Plasma Control

Course on tokamak engineering, diagnostics and operation

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- Introduction
- PID Control
- State-Space Modelling
- MIMO Control
- ISTTOK configuration
- ISTTOK magnetic control and signal processing

Mathematical Modelling of Dynamic Systems

Dynamic systems that are composed of linear time-invariant (constant-coefficient) differential equation are called linear time-invariant systems. Systems that are represented by differential equations whose coefficients are functions of time are called linear time-varying systems.

The transfer function of a linear, time-invariant, differential equation system is defined as the ratio of the Laplace transform of the output (response function) to the Laplace transform of the input (driving function).

$$T(s) = \frac{Y(s)}{U(s)}$$

Ogata K.,"Modern Control Engineering"

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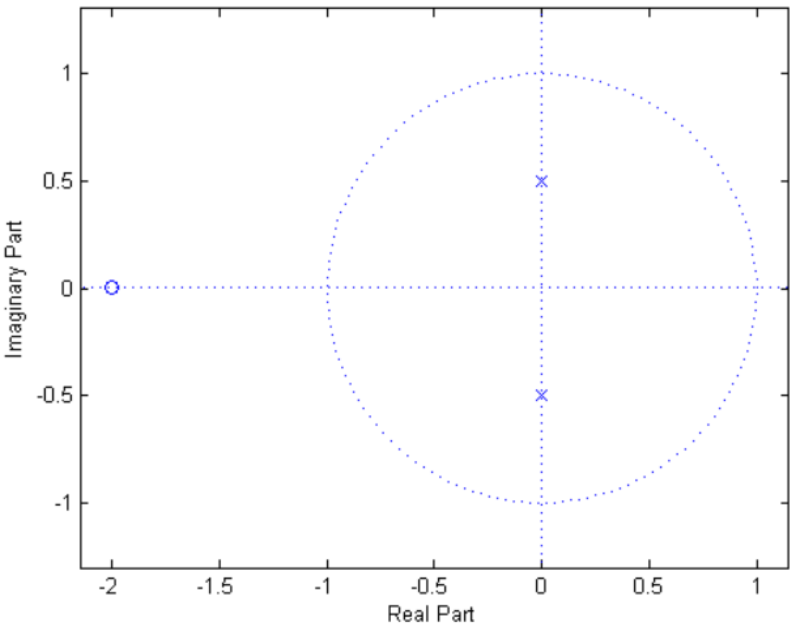
Mathematical Modelling of Dynamic Systems



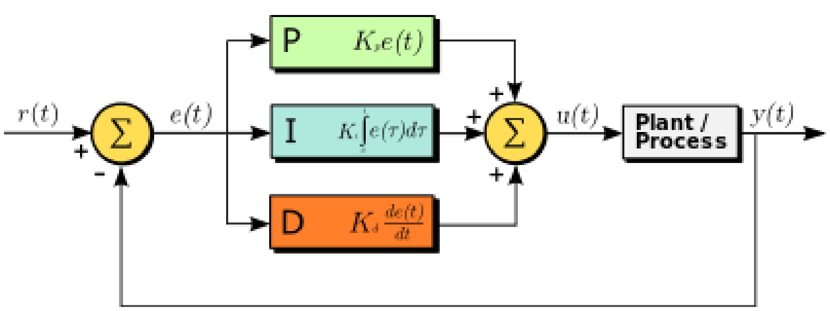
$$T(s) = \frac{s+2}{s^2 + \frac{1}{4}}$$

$$s = -2$$

$$s = \pm \frac{i}{2}$$

PID Control

A **Closed-Loop** Control System utilizes feedback to compare the actual output to the desired output response

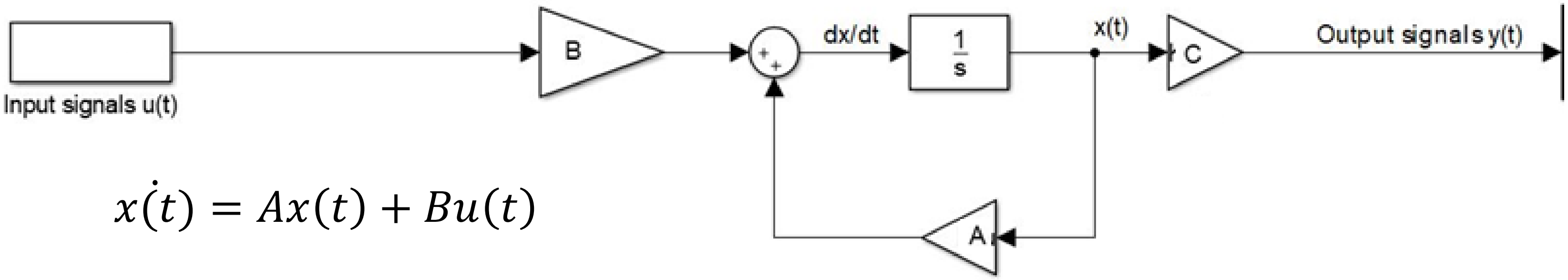


A proportional controller (P) will have the effect **of reducing the rise time** and will reduce, but never eliminate, the steady-state error.

The integral control (I) will have the effect of eliminating **the steady-state error**, but it may make the transient response worse.

A derivative control (D) will have the effect of increasing the **stability of the system**, reducing the overshoot, and improving the transient response.

State-Space Model



$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t)$$

In control engineering, a **state-space representation** is a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations, were A,B,C and D are constant matrices.

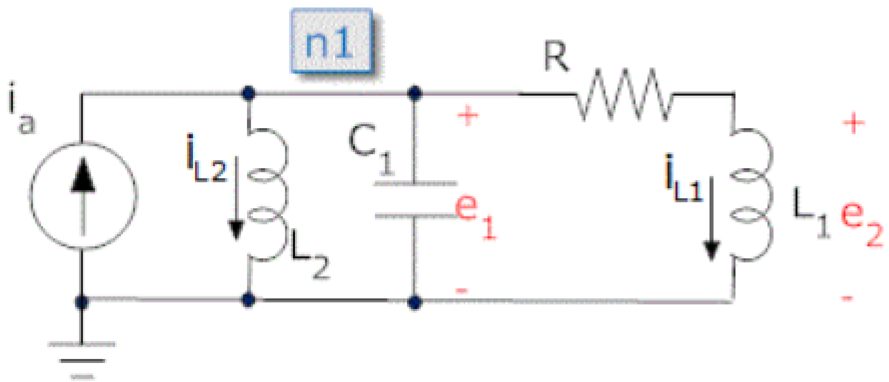
Discrete equations →

$$x[k+1] = A_d x[k] + B_d u[k]$$

$$y[k] = C_d x[k] + D_d u[k]$$

State-Space Model

Let's get the State-Space model of this easy circuit!!!!!



Output : e_2
Input : i_a

Chen C.,"Linear Shystem Theory and Design"

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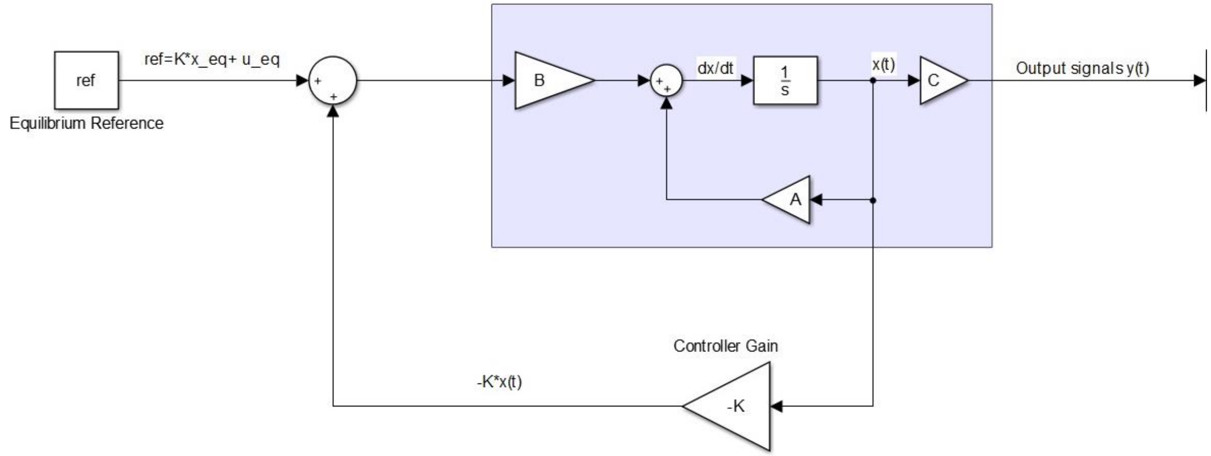
MIMO control



