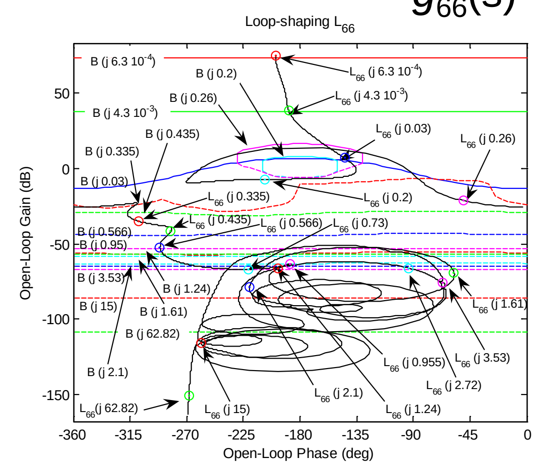
$g_{55}(s)$



$g_{51}(s)$



$g_{33}(s)$



$g_{66}(s)$

$$\mathbf{G}(s)=\begin{bmatrix} g_{11}(s) & 0 & 0 & 0 & 0 & 0 \\ 0 & g_{22}(s) & 0 & 0 & 0 & 0 \\ 0 & 0 & g_{33}(s) & 0 & 0 & 0 \\ 0 & g_{42}(s) & 0 & g_{44}(s) & 0 & 0 \\ g_{51}(s) & 0 & 0 & 0 & g_{55}(s) & 0 \\ 0 & 0 & 0 & 0 & 0 & g_{66}(s) \end{bmatrix}$$

Controller evaluation and comparison (I)

- Non-diagonal MIMO QFT (1st option)
- H-infinity (provided by ESA)
- Diagonal MIMO QFT (2nd option)

Non-diagonal MIMO QFT has
8 elements
of order: from 3 to 14.

$$\mathbf{G}(s)=\begin{bmatrix} g_{11}(s) & 0 & 0 & 0 & 0 & 0 \\ 0 & g_{22}(s) & 0 & 0 & 0 & 0 \\ 0 & 0 & g_{33}(s) & 0 & 0 & 0 \\ 0 & g_{42}(s) & 0 & g_{44}(s) & 0 & 0 \\ g_{51}(s) & 0 & 0 & 0 & g_{55}(s) & 0 \\ 0 & 0 & 0 & 0 & 0 & g_{66}(s) \end{bmatrix}$$

H-infinity expressed as transfer
functions has
36 elements
of order 42.

$$\mathbf{G}(s)=\begin{bmatrix} g_{11}(s) & g_{12}(s) & g_{13}(s) & g_{14}(s) & g_{15}(s) & g_{16}(s) \\ g_{21}(s) & g_{22}(s) & g_{23}(s) & g_{24}(s) & g_{25}(s) & g_{26}(s) \\ g_{31}(s) & g_{32}(s) & g_{33}(s) & g_{34}(s) & g_{35}(s) & g_{36}(s) \\ g_{41}(s) & g_{42}(s) & g_{43}(s) & g_{44}(s) & g_{45}(s) & g_{46}(s) \\ g_{51}(s) & g_{52}(s) & g_{53}(s) & g_{54}(s) & g_{55}(s) & g_{56}(s) \\ g_{61}(s) & g_{62}(s) & g_{63}(s) & g_{64}(s) & g_{65}(s) & g_{66}(s) \end{bmatrix}$$

Diagonal MIMO QFT has
6 elements
of order: from 5 to 14.

$$\mathbf{G}(s)=\begin{bmatrix} g_{11}(s) & 0 & 0 & 0 & 0 & 0 \\ 0 & g_{22}(s) & 0 & 0 & 0 & 0 \\ 0 & 0 & g_{33}(s) & 0 & 0 & 0 \\ 0 & 0 & 0 & g_{44}(s) & 0 & 0 \\ 0 & 0 & 0 & 0 & g_{55}(s) & 0 \\ 0 & 0 & 0 & 0 & 0 & g_{66}(s) \end{bmatrix}$$

Controller	Number of Multiplications	Number of Sums
Non-diagonal MIMO QFT	**130**	**124**
H-infinity	2994	2988
Diagonal MIMO QFT	116	110

Time-domain analysis. Results (I)

- Non-diagonal MIMO QFT (1st option)
- H-infinity (provided by ESA)
- Diagonal MIMO QFT (2nd option)

Evaluation Criteria

For each controller:

the greatest value over the 300 uncertain cases is shown for:

- Position errors: the maximum
  the standard deviation

- Attitude errors: the maximum
  the standard deviation

- Actuator commands: the maximum

in all axes.

Time-domain analysis. Results (II)

	Specification	Requirement	Benchmark	Non-diagonal MIMO QFT Controller	Diagonal MIMO QFT Controller	H-infinity Controller
1	Maximum Position Error X (μm)	< 1 μm	B1	**0.0131**	**0.0131**	0.0293
			B2	**0.0816**	**0.0816**	0.511
2	Maximum Position Error Y (μm)	< 1 μm	B1	**0.0120**	**0.0120**	0.0299
			B2	**0.0120**	**0.0120**	0.0299
3	Maximum Position Error Z (μm)	< 1 μm	B1	**0.0288**	**0.0288**	0.0292
			B2	**0.0288**	**0.0288**	0.0292
4	Maximum Attitude Error X (mas)	< 25.5 mas	B1	**25.27**	25.31	25.95
			B2	**25.27**	25.31	25.95
5	Maximum Attitude Error Y (mas)	< 25.5 mas	B1	**22.91**	22.99	23.21
			B2	**22.55**	23.75	28.91
6	Maximum Attitude Error Z (mas)	< 25.5 mas	B1	**21.15**	**21.15**	22.84
			B2	**21.15**	**21.15**	22.84

Time-domain analysis. Results (III)

	Specification	Requirement	Benchmark	Non-diagonal MIMO QFT Controller	Diagonal MIMO QFT Controller	H-infinity Controller
7	Std. Deviation of Position Error X (µm)	< 0.33 µm	B1	**0.00275**	0.00276	0.00686
			B2	**0.0511**	**0.0511**	0.341
8	Std. Deviation of Position Error Y (µm)	< 0.33 µm	B1	**0.00265**	0.00266	0.00722
			B2	**0.00265**	0.00266	0.00722
9	Std. Deviation of Position Error Z (µm)	< 0.33 µm	B1	**0.00668**	**0.00668**	0.00691
			B2	**0.00668**	**0.00668**	0.00691
10	Std. Deviation of Attitude Error X (mas)	< 8.5 mas	B1	**5.57**	**5.57**	5.68
			B2	**5.57**	**5.57**	5.68
11	Std. Deviation of Attitude Error Y (mas)	< 8.5 mas	B1	**5.76**	**5.76**	6.01
			B2	**5.80**	5.85	8.23
12	Std. Deviation of Attitude Error Z (mas)	< 8.5 mas	B1	**4.83**	**4.83**	5.00
			B2	**4.83**	**4.83**	5.00

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Radio telescope azimuth-axis Servo control system

Modeling, QFT control system design and analysis

Prof. Mario Garcia-Sanz (CWRU)

- Objective

To designed a high-performance control solution (servo system) for the azimuth axis of a radio telescope :

- ***velocity control loop***
- ***position control loop***

Dealing with the existing ***model uncertainty*** (robust control)

and achieving ***five simultaneous control objectives***:

- stability,
- tracking of the azimuth axis telescope position,
- regulation of the azimuth axis telescope velocity,
- rejection of unpredictable wind disturbances,
- reduction of dish and feed-arm vibration.

- Modeling (I)

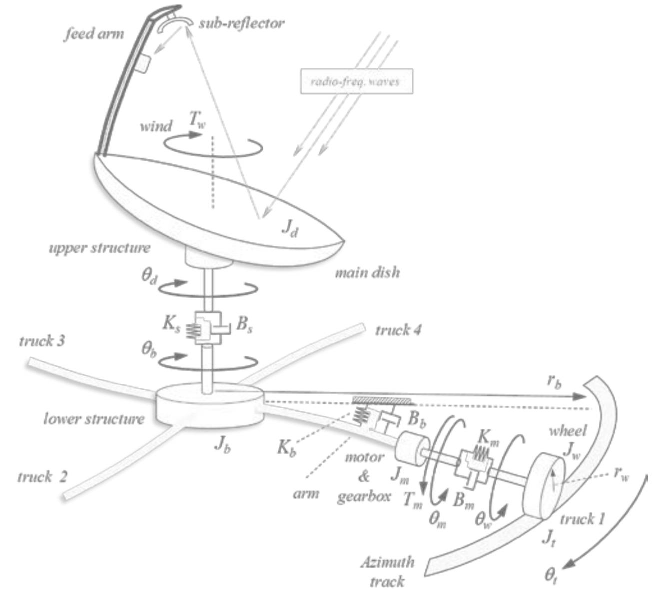
$$\boldsymbol{x}'(s) = \boldsymbol{A}\,\boldsymbol{x}(s) + \boldsymbol{B}\,\boldsymbol{u}(s)$$

$$\boldsymbol{y}(s) = \boldsymbol{C}\,\boldsymbol{x}(s)$$

$$\boldsymbol{x} = \begin{bmatrix} \dot{\boldsymbol{q}} \\ \boldsymbol{q} \end{bmatrix} = [\dot\theta_d \quad \dot\theta_b \quad \dot\theta_t \quad \dot\theta_m \quad \theta_d \quad \theta_b \quad \theta_t \quad \theta_m]^T$$

$$\boldsymbol{y} = [\dot\theta_m \quad \theta_d]^T$$

$$\boldsymbol{u} = [T_w \quad T_m]^T$$



Picture from book: Mario Garcia-Sanz, "*Robust control engineering: practical QFT solutions*", CRC Press, 2017.

