Automation and Control Laboratory

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Automation and Control Laboratory

Course objective:

- Provide the ability to apply control structures on real systems and to critically analyse their modelling, by means of different experimental and numerical experiences.

Reference areas:

- Industrial automation
- Process control
- Vibration control
- Motion control
- Electrical drives and machine
- Robotics
- …

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Prerequisites:

- System dynamics and modelling
  (mechanical, electrical, process)
- Drives and actuators
  (electrical and pneumatic actuators)
- Fundamentals of control engineering
  (Classical control theory, PID regulators)
- Automatic control and process control
  (Modern control – state observers – pole placement and optimal control)
- Robotics
  (Robot kinematic and dynamics)
- Industrial Automation/Informatics
  (Discrete event systems, digital control – PLC – PID controller design)

Automation and Control Laboratory

- Experimental applications emulating automatic plants or reproducing systems or processes to be controlled.
- Single experience assigned to a team of students that develop it autonomously and thoroughly during all the course duration

Automation and Control Laboratory

Available experiences:

1. Automation of an elevator plant
2. Control of electric drives and pneumatic actuators in an automated plant
3. Setup and programming of a robot-cell manufacturing task
4. Control of an induction (asynchronous) motor
5. Control of a permanent-magnet DC motor
6. Control of a permanent-magnet synchronous motor
7. Control of linear vibrations
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9. Motion control in an industrial plant
10. Motion control of a pendulum

Automation and Control Laboratory

Available experiences:

11. Control of a multi-tank system
12. Control of a magnetic levitation system
13. Control of a flexible link
14. Heat-flow control

Automation and Control Laboratory

Course organisation

- 7 h per week on average (every Monday 2:15-7:15 pm – every other Friday 8:15 am -12:15 pm) with teachers (tutors) supporting the development of the experiences and orienting the progress phases. <u>The attendance to the laboratory hours is mandatory</u>

What is required to each team

- Development of numerical model/s for the assigned experience
- Identification of system parameters
- Implementation and verification of control logics on the numerical model
- Implementation and verification of control logics on the real system
- Experimental tests and comparison between experimental and numerical results
- Final report on the carried out activities
- Final presentation(*) to the classroom

What is required to each student

- Active involvement in the activities of the team
- Critical participation to the final presentation(*) of the other teams

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Evaluation criteria

- <u>Evaluation of the team activities and of the single student contribution to the team activities, mainly based on participation to the laboratory activities during official hours (single student) (tutor)</u>
- Evaluation of the final report (team) (tutor + all teachers)
- Evaluation of the final presentation (single student) (all teachers)
- (Evaluation of the participation to the final presentation of the other student (single student))

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Important dates

- March 10th, 2016 – 2:00 pm Deadline for the “Assignment Form” submission.
- June 21st, 2016 Deadline for the report submission.
- June 24th and July 4th, 2016 Final presentations (the presence and presentation by all teams/students is mandatory)

Evaluation process has to be definitively completed by September 30th, 2016. The project validity ends on that day.

Practical information

- All the activities take place in the Mechatronic Lab (room 69, ground floor of the Department of Mechanical Engineering, building B23, Campus Bovisa Sud, via La Masa 1, Milan)

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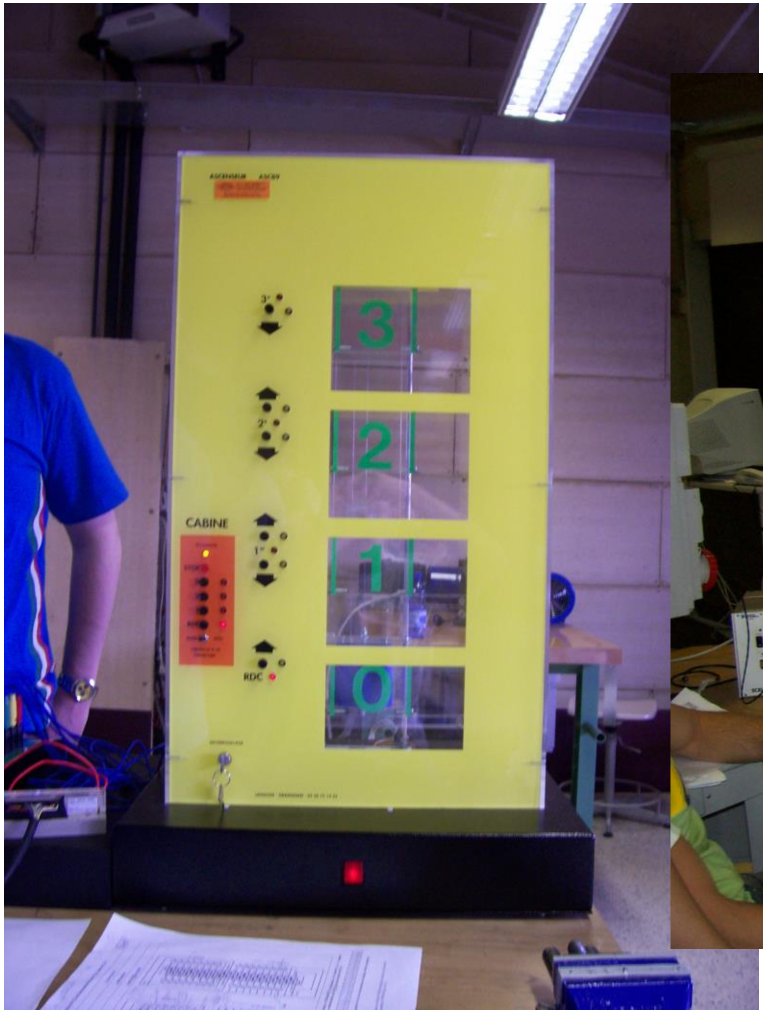
Automation of an elevator plant

- Small scale model of an elevator with 4 floors
- Typical example of discrete event system to be controlled
- The control system is based on a PLC (ABB)
- The motion actuations are electromechanical
- The control typology can be developed through increasing complexity levels.

Model of the 4-floors elevator



Main features

4 FLOORS, EACH ONE EQUIPPED WITH:	•1 door with electric opening •1 closed-door optical detector •1 open-door optical detector •2 non-programmable safety limits for open/closed door •1 button for ascending calls (except for the third floor) with light sign •1 button for descending calls (except for the ground floor) with light sign •1 light sign for car presence •1 car presence detector
CAR INTERNAL COMMAND	•4 button for the different floors •1 stop button •1 switch for simulating an obstacle to door closure •4 light signs indicating the floor •1 light sign inside the car

Modelling and control approaches

- The system and the control evolve through discrete events.
- Possible modelling option:
  - * finite state automaton (finite state machine)
  - * Petri net
  - * Flow diagram
  - * SFC (Sequential Functional Chart aka GRAFCET)
  - * other forms

Development step with increasing complexity levels

- Definition and preliminary description of two basic control logics:
    a) Logic without call storage
    b) Logic with call storage and intermediate stops

    - Accurate description of the sequences and modelling.
    - Characterisation of the command outputs and of the sensor and command signals (level and car calls)
    - Implementation of the two logics a) and b) on the PLC (ladder diagram/ structure text /any of IEC 61131)
    - Addition of all the safety features (obstacle detector and emergency stop)

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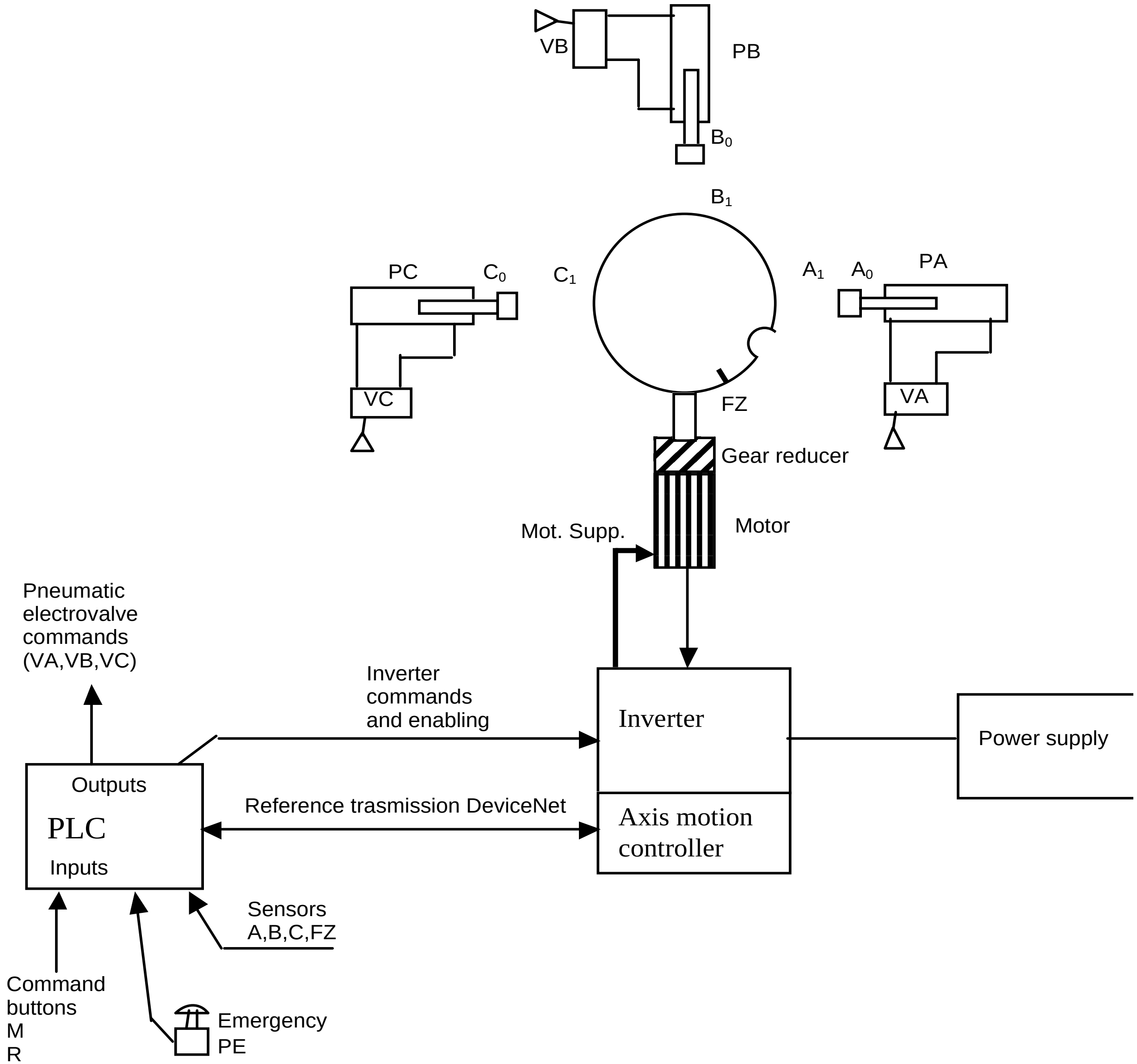
Control of electric drives and pneumatic actuators

The emulated plant is composed by:
• a rotating plate, actuated through a brushless motor;
• three pneumatic actuators (double effect cylinders) that execute synchronised actions.

The rotating plate has a mark, representing the position of the specimen to be processed. The mark/specimen have to be moved according to a pre-defined sequence to different angular position, corresponding to the pneumatic cylinders' actions.

System overview

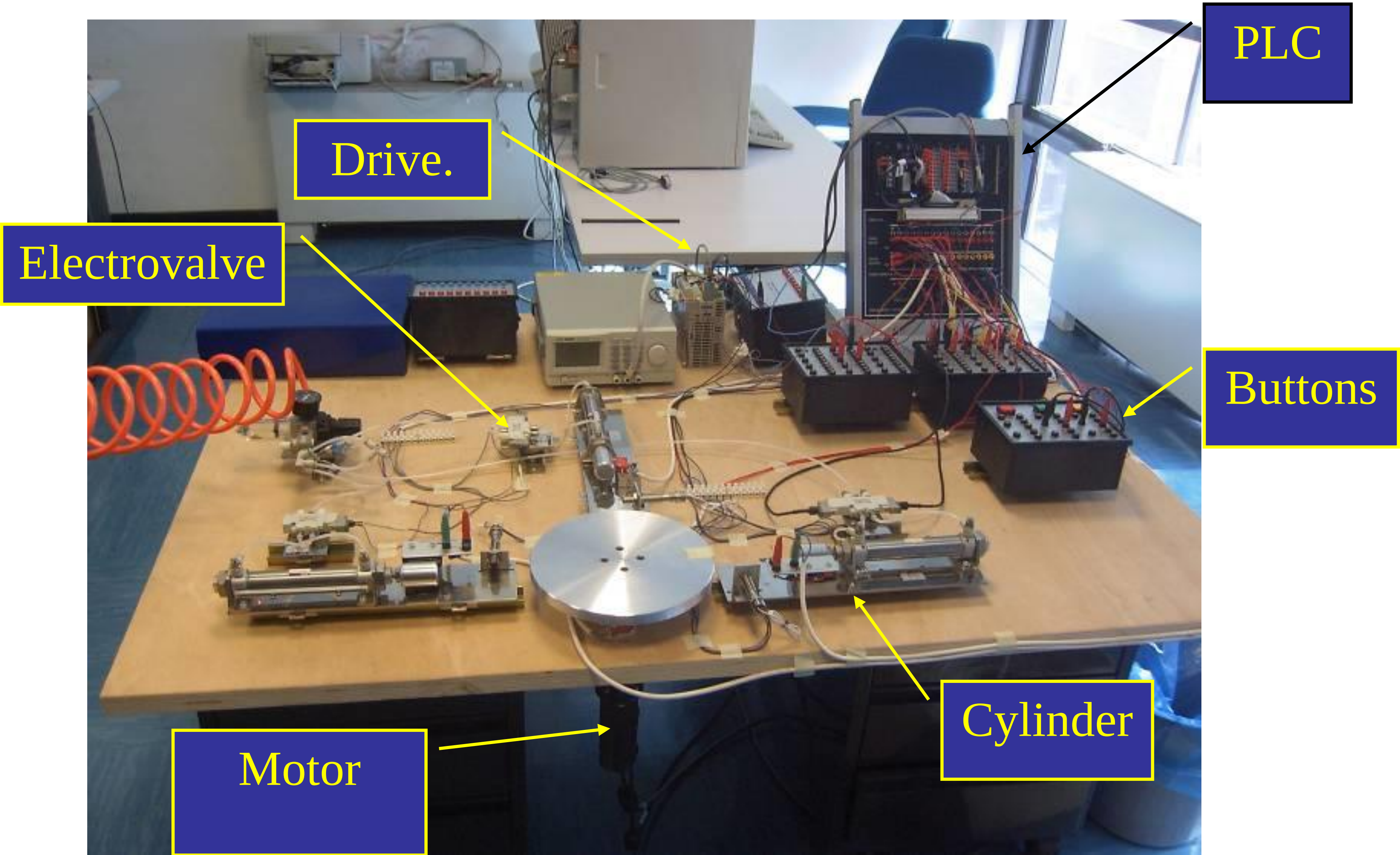


Control of electric drives and pneumatic actuators

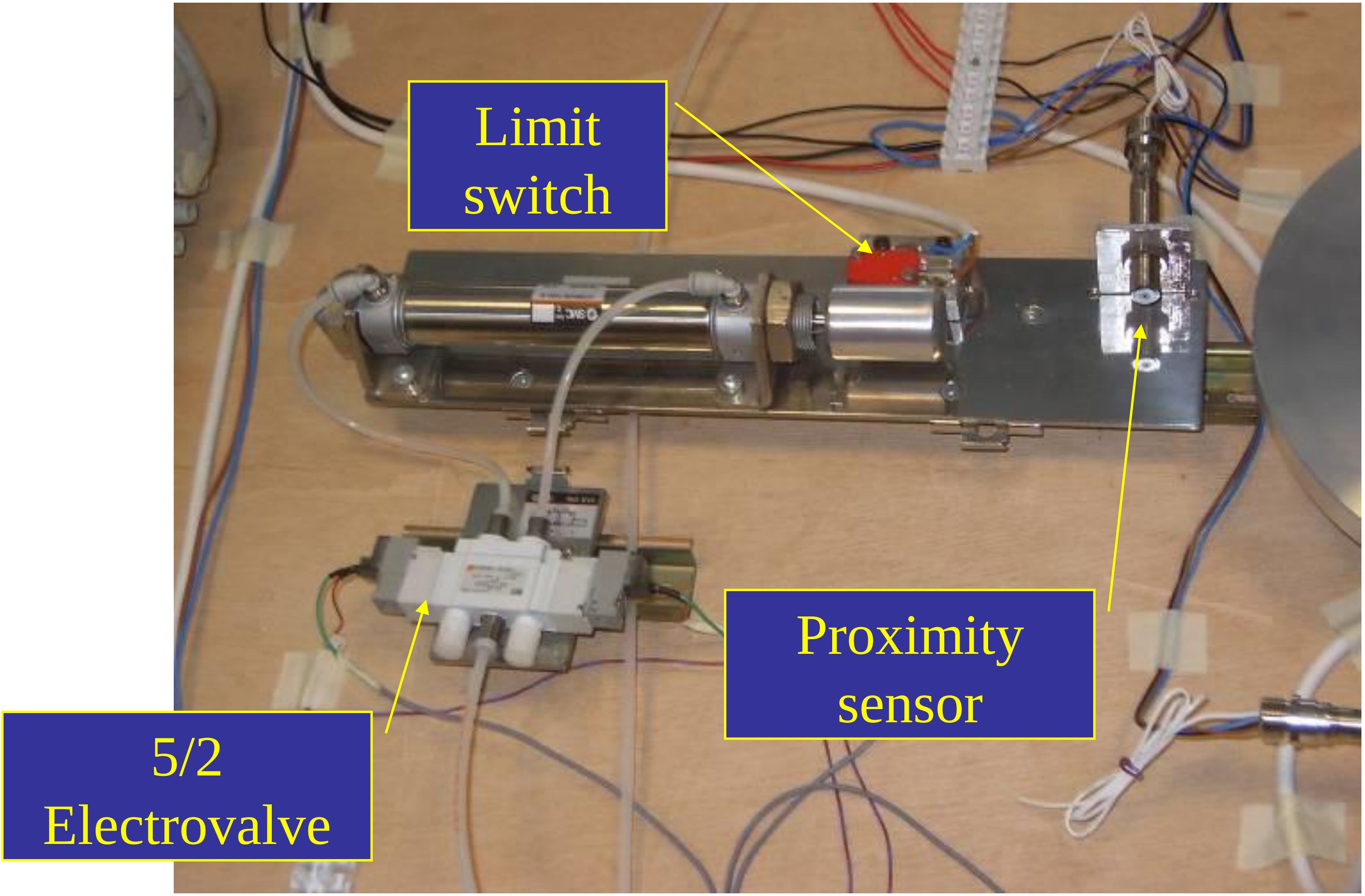
The system is made up with industrial components:

• Electrical drive: industrial inverter + direct drive brushless motor;
• Software environment for the interface with the inverter, equipped with a data acquisition system;
• Programmable axis motion controller with developing environment
• PLC (programmable logic controller) with interfacing and programming software;
• 3 double effect pneumatic cylinders, electrovalves and proximity sensors;

System overview



Pneumatic actuator with sensor and electrovalve



Basic sequence handling

1. When switched on for the first time or for a reset command (RZ) all the pneumatic cylinders are forced to the resting position and the plate is moved to the zero position (corresponding to the limit switch FZ activation).
2. After the first step the system waits for the start command (button M).
3. The plate is moved to A position and the first pneumatic cylinder is actuated.
4. The A cylinder is brought back to the resting position.

Basic sequence handling

5. When the A cylinder is back to the resting position the plate is moved to position B.
6. The B cylinder is actuated and then brought back to the resting position.
7. The plate is moved to C position and the sequence for the C cylinder is performed.
8. The plate is moved back to the zero position and the system waits for a new start command (back to step 2 of the sequence).

Experience overview

PLC and pneumatic actuators:

- PLC programming for the defined sequence
- Management of the position loop and generation of the speed reference to be transmitted to the inverter
- Pneumatic actuators' command
- Management of process start and stop, emergency and system reset
- Management of different sequences configurable through HMI

Electrical drive:

- Calibration of the control loops for the plate motion control, through the programmable industrial inverter and the axis motion controller
- Management of the moving sequence, stop and emergency
- Acquisition of the speed reference

Execution steps

PLC

- Definition of the sequence through a “descriptive” SFC
- Functional SFC (basic and “complex” sequence)
- Sensor assignment
- PLC programming (ladder diagram/ structure text /any of IEC 61131)
- Test

Electric drive

- Calibration of the speed control loop, through comparison with a Matlab/simulink model and/or experimental optimisation
- Communication with the PLC

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Robot-cell Manufacturing Task

Objectives:

• design and setup of the layout for a manufacturing robotic cell

• design of robot-based manufacturing tasks

• programming of robot-level code for task execution

• robot I/O interfaces: electrical and pneumatic equipment, PC interfaces

• intra-task item inspection with vision system (robot-PC interfaced)

• intra-task item measurement with LASER devices

• pre-processing measurement of robot repeatability

Tools:

• Robot Staubli RX90, 2 Machining Centers mockups (with pneumatic clampers)

• pneumatic/elettrical custom circuitry, LASER, camera

Robot-cell Manufacturing Task

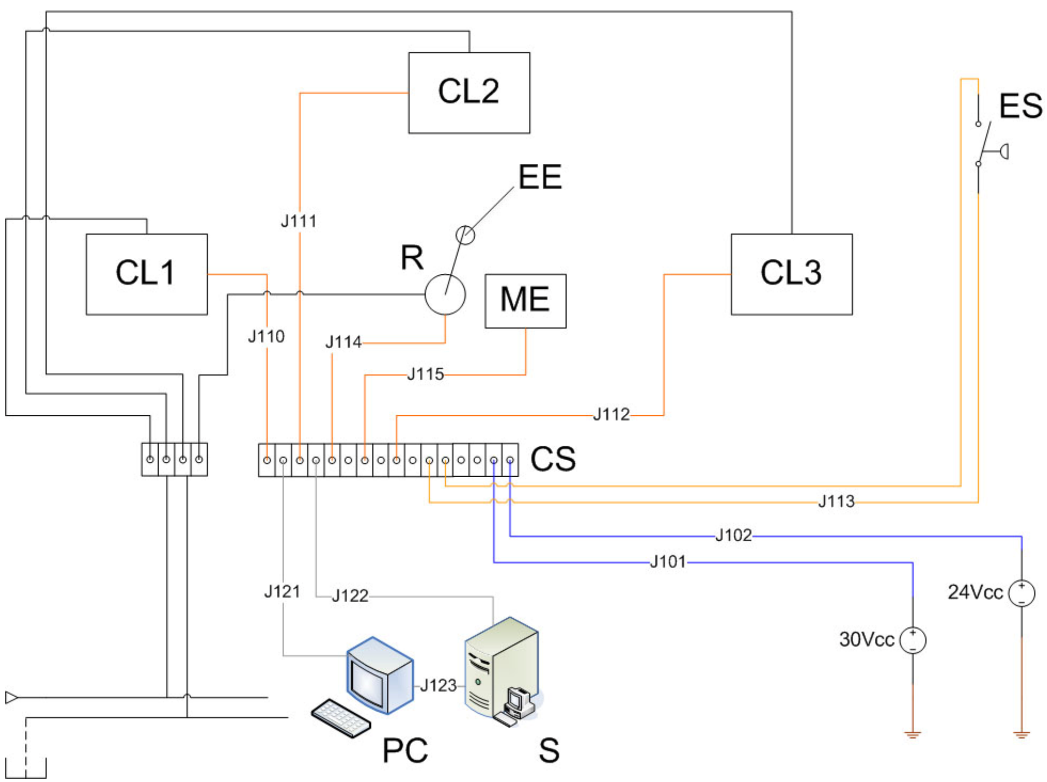
Steps:

1. Cell layout, robot equipment and Machining Centres setup, cabling and robot I/O checkup
2. Kinematic model, analysis of configurations and positions, simulation
3. Modeling of the task (finite state machine and queuing), robot tasks programming
4. External interfaces: (Matlab/RS232 for vision-based item inspection, I/O custom circuitry /robot for LASER signal processing)
5. Robustness against failures/DoS coded into the work program
6. Measure of positioning repeatability
7. …

Robot-cell Manufacturing Task

Step 1:

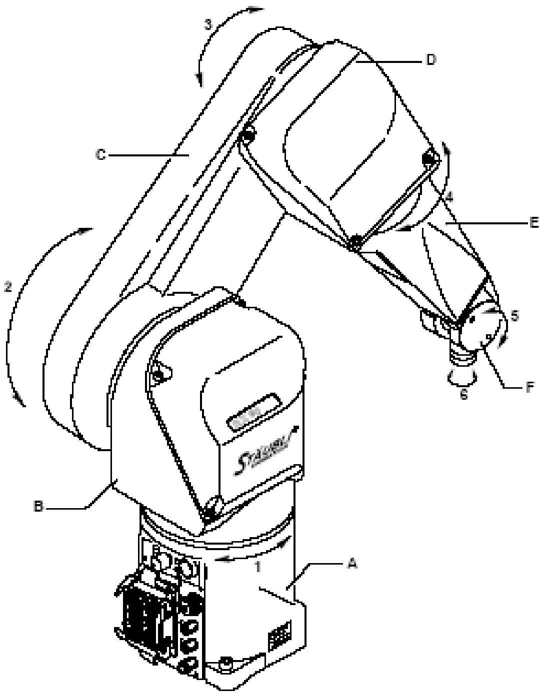
Cell **layout**, robot equipment and Machining Centres setup, cabling and robot I/O checkup

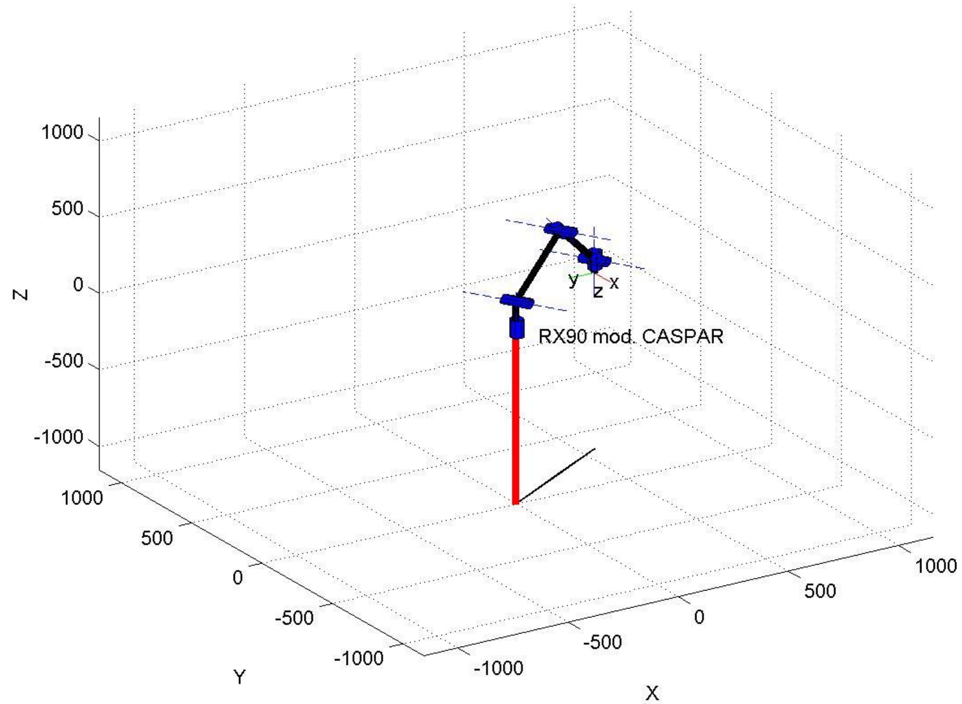


Robot-cell Manufacturing Task

Step 2:
Kinematic model, analysis of configurations and positions, simulation

Based on Robotics Toolbox: checking of robot configurations within workspace, analytic solution of inverse kinematics, trajectories testing, simulation of motion laws in joints or operational spaces



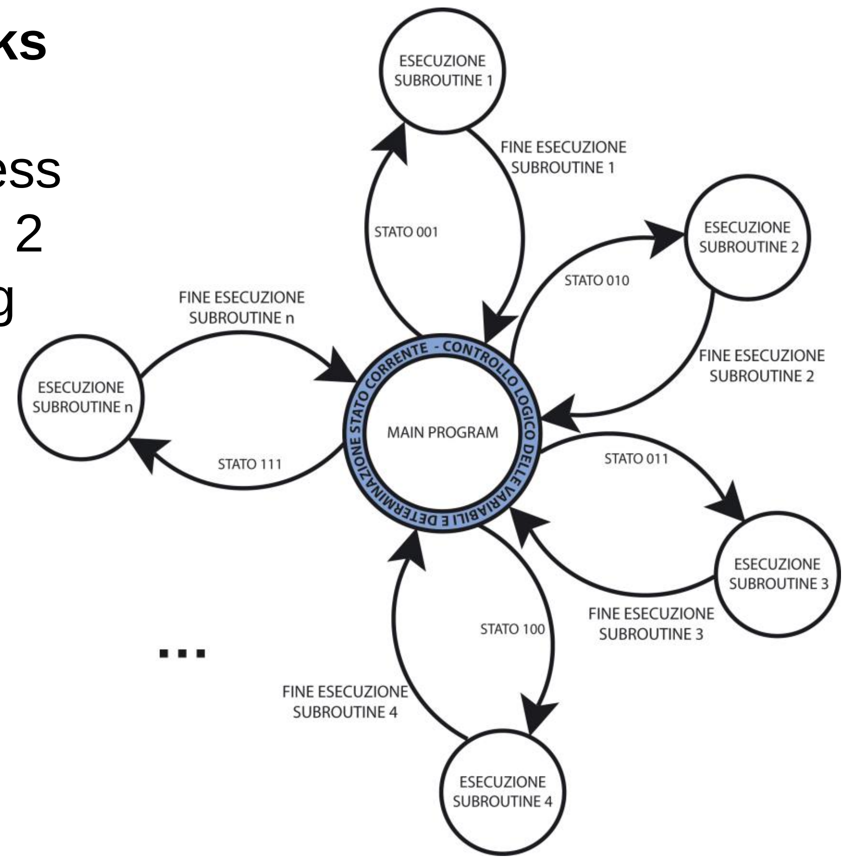


Robot-cell Manufacturing Task

Step 3:

Modeling of the task (finite state machine and queuing), robot tasks programming

Design of task: the technological process includes 2 items to be machined on 2 MCs, eventually with double loading on MCs. The robot is in charge of handling/moving the items.



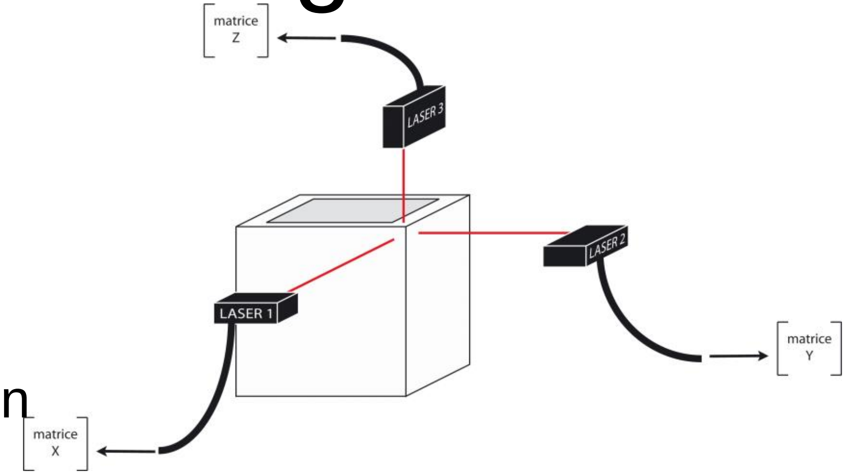
Step 5:

Robustness against failures/DoS coded into the work program

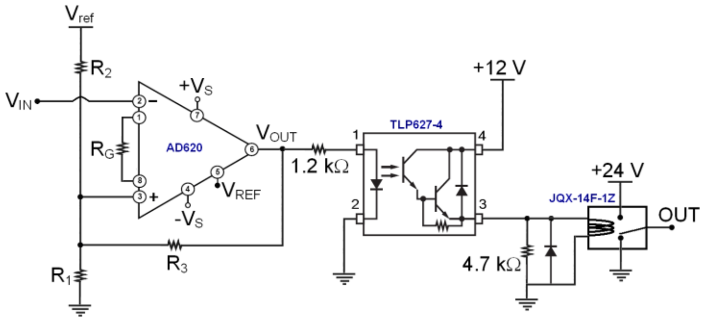
Coding of emergency and/or failure mode sequences in case of detection of I/O errors, detectable electrical or mechanical failures, items stuck...

Robot-cell Manufacturing Task

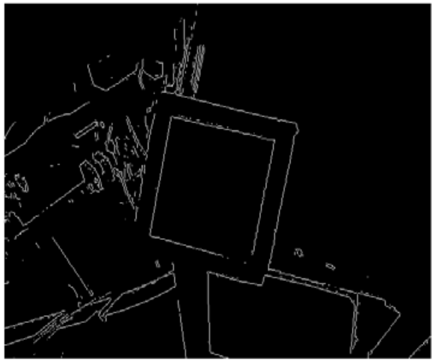
Step 4: External interfaces



Matlab/RS232 for vision-based item identification in order to set the working path for identified items, in line detection of size faults in order to dispose faulty items



I/O custom circuitry for processing the LASER measures: in line *precision* detection of size faults in order to dispose faulty items, setup for repeatability measures

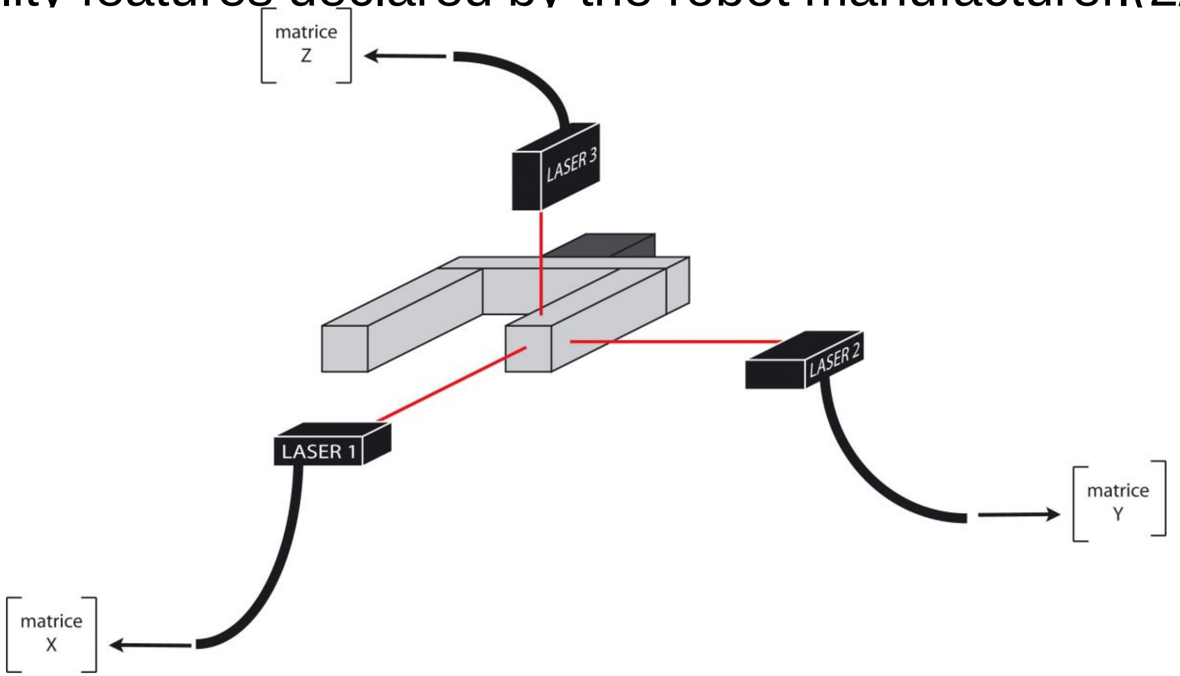


Robot-cell Manufacturing Task

Step 6:
Measure of positioning repeatability.

end-effector position is repeatedly sampled at the end point of some trajectories (possibly) run at maximum speed, aligned with all 3 orthogonal axes.

the deviation/scattering of sampled values should be similar to repeatability features declared by the robot manufacturer.(2/100 mm).



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Control of an induction (asynchronous) motor

- System to be controlled: asynchronous motor (speed regulation)
- Electrical actuator: Inverter + asynchronous mot, Texas/Technosoft controller
- Software environment:

  Matlab/Simulink => “C”
- Control to be implemented:

  - State and speed estimation (double observer)

  - Field oriented control

Dynamic model of the asynchronous machine

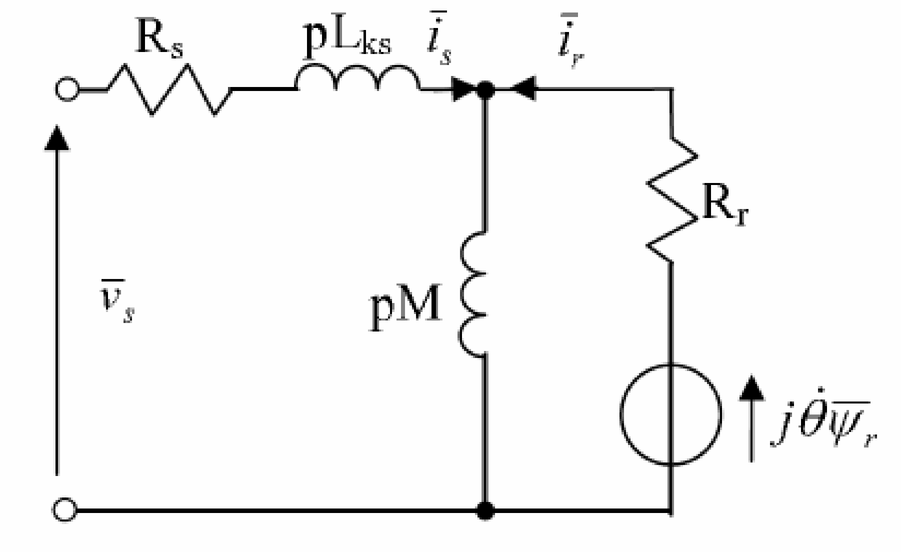
$$\overline{v}_s = R_s \overline{i}_s + p\overline{\psi}_s$$

$$0 = R_r \overline{i}_r + p\overline{\psi}_r - j\dot{\theta}\overline{\psi}_r$$

$$T = n\frac{n}{L_{ks}} \cdot \overline{\psi}_r \wedge \overline{\psi}_s = n\frac{n}{L_{ks}} \cdot \psi_r \cdot \psi_s \cdot sin\,\varepsilon$$

$$\overline{\psi}_s = L_{ks}\overline{i}_s + \overline{\psi}_r$$

$$\overline{\psi}_r = M(\overline{i}_r + \overline{i}_s)$$



Flux estimation

The knowledge of machine parameters and of measured $\overline{v}_s, \overline{i}_s$ and $\dot{\theta}$ allows to obtain the rotor and/or the stator flux.
The motor torque can be also estimated accordingly.
The first estimation method 1) is adressed as V-I, the second one 2) as I-ω
The observer 1) works better for high high speeds while 2) works better for low speeds.
Thus, joining the two observer an optimal estimation can be obtained.

