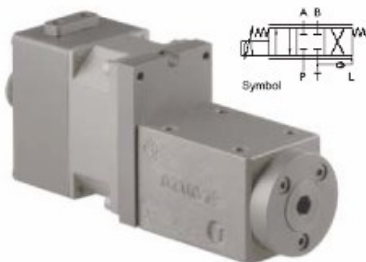
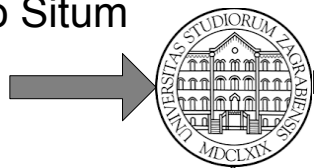


PNEUMATIKA I HIDRAULIKA

SERVO HIDRAULIKA

Prof. dr. sc. Željko Šitum



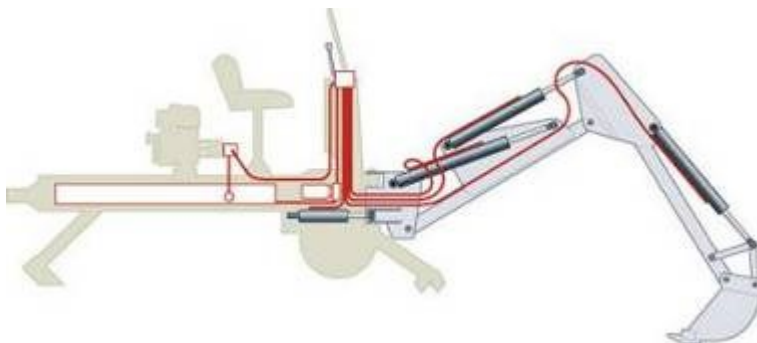
Laboratorij za automatiku i robotiku

Katedra za strojarsku
 automatiku

Zavod za robotiku i
 automatizaciju
 proizvodnih sustava

Sadržaj predavanja

- **Klasična** hidraulika i pneumatika
- **Proporcionalna** hidraulika i pneumatika
- **Servo** hidraulički sustavi
- **Eksperimentalni rezultati** regulacije hidrauličkih i pneumatskih sustava
- **Pravci razvoja** suvremenih hidrauličkih i pneumatskih sustava



Hidraulički razvodnici

Dvopoložajni razvodnici

Uključno-isključni (on-off)
elektromagneti



Elektromagnetski razvodnik

**KLASIČNA
HIDRAULIKA**

Razvodnici s kontinuiranim djelovanjem

proporcionalni elektromagneti

elektromehanički pretvornik



Proporcionalni razvodnik

**PROPORCIONALNA
HIDRAULIKA**



Servorazvodnik

SERVOHIDRAULIKA

Omogućuju da se velikim inercijskim opterećenjima upravlja uz visoku točnost upravljanja, veliku brzinu odziva i velika pojačanja snage.

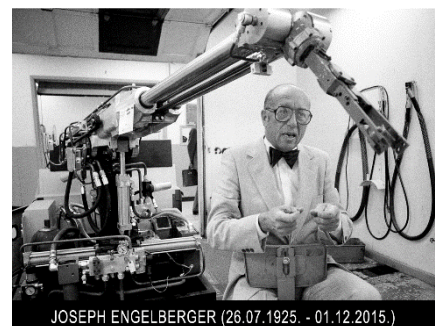
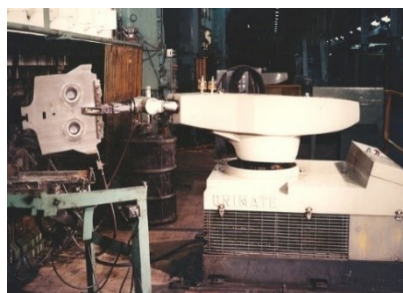
Prednosti EHSS:

- krute karakteristike sile/momenta
- velika specifična snaga

Primjena EHSS:

- vojna tehnika
- numerički upravljani alatni strojevi
- industrijska robotika

Unimate robot

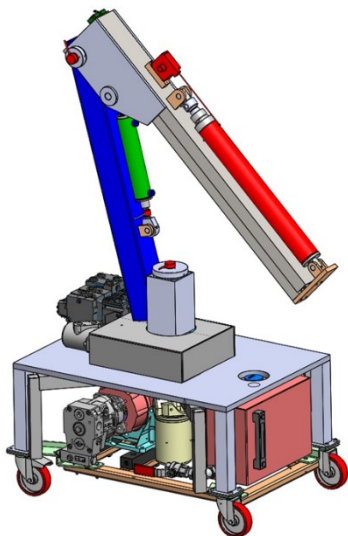


JOSEPH ENGELBERGER (26.07.1925. - 01.12.2015.)



J. Engelberger † 2015. i G. Devol † 2011.

PROJEKT - Elektrohidraulički robotski manipulator (EHROM) za velike nosivosti



PROJEKT - Elektrohidraulički robotski manipulator (EHROM) za velike nosivosti



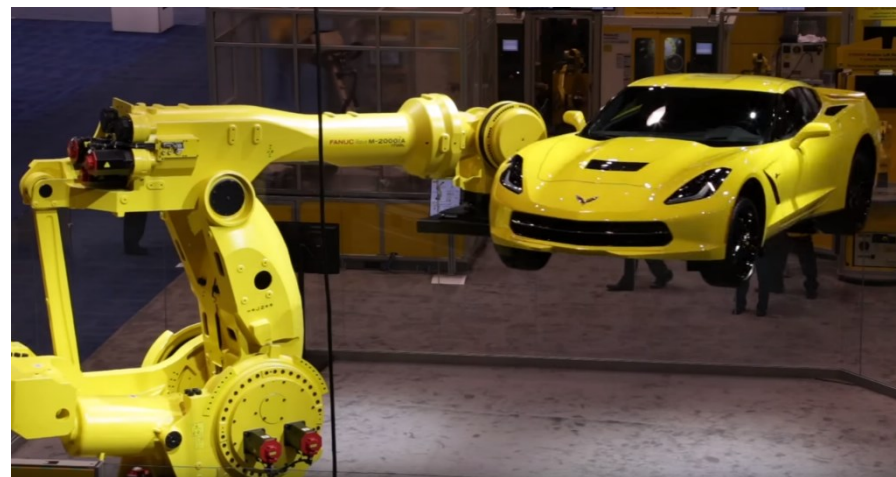
EHROM robotski manipulator
3 SSG
Masa 515 kg
Nosivost >200 kg



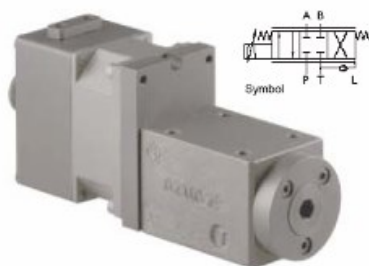
ABB IRB robot
6 SSG
Masa 1000 kg
Nosivost 40 kg



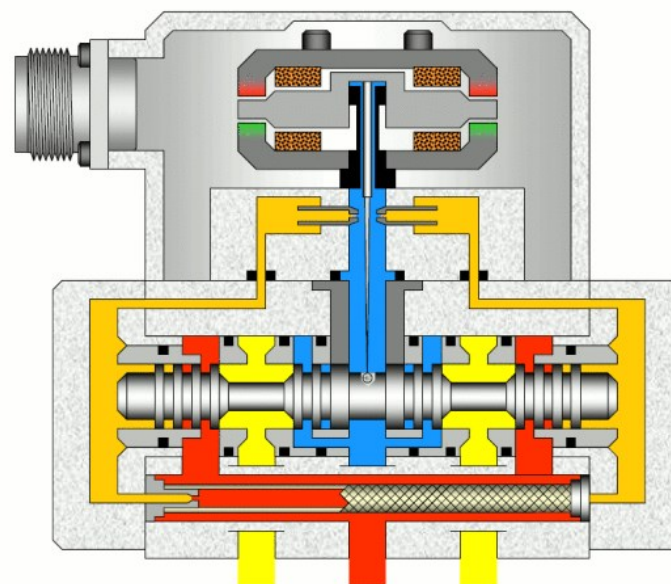
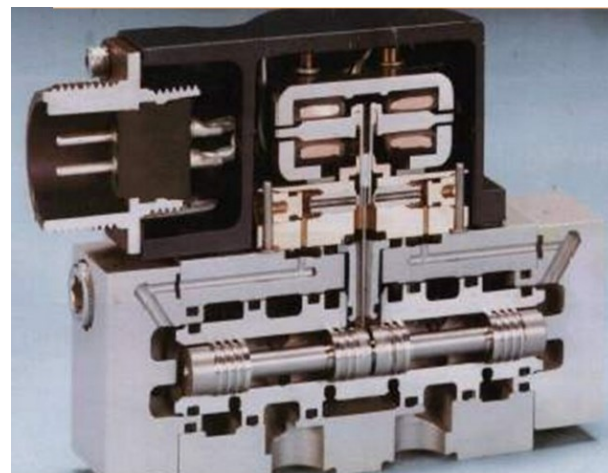
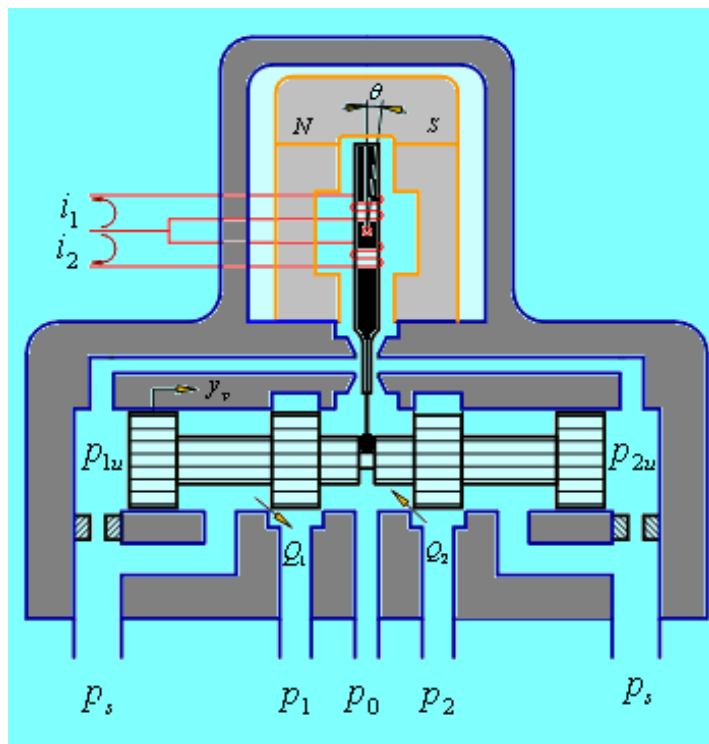
FANUC robot M-2000iA/2300
6 SSG
Masa 8600 kg
Nosivost 1200 kg



Najvažniju i najprecizniju komponentu u EHSS predstavlja elektrohidraulički servorazvodnik



Shema elektrohidrauličkog servorazvodnika s dva stupnja pojačanja s mehaničkom povratnom vezom

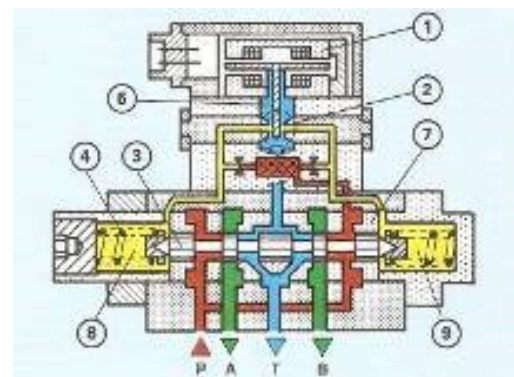


Princip rada servorazvodnika

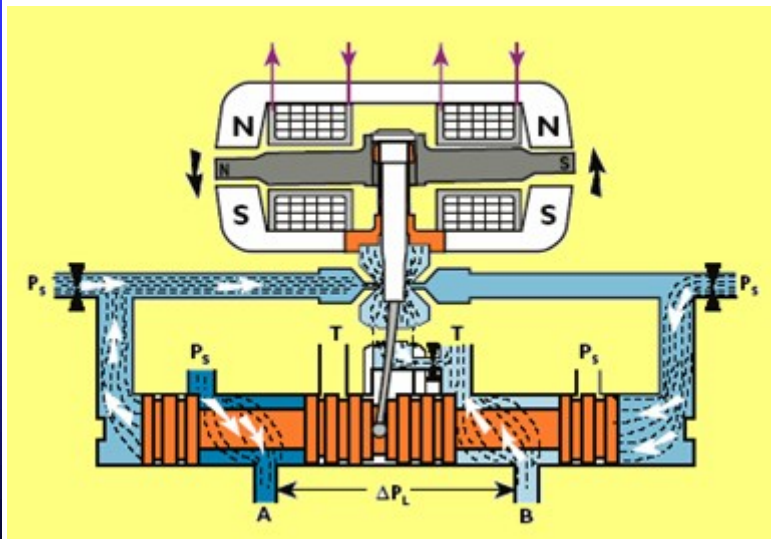
Servoventili

SERVOVENTILI mogu biti s:

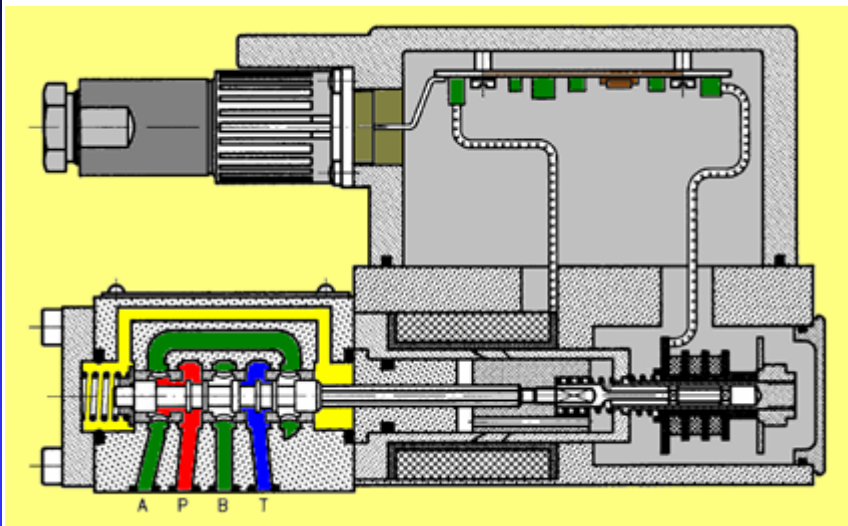
- MEHANIČKOM povratnom vezom
- ELEKTRIČNOM povratnom vezom
- TLAČNOM povratnom vezom



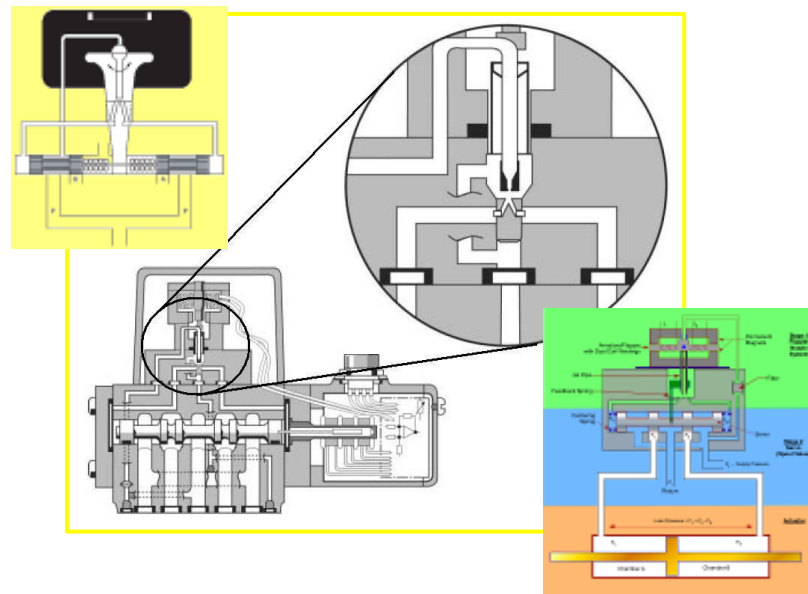
1. Sustav mlaznica – odbojna pločica (‘Flapper-Nozzle’)



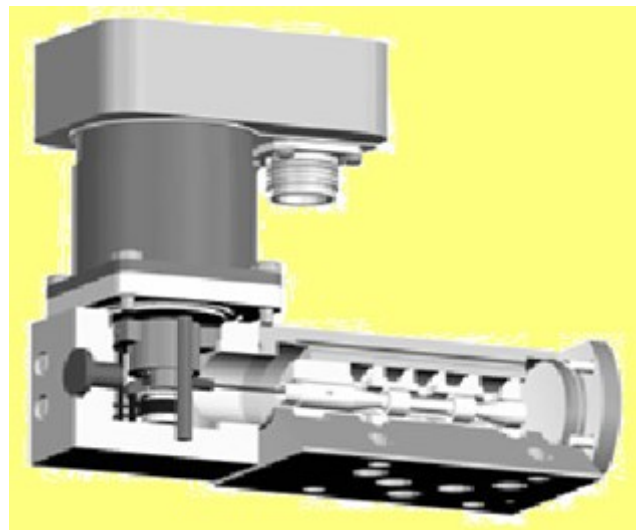
3. Elektromagnetski servo ventil (‘Servo solenoid valve’)



2. Sustav sapnica – cijev (lula) (‘Jet pipe’)

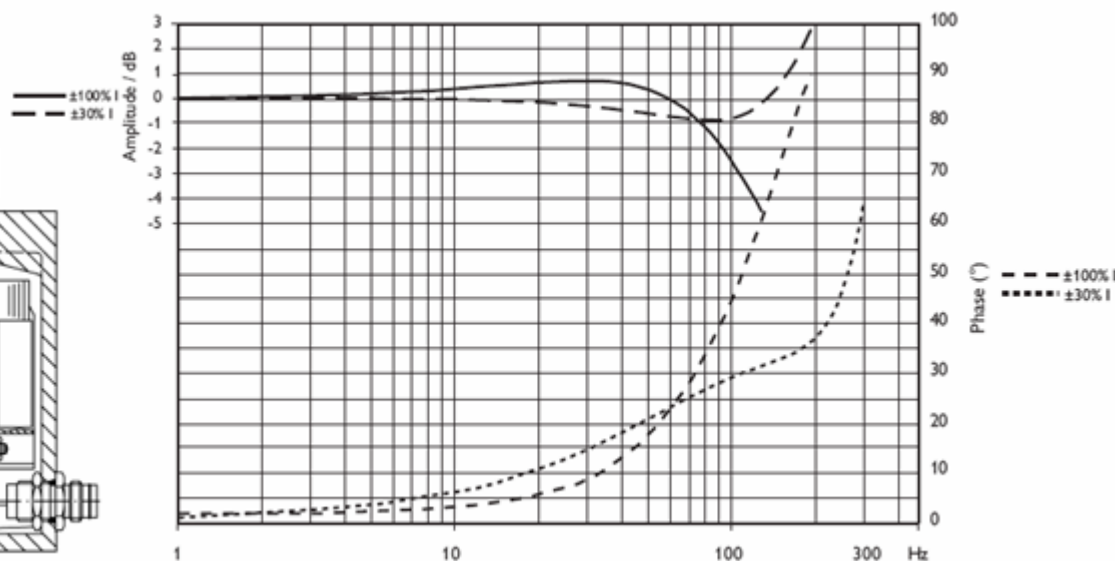
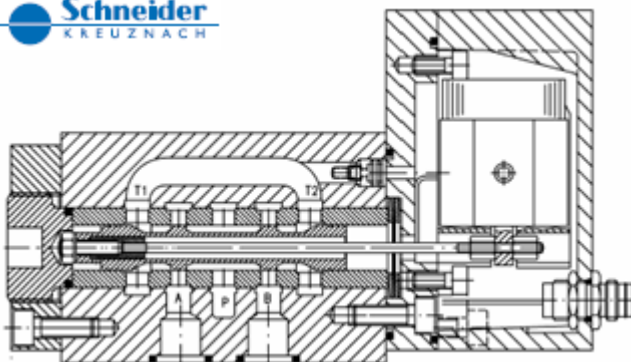
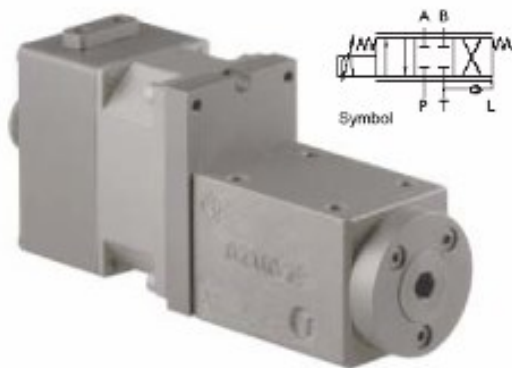


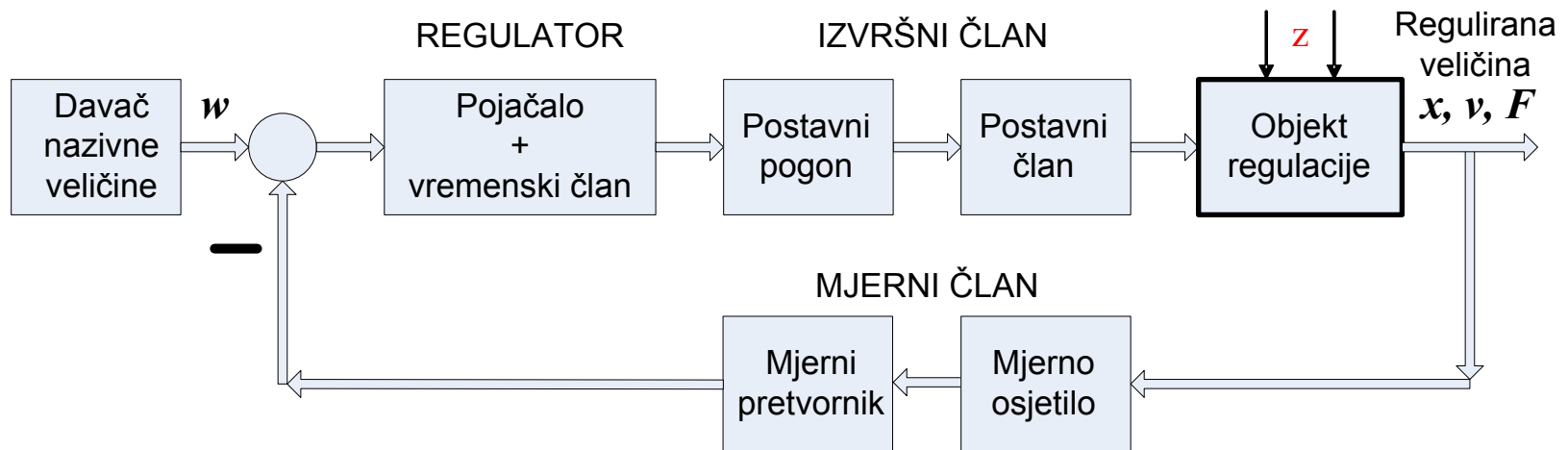
4. Elektromotorni rotacijski pogon (‘Rotary electric motor’)



ZNAČAJKE SERVOVENTILA:

- Mogućnost upravljanja vrlo velikim snagama s malim upravljačkim signalom
- Visoka točnost pozicioniranja velikih masa u kratkom vremenu
- Vrlo visoka cijena zbog velike preciznosti izrade
- Skupa uporaba, jer radna tekućina mora biti dobro filtrirana
- Obično imaju dva (za velike protoke i tri) stupnja pojačanja

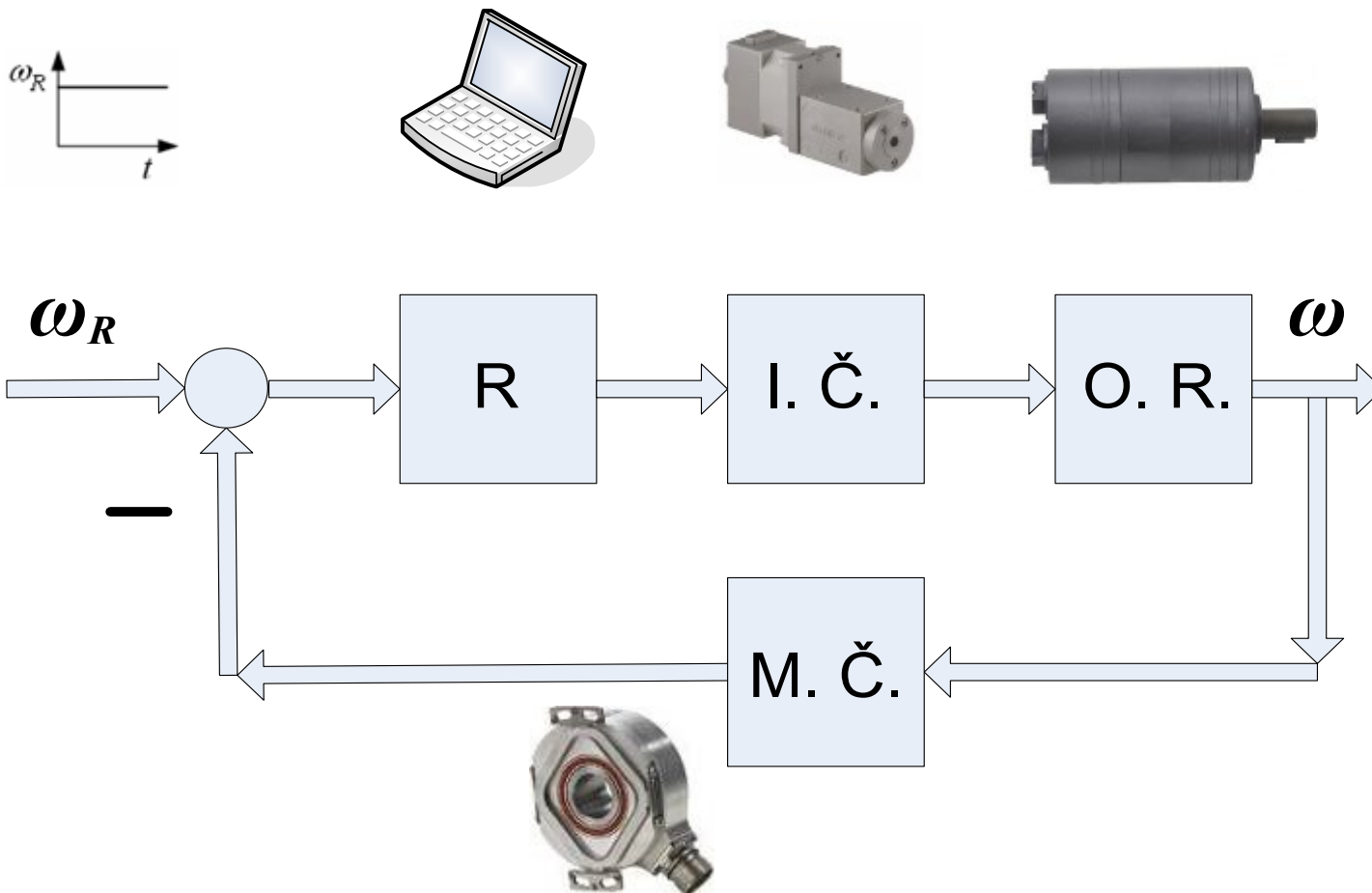




REGULACIJA – proces pri kojem izlazna veličina djeluje povratno na ulaznu veličinu održavajući željeno stanje. Uvijek je prisutna negativna povratna veza.

