Appendix F

Stability Analysis in the Columbus Active Thermal Control System

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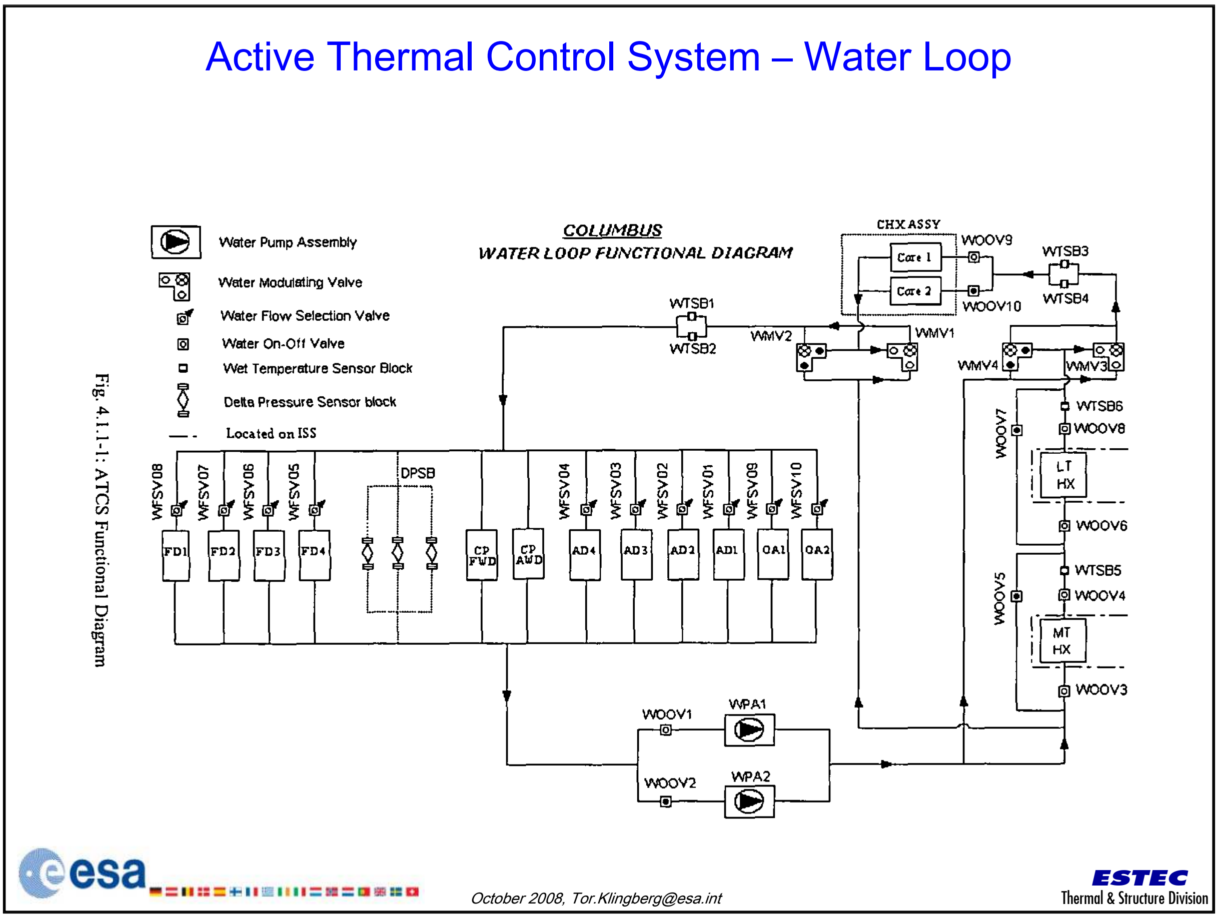
Abstract

Using analytical control theory and ESATAN simulation to analyze the stability margin of the Columbus ATCS under different conditions.


