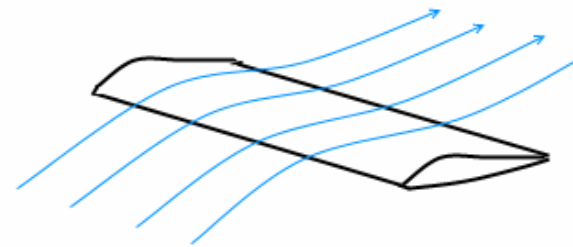
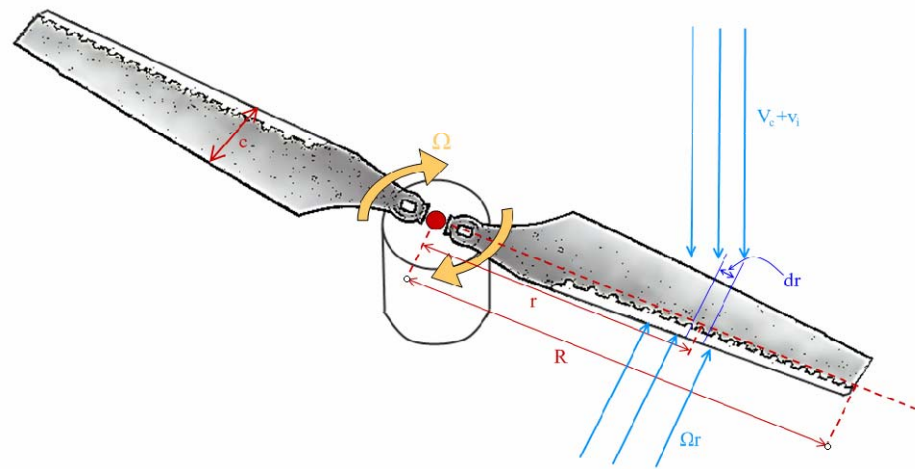


Analiza rada aktuatora

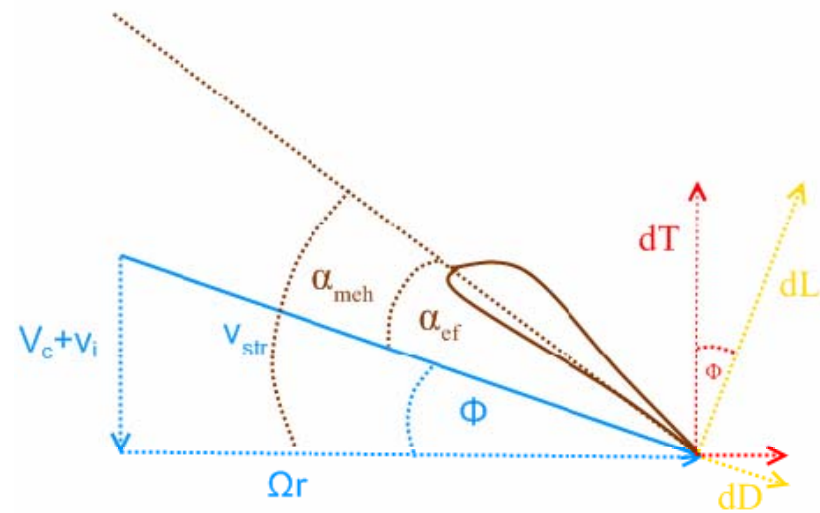
$$F = f(\Omega)$$



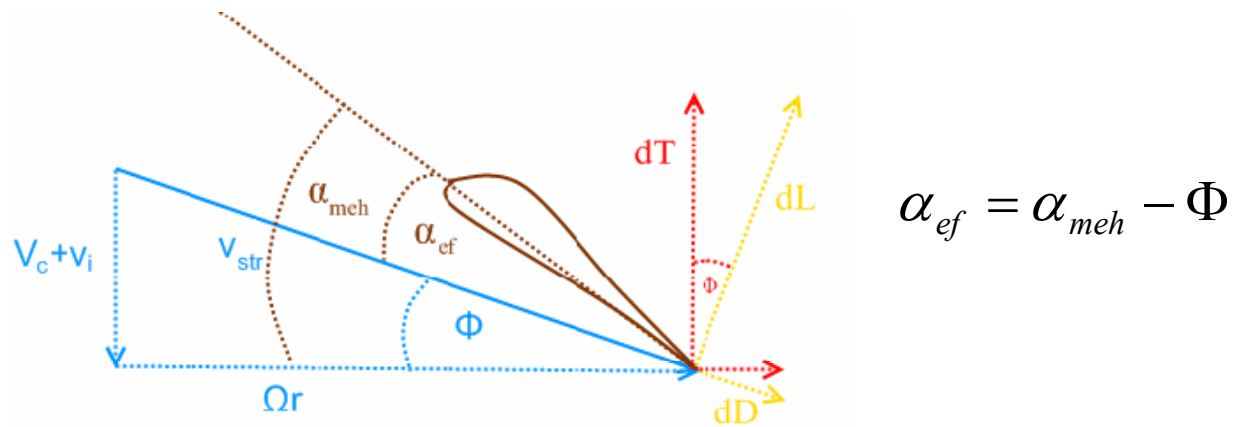
$$\vec{v}_{str} = \vec{V}_c + \vec{v}_i + \vec{\Omega} \times \vec{r}$$

$$|\vec{v}_{str}| = v_{str} = \sqrt{(V_c + v_i)^2 + \Omega^2 r^2}$$

$$\Omega r \gg (V_c + v_i) \Rightarrow v_{str} = \Omega r$$



Analiza rada aktuatora



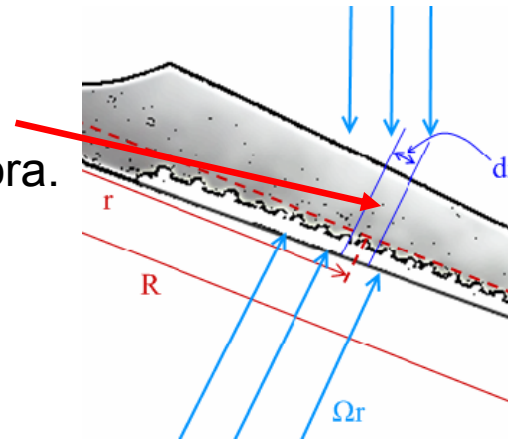
$$\sin(\Phi) = \frac{V_c + v_i}{\Omega r}$$

$$\Omega r \gg V_c + v_i \Rightarrow \sin(\Phi) \approx \Phi$$

$$\Rightarrow \Phi = \frac{V_c + v_i}{\Omega r}$$

Analiza rada aktuatora

Promatra se uzgon djelića rotora.

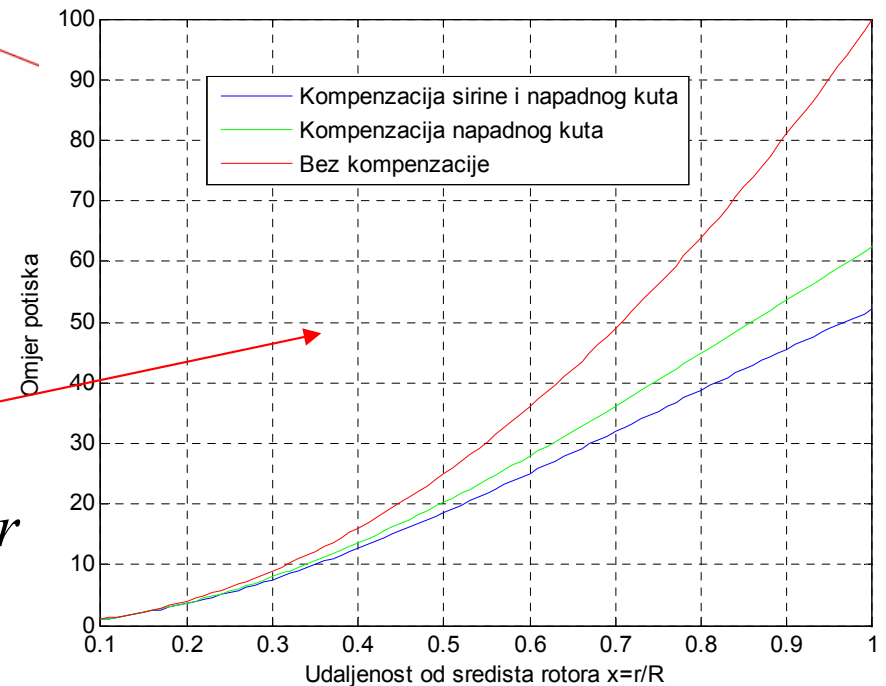


$$dL = \frac{1}{2} \rho \cdot v_{str}^2 C_L dS$$

$$v_{str} \approx \Omega r, \quad dS = c(r) dr$$

$$C_L = 2\pi\alpha_{ef} = 2\pi \left(\alpha_{meh}(r) - \frac{V_c + v_i(r)}{\Omega r} \right),$$

$$dL = \frac{1}{2} \rho 2\pi (\Omega r)^2 \left[c(r) \left[\alpha_{meh}(r) - \frac{V_c + v_i(r)}{\Omega r} \right] \right] dr$$