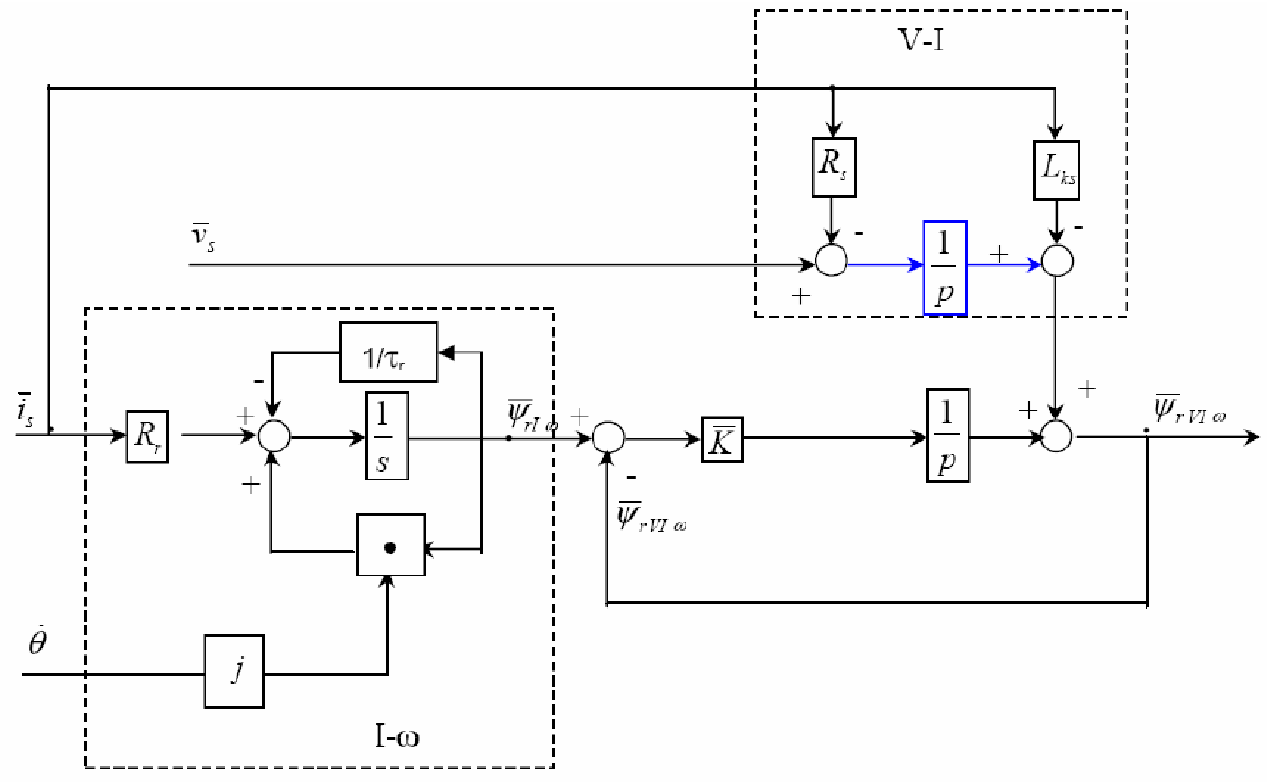
1) $$\overline{\psi}_{s,VI} = \frac{1}{p}(\overline{v}_s - R_s \overline{i}_s)$$

2) $$\overline{\psi}_{r,I\omega} = \frac{R_r}{p + \tau_r - j\dot{\theta}} \overline{i}_s \qquad \left(\tau_r = \frac{M}{R_r}\right)$$

$$T = n \frac{n}{L_{ks}} \cdot \overline{\psi}_r \wedge \overline{\psi}_s = n \frac{n}{L_{ks}} \cdot \psi_r \cdot \psi_s \cdot sin\, \varepsilon$$

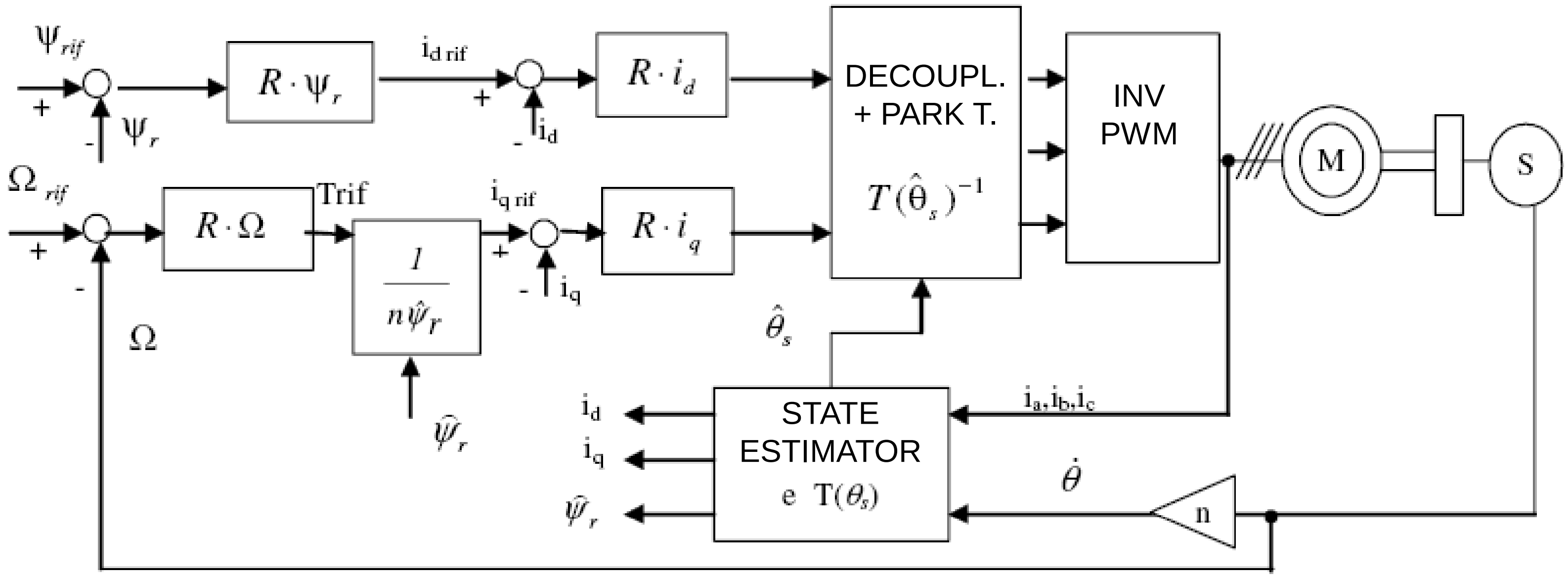
Double observer V-I-ω

The two observer can be joined through a closed-loop leading to a new observer that minimises the errors of the two original observers

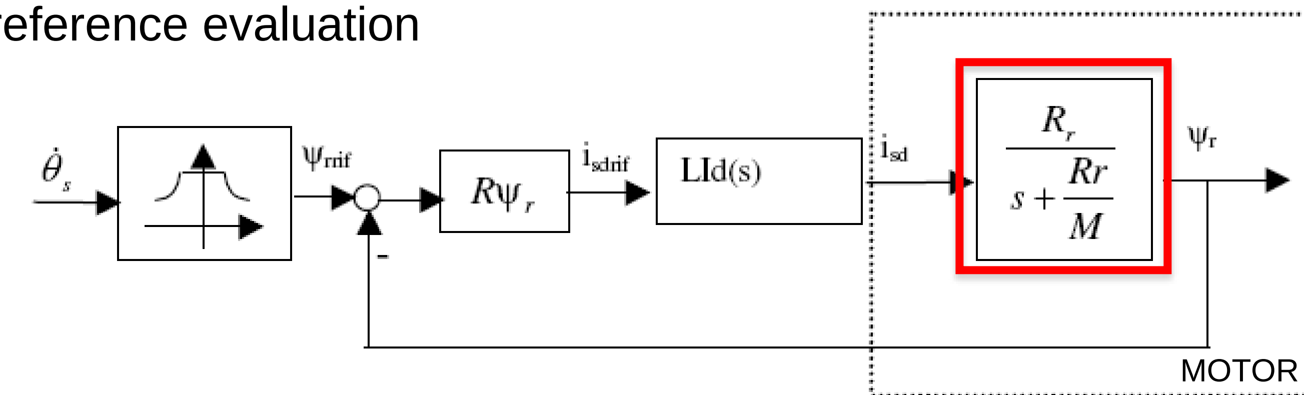


$$\bar{\psi}_{rVI\omega} = \frac{\bar{K}}{s+\bar{\bar{K}}}\bar{\psi}_{r,I\omega} + \frac{s}{s+\bar{\bar{K}}}\bar{\psi}_{rVI}$$

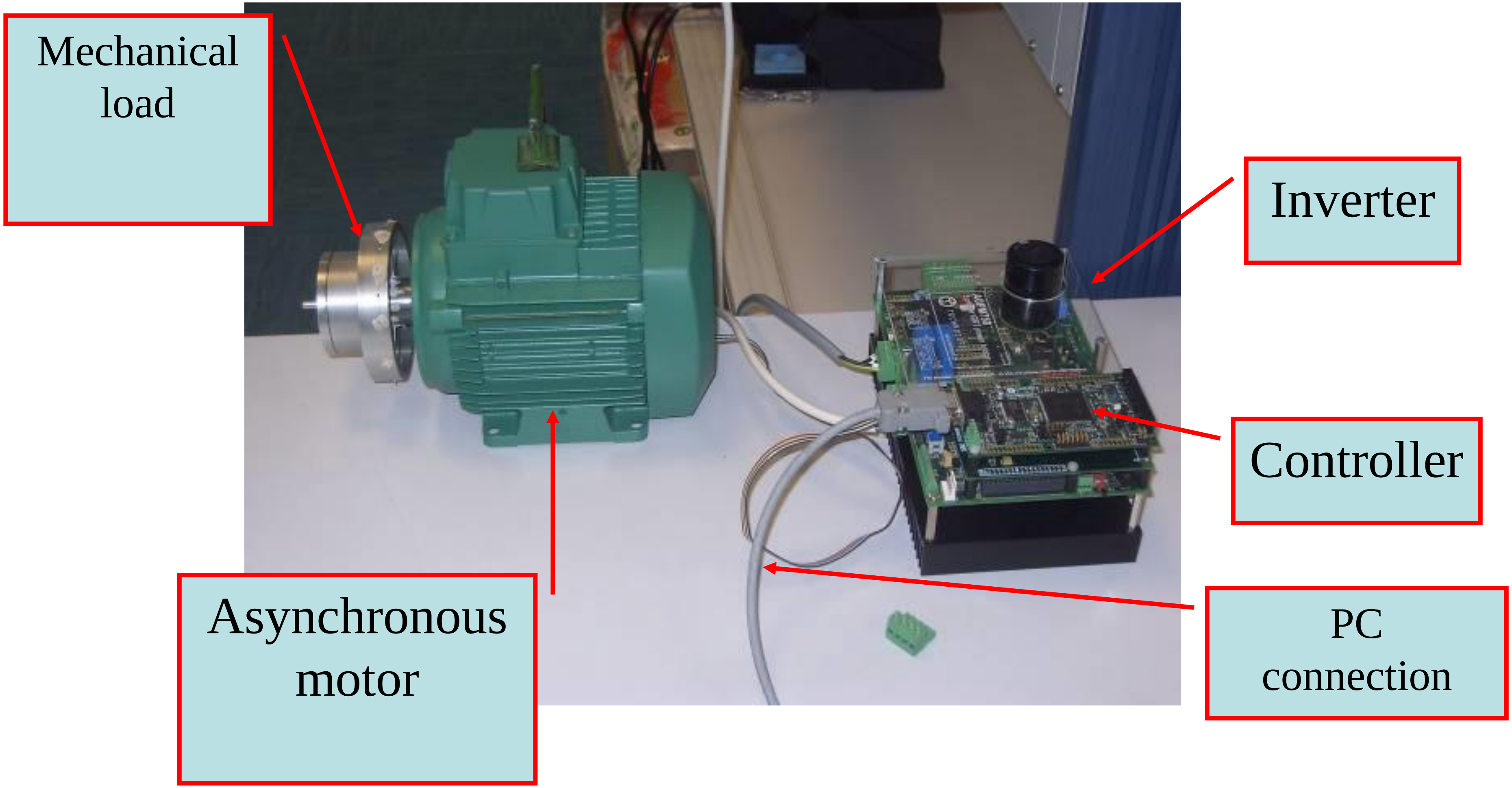
Field oriented control



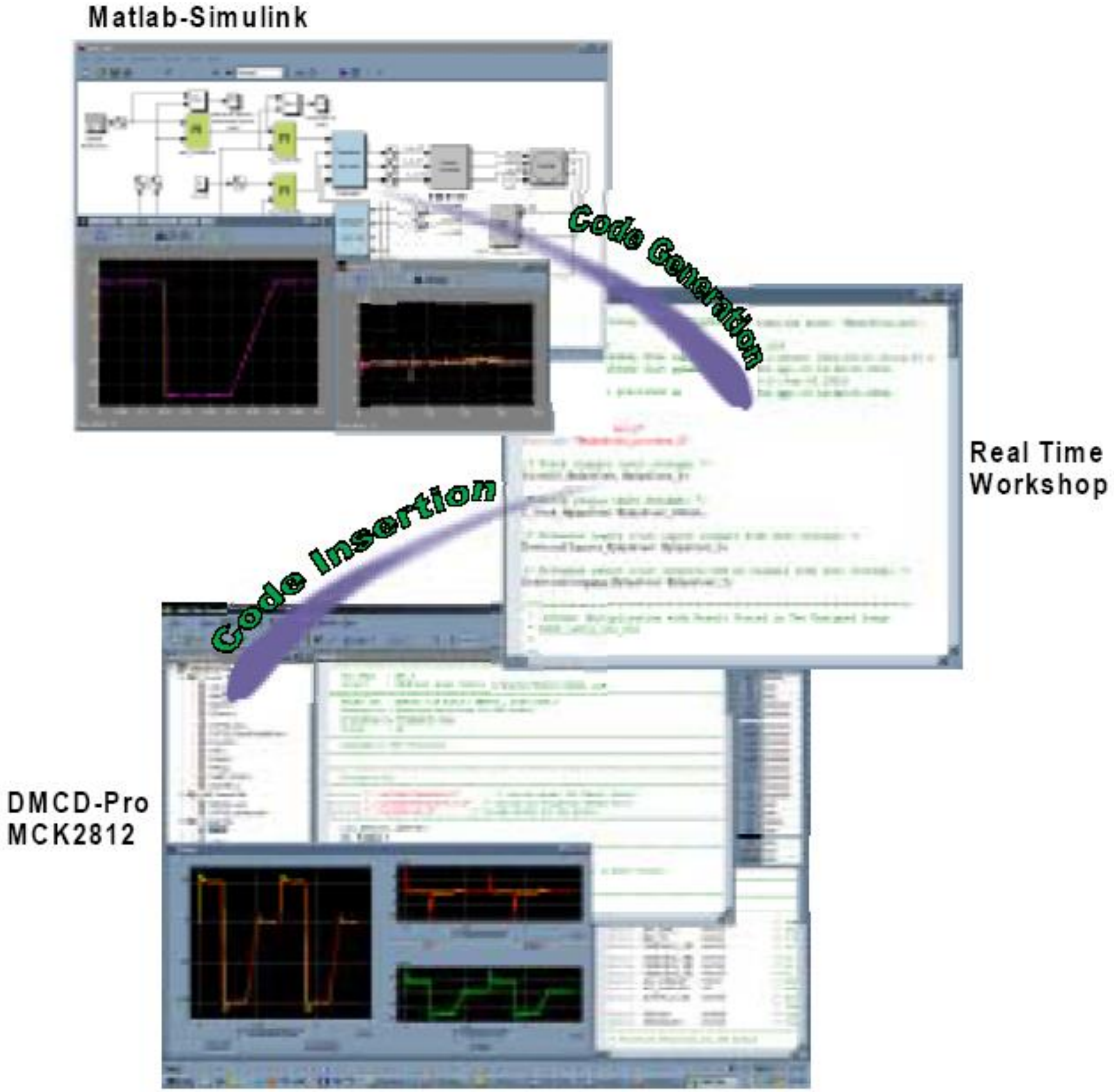
Flux regulation loop and
reference evaluation



System overview



Development environment



Execution steps

- Definition of matlab/simulink model
- Implementation of V-I and I-ω observers (simulation)
- Implementation of V-I-ω observer (simulation)
- Definition of the speed estimation systems
- Verification through simulation
- Implementation on the Tecnosoft controller and verification of the performances of:

  1. V-I and I-ω observers

  2. V-I-ω observer

  3. field oriented control

  (4. sensorless control)

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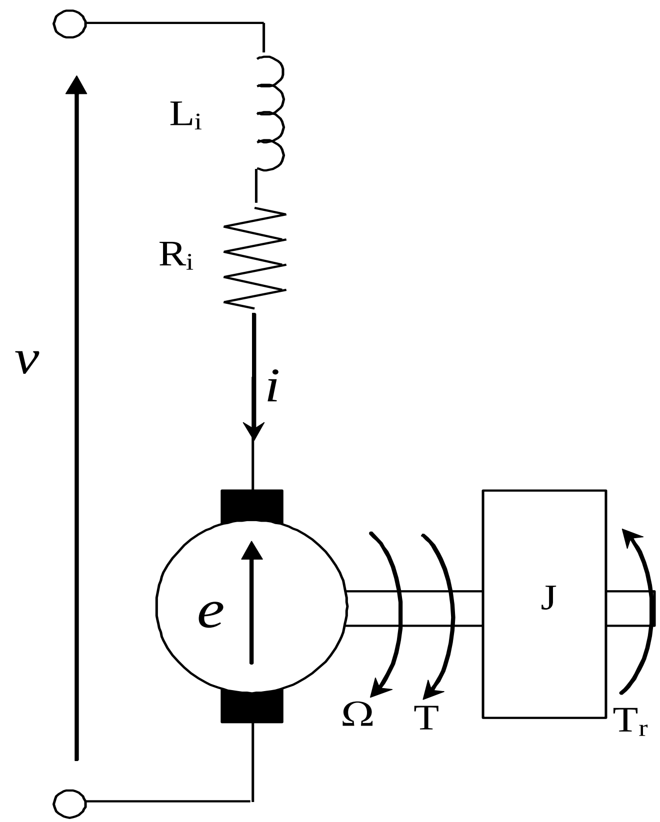
Permanent magnet DC machine

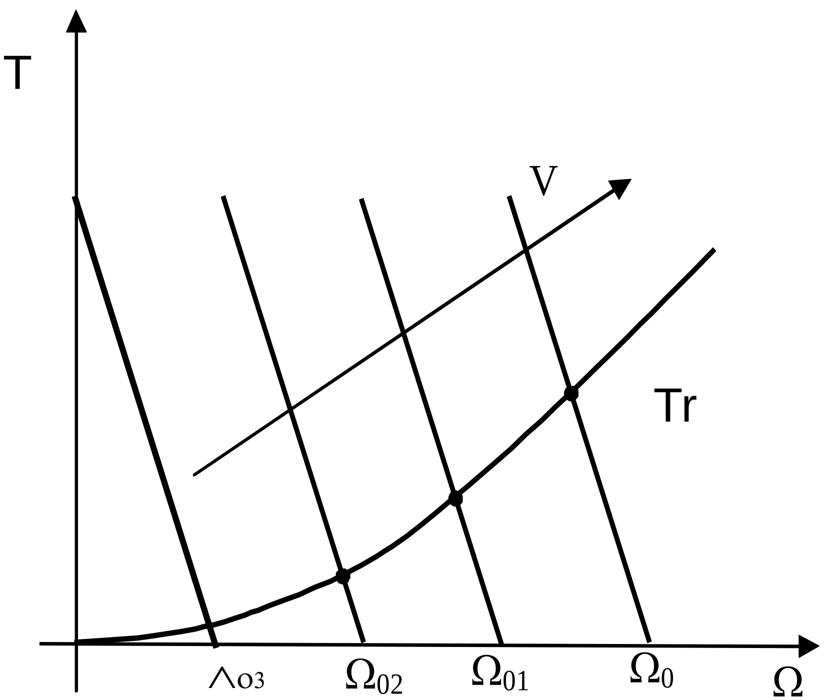
- The equivalent circuit represents the dynamic model of the machine.
- The state equations of the motor with inertial load J, resisting torque T_r can be written as (the state is represented by i,W):



$$v = R_i i + L_i di/dt + e \qquad e = KW$$

$$T = T_r + JdW/dt \qquad T = Ki$$

Armature regulation (variation of voltage V)



Through an adjustable voltage *V* source (converter) different characterisitcs T(W) can be obtained, presenting diffetent W_0 (speed corresponding to zero current and torque, $W_{0i}=V_i/K$)

The following relationship applies:

$$T(W) = KI = K\frac{V - E}{R_i} = \frac{K^2}{R_i}(W_0 - W) = \frac{K^2}{R_i}(V/K - W)$$

All the characteristics have the same slope, but permit the motor operation in any point

Motor block diagram

Moving to the Laplace domain, the motor can be represented by the following block diagram.

$$v = R_i i + L_i di / dt + e$$

$$T = T_r + J dW / dt$$

$$e = KW$$

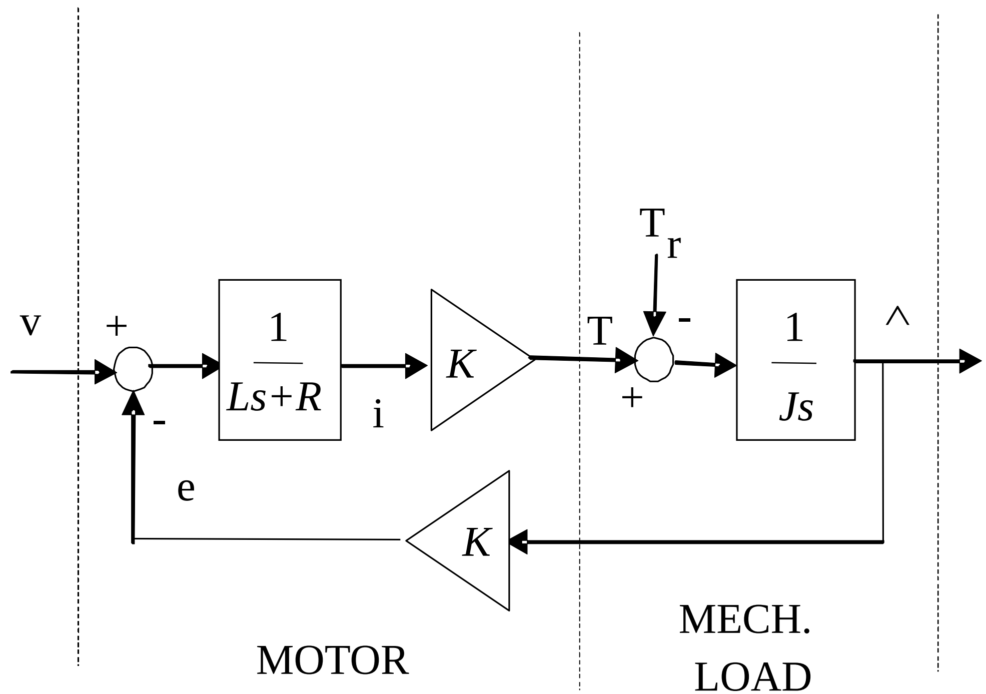
$$T = Ki$$

$$V\text{-}E = R_i\, I + L_i\, s\, I$$

$$T\text{-}T_r = J_i\, s \wedge$$

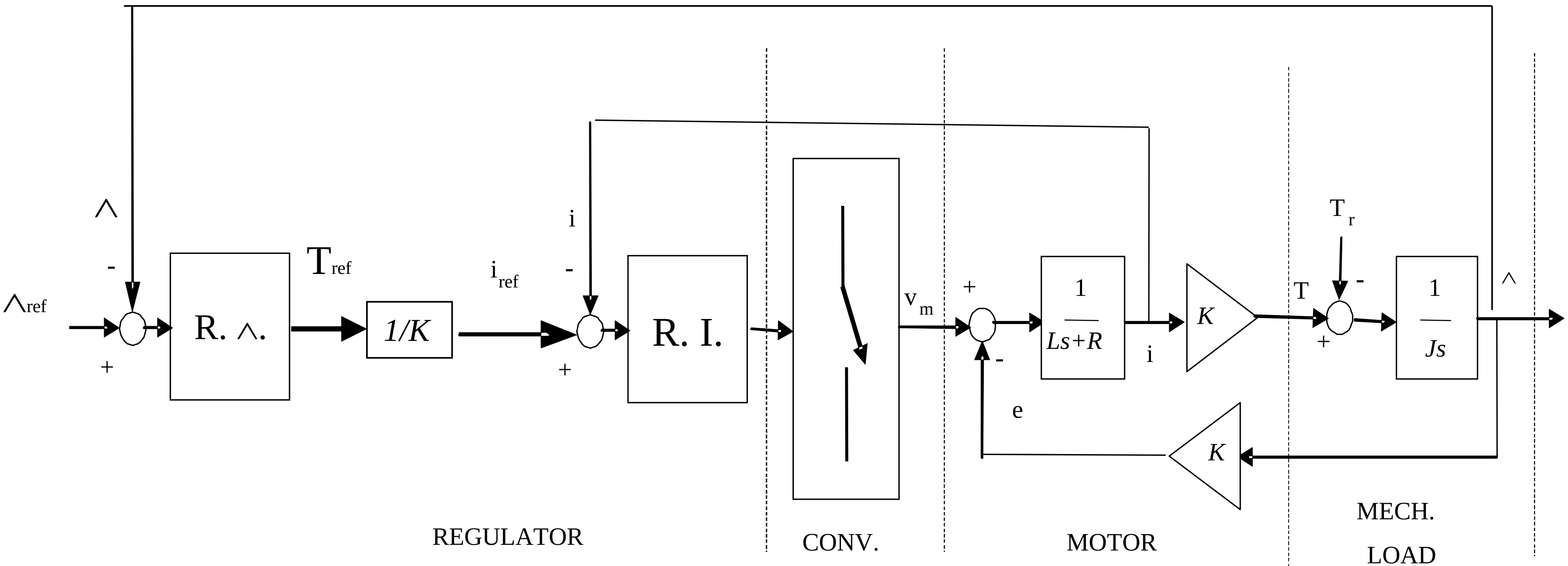
$$I = \frac{V - E}{R_i + L_i s}$$

$$\Omega = \frac{T - Tr}{Js}$$



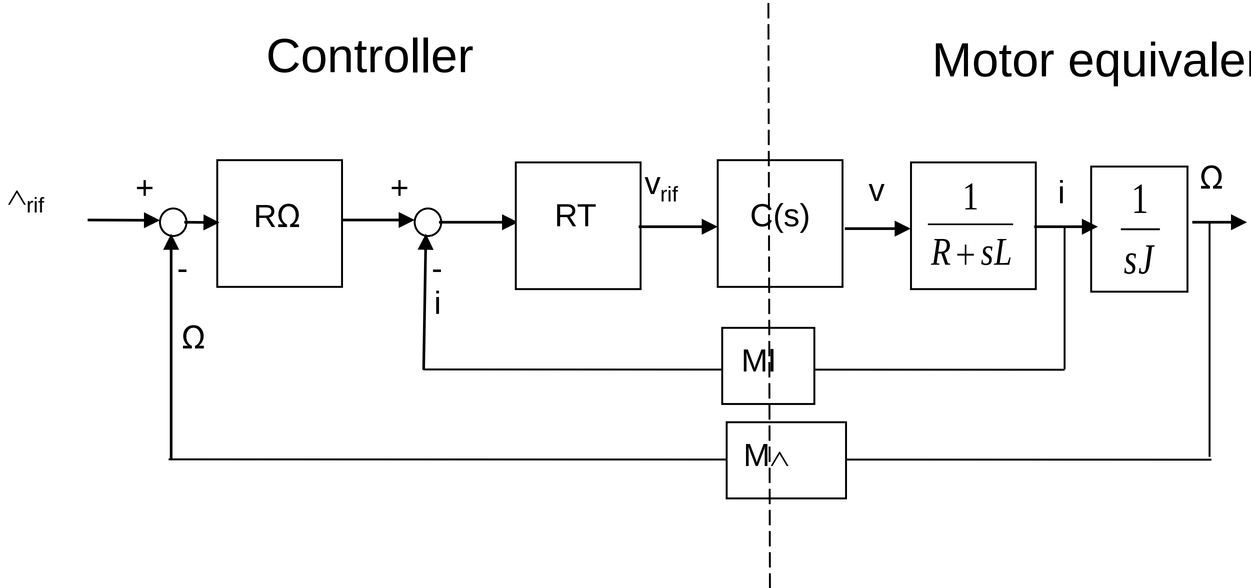
The control block scheme

- The torque reference can descend from an external loop regulating the speed
- Thus, there are two nested loops: the inner one regulates the current/torque, the outer one regulates the speed.
- A coupling exists between the mechanical and electrical parts of the system, through the e.m.f. *e=K*⋀

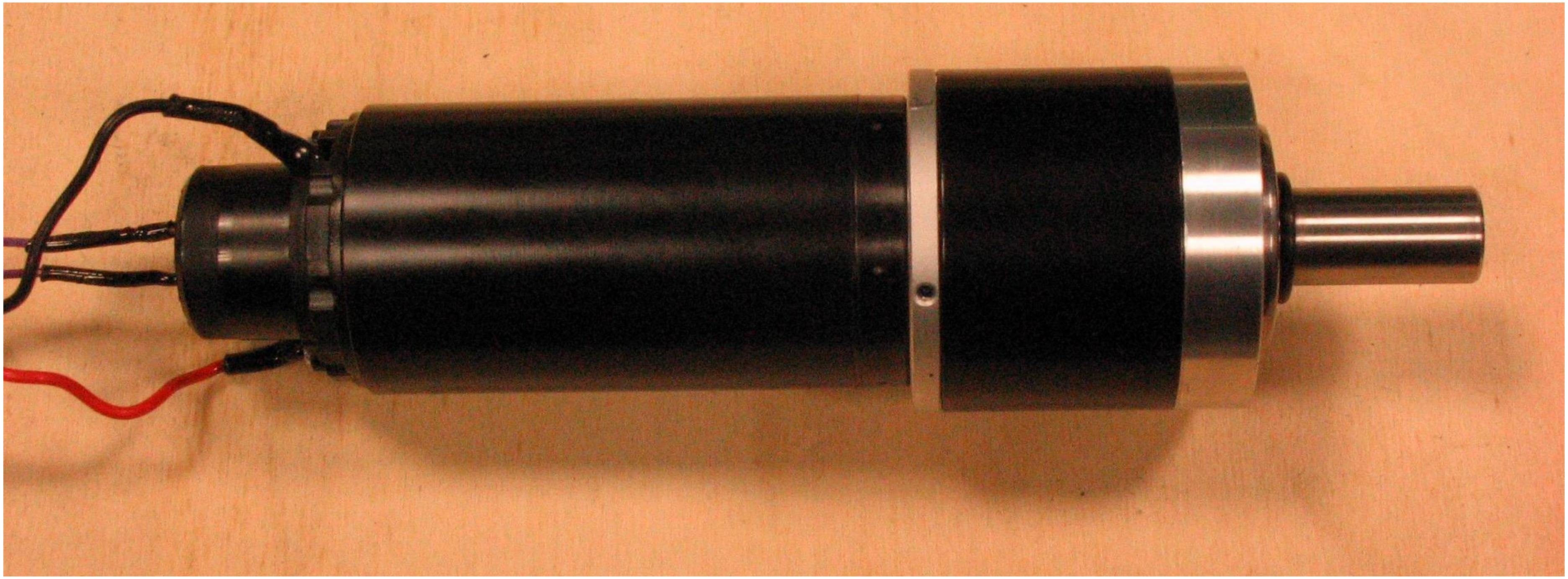


Speed and current regulation with feed-forward action on e.m.f.

• Speed and current loops can be implemented as nested loops, that do not present residual coupling, by adding a feed-forward contribution to the current loop, which compensate the emf.
• C(s) represent the transfer function of the converter, depending on the type of converter, and can be neglected as a first approximation.
• The calibration of the loops should be done considering that the internal loop has to be faster than that of the external one.



Permanent magnet DC gearmotor (24 V 75 W) with tachometric sensor



Microchip Development Board MCLV-32

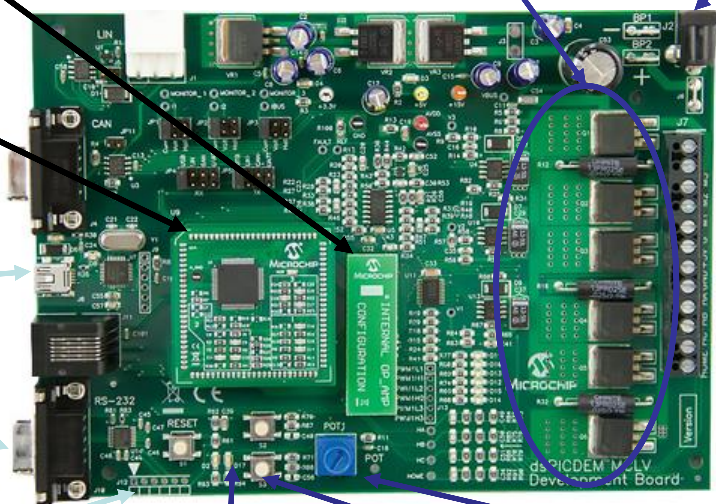
Internal or External OpAmp

16-bit Digital Signal Processor (fixed point)

Full Bridge Three-Phase Inverter

Control Power Input (12V-24V)

Motor Power Input 48V



MiniUSB Signal Output

RS-232 Signal Output

Motor Output Three-Phase **48V-15A**

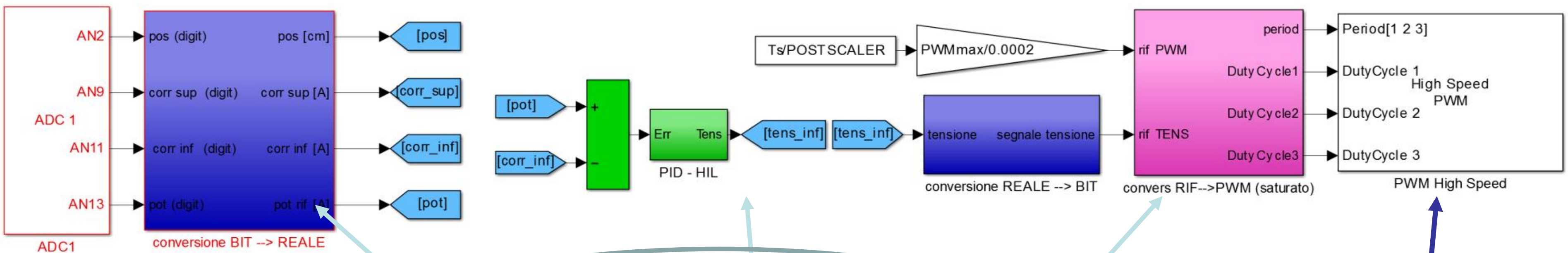
Hall Sensors

PICKit3 Programmer Connection

Digital Debugging Led

Potentiometer and Digital Buttons (1,2 and reset)

MCLV-2 – Simulink Blocks



Custom Conversion Block to get signals in the international sistem units

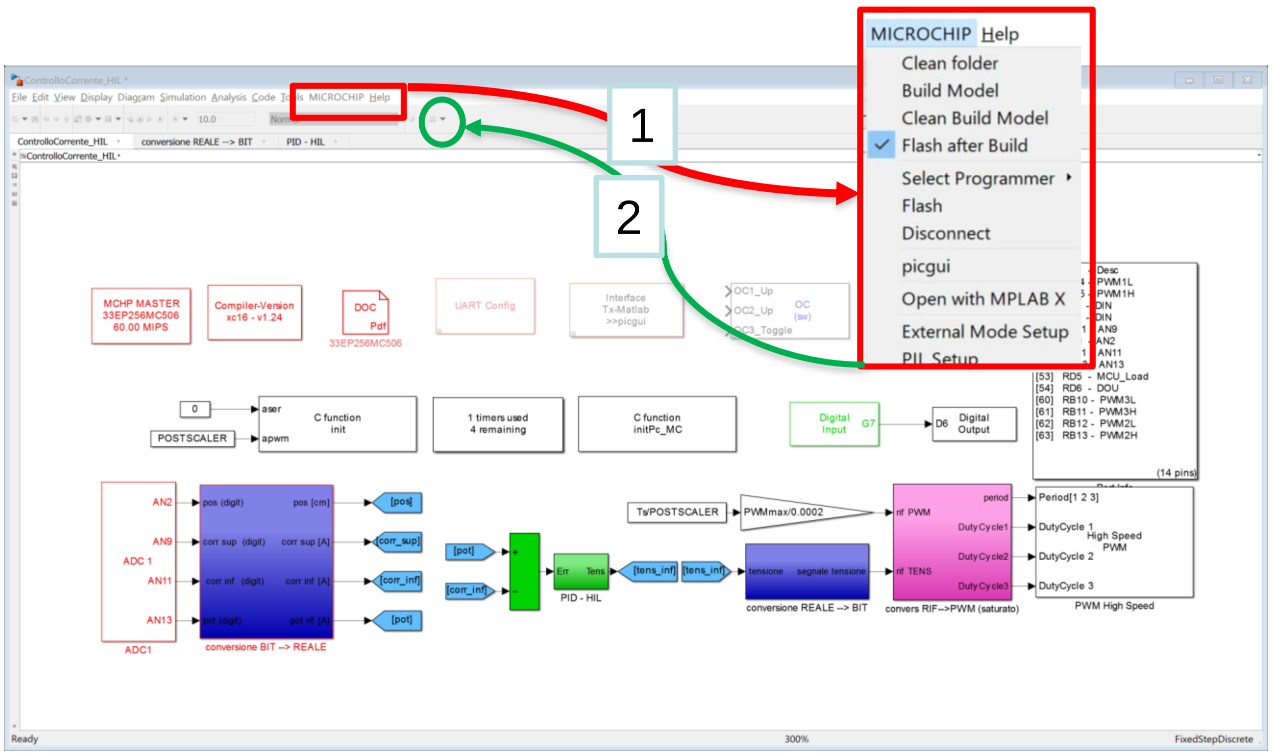
Conversion to PWM duty cycle

Control logic

Analog to Digital Converter (bit signals)

Duty cycle control signals sent to the inverter

Building the Software on the Board



Execution steps

1. Identification of the system parameters from catalogues, measures and calculations (R, L, Jmot etc. etc.).
2. Implementation of Matlab/Simulink simulation model
3. Implementation and tuning of the current and speed loop (classical solution with PI-PI nested loops) with or without feed-forward on the current loop (comparisons for different inertial loads).
4. Speed estimation (sensorless application)
5. Implementation of the control SW on the real system and comparison between numerical and experimental results for all the control architectures.