$$\boldsymbol{A} = \begin{bmatrix}
-\frac{B_s}{J_d} & \frac{B_s}{J_d} & 0 & 0 & -\frac{K_s}{J_d} & \frac{K_s}{J_d} & 0 & 0 \\
\frac{B_s}{J_b} & \frac{-(B_s+N\,B_b)}{J_b} & \frac{N\,B_b}{J_b} & 0 & \frac{K_s}{J_b} & \frac{-(K_s+N\,K_b)}{J_b} & \frac{N\,K_b}{J_b} & 0 \\
0 & \frac{B_b}{J_w R^2 + J_t} & \frac{-(B_b+R^2 B_m)}{J_w R^2 + J_t} & \frac{R\,B_m}{J_w R^2 + J_t} & 0 & \frac{K_b}{J_w R^2 + J_t} & \frac{-(K_b+R^2 K_m)}{J_w R^2 + J_t} & \frac{R\,K_m}{J_w R^2 + J_t} \\
0 & 0 & \frac{R\,B_m}{J_m} & \frac{-B_m}{J_m} & 0 & 0 & \frac{R\,K_m}{J_m} & \frac{-K_m}{J_m} \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}
\qquad
\boldsymbol{B} = \begin{bmatrix}
\frac{1}{J_d} & 0 \\
0 & 0 \\
0 & 0 \\
0 & \frac{1}{J_m} \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}$$

$$\boldsymbol{C} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

- Servo system

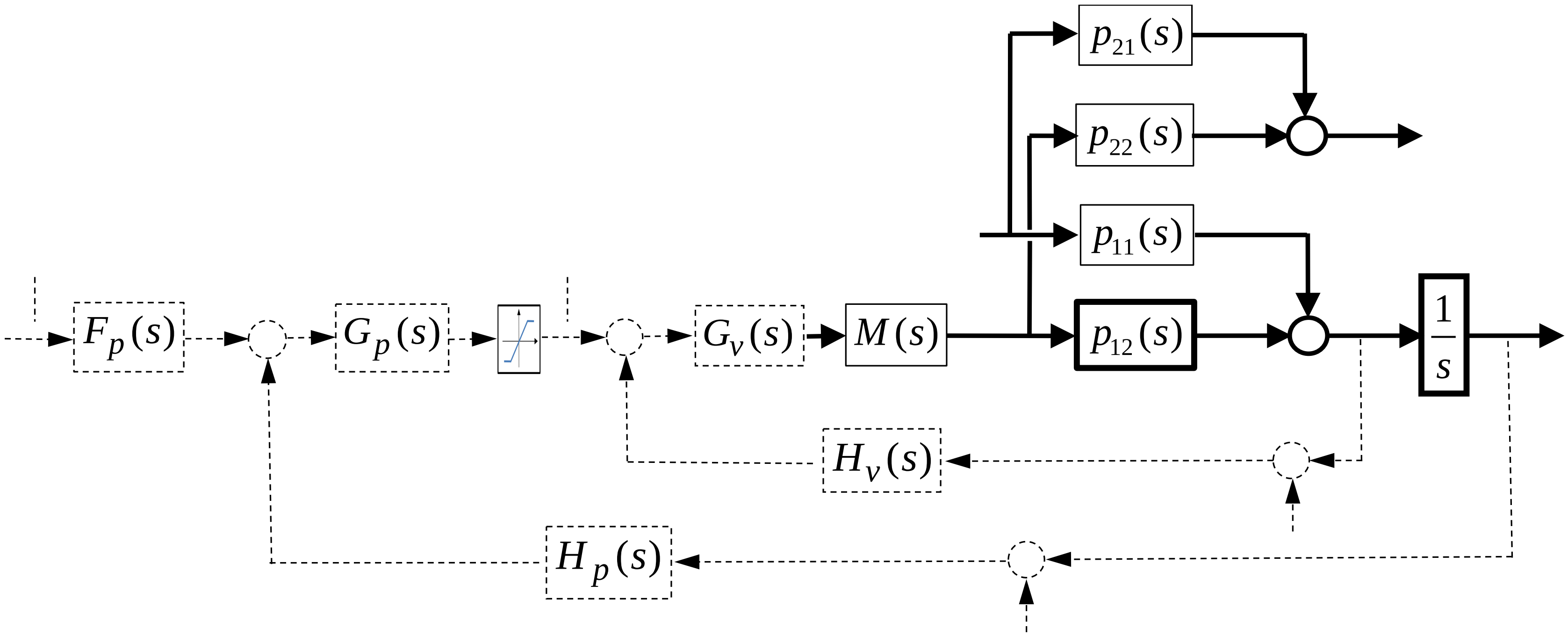
$$P(s) = C(sI - A)^{-1} B$$

$$y(s) = P(s)u(s)$$

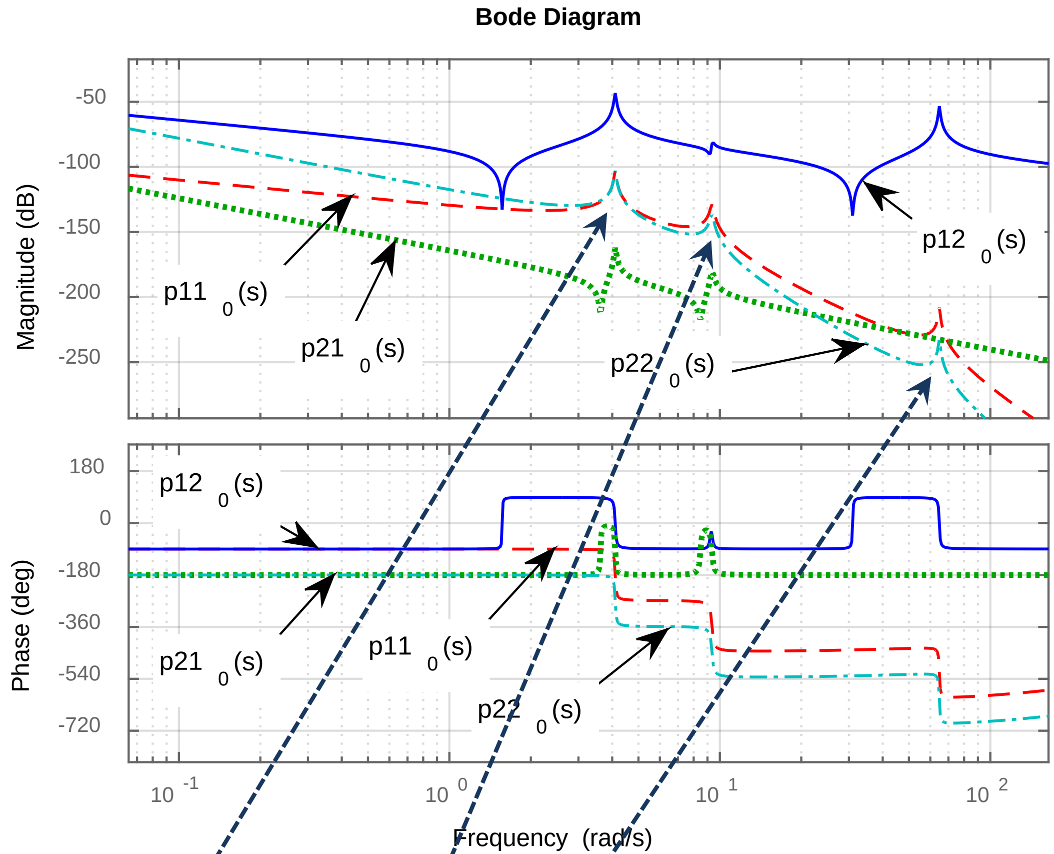
$$\begin{bmatrix} \dot{\theta}_m(s) \\ \theta_d(s) \end{bmatrix} = P_{2\times 2}(s) \begin{bmatrix} T_w(s) \\ T_m(s) \end{bmatrix}$$

$$\dot{\theta}_m(s) = p_{11}(s)T_w(s) + p_{12}(s)T_m(s)$$

$$\theta_d(s) = p_{21}(s)T_w(s) + p_{22}(s)T_m(s)$$



- Analysis



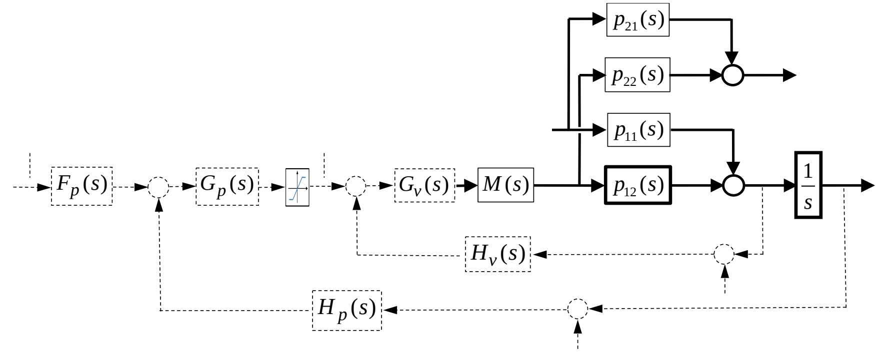
$$\dot{\theta}_m(s) = p_{11}(s)T_w(s) + p_{12}(s)T_m(s)$$

$$\theta_d(s) = p_{21}(s)T_w(s) + p_{22}(s)T_m(s)$$

Three main resonance modes.

- $\omega = 4.1$ rad/sec (0.65 Hz), represents the vibration of the dish, feed arm and upper structure in the azimuth direction (θ_d).
- $\omega = 9.35$ rad/sec (1.49 Hz), represents the vibration of the lower structure and arms in the azimuth direction (θ_b).
- $\omega = 64.8$ rad/sec (10.31 Hz), represents the vibration of the shaft of the motors (θ_m).

- QFT Velocity control (I)



Control specifications

-Type 1: Stability specification

$$\left|T_1(j\omega)\right| = \left|\frac{p_{12}(j\omega)G_v(j\omega)}{1+p_{12}(j\omega)G_v(j\omega)}\right| \le \delta_1(\omega) = Ws = 1.46$$

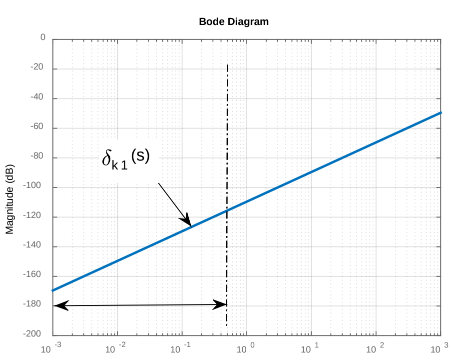
$\omega \in [0.01\ \ 0.05\ \ 0.1\ \ 0.5\ \ 1\ \ 1.5\ \ 2\ \ 3\ \ 4\ \ 5\ \ 10\ \ 50\ \ 60\ \ 65\ \ 70\ \ 100\ \ 500]$ rad/sec

-Type k1: Wind disturbances $T_w(s)$ over $\theta'_m(s)$ via $p_{11}(s)$

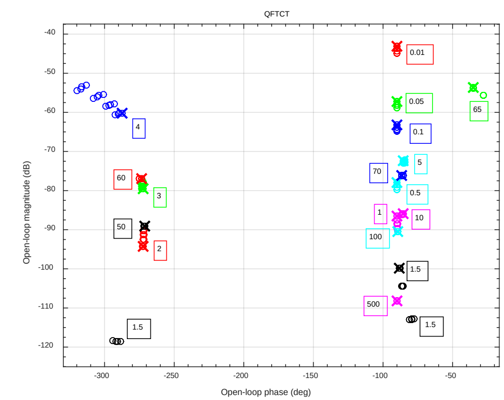
$$\left|T_{k1}(j\omega)\right| = \left|\frac{\dot{\theta}_m(j\omega)}{T_w(j\omega)}\right| = \left|\frac{p_{11}(j\omega)}{1+p_{12}(j\omega)G_v(j\omega)}\right| \le \delta_{k1}(\omega)$$

$$\delta_{k1}(\omega) = \frac{\left(\frac{s}{a_{k1}}\right)}{\left(\frac{s}{a_{k1}}\right)+1};\ a_{k1} = 3\times 10^5;$$