ZNAČAJKE:

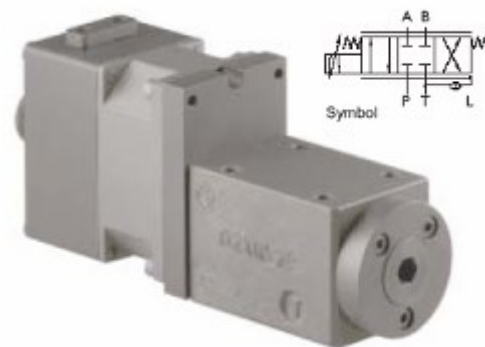
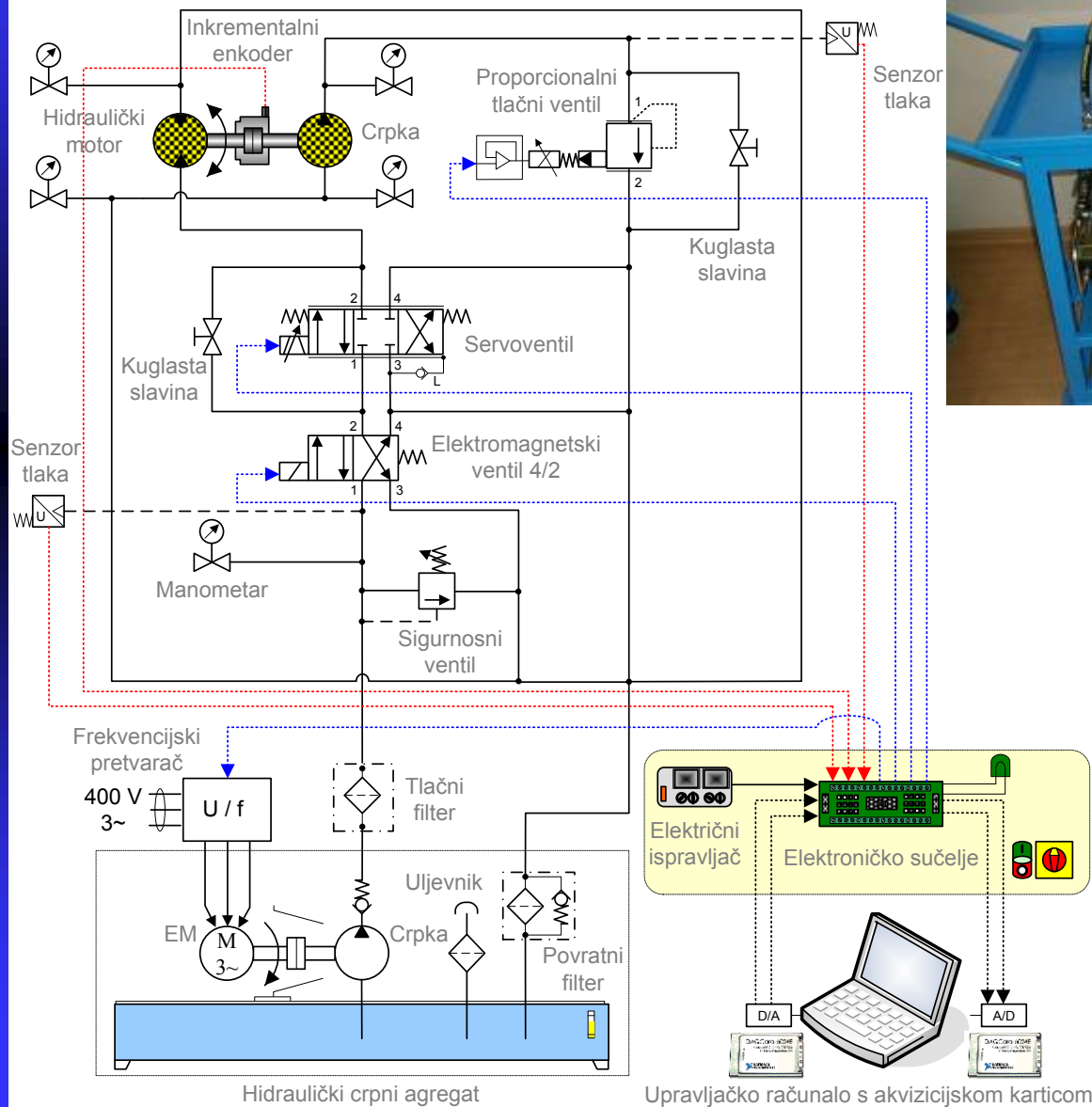
- Zatvoreni regulacijski krug - povratna veza
- Zbog uvođenja povratne veze regulacijski krug može postati nestabilan



ZATVORENI REGULACIJSKI KRUG !

Elektrohidraulički servosustav

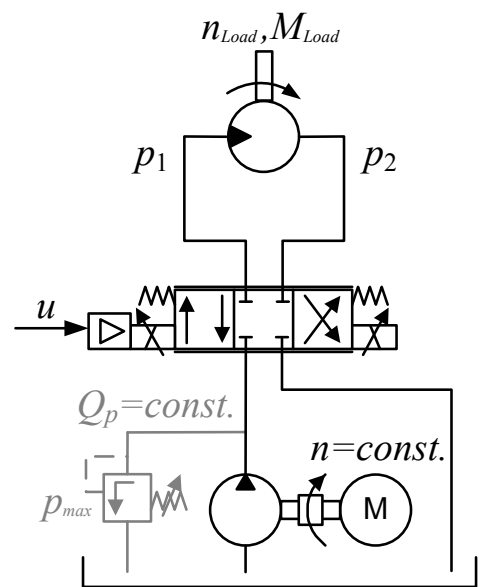
Modul za regulaciju rotacijskog gibanja



Upravljačko računalo s akvizicijskom karticom

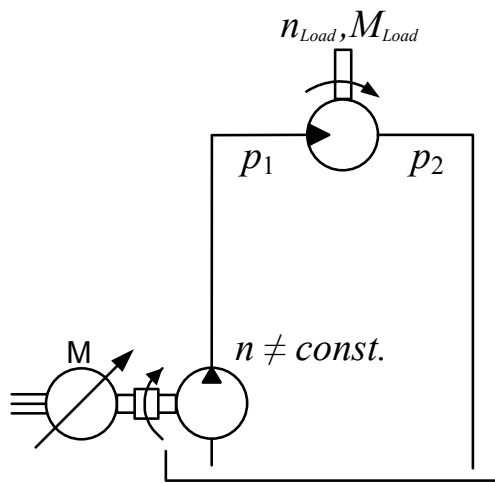
■ OSNOVNI NAČINI UPRAVLJANJA HIDRAULIČKOM ENERGIJOM

PRIGUŠENJE RADNOG FLUIDA

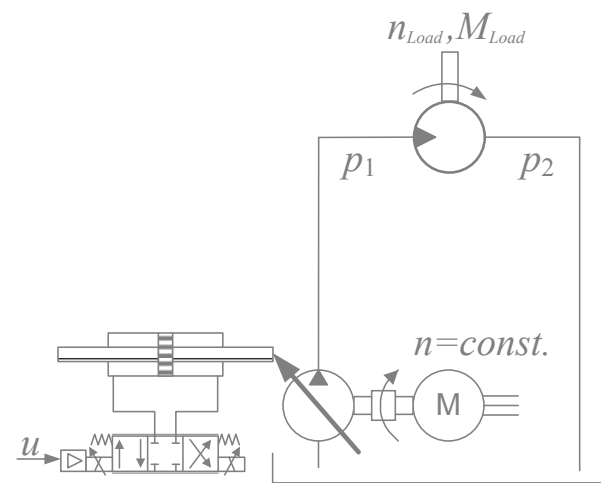


Prigušenjem na
proporcionalnom ili
servoventilu

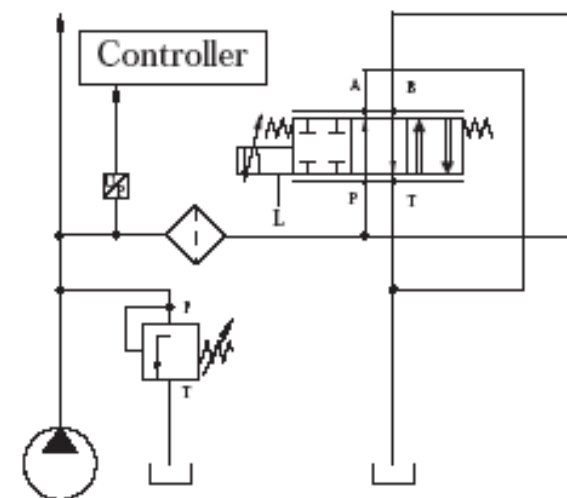
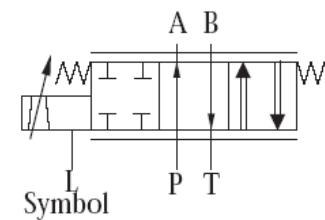
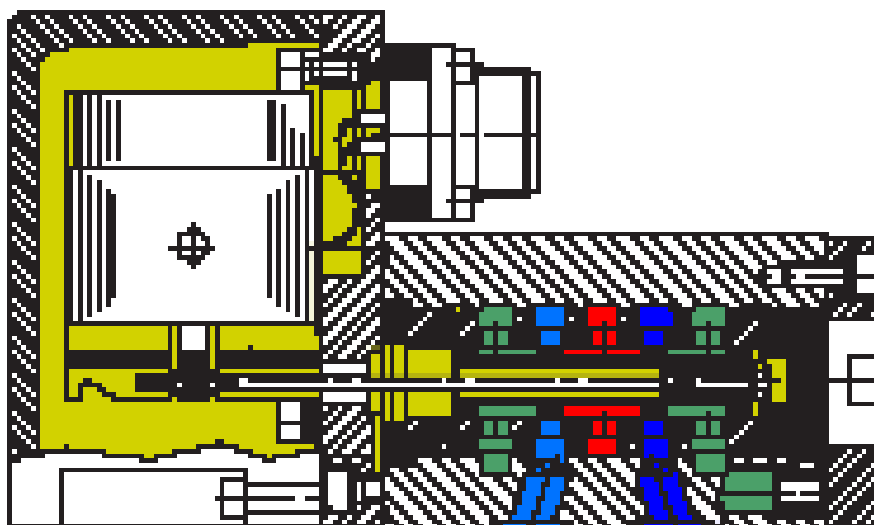
PROMJENA PROTOKA RADNOG FLUIDA



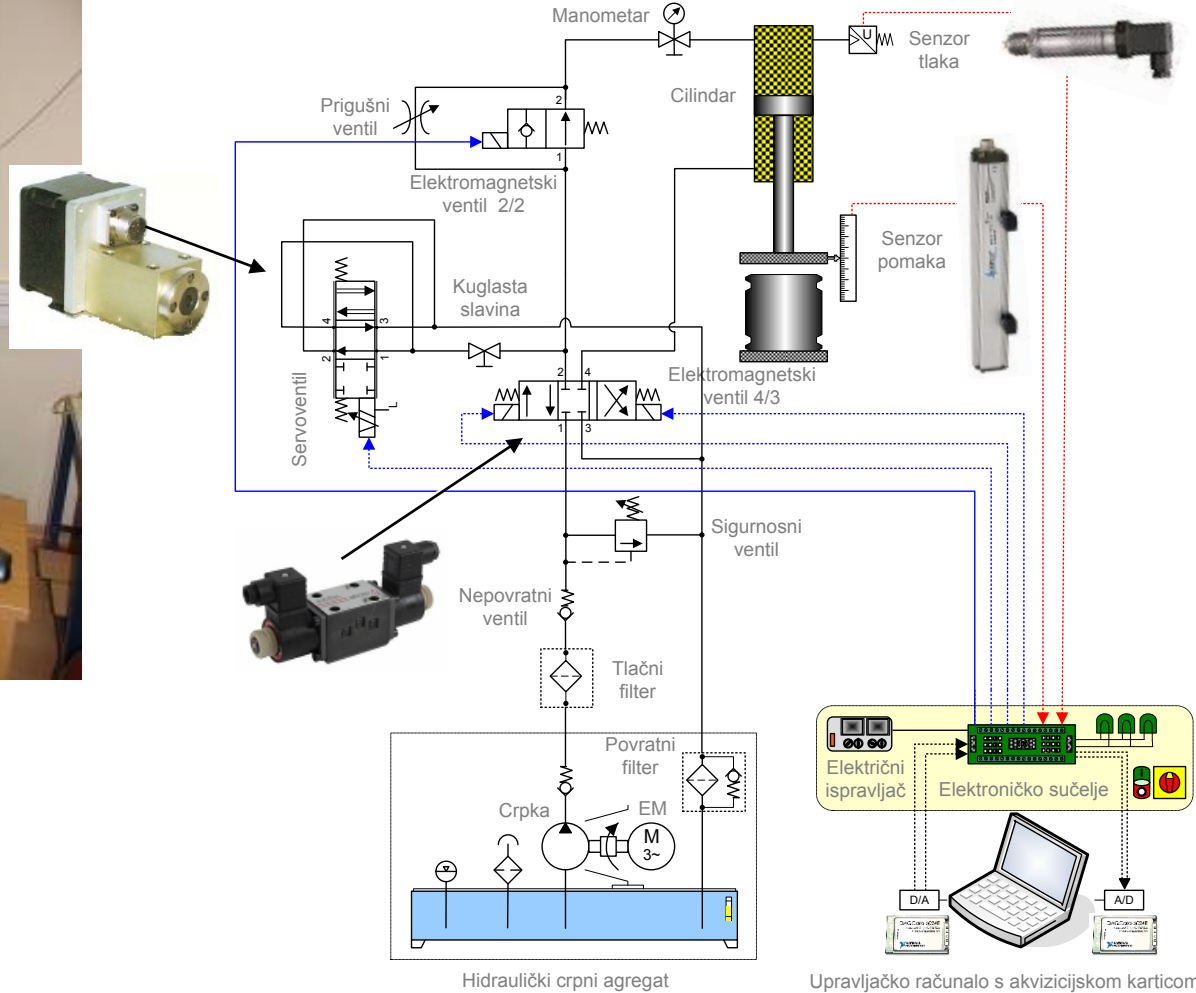
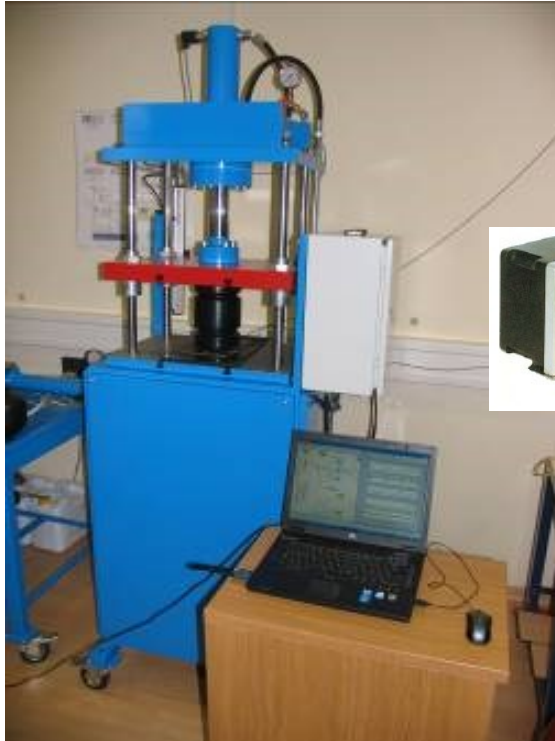
Električni motor promjenljive brzine
+
Crpka konstantnog volumena dobave



Električni motor konstantne brzine
+
Crpka promjenljivog volumena dobave



Modul za regulaciju sile - hidraulička preša

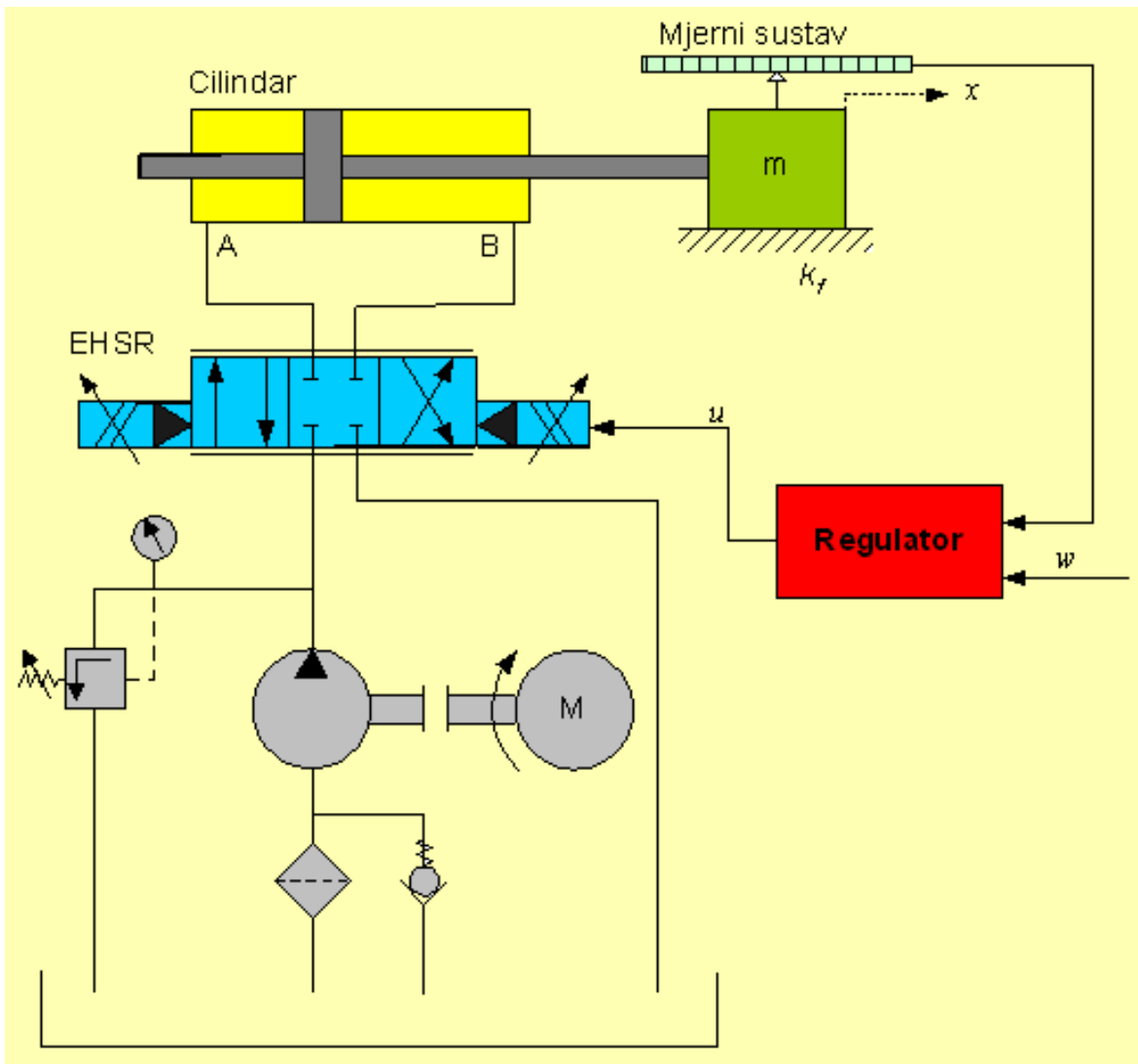




Series DYP**
Pneumatic Servo Valves
(Flapper - Nozzle & Direct - Drive Style)

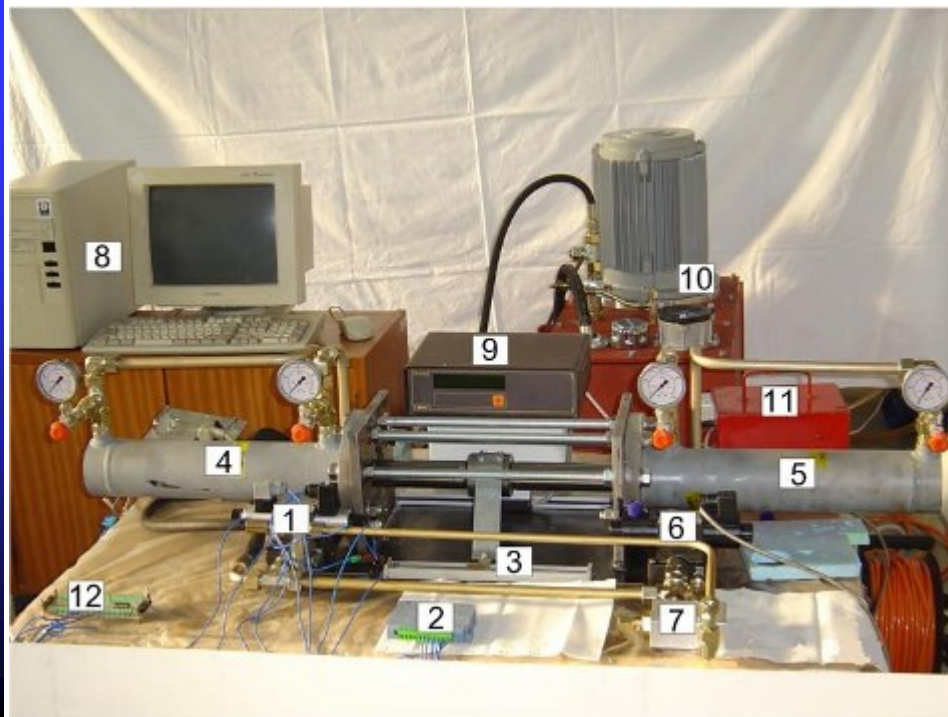


Regulacija elektrohidrauličkog servo sustava



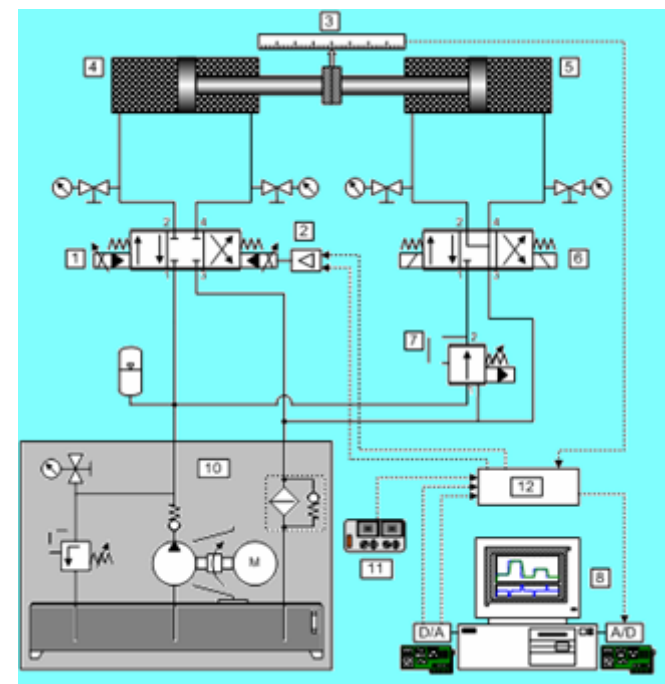
ZATVORENI REGULACIJSKI KRUG !