Stability Analysis of the Columbus
Active Thermal Control System
Tor Klingberg


Active Thermal Control System – Water Loop
COLUMBUS
WATER LOOP FUNCTIONAL DIAGRAM
Water Pump Assembly
Water Modulating Valve
Water Flow Selection Valve
Water On-Off Valve
Wet Temperature Sensor Block
Delta Pressure Sensor block
Located on ISS
Fig. 4.1.1-1: ATCS Functional Diagram
CHX ASSY
Core 1
Core 2
WOOV9
WOOV10
WTSB3
WTSB4
WTSB1
WTSB2
WMV2
WMV1
WMV4
WMV3
WTSB6
WOOV8
WOOV7
LT HX
WOOV6
WTSB5
WOOV4
WOOV5
MT HX
WOOV3
WFSV08
WFSV07
WFSV06
WFSV05
DPSB
WFSV04
WFSV03
WFSV02
WFSV01
WFSV09
WFSV10
FD1
FD2
FD3
FD4
CP FWD
CP AWD
AD4
AD3
AD2
AD1
OA1
OA2
WOOV1
WPA1
WOOV2
WPA2
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Verification

- The Columbus ATCS has been verified by simulation using ESATAN/FHTS and physical testing.
- However, no theoretical analysis of the stability has been performed.
- Using control theory, the stability of a (simplified) system can be verified analytically.
- This analysis can also show what control parameters are most stable.

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Stability analysis

- Make a simplified model of the system
- Mathematical description of relations between variables
- Linear transfer function description
- Calculate stability and stability margin using Nyquist criterion.

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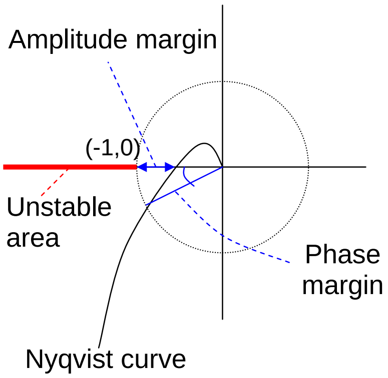
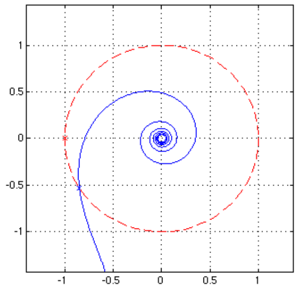
Stability criterions



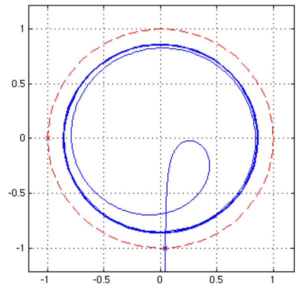
- Amplitude margin: Distance between where the Nyqvist curve crosses the real axis and the point (-1,0).

  Problem: There may be several crossings.



- Phase margin: Angle between the real axis and where the Nyqvist curve crosses the unit circle.

  Problem: With a high derivative (D) control constant, the Nyqvist curve will go into a large circle. Not as stable as the phase margin indicates



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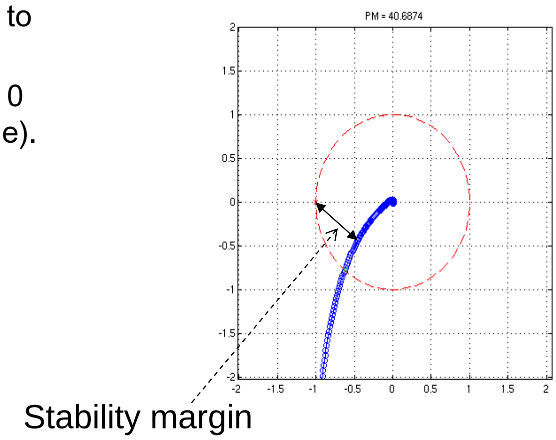
Stability criterions

- Instead, use the shortest distance between the Nyqvist curve and the point (-1,0) to measure stability margin.
- The value will range from 0 (unstable) to 1 (very stable).