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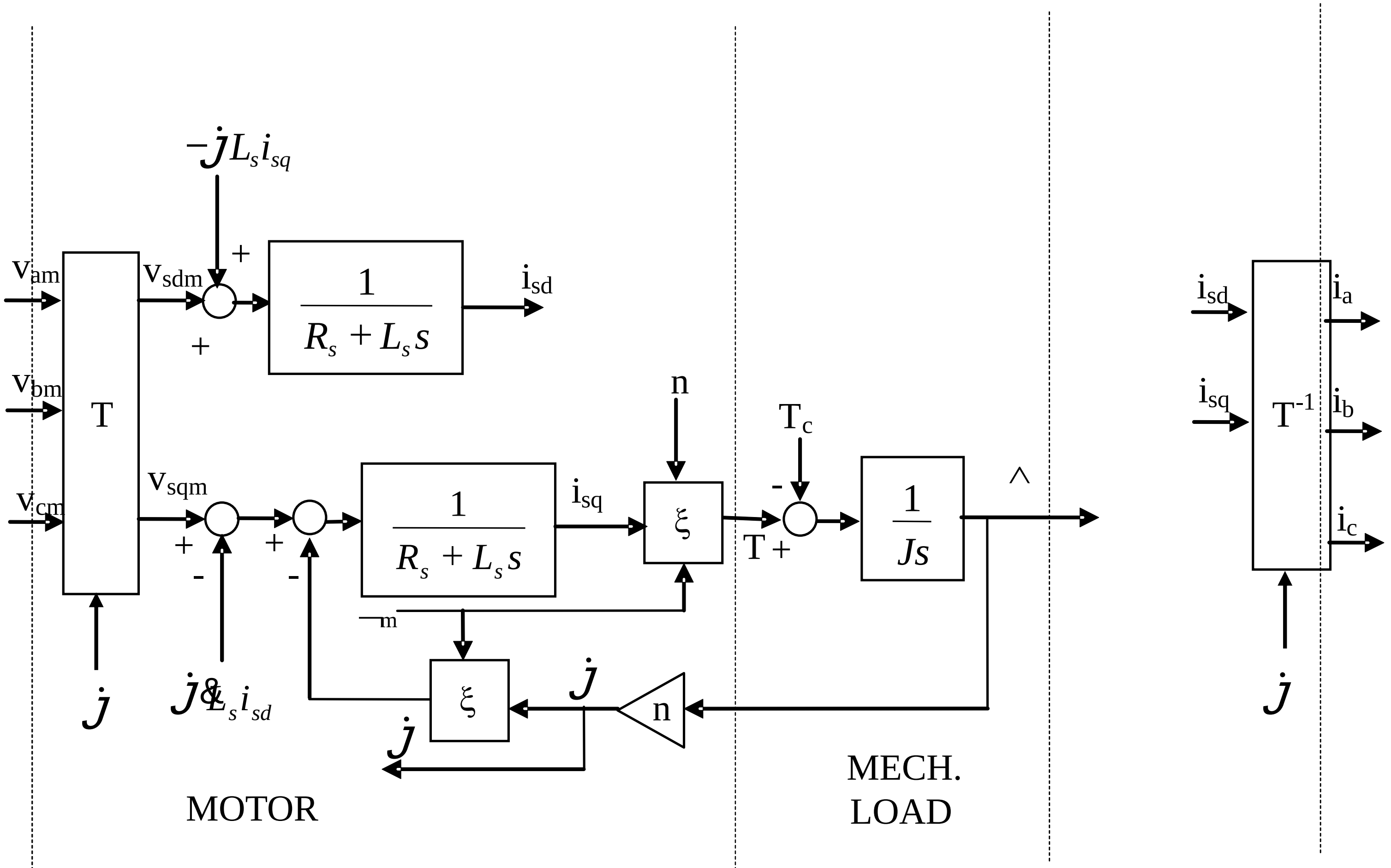
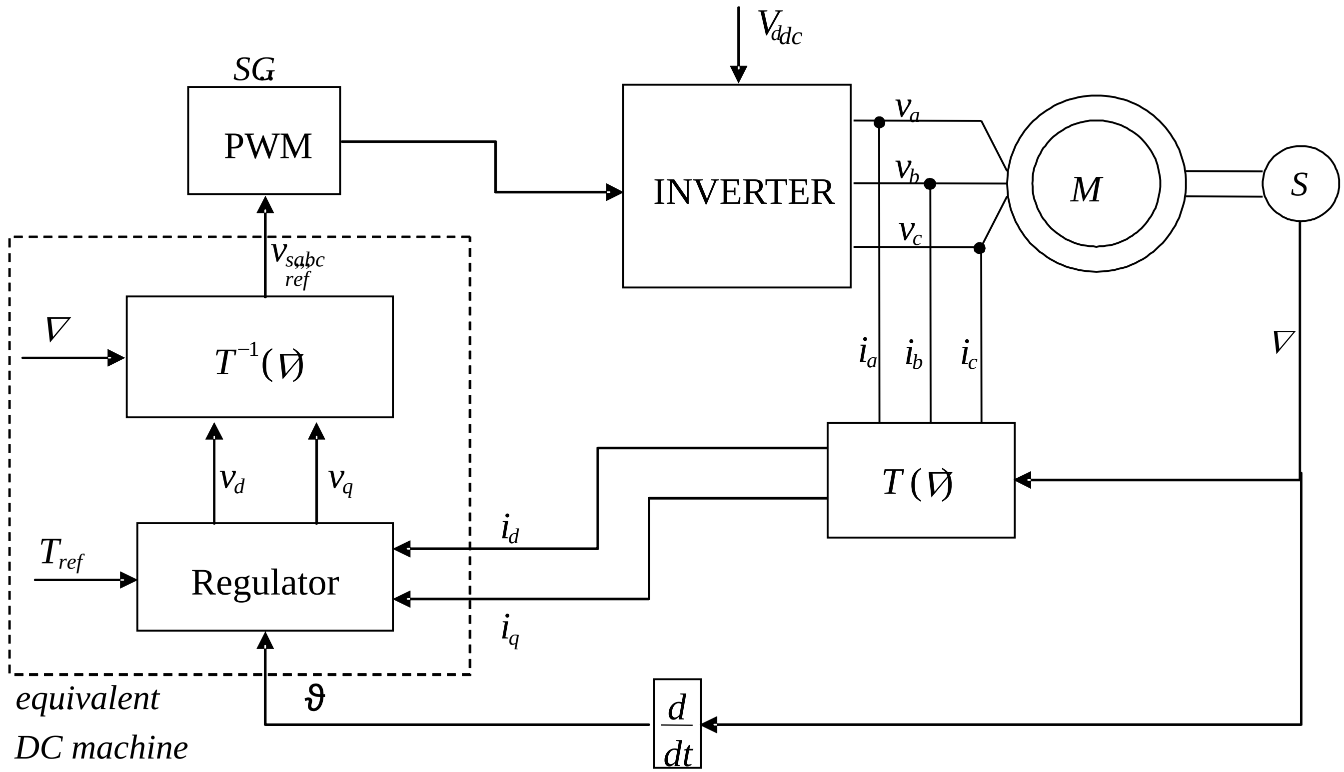
10. Motion control of a pendulum

Synchronous motor: block diagram



The correspondance between phase voltages and currents (v_a,v_b, v_c and i_a,i_b, i_c) and the voltage and current vector components (v_{sd}, v_{sq} e i_{sd}, i_{sq}) is highlited

Synchronous motor: provisional control scheme



•Control is carried out on the vector components, i.e. by controlling a sort of virtual "equivalent" DC machine;

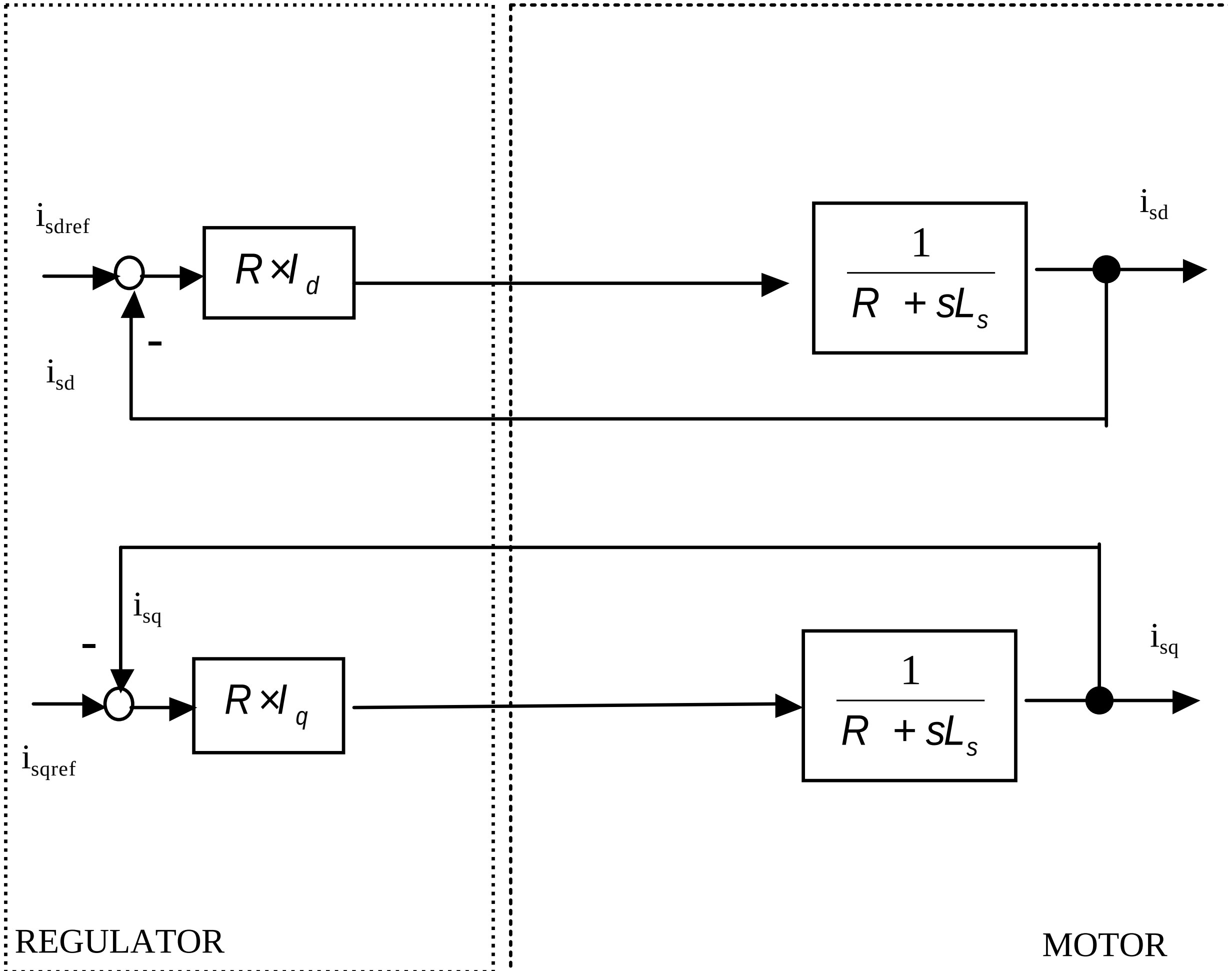
•i_d, i_q components are obtained from measured i_a,i_b e i_c through *T(ϑ)* transformation;

•The voltages $v_{a,b,c\ ref}$ to be applied are obtained from $v_{d,q}$ through the inverse transormation $T^{-1}(\vartheta)$;

•Two block are present: i) an evaluation block SG which evaluate PWM pulses ii) the inverter which applies PWM pulses to the machine, supplying the voltages required for control.

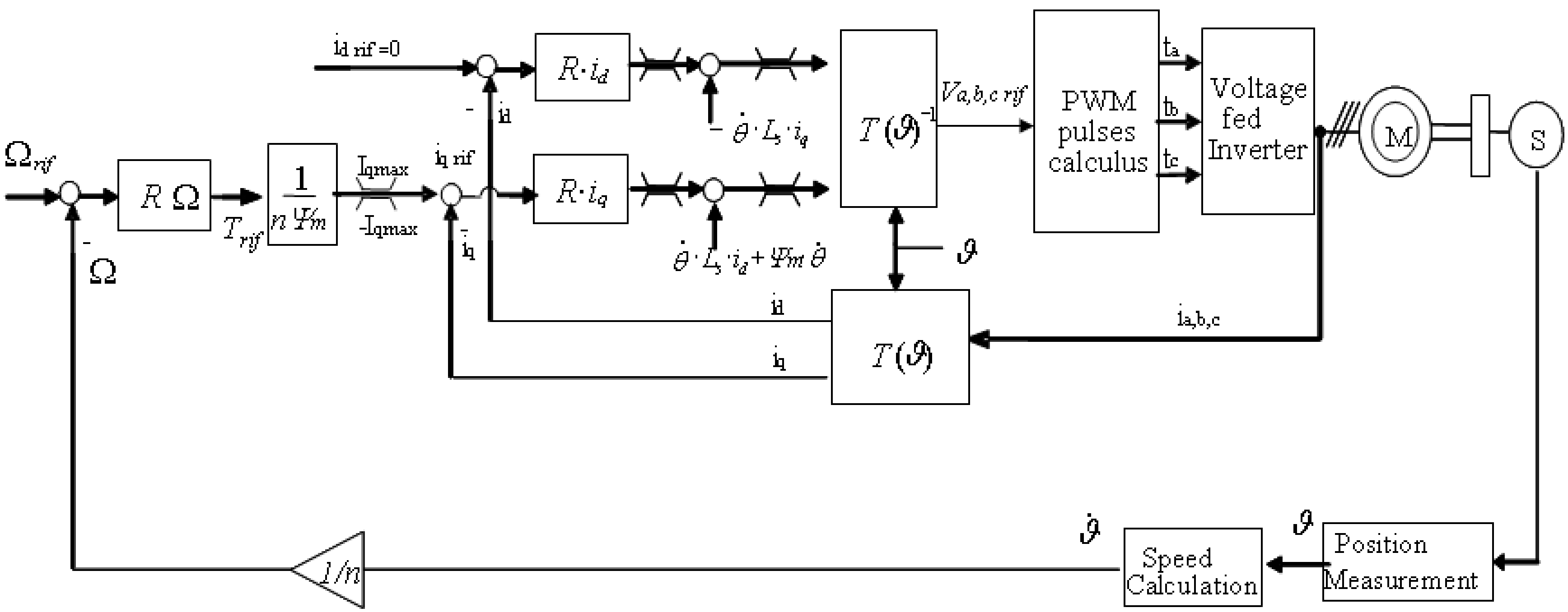
Decoupled loops

Feed-forward contribution to current regulator required.



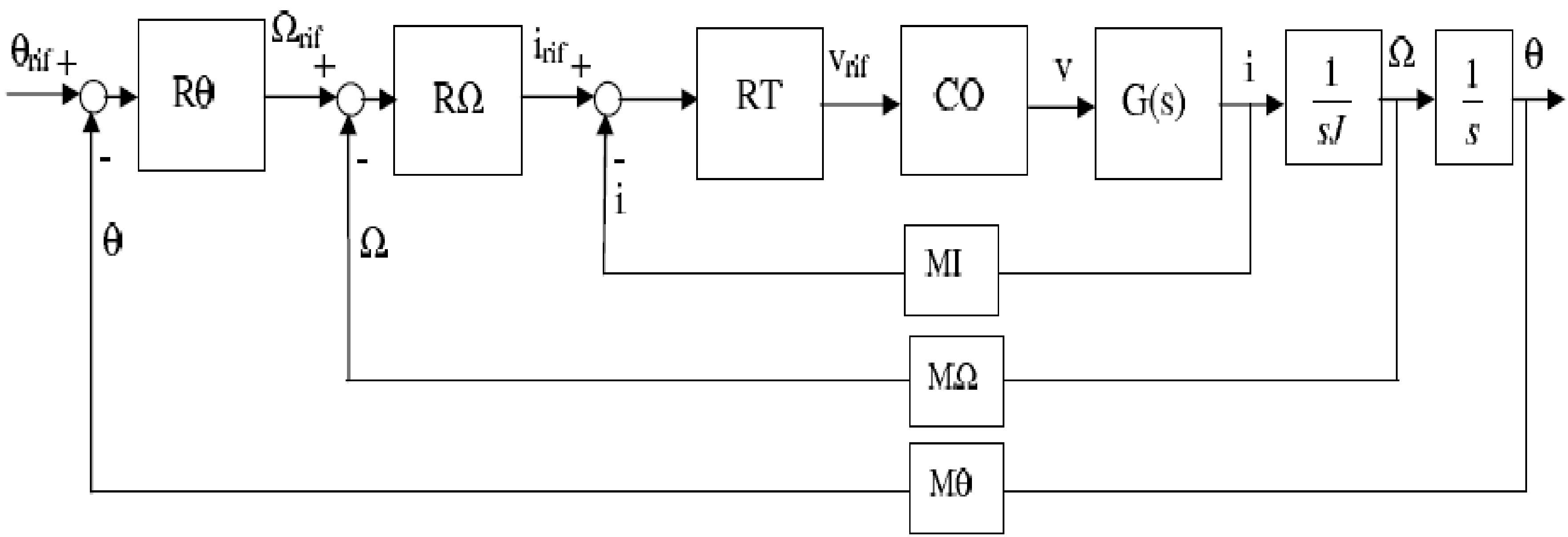
Overall speed regulation scheme

Saturations in evidence



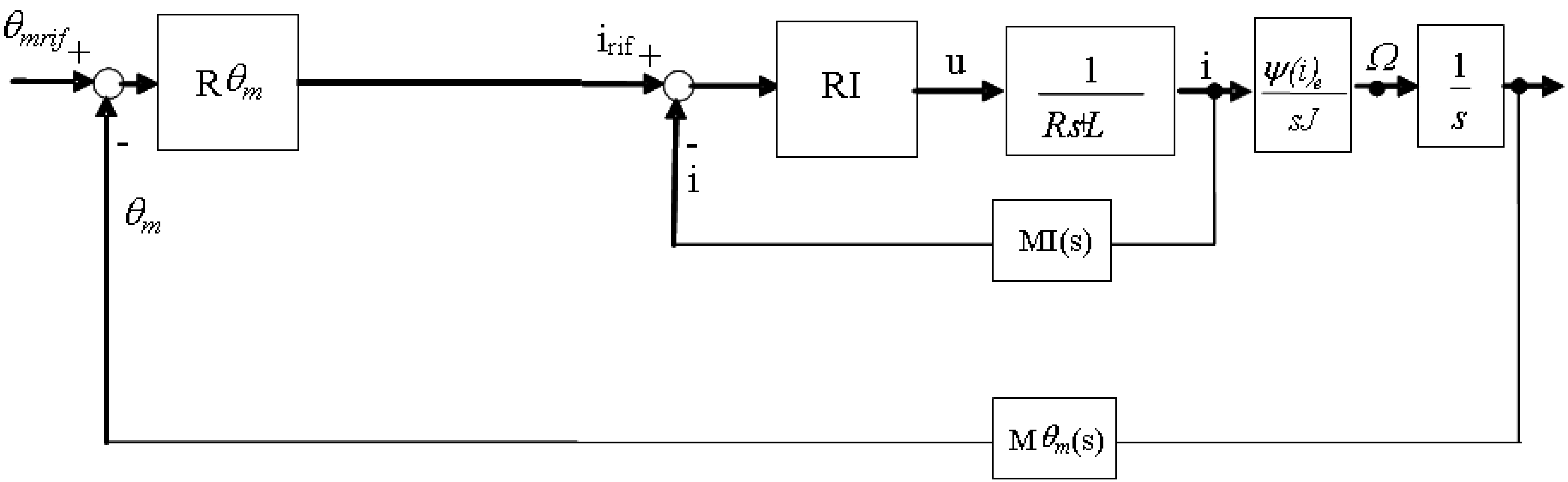
Position control 1

Nested loops with Position, Speed and Torque (Current) regulation



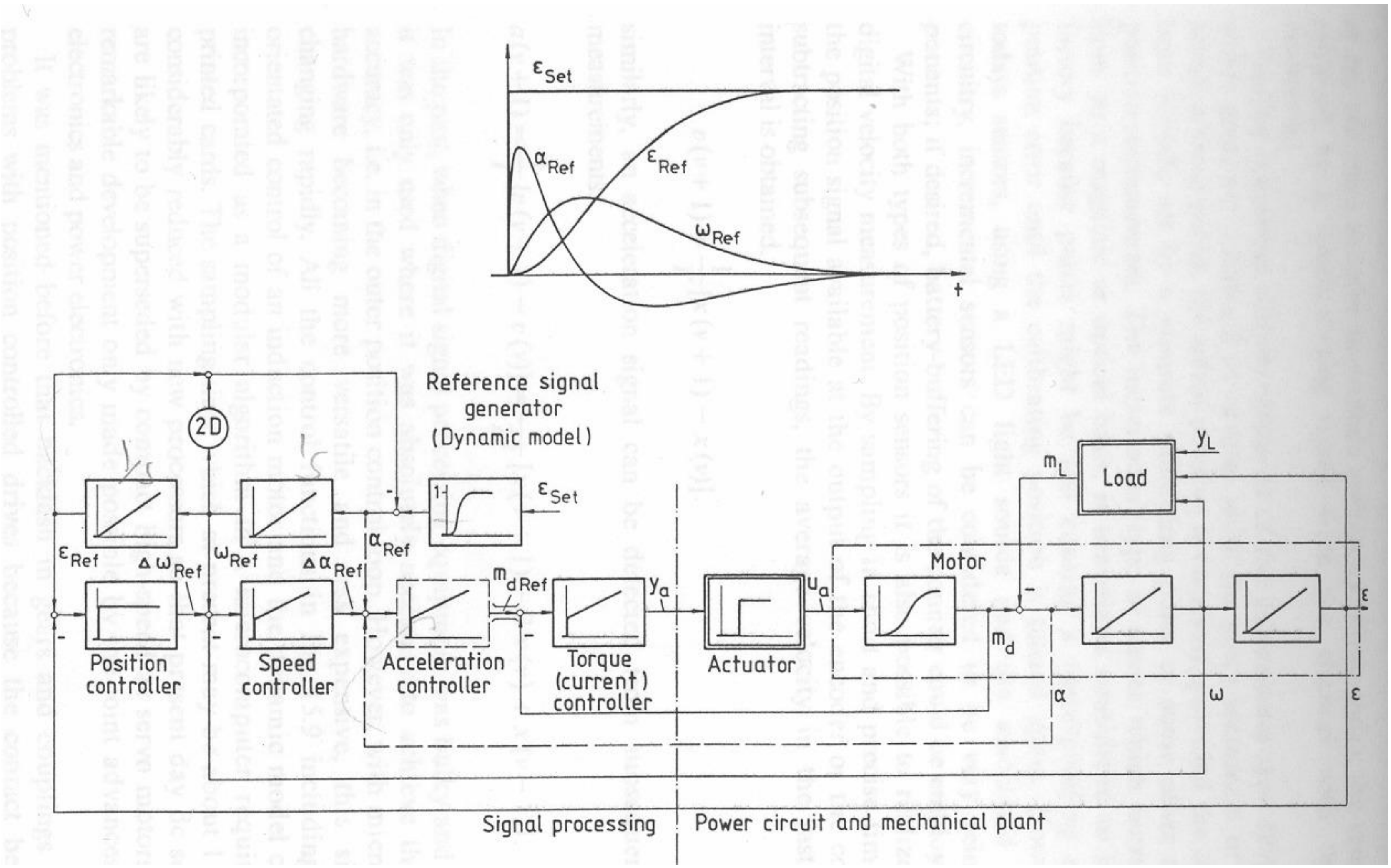
Positon control 2

Nested loops with Position and Torque (Current) regulation

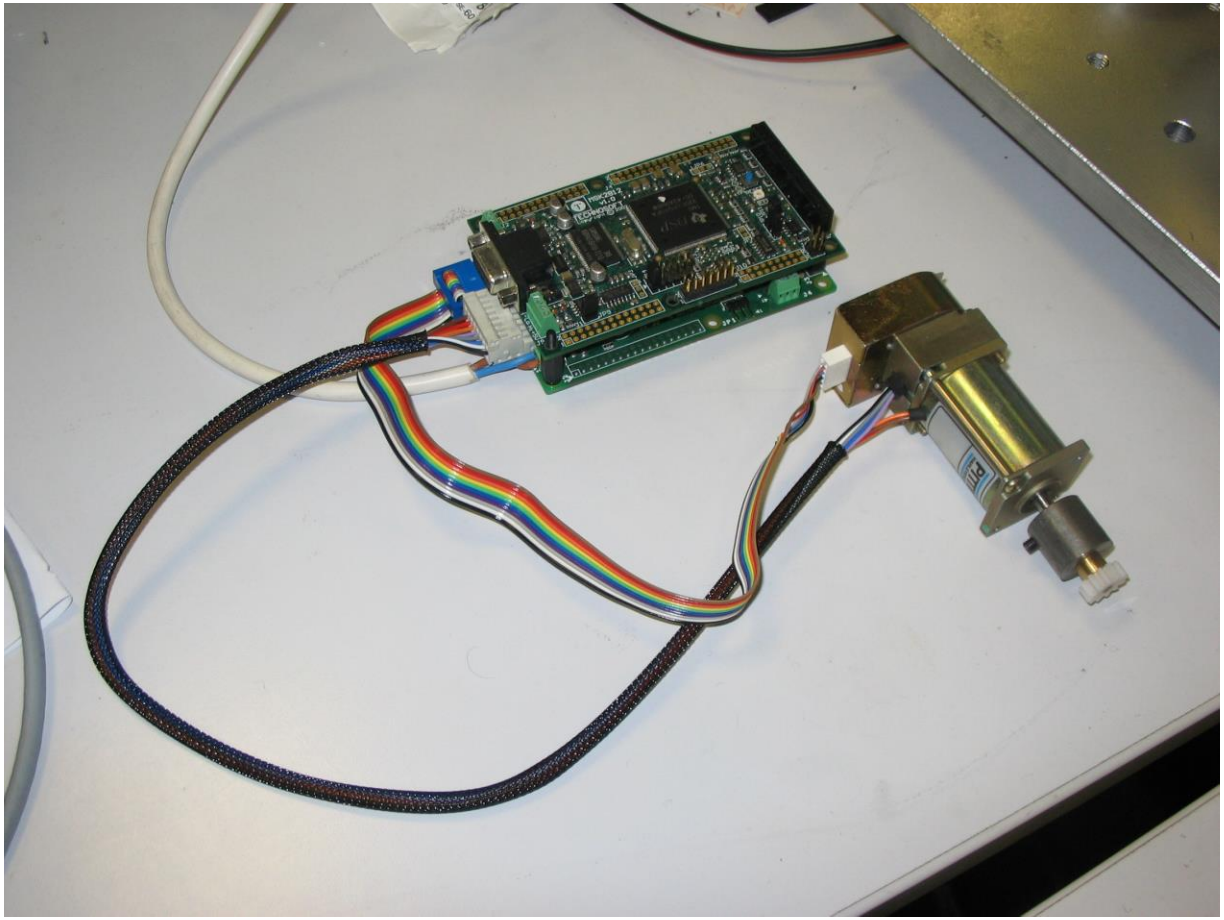


Position control 3

P-PI-PI or PD-PI control and input shaping

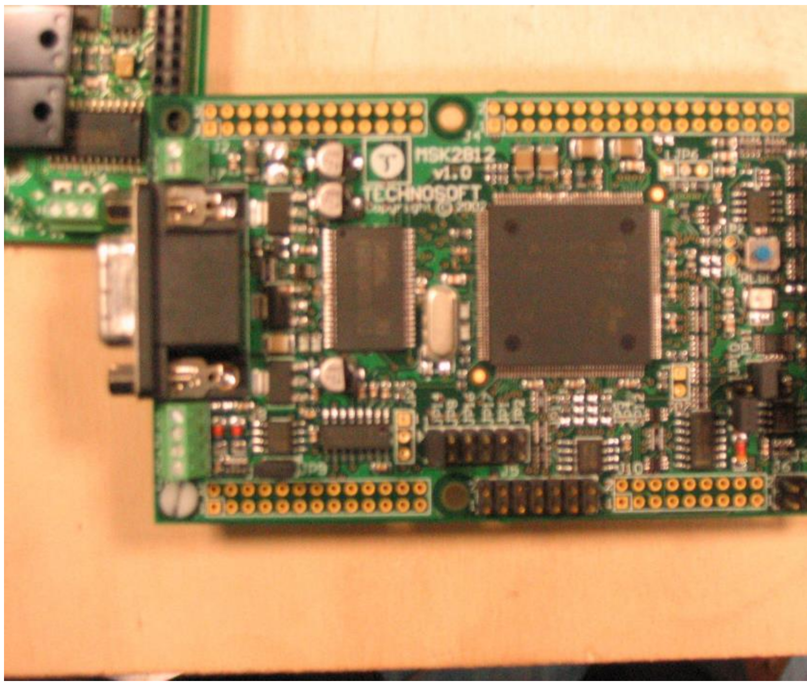


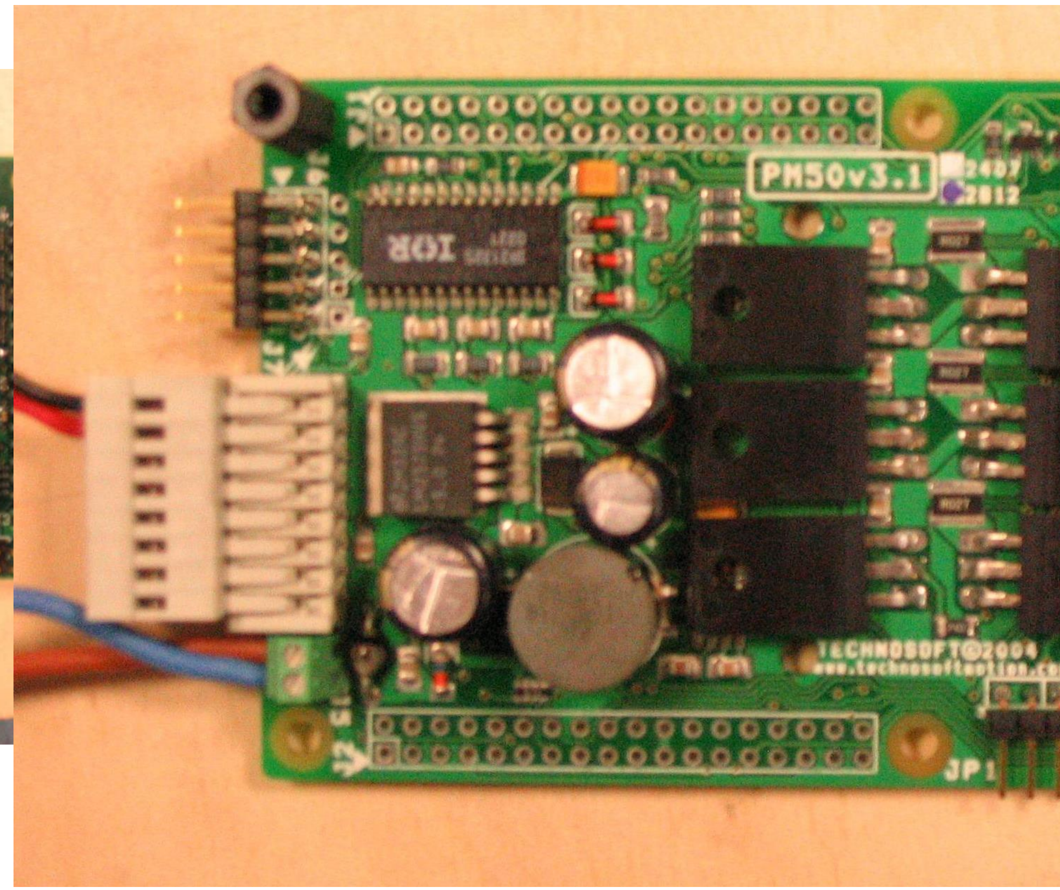
Permanent magnet brushless motor



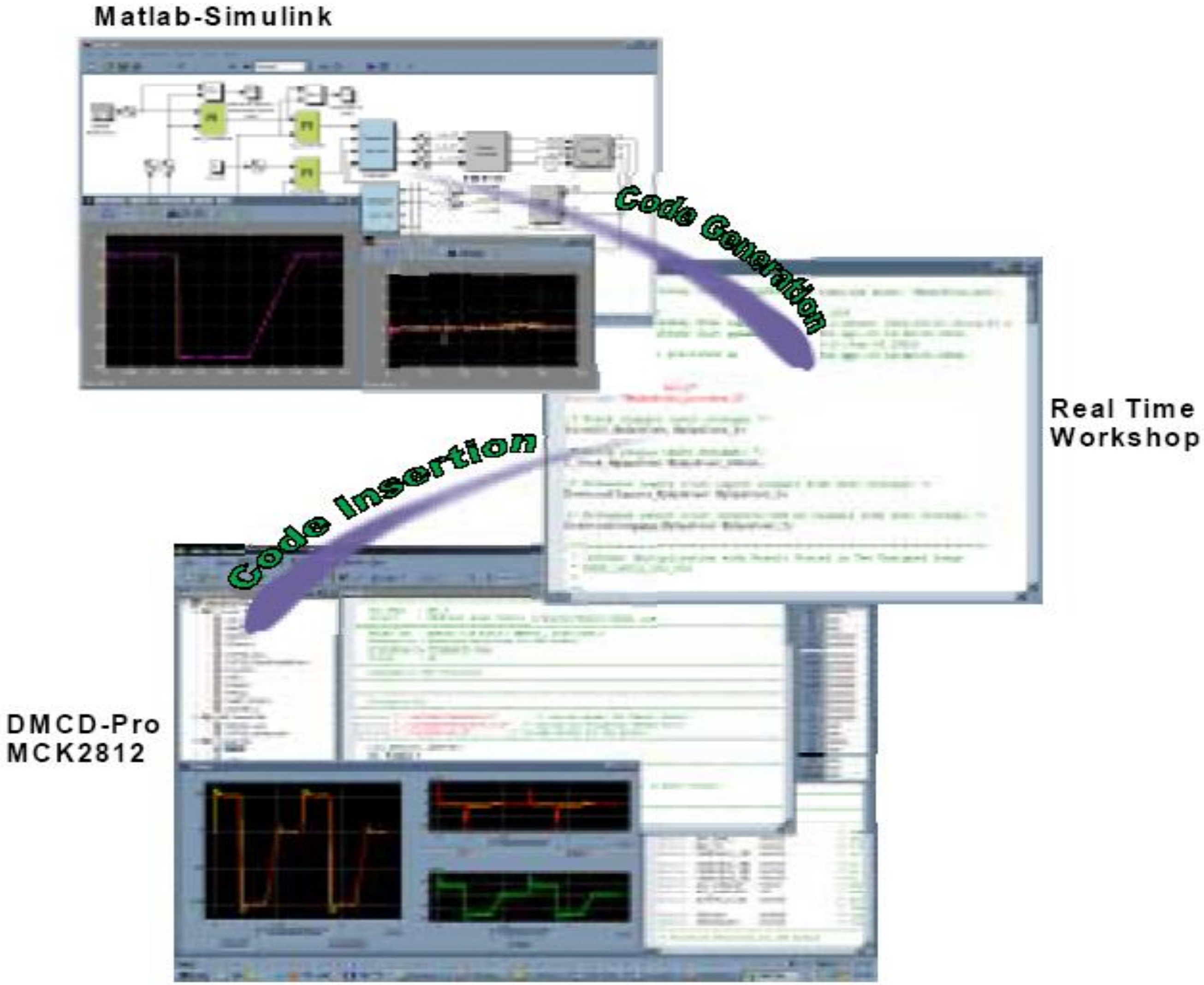
DSP controller

Power converte
(Chopper or Inverter 150





Development environment



Execution steps

1. Identification of the system parameters from catalogues, measures and calculations (R, L, Jmot etc. etc.).
2. Implementation of Matlab/Simulink simulation model
3. Implementation and tuning of the current and speed loop (classical solution with PI-PI nested loops) with or without Feed-Forward on the current loop.
4. Implementation of the control SW on the real system and comparison between numerical and experimental results for all the control architectures.
5. Position control (P-PI-PI, PI-PD)
6. Dynamic-reference generator (optional)

Automation and Control Laboratory

Available experiences:

1. Automation of an elevator plant
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3. Setup and programming of a robot-cell manufacturing task
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5. Control of a permanent-magnet DC motor
6. Control of a permanent-magnet synchronous motor
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8. Control of torsional vibrations
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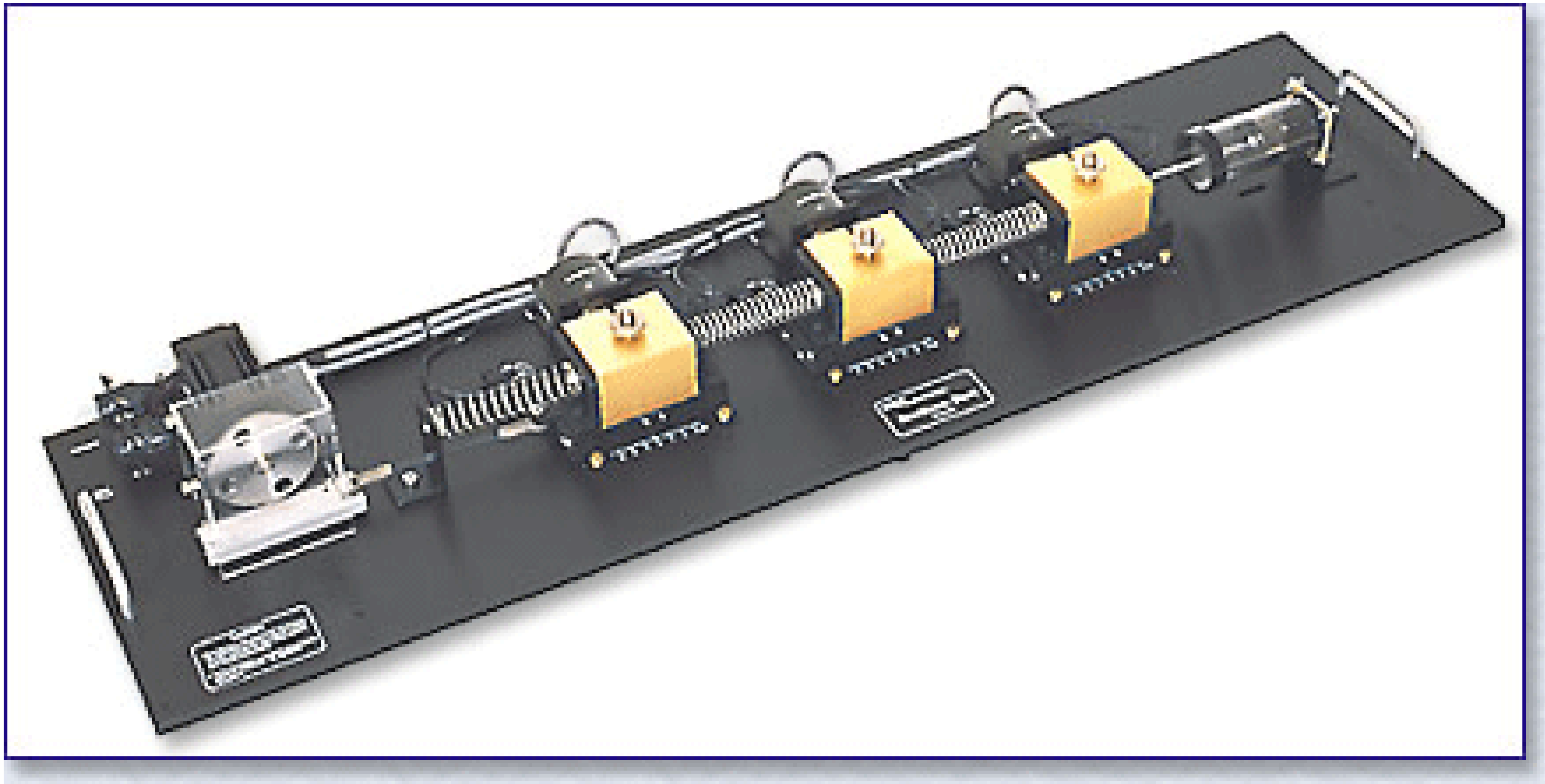
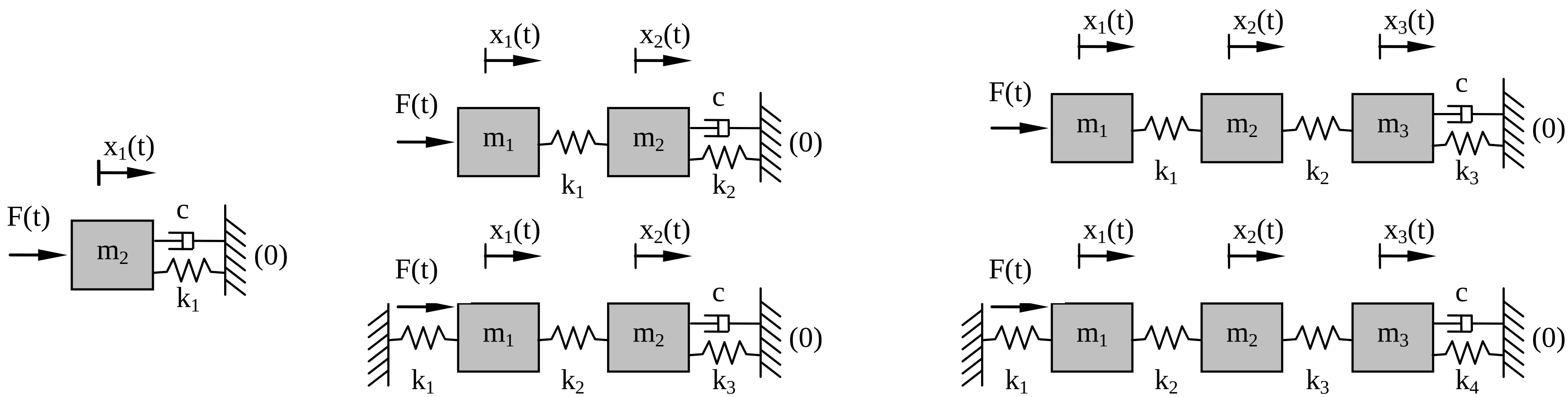
10. Motion control of a pendulum

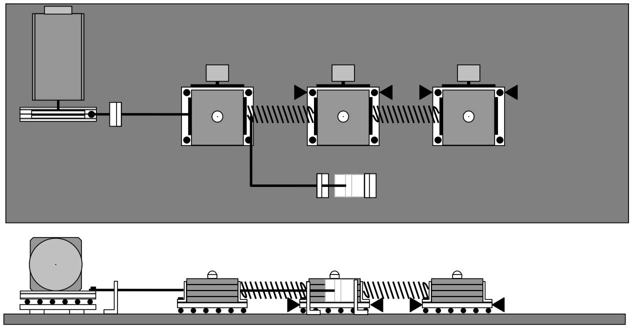
Linear vibrations

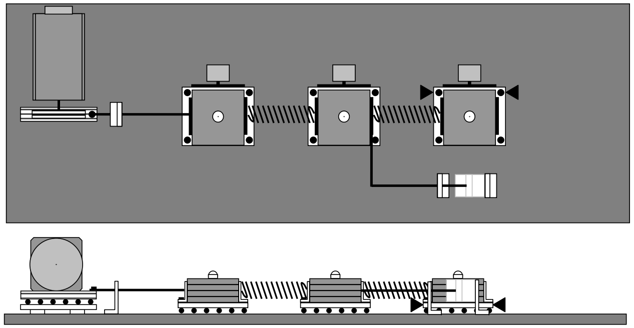


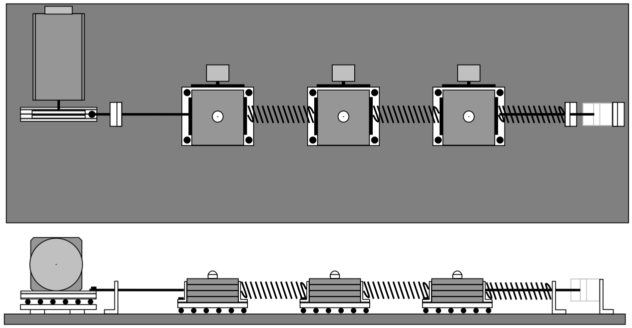
Linear vibrations: overview

The system is able to emulate several real systems composed by rigid bodies connected by flexible elements.
The system is composed by 3 masses and different springs for the connection to the ground or between the masses
By applying different connections 1, 2 and 3 dof systems can be realised.