Regulacija hidrauličkog sustava primjenom proporcionalnog ventila



Oznake:

- | | |
|--------------------------------|--------------------------------|
| 1 – Proporcionalni ventil | 7 – Tlačni ventil |
| 2 – Elektroničko pojačalo | 8 – Upravljačko računalo |
| 3 – Linearni potencijometar | 9 – Numerički pokazivač |
| 4 – Pogonski cilindar | 10 – Hidraulički crpni agregat |
| 5 – Cilindar za opterećenje | 11 – Električni ispravljač |
| 6 – Direktno upravljani ventil | 12 – Elektroničko sučelje |



Prijenosna funkcija prop. ventila:

$$\frac{y_v(s)}{i(s)} = \frac{K_v \omega_v^2}{s^2 + 2\zeta_v \omega_v s + \omega_v^2}$$

gdje je:

y_v – pozicija prop. ventila [m]

i – ulazna struja prop. ventila [A]

K_v – koef. pojačanja prop. ventila [m/A]

ω_v – vlastita frekvencija prop. ventila [rad/s]

ζ_v – koeficijent prigušenja prop. ventila

Protok kroz prop. ventil:

$$Q_1(y_v, p_1) = \begin{cases} y_v \cdot \sqrt{|p_s - p_1|} \cdot \text{sign}(p_s - p_1) & \text{za } y_v \geq 0 \\ y_v \cdot \sqrt{|p_1 - p_a|} \cdot \text{sign}(p_1 - p_a) & \text{za } y_v < 0 \end{cases}$$

$$Q_2(y_v, p_2) = \begin{cases} -y_v \cdot \sqrt{|p_2 - p_a|} \cdot \text{sign}(p_2 - p_a) & \text{za } y_v \geq 0 \\ -y_v \cdot \sqrt{|p_s - p_2|} \cdot \text{sign}(p_s - p_2) & \text{za } y_v < 0 \end{cases}$$

gdje je:

p_s – tlak napajanja [Pa]

p_a – tlak spremnika [Pa]

Ravnoteža sila na klipu cilindra:

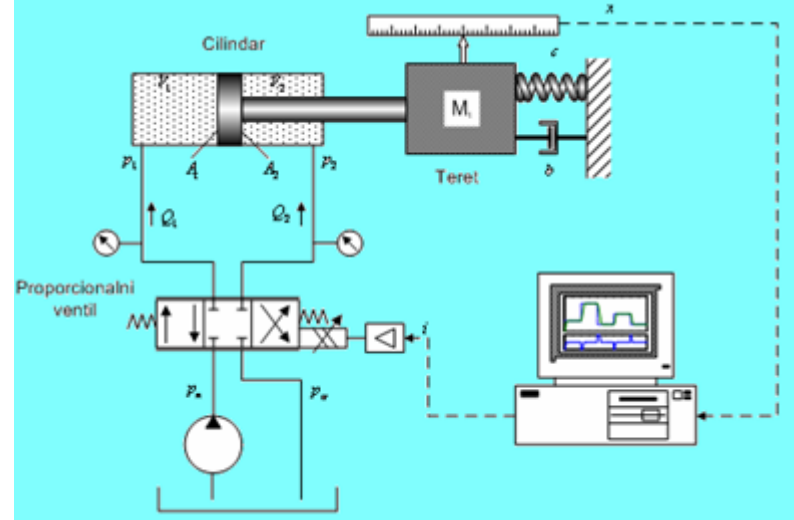
$$p_1 \cdot A_1 - p_2 \cdot A_2 = M_t \cdot \ddot{x}_p + b \cdot \dot{x}_p + c \cdot x_p + F_L$$

gdje je:

M_t – masa tereta [kg]

b – koeficijent trenja [Ns/m]

c – koeficijent elastičnosti tereta [N/m]



Promjena tlaka u komorama cilindra:

$$\frac{dP_1}{dt} = \frac{B}{V_0 + A_1 x_p} (Q_1 - A_1 \dot{x}_p)$$

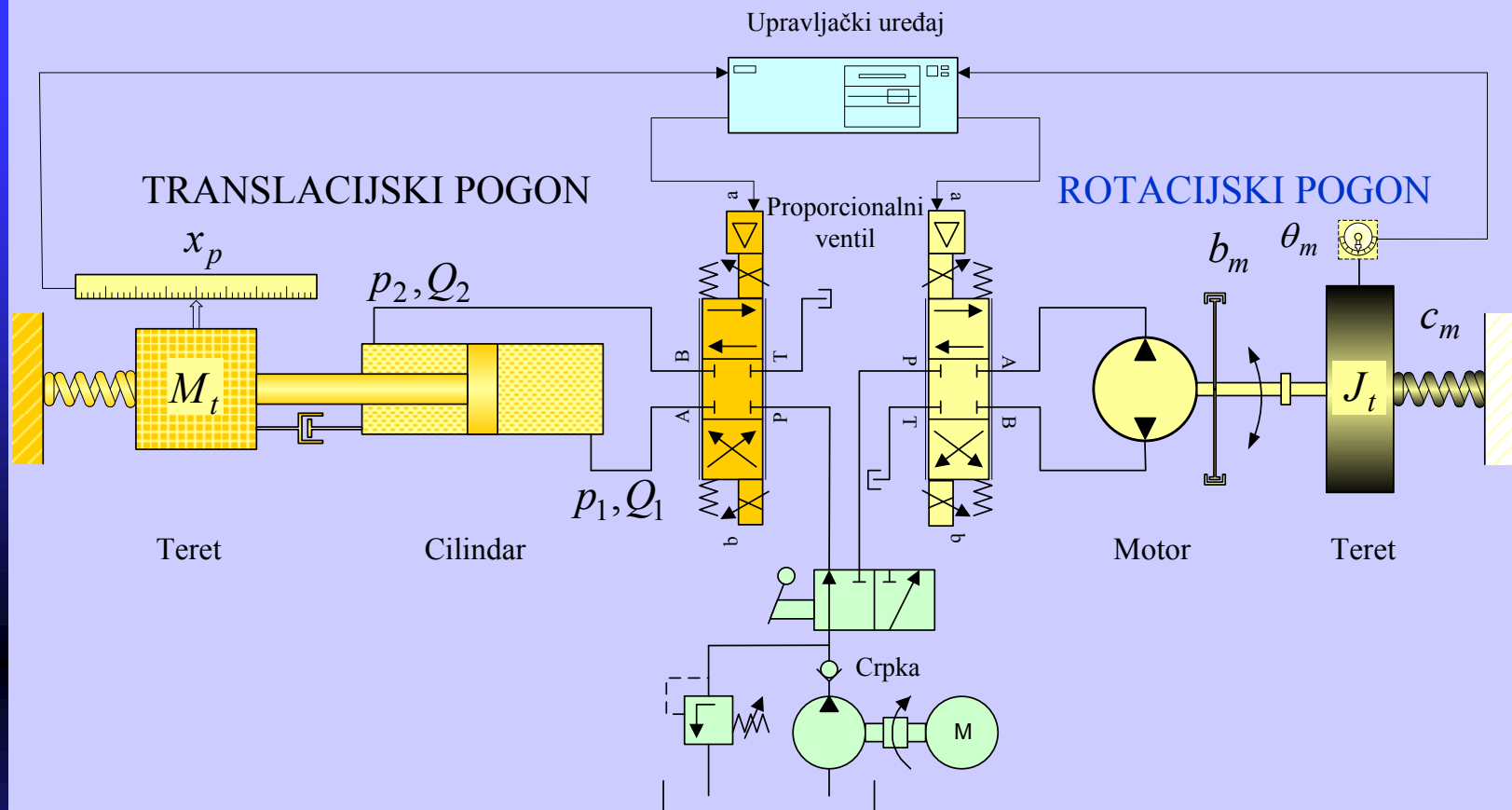
$$\frac{dP_2}{dt} = \frac{B}{V_0 - A_2 x_p} (Q_2 + A_2 \dot{x}_p)$$

gdje je:

B – modul stlačivosti tekućine [Pa]

V_0 – poluvolumen cilindra [m³]

A – površina popr. presjeka klipa [m²]

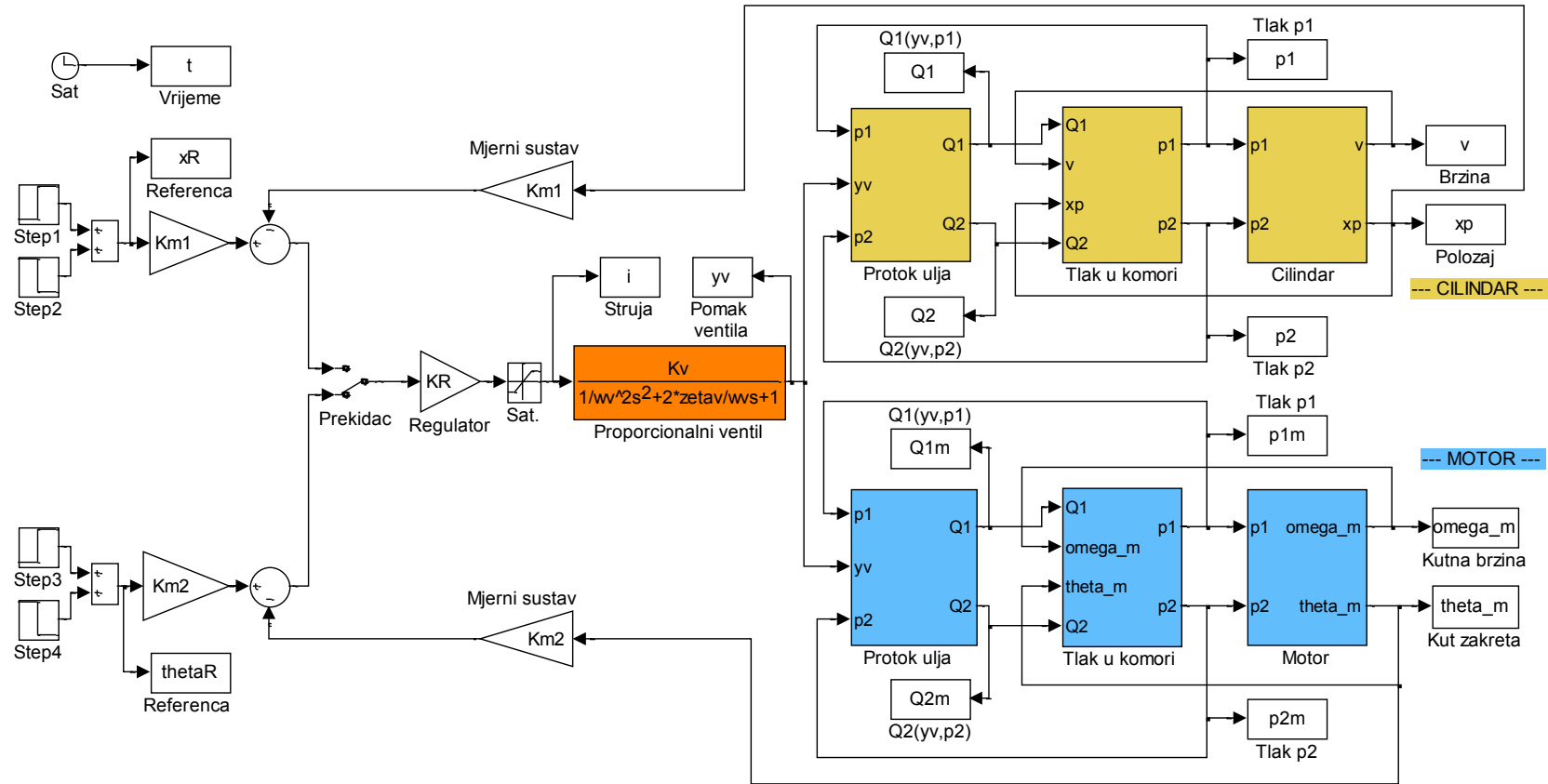


TRANSLACIJSKI POGON

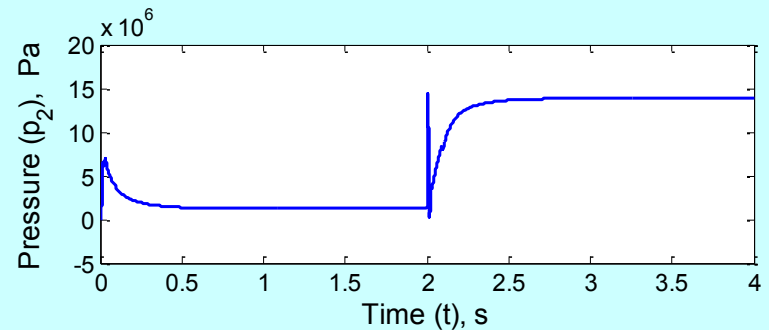
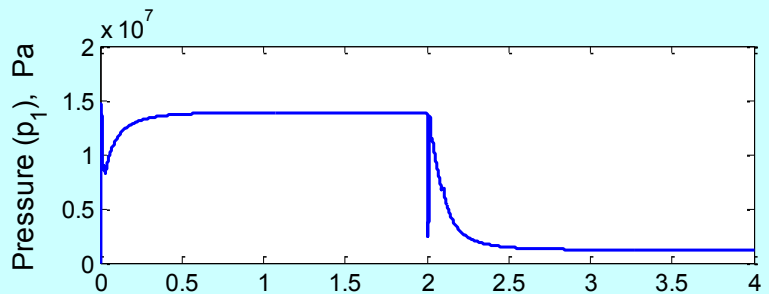
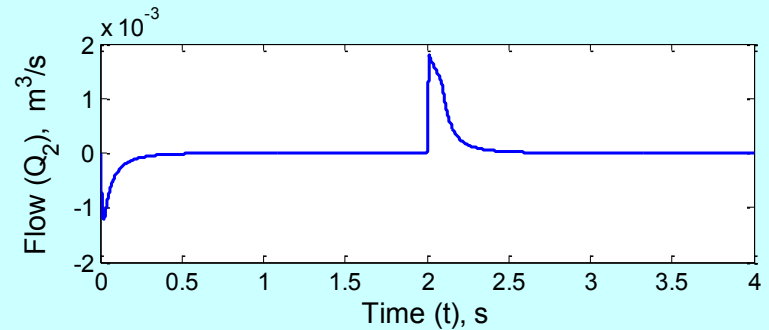
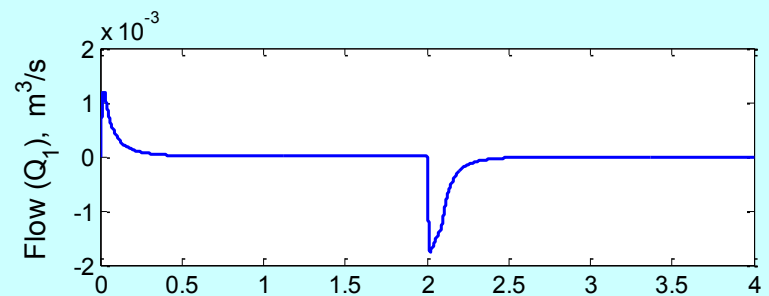
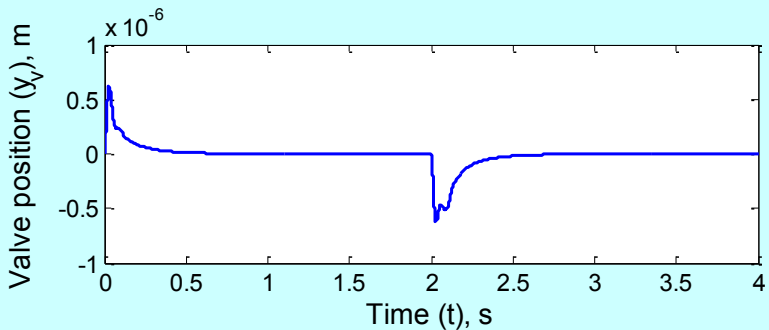
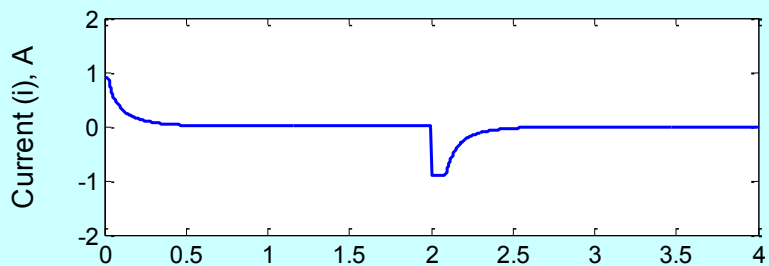
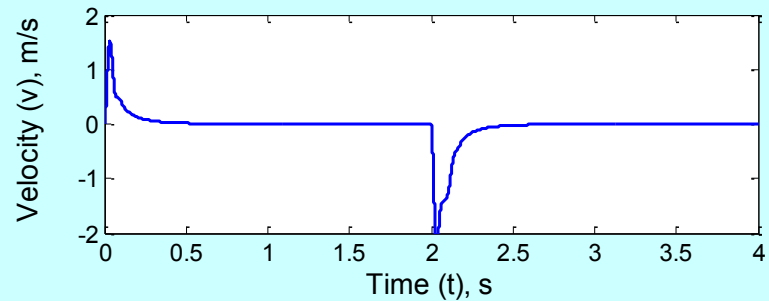
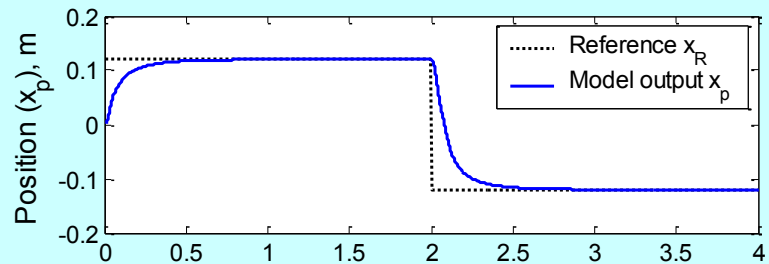
x_p	\Leftrightarrow	θ_m
M_t	\Leftrightarrow	J_t
A_p	\Leftrightarrow	q_{rm}
F_L	\Leftrightarrow	T_L
b, c	\Leftrightarrow	b_m, c_m

ROTACIJSKI POGON

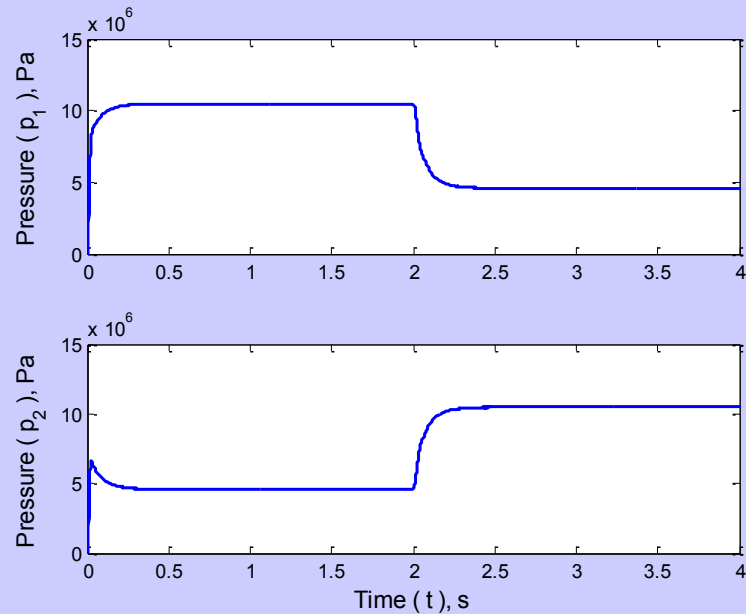
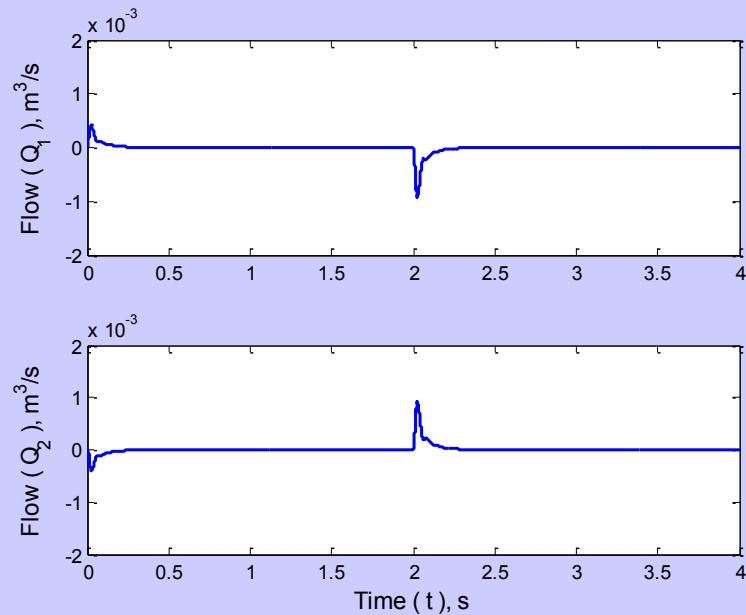
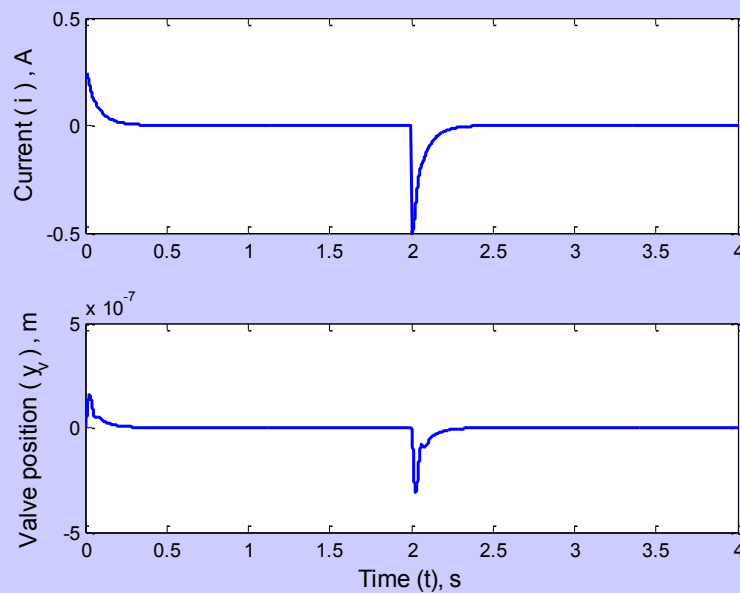
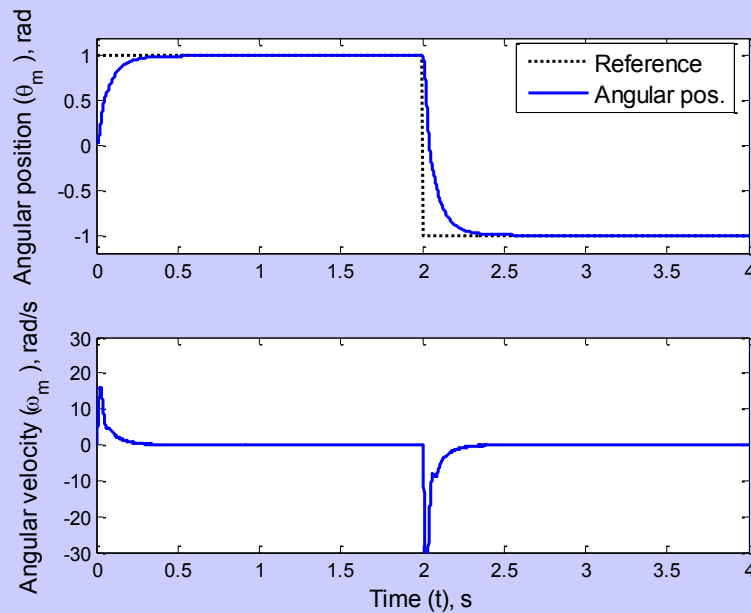
Simulacijski model EHSS