Analiza rada aktuatora

Integriranjem po cijeloj dužini rotora (uz lin. ovisnost $c(r)$ i $\alpha_{meh}(r)$)

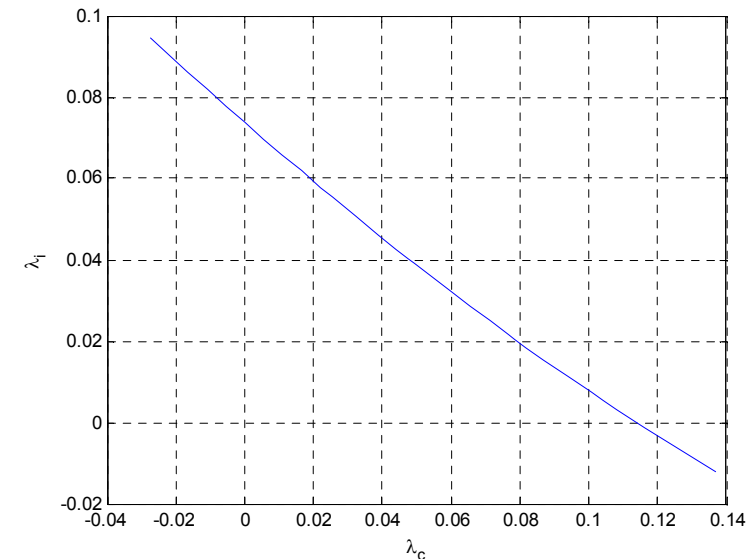
$$T = \frac{1}{4} \rho 2\pi R^3 \Omega^2 c \left(\frac{2}{3} \Theta_0 - \lambda_i - \lambda_c \right)$$

Θ_0 - mehanički napadni kut izmjeren na $\frac{3}{4} R$

c - širina elise rotora izmjerena na $\frac{3}{4} R$

$$\lambda_i = \frac{v_{iR}}{\Omega R}$$

$$\lambda_c = \frac{V_c}{\Omega R}$$



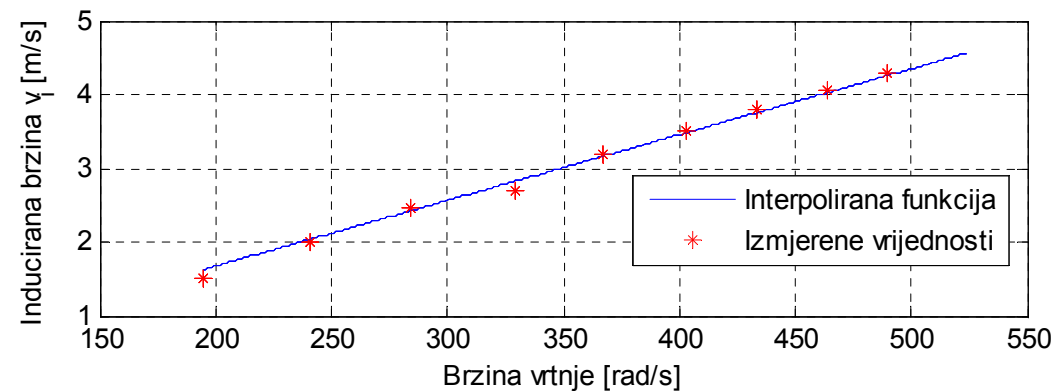


Mjerenje parametara aktuatora

Napon	Brzina vrtnje rotora ω <i>rad/s</i>	Brzina toka v_2 <i>m/s</i>	Inducirana brzina v_i <i>m/s</i>
4,04	194,465	3	1,5
5,01	241,170	4	2
5,99	284,105	4,9	2,45
6,99	328,820	5,4	2,7
8	367,357	6,4	3,2
8,99	403,171	7	3,5
10,01	433,540	7,6	3,8
10,99	464,223	8,1	4,05
12,05	490,088	8,6	4,3

Ovisnost v_i

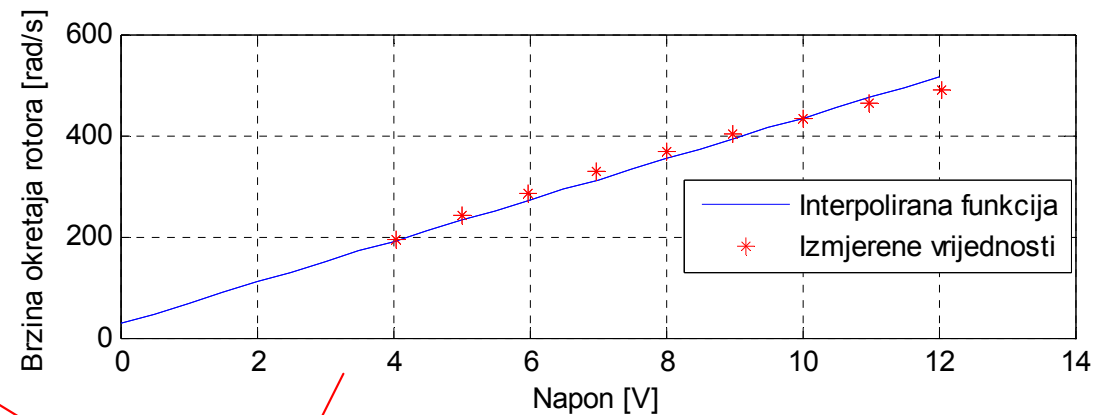
$$\lambda_i = \frac{v_i}{\Omega R} = 0.0802 \quad \text{za } V_c = 0.$$



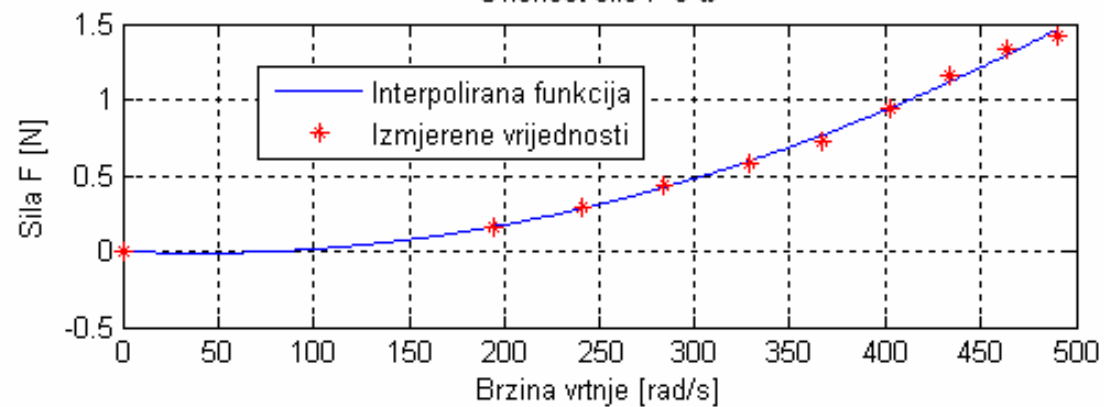


Mjerenje parametara aktuatora

Napon [V]	Sila potiska [N]
4,02	0,16
4,99	0,29
6,01	0,44
7	0,58
8	0,72
9	0,94
10,02	1,16
11,01	1,34
12,01	1,42



Ovisnost sile F o ω



Actuatori i senzori

Servo motori



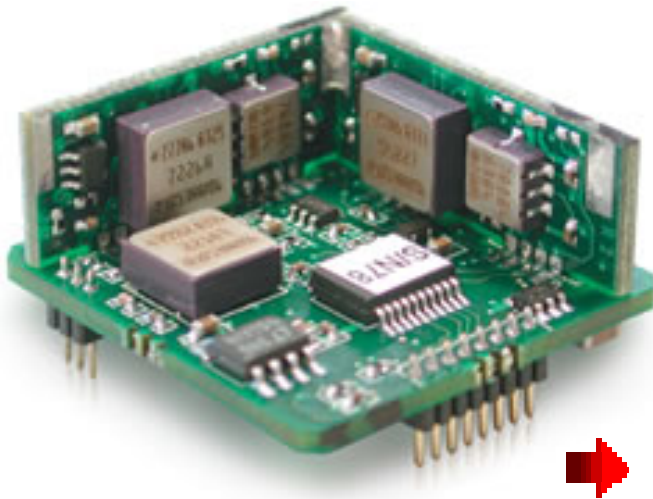
Benzinski motori



Electrični motori

Actuatori i senzori

IMU – inercijalni mjerni sustav



- 3 akcelerometra
- 3 žiroskopa
- 3 magnetometra



Obrada signala mjerenja
- Kalmanov filter



Actuatori i senzori

IMU – inercijalni mjerni sustav

MTi TECHNICAL SPECIFICATIONS

Attitude and Heading

Static accuracy (roll/pitch)	<0.5 deg
Static accuracy (heading) ¹	<1 deg
Dynamic accuracy ²	2 deg RMS
Angular resolution ³	0.05 deg
Dynamic range:	
- Pitch	± 90 deg
- Roll/Heading	± 180 deg
Maximum update rate:	
- Onboard processing	120 Hz
- External processing	512 Hz