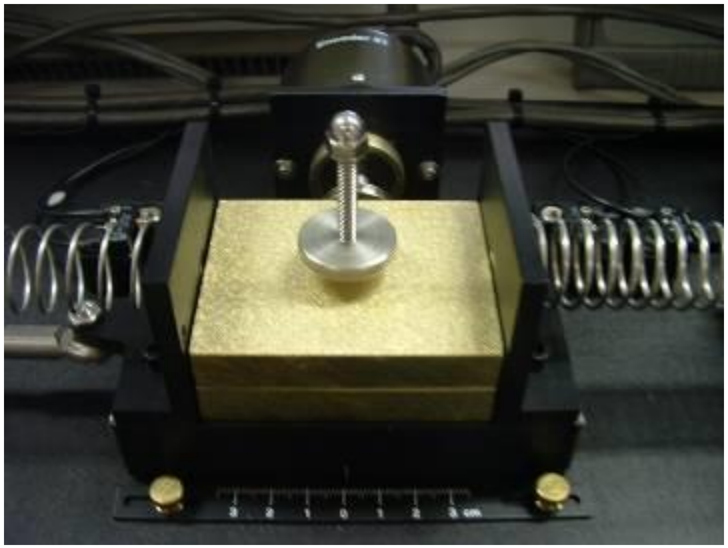


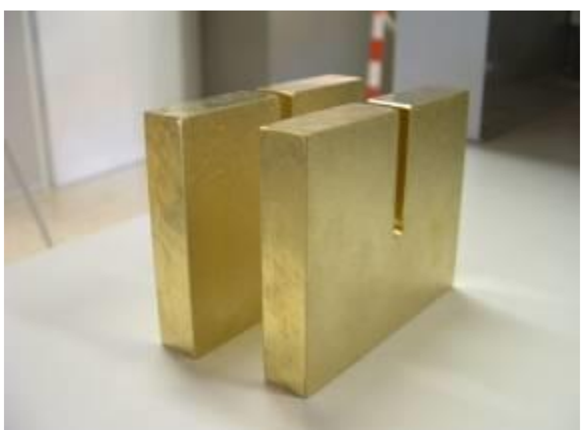




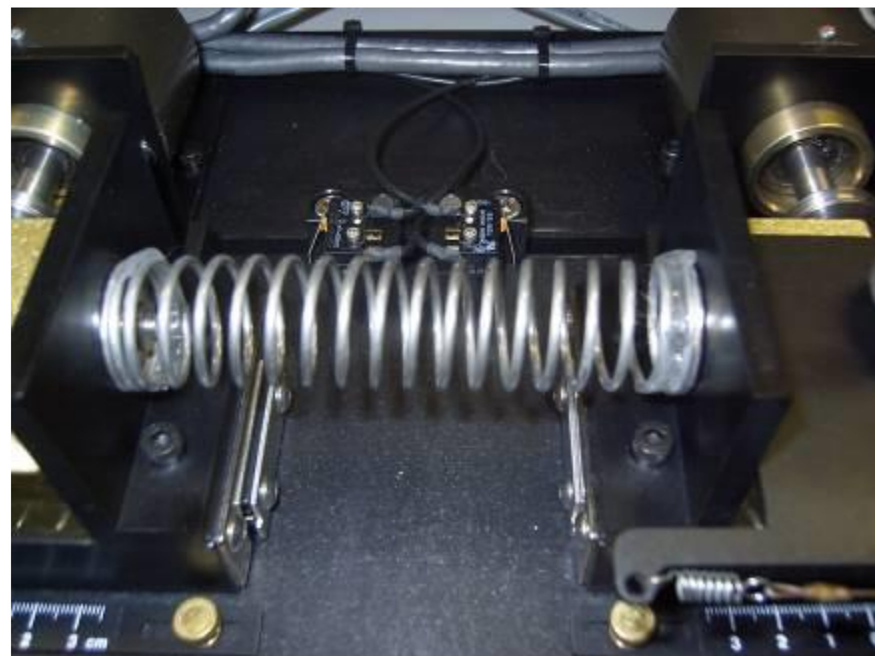
Linear vibrations: overview

The inertia of the moving masses can be varied by changing the number of brass weights (500 ± 5g weight each).



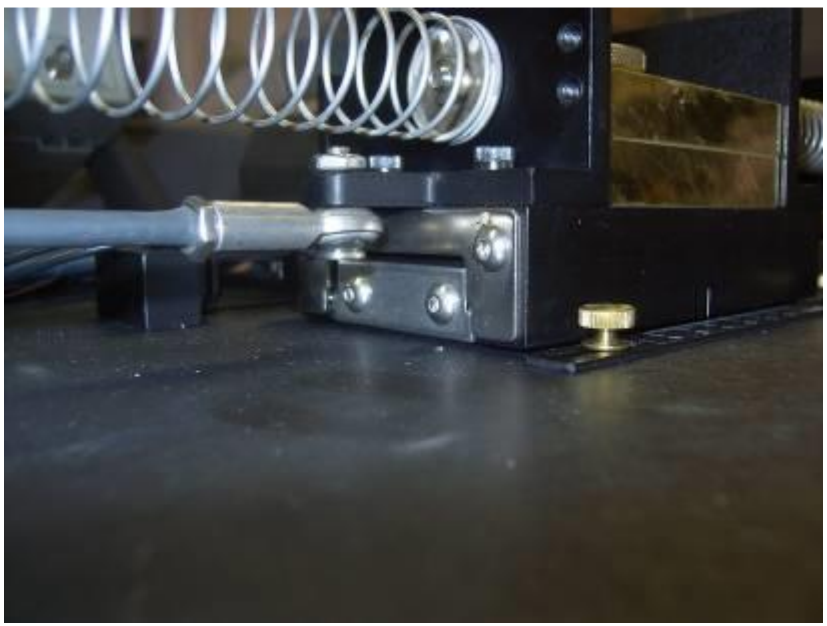


The bi-directional springs can be dismounted and changed. Springs with different stiffness are available.

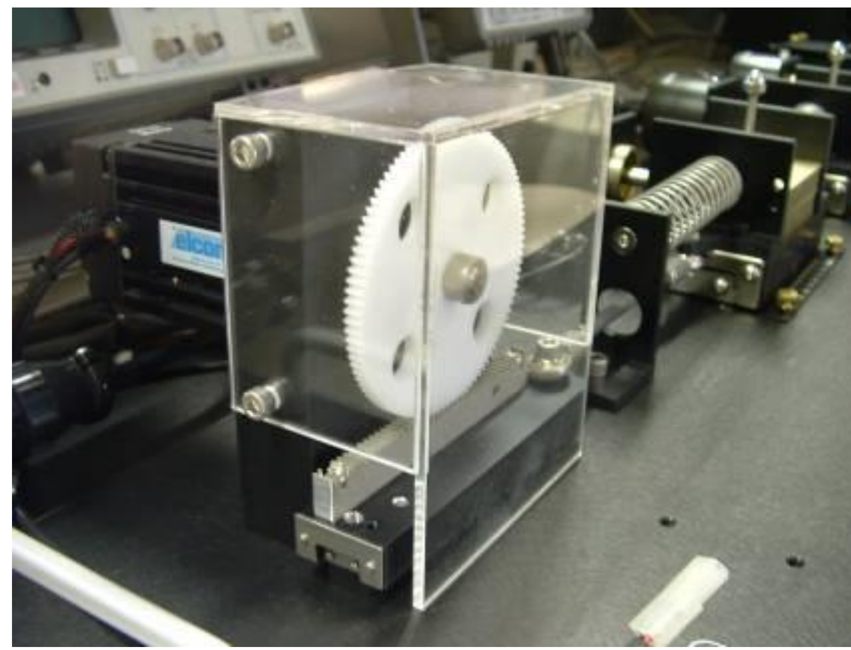


Linear vibrations: overview

The mass carriage suspension is an anti-friction ball bearing type with approximately ± 3 cm available travel.

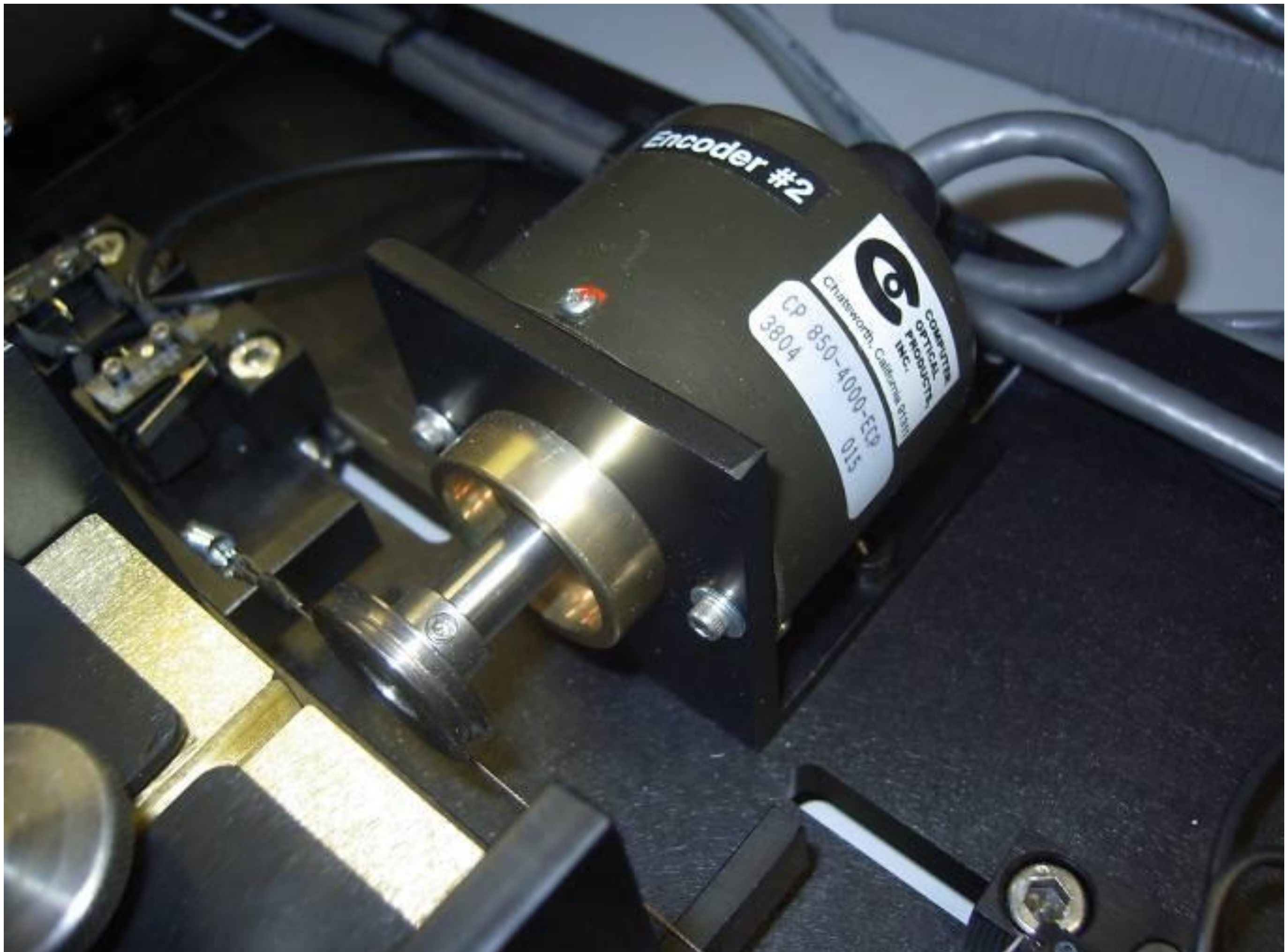


The linear drive is comprised of a gear rack suspended on an anti-friction carriage and a pinion (pitch diameter 7.62 cm (3.00 in)) coupled to the (DC) motor shaft. The carriage is rigidly connected to the first mass.



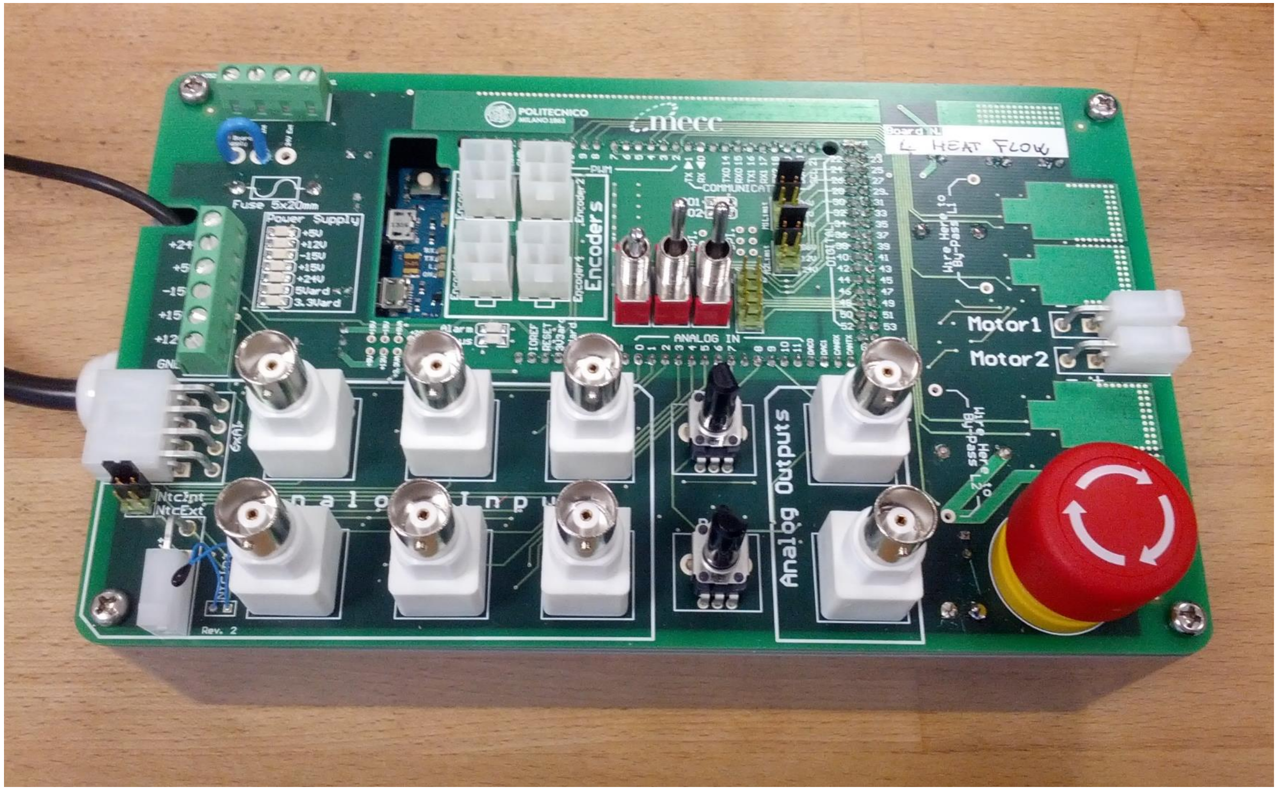
Linear vibrations: overview

Optical encoders measure the mass carriage positions – through a capstan system with pinion pitch diameter 3.18 cm (1.25 in)

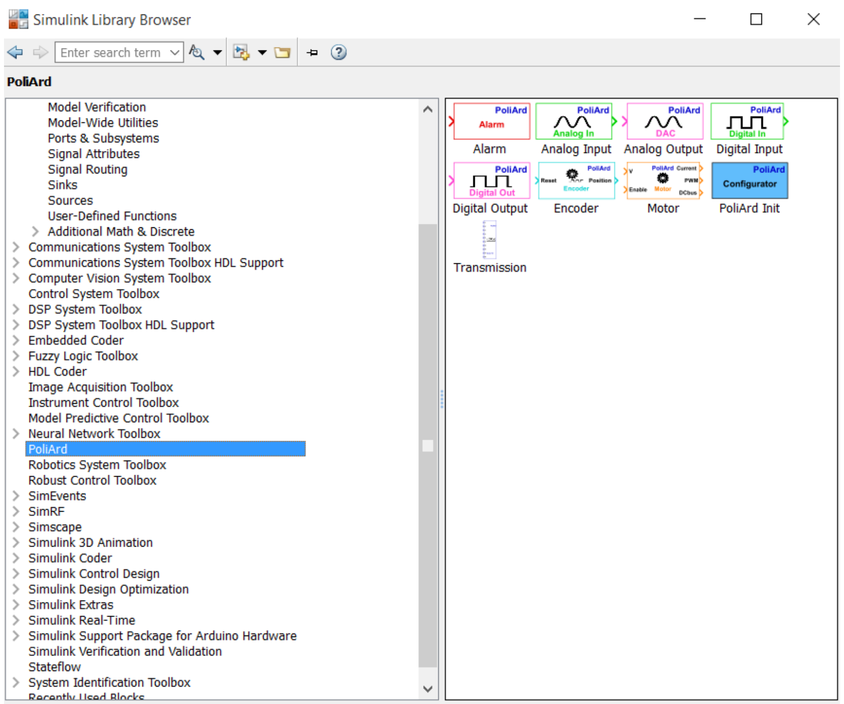


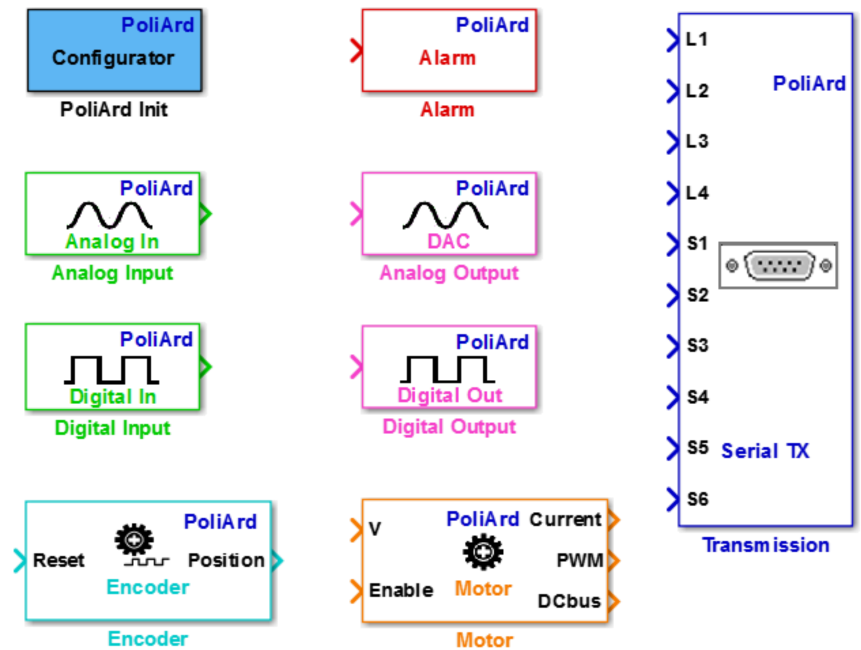
PoliArd Board

PoliArd Board allows to perform real-time control logics thanks to an **Arduino Due** board (32-bit ARM Cortex-M3).

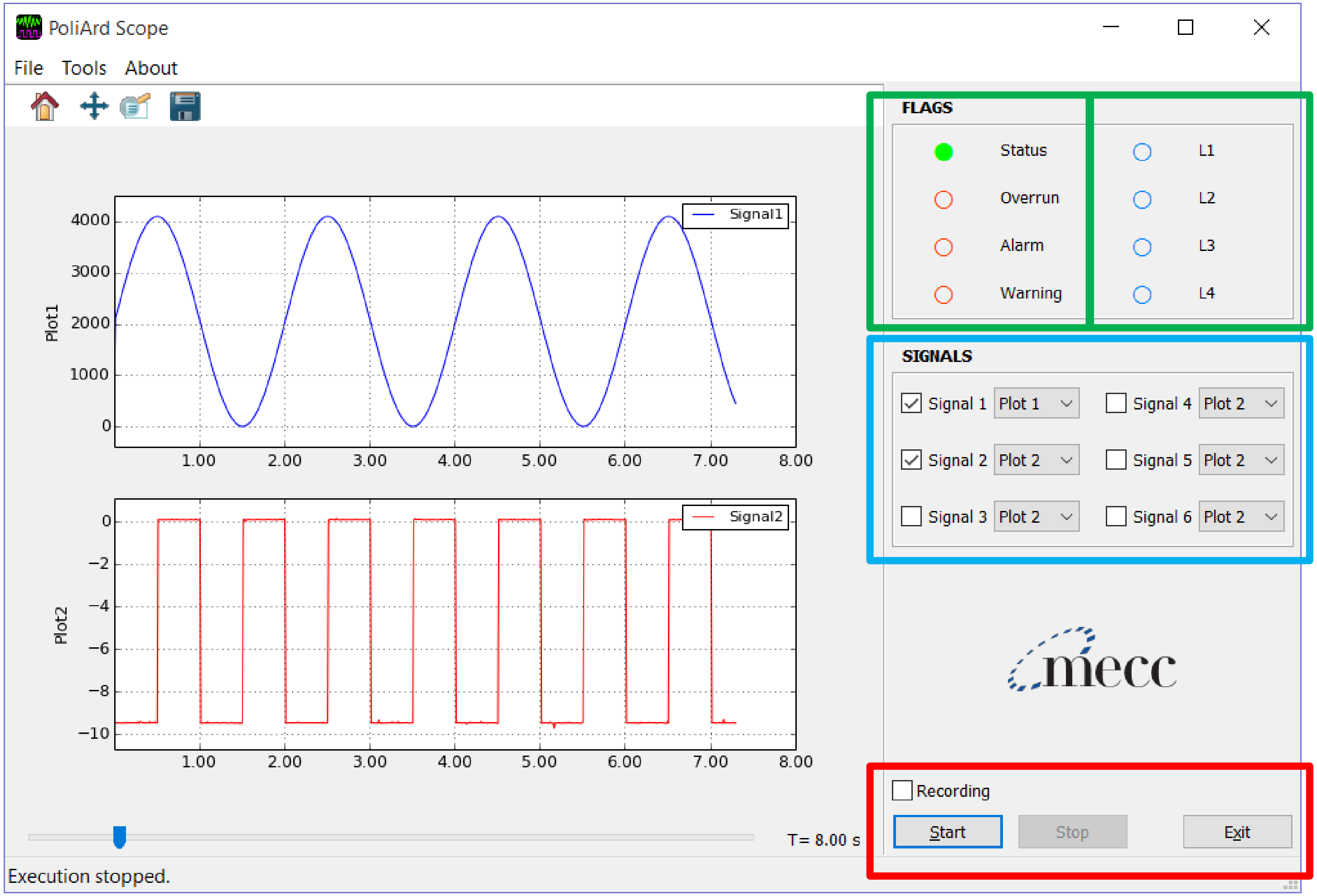


PoliArd Library





PoliArd Scope



Boolean flags visualization

Float signals configuration

Acquisition controls

Execution steps

Consider different system configurations (with increasing difficulty levels). Steps for each subsystem:

1. Development of models for simulation (time domain) and for control synthesis and tuning (Laplace domain)
2. Identification of unknown parameters of the model/s
3. Numerical implementation and verification of different control logics (for position control of one of the masses) (classical control and modern control, if appl.)
4. Implementation of the control on the real system and comparison between numerical and experimental results (with possible optimisation of the control parameters for the real system)
5. Comparison of the performances of the different control logics/calibrations (robustness)

Automation and Control Laboratory

Available experiences:

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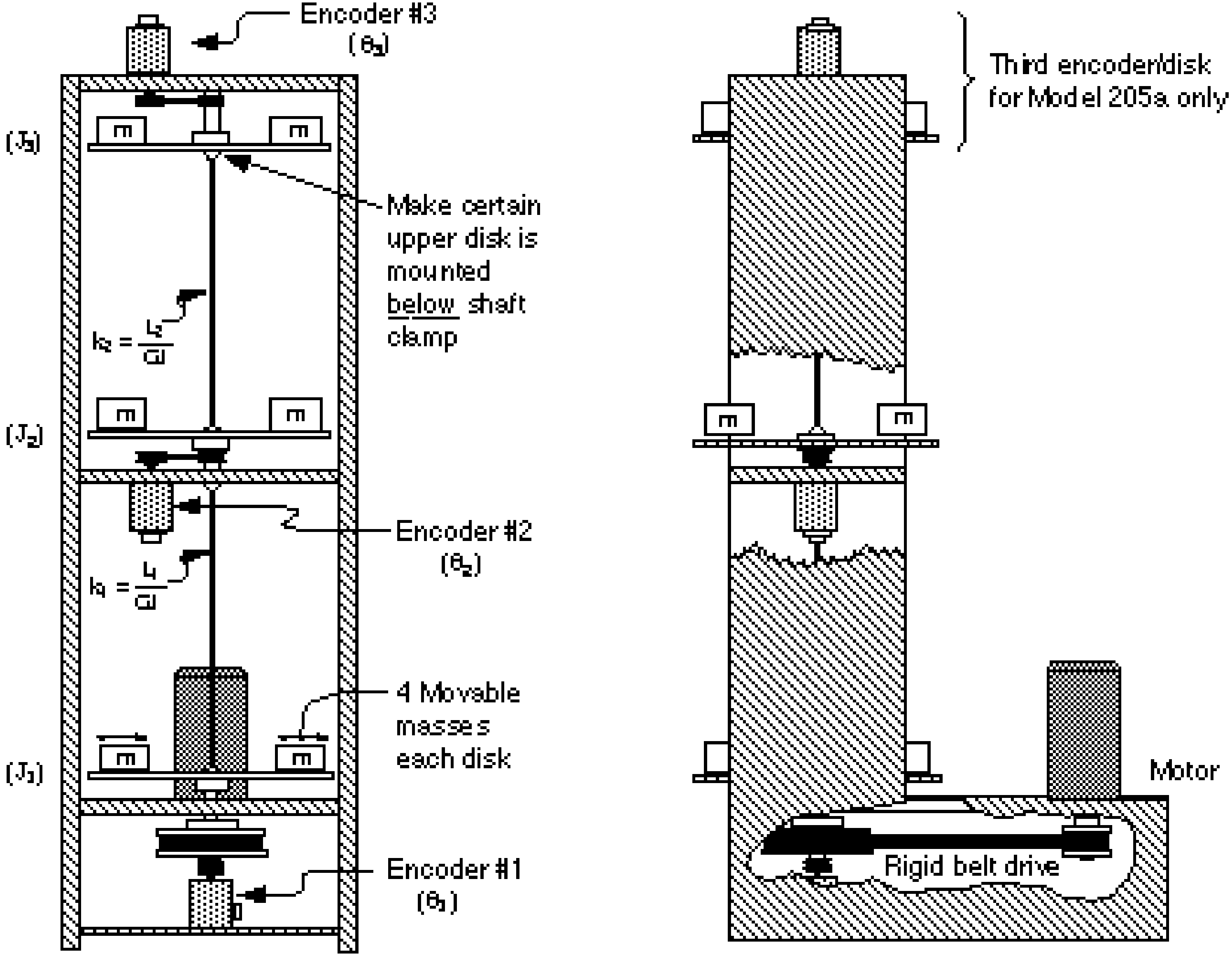
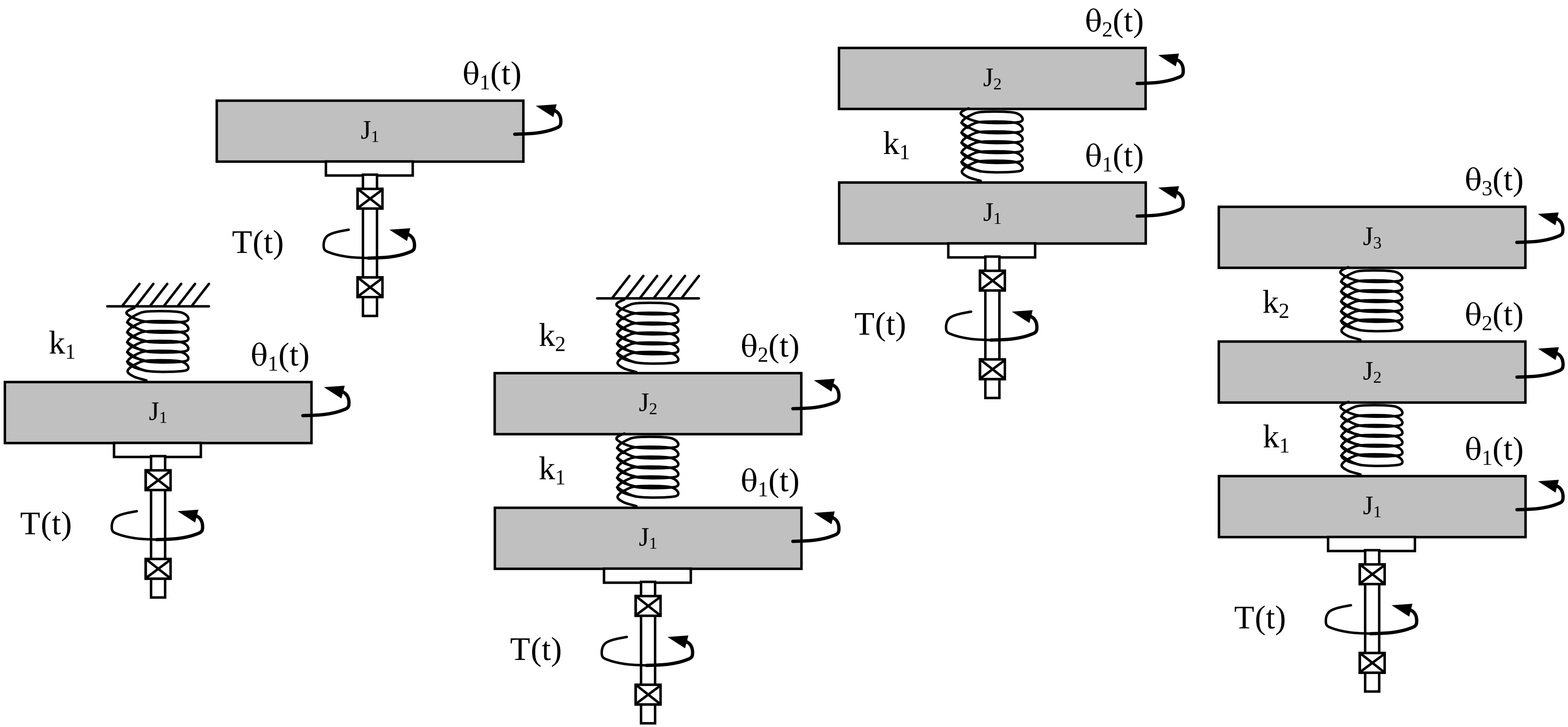
Torsional vibrations

Torsional vibrations: overview



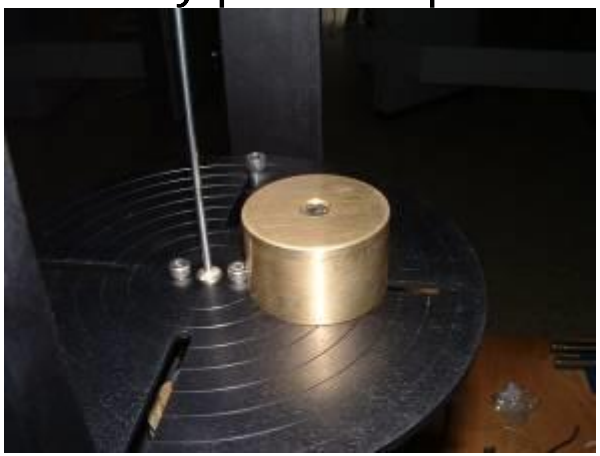
Torsional vibrations: overview

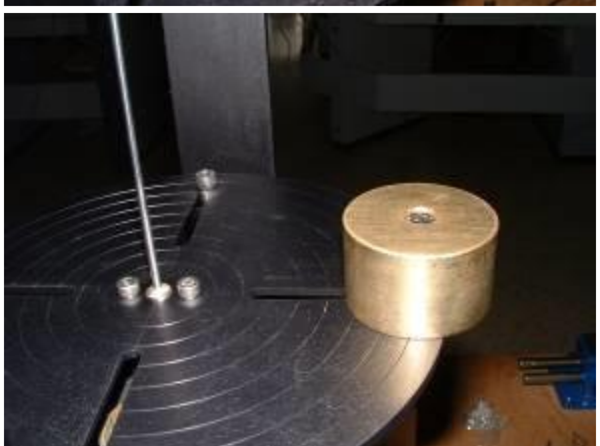
The system is made of 3 disks and 2 connecting torsional springs. By constaining the disks to the support structure it is possible to consider sytems with 1, 2 and 3 dof.



Torsional vibrations: overview

The user may change inertia values by changing the number of masses and/or their location on a given disk. The user should verify that the disks, belts, and pulleys are properly aligned and secured and rotate freely prior to operation.

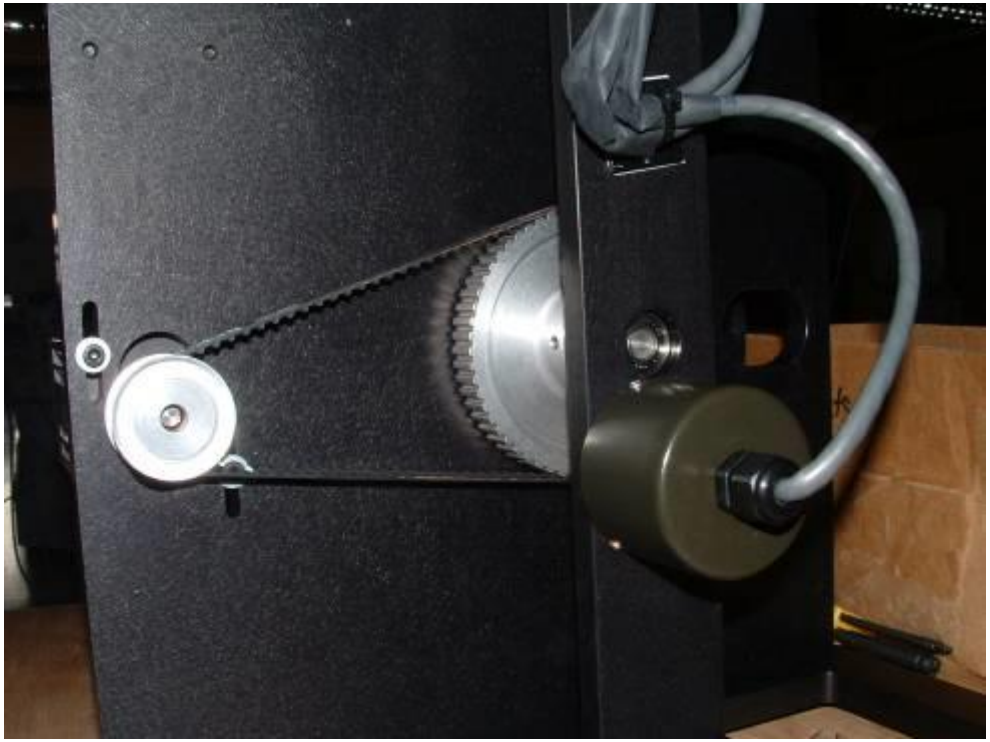




The torsional springs can't be unmounted.

Torsional vibrations: overview

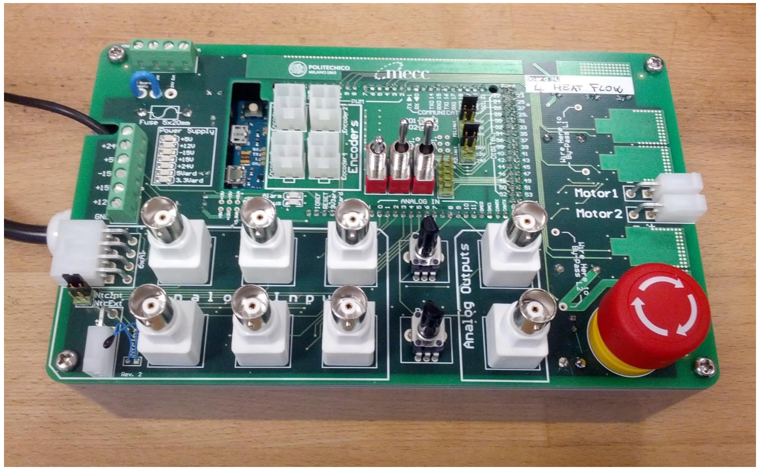
The shaft is driven by a DC motor connected via a rigid belt (negligible tensile flexibility) and pulley system.

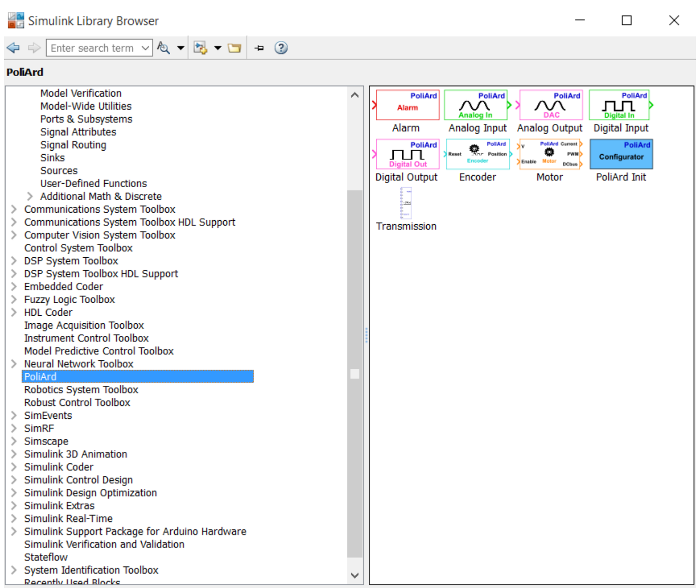


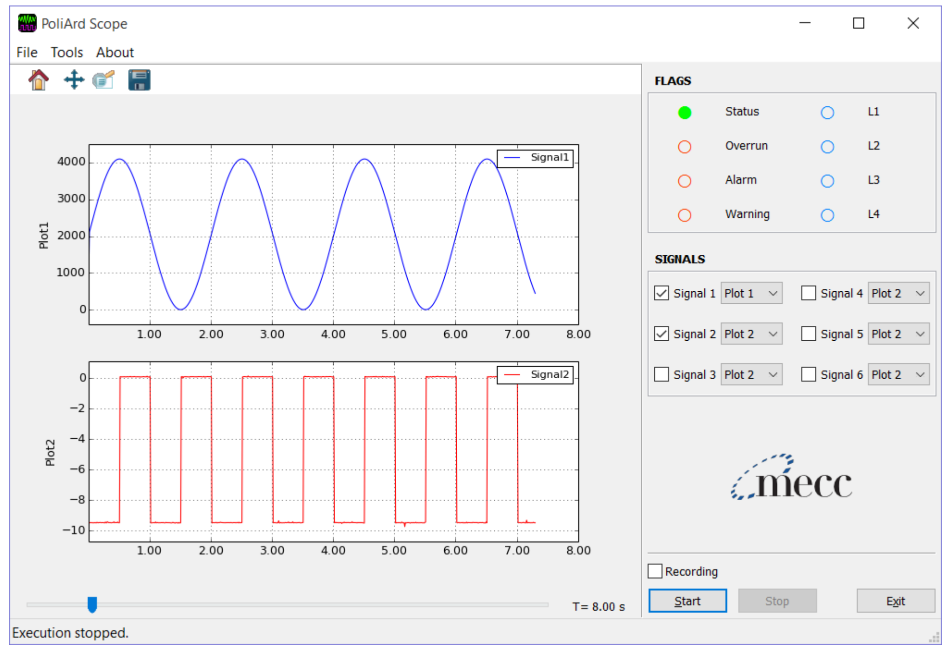
Torsional vibrations: overview

Optical encoders connected to the disks by rigid belts/pulleys measures rotation of the disks.