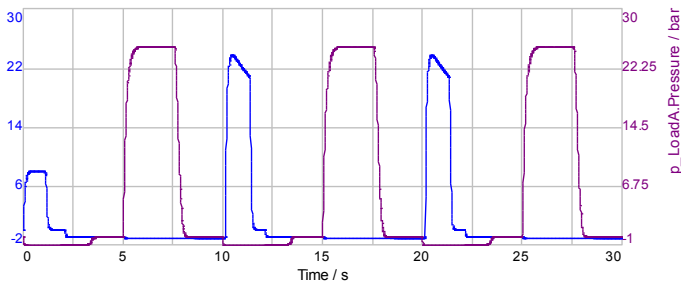
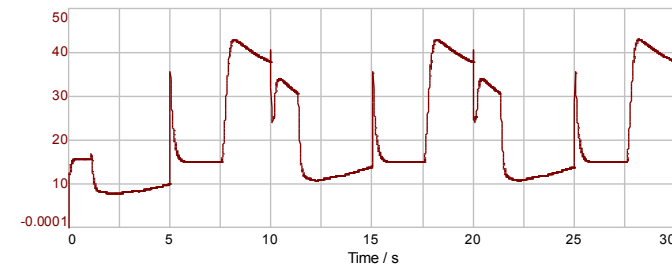
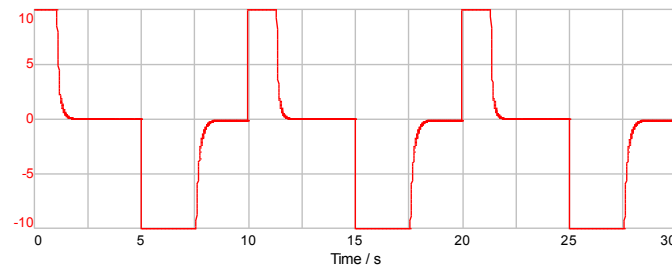
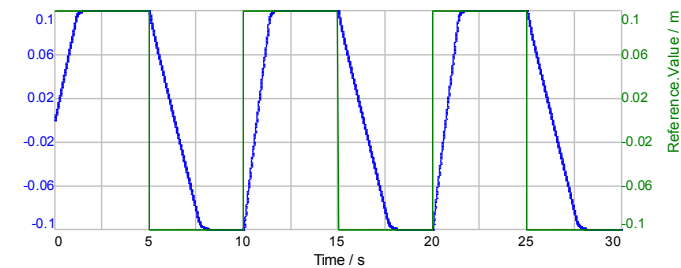
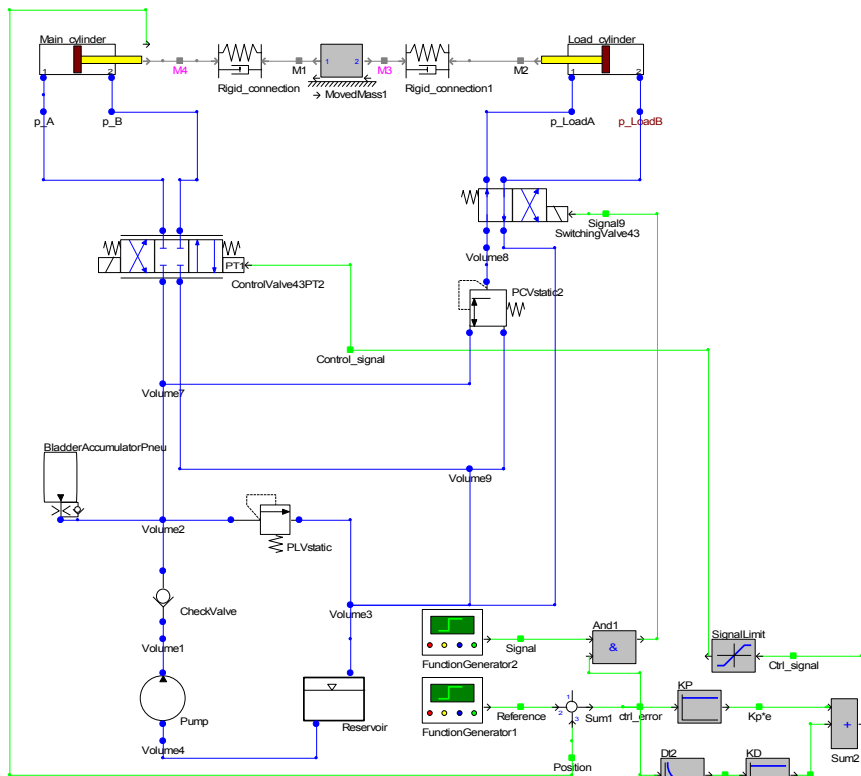


Simulacijski rezultati - CILINDAR



Simulacijski rezultati - MOTOR





Jednadžba protoka:

$$Q_L = C_d w \sqrt{\frac{2}{\rho} \left(\frac{p_s - p_L}{2} \right)} y_v$$

Linearizacija:

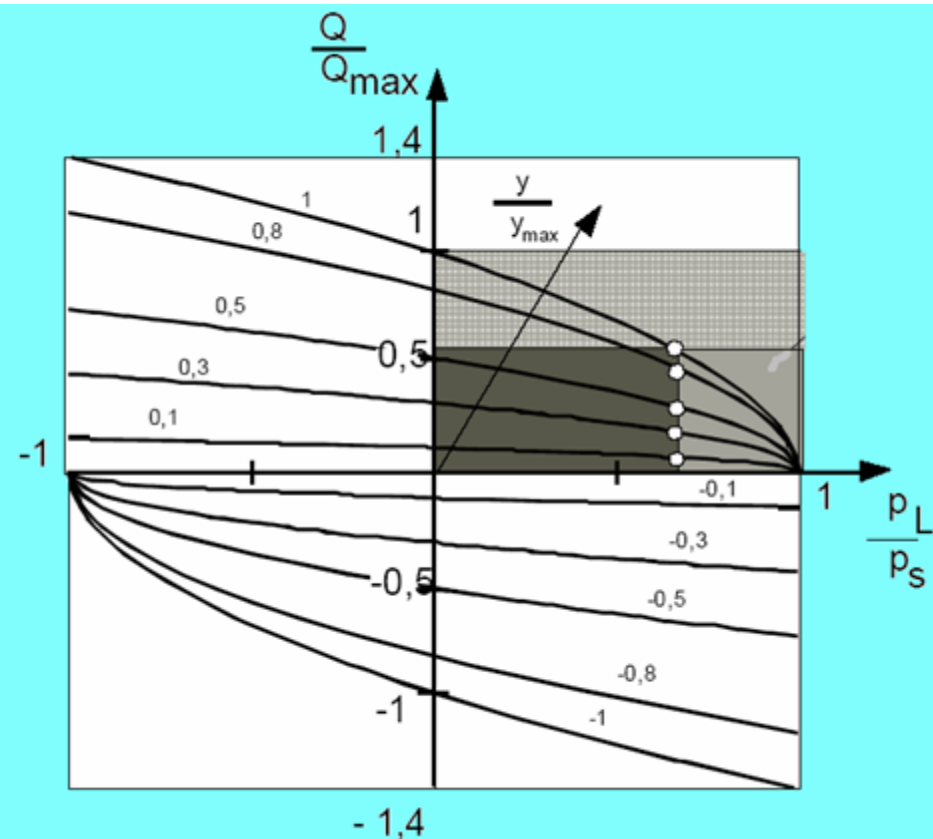
$$\Delta Q_L = \frac{\partial Q_L}{\partial y_v} \Delta y_v + \frac{\partial Q_L}{\partial p_L} \Delta p_L$$

$$\frac{\partial Q_L}{\partial y_v} = C_d d_v \pi \sqrt{\frac{p_s - p_L}{\rho}} = K_q$$

→ Koeficijent pojačanja protoka

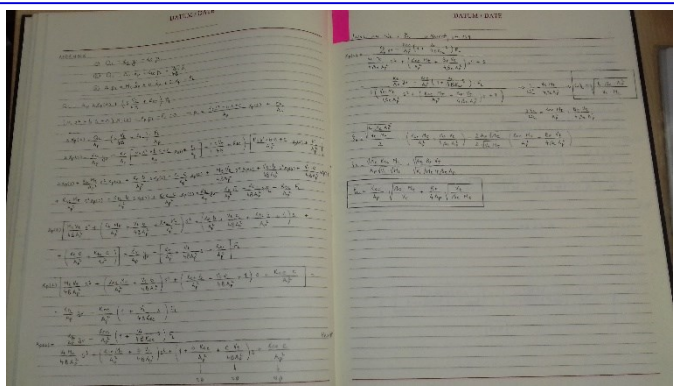
$$\frac{\partial Q_L}{\partial p_L} = \frac{C_d d_v \pi y_v \sqrt{\frac{p_s - p_L}{\rho}}}{2(p_s - p_L)} = K_c$$

→ Koeficijent istjecanja ventila



$$\begin{aligned} Q_L &= K_q \cdot y_v - K_c \cdot p_L \\ Q_L &= A_p \cdot \dot{x}_p + K_{tc} \cdot p_L + \frac{V_t}{4B} \cdot \dot{p}_L \\ A_p \cdot p_L &= M_t \cdot \ddot{x}_p + b \cdot \dot{x}_p + c \cdot x_p + F_L \end{aligned}$$

$$\begin{aligned} &\vdots \\ x_p(s) &= \frac{\frac{K_q}{A_p} y_v(s) - \frac{K_{ce}}{A_p^2} \left(1 + \frac{V_t}{4B K_{ce}} s \right) \cdot F_L(s)}{\frac{V_t M_t}{4B A_p^2} s^3 + \left(\frac{K_{ce} M_t}{A_p^2} + \frac{b \cdot V_t}{4B A_p^2} \right) s^2 + \left(1 + \underbrace{\frac{b \cdot K_{ce}}{A_p^2}}_{\approx 0} + \underbrace{\frac{c \cdot V_t}{4B A_p^2}}_{\approx 0} \right) s + \underbrace{\frac{K_{ce} \cdot c}{A_p^2}}_{\approx 0}} \end{aligned}$$



Položaj klipa:

$$x_p(s) = \frac{\frac{K_q}{A_p} y_v(s) - K_F (\tau s + 1) F_L(s)}{s \left(\frac{1}{\omega_h^2} s^2 + \frac{2\zeta_h}{\omega_h} s + 1 \right)}$$

Vlastita frekvencija

$$\omega_h = \sqrt{\frac{4B A_p^2}{V_t M_t}}$$

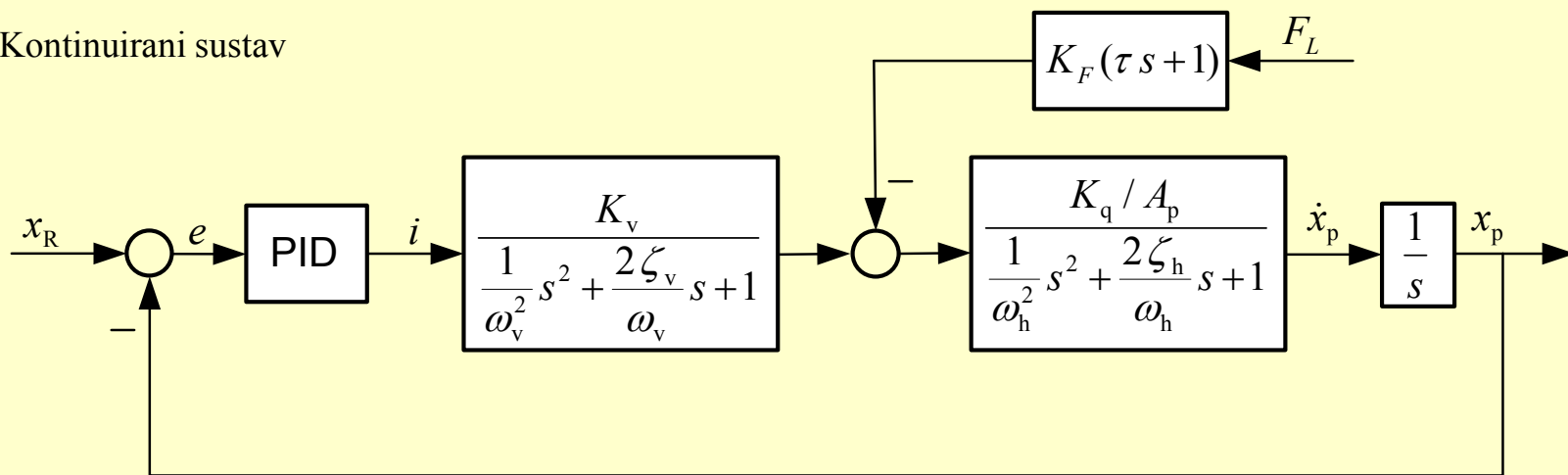
Stupanj prigušenja

$$\zeta_h = \frac{K_{ce}}{A_p} \sqrt{\frac{B M_t}{V_t}} + \frac{b}{4 A_p} \sqrt{\frac{V_t}{B M_t}}$$

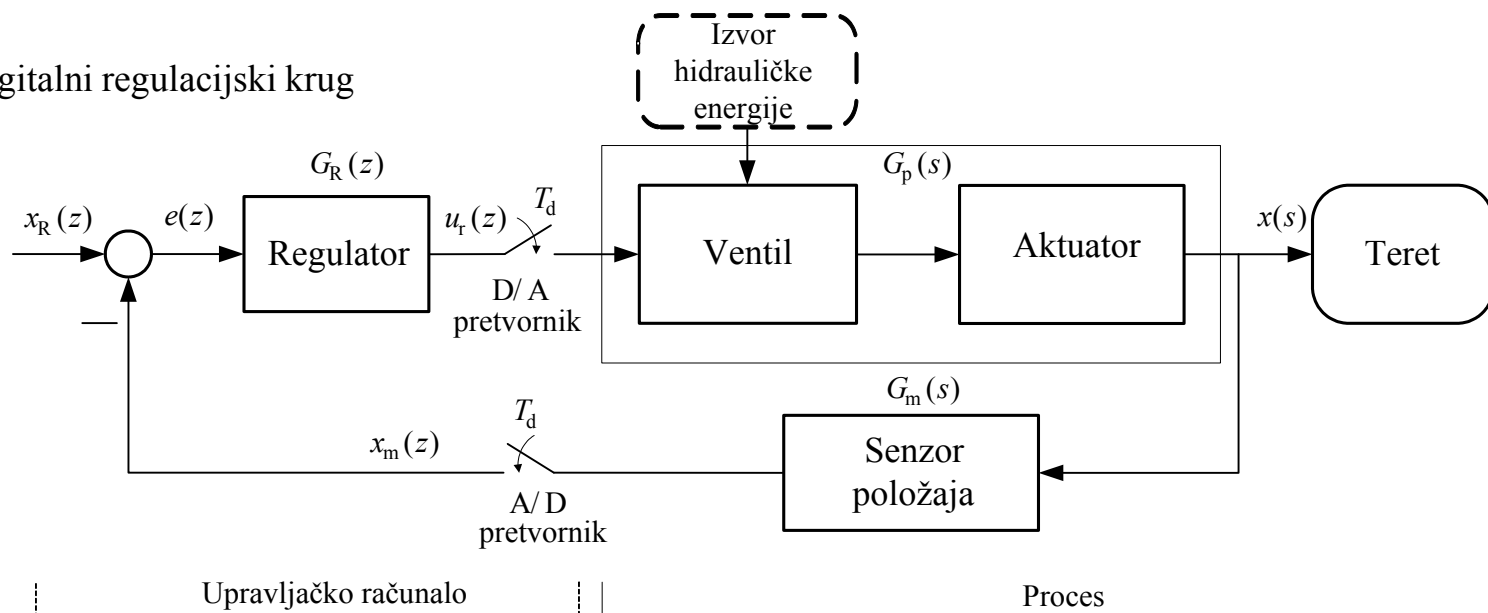
$$\begin{aligned} K_F &= \frac{K_{ce}}{A_p^2} \\ \tau &= \frac{V_t}{4B K_{ce}} \end{aligned}$$

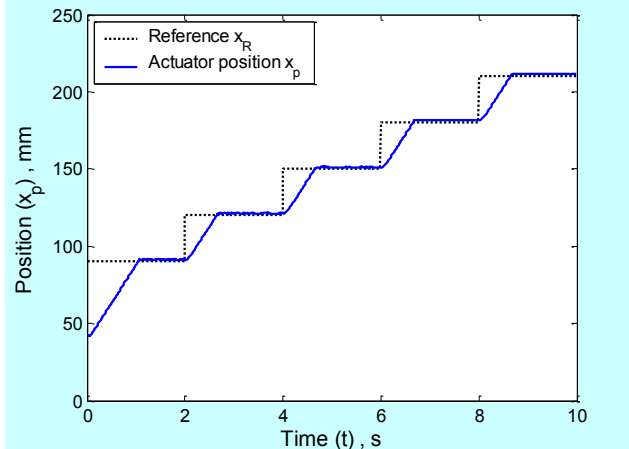
$$K_{ce} = K_c + K_{tc}$$

Kontinuirani sustav

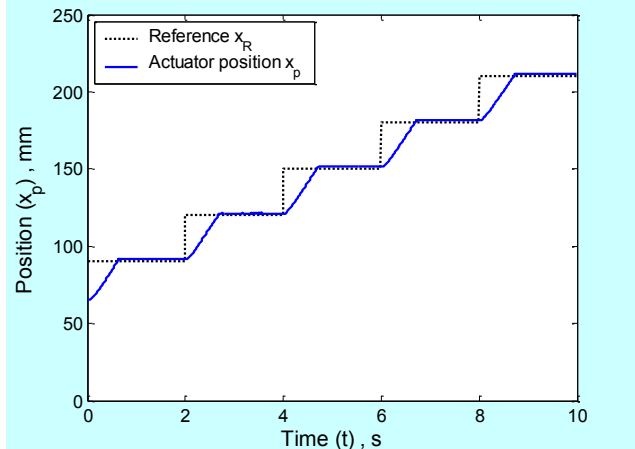


Digitalni regulacijski krug



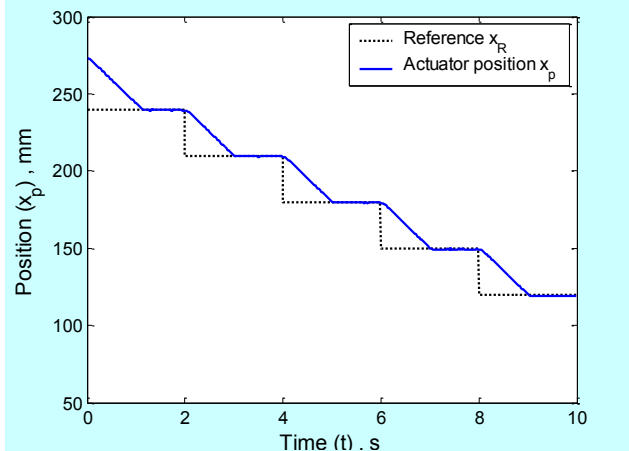
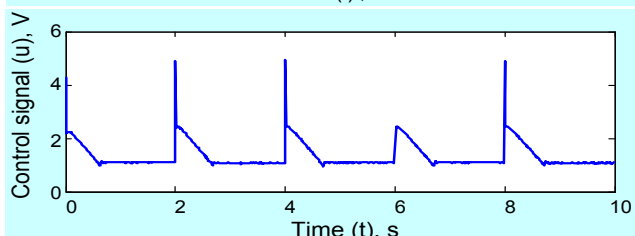
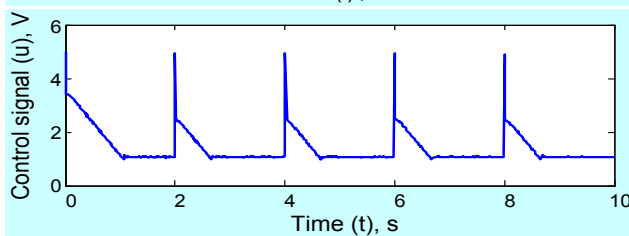


(a)

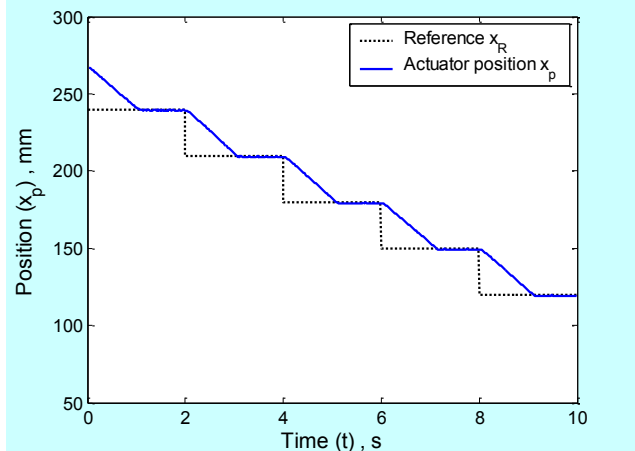


(b)

$F_L = 21500 \text{ N}$

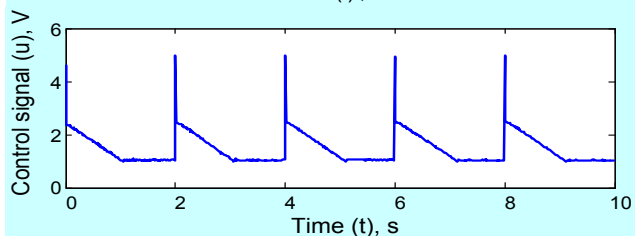
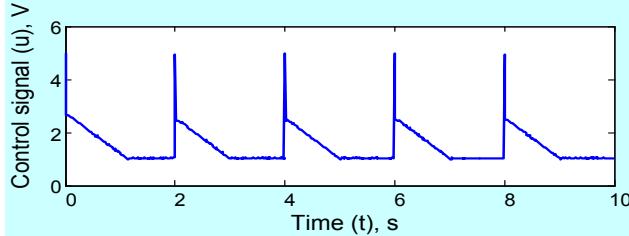


(c)

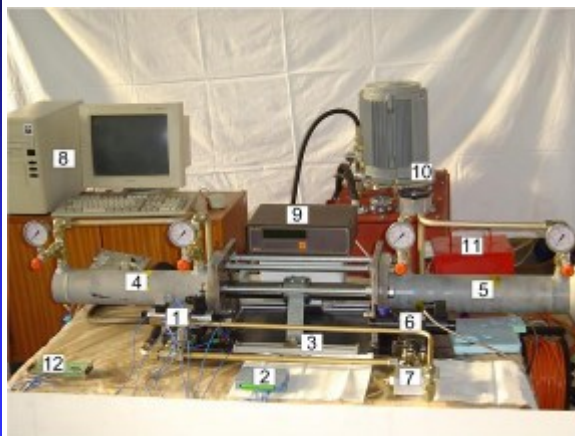
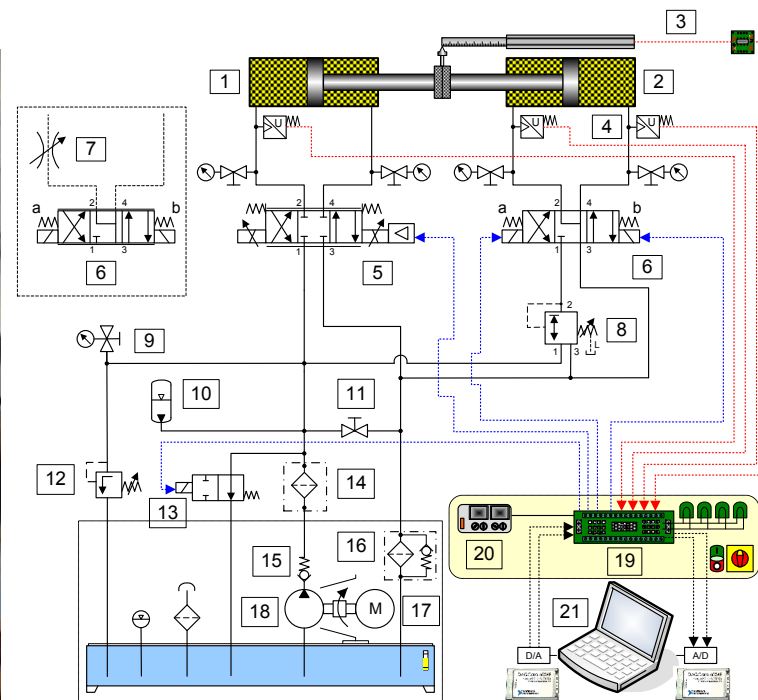


(d)

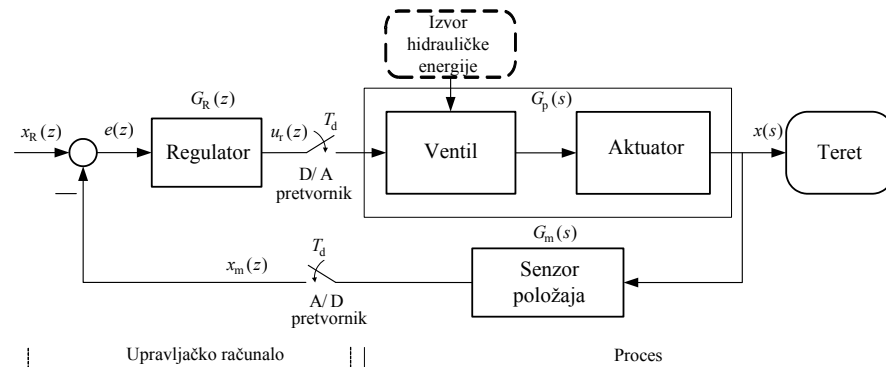
$F_L = 21500 \text{ N}$



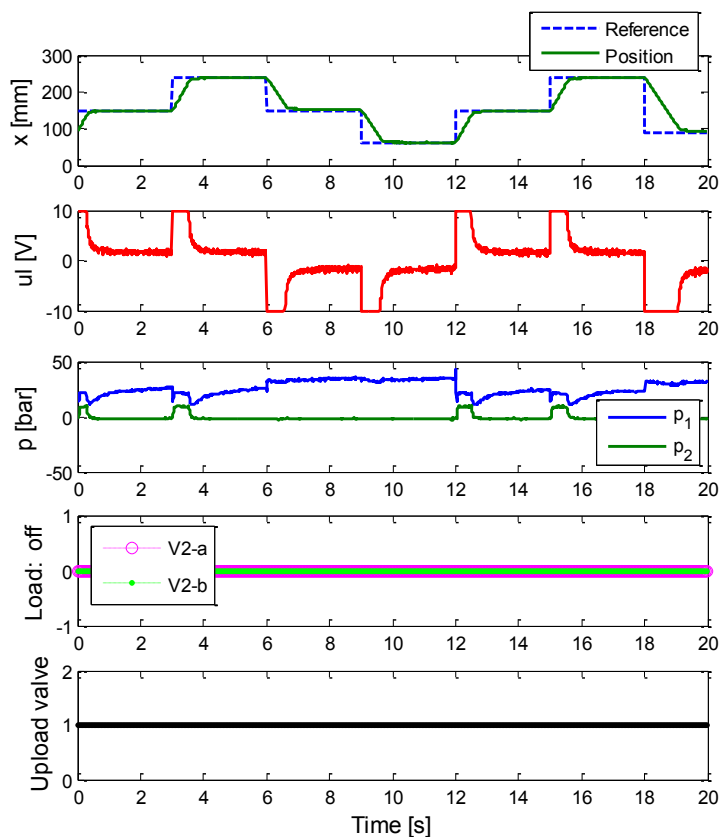
Modul za regulaciju translacijskog gibanja



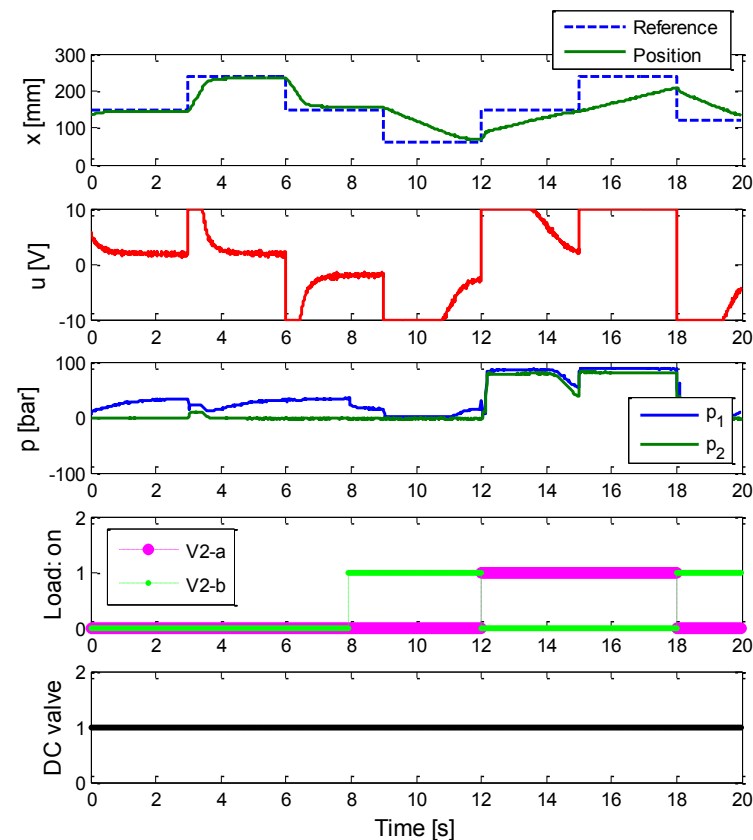
- | | |
|-------------------------------------|--|
| 1–Main cylinder | 12–System pressure relief valve |
| 2–Load cylinder | 13–Upload valve |
| 3–Linear encoder | 14–Pressure filter |
| 4–Pressure sensor | 15–Check valve |
| 5–Proportional control valve | 16–Return flow filter |
| 6– Directional control valve | 17–Electric motor |
| 7–Throttle valve | 18–Gear pump |
| 8–Pressure control valve | 19–Electronic interface |
| 9–Pressure gauge | 20–DC power supply unit |
| 10–Hydraulic accumulator | 21– Control computer with DAQ/control card |
| 11–Shut-off valve | |



With integrated electronics (OSE)
Type 4VRAE...