Interfacing

Digital interface	RS-232, RS-485, RS-422 (max 921k6 bps) and USB (ext. converter)
Operating voltage	4,5 - 30V
Power consumption	350 mW
Interface options i/o	SyncOut, AnalogIn, SyncIn (depends on digital interface)

Maximum operational limits

Ambient temperature	
Operating range ⁴	-20...+60 °C



Actuatori i senzori

IMU – inercijalni mjerni sustav

INDIVIDUAL SENSOR SPECIFICATIONS

Sensor performance

Dimensions
Full Scale (standard)
Linearity
Bias stability⁵
Scale Factor stability⁵
Noise
Alignment error
Bandwidth
Max update rate

Rate of turn

3 axes
 ± 300 deg/s
0.1% of FS
1 deg/s
-
0.05 deg/s/ $\sqrt{\text{Hz}}$
0.1 deg
40 Hz
512 Hz

Acceleration

3 axes
 ± 50 m/s²
0.2% of FS
0.02 m/s²
0.03%
0.002 m/s²/ $\sqrt{\text{Hz}}$
0.1 deg
30 Hz
512 Hz

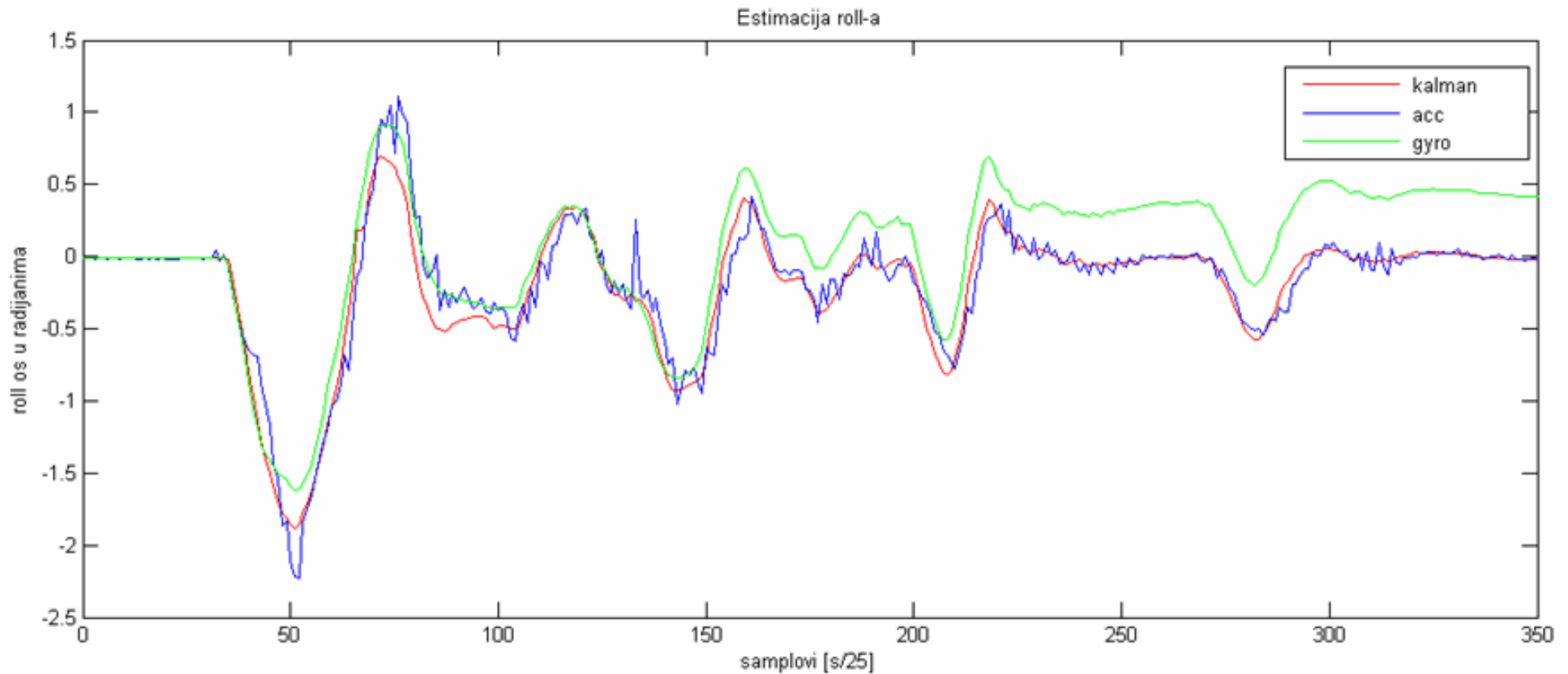
Magnetic field

3 axes
 ± 750 mGauss
0.2% of FS
0.1 mGauss
0.5%
0.5 mGauss
0.1 deg
10 Hz
512 Hz



Actuatori i senzori

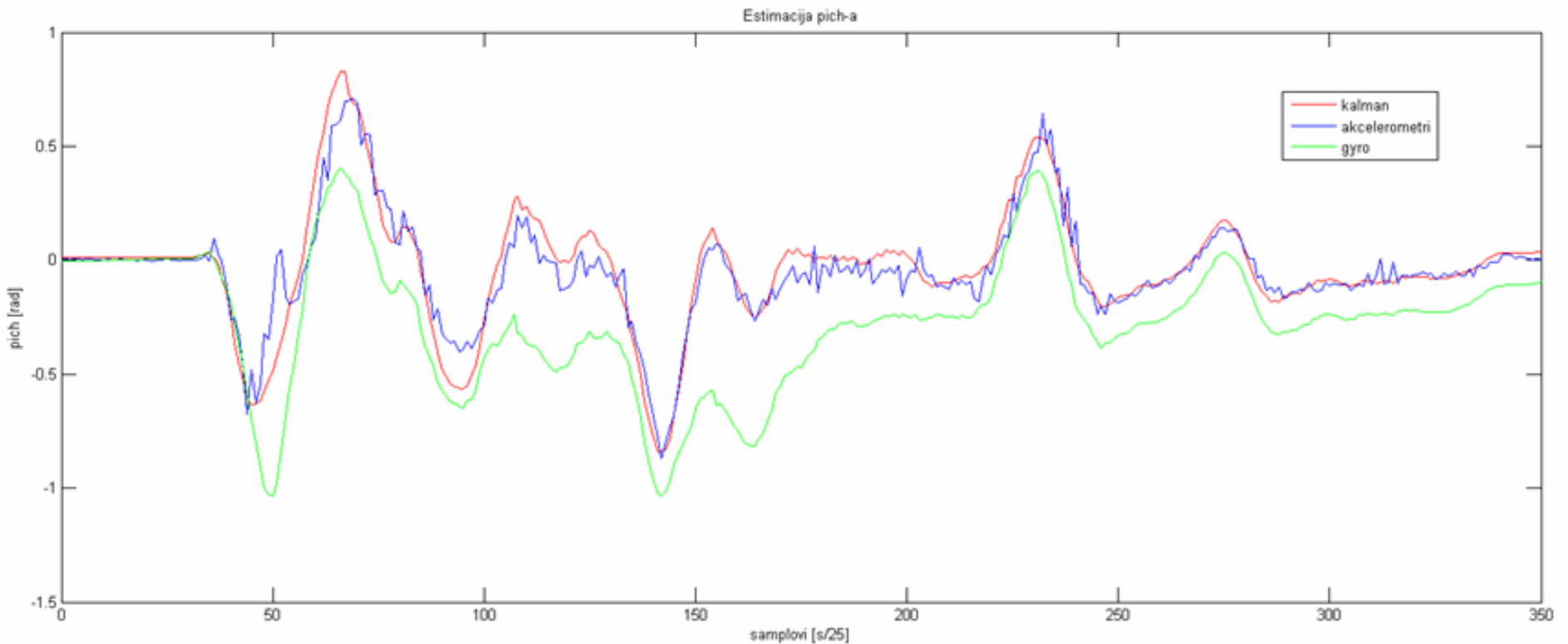
IMU – inercijalni mjerni sustav





Actuatori i senzori