$$u = -Kx + ref$$

$$\dot{x} = (A - BK)x$$

$$ref = Kx_{eq} + u_{eq}$$

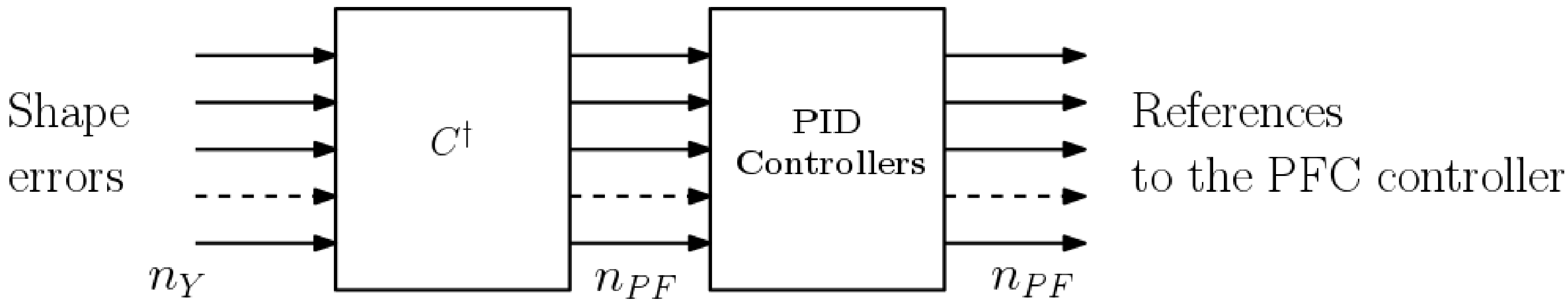
Theorem : The pair $(A - BK, B)$, for any 1xn real constant vector **k** is controllable if and only (A,B) is controllable.

LQR (Optimal Control)

- An **LQR-controlled** system has good stability margins at the plant inputs.
- **Q** and **R** are the **diagonal chosen** constant weighting matrices. **Q** penalizes in the cost function the **states** and **R** the **inputs**.

MIMO control

The Xtreme Shape Controller (XSC)

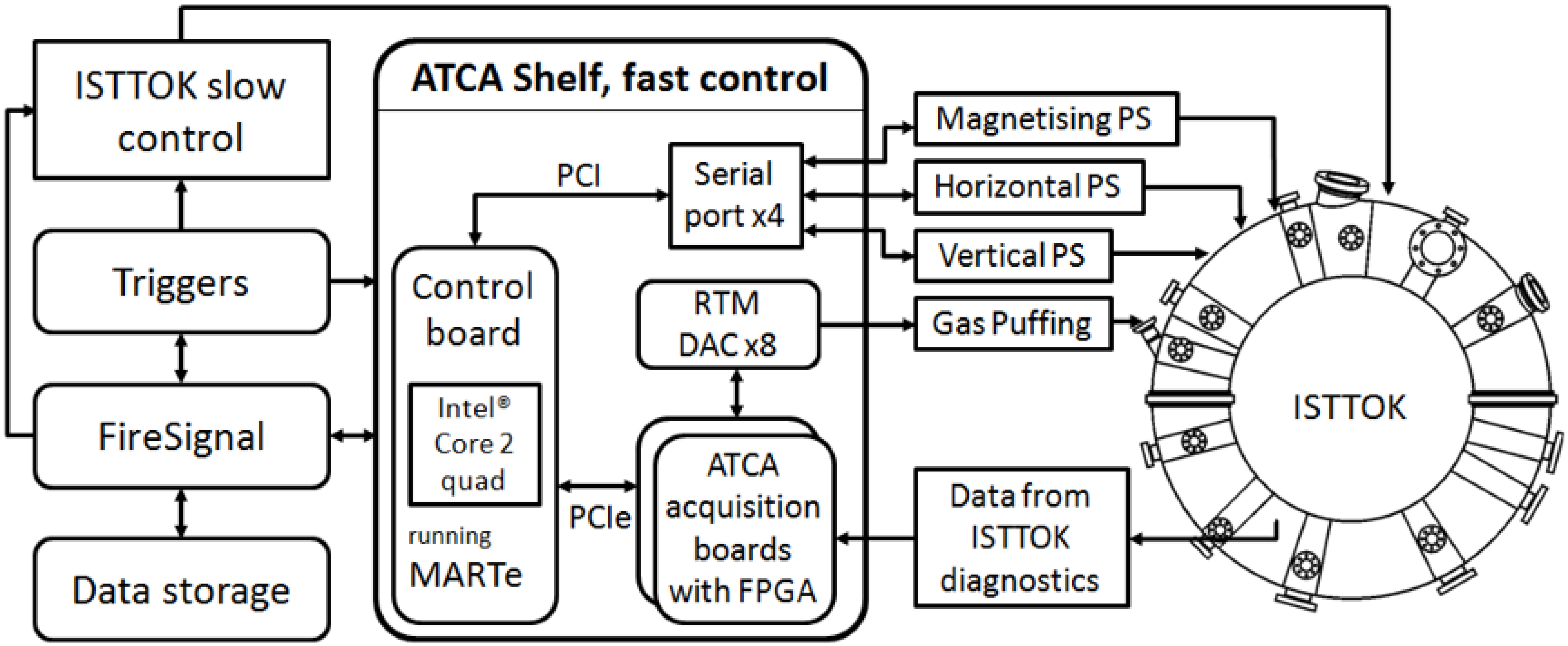


From $\delta Y(s) = C \cdot I_{PF_{ref}}(s)$ it follows that the PF currents needed to track the desired shape (in a **least-mean-square sense**) are given by

$$\delta I_{PF_{ref}} = C^\dagger \delta Y$$

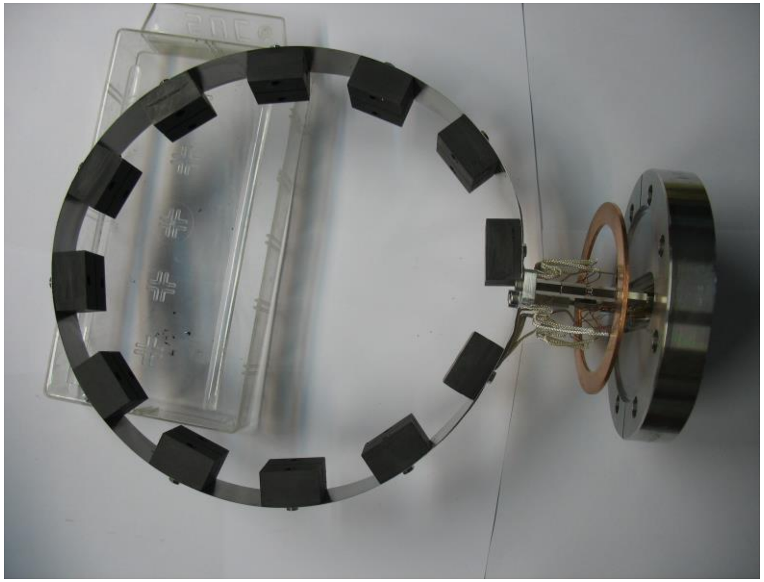
where $C^\dagger$ the pseudo inverse of the C matrix, which can be computed using SVD