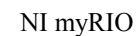
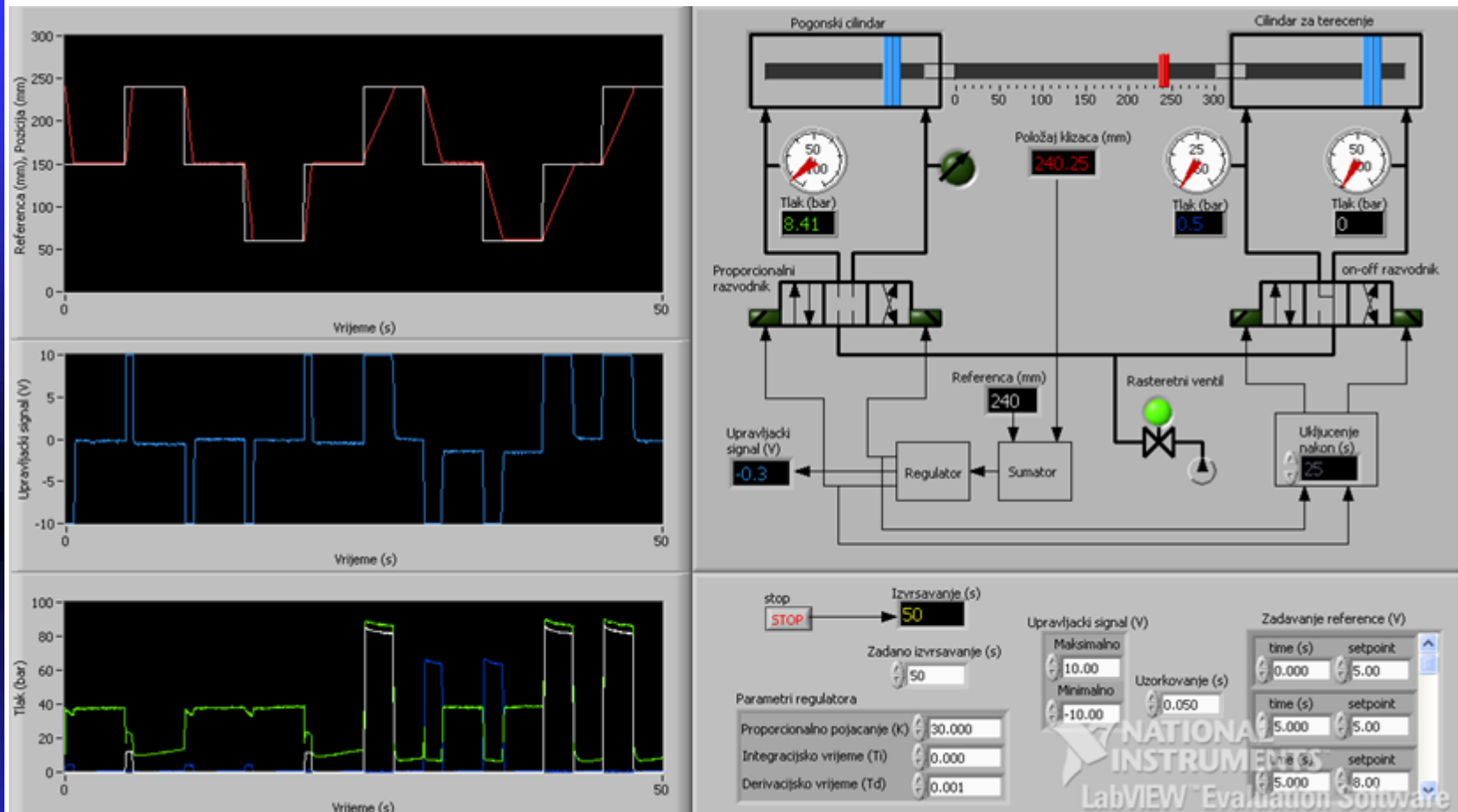


Bez opterećenja



S opterećenjem

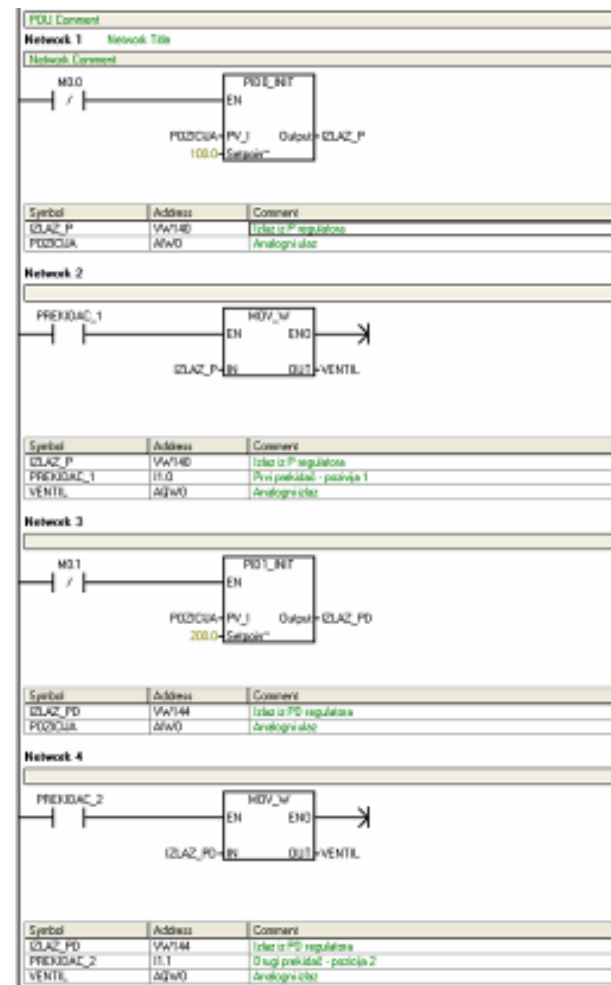
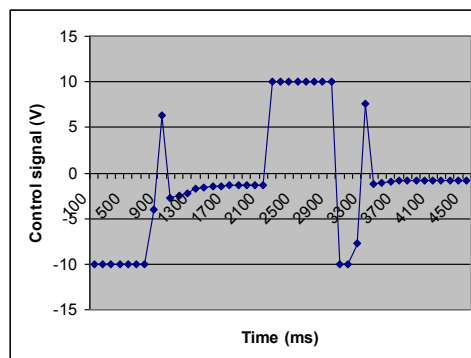
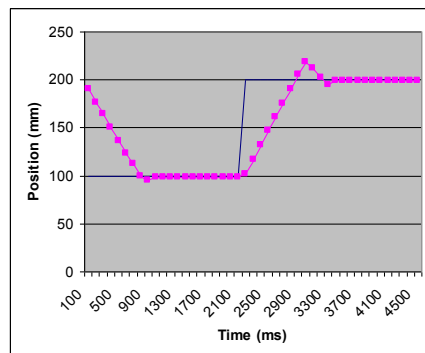
Regulacija hidrauličkog sustava pomoću grafičkog programa **LabVIEW** i upravljačkog uređaja **CompactRIO**



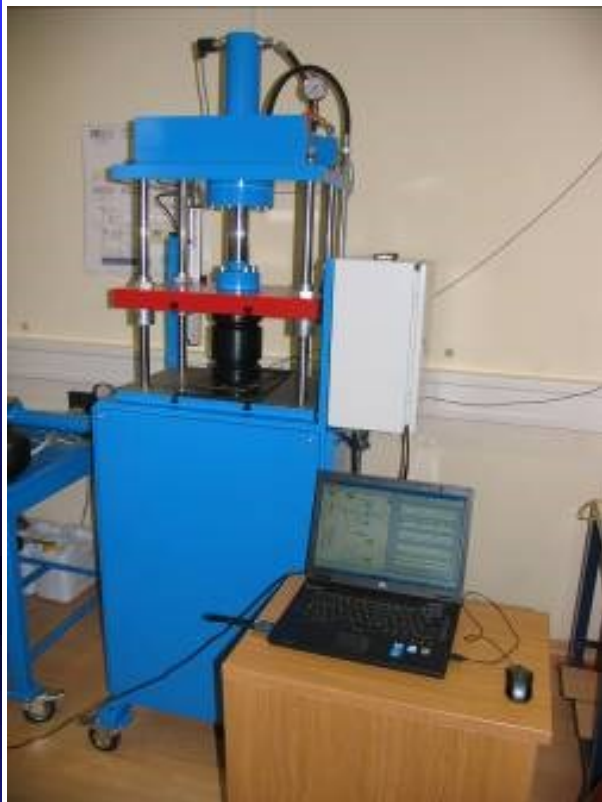
Eksperimentalni rezultati

Upravljački uređaj - PLC

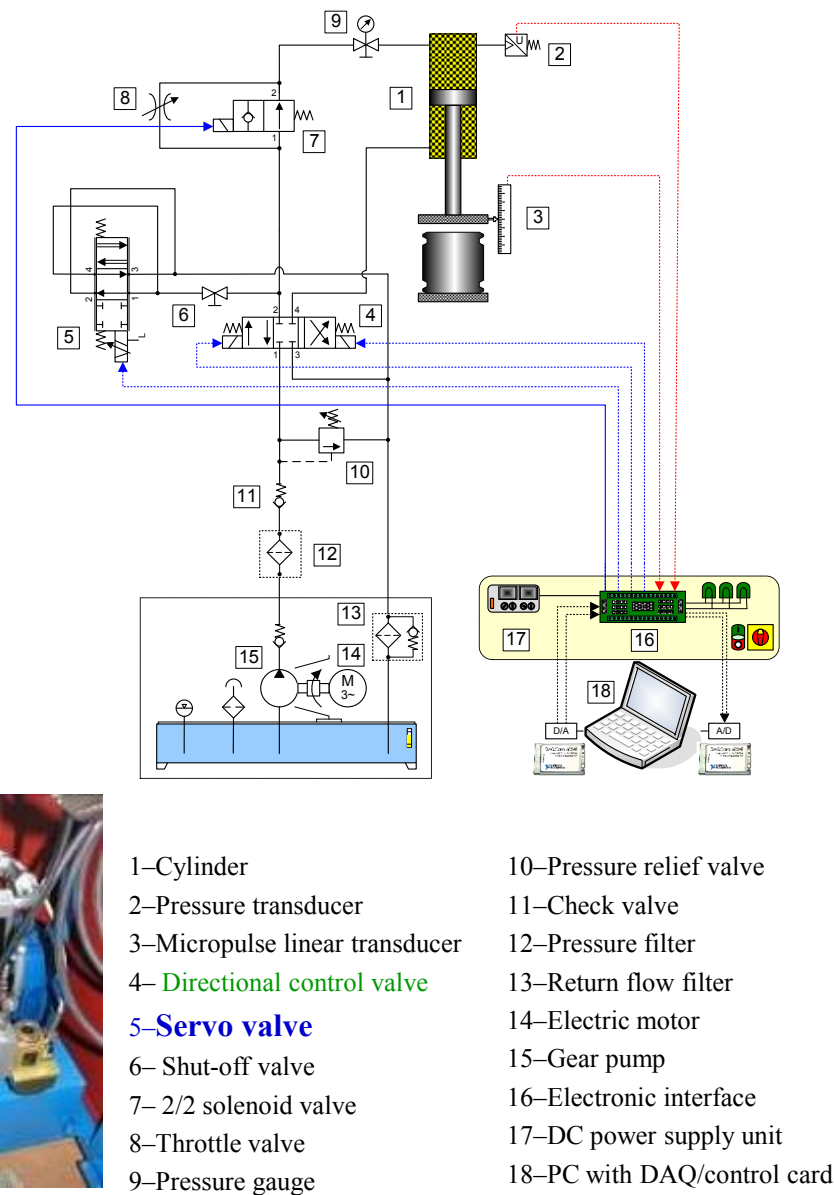
- Regulacija hidrauličkog sustava primjenom SIMATIC S7-200 PLC-a

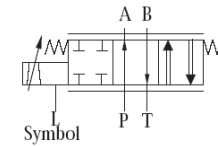
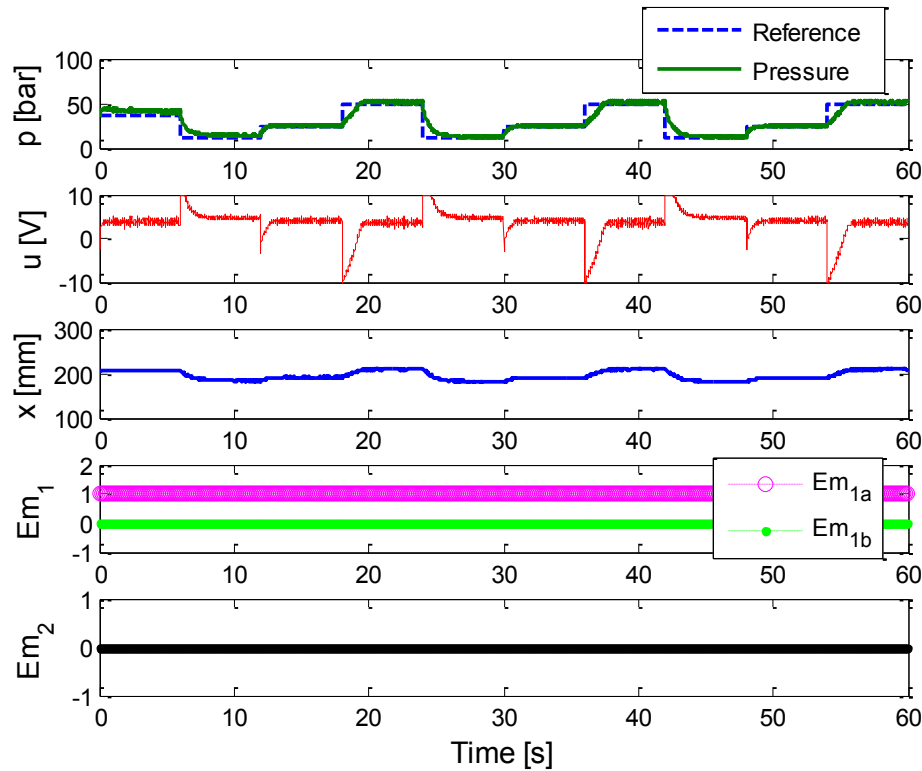


Modul za regulaciju sile (hidraulička preša)

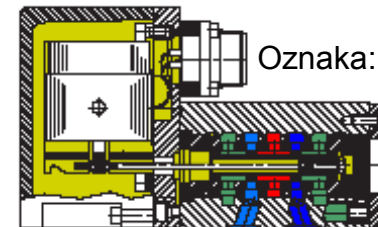


Stražnja strana

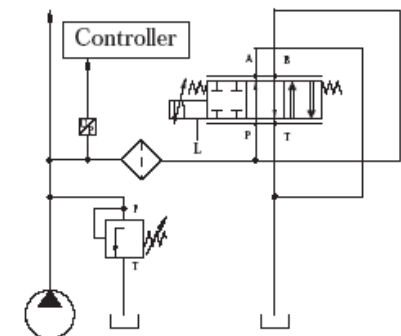




Schneider
KREUZNACH

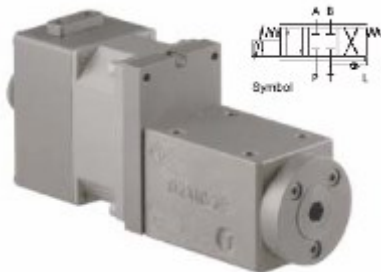
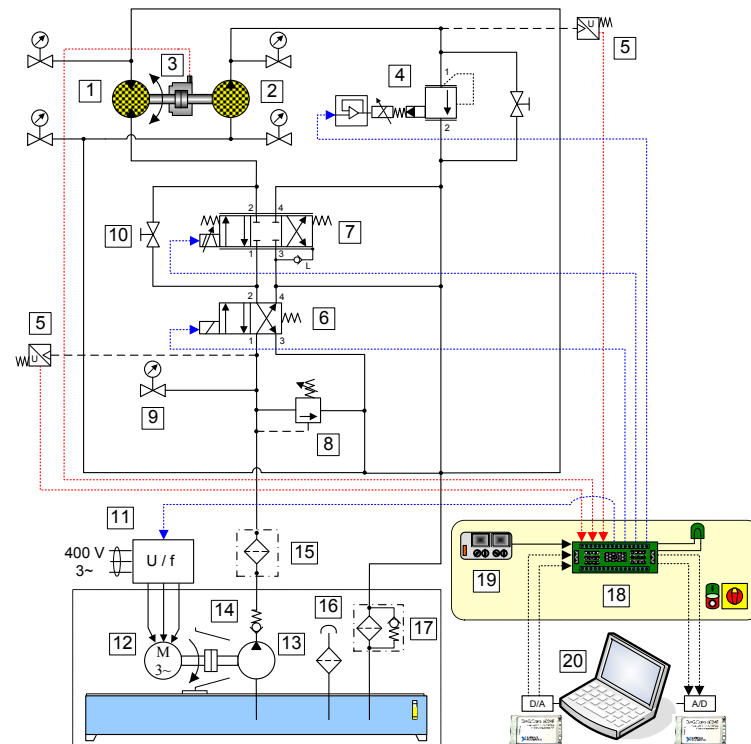
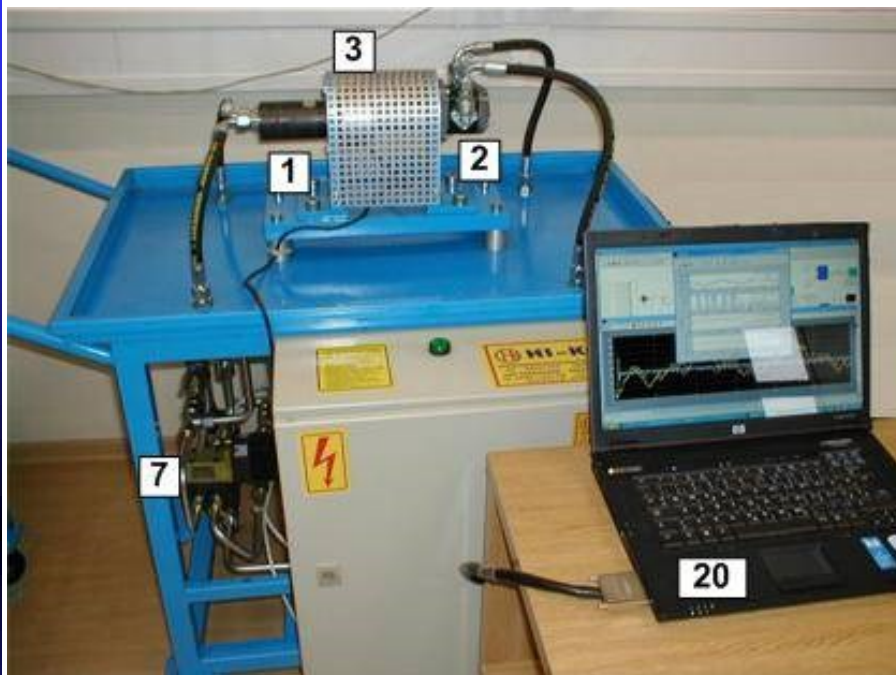


Oznaka: HVM 025-005-1200-0



Modul za regulaciju sile

Modul za regulaciju rotacijskog gibanja



Schneider
KREUZNACH
HVM 061-005-1300-0A-E1



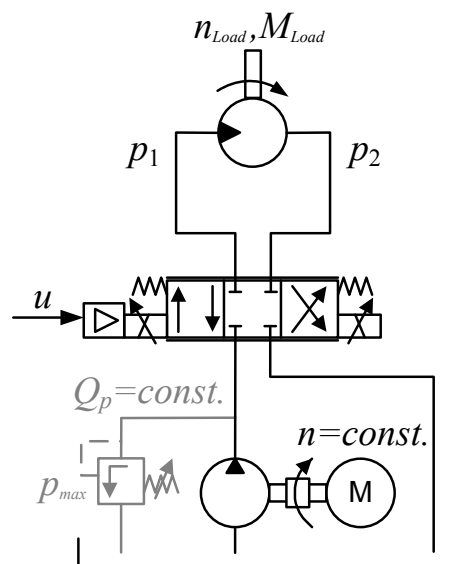
SIEMENS
SINAMICS G110

- 1 – Hydraulic motor (gerotor)
- 2 – Gear pump
- 3 – Rotary encoder
- 4 – Proportional pressure valve
- 5 – Pressure transducer
- 6 – Directional control valve
- 7 – **Servo valve**
- 8 – System pressure relief valve
- 9 – Pressure gauge
- 10 – Shut-off valve

- 11 – **Frequency converter**
- 12 – Electric motor
- 13 – Gear pump
- 14 – Check valve
- 15 – Pressure filter
- 16 – Filter for filling
- 17 – Return flow filter
- 18 – Electronic interface
- 19 – DC power supply unit
- 20 – PC with DAC card