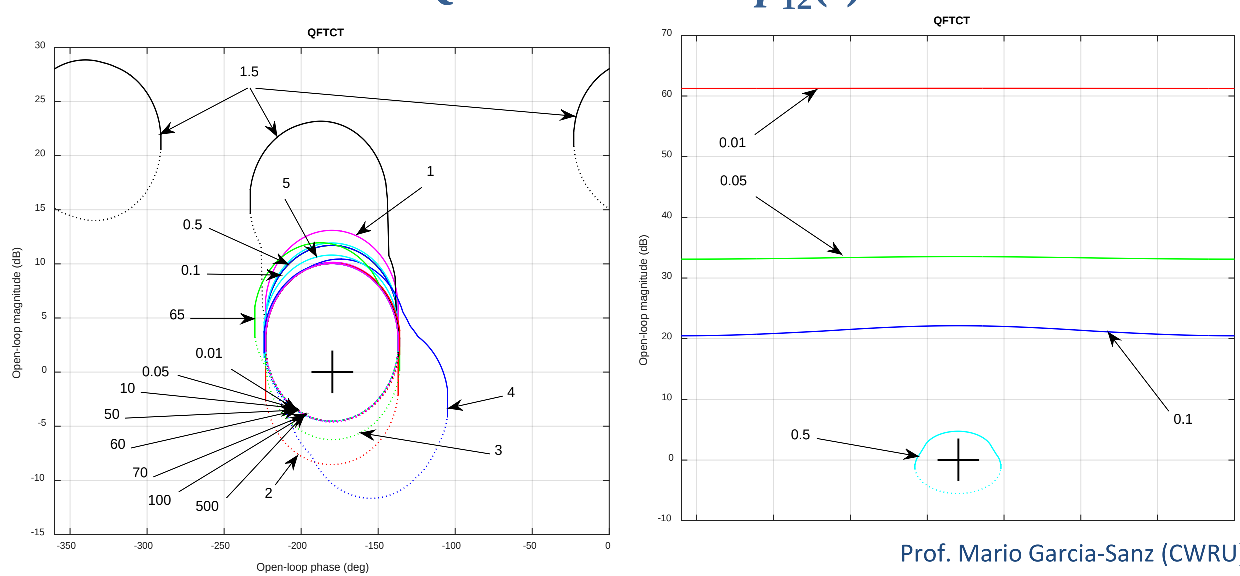
$\omega \in [0.01\ \ 0.05\ \ 0.1\ \ 0.5]$ rad/sec



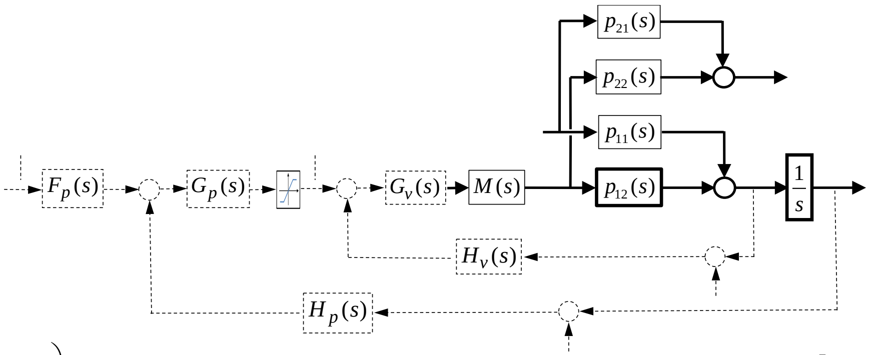
QFT templates for $p_{12}(s)$



QFT bounds for $p_{12}(s)$

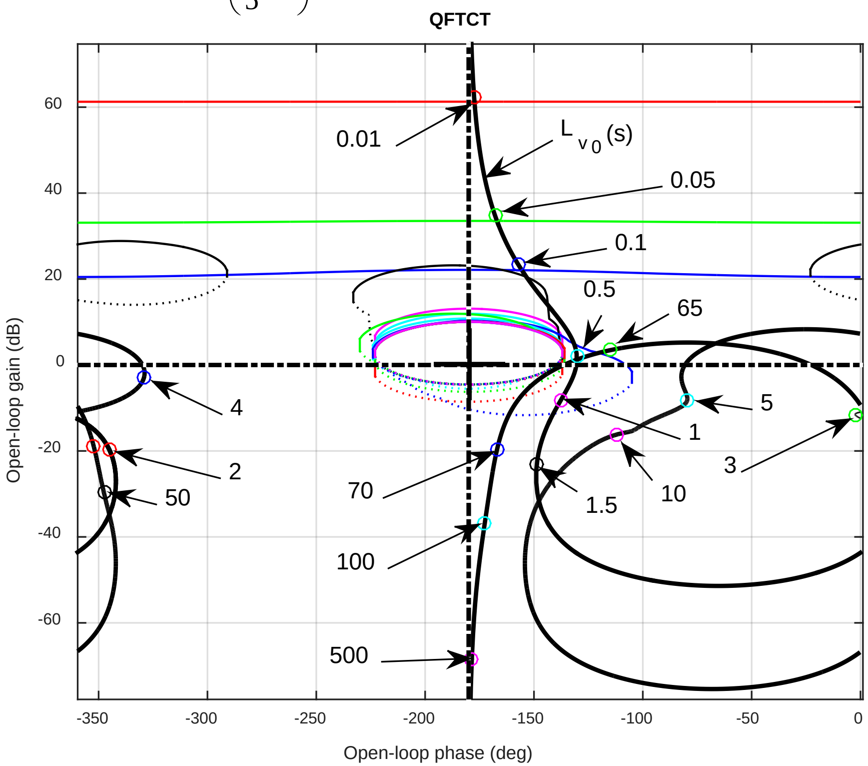


- QFT Velocity control (II)

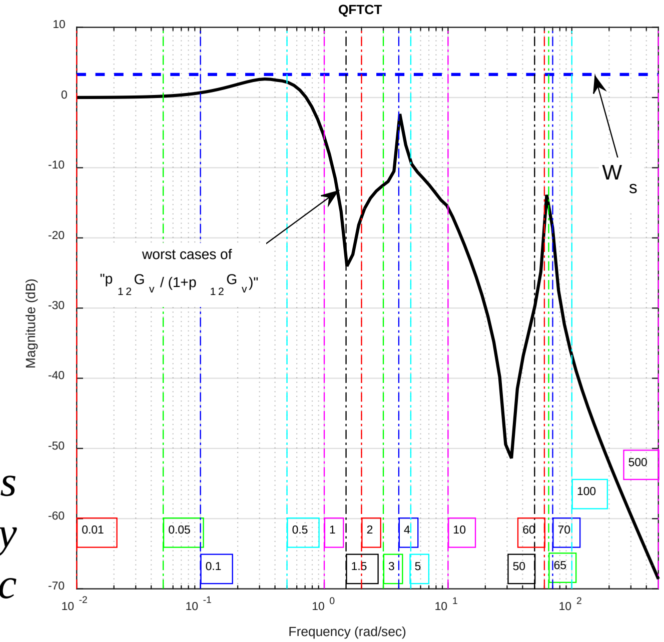


Feedback controller $G_v(s)$

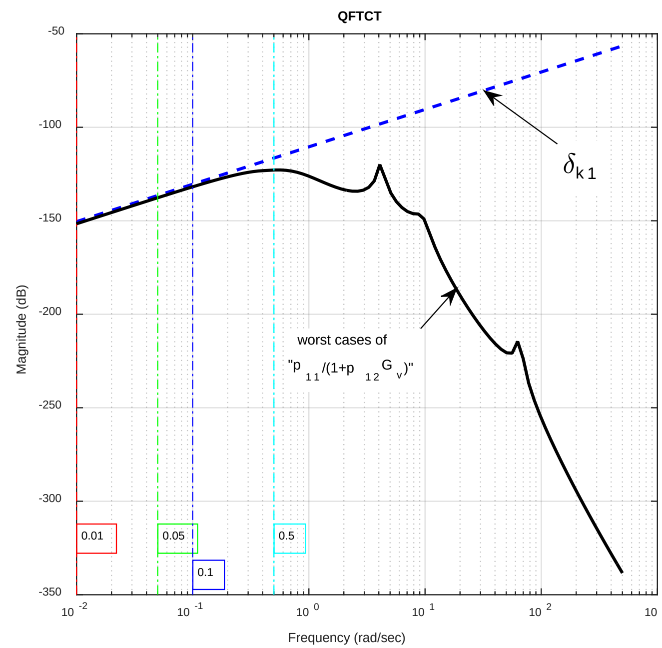
$$G_v(s) = \frac{1900\left(\frac{s}{0.2}+1\right)}{s\left(\frac{s}{5}+1\right)} \frac{(s^2+0.8s+16)}{(s^2+8s+16)}$$



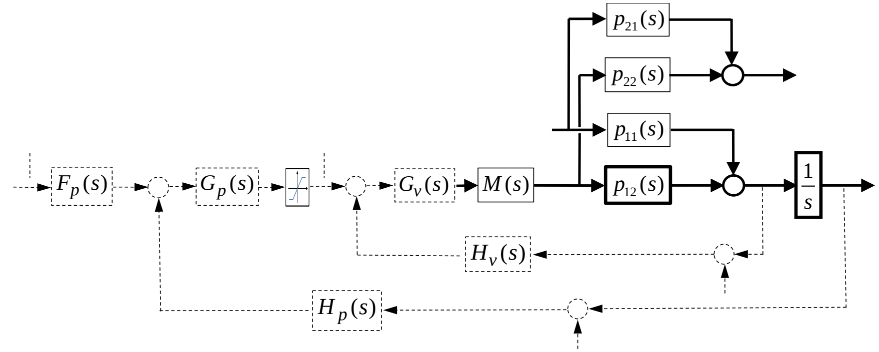
Analysis Stability spec



Analysis Wind disturbance rejection spec



- QFT Position control (I)



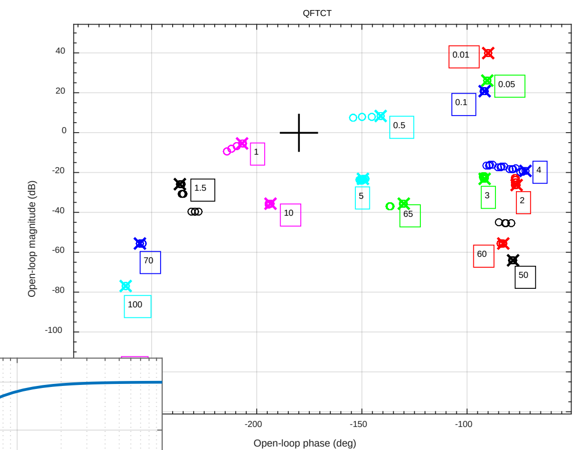
Control specifications

-Type 1: Stability specification

$$|T_1(j\omega)| = \left|\frac{p_p(j\omega)G_p(j\omega)}{1+p_p(j\omega)G_p(j\omega)}\right| \le \delta_1(\omega) = Ws = 1.46$$

$\omega \in [0.01\ \ 0.05\ \ 0.1\ \ 0.5\ \ 1\ \ 1.5\ \ 2\ \ 3\ \ 4\ \ 5\ \ 10\ \ 50\ \ 60\ \ 65\ \ 70\ \ 100\ \ 500]$ rad/sec