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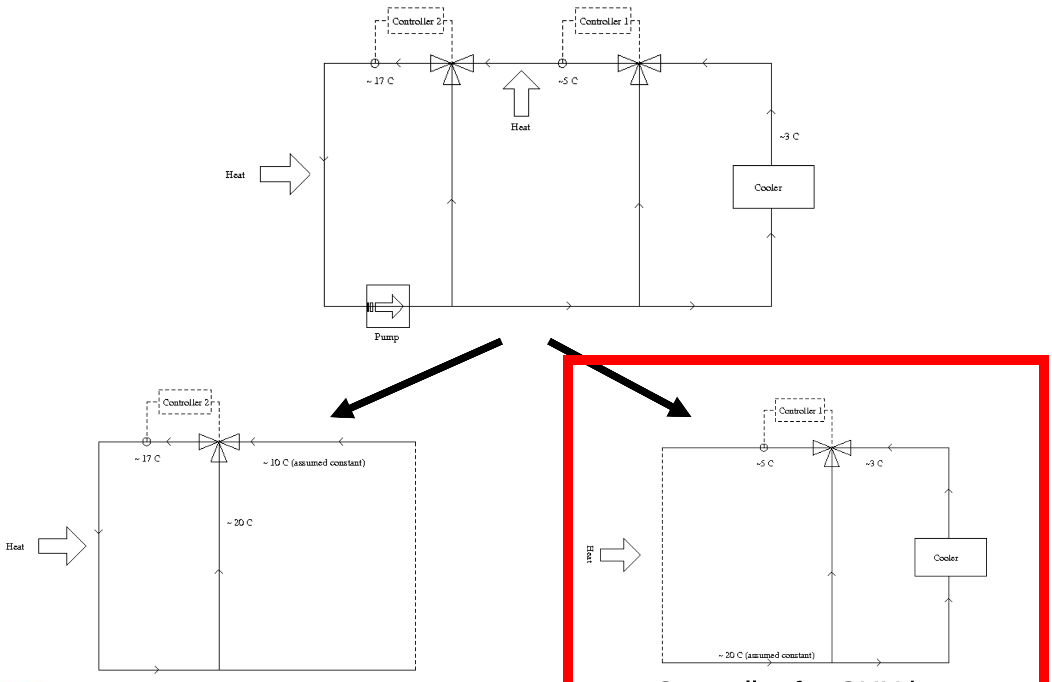
Separate into two parts



Controller for plenum input

Controller for CHX input

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Mathematical model

- Each of the two loops is described by a simplified mathematical model.
- A system of differential equations connecting valve position, hydraulic resistances, water flow rates and temperatures.

Hydraulic resistance:

$$K_{hx}(\alpha) = K_{hx}^{pipe} + K_{hx}^{valve}(\alpha)$$
$$K_{by}(\alpha) = K_{by}^{pipe} + K_{by}^{valve}(\alpha)$$

Water flow speed:

$$K_{hx}\dot{m}_{hx}^2 = K_{by}\dot{m}_{by}^2$$
$$\dot{m}_{hx} + \dot{m}_{by} = \dot{m}_0$$

Water mixing in valve:

$$\dot{m}_{hx}T_{LT}(t-\tau_{ltv}) + \dot{m}_{by}T_0(t-\tau_{iv}) = \dot{m}_0 T_{out}(t)$$

MT and LT heat exchangers:

$$M_{MT}\frac{dT_{MT}}{dt} + \dot{m}_{hx}T_{MT} = \varepsilon_{MT}\dot{m}_{hx}T_{NH_3MT} + (1-\varepsilon_{MT})\dot{m}_{hx}T_0$$
$$M_{LT}\frac{dT_{LT}}{dt} + \dot{m}_{hx}T_{LT} = \varepsilon_{LT}\dot{m}_{hx}T_{NH_3LT} + (1-\varepsilon_{LT})\dot{m}_{hx}T_{MT}$$

Temperature sensor:

$$\tau_s\frac{dT_s(t)}{dt} + T(t)_s = T_{LT}(t-\tau_{vs})$$

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Linearization

- The differential equations are linearized around a working point and Laplace transformed into a system of transfer functions.
- Example: Heat exchanger temperature equation:

$$M\frac{dy}{dt} + \dot{m}y = \varepsilon\dot{m}u \quad \longrightarrow \quad Y(s) = \underbrace{\frac{\varepsilon\dot{m}}{Ms+\dot{m}}}_{G(s)} U(s)$$