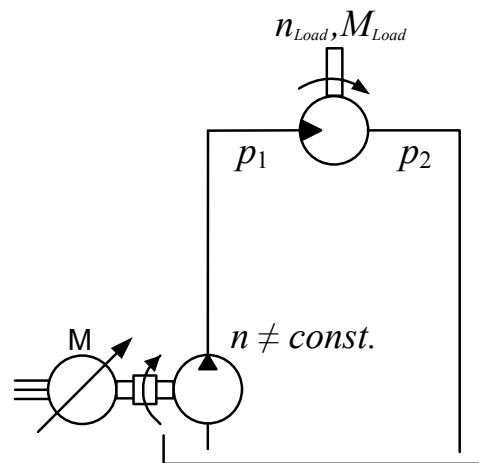
■ OSNOVNI NAČINI UPRAVLJANJA HIDRAULIČKOM ENERGIJOM

RESISTIVE CONTROL PRINCIPLE

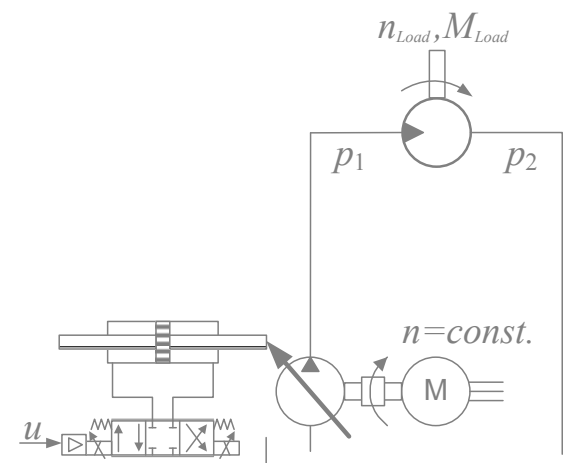


Throttling on proportional
or servo valve

VOLUMETRIC CONTROL PRINCIPLE



Variable-speed electric motor
+
Constant displacement pump



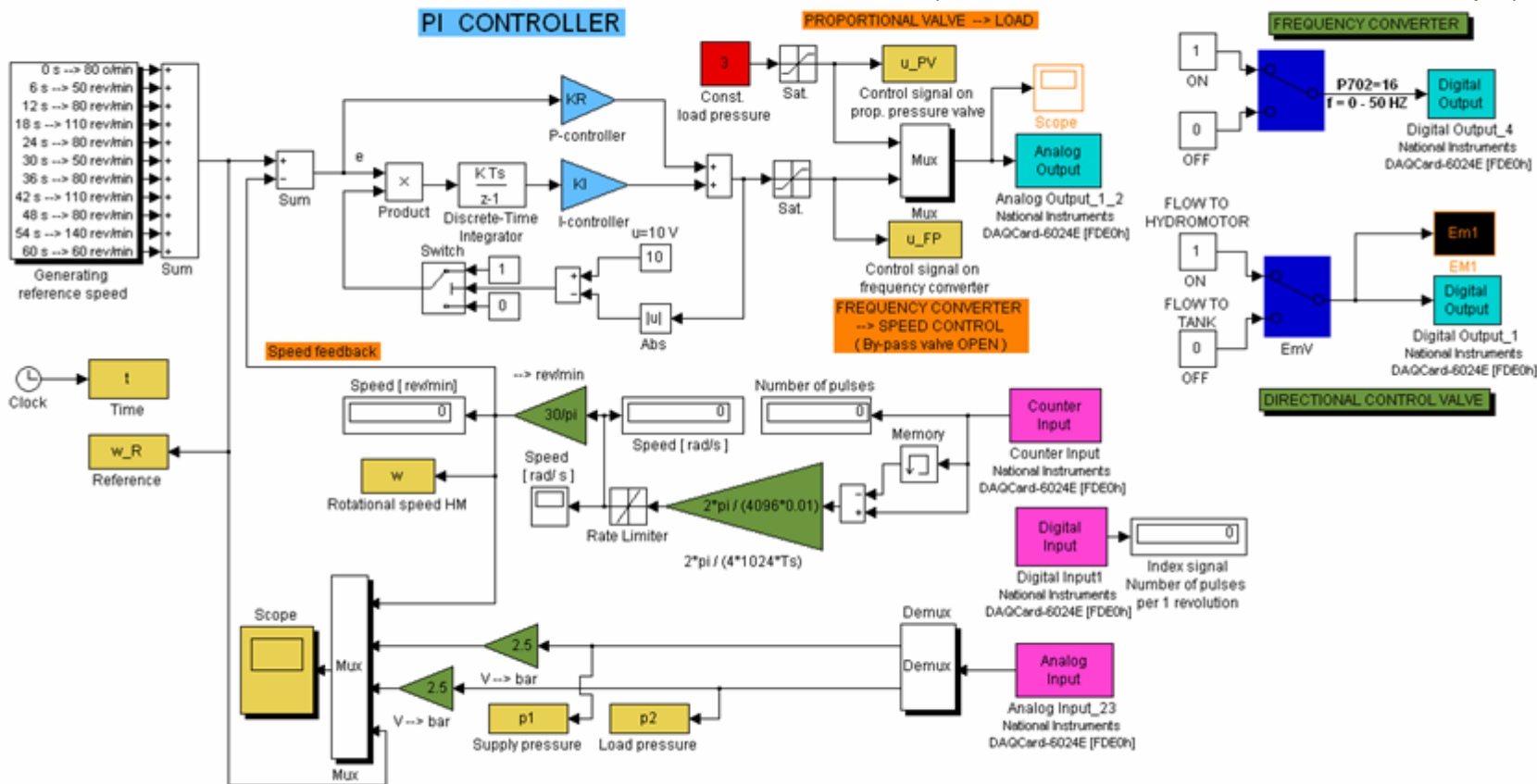
Constant-speed electric motor
+
Variable displacement pump

Upravljački program

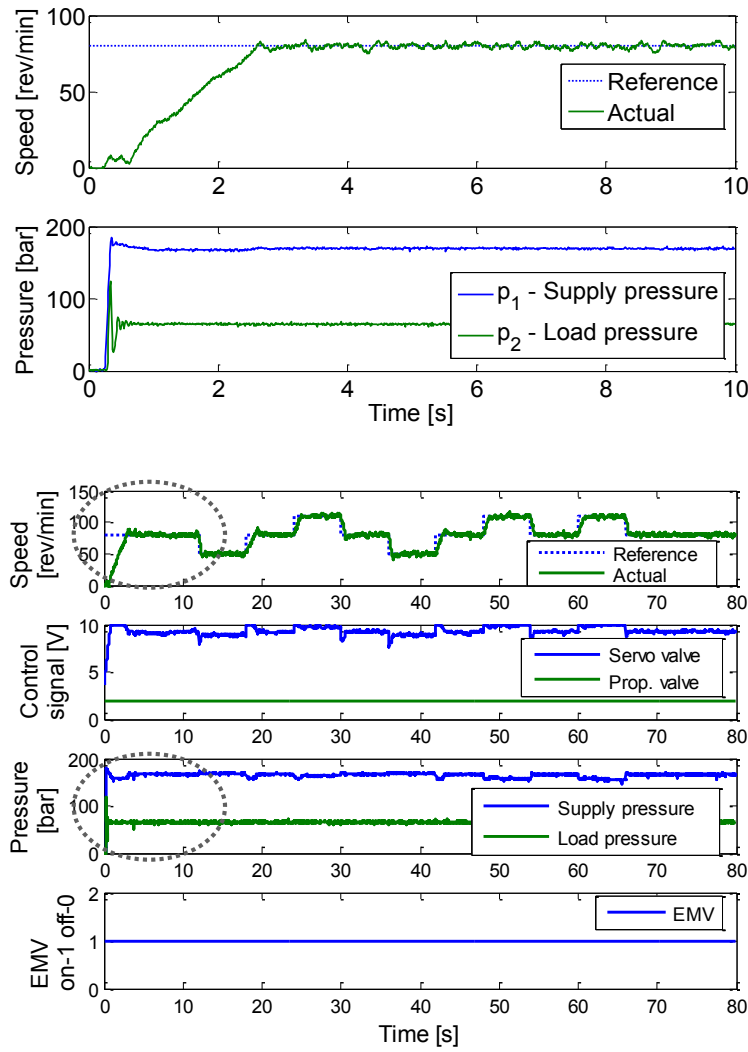


SPEED CONTROL USING VOLUMETRIC CONTROL PRINCIPLE

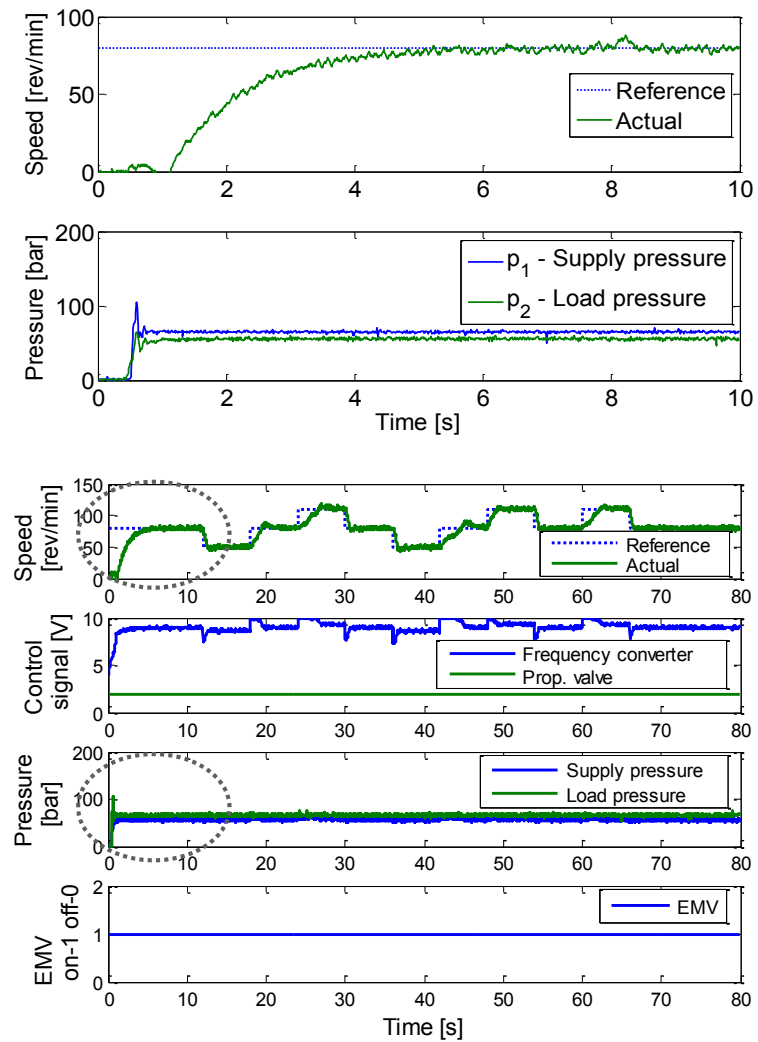
(MATLAB/SIMULINK/Real-Time Workshop®)



■ Princip prigušenja radnog fluida



■ Princip promjene volumena radnog fluida





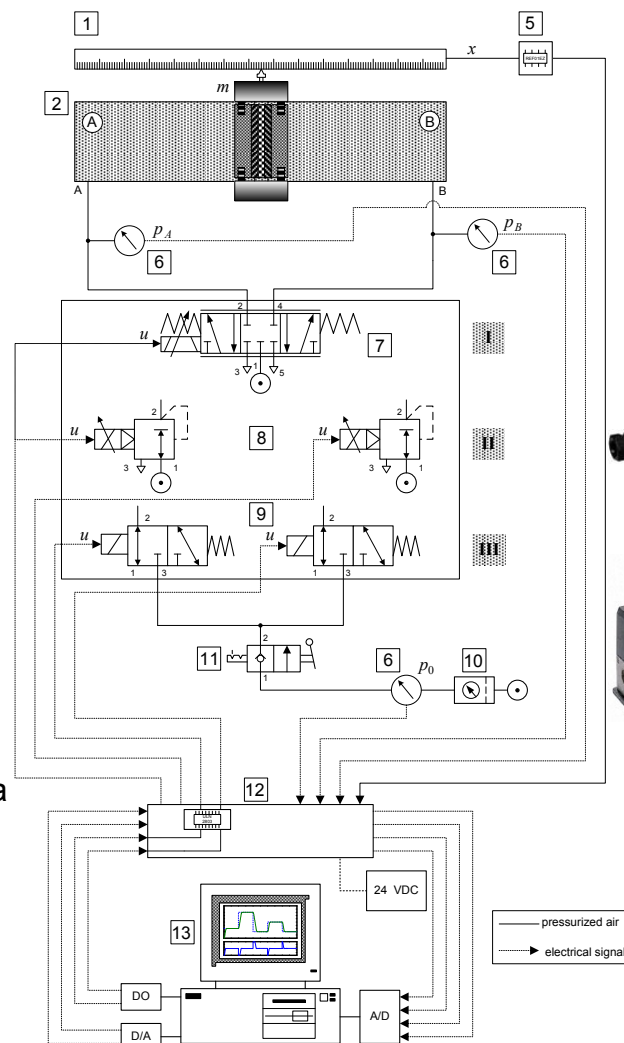
- 1 - linearni potencijometar
- 2 - pneumatski cilindar bez klipnjače
- 3 - teret mase 3.8 kg
- 4 - rotacioni potencijometar
- 5 - elektronički sklop za održavanje reference napona
- 6 - senzori tlaka

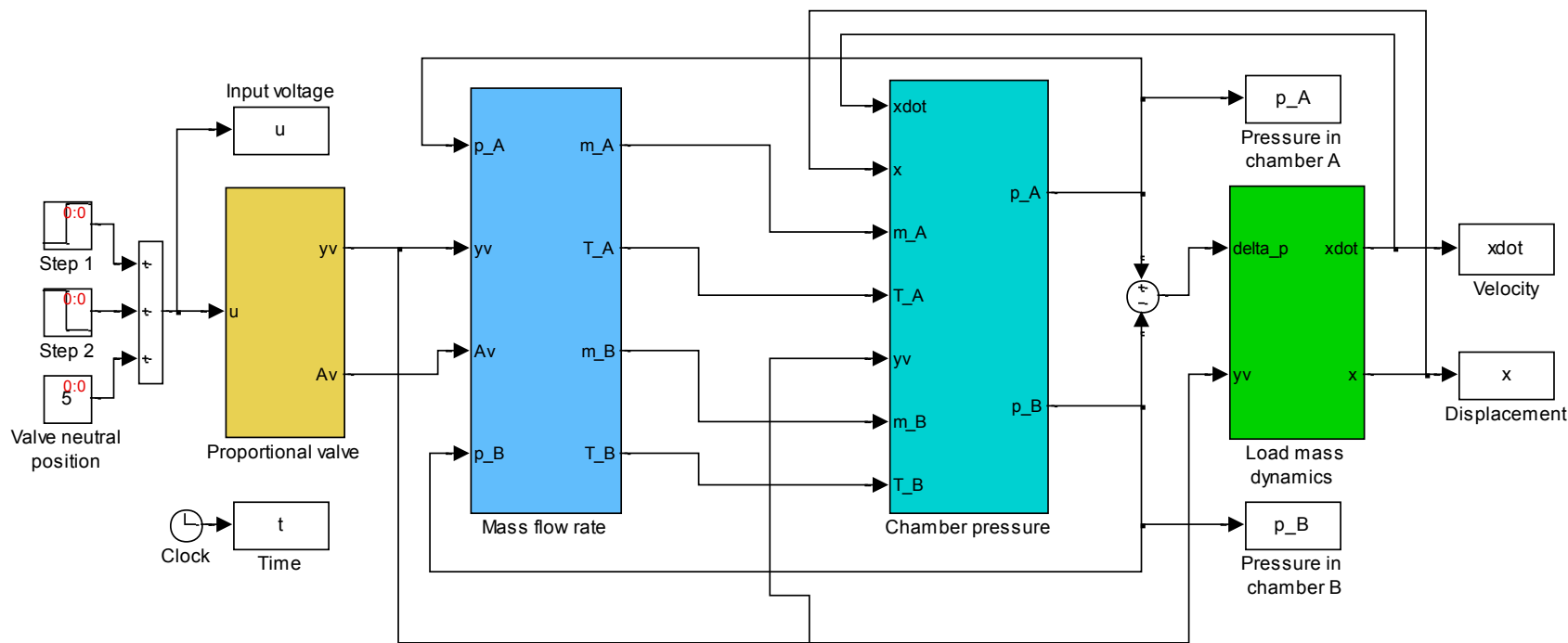
- 7 - proporcionalni ventil
- 8 - proporcionalni tlačni regulatori
- 9 - elektromagnetski dvopoložajni ventili
- 10 - pripremna grupa (filter-regulator-senzor tlaka)
- 11 - ventil za otvaranje/zatvaranje dovoda zraka
- 12 - elektroničko sučelje
- 13 - upravljačko računalo s akvizicijskom karticom

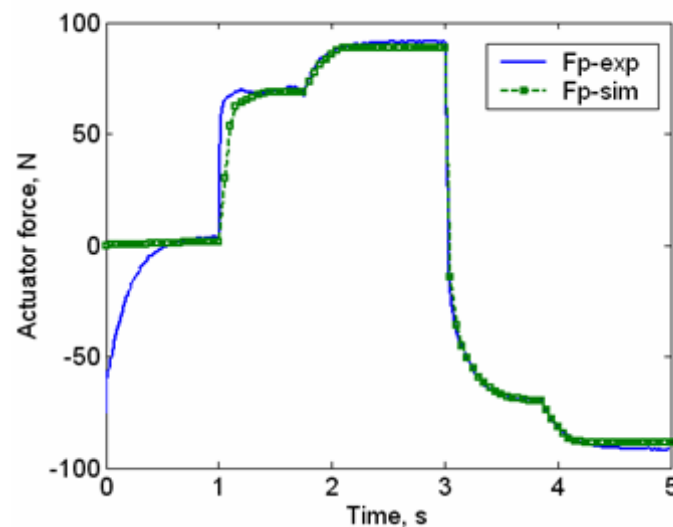
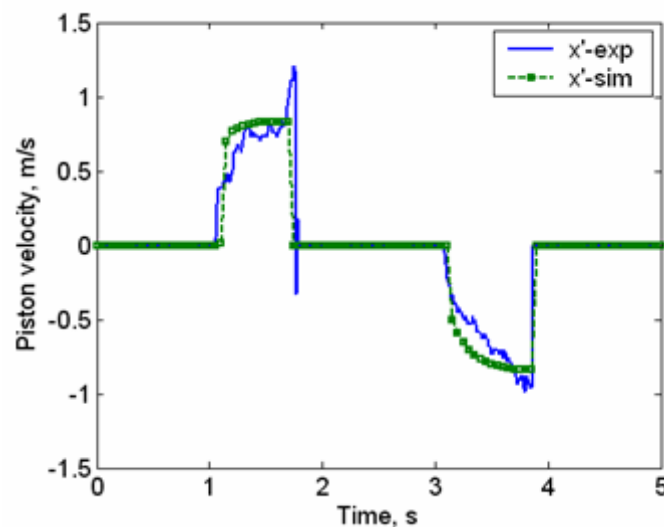
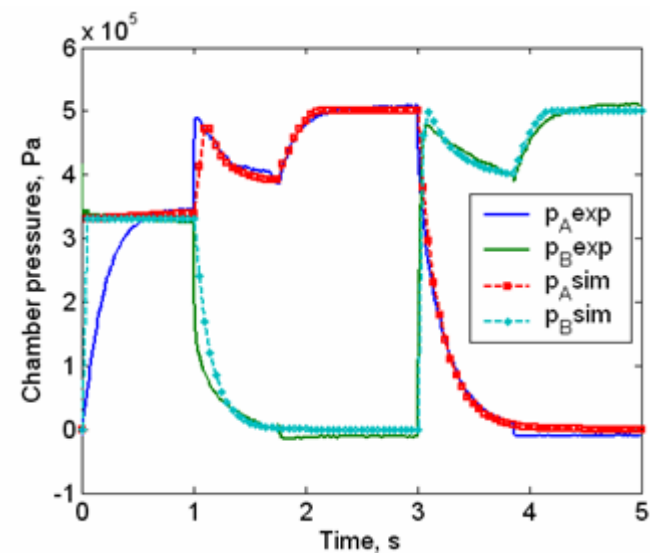
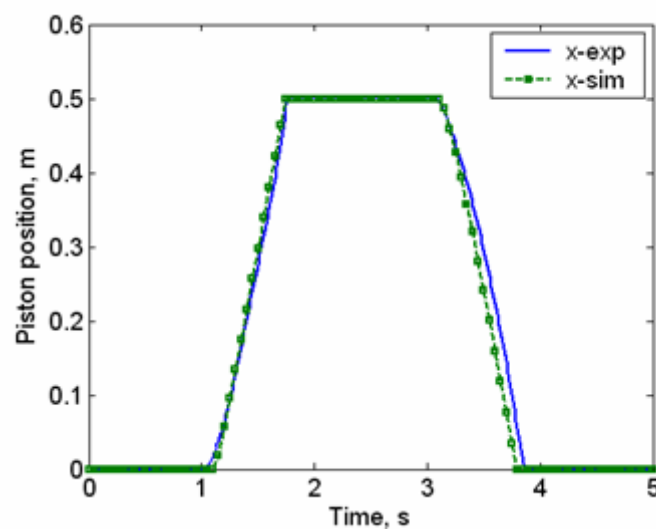
Regulacija pneumatskih sustava

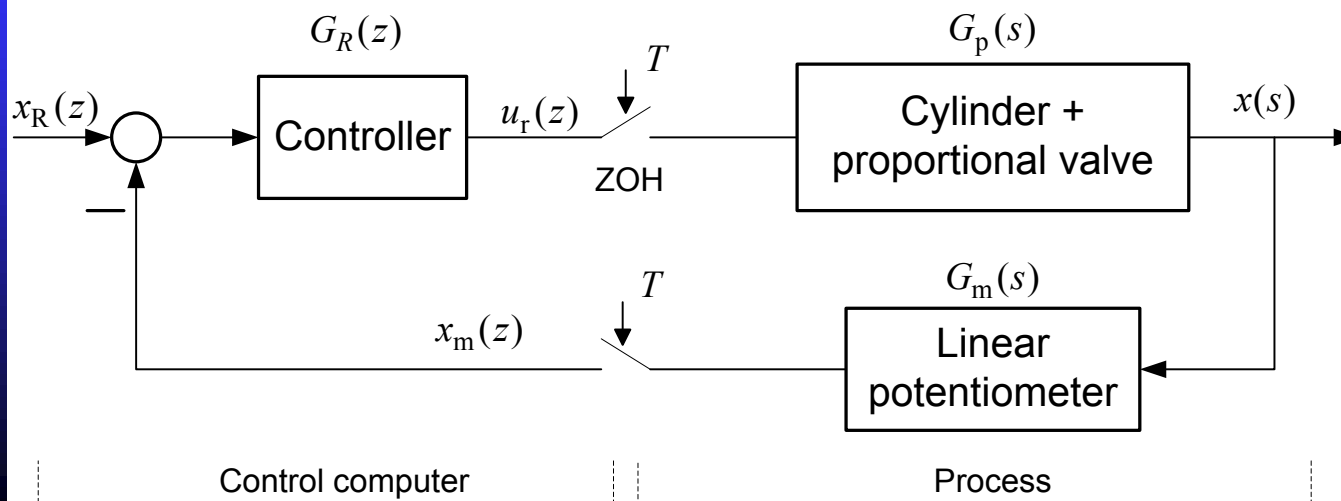


- 1 - linearni potencijometar
- 2 - pneumatski cilindar bez klipnjače
- 3 - teret mase 3.8 kg
- 4 - rotacioni potencijometar
- 5 - elektronički sklop za održavanje reference napona
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- 7 - proporcionalni ventil
- 8 - proporcionalni tlačni regulatori
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- 11 - ventil za otvaranje/zatvaranje dovoda zraka
- 12 - elektroničko sučelje
- 13 - upravljačko računalo s akvizicijskom karticom









Controller structures for position control:

- PD controller
- PVA controller
- PV Δ P controller
- PD-PI controller
- Nonlinear PI controller
- Sliding mode controller
- Fuzzy controller
- Fuzzy PID Gain Scheduling
- ...