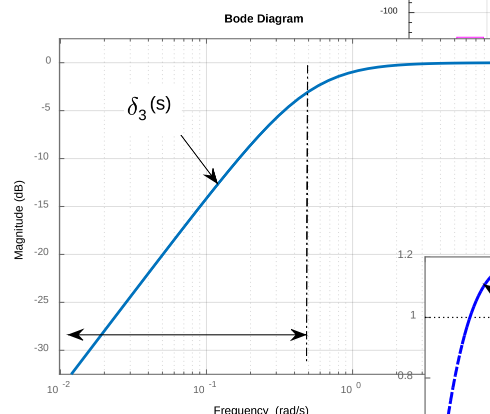
QFT templates for $p_p(s)$



-Type 3: Sensitivity or Disturbances at plant output specification

$$|T_3(j\omega)| = \left|\frac{\theta_m(j\omega)}{d_o(j\omega)}\right| = \left|\frac{1}{1+p_p(j\omega)G_p(j\omega)}\right| \le \delta_3(\omega) = \frac{\left(\frac{s}{a_d}\right)}{\left(\frac{s}{a_d}\right)+1};\ a_d = 0.5$$

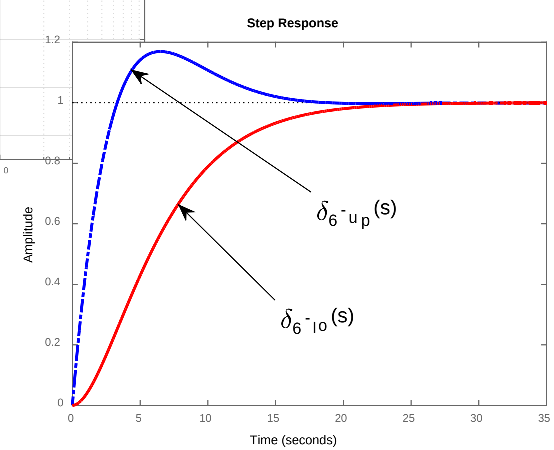
$\omega \in [0.01\ \ 0.05\ \ 0.1\ \ 0.5]$ rad/sec



-Type 6: Reference tracking specification

$$\delta_{6\_lo}(s) = \frac{1}{\left[\left(\frac{s}{a_L}\right)+1\right]^2};\ a_L = 0.292$$

$$\delta_{6\_up}(s) = \frac{\left[\left(\frac{s}{a_U}\right)+1\right]}{\left[\left(\frac{s}{\omega_n}\right)^2+\left(\frac{2\zeta s}{\omega_n}\right)+1\right]};\ a_U = 0.215;\ \zeta = 0.8;\ \omega_n = \frac{1.25\,a_U}{\zeta}$$



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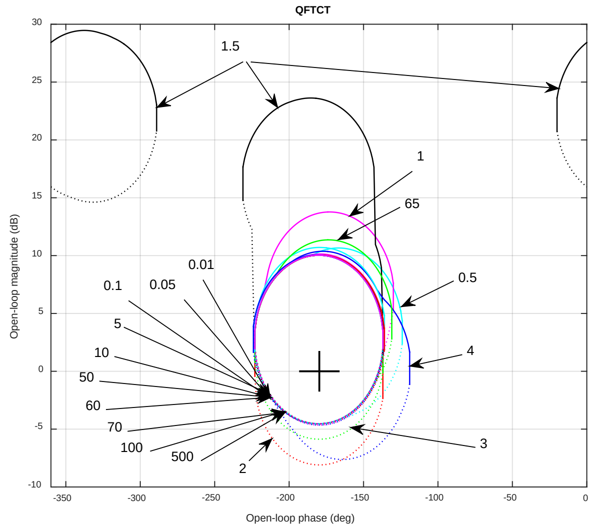
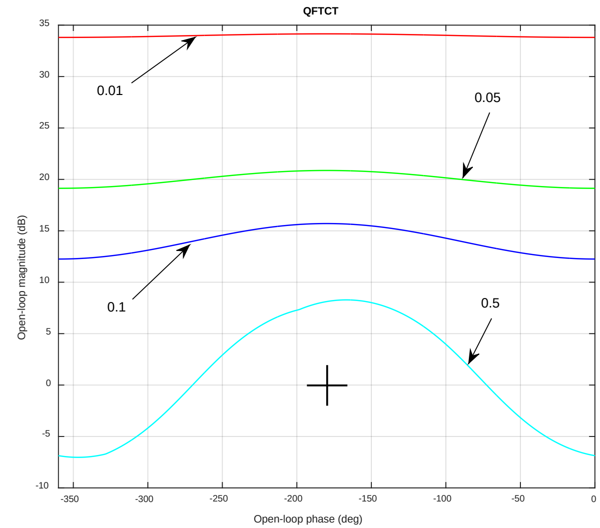
- QFT Position control (II)

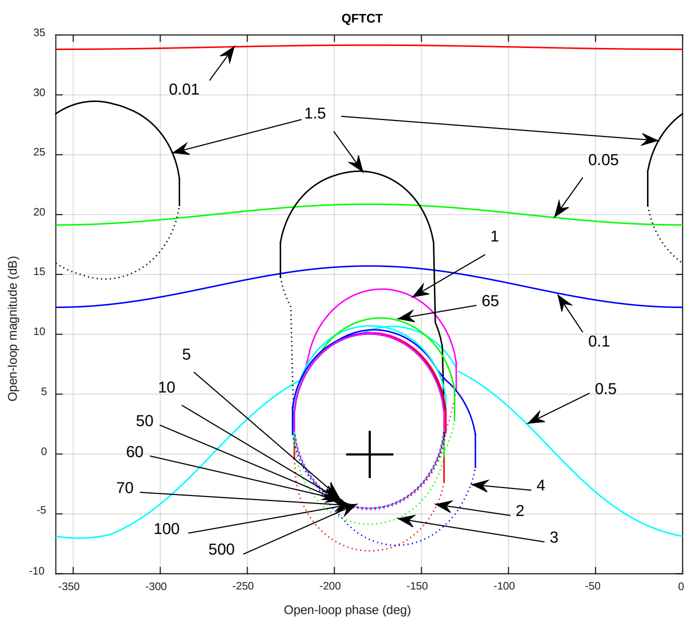


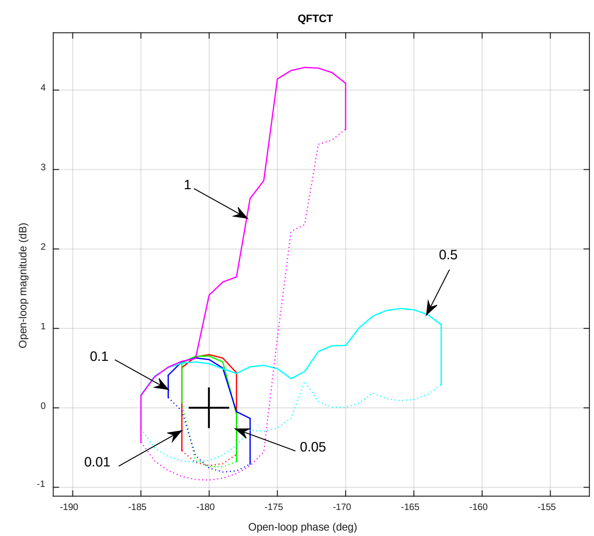
-*Type 1: Stability*



Type 3: Sensitivity

QFT bounds for $p_p(s)$





-*Type 6: Reference tracking*

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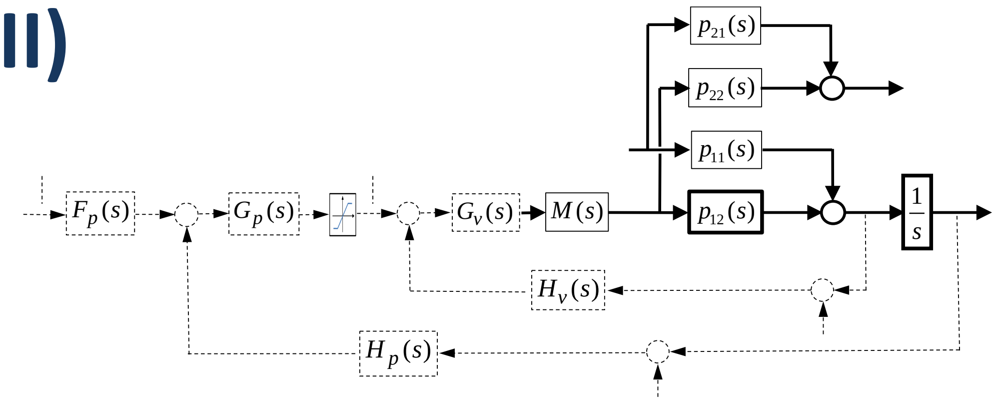
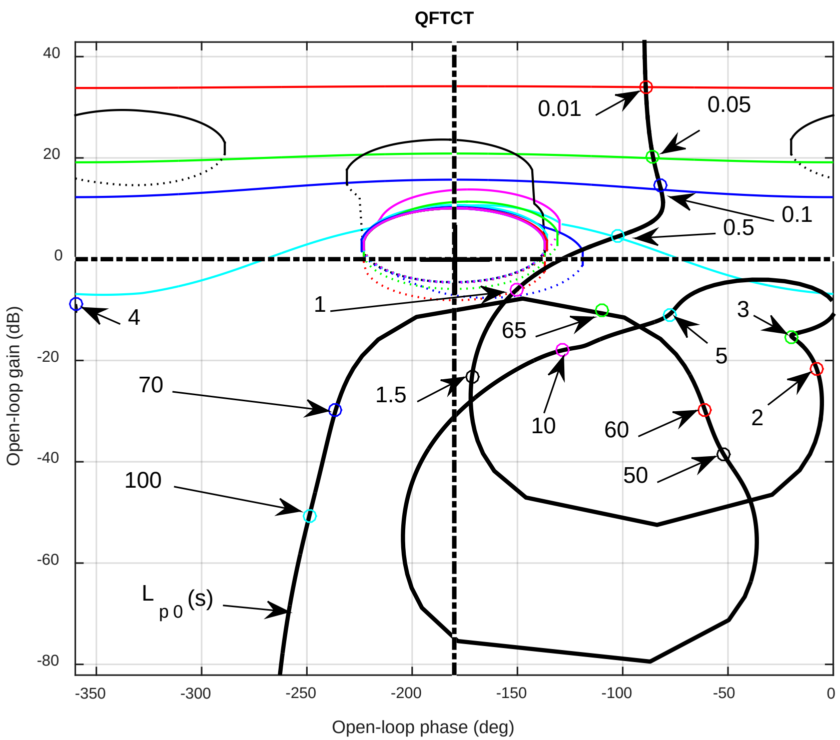
- QFT Position control (III)