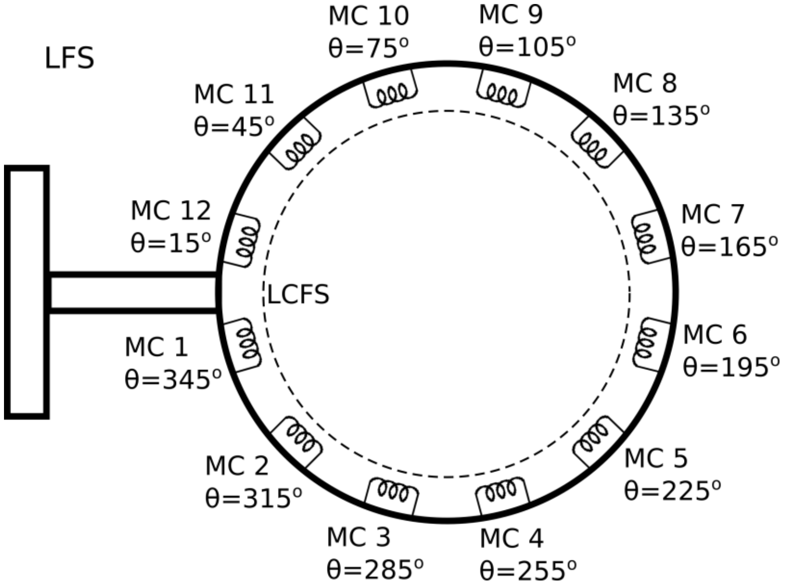
ISTTOK Control System



GAM : General Application Module

ISTTOK Mirnov Coils

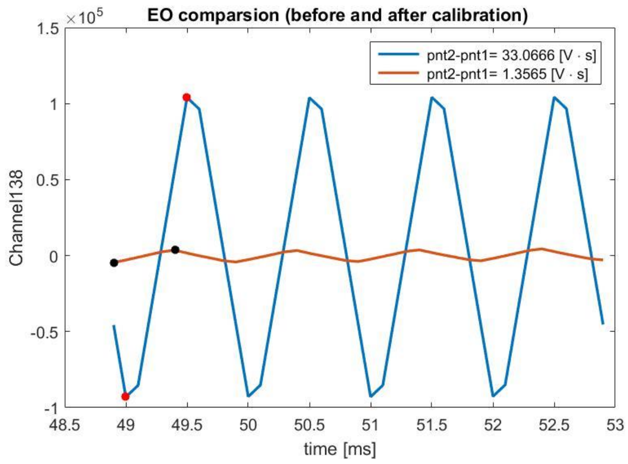


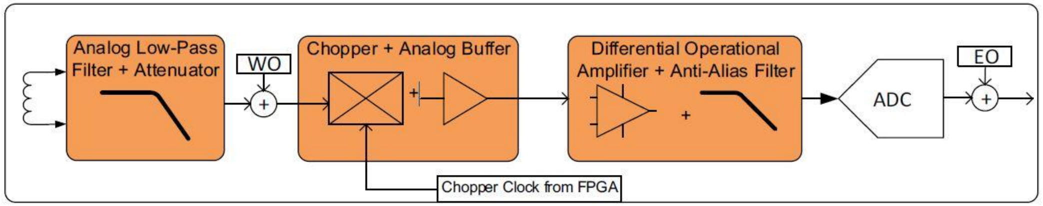


- 50 turns
- 49 mm^2
- Distance from the center of the chamber to the limiter : 8.5 [cm]
- Distance from the center of the chamber to the center of the coils: 9.35 [cm]

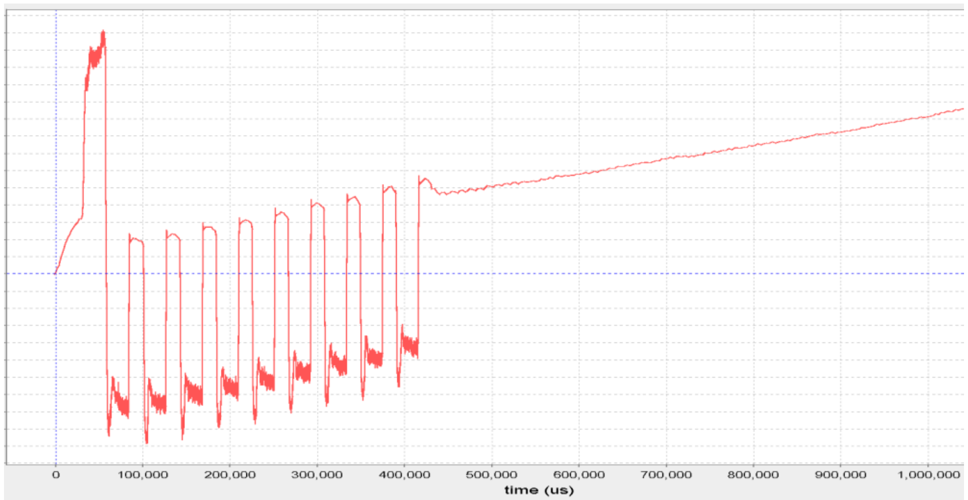
ISTTOK Signal Processing

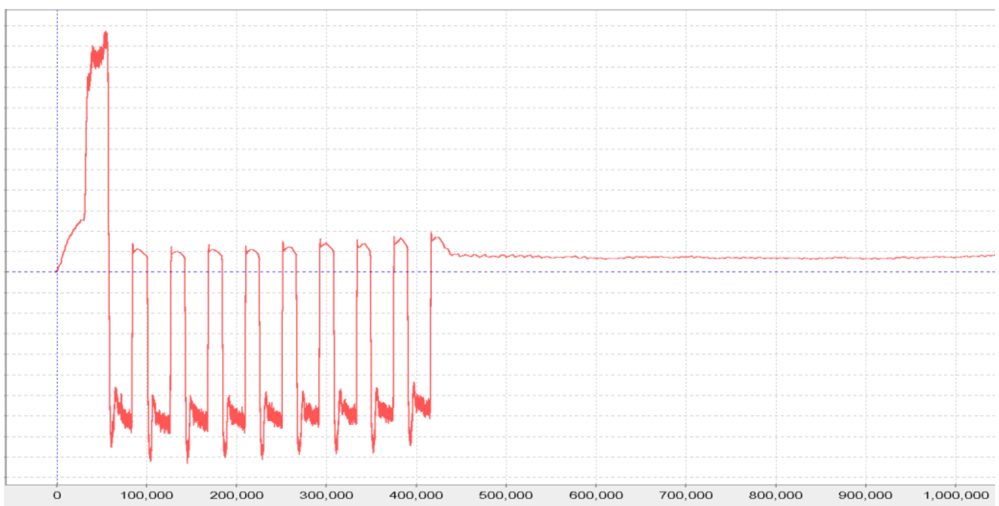
- Real time integration of the magnetic diagnostic
- Software calibration for minimization of the Electronic Offset (EO)
- Real-time subtraction of Wiring Offset (WO)
- Set of 12 Mirnov probes