PoliArd board







Execution steps

Consider different system configurations (with increasing difficulty levels). Steps for each subsystem:

1. Development of models for simulation (time domain) and for control synthesis and tuning (Laplace domain)
2. Identification of unknown parameters of the model/s
3. Numerical implementation and verification of different control logics (for position control of one of the masses) (classical control and modern control, if appl.)
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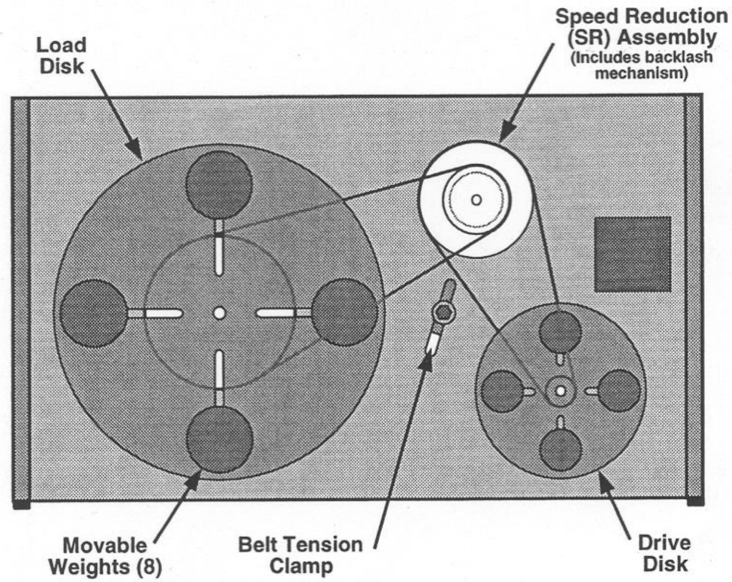
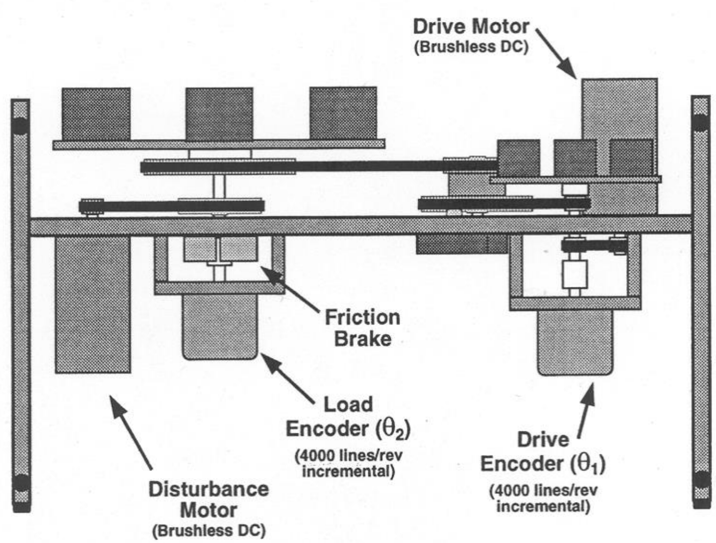
Industrial plant



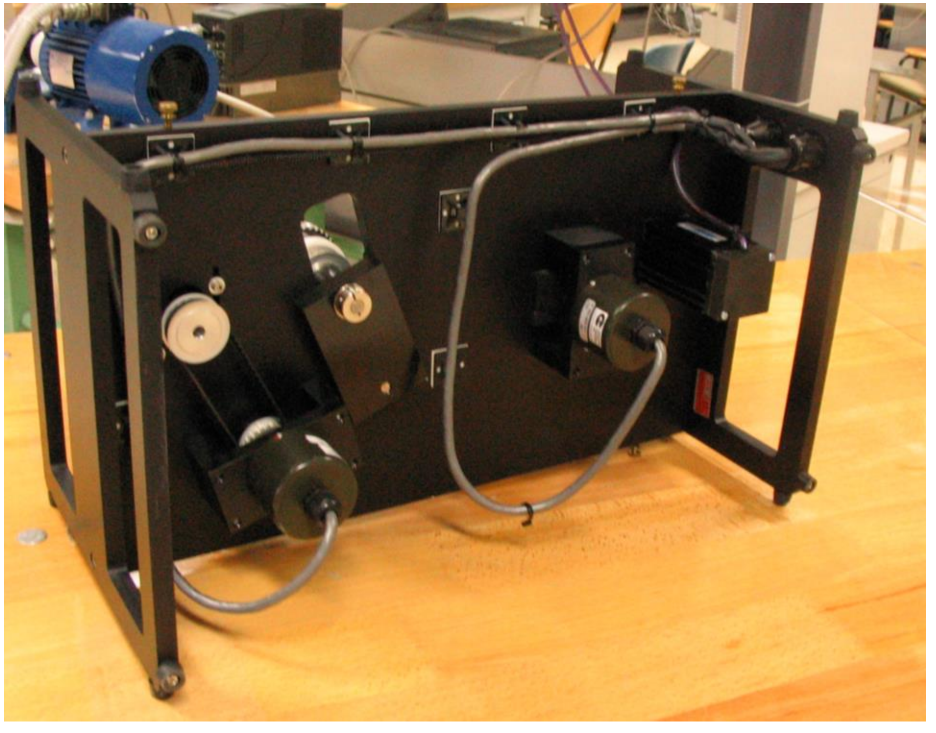


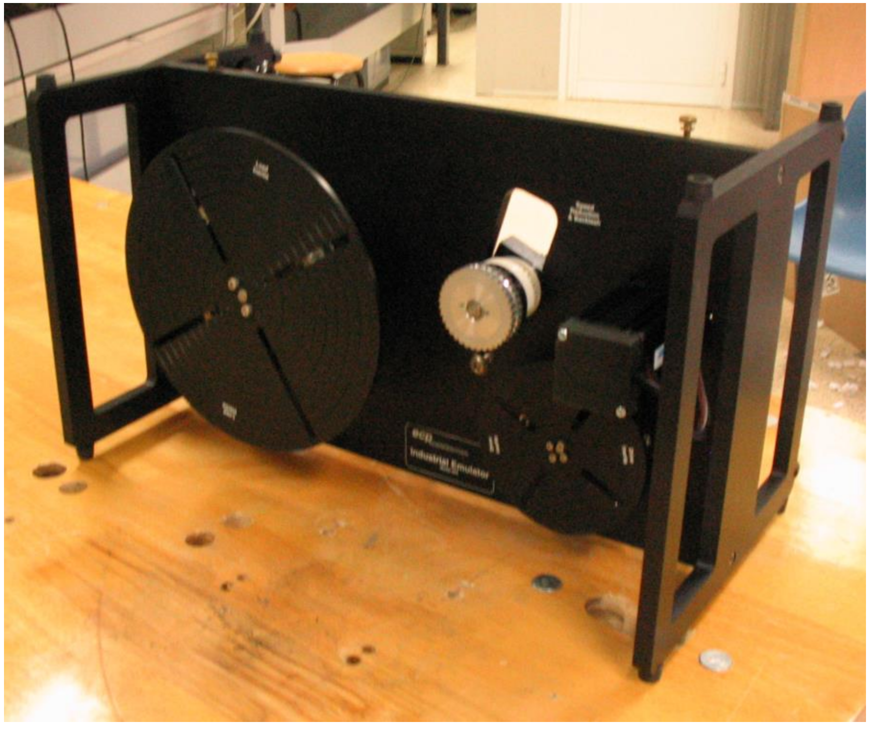
The system consists of a *drive motor* which is coupled via a timing belt to a *drive disk* with variable inertia. Another timing belt connects the drive disk to the *speed reduction (SR)* assembly while a third belt completes the drive train to the *load disk.* The load and drive disks have variable inertia which may be adjusted by moving (or removing) brass weights.

Speed reduction is adjusted by interchangeable belt pulleys in the SR assembly.

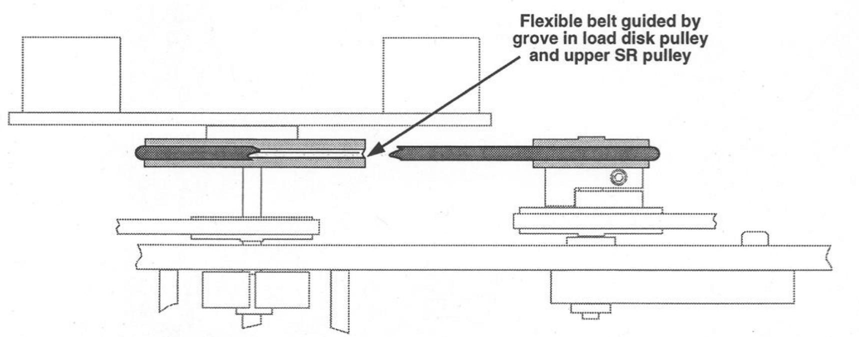
A disturbance motor is connected to the load to give any kind of resisting torque.

Industrial plant: overview





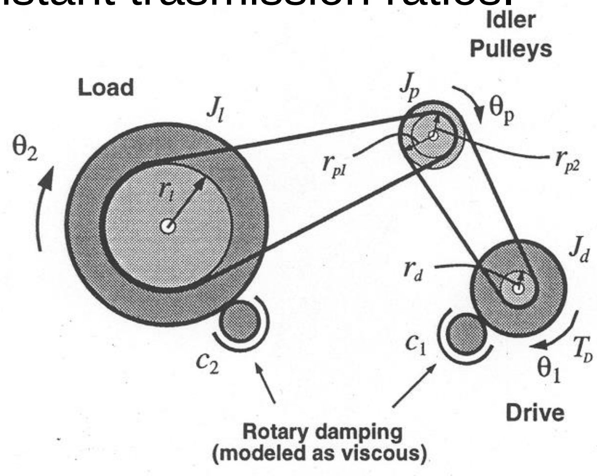
Industrial plant: overview

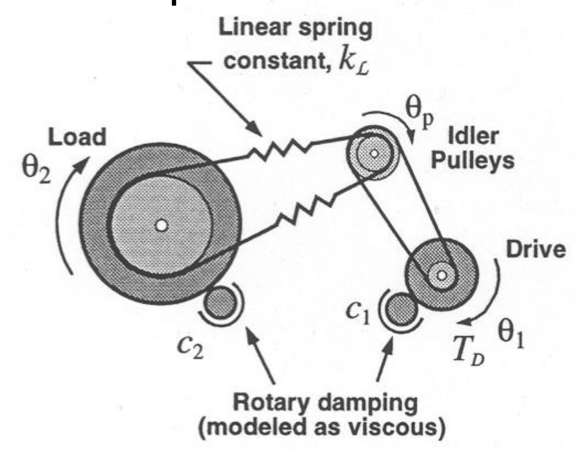


The belt connecting the speed reduction assembly and the drive disk can be rigid or flexible. Backlash may be introduced through a mechanism incorporated in the SR assembly.

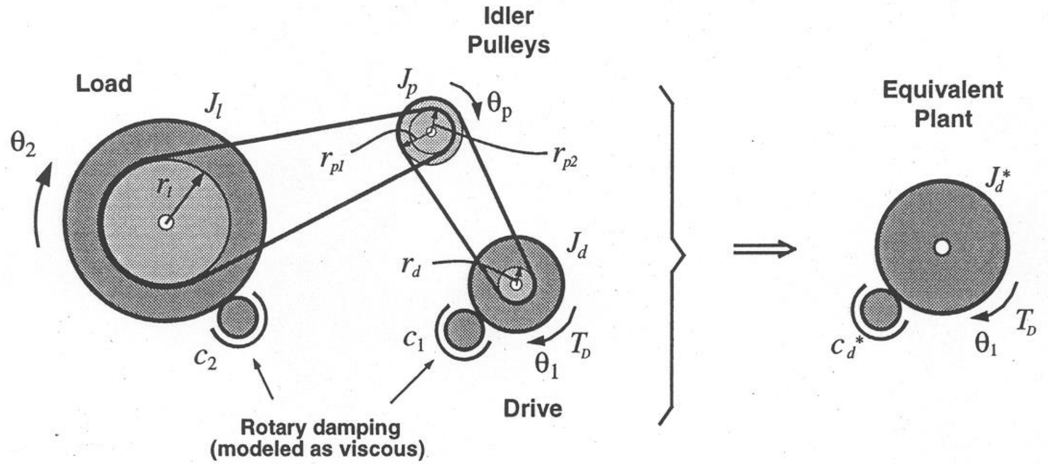
1 dof system
The rotations are related through constant trasmission ratios.

2 dof system
The rotations of the drive and of the load are independent.



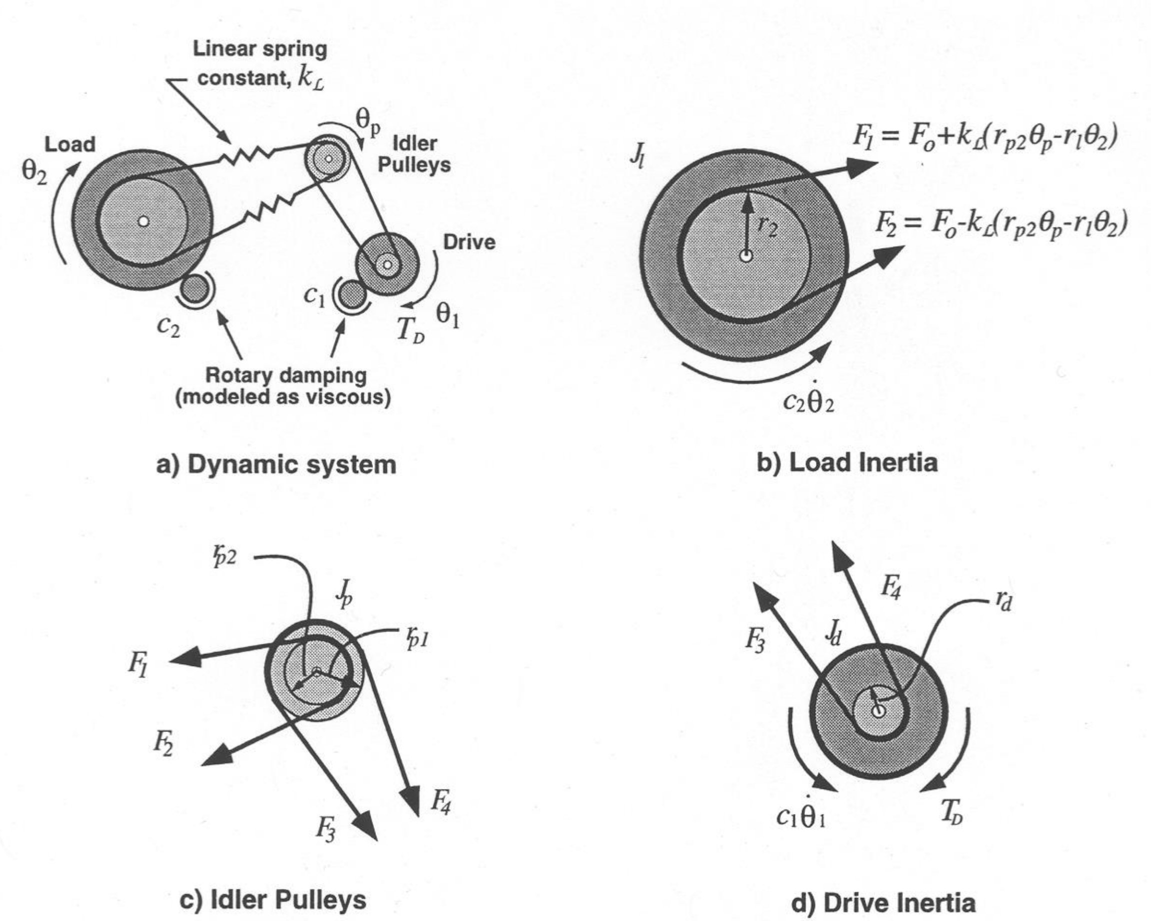


Subsystem 1



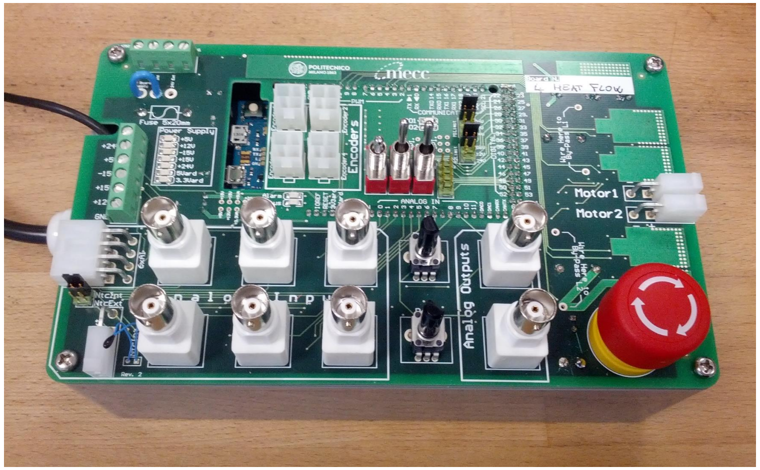
Idler
Pulleys
Load
J_l
J_p
θ_p
θ_2
r_{p1}
r_{p2}
r_1
J_d
r_d
c_2
c_1
T_D
θ_1
Drive
Rotary damping
(modeled as viscous)
Equivalent
Plant
J_d^*
T_D
θ_1
c_d^*

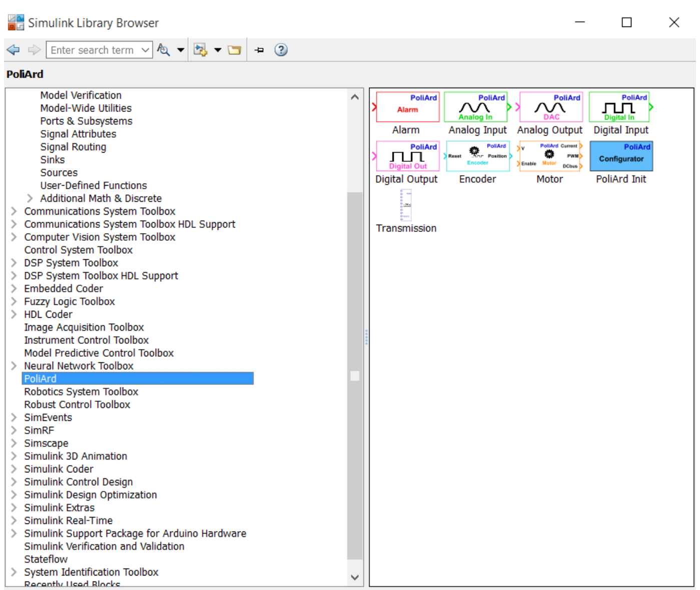
Subsystem 2

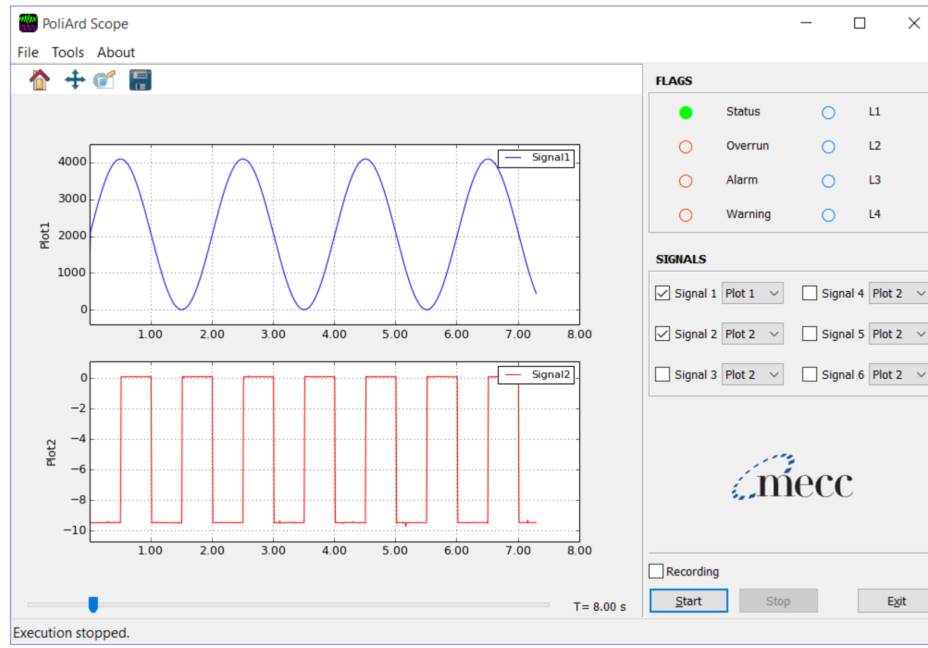


Linear spring constant, k_L
θ_p
Idler Pulleys
Load
θ_2
Drive
c_1
θ_1
c_2
T_D
Rotary damping (modeled as viscous)
a) Dynamic system
J_l
$F_1 = F_o + k_L(r_{p2}\theta_p - r_l\theta_2)$
r_2
$F_2 = F_o - k_L(r_{p2}\theta_p - r_l\theta_2)$
$c_2\dot{\theta}_2$
b) Load Inertia
r_{p2}
J_p
r_{p1}
F_1
F_2
F_3
F_4
c) Idler Pulleys
F_4
r_d
F_3
J_d
$c_1\dot{\theta}_1$
T_D
d) Drive Inertia

PoliArd board







Execution steps

Consider different system configurations (with increasing difficulty levels). Steps for each subsystem:

1. Development of models for simulation (time domain) and for control synthesis and tuning (Laplace domain)
2. Identification of unknown parameters of the model/s
3. Numerical implementation and verification of different control logics (for position control of one of the masses) (classical control and modern control, if appl.)
4. Implementation of the control on the real system and comparison between numerical and experimental results (with possible optimisation of the control parameters for the real system)
5. Comparison of the performances of the different control logics/calibrations (robustness)
6. Development of a speed observer for the load disk

Automation and Control Laboratory

Available experiences:

1. Automation of an elevator plant
2. Control of electric drives and pneumatic actuators in an automated plant
3. Setup and programming of a robot-cell manufacturing task
4. Control of an induction (asynchronous) motor
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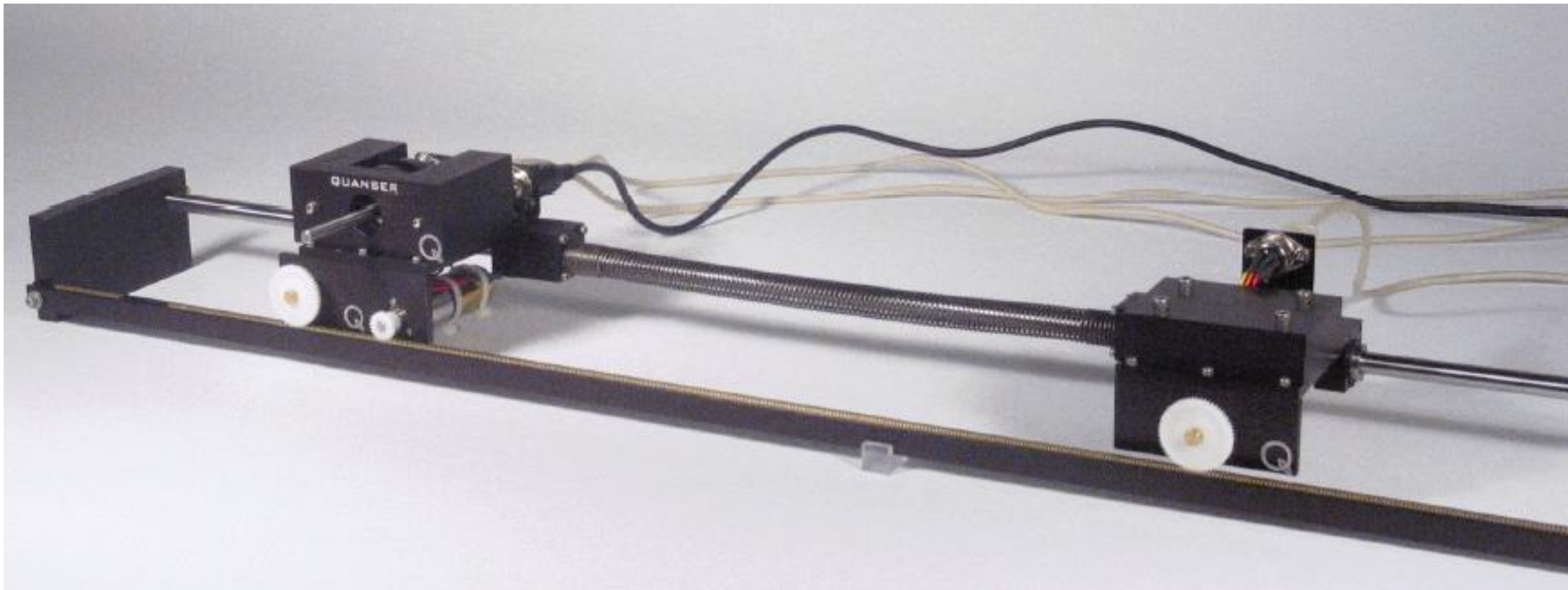
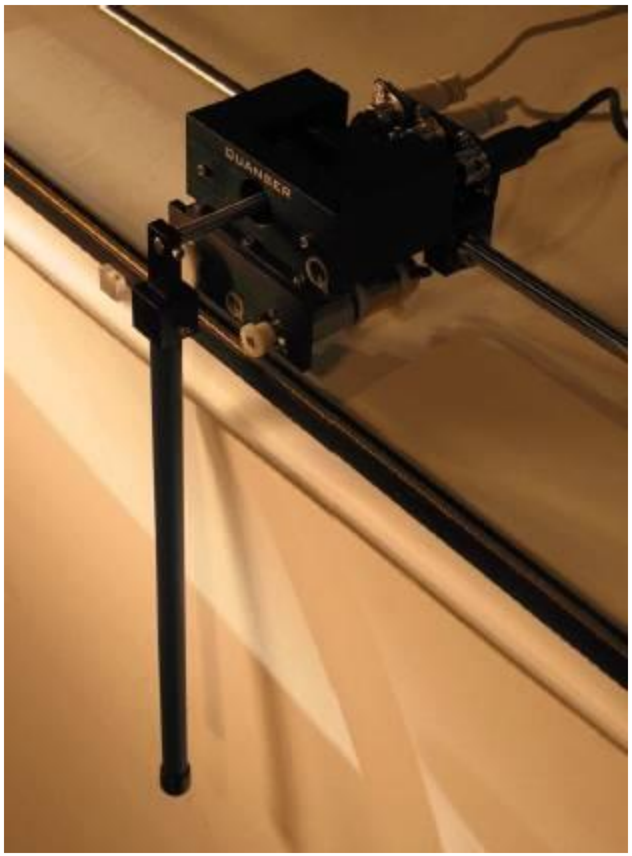
Linear pendulum - Quanser

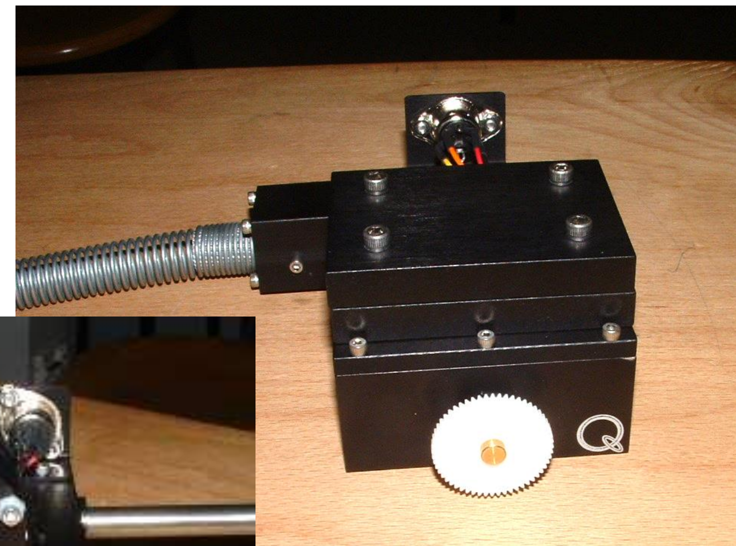


QUANSER
INNOVATE. EDUCATE.

System overview

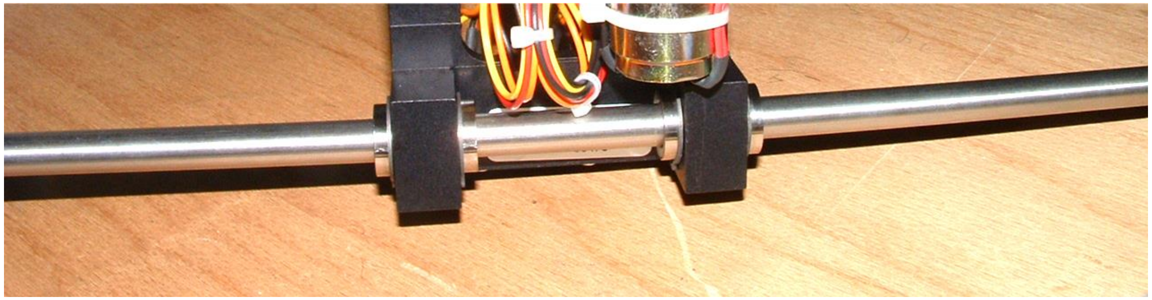
The system consists of two aluminium carts that can be connected through a linear spring.





System overview

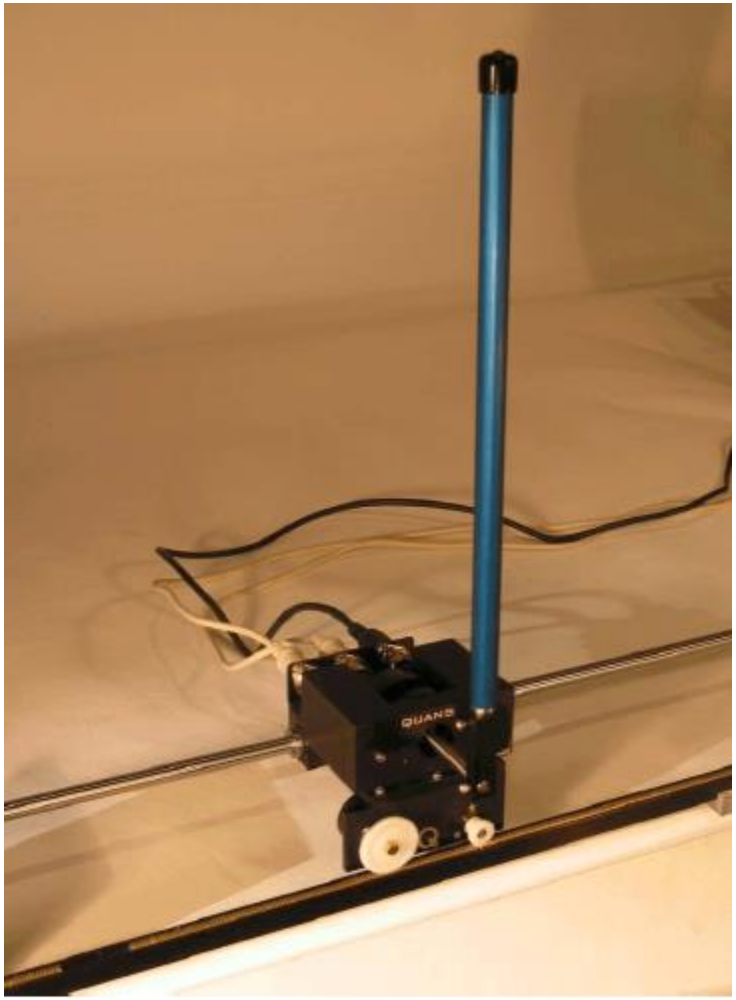
One cart is driven by a DC motor equipped with a planetary gearbox. The carts slide along a stainless steel shaft using linear bearings.



The motorised cart is driven via a rack and pinion mechanism.

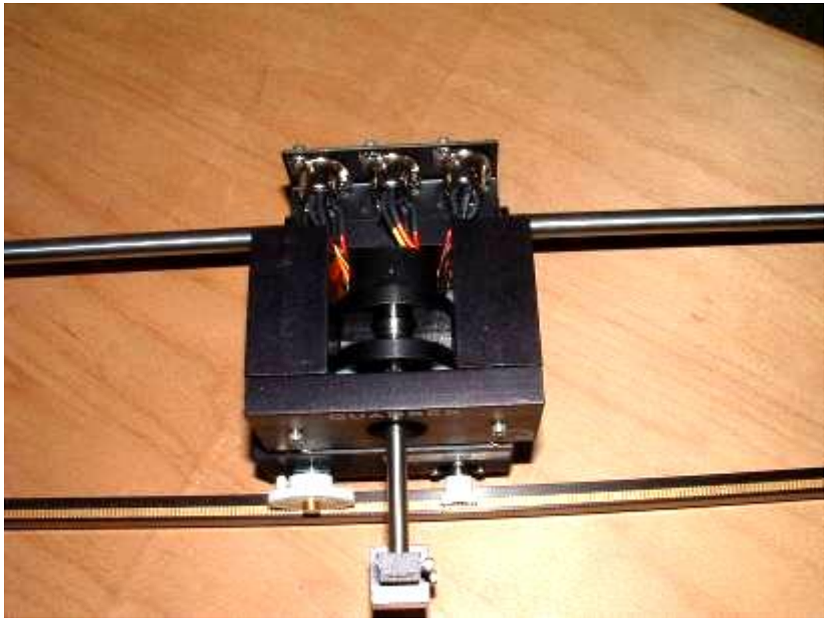
System overview

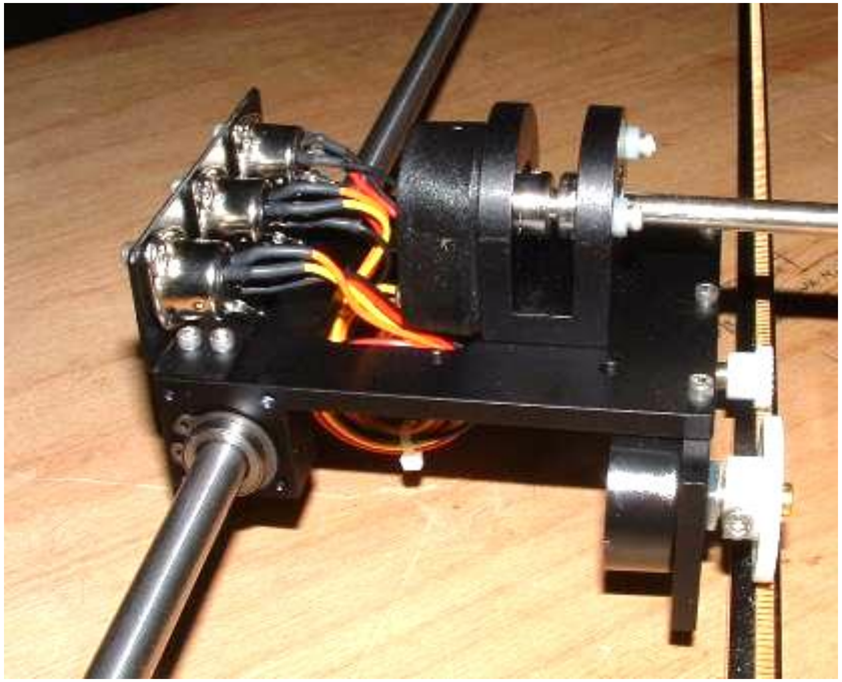
The motorised cart is equipped with a rotary joint having horizontal axis. Different pendula can be connected.



System overview

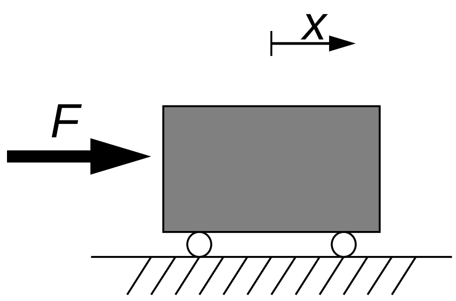
The system is equipped with encoders thus allowing the pendulum to perform multiple turns and is suited for self-erecting and gantry experiments. The cart positions are sensed via quadrature incremental encoders whose shafts mesh with the track via additional pinions.