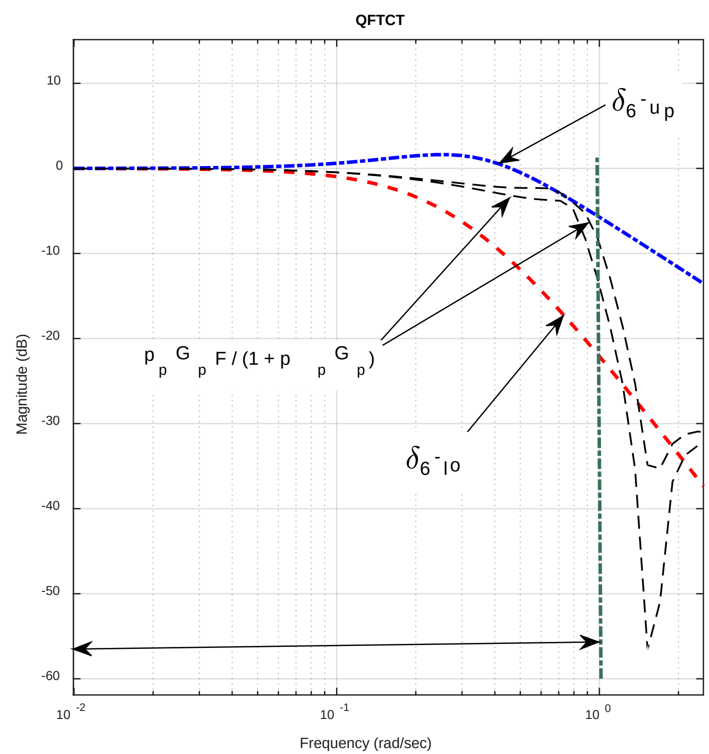


Feedback controller $G_p(s)$



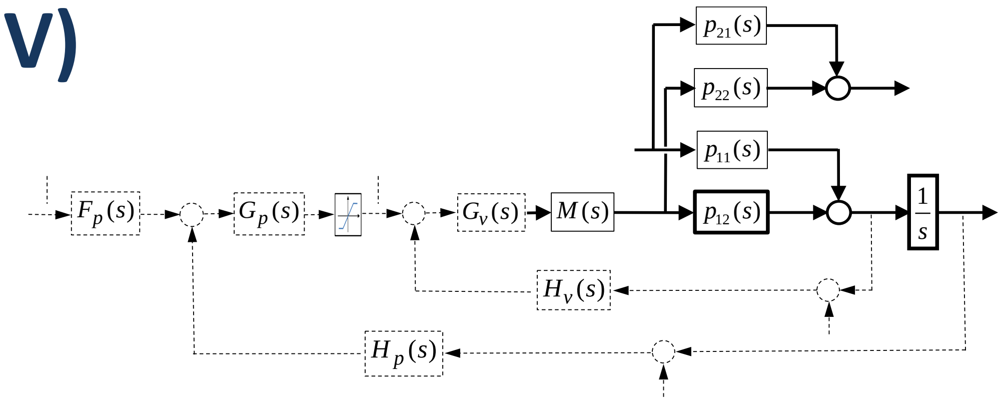
$$G_p(s) = \frac{0.5\left(\frac{s}{0.6}+1\right)}{\left(\frac{s}{25}+1\right)}$$

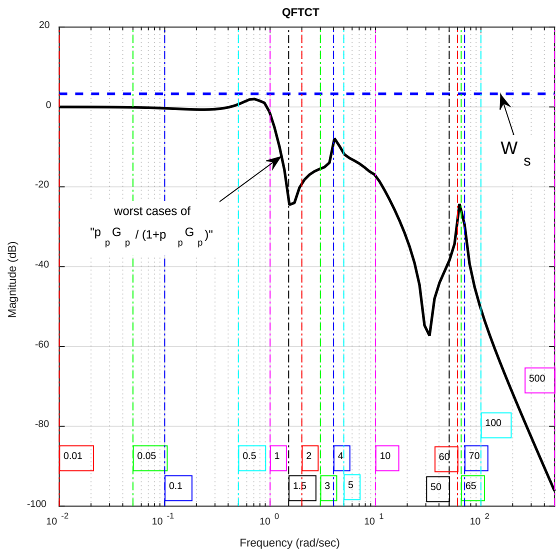
Prefilter $F_p(s)$



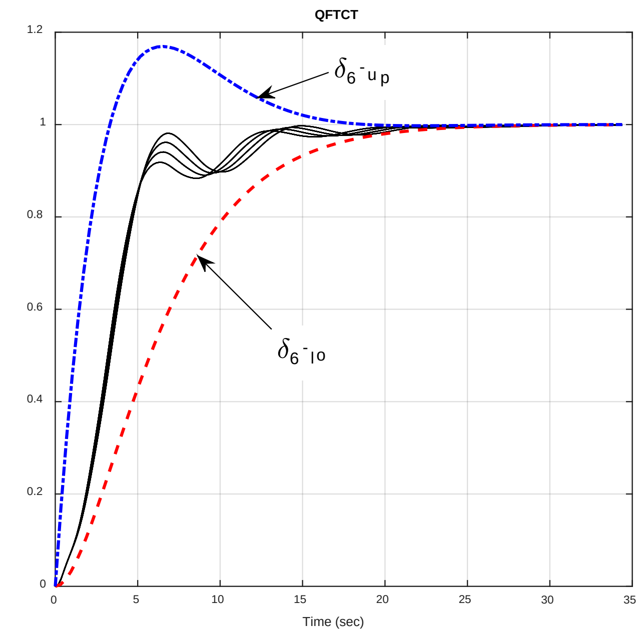
$$F_p(s) = \frac{\left(\frac{s}{0.3}+1\right)}{\left(\frac{s}{0.38}+1\right)^2}$$

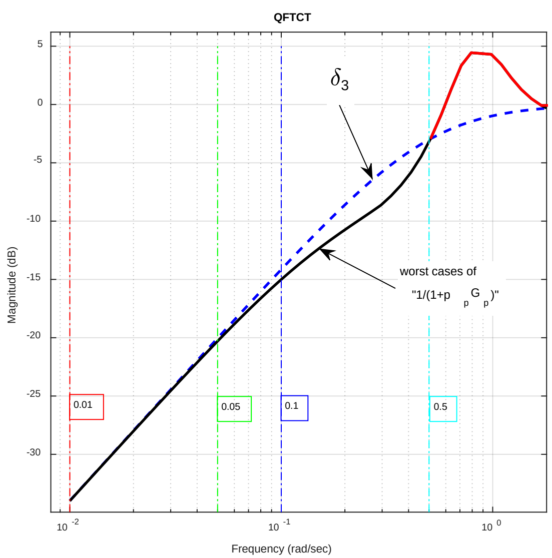
- QFT Position control (IV)