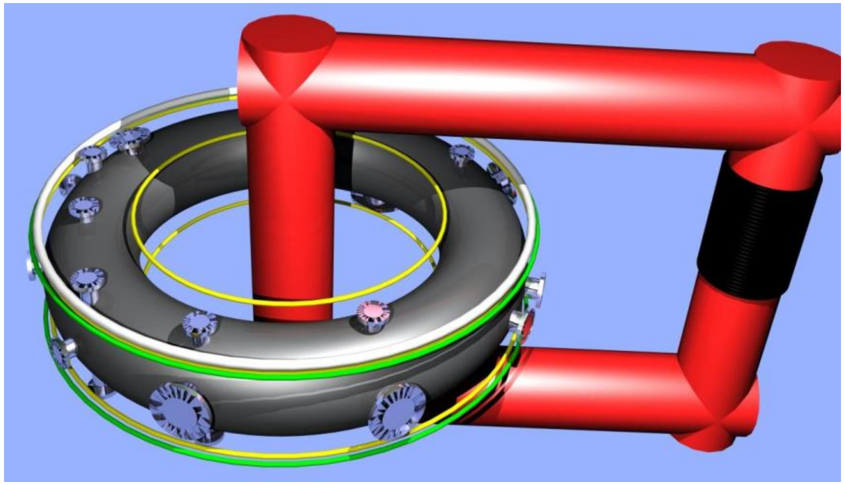
ISTTOK Signal Processing





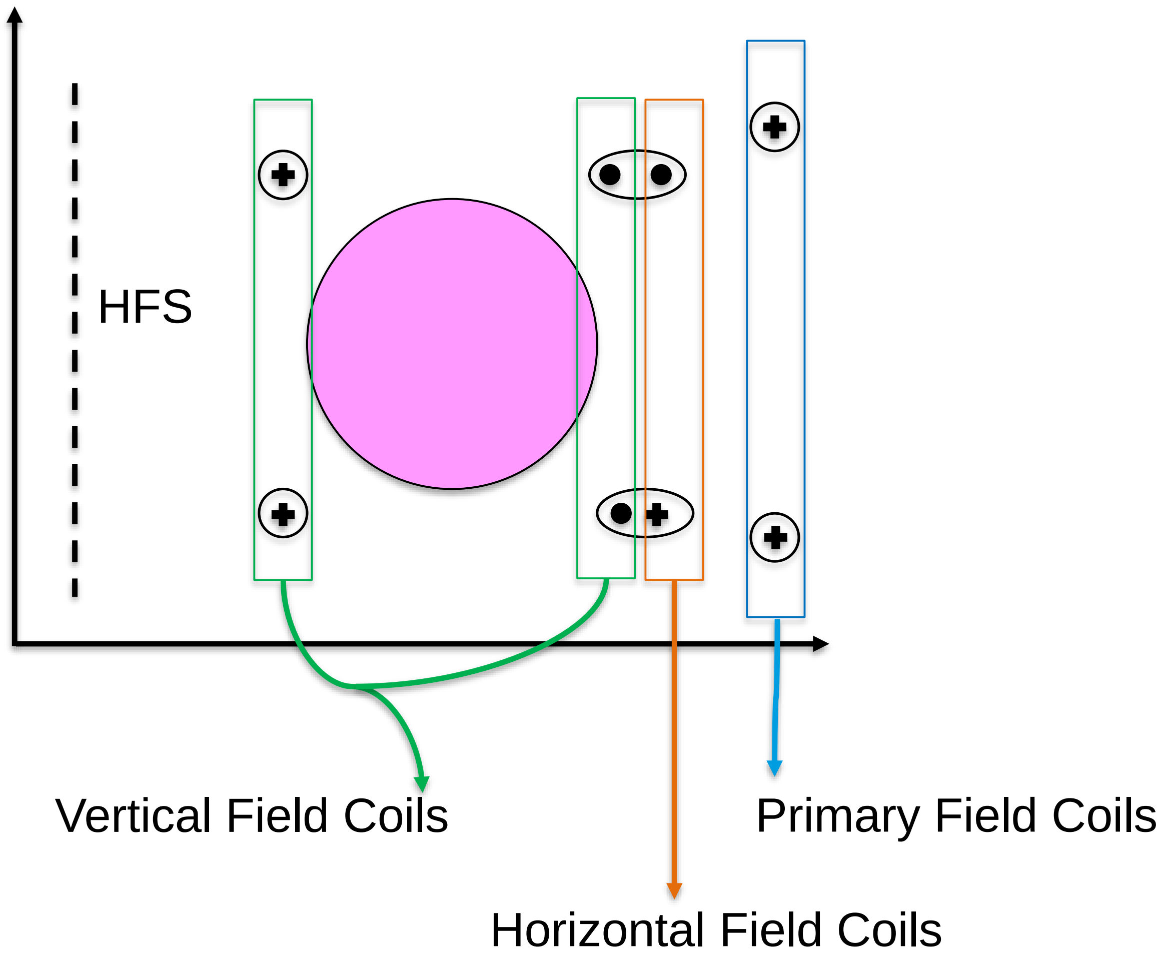
- The correction of the Wiring offset (WO) is performed on real-time.
- During shot, we have a couple of minutes before the presence of any magnetic field.
- Every second before the presence of fields the GAM measures the slope of the WO and makes and average
- During the discharge in each MARTe cycle the calculated slope is subtracted from each channel

ISTTOK magnetic topology

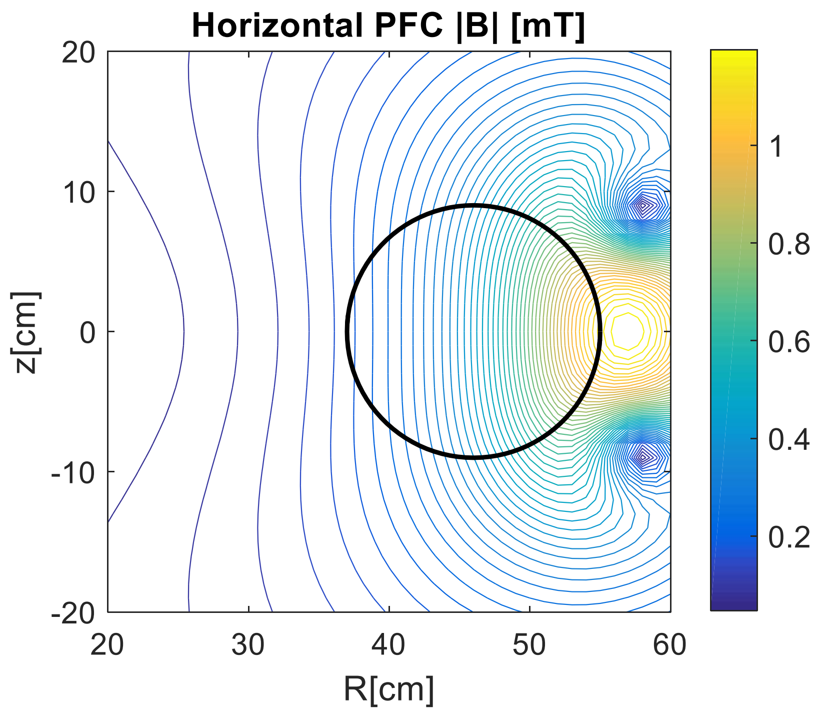


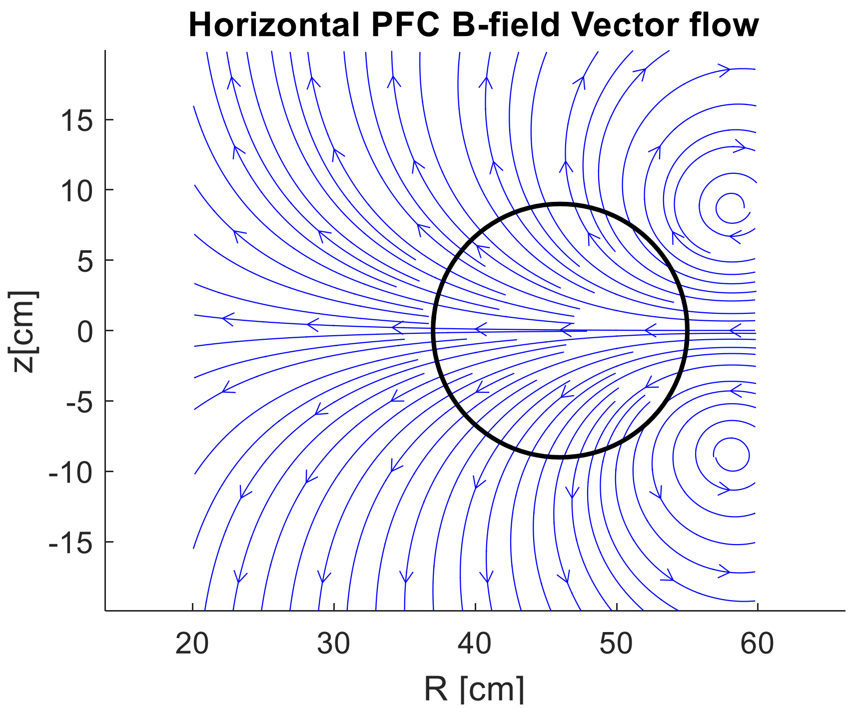
- Primary Coils (white) : 2 coils, 14 turns, $R_{1,2}$=62 [cm],z=±13[cm]
- Vertical Coils(yellow): 4 coils, 5 turns, $R_{1,2}$=58 [cm],$R_{2,3}$=35 [cm],z=±7 [cm]
- Horizontal Coils(green): 2 coils , 4 turns, $R_{1,2}$=58 [cm],z=±7[cm]