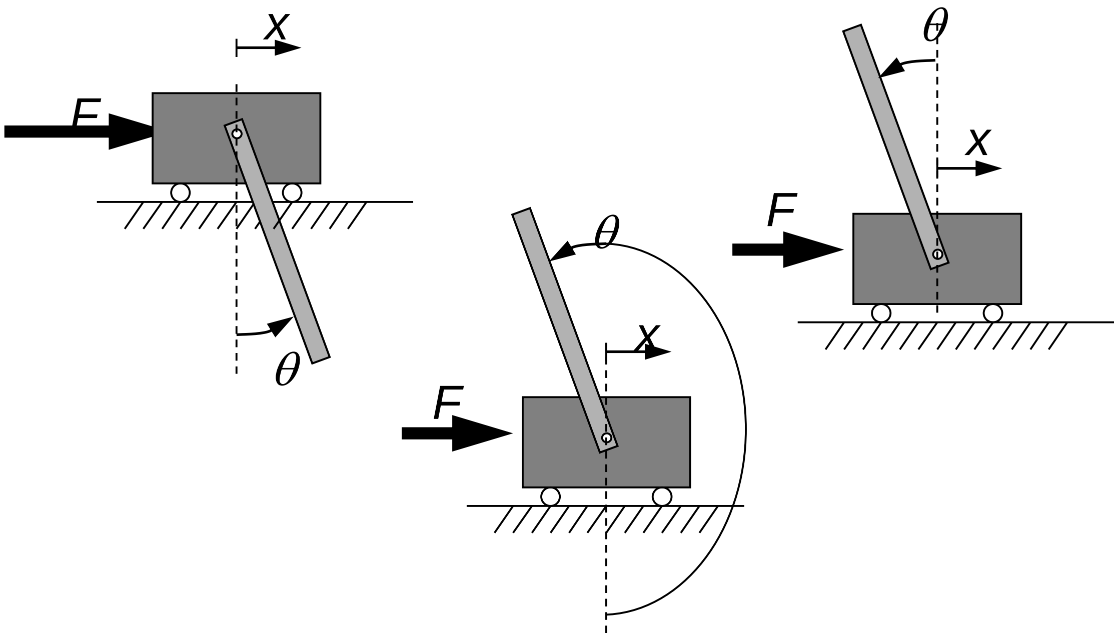


Subsystem

Linear pendulum



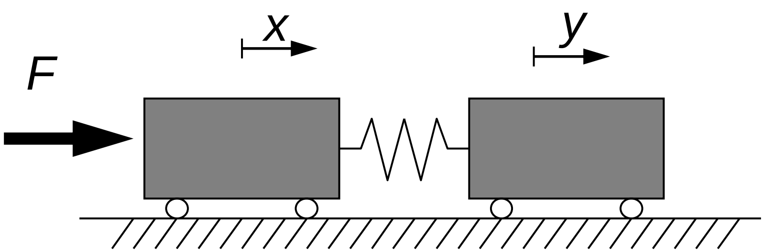
1 dof



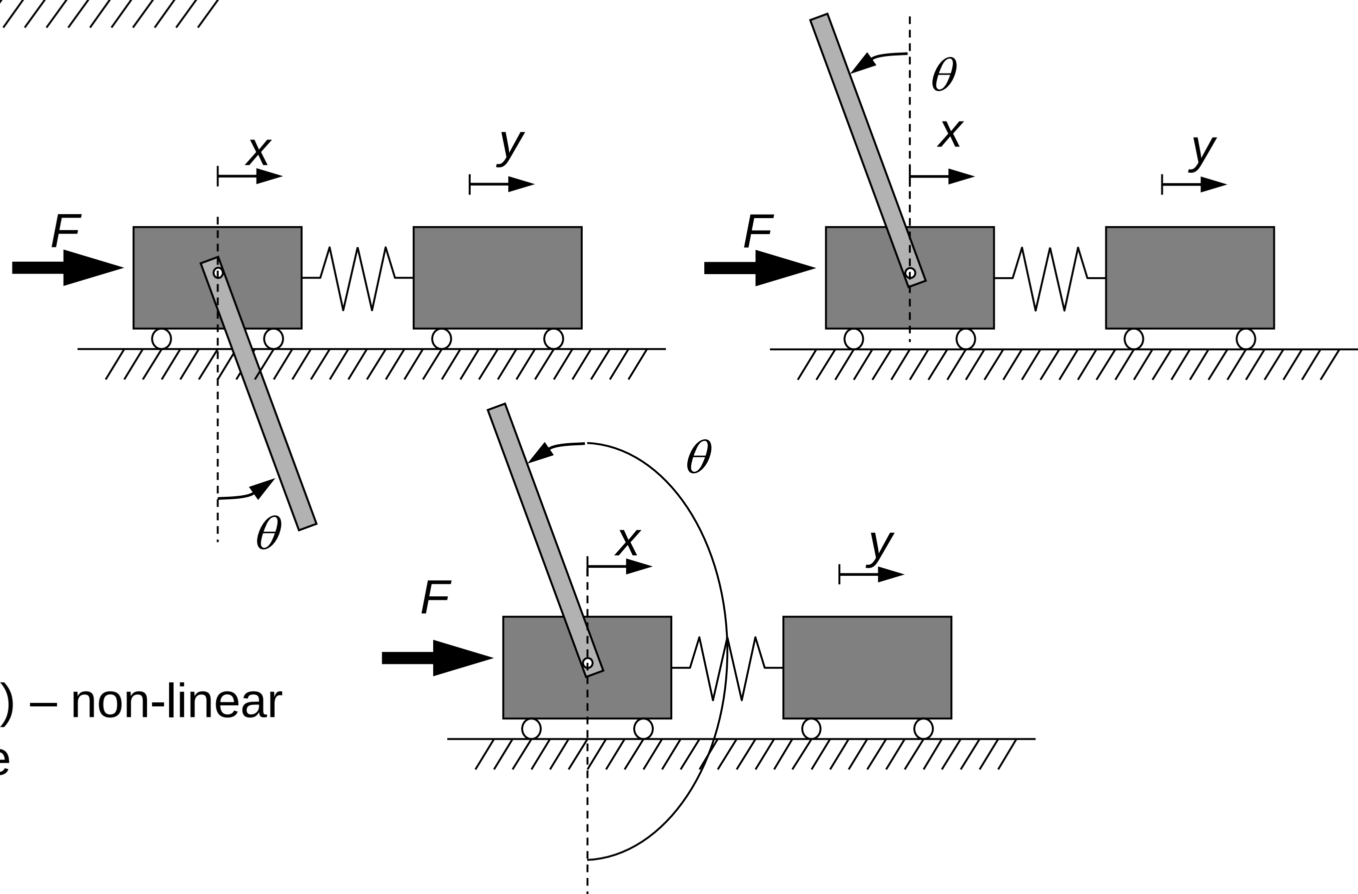
2 dof:

linear (linearised) – non-linear
stable – unstable

Subsystem
Linear pendulum



2 dof

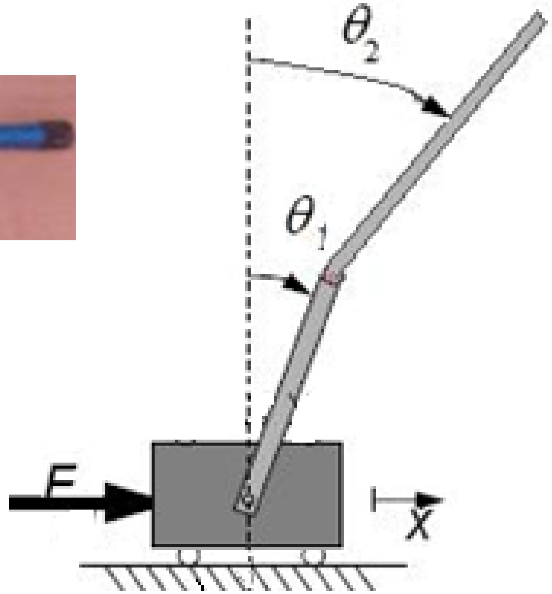


3 dof:

linear (linearised) – non-linear
stable – unstable

Subsystem
Linear pendulum

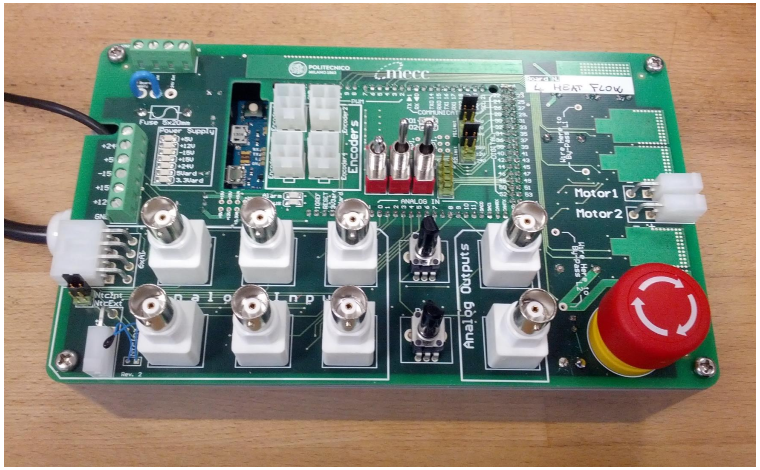
Double pendulum

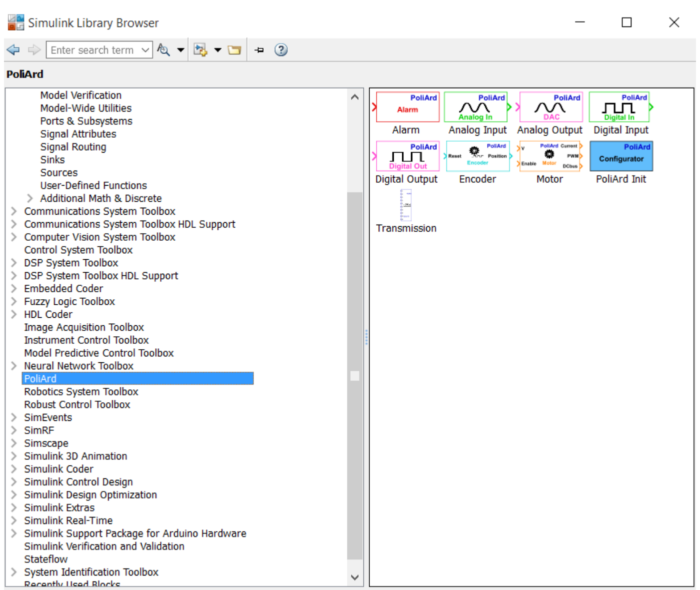


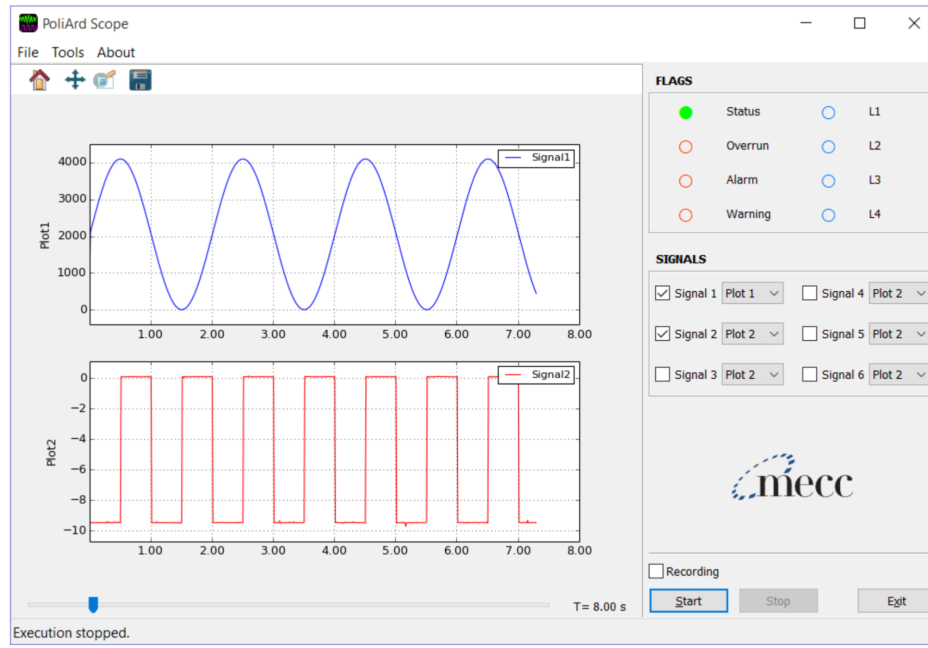
3 dof:

linear (linearised) – non-linear
stable – unstable

PoliArd board







Execution steps

Consider different system configurations (with increasing difficulty levels). Steps for each subsystem:

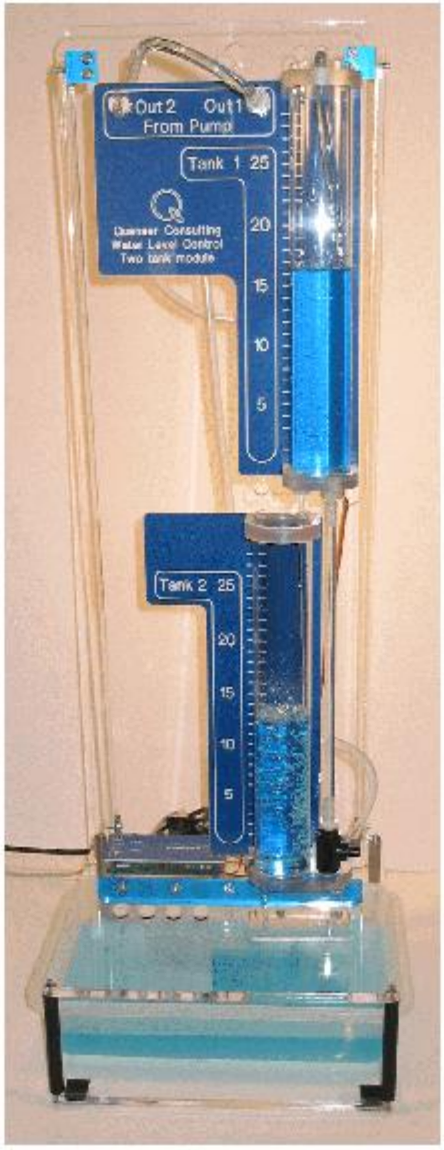
1. Development of models for simulation (time domain) and for control synthesis and calibration (Laplace domain)
2. Identification of unknown parameters of the model/s
3. Numerical implementation and verification of different control logics (classical control and modern control, if applicable)
4. Implementation of the control on the real system and comparison between numerical and experimental results (with possible optimisation of the control parameters for the real system)
5. Comparison of the performances of the different control logics/calibrations (robustness)

Automation and Control Laboratory

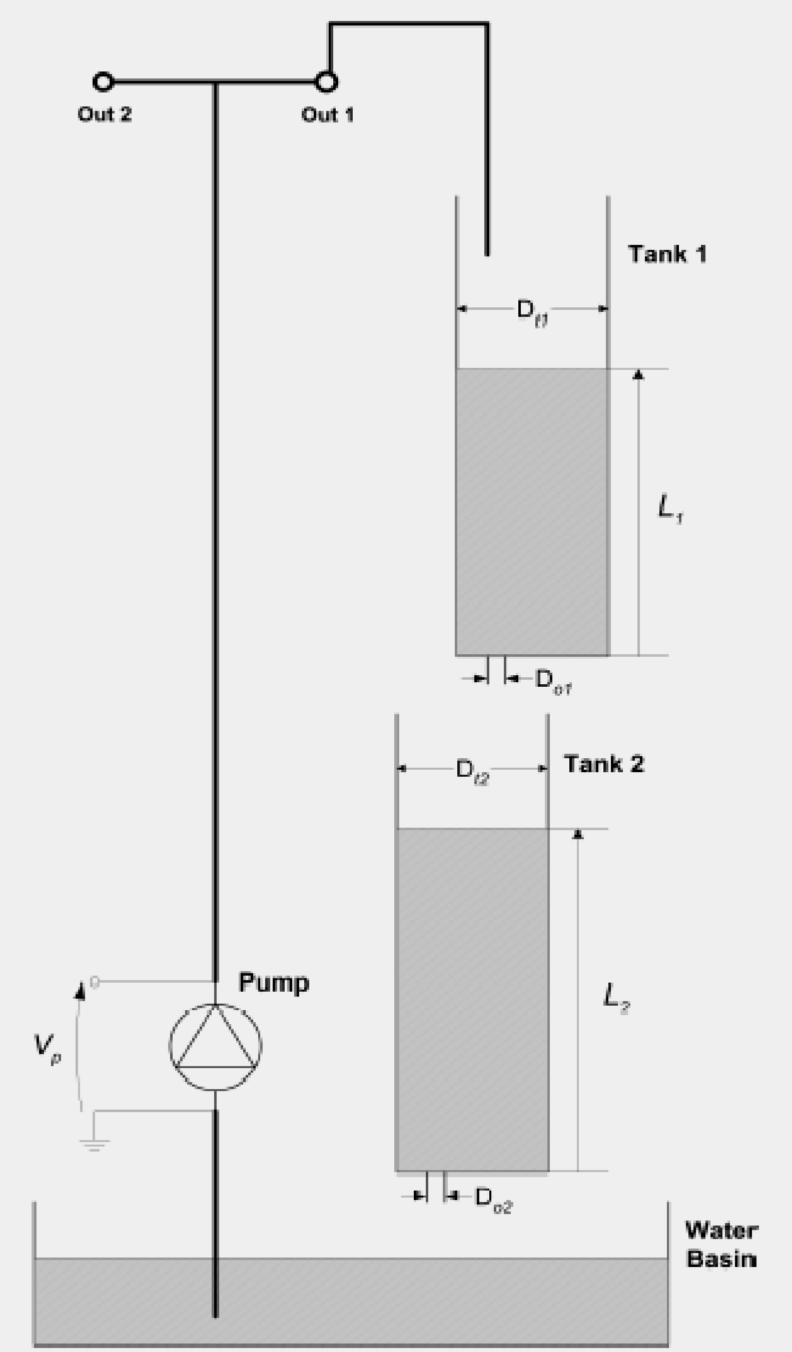
Available experiences:

11. Control of a multi-tank system
12. Control of a magnetic levitation system
13. Control of a flexible link
14. Heat-flow control

Multi-Tank



- Two-tank plant consisting of a pump with a water basin and two tanks of uniform cross sections.
- Both tanks can receive water flow from the pump.
- The flow from the upper tank flows into the lower tank through an orifice
- The flow from the second tank flows into the main reservoir.
- Pressure sensor at the bottom of the tank allow to measure the water level.
- Example of process control.



Scheme, definitions and configurations

$L_{1,2}$ water levels

$D_{T1,T2}$ tank diameters

$D_{O1,O2}$ orifice diameters

Vp pump supply voltage

- The pump flow is proportional to the DC motor speed that is related to the supply voltage.
- It is possible to configure the system so that the pump feeds only into tank 1 (SISO).
- In the second (complete) configuration the pump feeds into tank 1 which in turn feeds into tank 2 (SIMO).
- The third configuration envisage that the pump feeds directly into tank 1 and tank 2 using a split flow.

Possible configurations

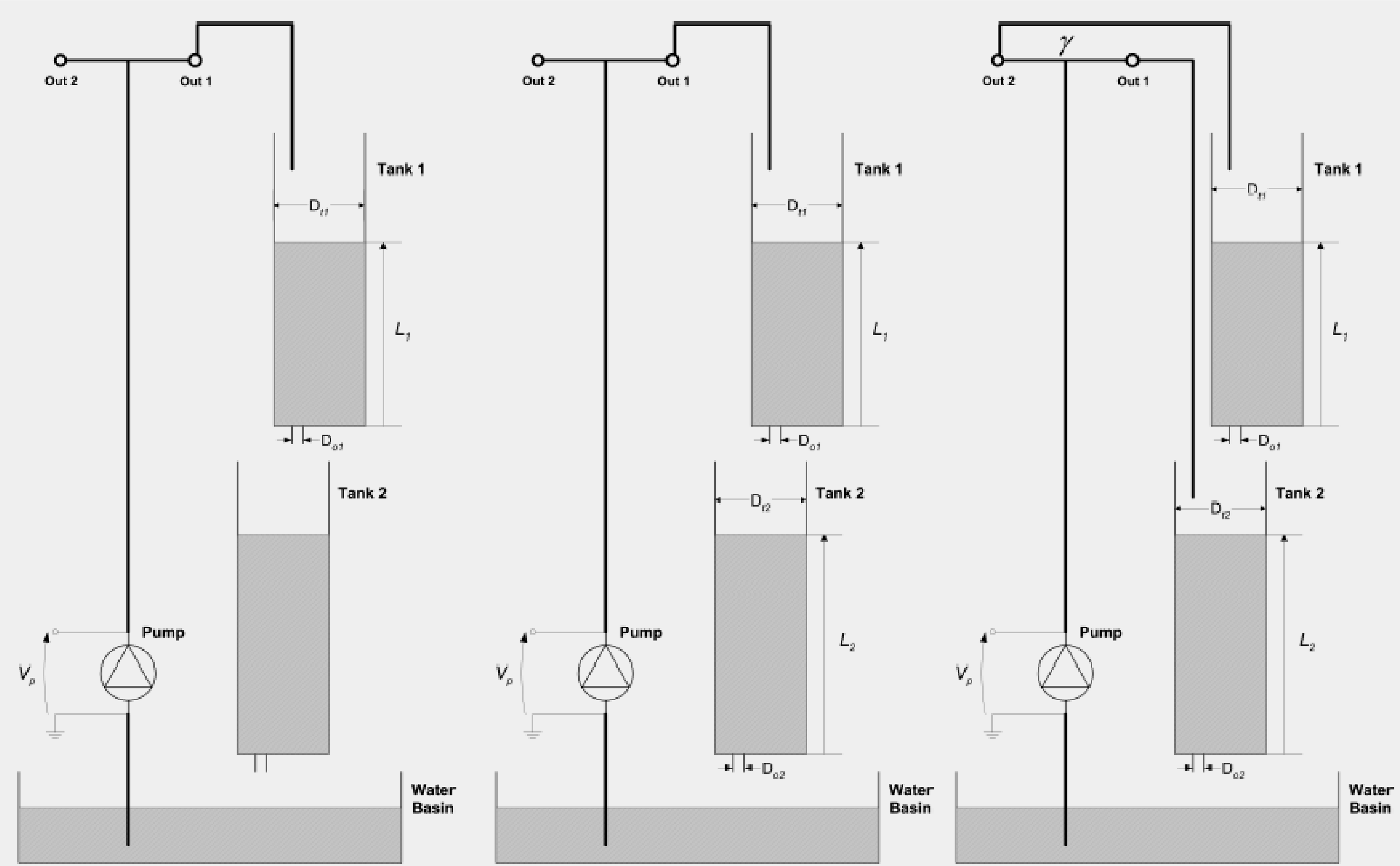


Figure 2 Configuration #1 Figure 3 Configuration #2 Figure 4 Configuration #3

Execution steps

* With configuration 1:

1. Modelling of the single tank (non-linear equations)
2. Linearisation and TF
3. Controllers' synthesis and verification with the non-linear model
4. Implementation on the real system and numerical-experimental comparison
5. Comparison of the different control logics/calibrations

* With configuration 2/3:

4. Modelling (non-linear) of the second tank
5. Different steps as for configuration 1

System modelling

$$\frac{\partial}{\partial t} L_1 = \mathrm{f}(L_1, V_p)$$

• The relationship between the water level variation, the level itself and the voltage applied to the pump has to be found.

$$F_{i1} = K_p \, V_p$$

• The inflow rate F_{i1} depends from supply voltage Vp proportionally (ideally, it could be necessary to identify the actual relationship)

$$v_{o1} = \sqrt{2} \, \sqrt{g \, L_1}$$

• The outflow speed from the tank can be evaluated throgh Bernoulli's equation for little orifices.

• The tank model can be obtained considering the mass balance principle (continuity equation)

• The model has to be linearised for control synthesis
• Non-linear model should be used for simulating the controlled system

Example of control structure for Tank1 Configuration #1

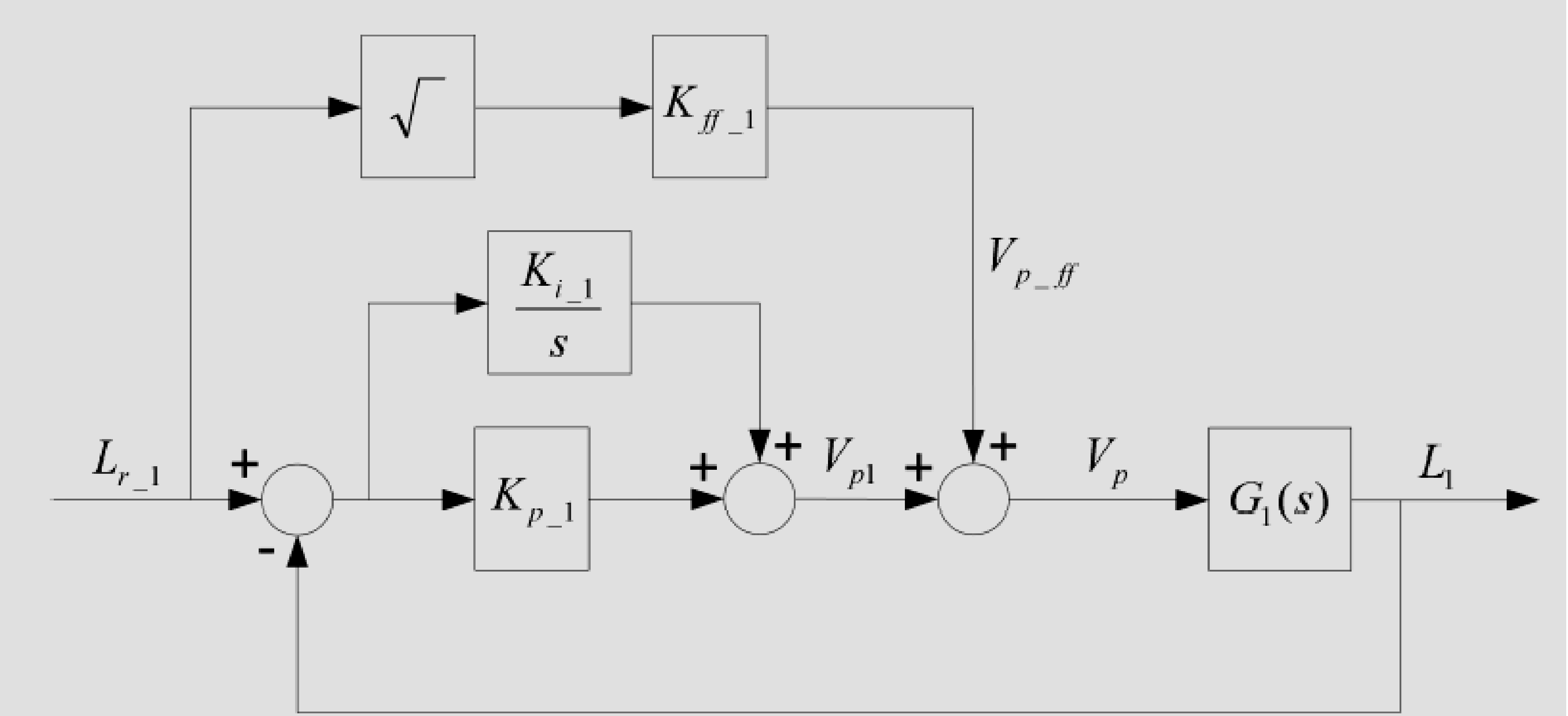


Figure 3 Tank 1 Water Level PI-plus-Feedforward Control Loop

Tank 1 control with PI and Feed-Forward action

Example of control structure for Tank2 Configuration #2

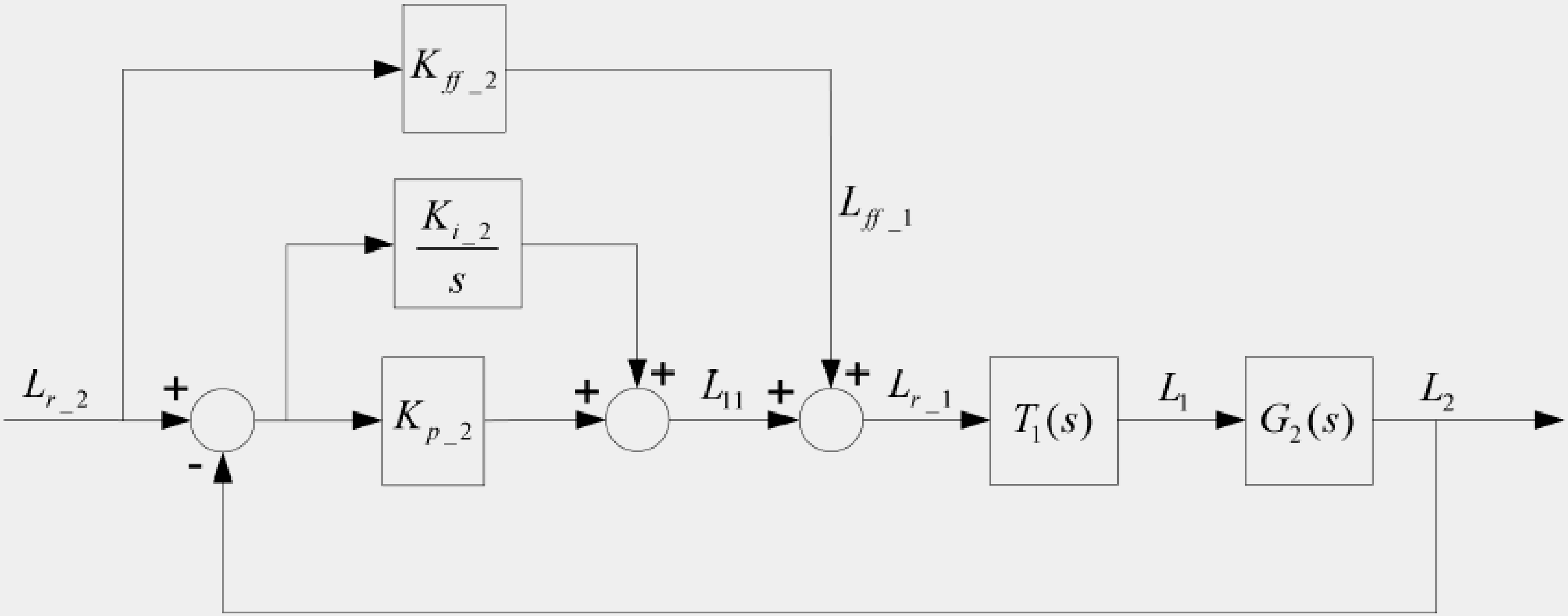
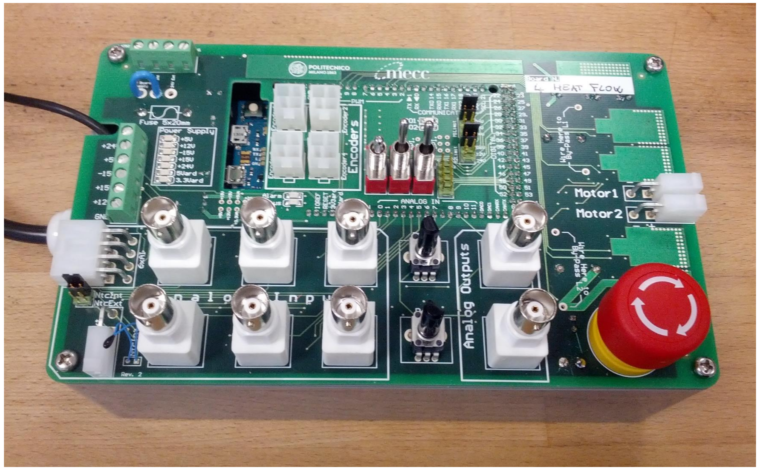
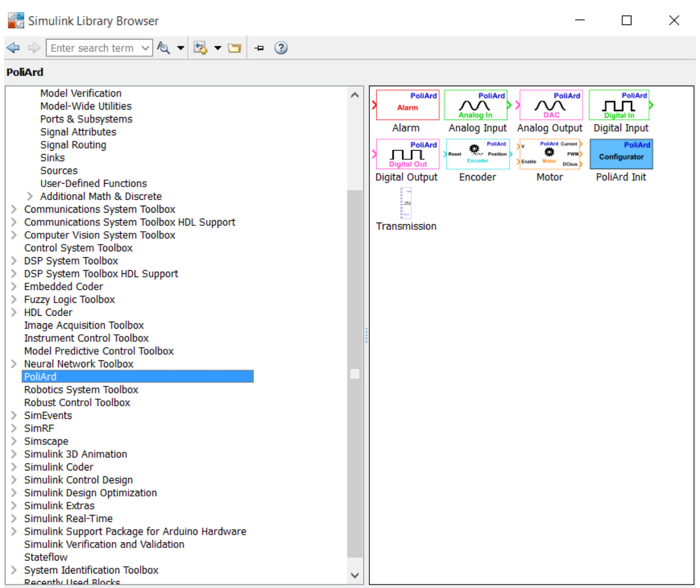


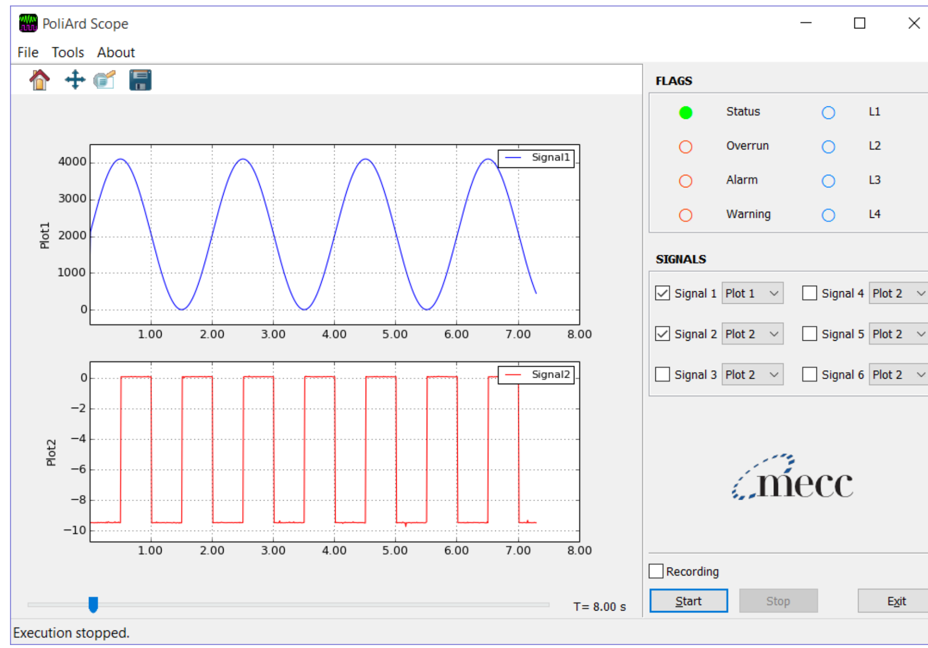
Figure 4 Tank 2 Water Level PI-plus-Feedforward Control Loop

- Tank 2 control with PI and Feed-Forward action
- $T_1(s)$ is the closed-loop TF for tank 1.
- Two nested loops.

PoliArd board







Automation and Control Laboratory

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MagLev - Quanser

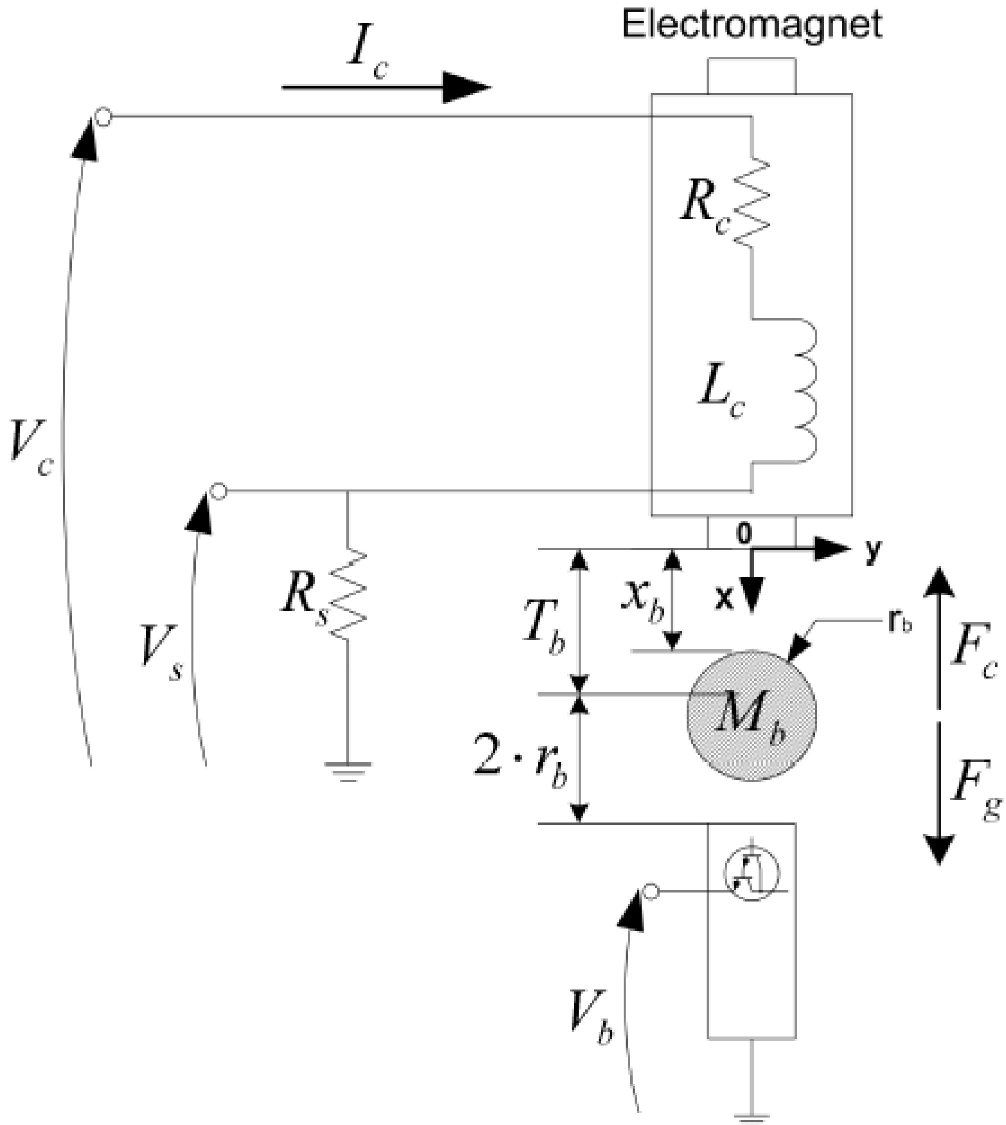
Figure 2 MAGLEV Plant: Front View
Figure 3 MAGLEV Plant: Back View

1) Overall enclosure
2) Solenoid coil
3) Coil steel core
4) Pedestal and positon sensor
5) Solid stainless steel ball
6) Interior lights
9) Coil connector
10) Position sensor connector
11) Current sensor connector
12) Inside chamber

Working principle

- The current passing through the electromagnet generate a magnetic field in the inside chamber
- The steel ball is attracted by the coil steel core
- The attraction force depends on the ball distance from the core and on the current
- The equilibrium position is reached when the magnetic attraction force is equal to the gravitational attraction force (note that the equilibrium positions of magnetic levitation system are inherently unstable in open loop)

System model



- Fc magnetic attraction force
- Fg gravitational force
- Vc output voltage
- Ic coil current
- Rc coil resistance
- Lc coil inductance
- xb ball distance from the core

System modelling

$$G_c(s) = \frac{I_c(s)}{V_c(s)}$$

The first step consists in the identification of the transfer function Between the applied voltage and the output current

This tranfer function can be obtained from the KLV applied to the electrical system

$$V_c(t) = (R_c + R_s)\, I_c(t) + L_c \left(\frac{d}{dt} I_c(t) \right)$$

Considering the mechanical part, the forces acting on the ball has to be considered

$$F_g = M_b\, g$$

Gravitational force

Magnetic force

$$F_c = -\frac{1}{2} \frac{K_m\, I_c^2}{x_b^2}$$

System modelling

$$F_c + F_g = -\frac{1}{2}\frac{K_m I_c^2}{x_b^2} + M_b g$$

Static equilibrium

Considering the dynamic equilibrium, by adding the $M_b\ddot{x}_b$ term corresponding to the inertial action, and simplifing the ball mass M_b , the following non-linear equation can be obtained:

$$\frac{\partial^2}{\partial t^2} x_b = -\frac{1}{2}\frac{K_m I_c^2}{M_b x_b^2} + g$$

This equation should be linearised for evaluating the transfer function between the current Ic(s) and the ball position Xb(s).

Current control

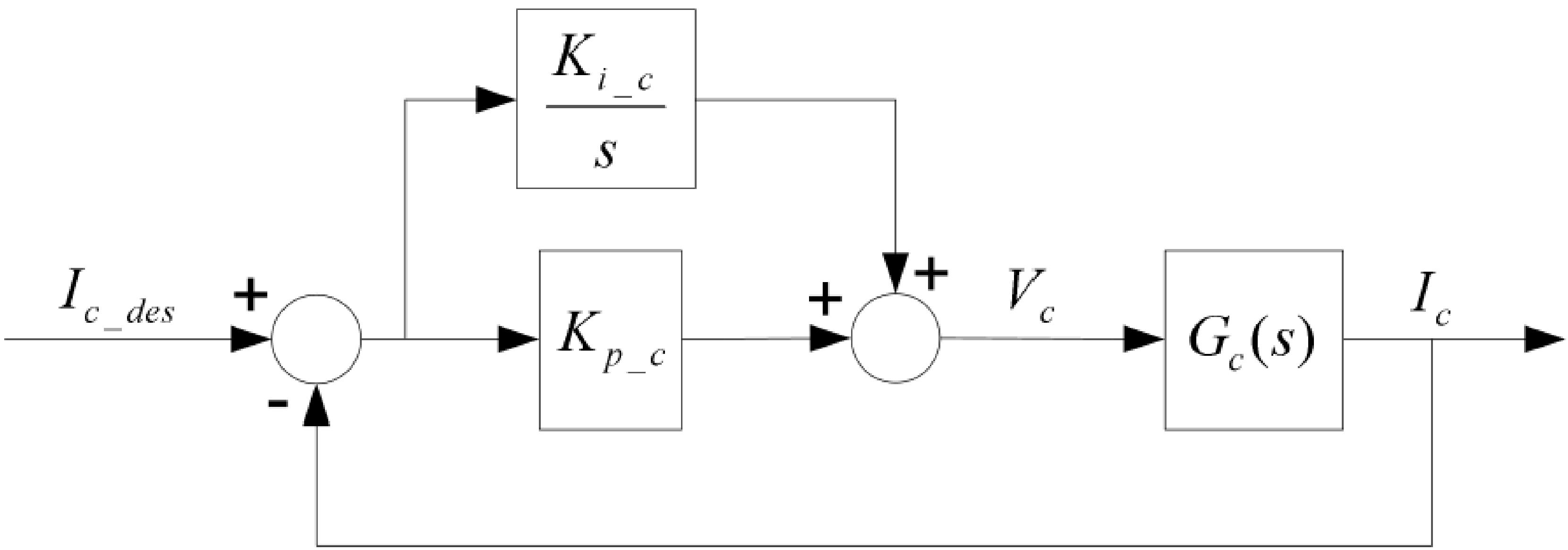


Figure 3 PI Current Control Loop

For the current control a PI regulator can be used, e.g. using classical control criteria or pole placement method.

Example of position control

- Gm(s) accounts for the closed loop function for current regulation
- Example of the control complete structure PI –V with additional feed-forward action
- Alternatives: pole placement, optimal control, ….