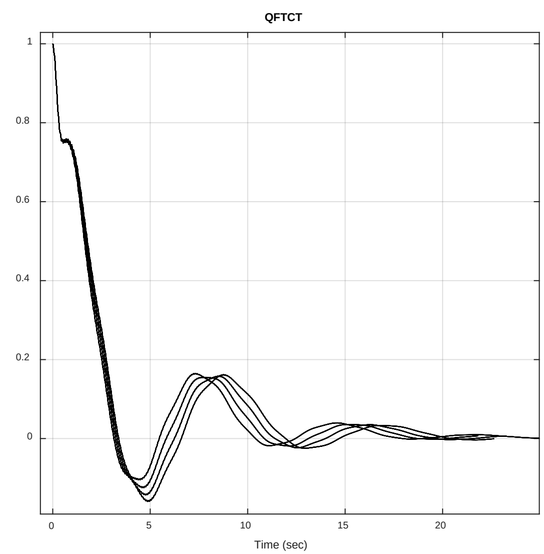




Analysis Stability spec





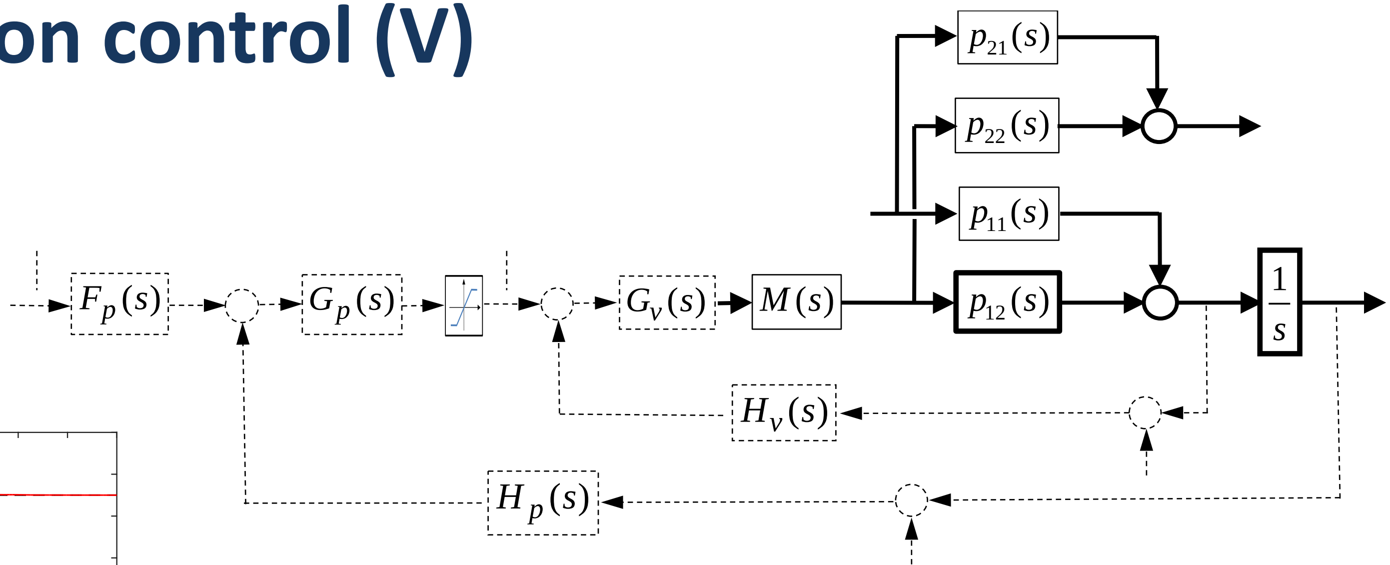


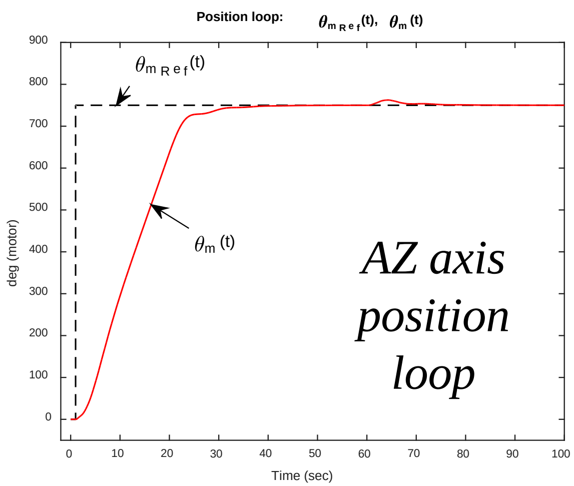
Analysis disturbance rejection spec

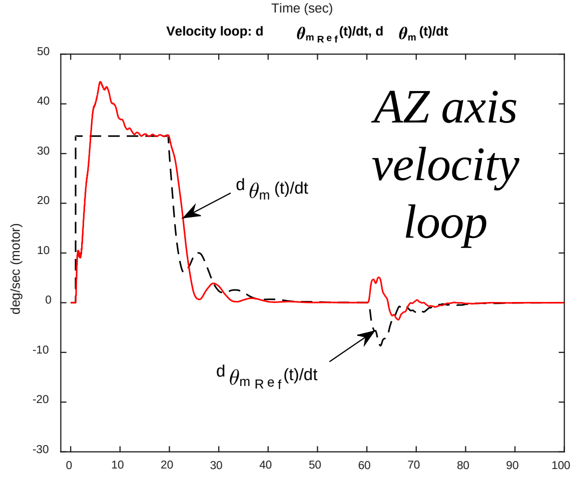
Analysis reference tracking spec

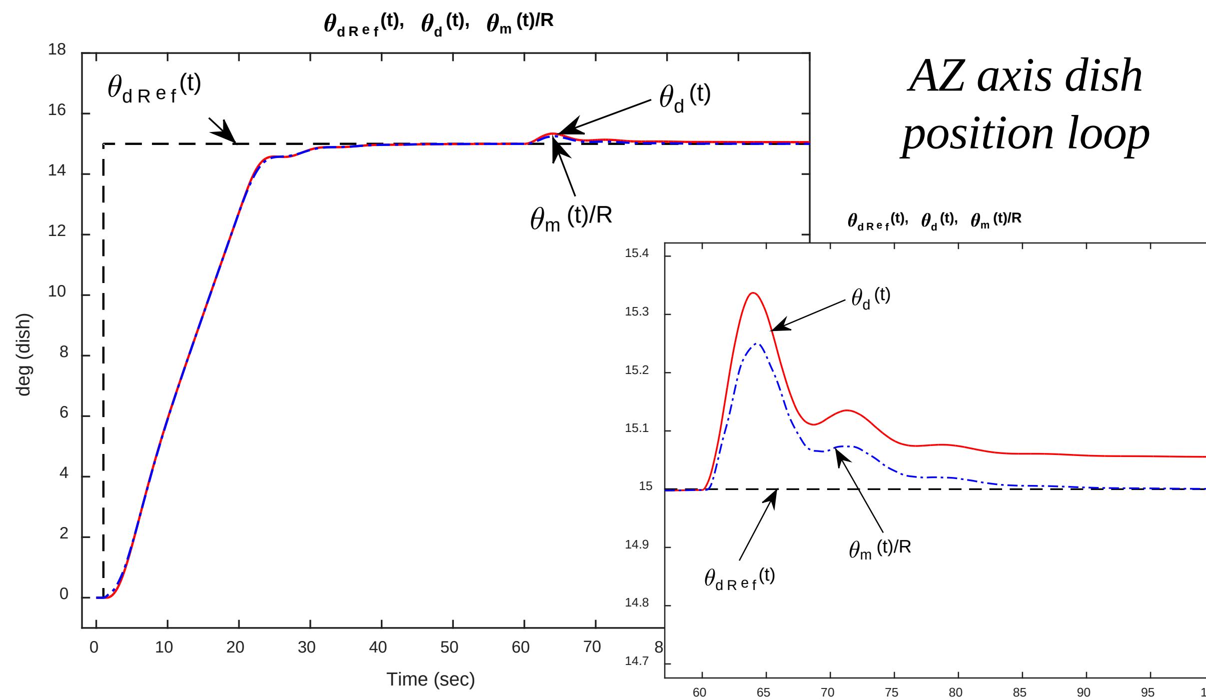
- QFT Position control (V)

Simulations









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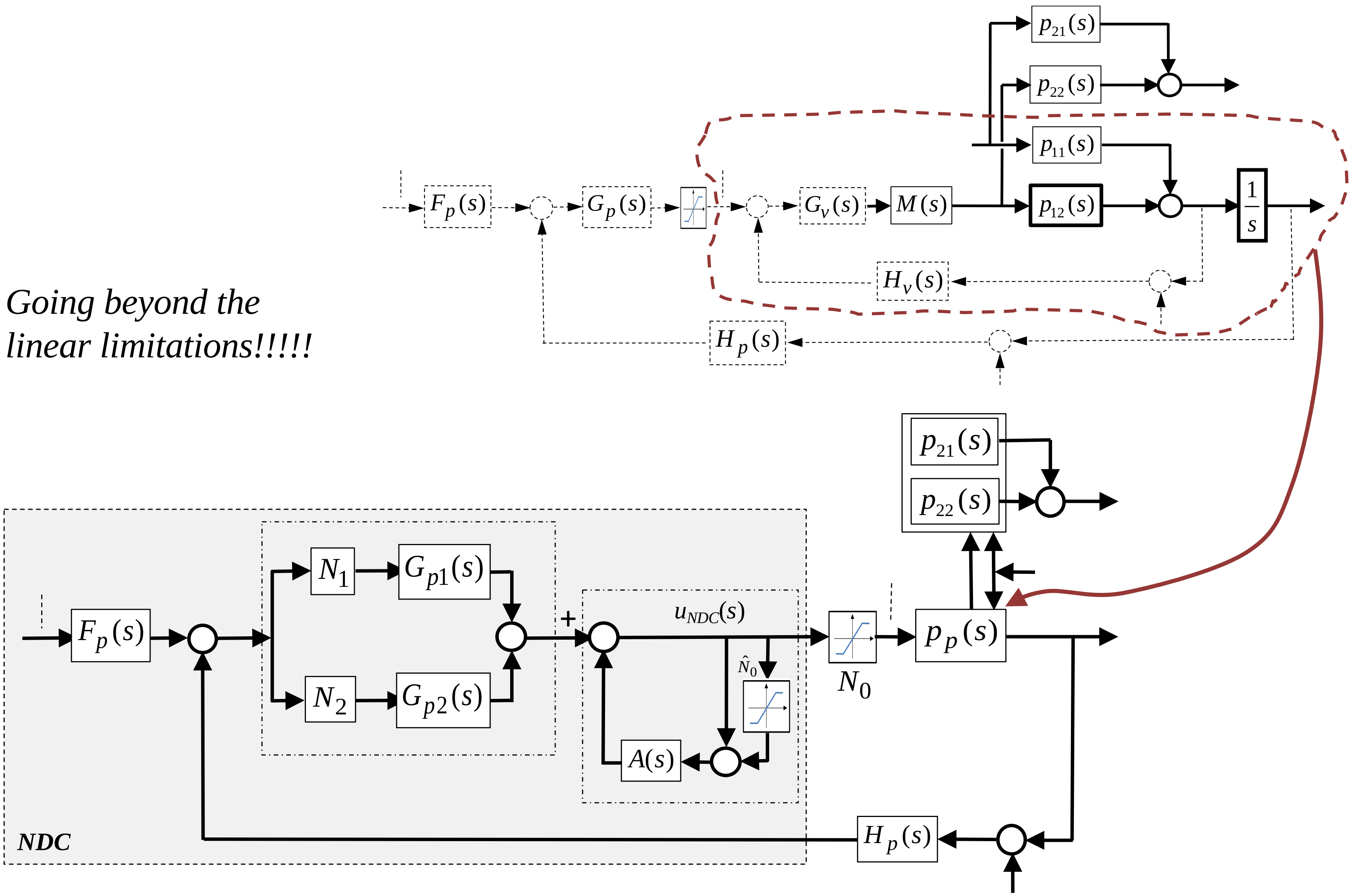
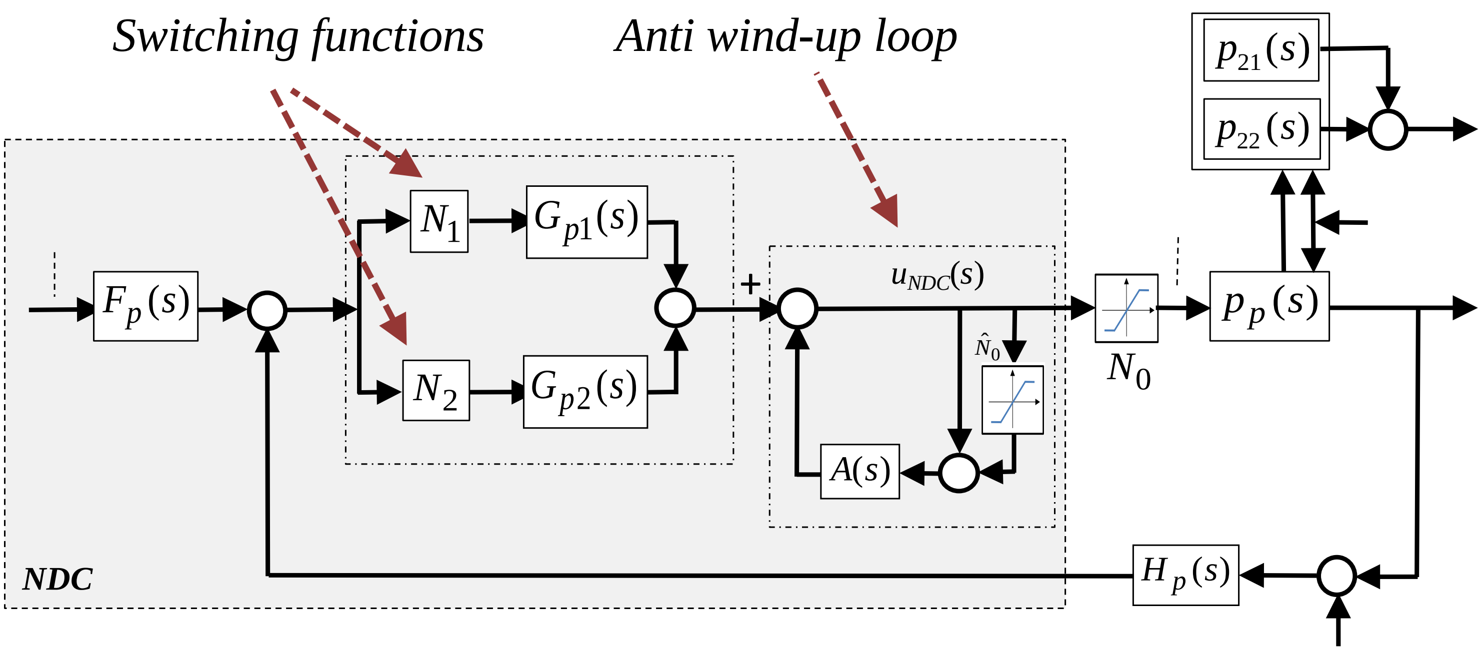
- QFT Nonlinear Dynamic controller (I)

Going beyond the linear limitations!!!!!