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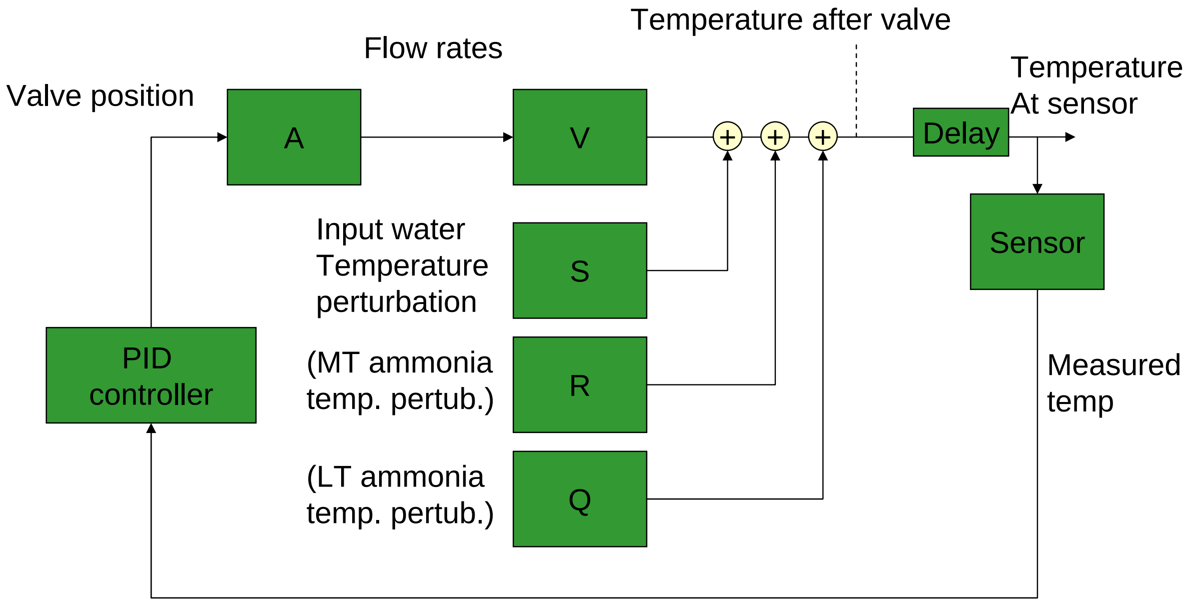
System of transfer functions



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Implementation

- A program using MATLAB to vary the control parameters and analyze the system stability in each case, making a map of possible control parameters.
- Loop through various PID parameters and determine stability margin in each case.

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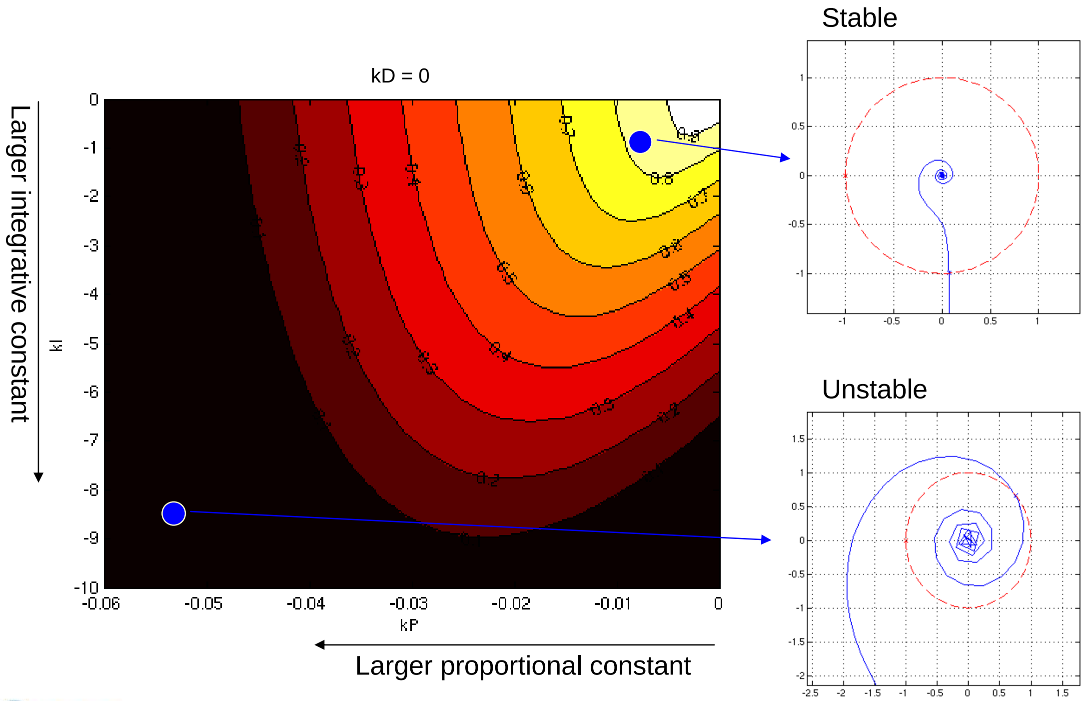
Example results