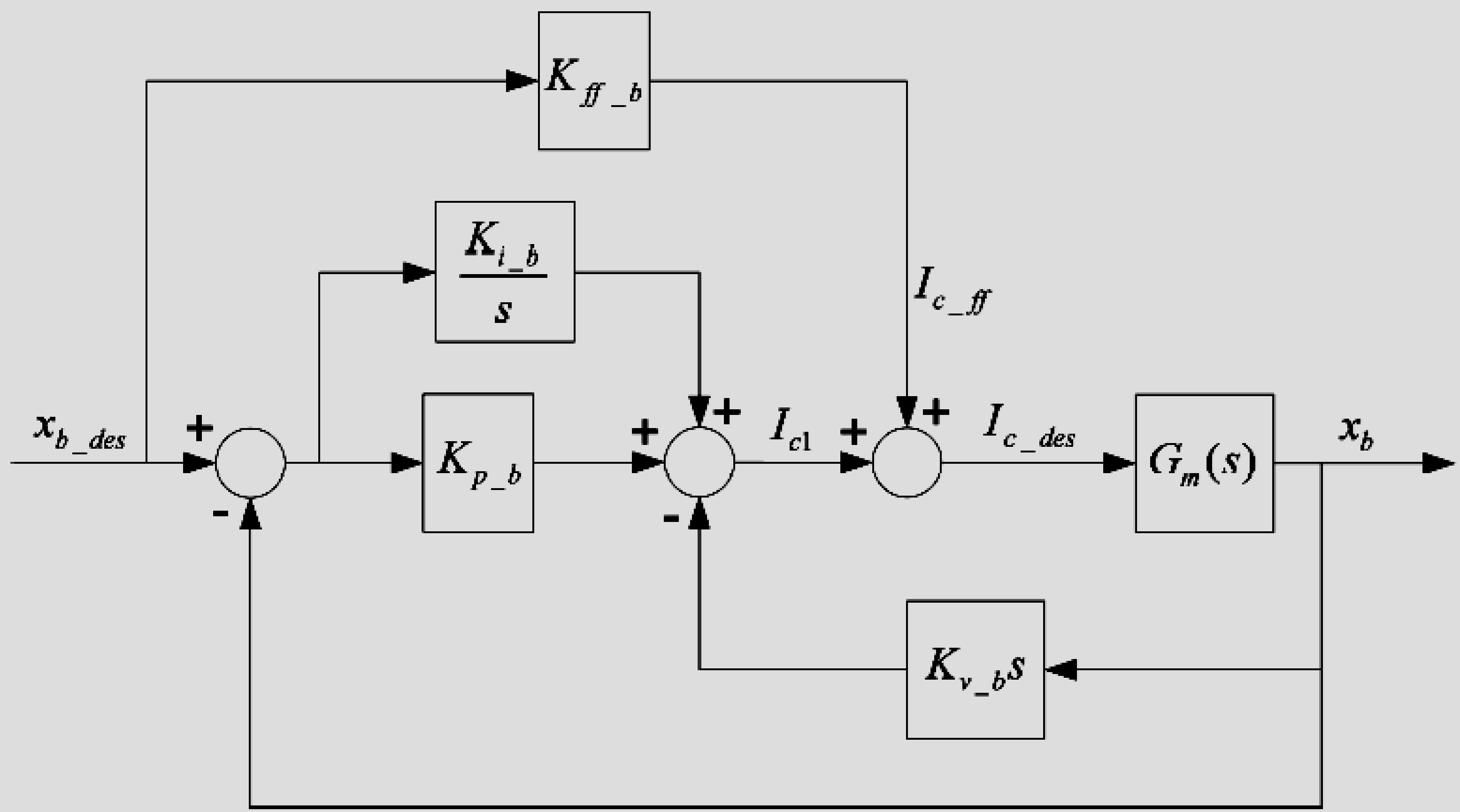
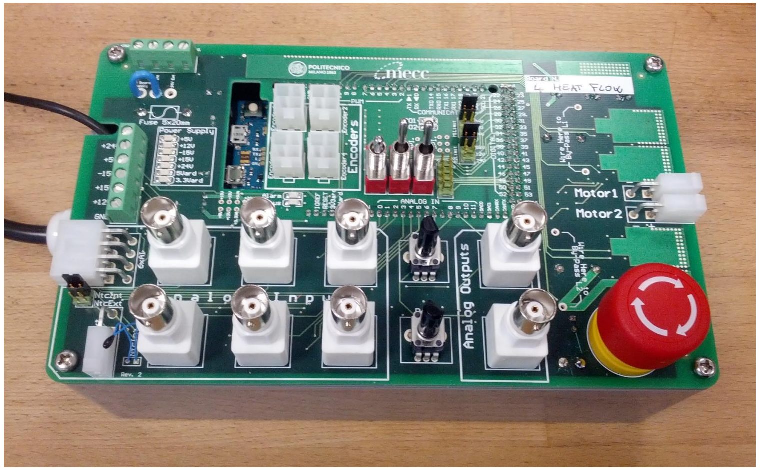
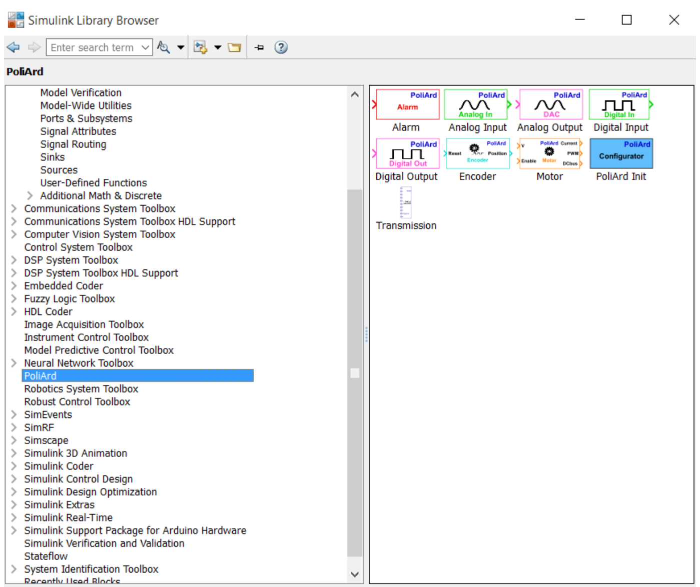
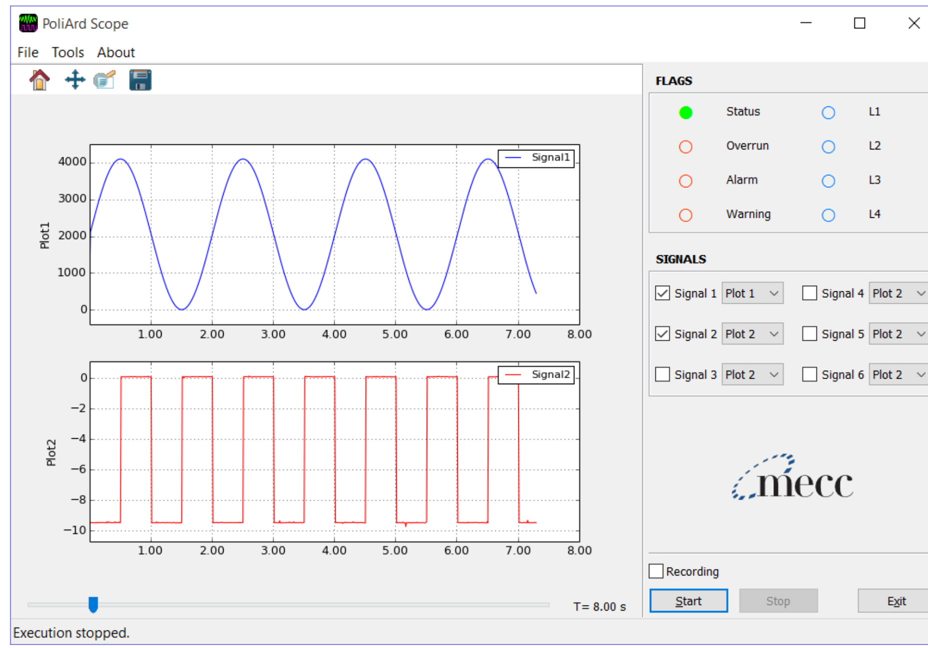


Figure 4 Ball Position PIV-plus-Feedforward Control Loop

PoliArd board







Maglev: execution steps

- Modelling and linearisation of the system.
- Numerical simulation.
- Current loop synthesis.
- Position-loop synthesis.
- …other kind of controllers
- Verification of the numerical model through comparison with experimental data.
- Experimental analysis of the different control schemes (static positioning, imposed motion,…).
- Results' analysis and comparison.

Automation and Control Laboratory

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Flexible link– Quanser

QUANSER
INNOVATE. EDUCATE.

Overview

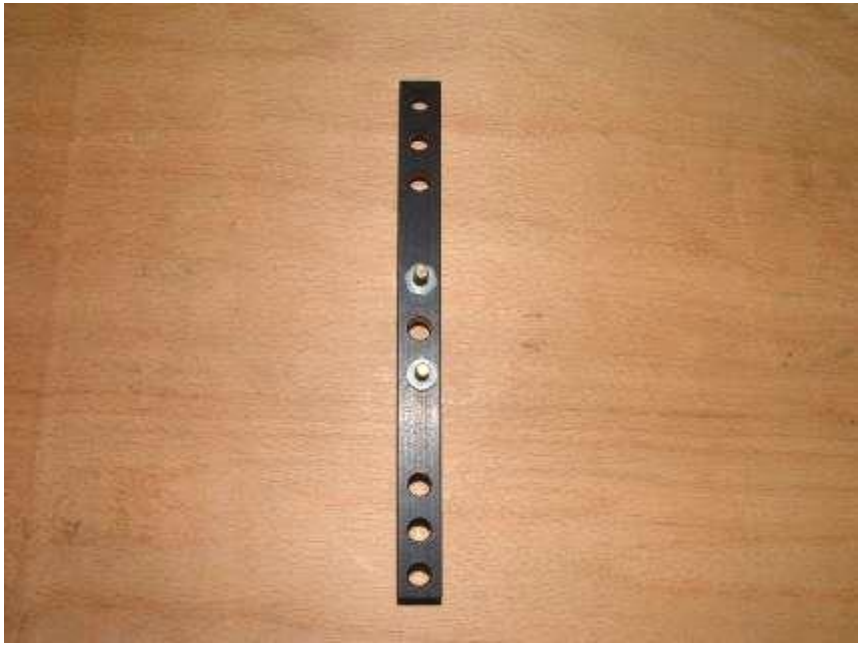
The system consists of a basic unit that can be equipped with different modula, simulating joint flexibility (ROTFLEX), link flexibility (FLEXGAGE) and a rotary pendulum (ROTPEN).

Subsystem 1 overview

The system consists of a DC motor in a solid aluminum frame. The motor is equipped with a gearbox. The gearbox output drives external gears. The basic unit is equipped with a an encoder to measure the output/load angular position.

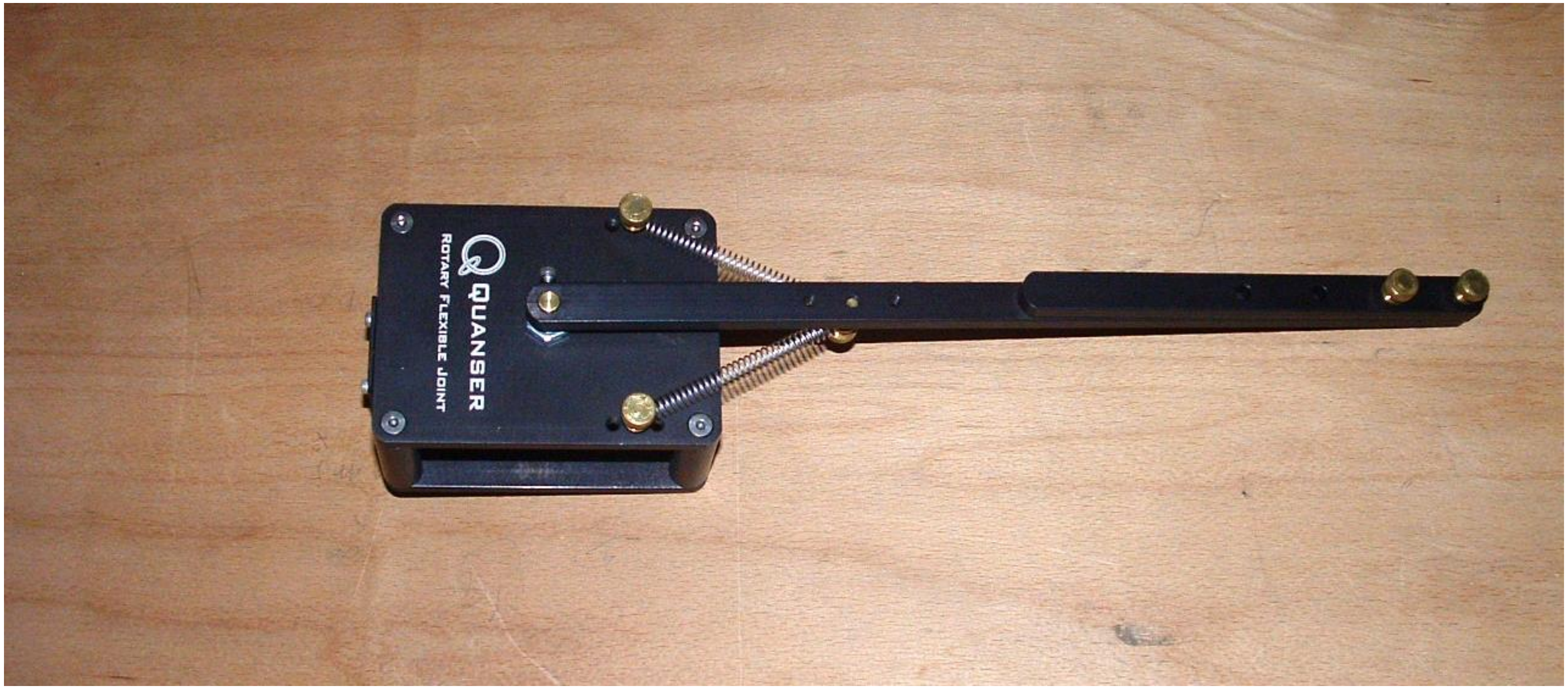
Subsystem 1 overview

It is possible to connect different mechanical loads to the central shaft.

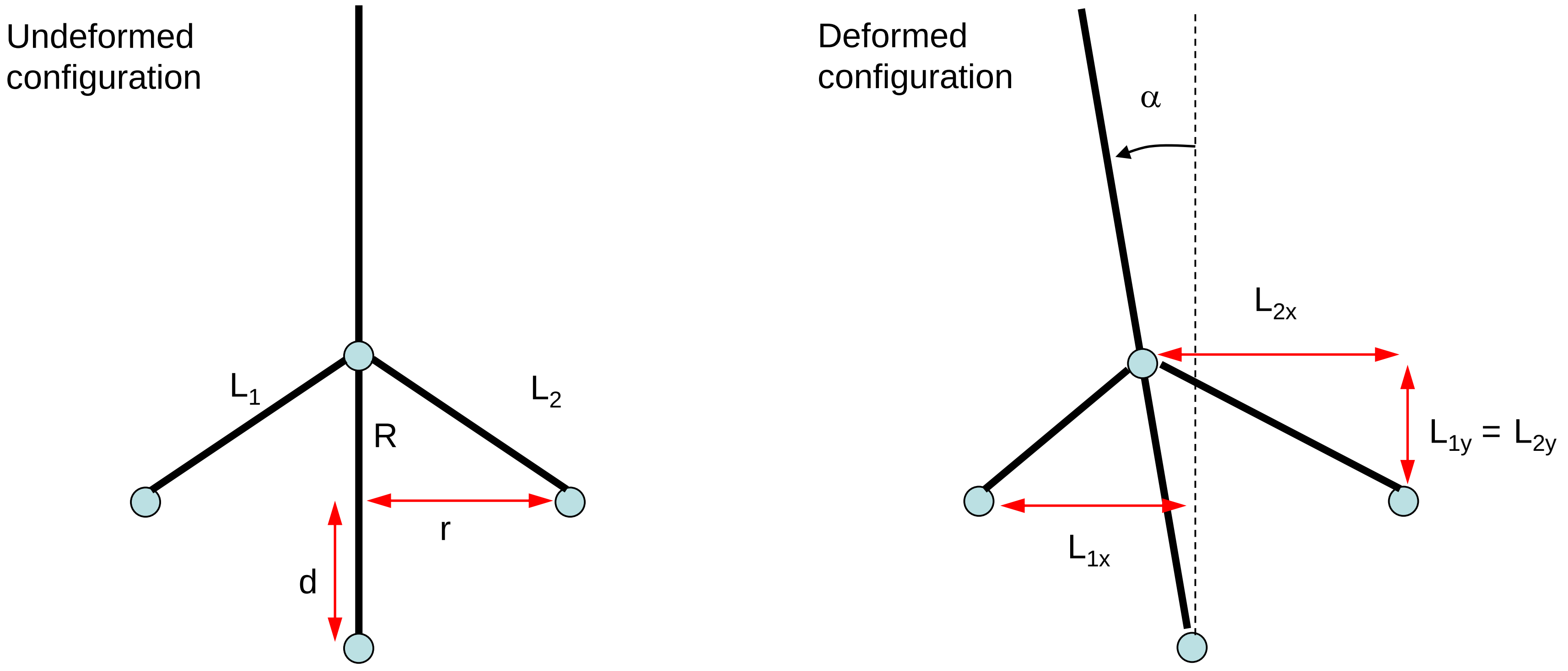


Subsystem 2 overview

The rotary flexible joint consists of a rotary sensor mounted in a solid aluminum frame and is designed to mount to a Quanser rotary plant. The sensor shaft is aligned with the motor shaft. One end of a rigid link is mounted to the sensor shaft. The link rotation is counteracted by two extension springs anchored to the solid frame resulting in an instrumented flexible joint. The spring anchor points are adjustable to three locations to obtain various stiffness constants.

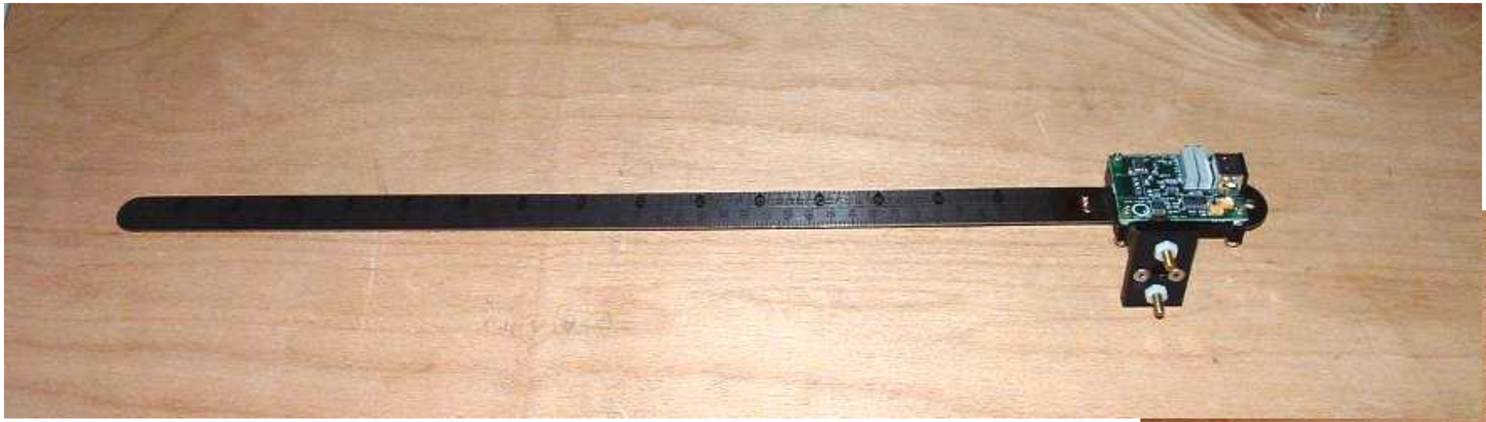


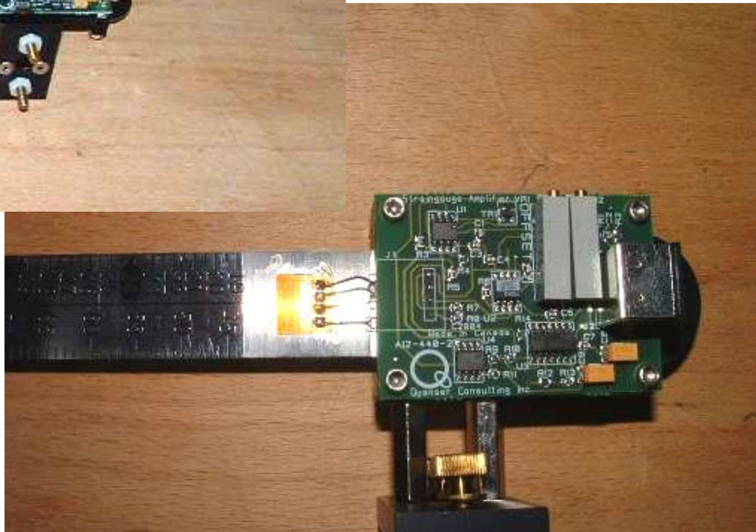
Subsystem 2 overview



Subsystem 3 overview

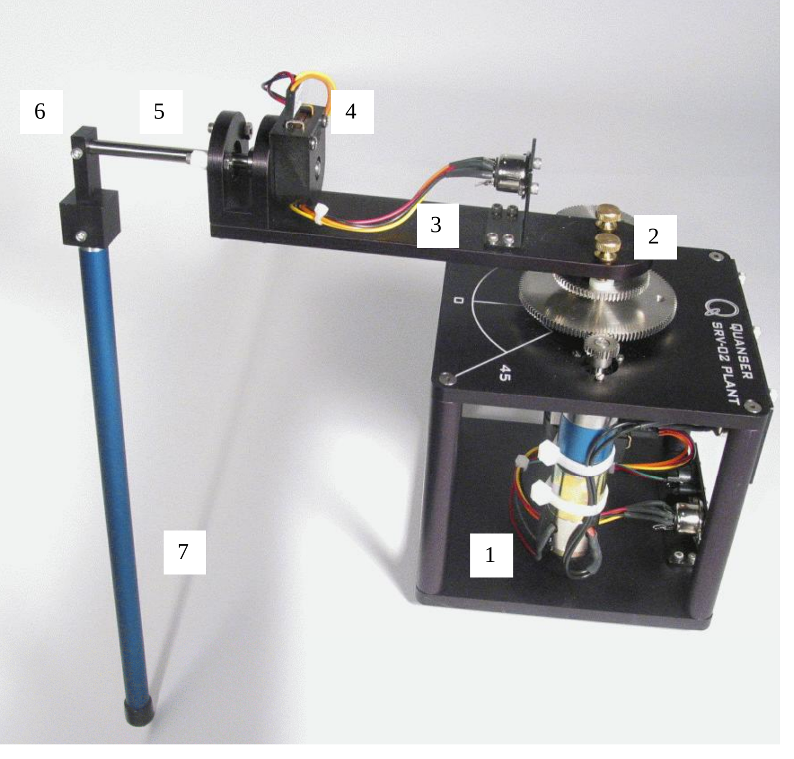
The rotary flexible link consists of a thin stainless steel flexible link with a strain gage mounted at the clamped end. The output is an analog signal proportional to the deflection of the link. The system is designed to mount on a Quanser rotary plant resulting in a horizontally rotating flexible link to perform flexible link control experiments.





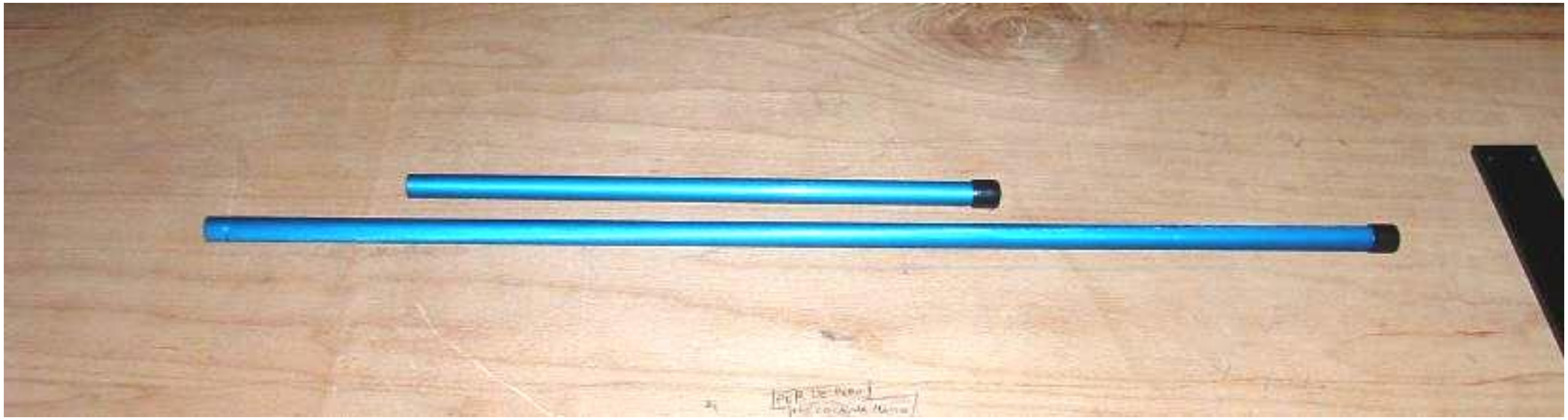
Subsystem 4 overview

The rotary pendulum module consists of a flat arm which is instrumented with a sensor at one end such that the sensor shaft is aligned with the longitudinal axis of the arm. A fixture is supplied to attach the pendulum to the sensor shaft. The opposite end of the arm is designed to mount to a Quanser rotary plant resulting in a horizontally rotating arm with a pendulum at the end.

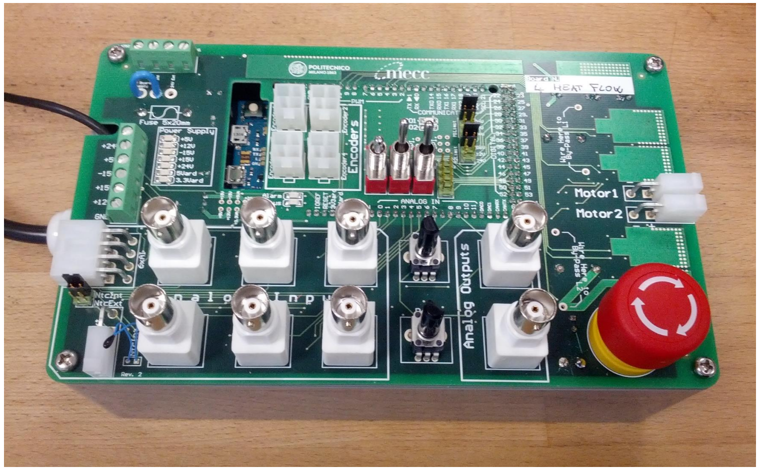


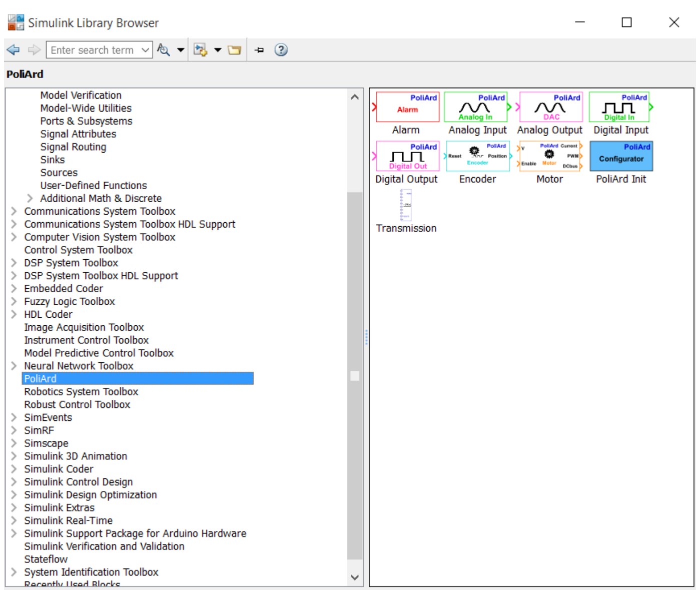
Subsystem 4 overview

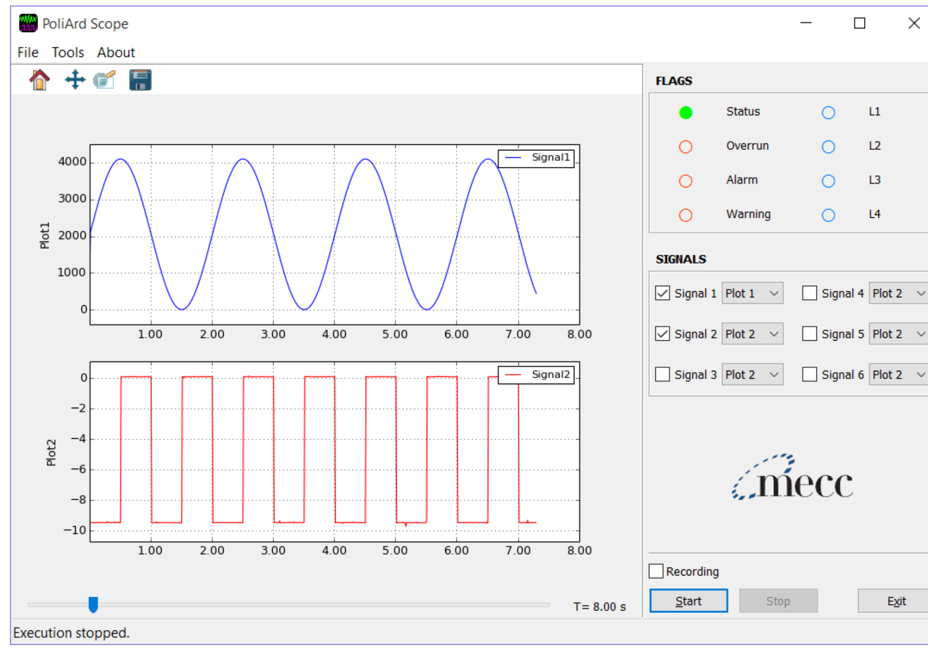
Different pendulum lengths are available.



PoliArd board







Execution steps

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Automation and Control Laboratory

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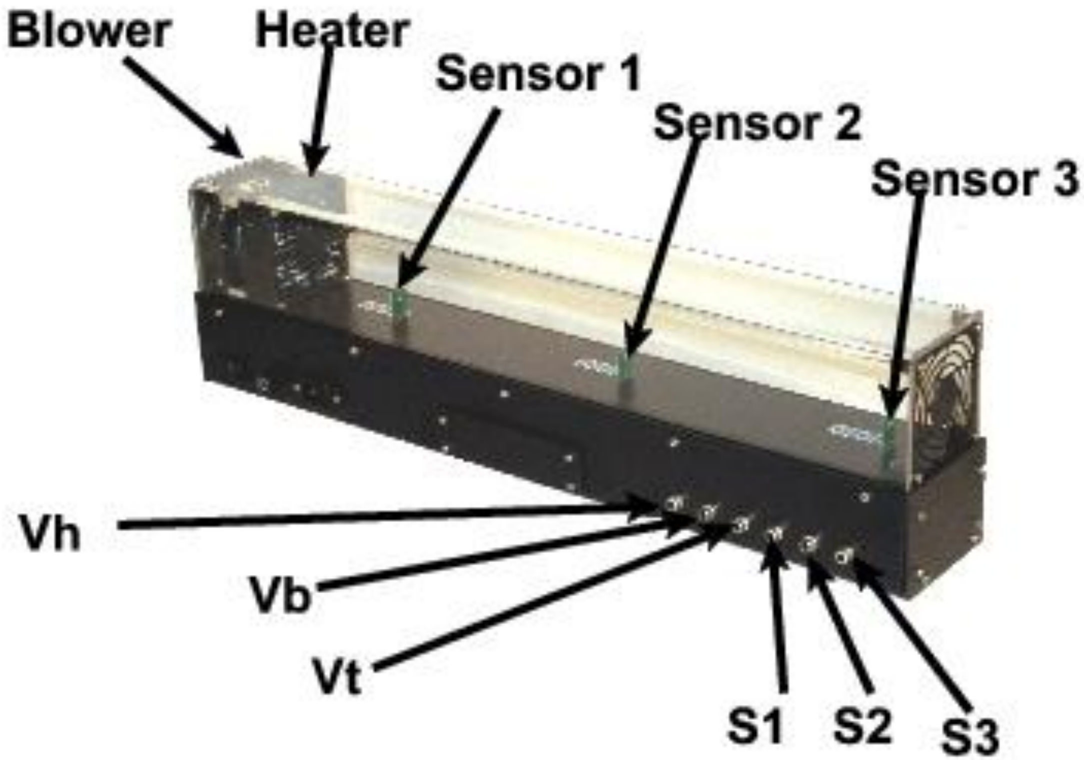
Heat Flow Control



Il system consists in a duct equipped with a Heater and a Blower at one end and three Temperature sensors located along the duct.
The power delivered to the heater and the fan speed are controlled using an analog signals Vh and Vb. Vt, S1, S2 and S3 are the analog signals corresponding to the measured fan speed and temperatures.

Development of the system model

Different options:

- Writing of a complete thermo-dynamical model and parameters' identification/evaluation (complex, but useful to get information on suitable models to be used/identified)
- Identification of an equivalent first order system (<u>from step response</u>)
- <u>Analyses of the frequency response function</u> and identification of the model from the system response.

- Auto-calibration methods.

Identification from step response

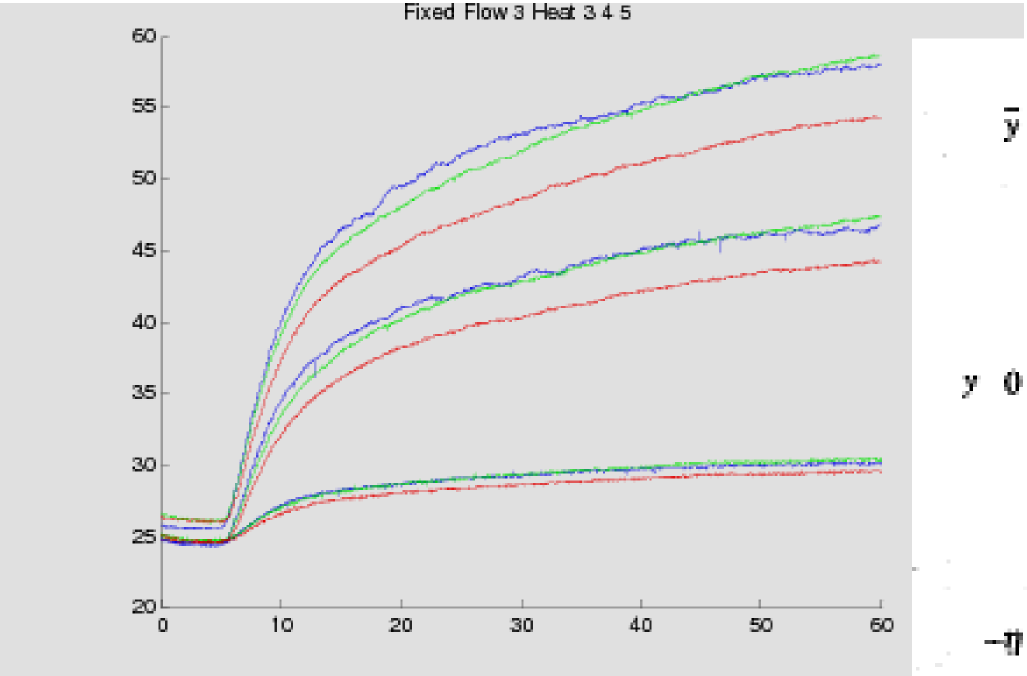
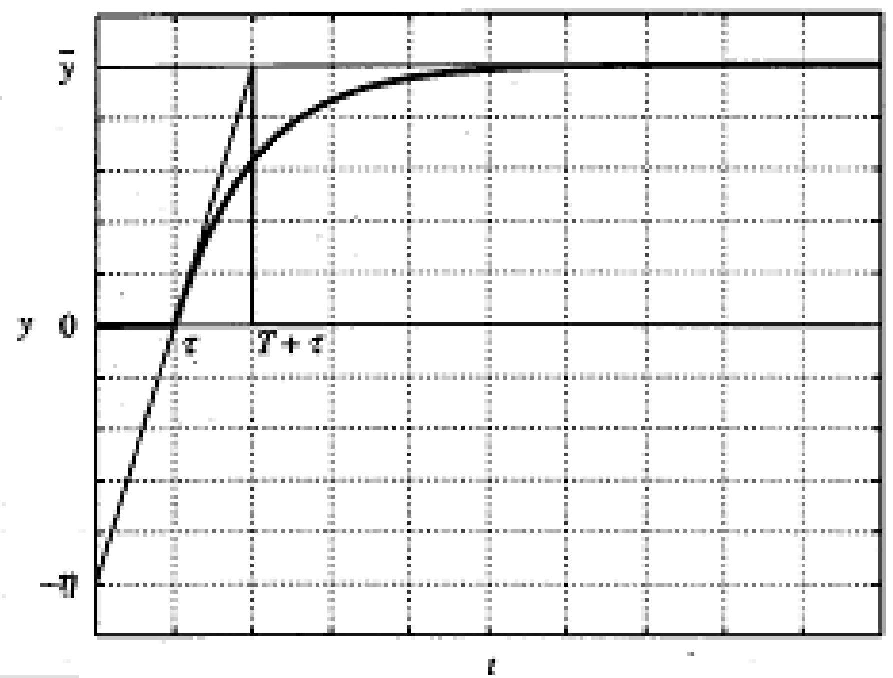


Figure 3 Step responses at the three sensors for VQ = 3 4 &5 and a fixed flow rate voltage volts.



• From step responses in different operating conditions (e.g. different heater powers), different first order TFs can be obtained (e.g. between the single temperature and the fan voltage):

$$\frac{T_i}{V_Q}\Big| = \frac{G}{\tau_n s+1}$$

Control with first order model (e.g. with PI regulator)

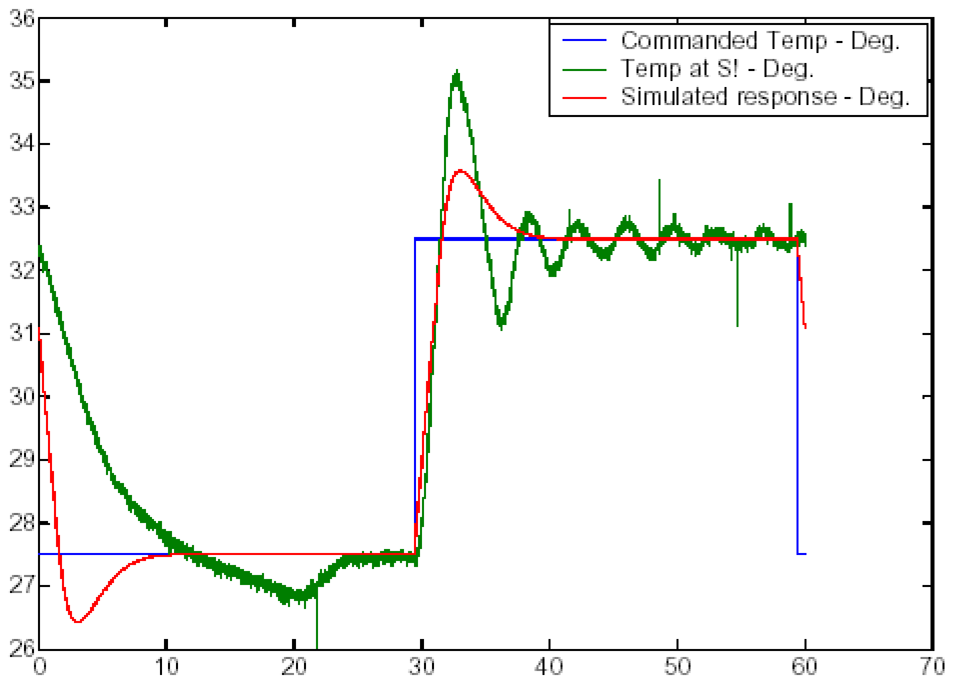
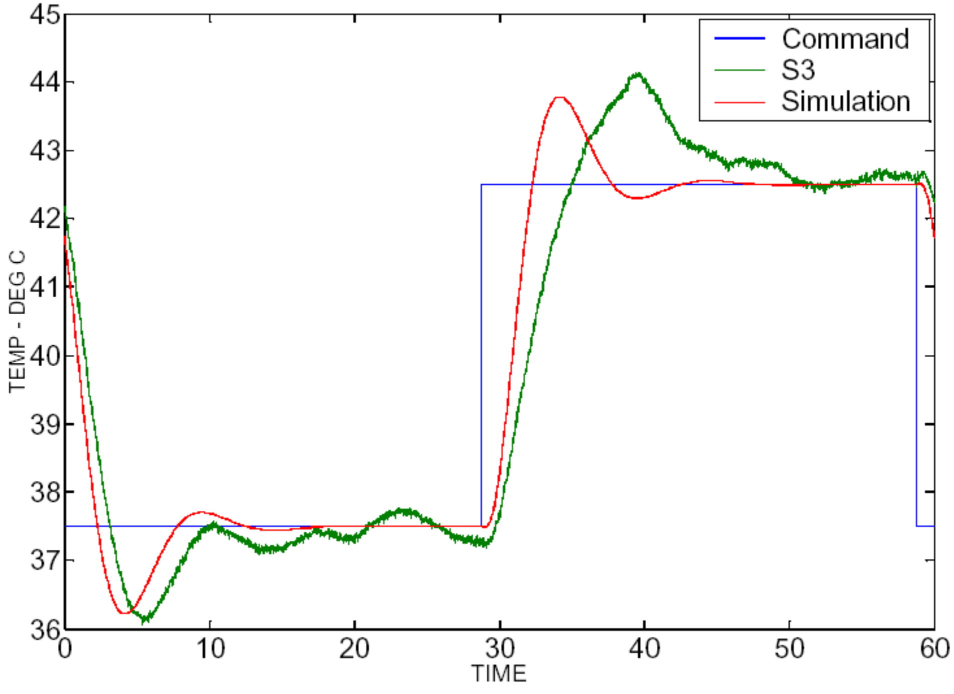


Figure 5 Square wave input response at sensor S1. Red trace shows simulated response of first order model.