Proportional directional control valve

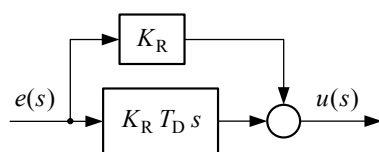
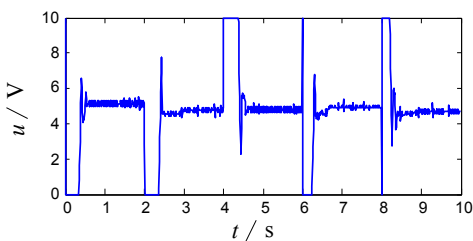
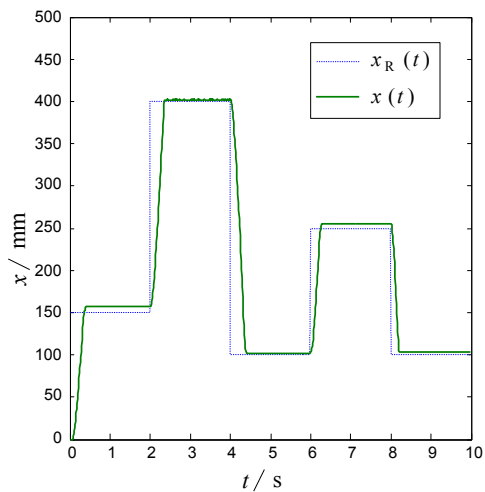


FESTO

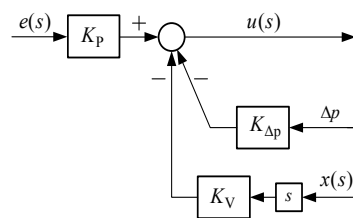
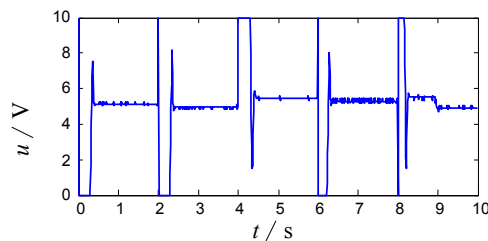
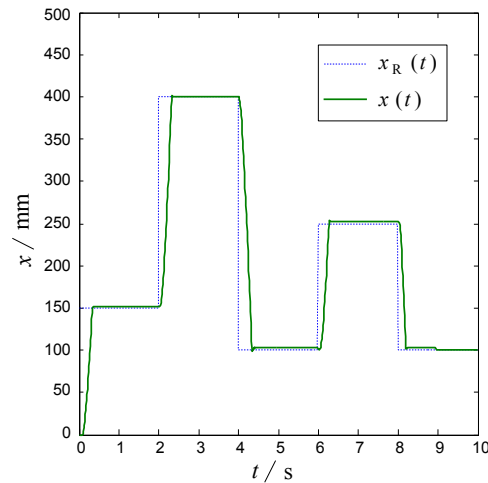
MPYE-5 1/8 HF-010B



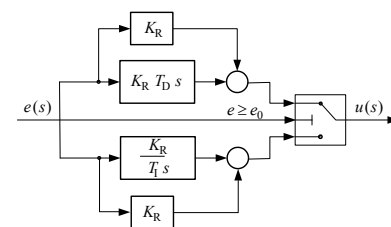
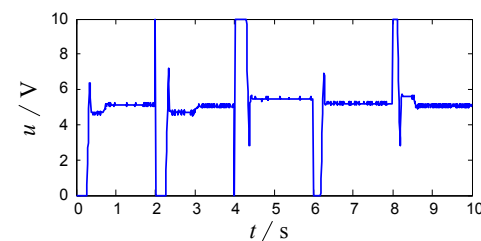
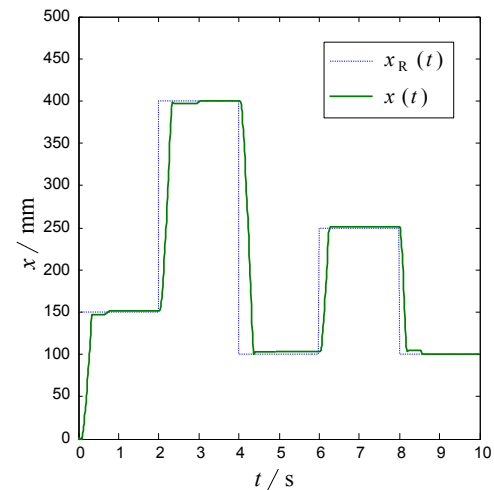
PD controller



PVΔP controller

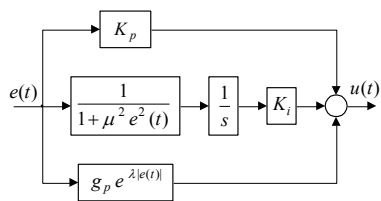
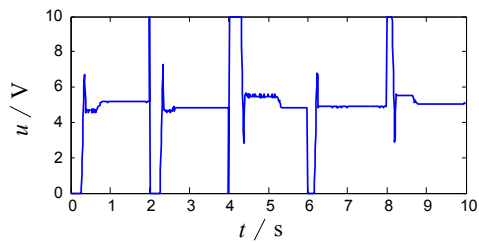
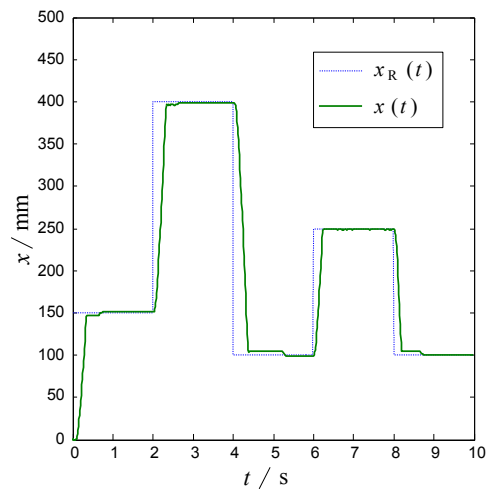


PD-PI controller

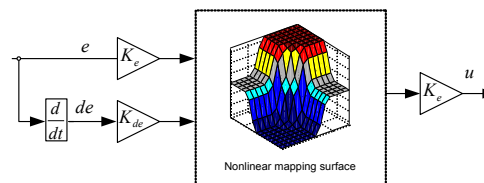
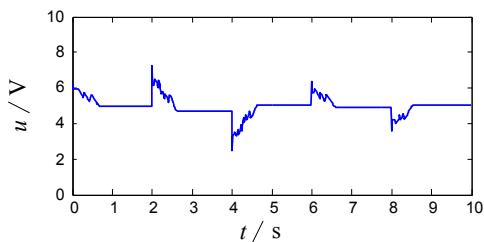
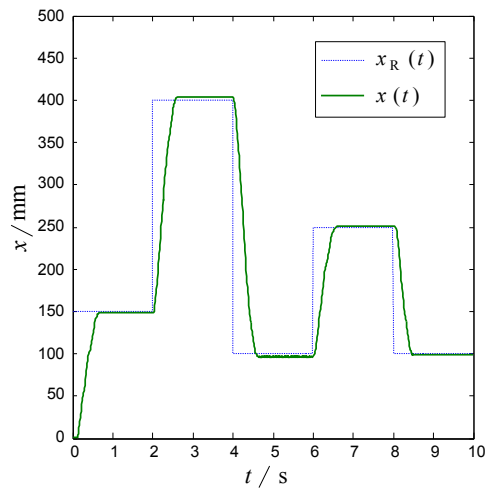




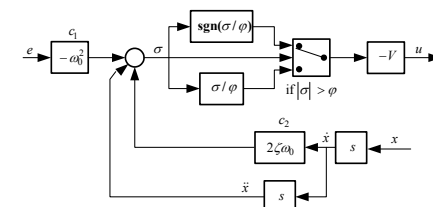
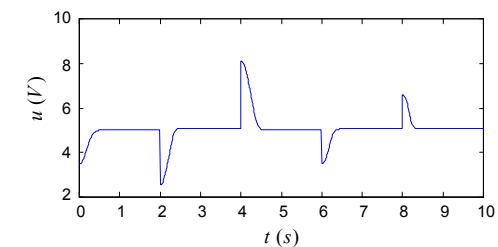
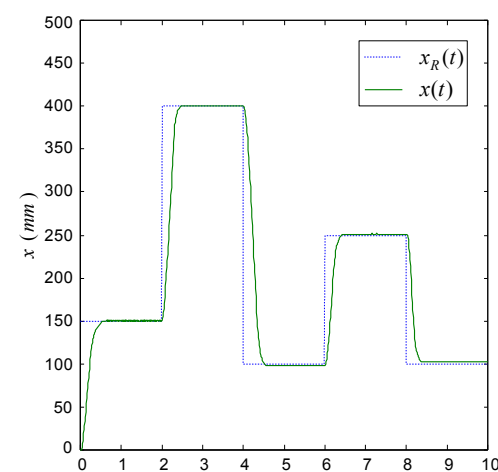
Nonlinear PI controller



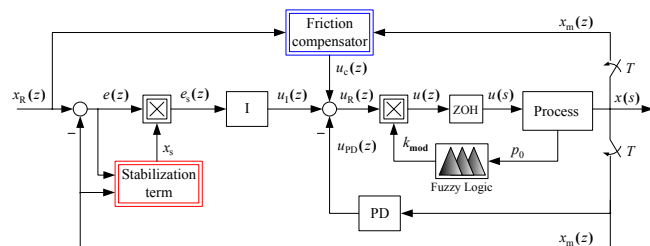
Fuzzy PD controller



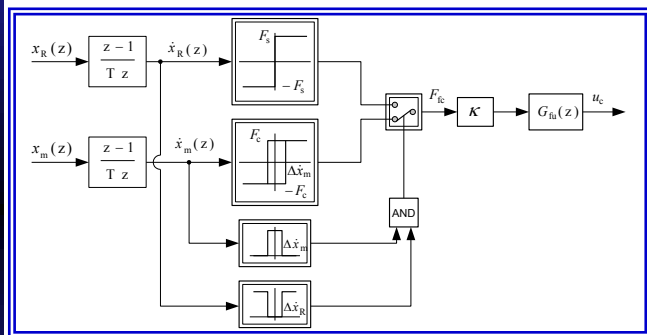
Sliding mode controller



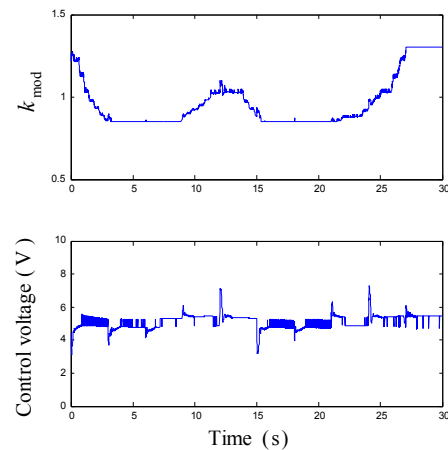
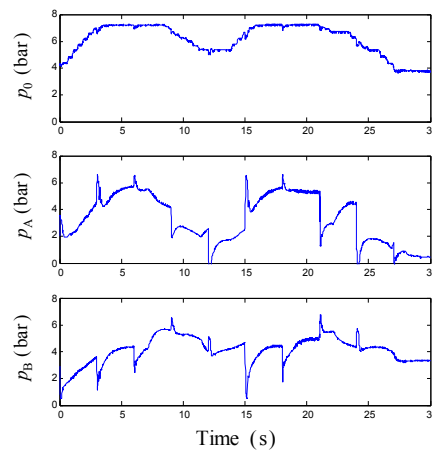
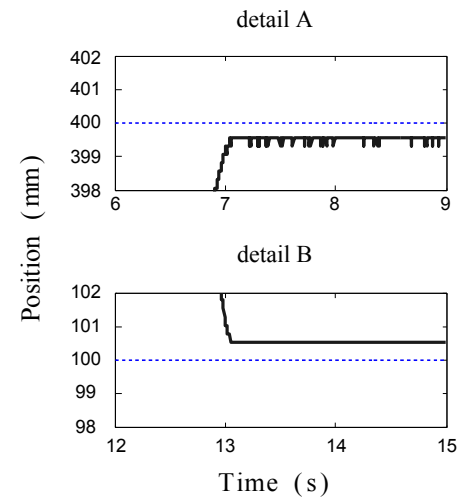
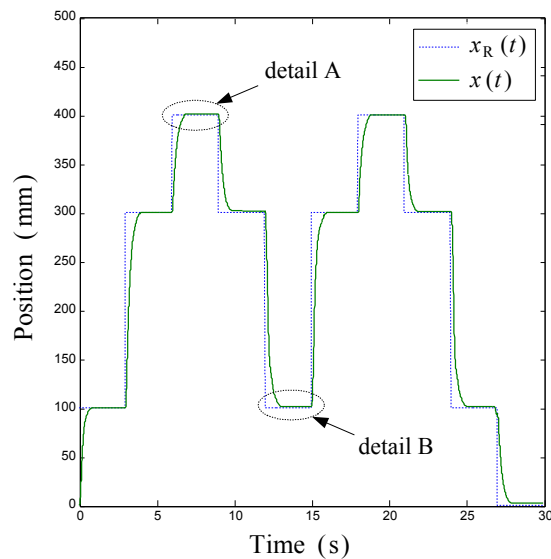
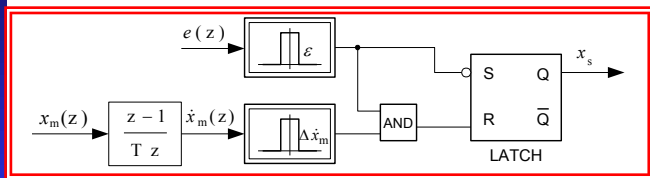
Eksperimentalni rezultati ...



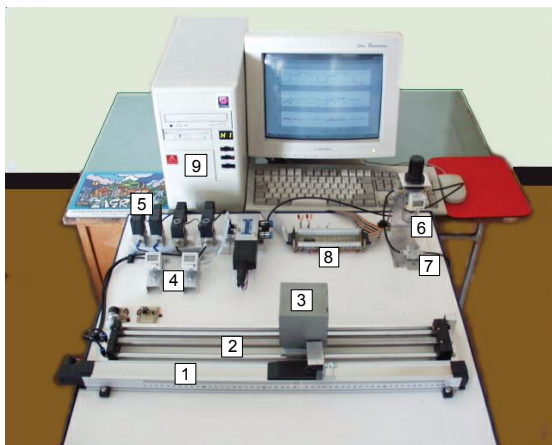
Friction compensator



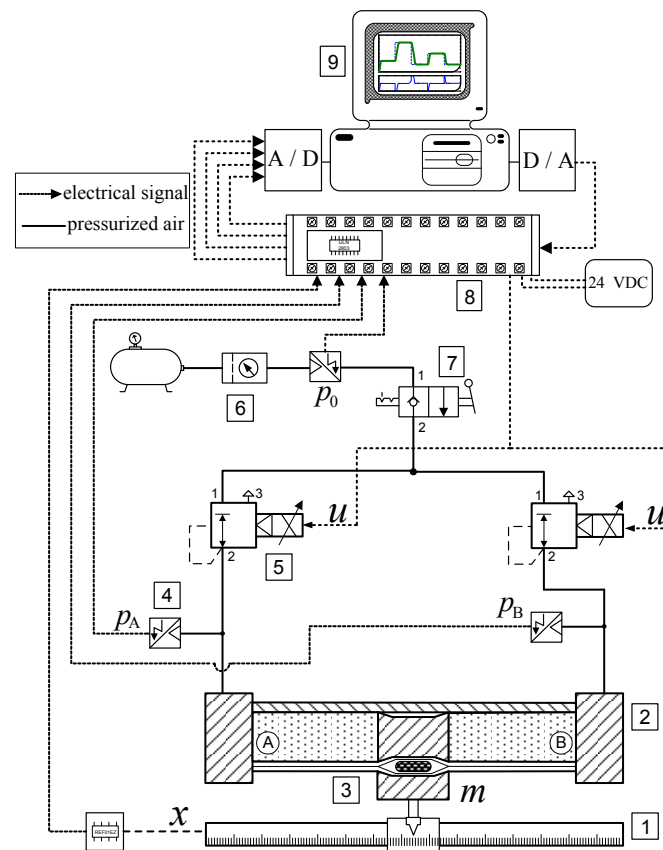
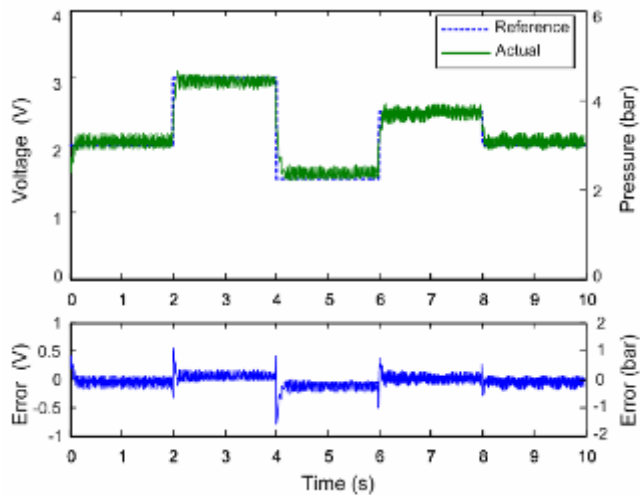
Stabilization term



Regulacija primjenom PROPORCIONALNIH TLAČNIH VENTILA

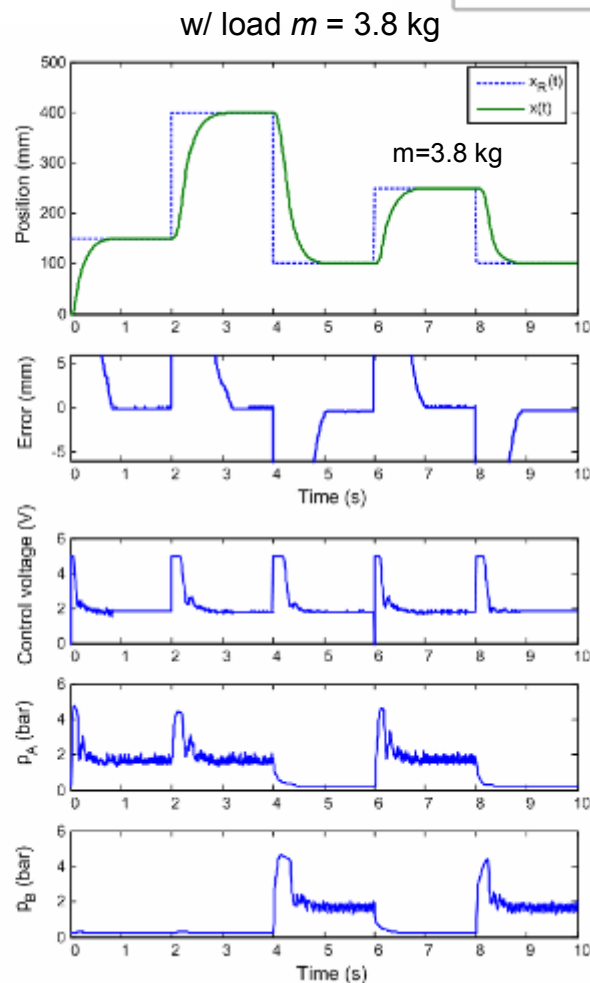
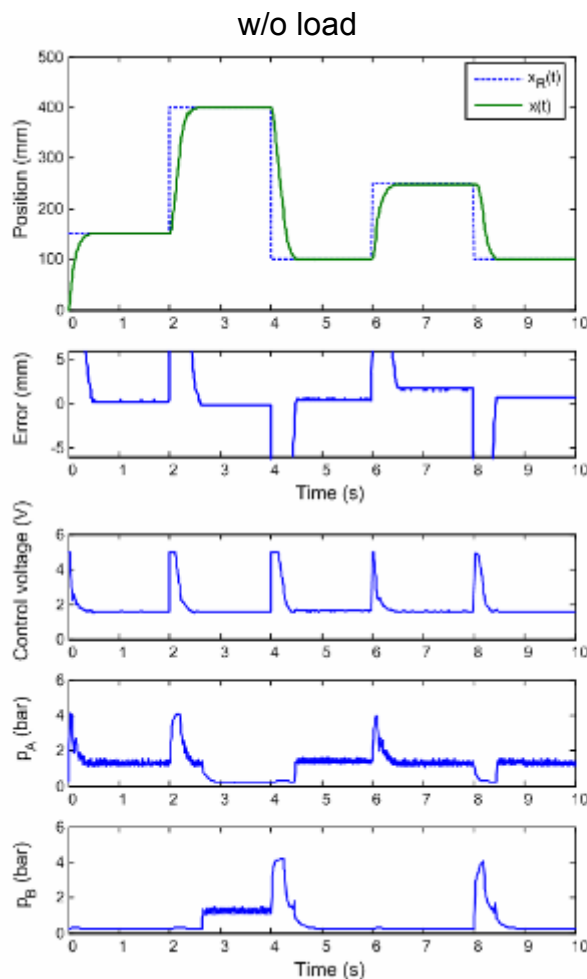
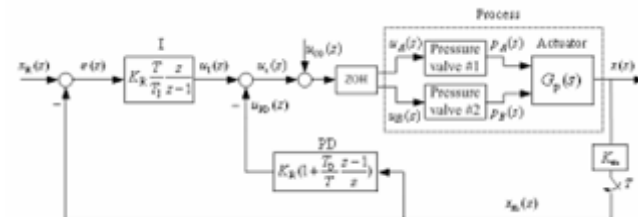


- 1 – Linear potentiometer (Festo MLO-POT-500-TLF),
- 2 – Pneumatic rodless cylinder (SMC CDY1S15H-500),
- 3 – Load mass 3.8 kg,
- 4 – Pressure transducer (SMC ISE4-01-26),
- 5 – E/P control valves (SMC E-P Hyreg VY1A00-M5),
- 6 – Filter-regulator unit,
- 7 – Air supply valve,
- 8 – Electronic interface,
- 9 – Computer with DAC card (Advantech PCL-812PG)



E-P Hyreg VY1A00-M5

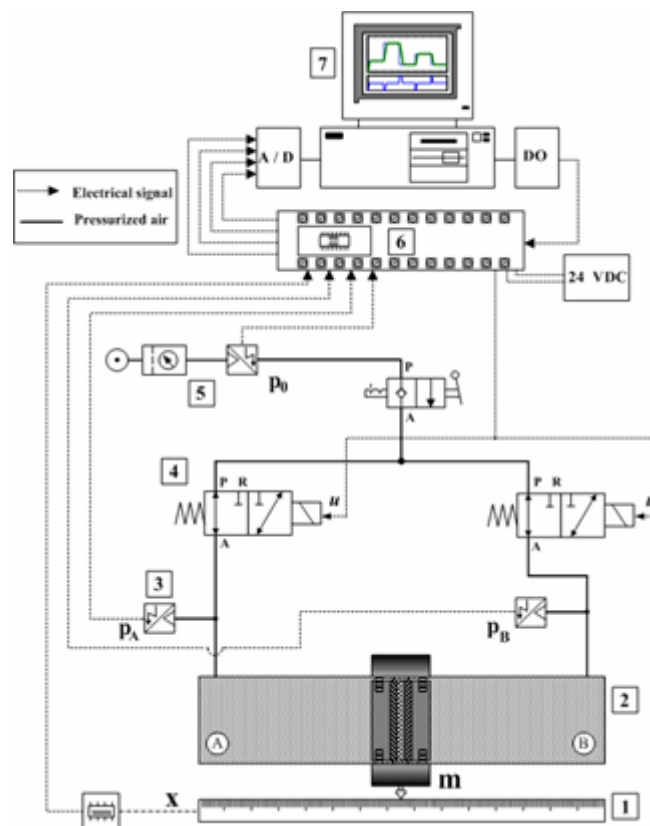
Regulacija primjenom **PROPORCIONALNIH TLAČNIH VENTILA**



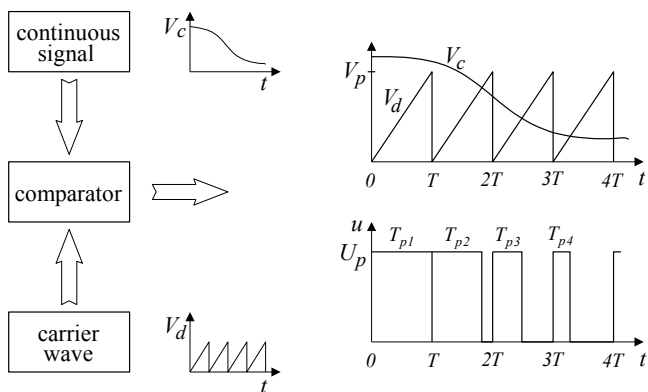
SMC

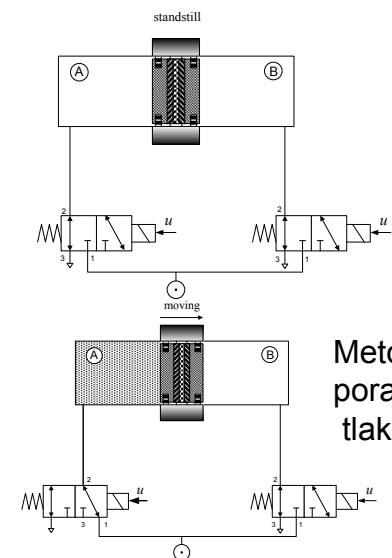
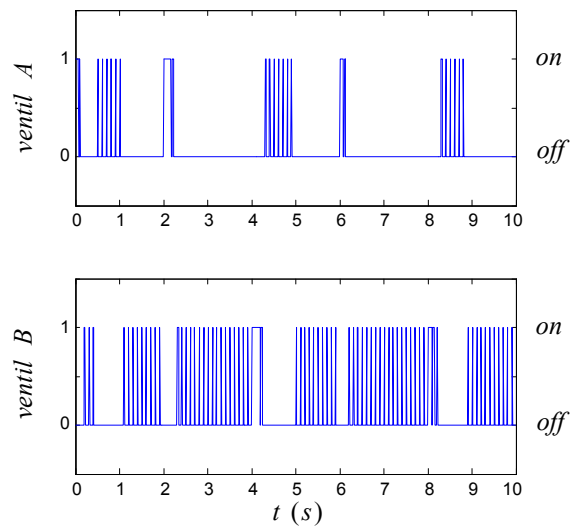
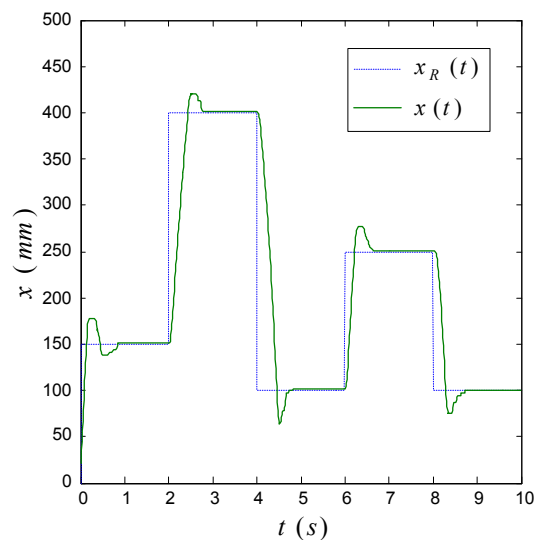
E-P Hyreg VY1A00-M5