ISTTOK magnetic topology



Horizontal Coils Poloidal Field Contribution





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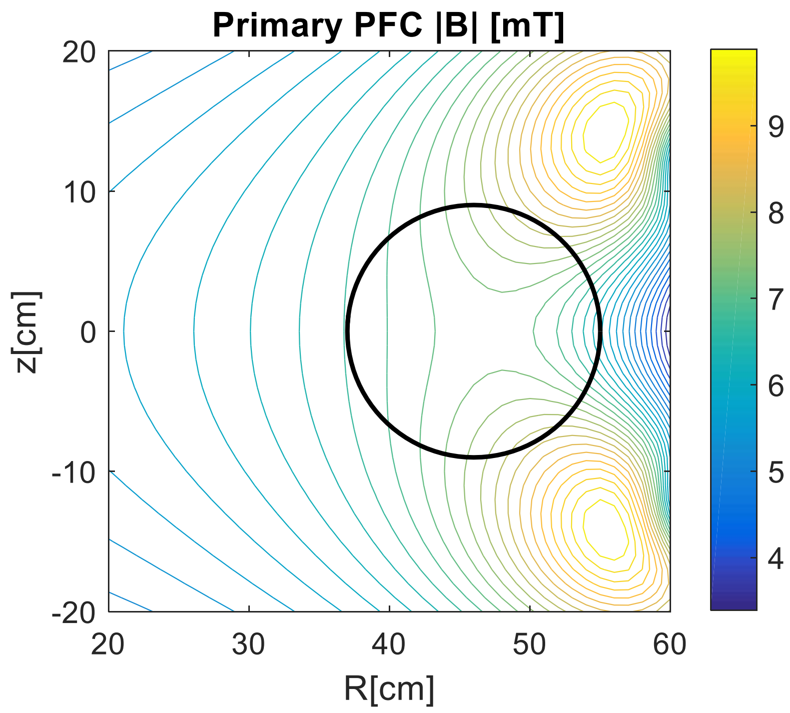
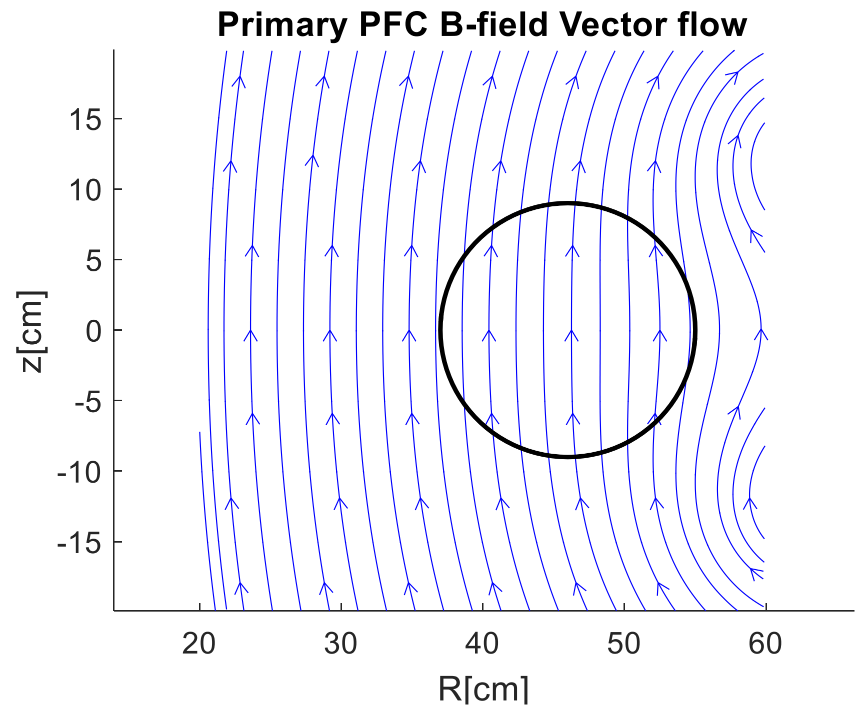
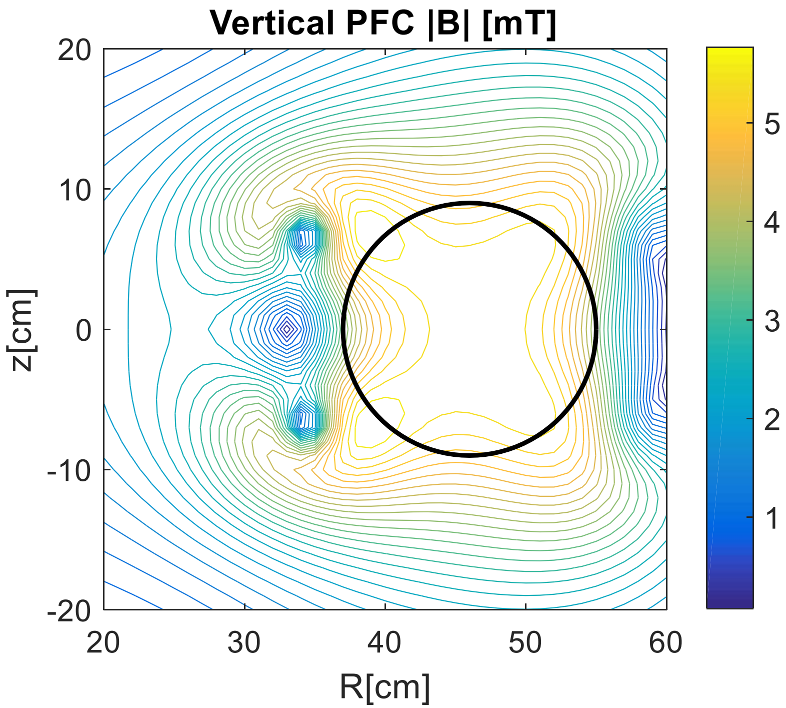
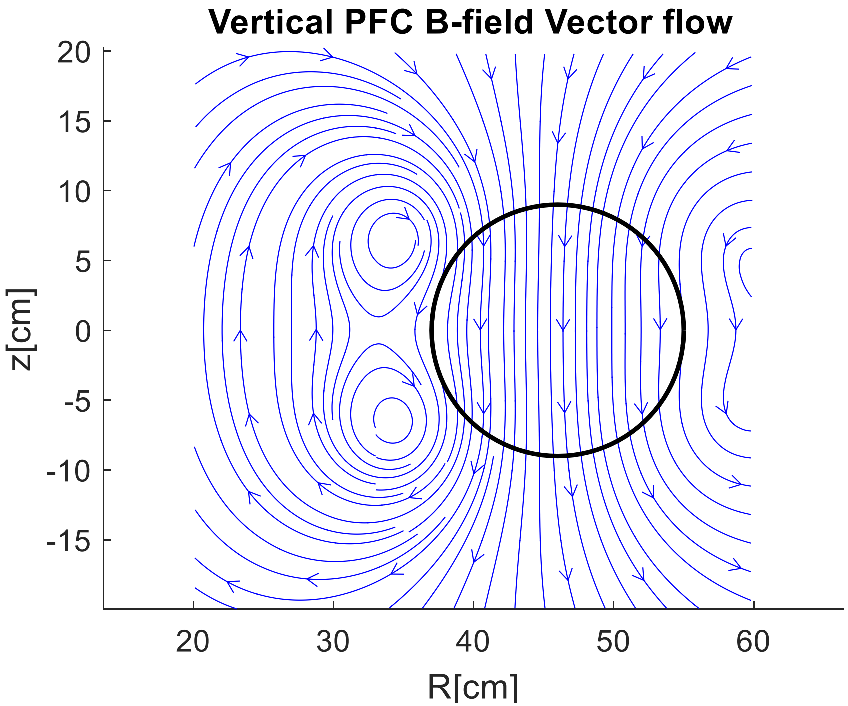
Primary Coils Poloidal Field Contribution