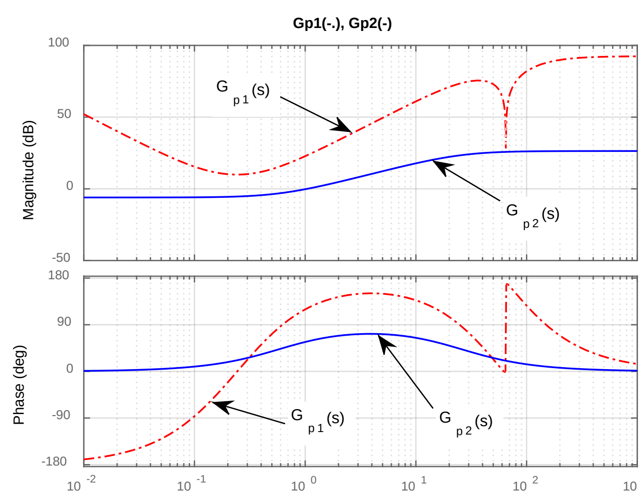


- QFT Nonlinear Dynamic controller (II)



Aggressive QFT controller

$$G_{p1}(s) = \frac{0.04\left(\frac{s}{0.134}+1\right)\left(\frac{s}{0.25}+1\right)\left(\frac{s}{0.3}+1\right)\left(\frac{s}{0.33}+1\right)}{s^2\left(\frac{s}{50}+1\right)\left(\frac{s}{70}+1\right)} \frac{(s^2+0.13s+4225)}{(s^2+130s+4225)}$$



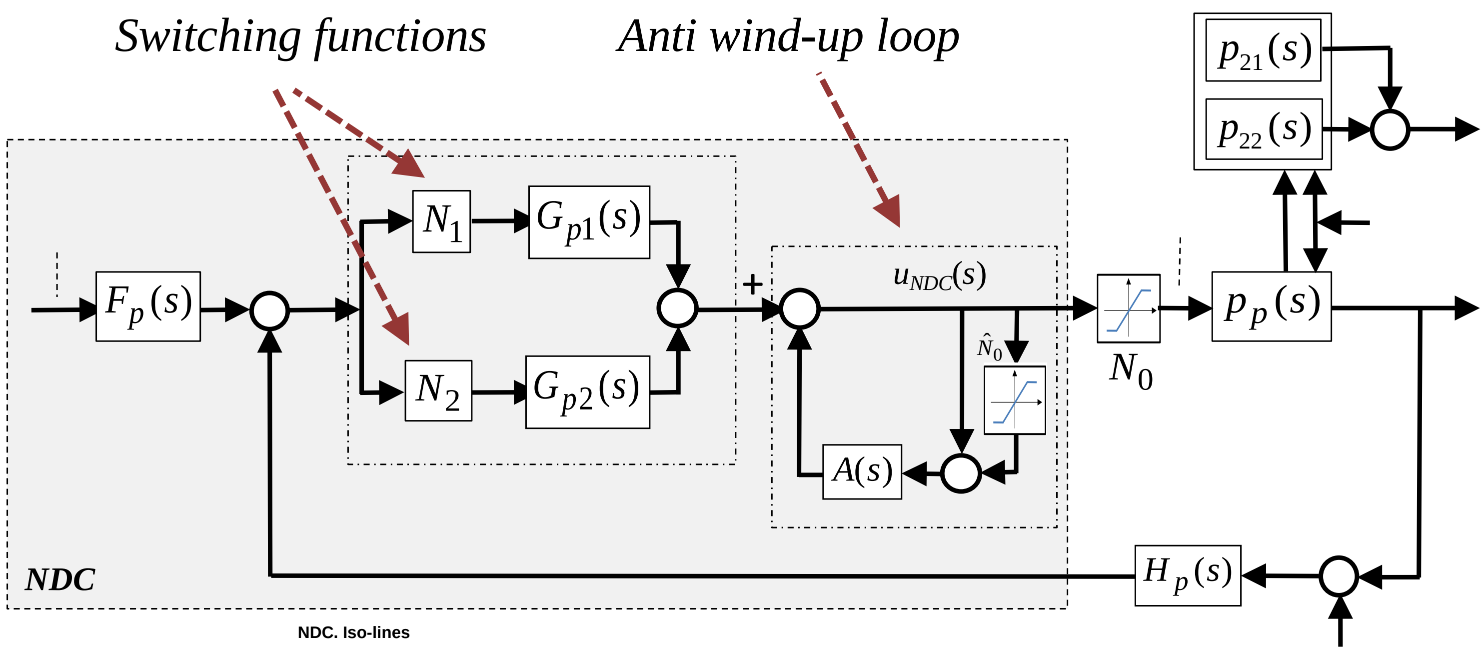
Moderate QFT controller

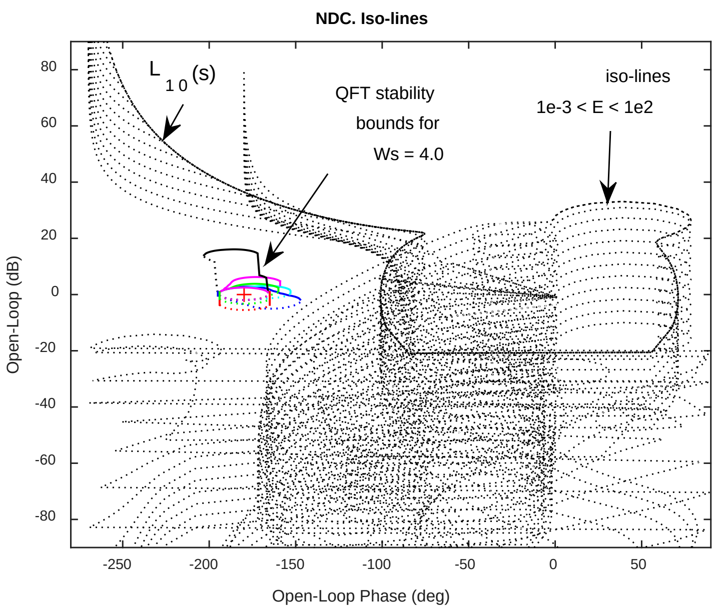
$$G_{p2}(s) = G_p(s) = \frac{0.5\left(\frac{s}{0.6}+1\right)}{\left(\frac{s}{25}+1\right)}$$

Prefilter

$$F_p(s) = \frac{\left(\frac{s}{0.3}+1\right)}{\left(\frac{s}{0.38}+1\right)^2}$$

- QFT Nonlinear Dynamic controller (III)





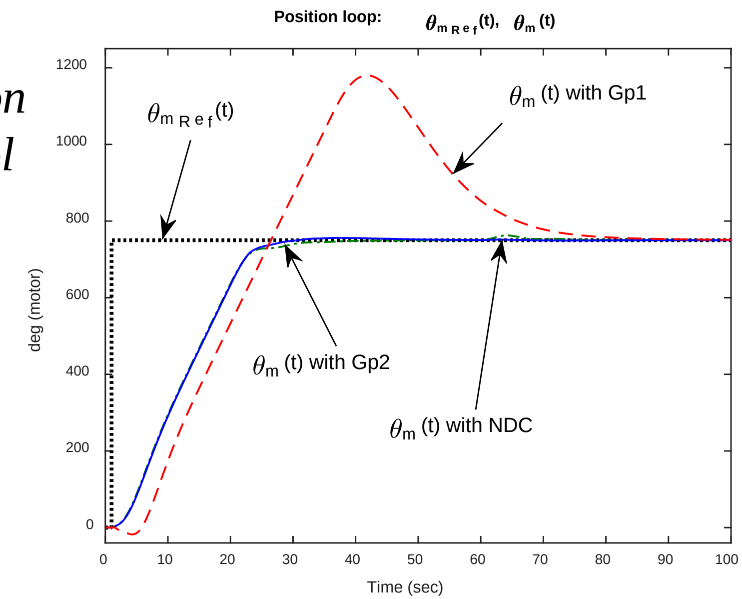
Stability

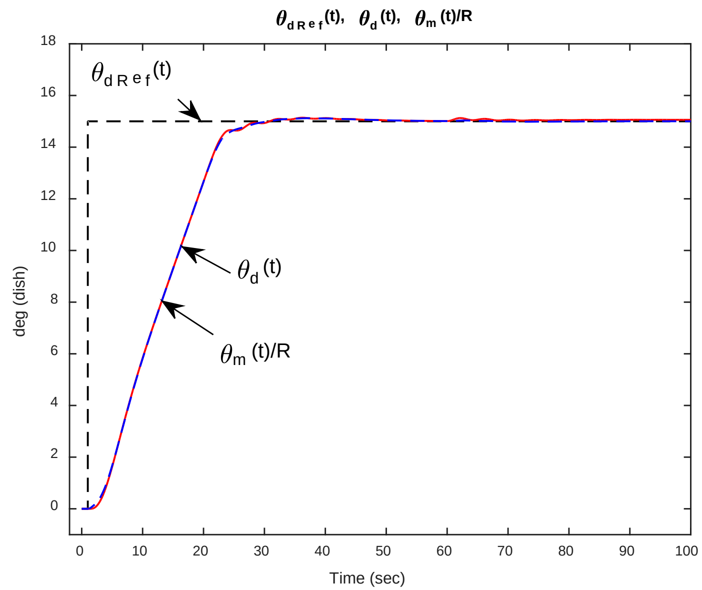
- *closed-loop system*
- *including cascade control loops (veloc. and posit.)*
- *switching functions*
- *and four nonlinearities*

$$L = p_p(s)DF_{N0}\left[\left(\frac{1}{1+A(s)DF_{\hat{N}0}}\right)G_{p1}(s)DF_{N1}+G_{p2}(s)DF_{N2}\right]$$

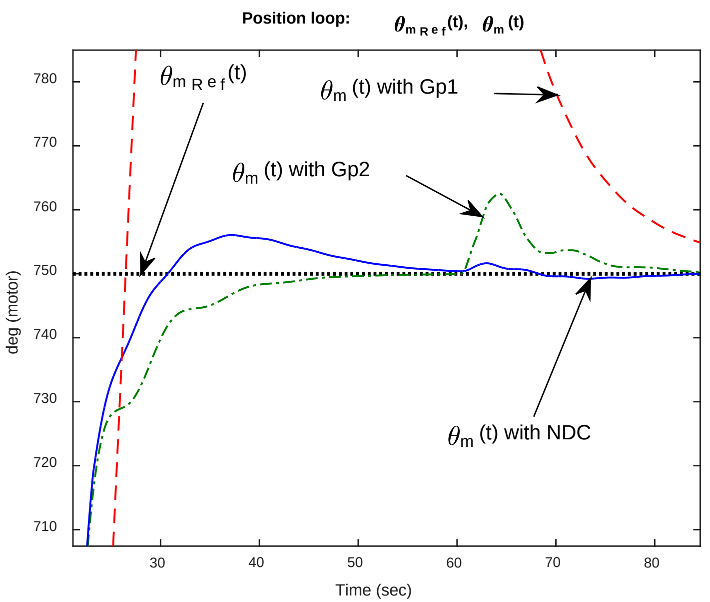
- QFT Nonlinear Dynamic controller (IV)