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Test cases

- Payload racks flow rate: high/low
- Racks heat load: high/low
- Temperature set-point at 5 or 10 °C
- Most likely to be unstable: low flow – high load – high setpoint.

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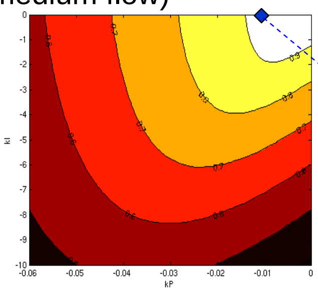
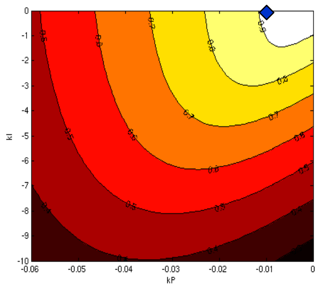
Results

Normal case (setpoint 5°C, medium flow)

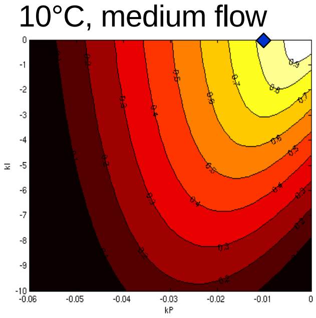


Current control parameters
kP = -0.011
kI = -0.00165
kD = 0

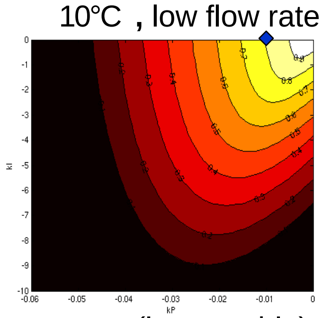
5°C, lower flow rate



10°C, medium flow



10°C , low flow rate



(least stable)

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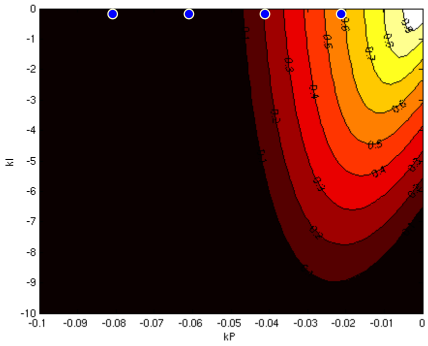
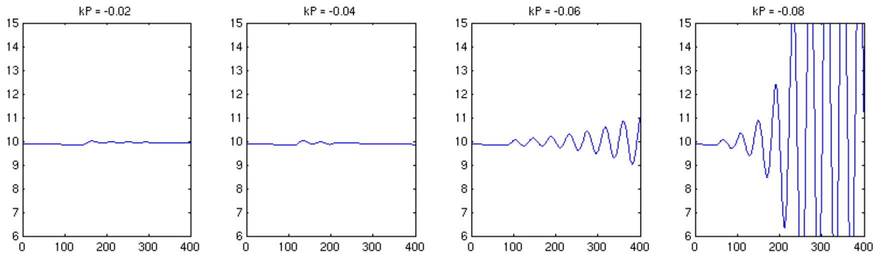
Comparison with simulation

MATLAB stability analysis result



ESATAN/FHTS transient simulation result



stable | stable | unstable | unstable

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Comments

- To the first order, the system is very simple:
  - A delay between the valve and sensor
  - The slowness of the sensor
- A delay is problematic for regulation. It can lead to oscillations with frequency matching the delay time.

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Further work

- Analyse the plenum input temperature controller.
- Investigate interactions between the two systems using a 2x2 matrix of transfer functions.
- Add temperature disturbances
  - Sine wave and ramp

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