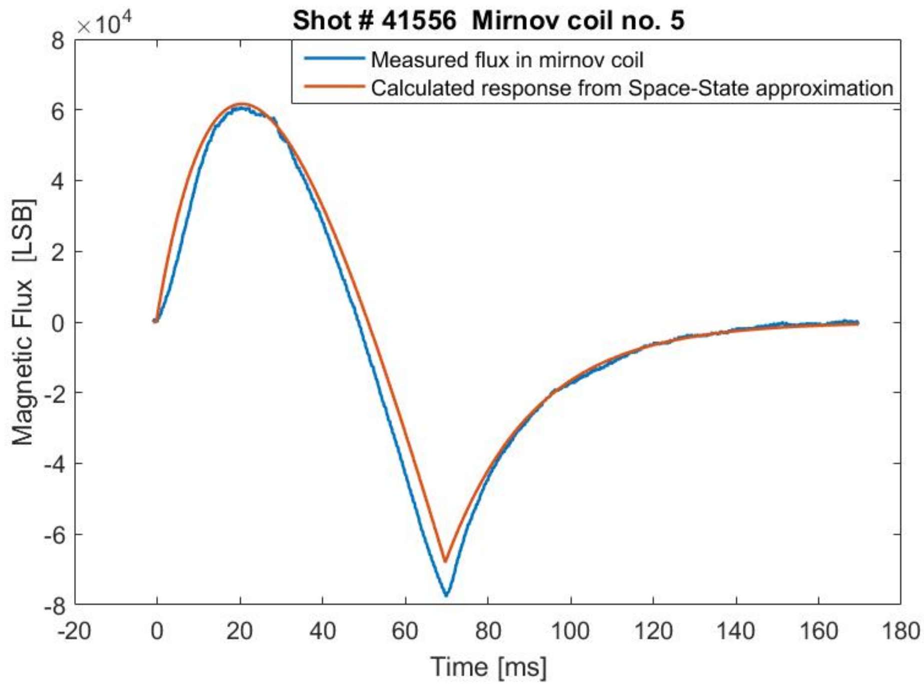


Vertical Coils Poloidal Field Contribution





ISTTOK external magnetic fluxes



>> systemIdentification

Characterization in vacuum of magnetic fluxes due to the currents in the PFC

State-Space model reconstruction of magnetic fluxes for each diagnostic

Real-time subtraction of computed external flux on every MARTe cycle

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ISTTOK plasma centroid position

$$H_{probe}^{i} = \frac{-ADC}{\mu_0 N_{turns} A_{probe}} \int_0^{\infty} v(t)dt$$

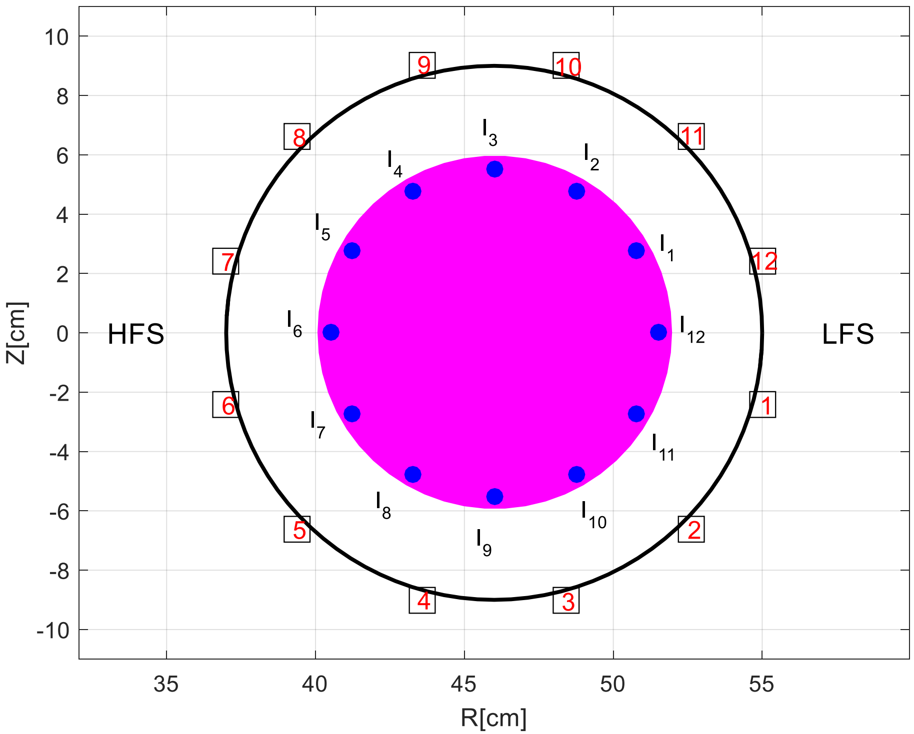
Let's make a cylindrical approximation for getting the plasma current centroid position

$$\Delta R = \frac{\sum_{i=1}^{12} R_{probe}^{i} \times H_{probe}^{i}}{\sum_{i=1}^{12} H_{probe}^{i}}$$

$$\Delta z = \frac{\sum_{i=1}^{12} z_{probe}^{i} \times H_{probe}^{i}}{\sum_{i=1}^{12} H_{probe}^{i}}$$

$$\mathrm{I}p = \frac{2\pi r_{probe}}{N_{probes}} \sum_{i=1}^{12} H_{probe}^{i}$$

ISTTOK plasma centroid position



$$i_{p,f} = M_{fp}^{\dagger} f_p$$

M_{fp} Matrix whose *ij*-element gives the contribution to the measurement *i* of a unitary current in the filament *j*

f_p Represents the measurement vector where the contribution given by the poloidal field coils has been subtracted

•Pironti A., *Magnetic Control of Tokamak Plasmas*, 2nd ed. Springer, 2016

ISTTOK Control

Which parameters do we want to control in ISTTOK?

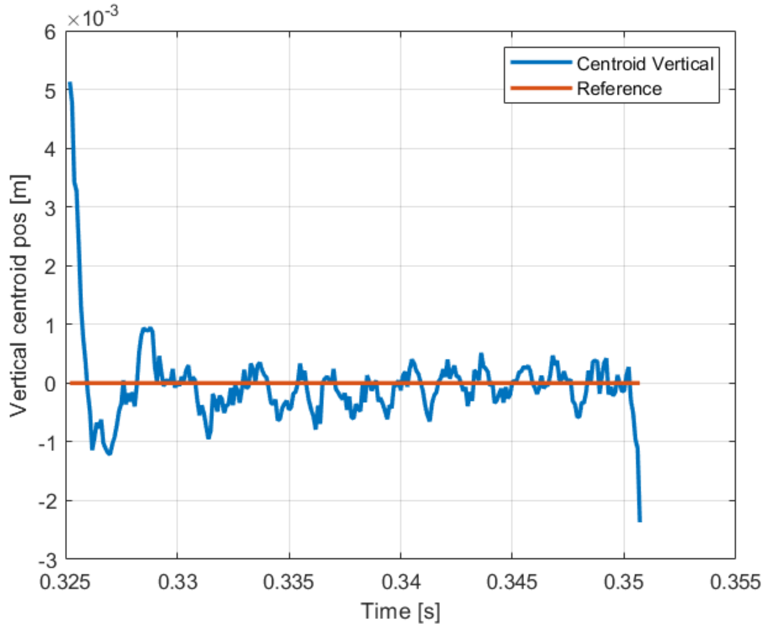
$$y = \begin{bmatrix} R_p \\ z_p \end{bmatrix}$$

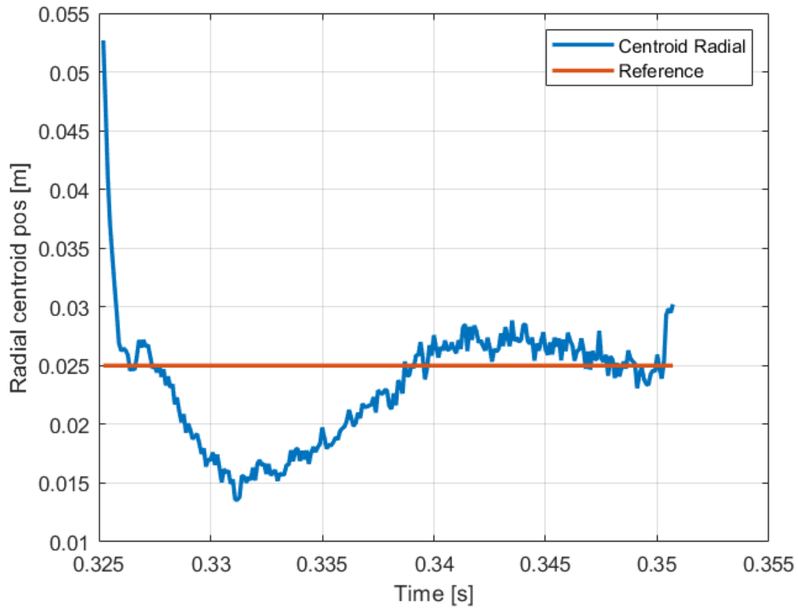
Which can be the inputs of our system?