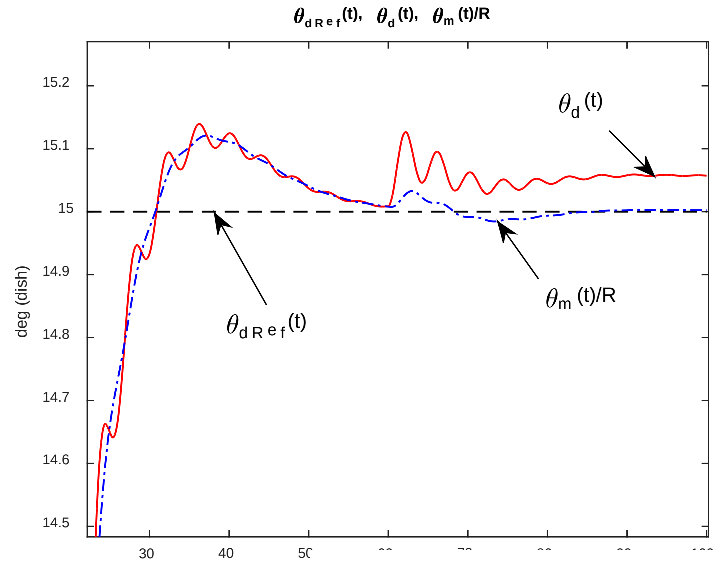
Position control





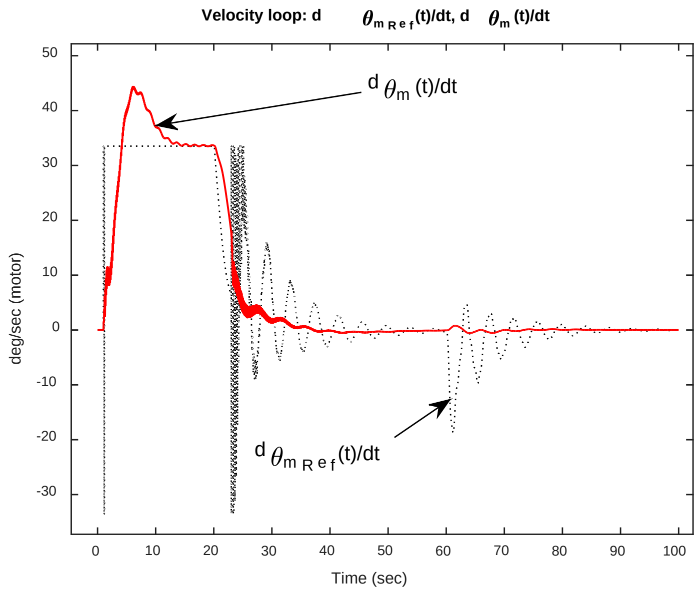
zoom

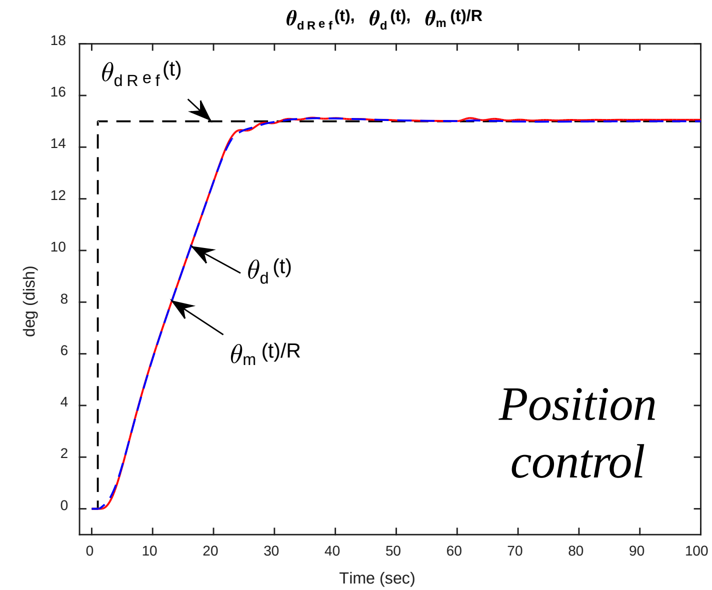




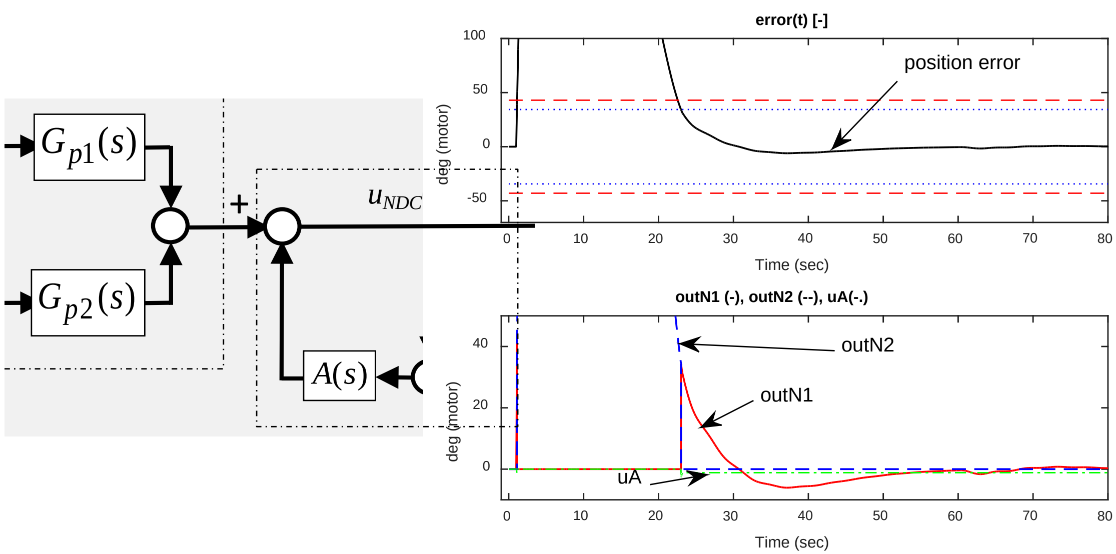
- QFT Nonlinear Dynamic controller (V)

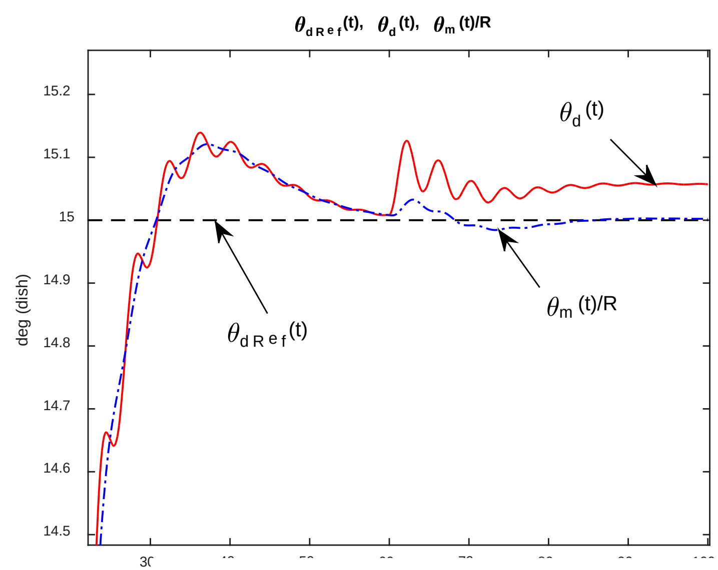
Velocity control





Position control



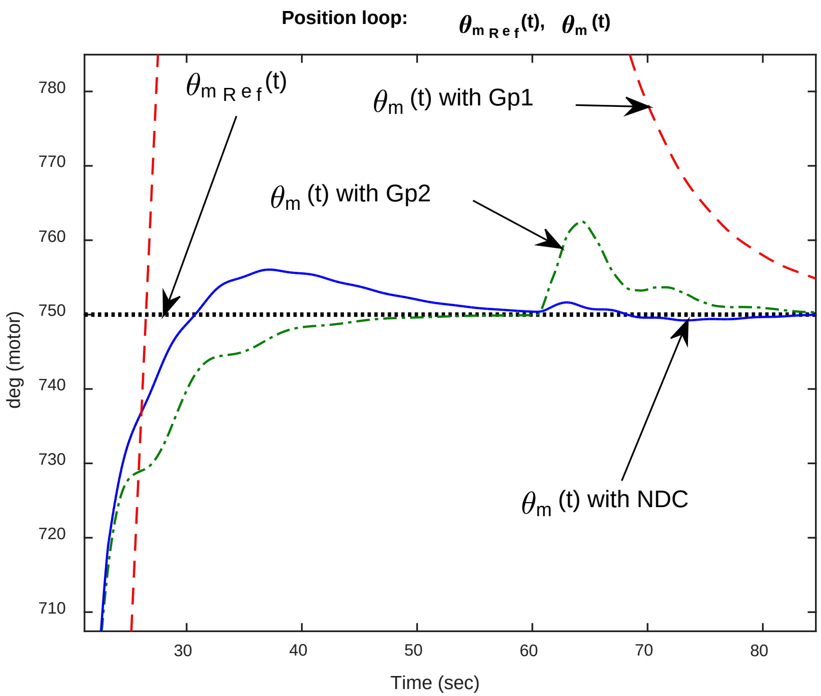


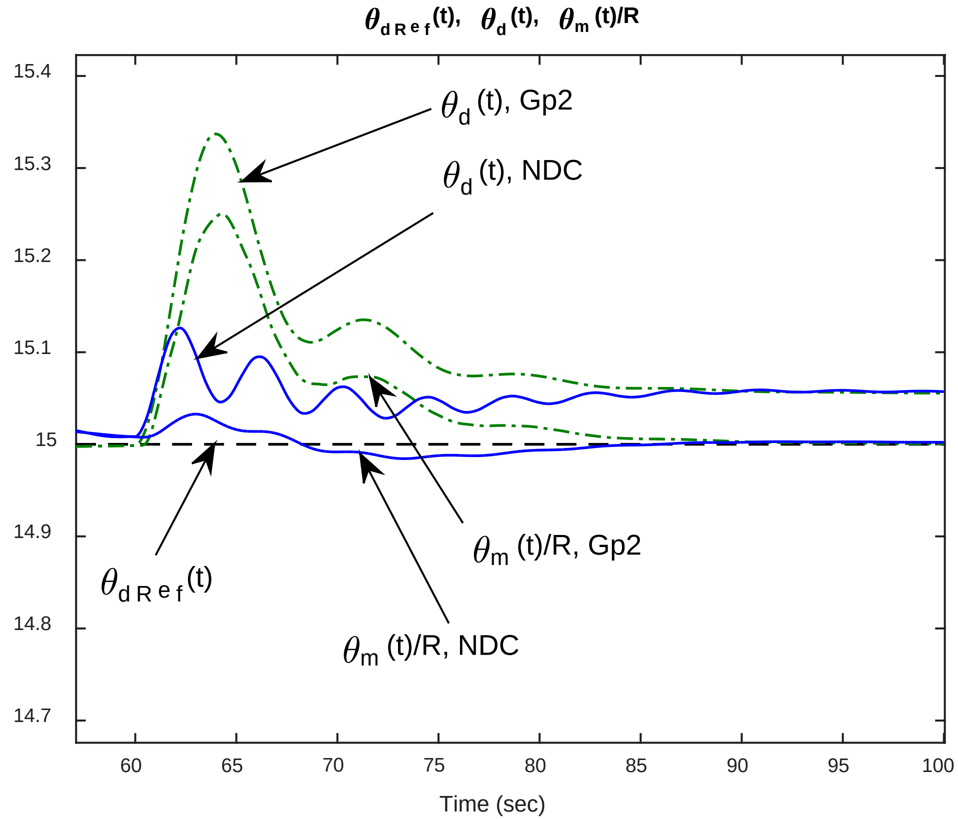
Prof. Mario Garcia-Sanz (CWRU)

- QFT Nonlinear Dynamic controller (VI)

Position control

Reference tracking
&
Wind disturbance rejection





Gp1 Aggressive QFT controller

Gp2 Moderate QFT controller

NDC Nonlinear dynamic control

- Summary

This case study has designed two control solutions for the ***velocity and position loops*** of a ***radio telescope servo system***.

The first solution is based on the ***robust QFT methodology*** and the second one proposes a ***QFT Nonlinear Dynamic Control strategy***.

Both designs deal with the ***uncertainty*** of the model and accomplish ***five simultaneous control objectives***:

- stability,
- tracking of the azimuth axis telescope position,
- regulation of the azimuth axis telescope velocity,
- rejection of unpredictable wind disturbances,
- reduction of dish and feed-arm vibration.