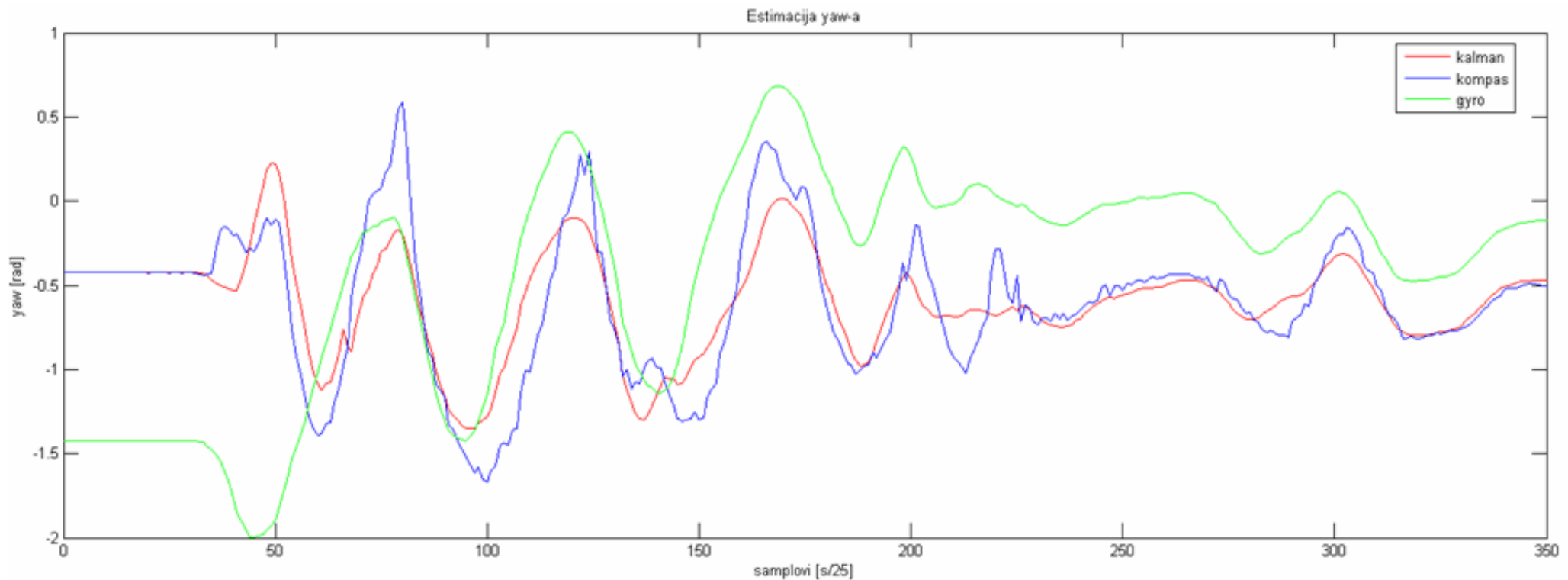
IMU – inercijalni mjerni sustav





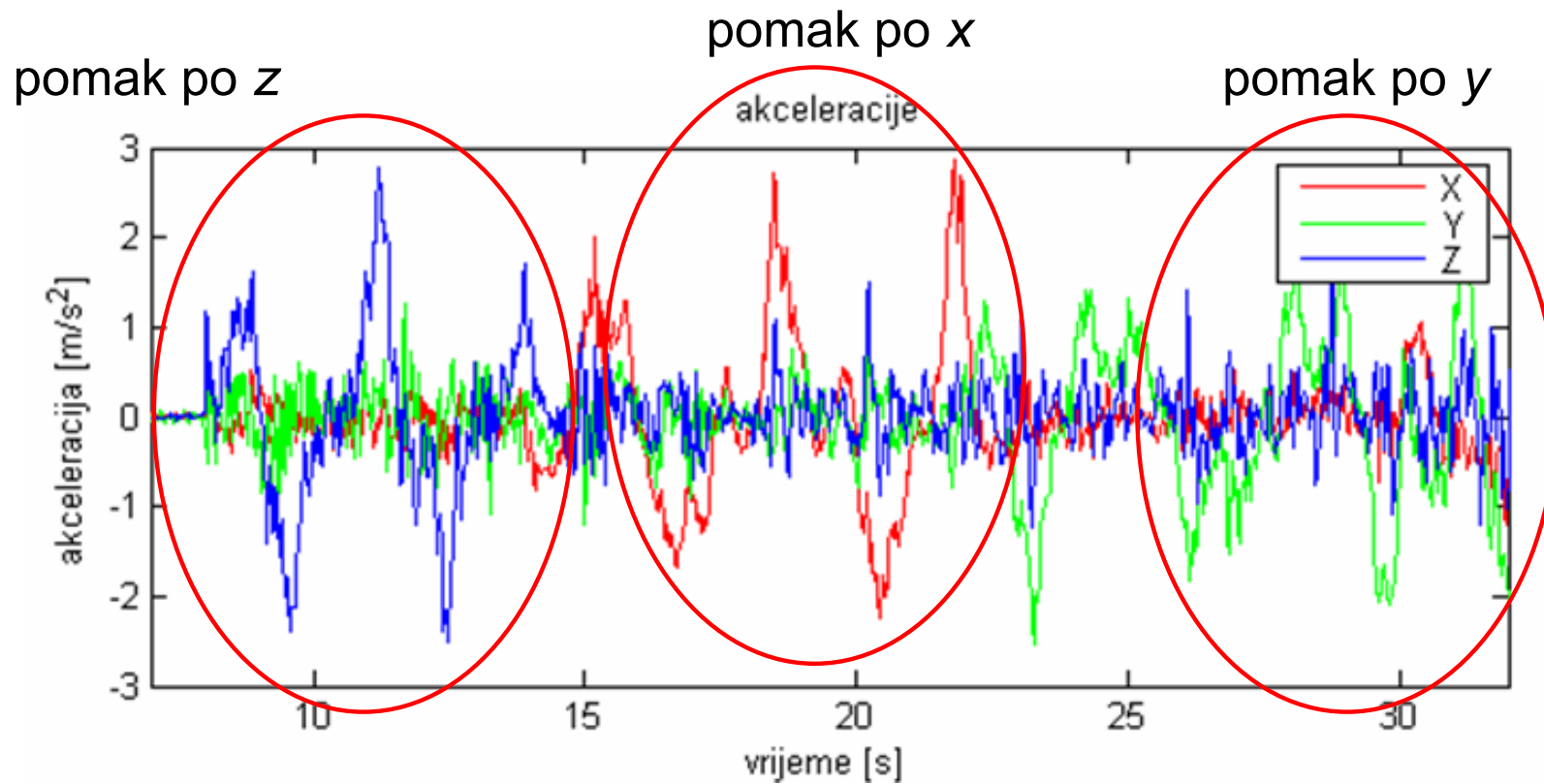
Actuatori i senzori

IMU – inercijalni mjerni sustav



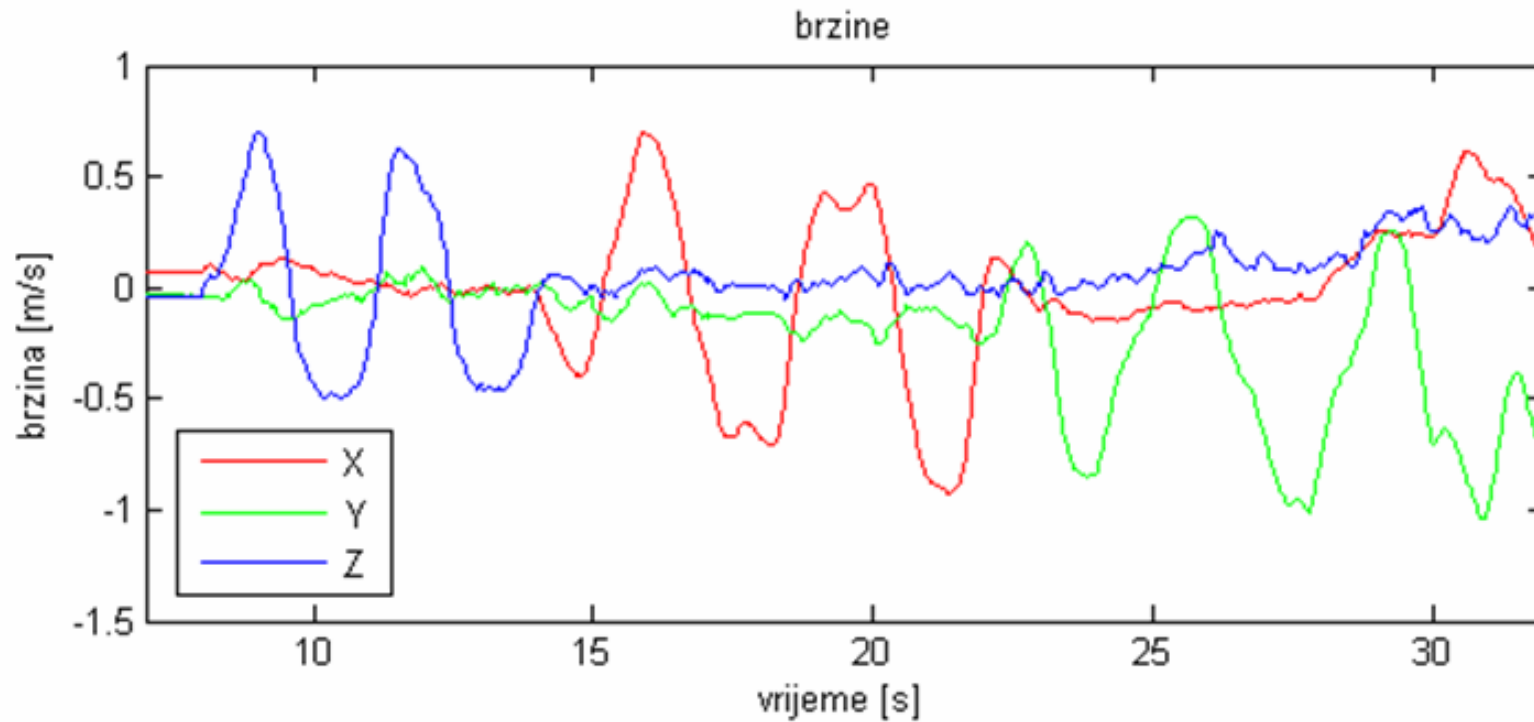
Actuatori i senzori

IMU – inercijalni mjerni sustav



Actuatori i senzori

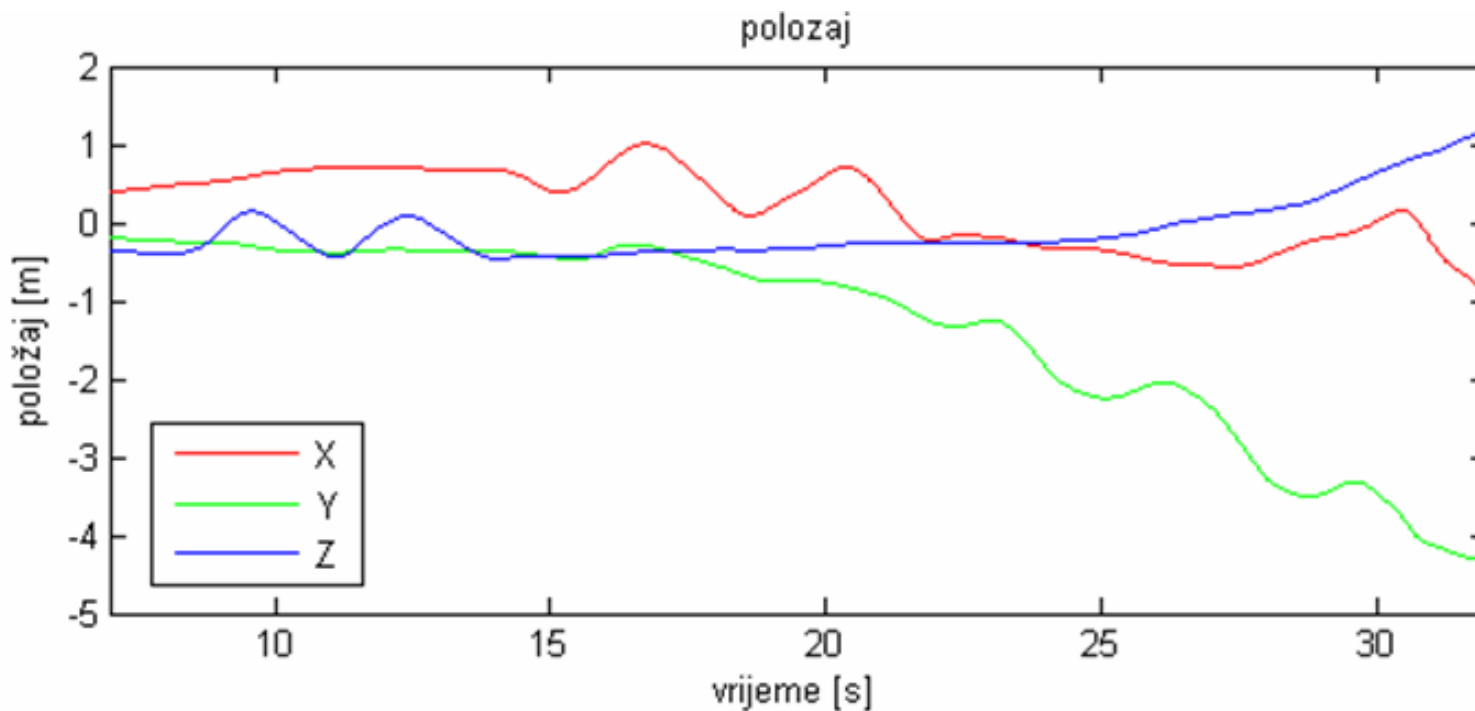
IMU – inercijalni mjerni sustav





Actuatori i senzori

IMU – inercijalni mjerni sustav

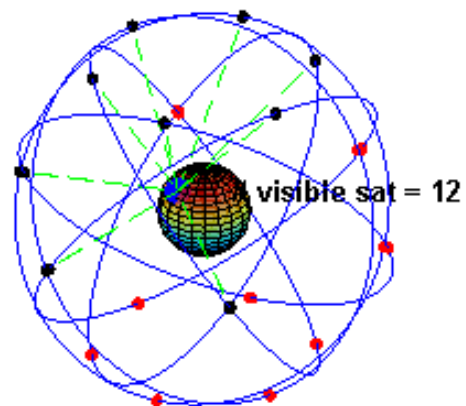


'drift' pozicije !

(pomak senzora bio je ± 60 cm)