Regulacija primjenom ELEKTROMAGNETSKIH DVOPOLOŽAJNIH VENTILA

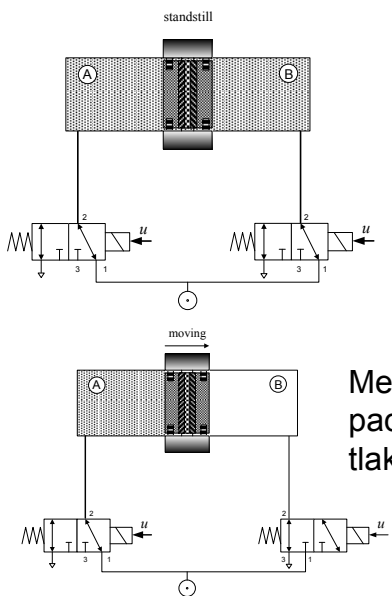
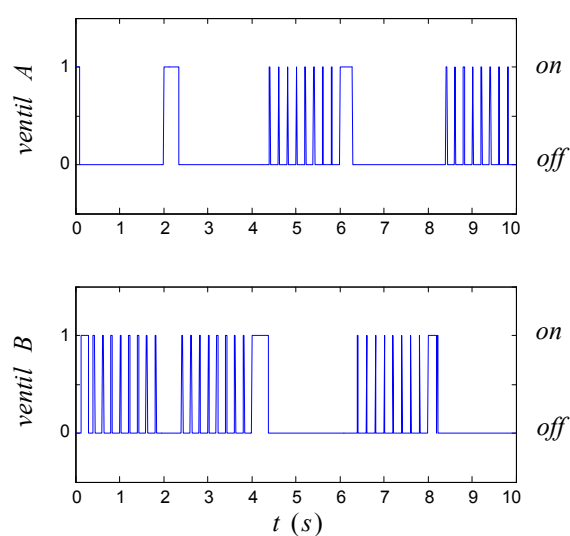
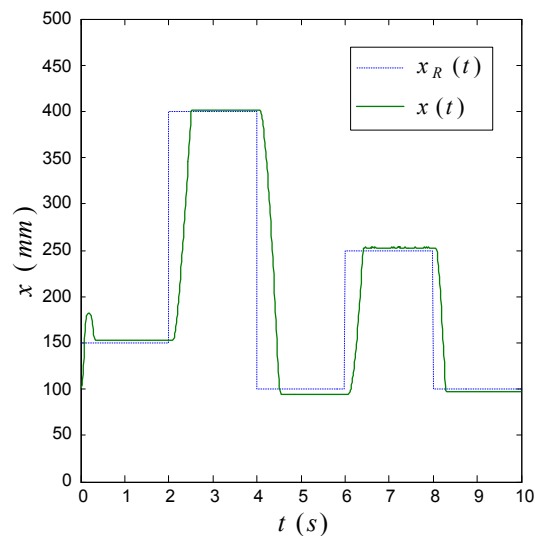


Realizacija PWM signala

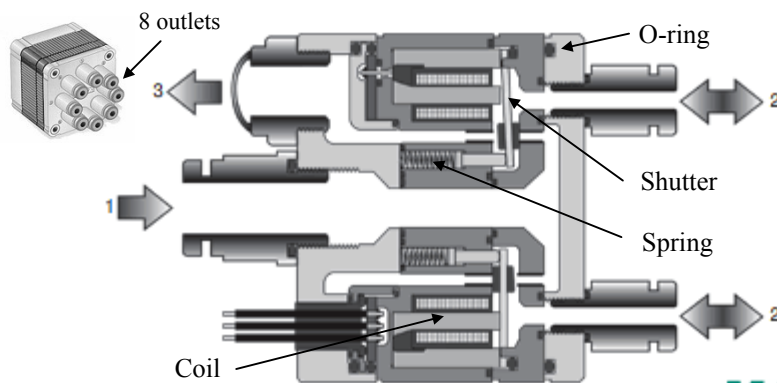




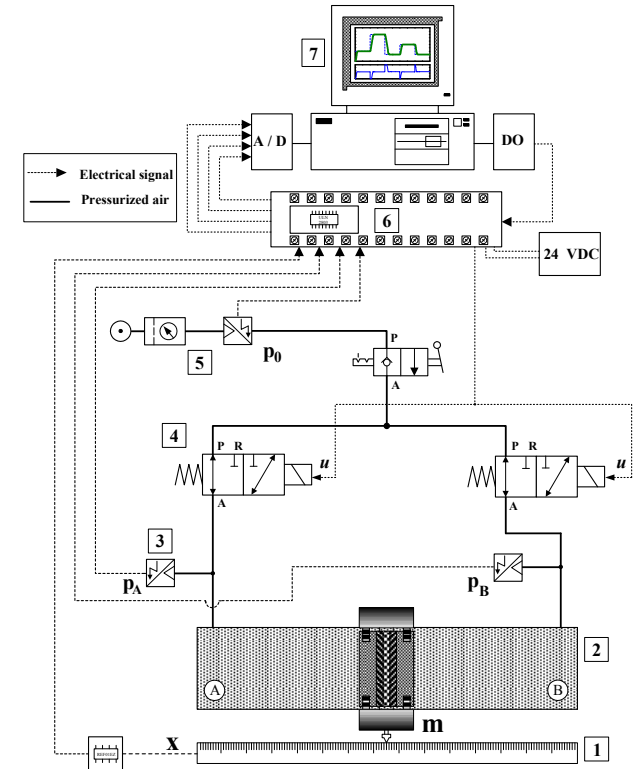
Metoda porasta tlaka



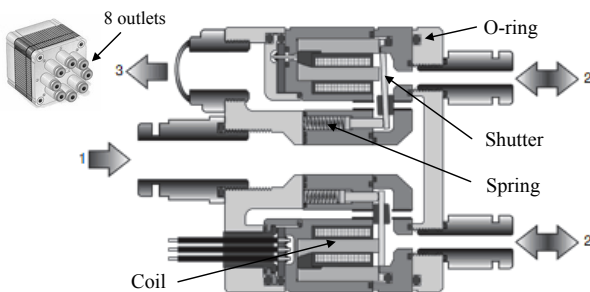
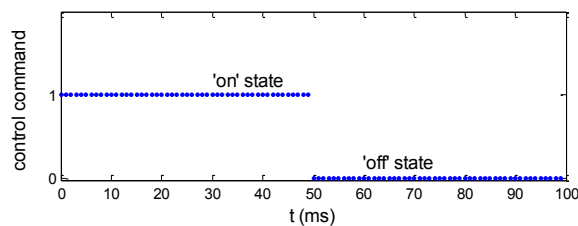
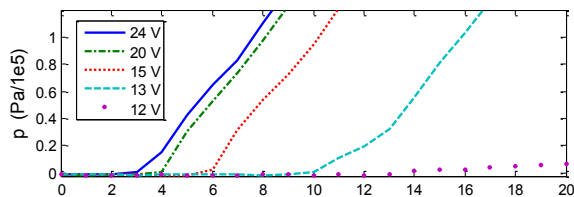
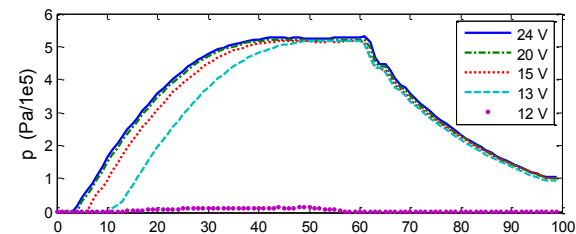
Metoda pada tlaka



MATRIX
mechatronics
X758-8-E-2-C-3-24

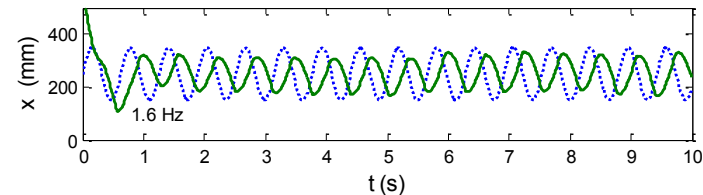
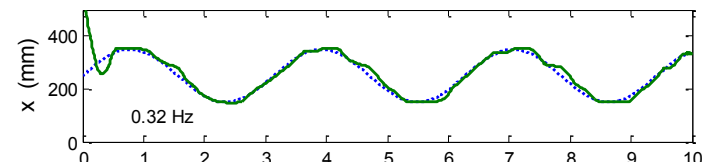
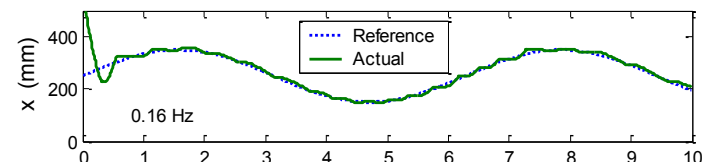
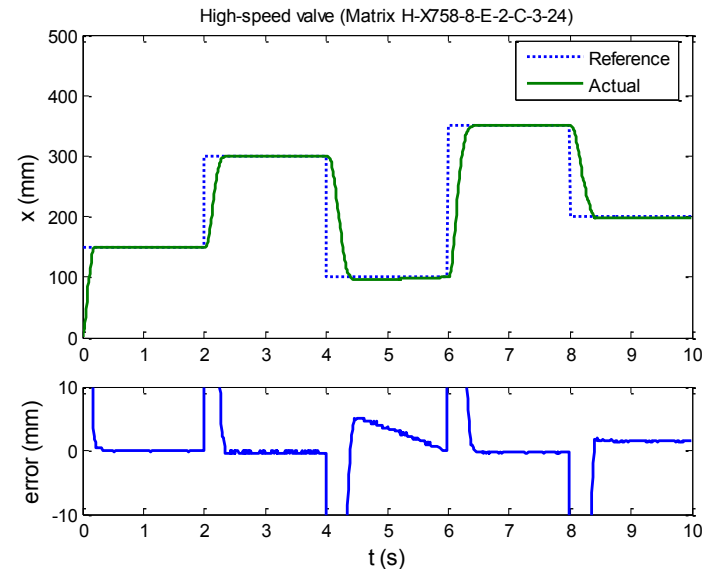


- 1—Linear potentiometer
- 2—Pneumatic rodless cylinder
- 3—Pressure sensor
- 4—High-speed valve, Matrix X758-8-E-2-C-3-24**
- 5—Filter-regulator unit
- 6—Darlington driver
- 7—Control computer with data-acquisition card
- 8—Proportional valve
- 9—On/off solenoid valves
- 10—Proportional pressure valves

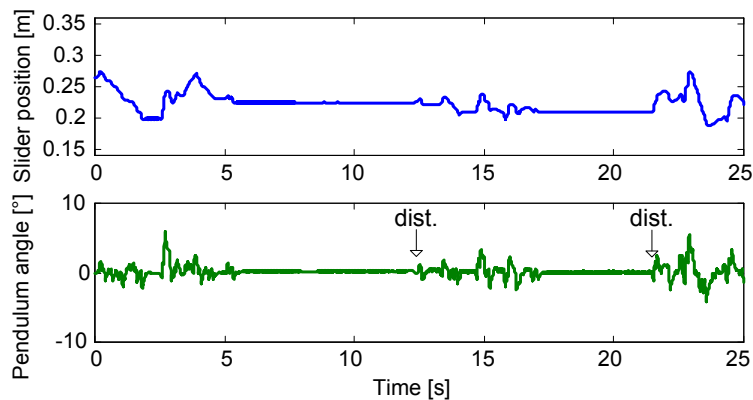


MATRIX
mechatronics

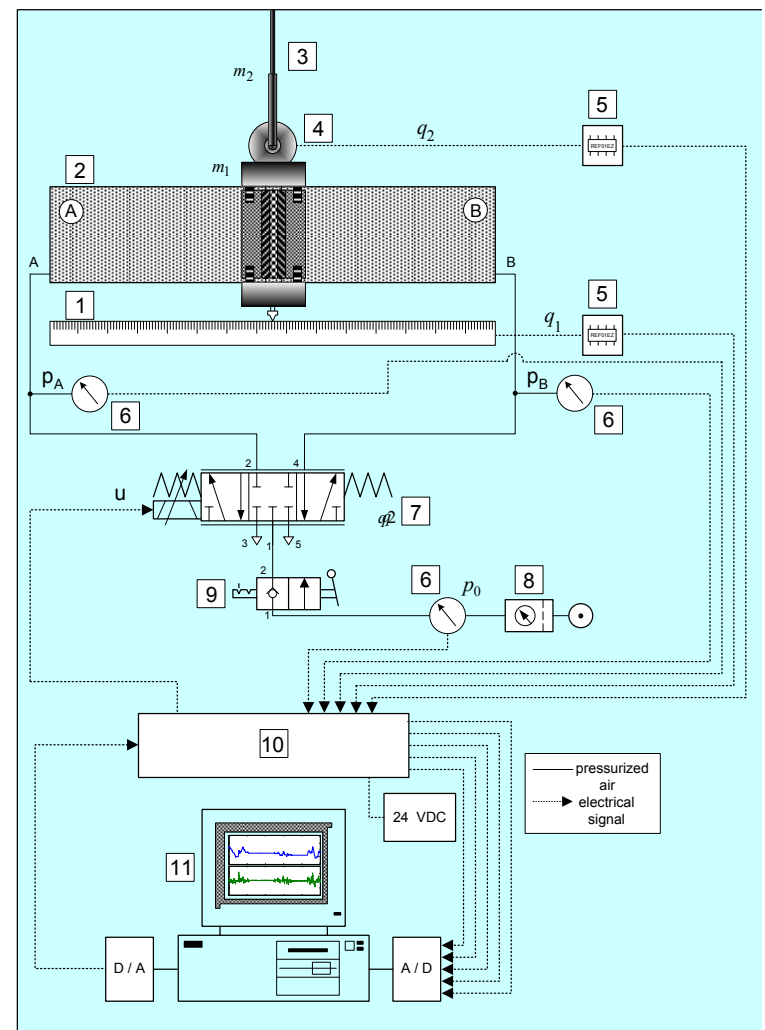
X758-8-E-2-C-3-24



Inverzno njihalo – 'inverted pendulum'

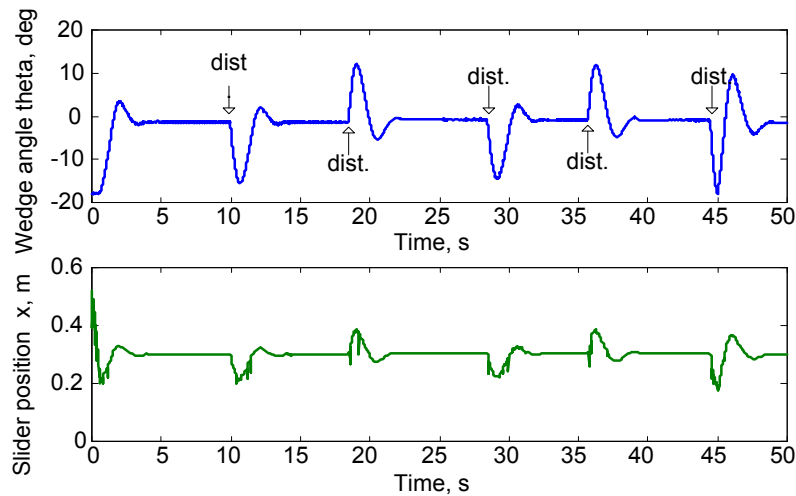
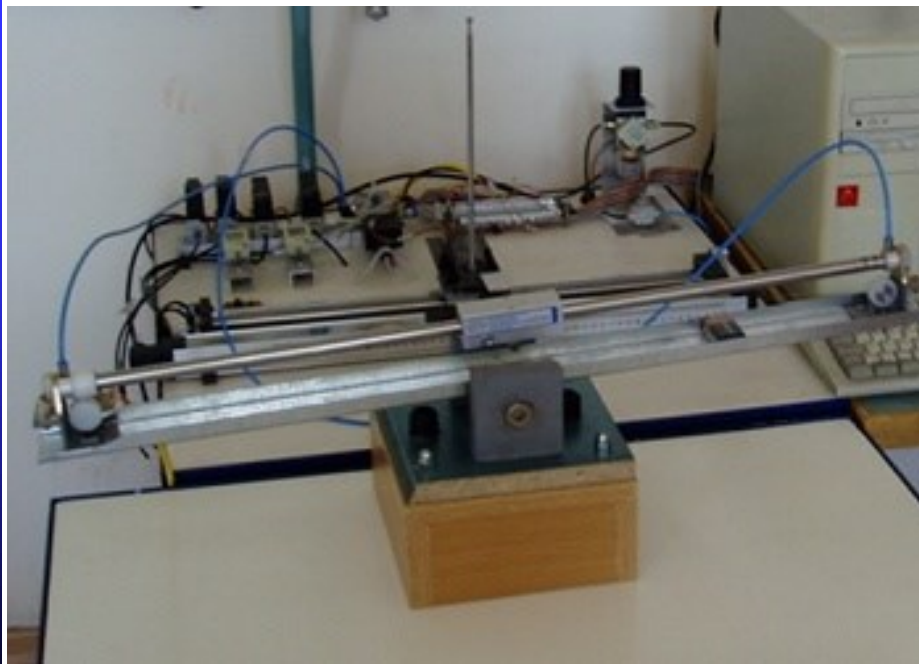


Eksperimentalni rezultati regulacije primjenom regulatora po varijablama stanja (LQR controller)

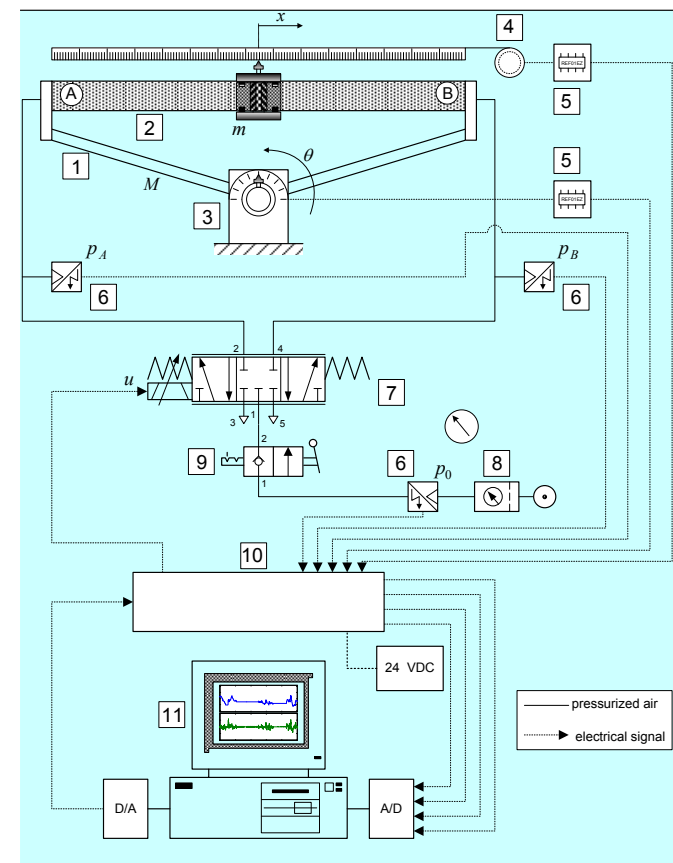


- | | |
|----------------------------------|-----------------------------------|
| 1. Linear potentiometer | 7. Proportional valve |
| 2. Rodless cylinder | 8. Filter with pressure regulator |
| 3. Inverted pendulum | 9. Air supply valve |
| 4. Rotational servopotentiometer | 10. Electronic interface |
| 5. Electronic reference card | 11. Control computer |
| 6. Pressure transducer | |

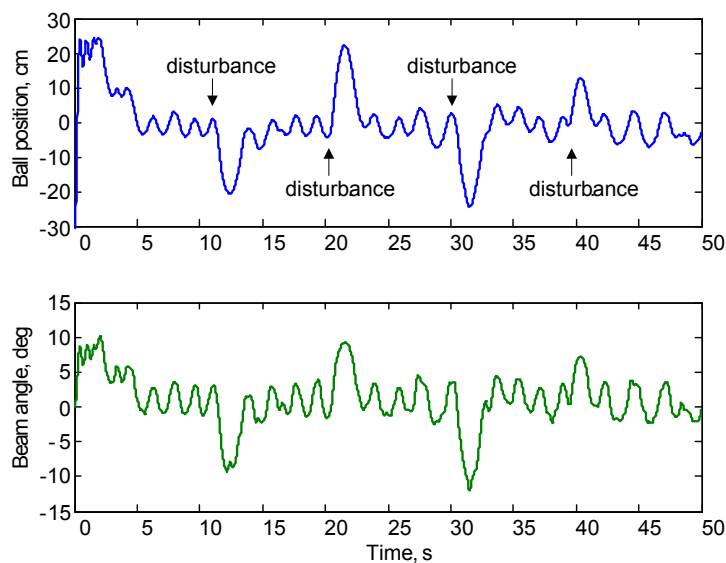
Inverzni klin – 'inverted wedge system'



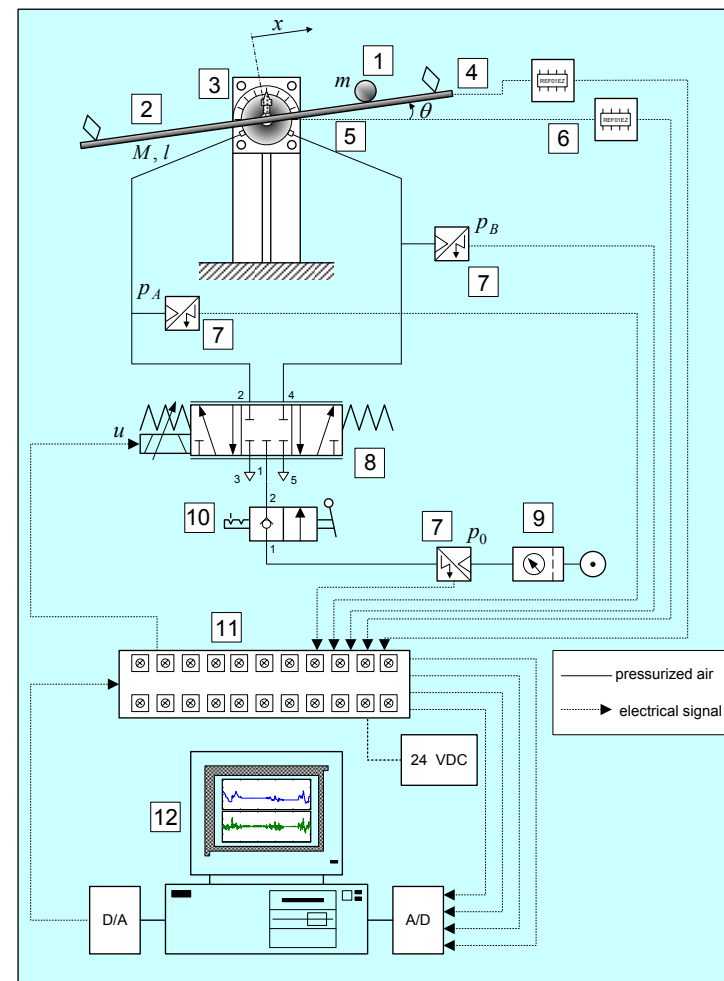
Eksperimentalni rezultati regulacije
primjenom regulatora po varijablama stanja
(LQR controller)



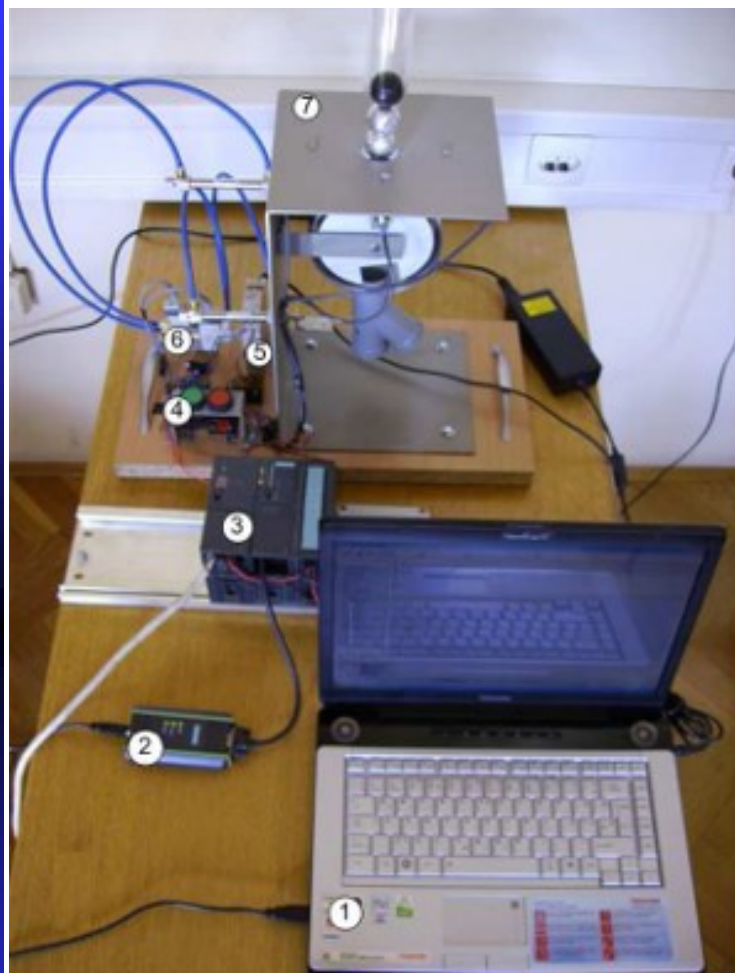
Kuglica na gredi – ‘ball and beam system’



Eksperimentalni rezultati regulacije
primjenom regulatora po varijablama stanja
(LQR controller)



- | | |
|--------------------------------|---------------------------|
| 1–Ball | 7–Pressure transducer |
| 2–Beam | 8–Proportional valve |
| 3–Pneumatic rotary drive | 9–Pressure valve & filter |
| 4–Resistive wires for x | 10–Air supply valve |
| 5–Rotational pot. for θ | 11–Electronic interface |
| 6–Electronic reference card | 12–Control computer |



1. PC laptop
2. PC adapter for communication
3. PLC SIMATIC S7-300
4. Start/Stop buttons
5. DC power supplies
6. Pneumatic solenoid 5/2 valves
7. Executive part of the sorting