$$u = \begin{bmatrix} I_{horizontal} \\ I_{vertical} \end{bmatrix}$$

ISTTOK Control

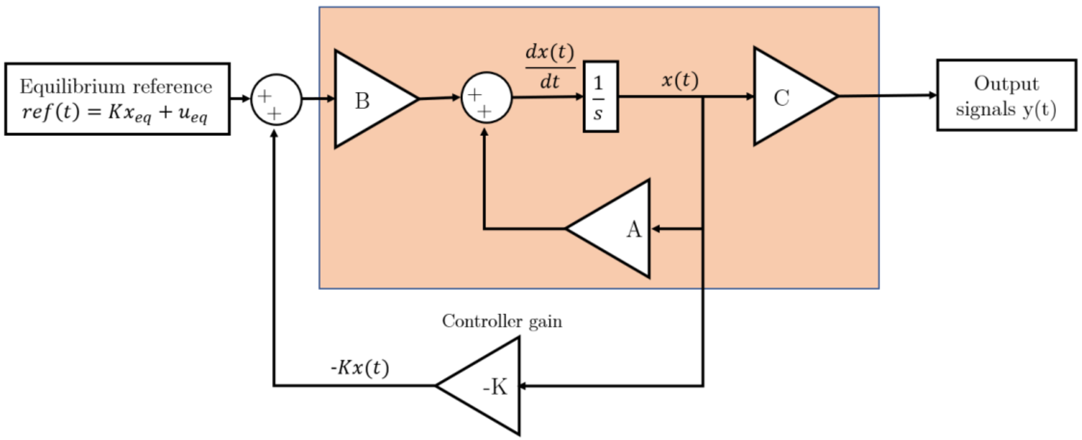
- PID Controllers





ISTTOK Control

- Data-driven MIMO model
- Theoretical State-Space model
- Design of a State-feedback controller and Kalman Filter



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ISTTOK Control

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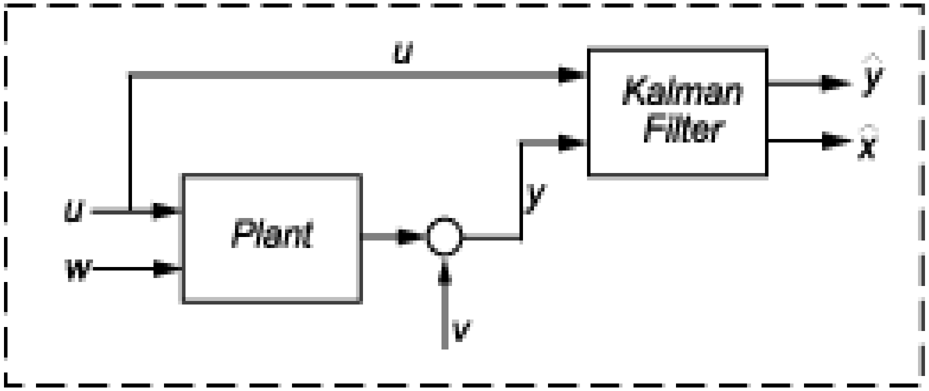
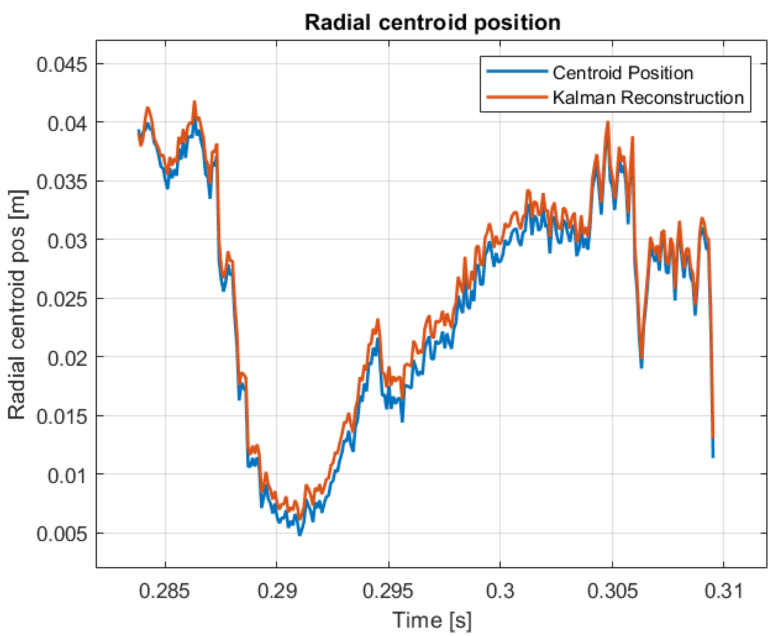
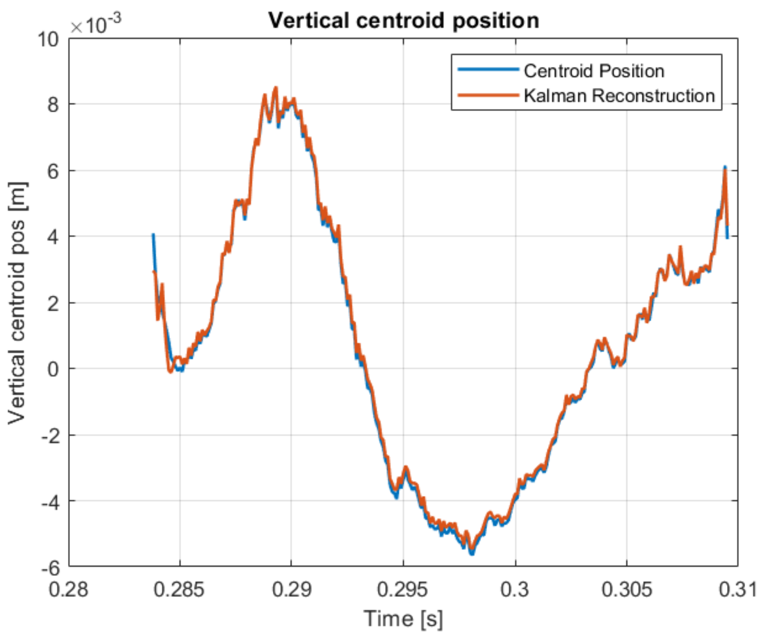


Kalman Estimator

ISTTOK Control

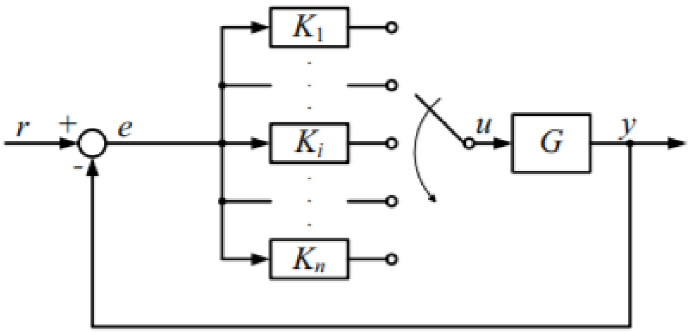
Kalman Filter is necessary to reconstruct the states in order to implement a states feedback control

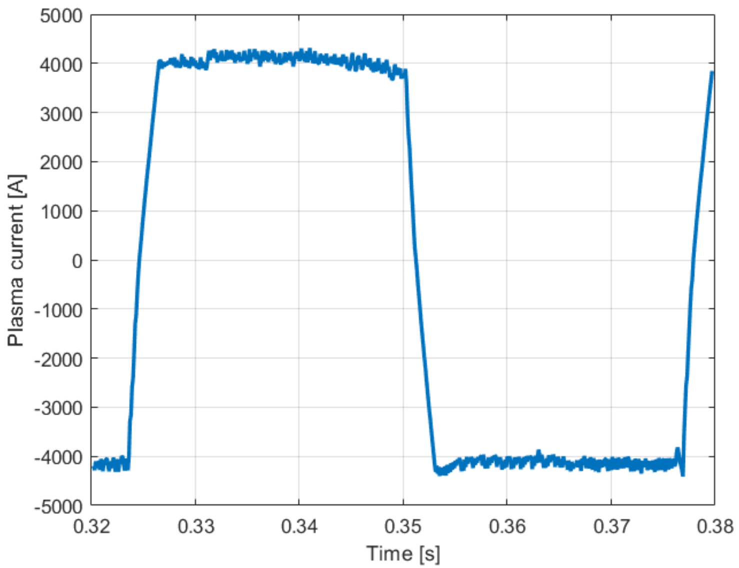




Currently we are working in the LQR controller for the centroid position in ISTTOK !!!!!