Actuatori i senzori

GPS – geostacionarni pozicijski sustav



Actuatori i senzori

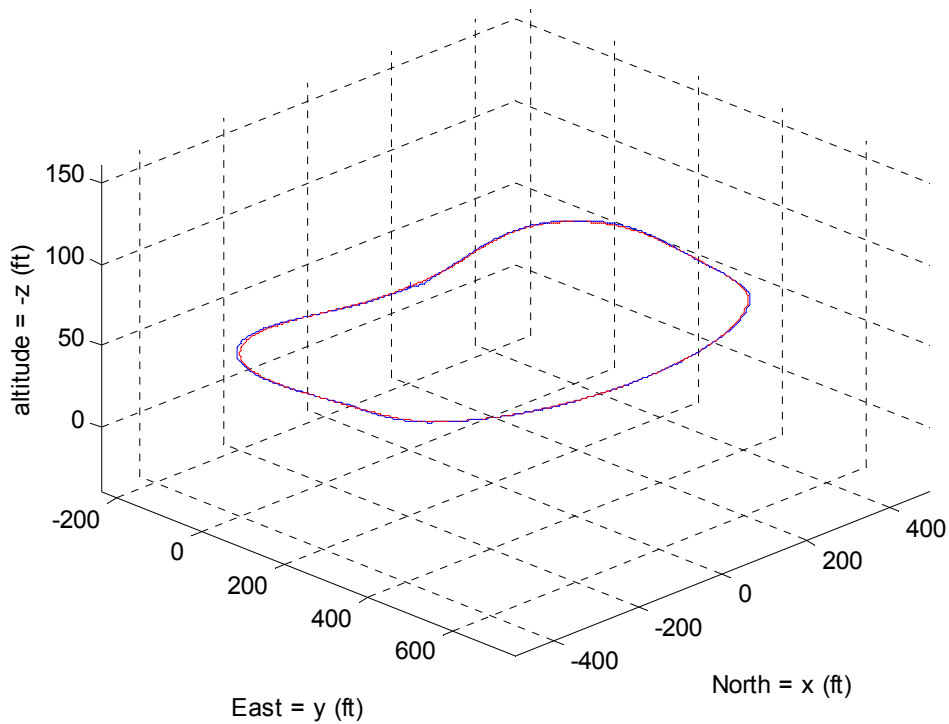
Vizualna povratna veza



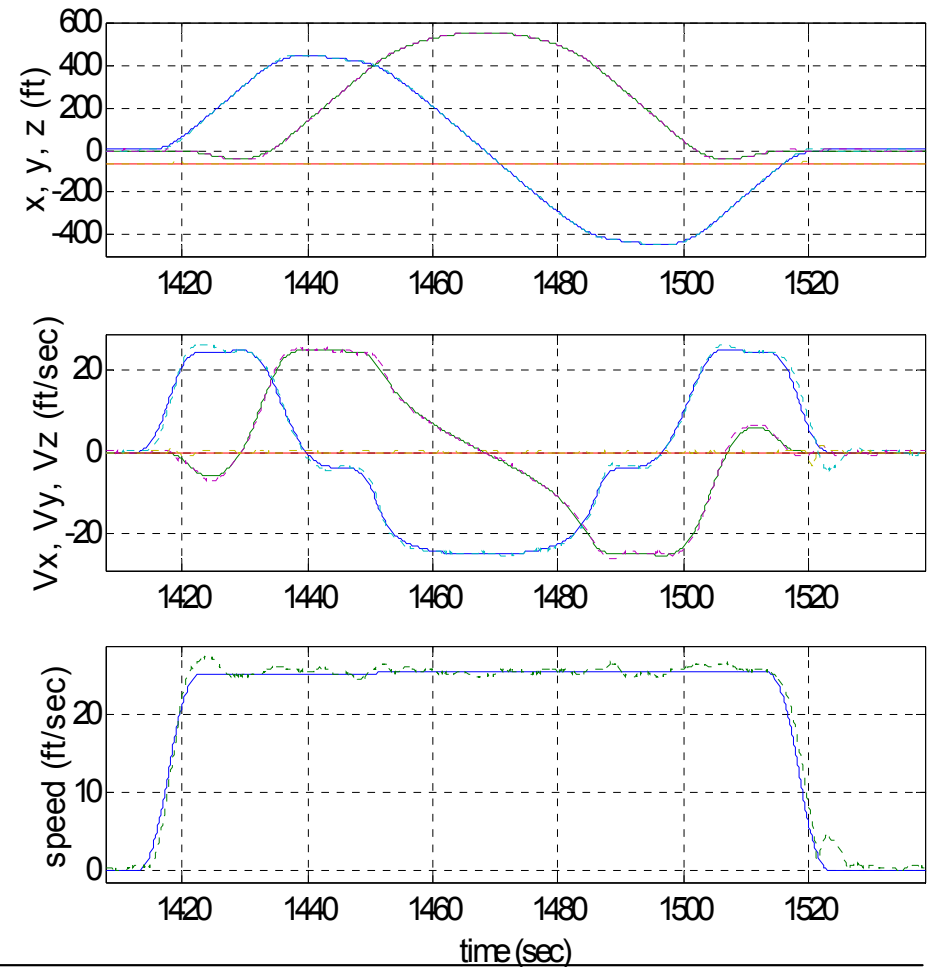


Upravljanje letjelicama

3D trajektorija

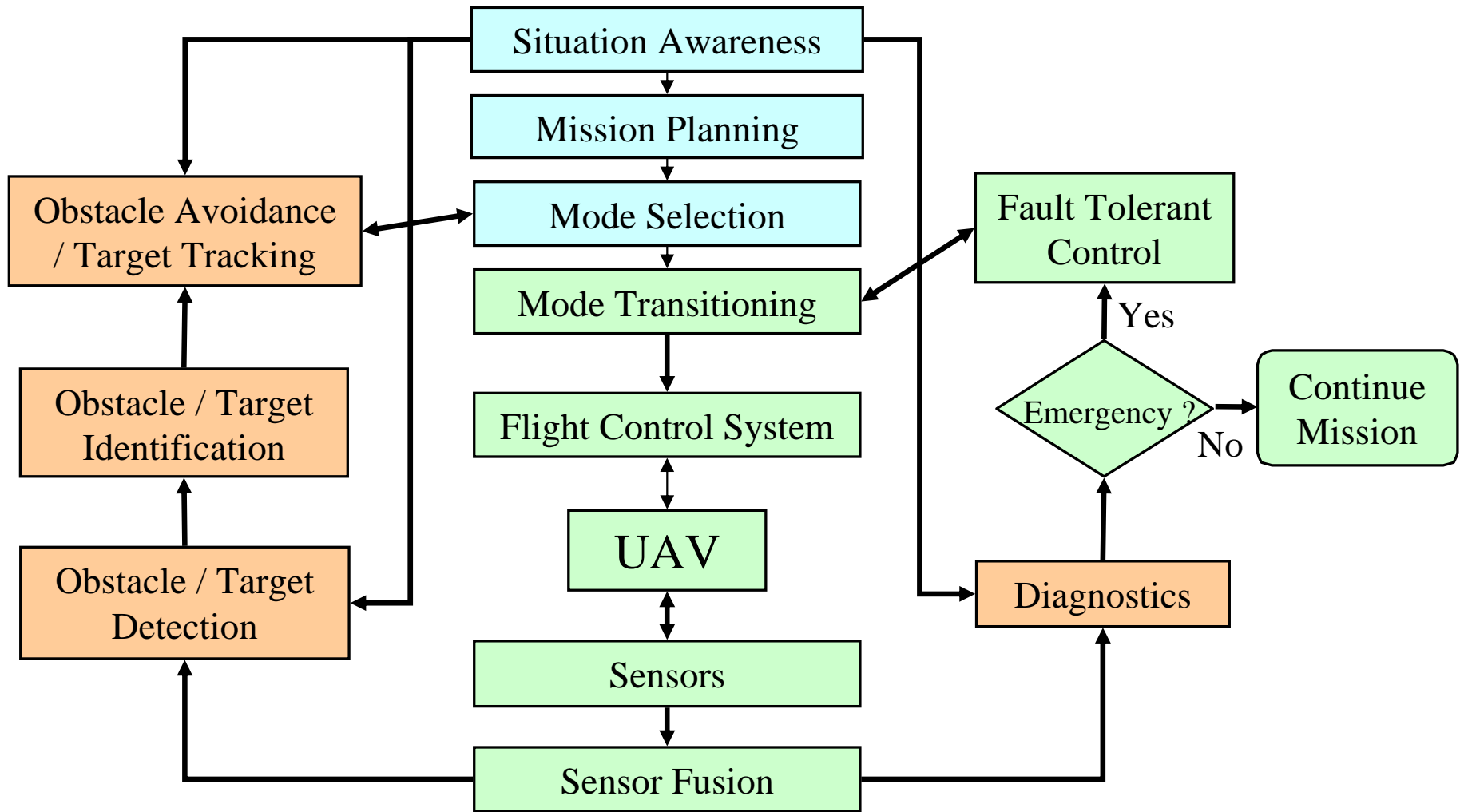


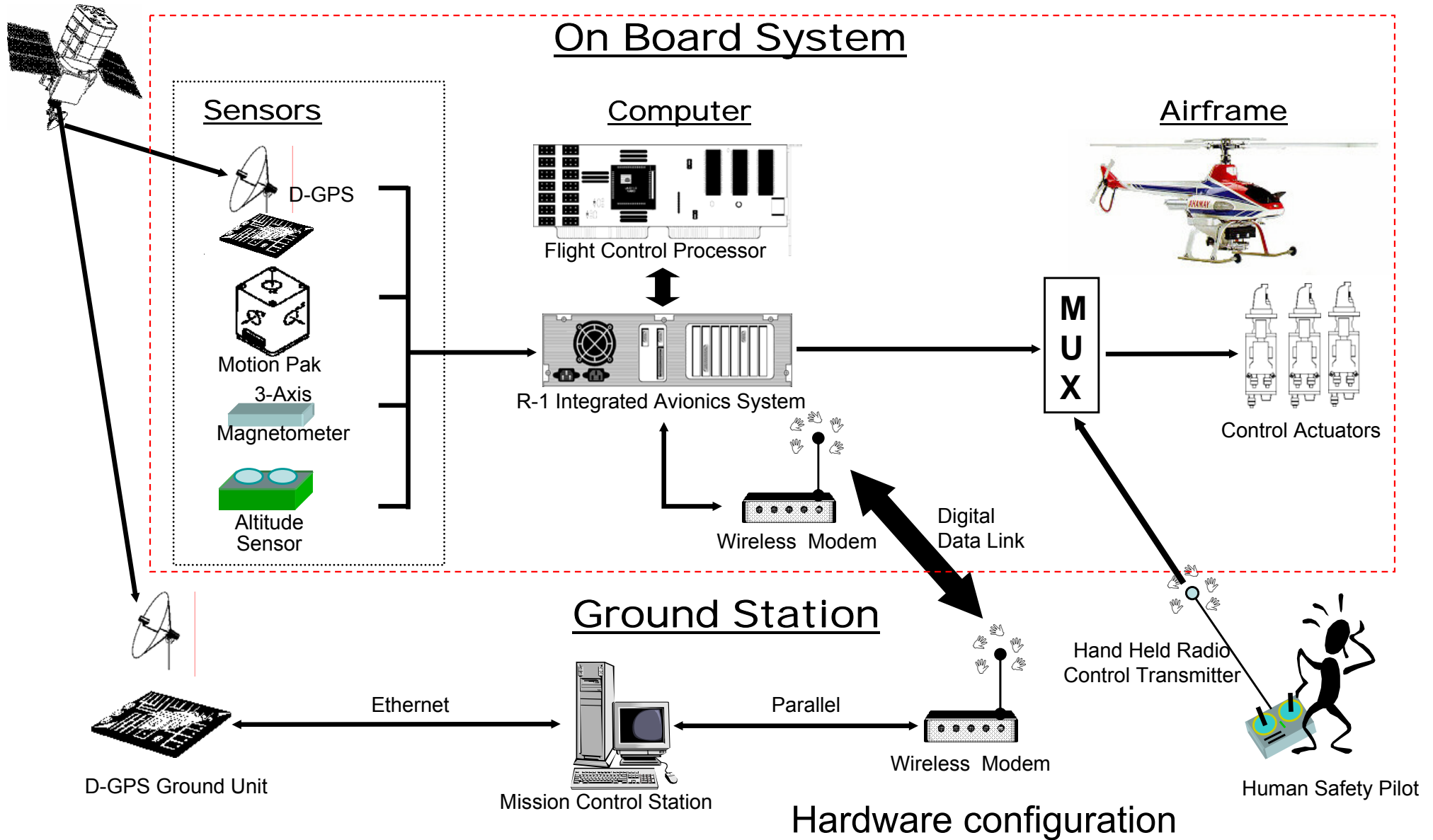
Pozicije i brzine





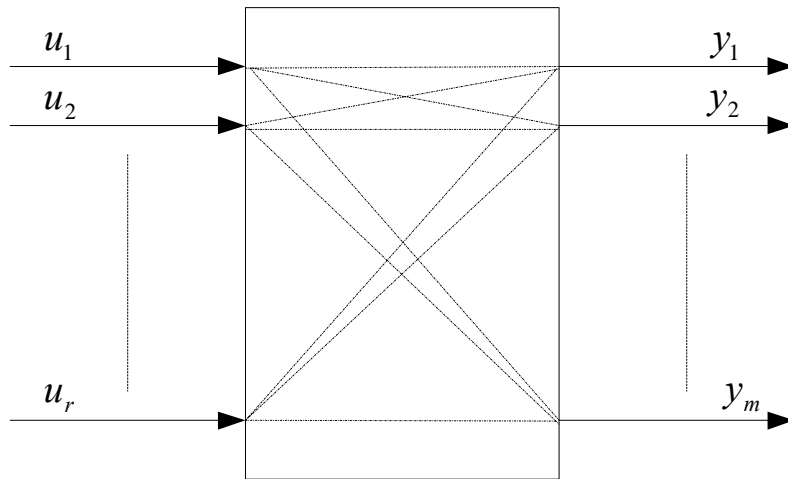
Upravljanje letjelicama







Upravljanje letjelicama

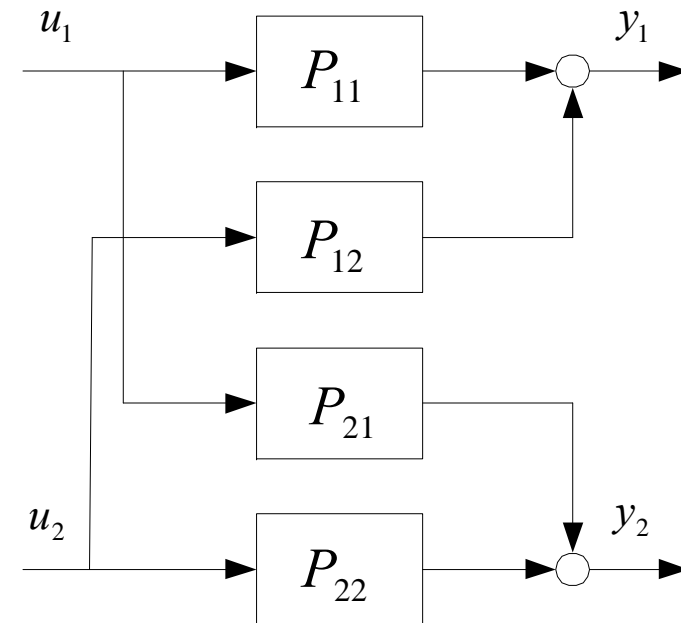


Helikopter

- sustav s više ulaza i više izlaza
- linearizacija u radnoj točki

- jedna postavna veličina može djelovati na više upravljanih veličina