The first order approximation may lead to significant differences with respect to the actual behaviour of the system.

Identification trough FRF analysis

- The identification is carried out through frequency analysis (e.g. forcing the system with random or sweep-sine signals)
- Control synthesis based on the new TF

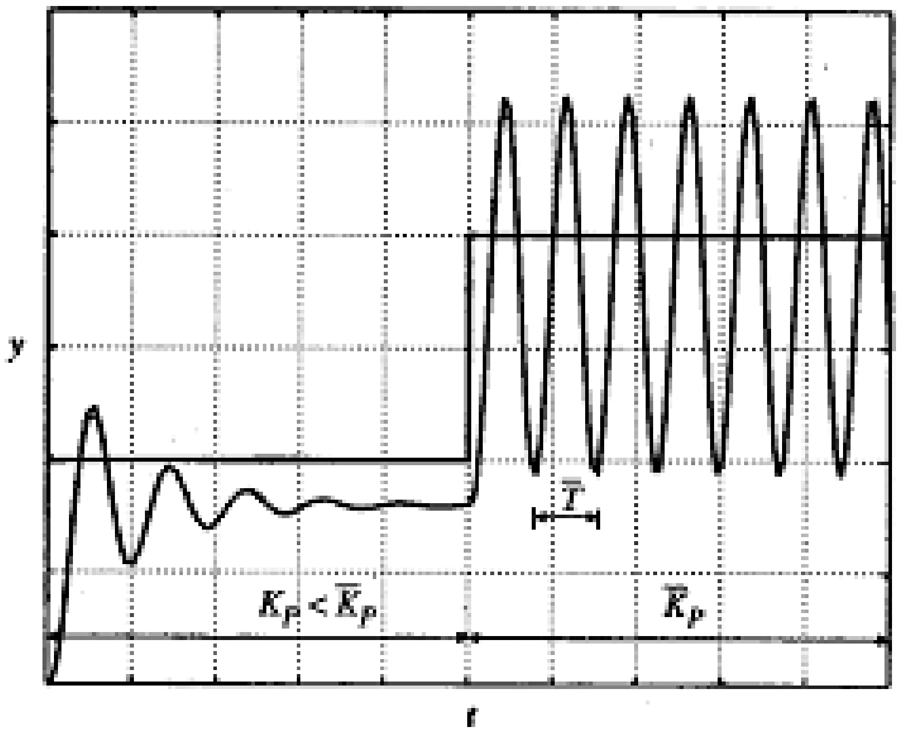


Auto-calibration

- Different available methods, e.g.:
  - Closed-loop Ziegler Nichols method;
  - Open-loop Ziegler Nichols method;
  - Relè method based on closed-loop Ziegler Nichols.

The procedure should be automatic (i.e. automatically performed by the system when switched on)

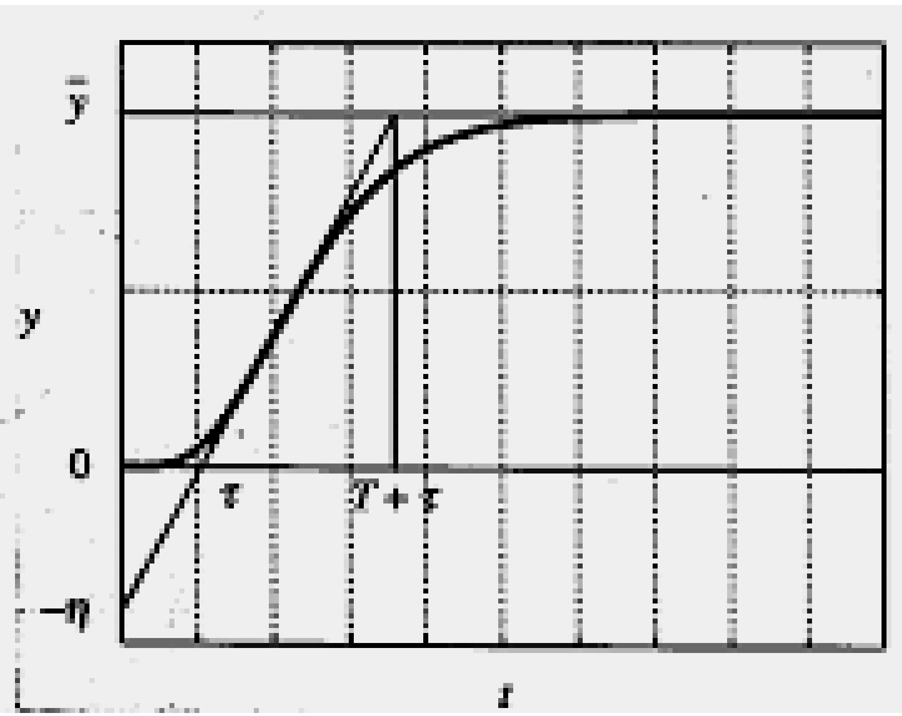
Closed-loop Ziegler Nichols method



- Closed-loop with a proportional regulator with increasing gain, untill stability limit is reached (permanent oscillations)
- The loop/s are then calibrated on the basis of tabulated values (depending on the K_P gain corresponding to the stability limit)

	K_P	T_I	T_D
P	$0.5\,\bar{K}_P$		
PI	$0.45\bar{K}_P$	$0.8\bar{T}$	
PID	$0.6\bar{K}_P$	$0.5\bar{T}$	$0.125\bar{T}$

Open-loop Ziegler Nichols method

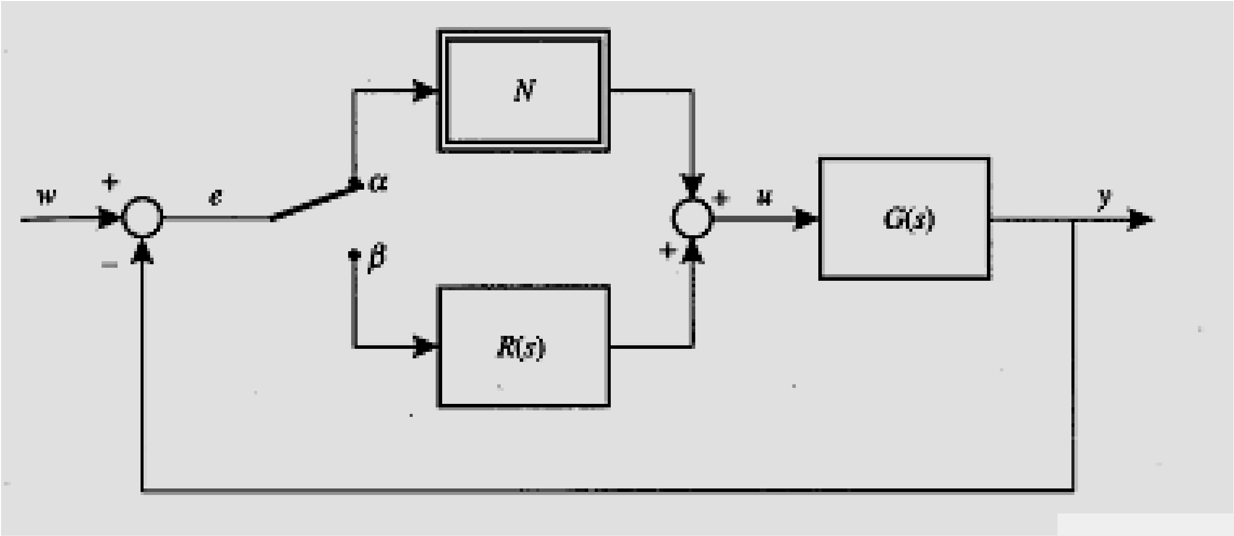


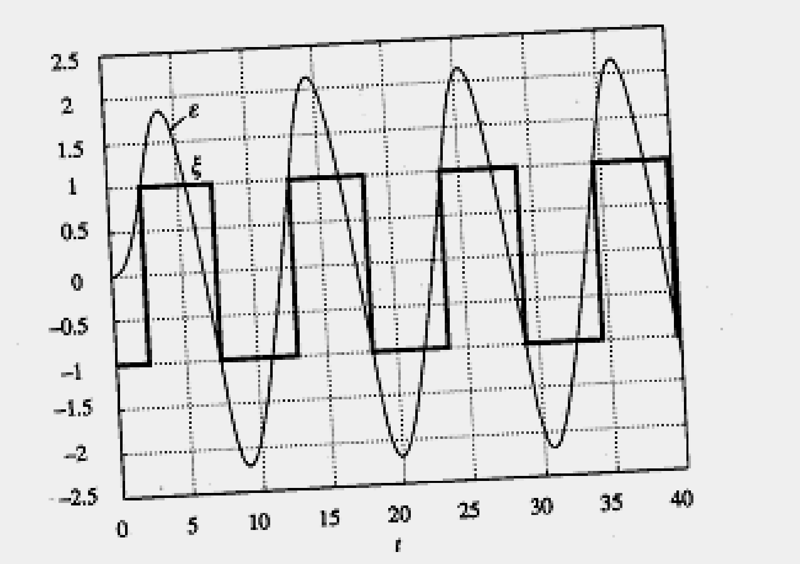
$$G_a(s) = \frac{\mu}{1+Ts}e^{-\tau s}$$

- From open-loop step response the two parameters | e *T* are identified
- The regulator is calibrated on the base of the table below

	K_P	T_I	T_D
P	$\frac{T}{\mu\tau}$		
PI	$\frac{0.9T}{\mu\tau}$	3τ	
PID	$\frac{1.2T}{\mu\tau}$	2τ	0.5τ

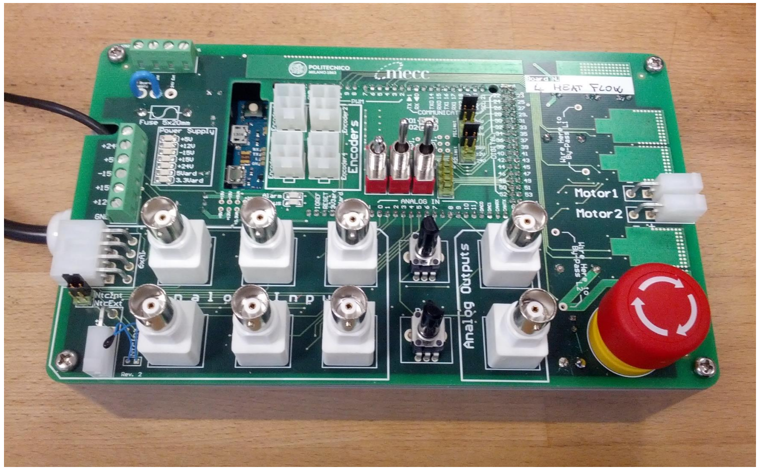
Relay method

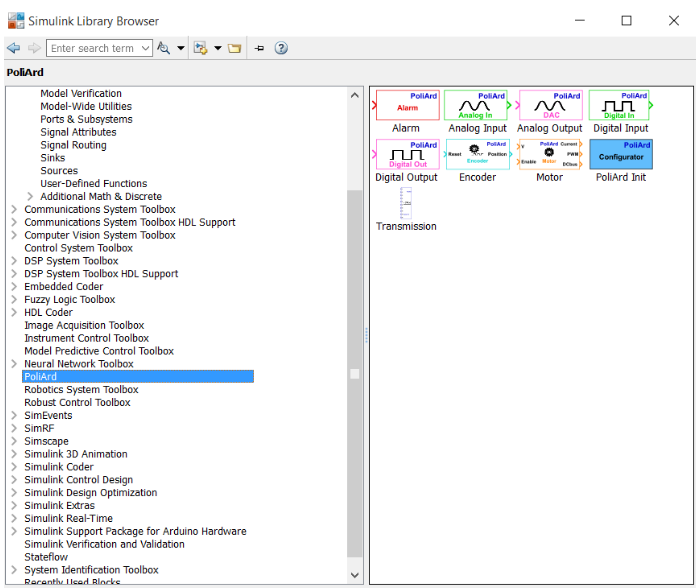


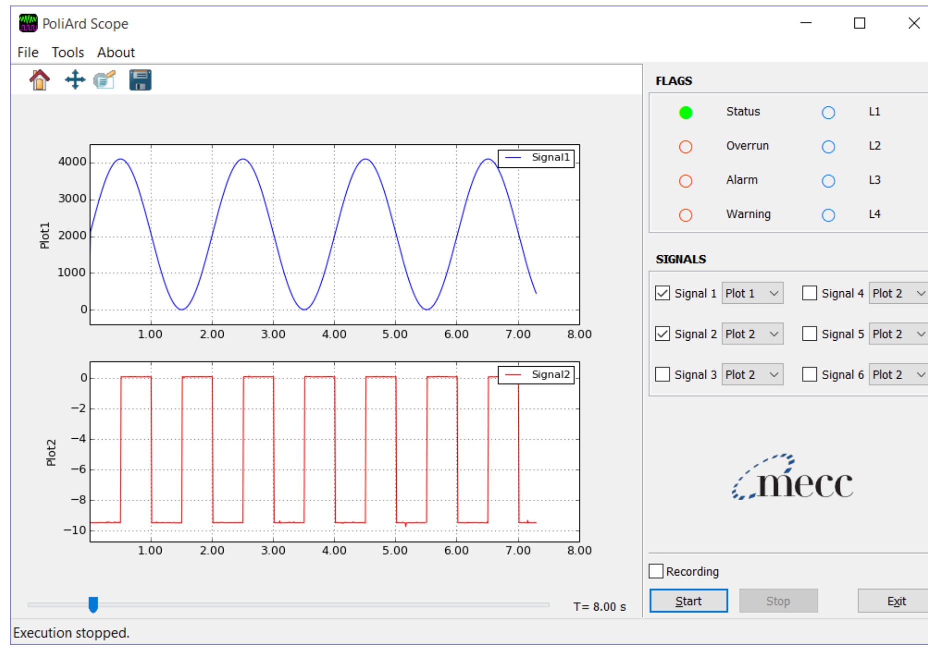


- Through the relè N, the system is led to permanent oscillations with 180° phase.
- Starting from the oscillation period the regulator is calibrated with the same tabulated values as for the closed-loop Ziegler-Nichols' method.

PoliArd board







Automation and Control Laboratory

Available experiences:

1. Automation of an elevator plant
2. Control of electric drives and pneumatic actuators in an automated plant
3. Setup and programming of a robot-cell manufacturing task
4. Control of an induction (asynchronous) motor
5. Control of a permanent-magnet DC motor
6. Control of a permanent-magnet synchronous motor
7. Control of linear vibrations
8. Control of torsional vibrations
9. Motion control in an industrial plant
10. Motion control of a pendulum

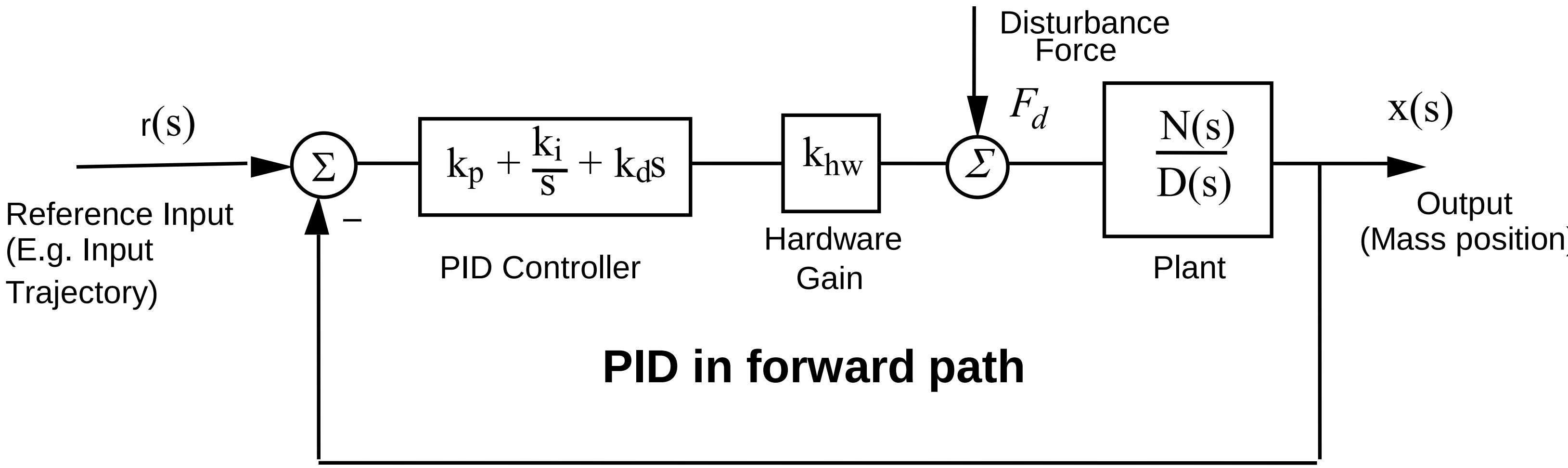
Automation and Control Laboratory

Available experiences:

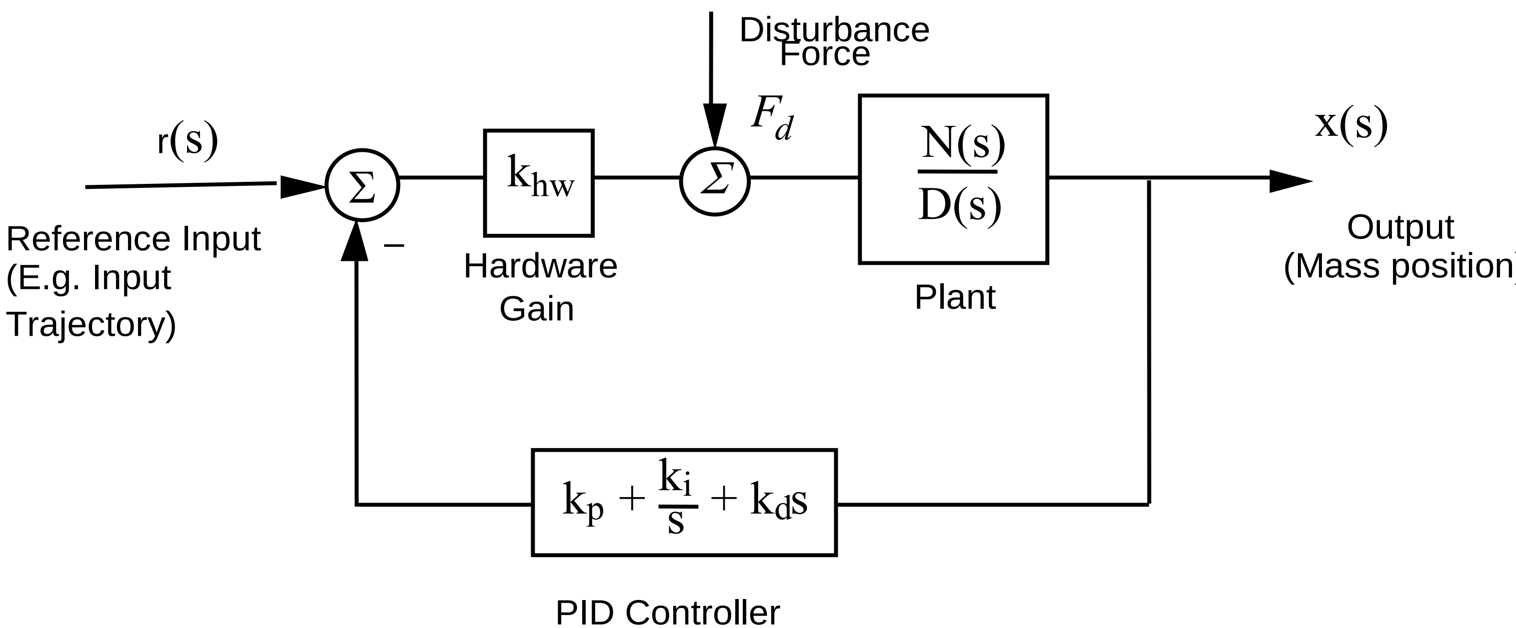
11. Control of a multi-tank system
12. Control of a magnetic levitation system
13. Control of a flexible link
14. Heat-flow control

Some possible suggestions on control logics

PID controller

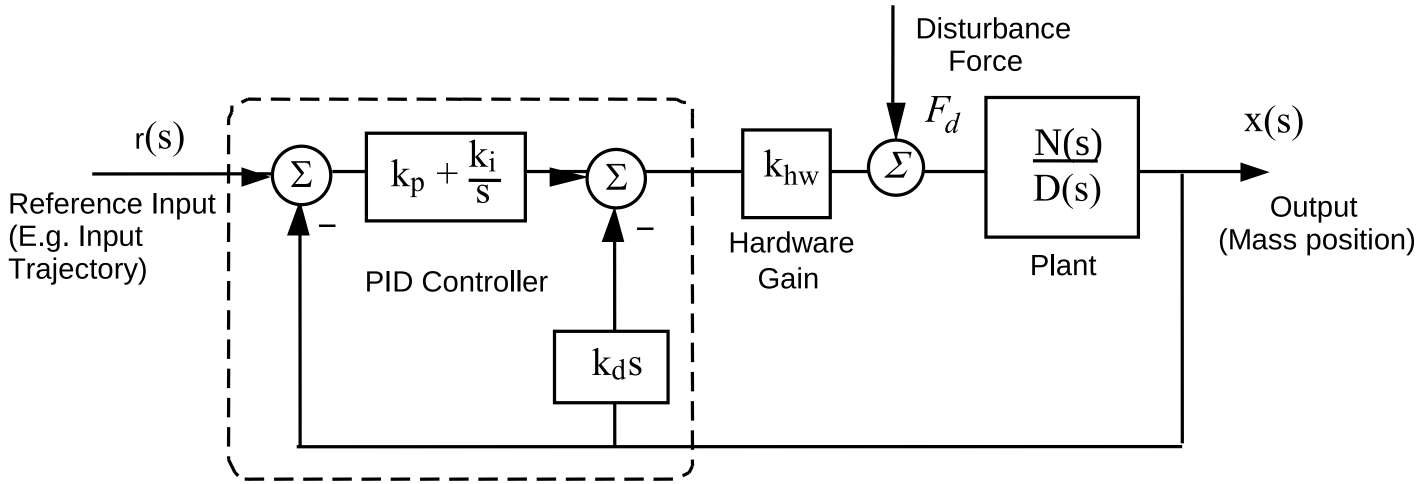


PID in forward path

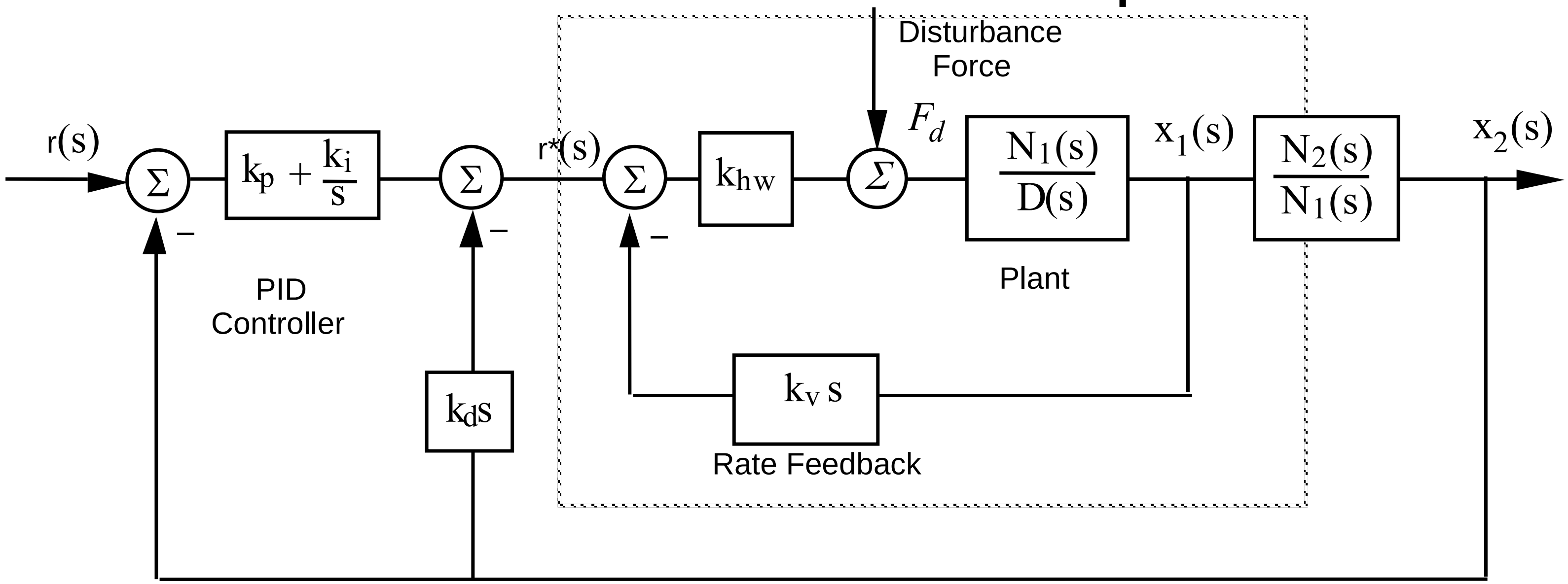


PID in return/reverse path

PID controller

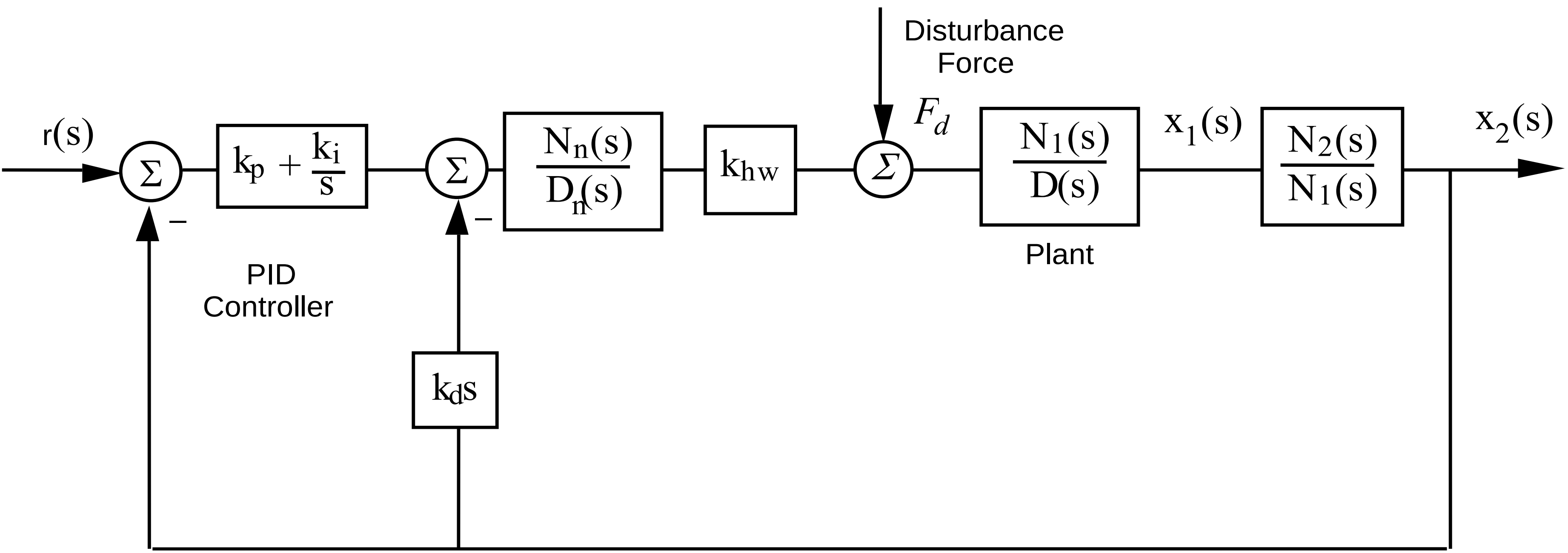


PID in forward-return/reverse path



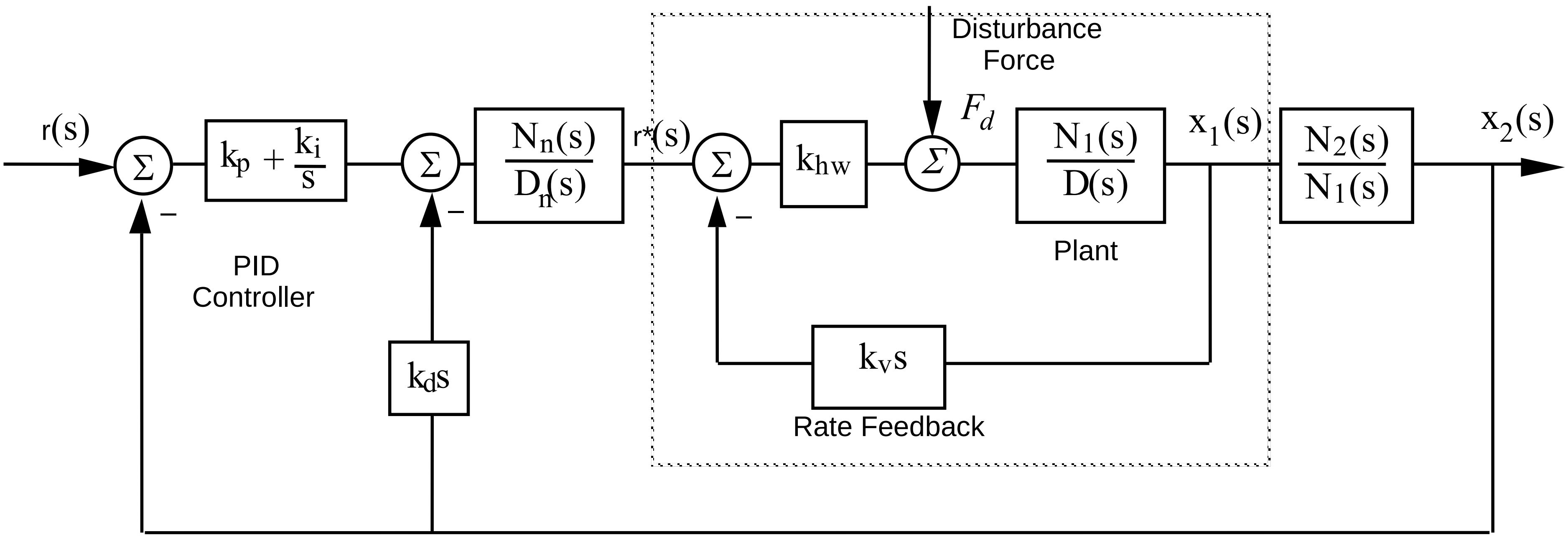
Nested PID in forward-return/reverse path

Controller



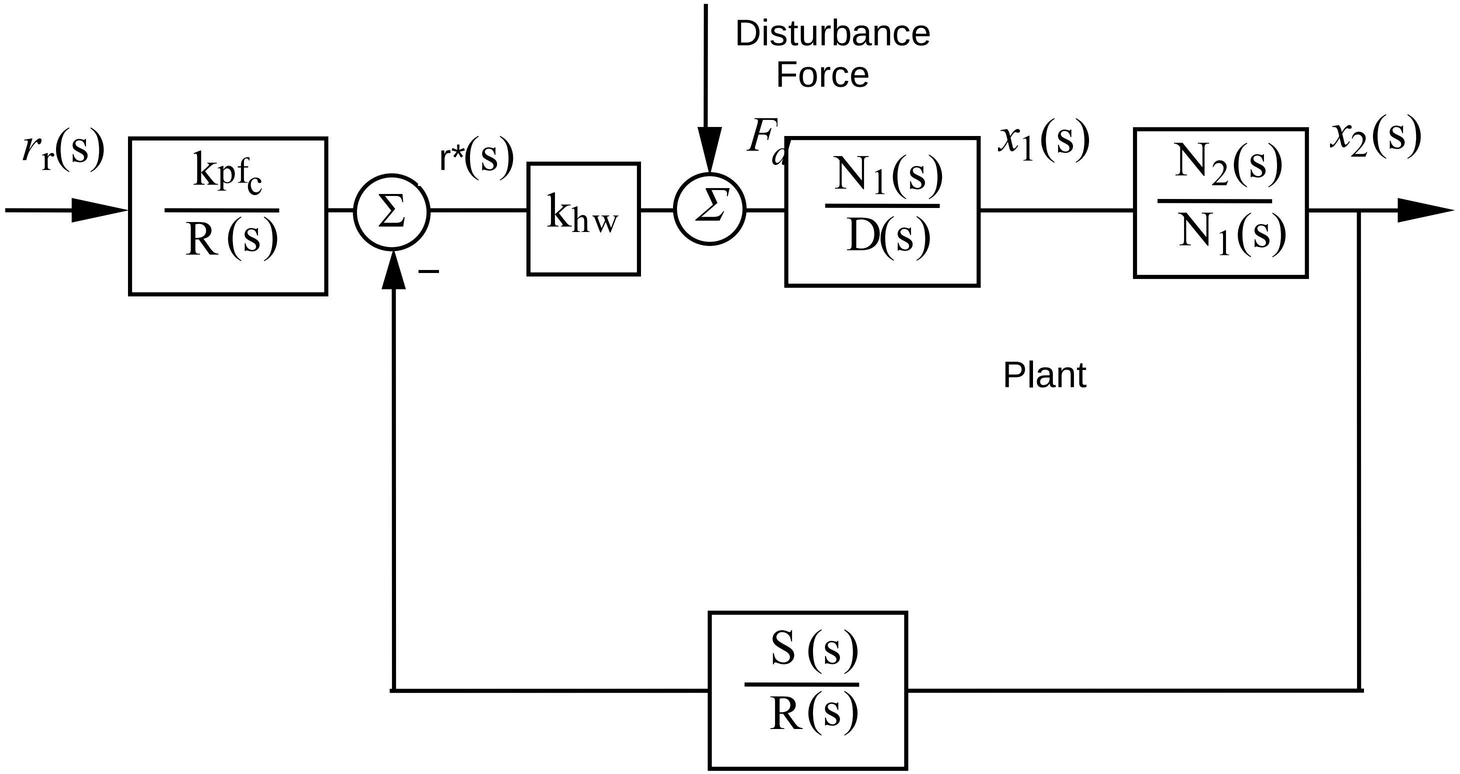
PID in forward-return/reverse path with Notch filter

Controller



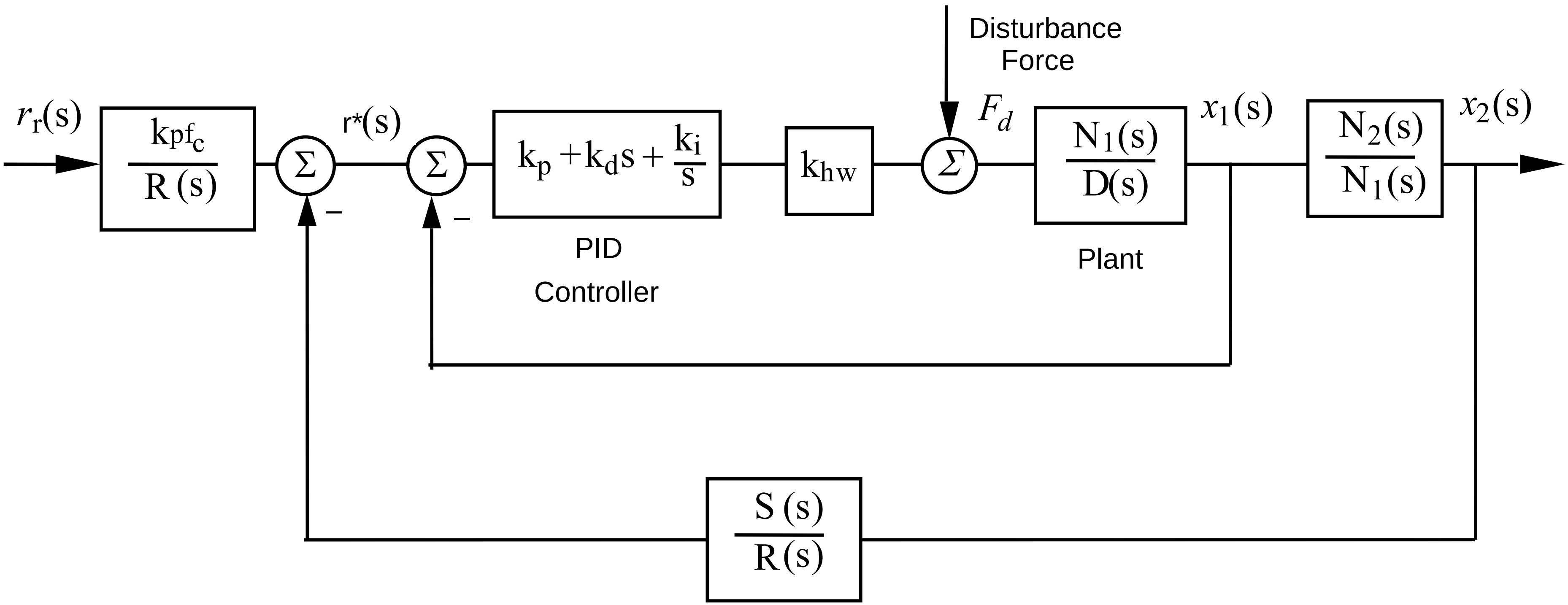
Nested PID in forward-return/reverse path and Notch filter

Controller



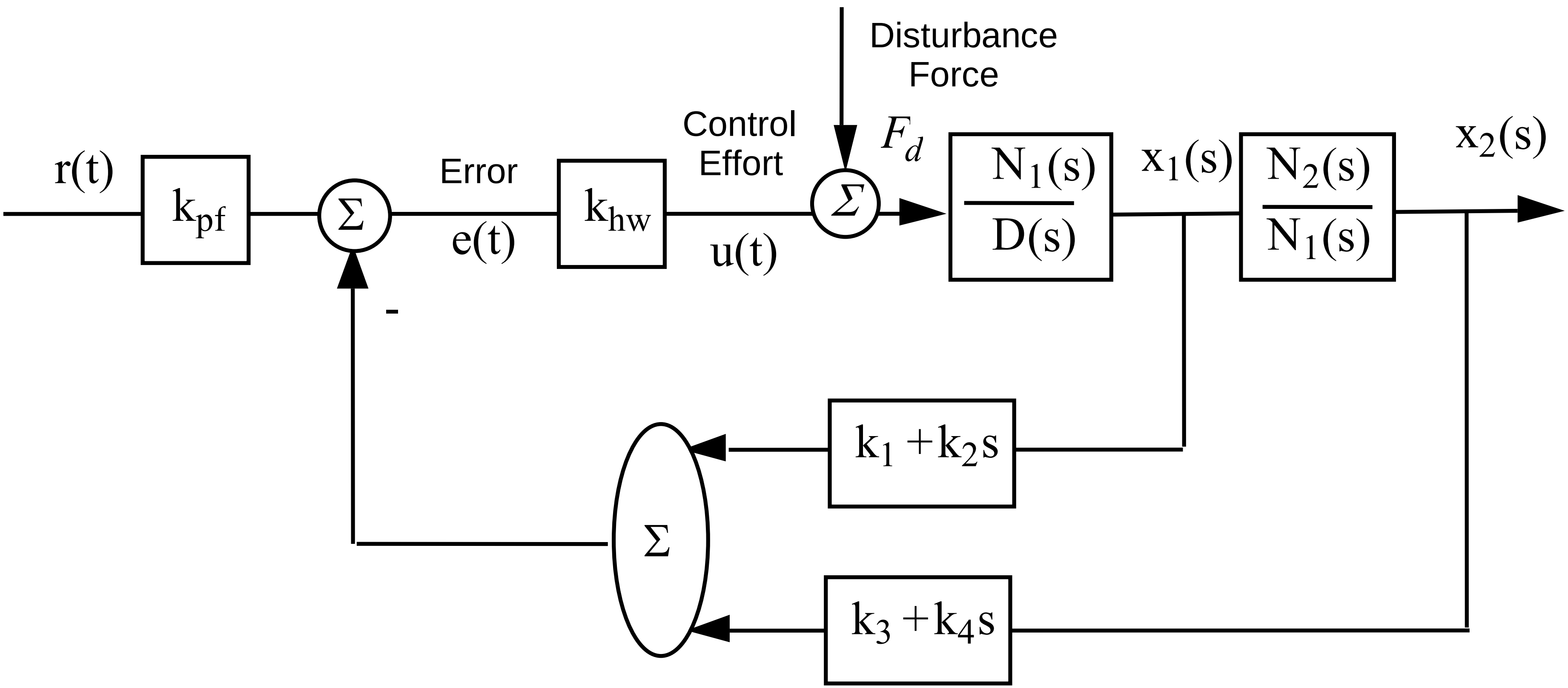
Pole placement

Controller



Pole placement and PID on one of the dof

Controller



Linear optimal controller with/without filters