Bumpless Transfer





Adaptive **switching** control presents a problem which is that the controller output can have **undesired transients**, called **'bumps'**, when the currently active controller and the new controller to be switched have **different outputs** at the switching instant. To attenuate these bumps associated with controller switching, a variety of **bumpless transfer methods** have been suggested over the years since the 1980's.

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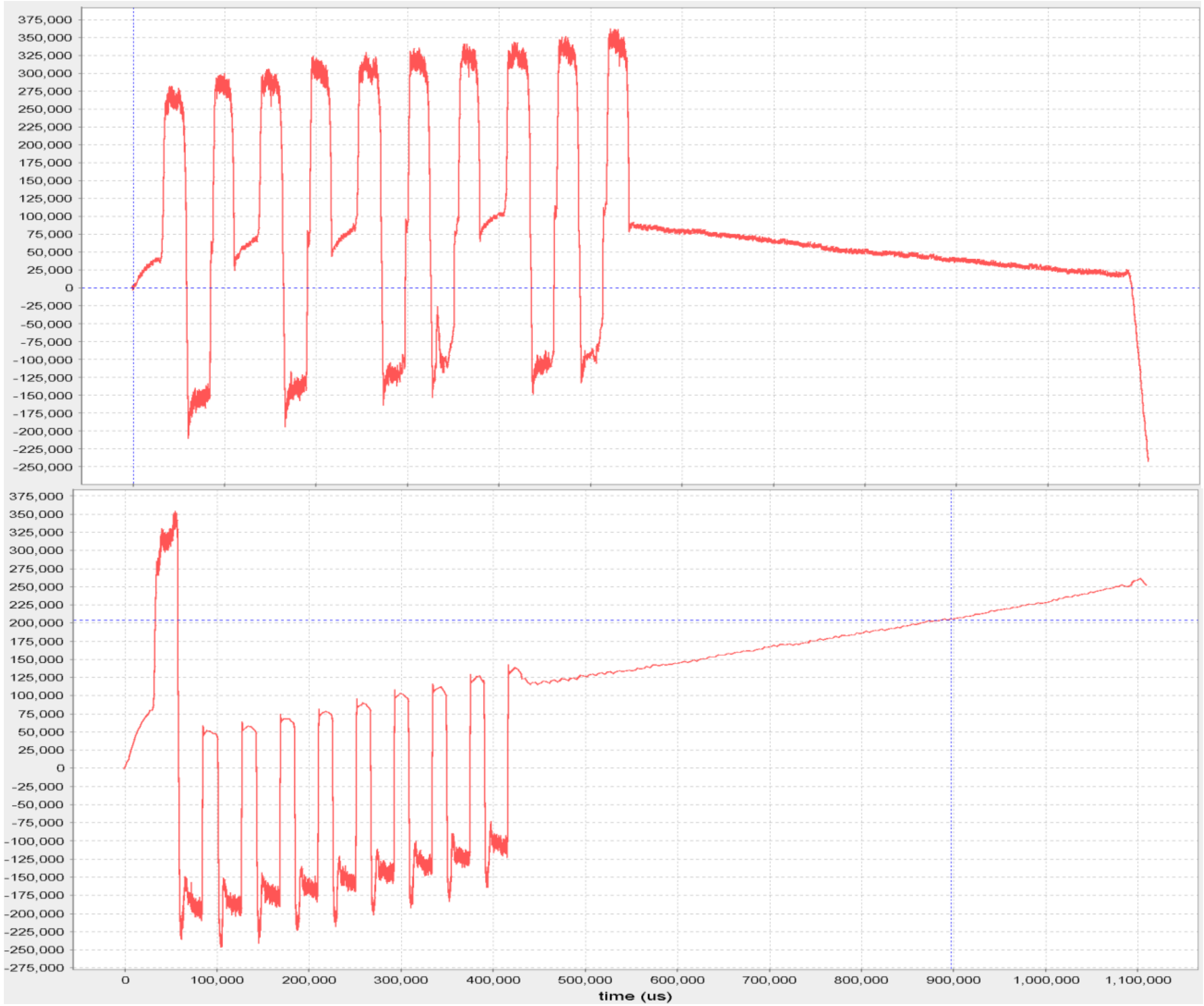
Common issues in the data acquisition process

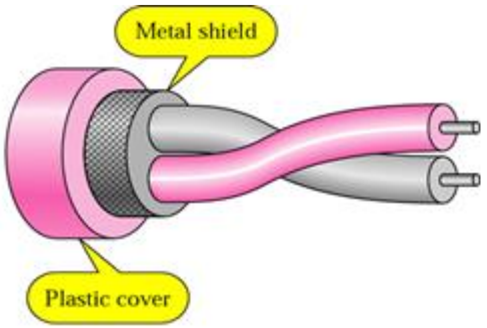


Coaxial cables

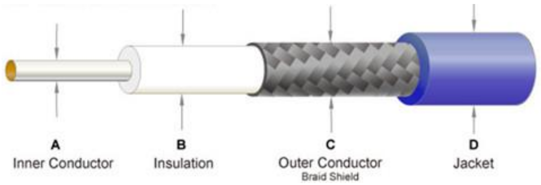
Twisted pair cables

Common issues in the data acquisition process

The twisting can avoid noise from outside sources, so this cable is best suited for carrying signals, it also eliminates inductive and capacitive coupling.



A coaxial cable has over 80 times the transmission capability of the twisted-pair. Coaxial cable has also been the mainstay of high speed communication, it supports greater cable lengths.



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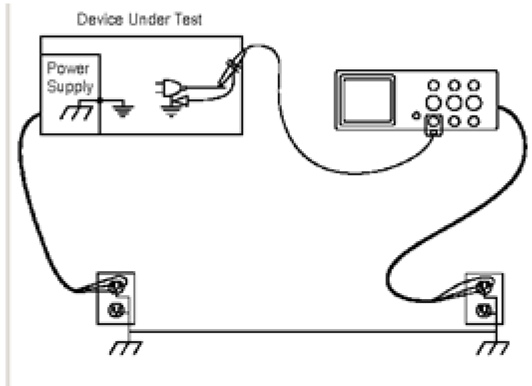

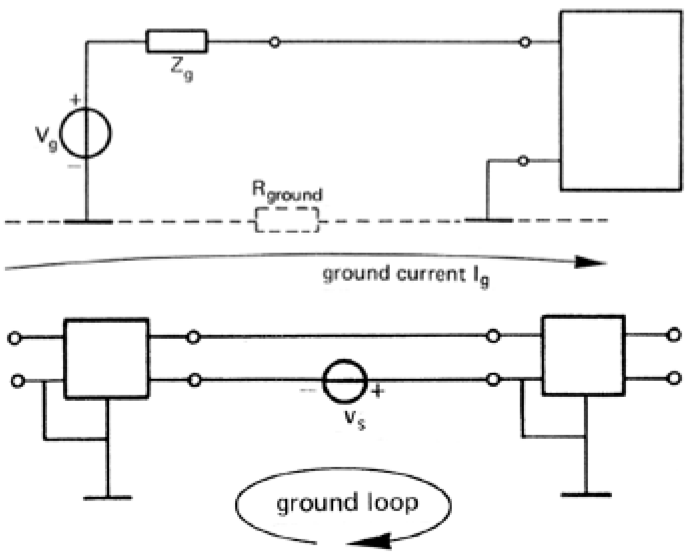

Ground loop occurs when two points of a circuit both intended to be at ground reference potential have a potential between them, this is a major cause of noise, when wiring must ensure that vulnerable signals are referenced to one point as ground.