=> *sprega varijabli sustava*

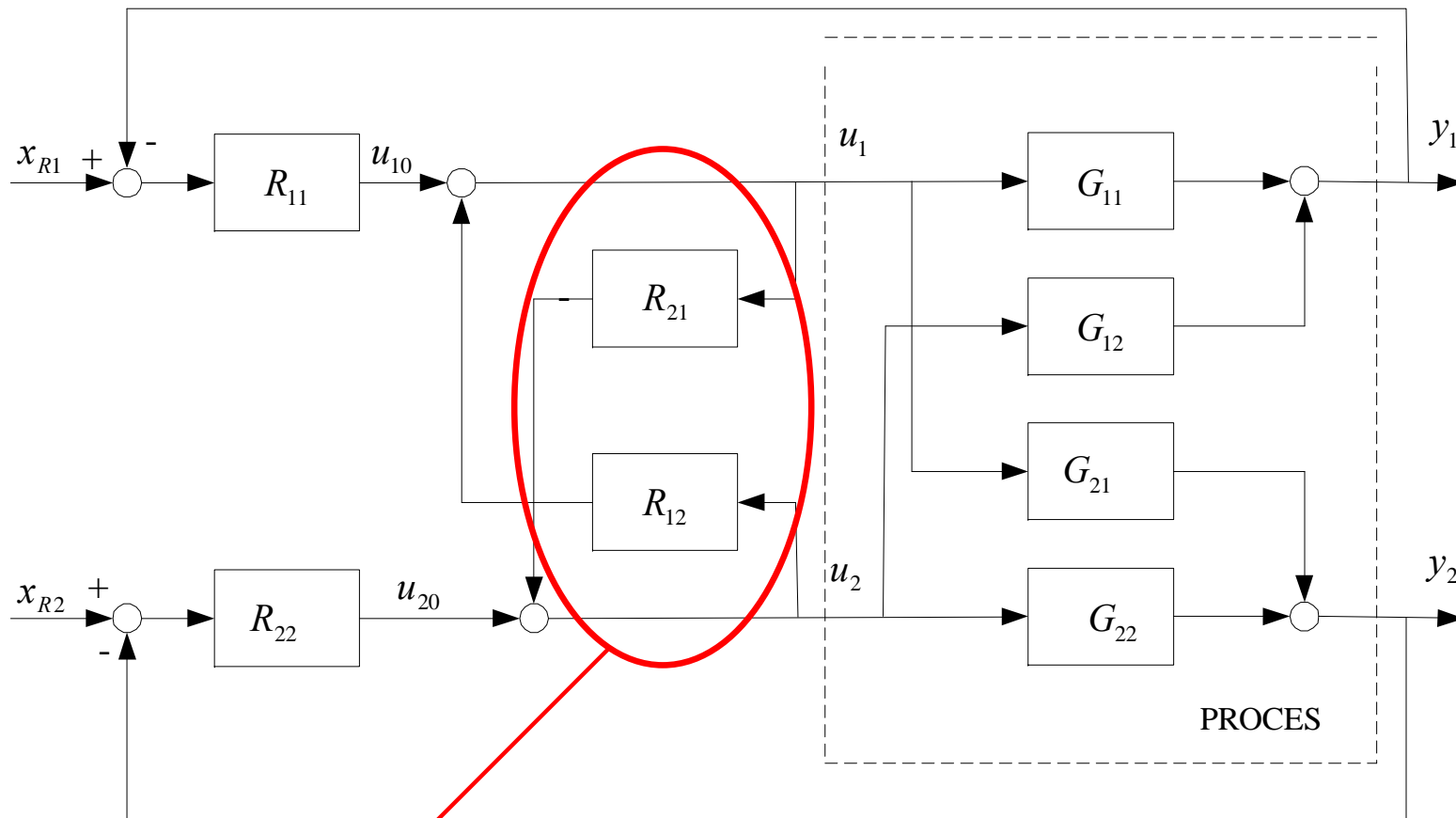
P - kanonicka struktura



$$\mathbf{Y}(s) = \mathbf{P}(s) \cdot \mathbf{U}(s)$$



Upravljanje letjelicama



Raspredni regulatori



Upravljanje letjelicama

$$U_1 = U_{10} + R_{12}U_2 \Rightarrow U_1 = \frac{U_{10} + R_{12}U_{20}}{1 - R_{12}R_{21}},$$

$$Y_1 = G_{11}U_1 + G_{12}U_2,$$

$$U_2 = U_{20} + R_{21}U_1 \Rightarrow U_2 = \frac{U_{20} + R_{21}U_{10}}{1 - R_{12}R_{21}},$$

$$Y_2 = G_{22}U_2 + G_{21}U_1,$$

$$Y_1 = \frac{1}{1 - R_{12}R_{21}} \left[(G_{11} + G_{12}R_{21})U_{10} + (G_{12} + G_{11}R_{12})U_{20} \right],$$

= 0

$$Y_2 = \frac{1}{1 - R_{12}R_{21}} \left[(G_{21} + G_{22}R_{21})U_{10} + (G_{22} + G_{21}R_{12})U_{20} \right],$$



Upravljanje letjelicama

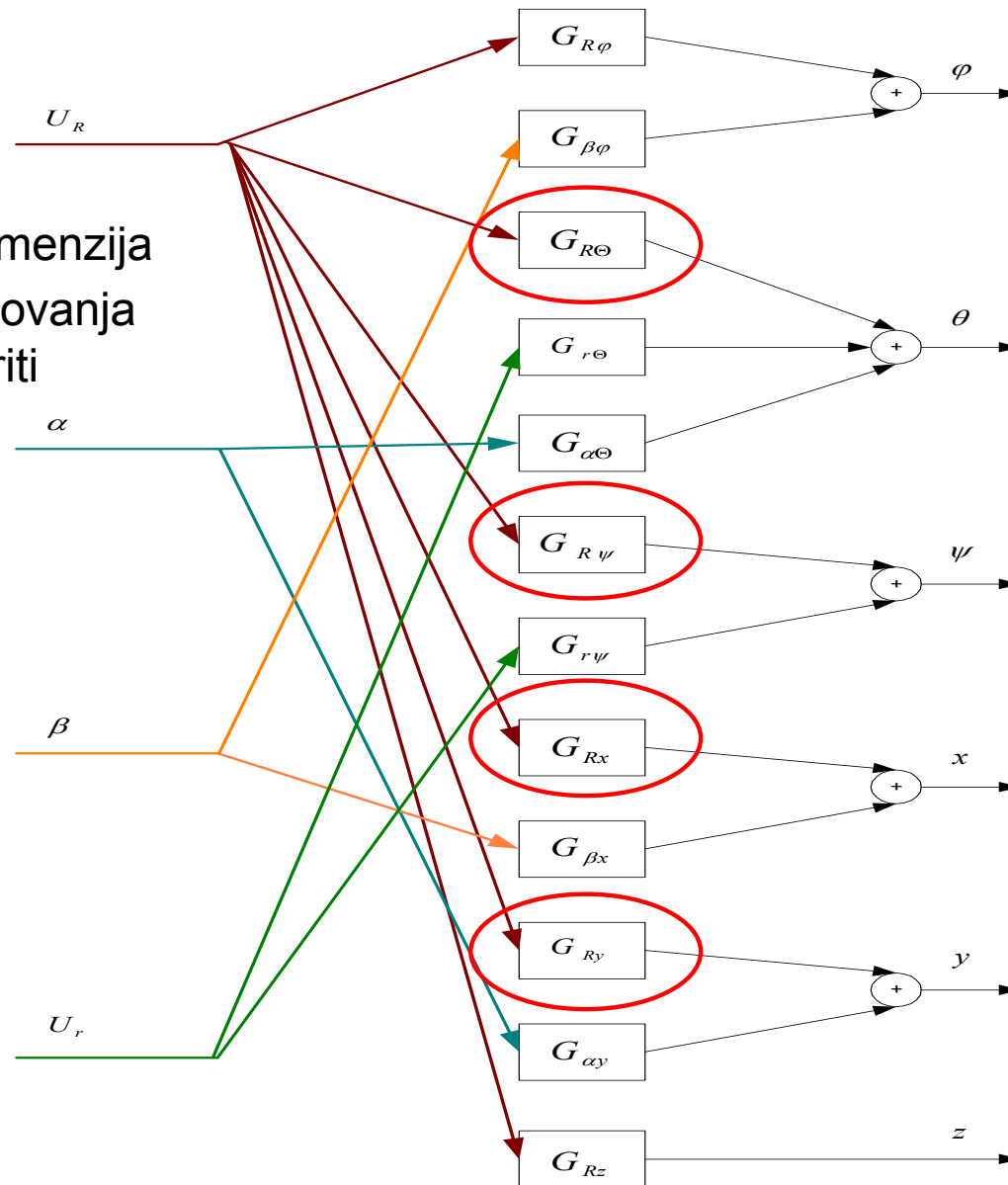
$$G_{12} + G_{11}R_{12} = 0 \Rightarrow R_{12} = -\frac{G_{12}}{G_{11}},$$

$$G_{21} + G_{22}R_{21} = 0 \Rightarrow R_{21} = -\frac{G_{21}}{G_{22}},$$

Problem praktične
ostvarivosti rasprednih
regulatora.

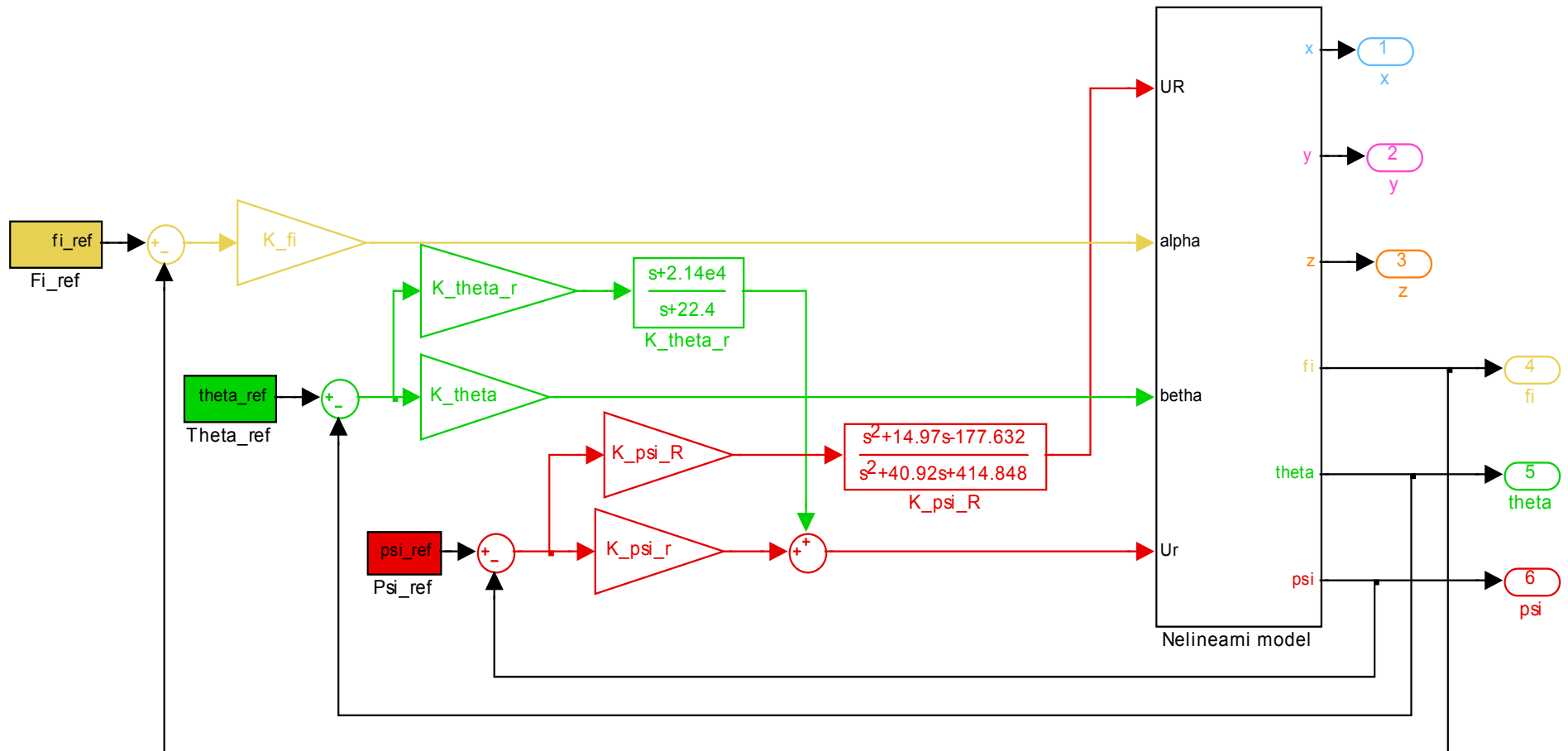


helikopter malih dimenzija
- većina međudjelovanja
može se zanemariti





helikopter malih dimenzija





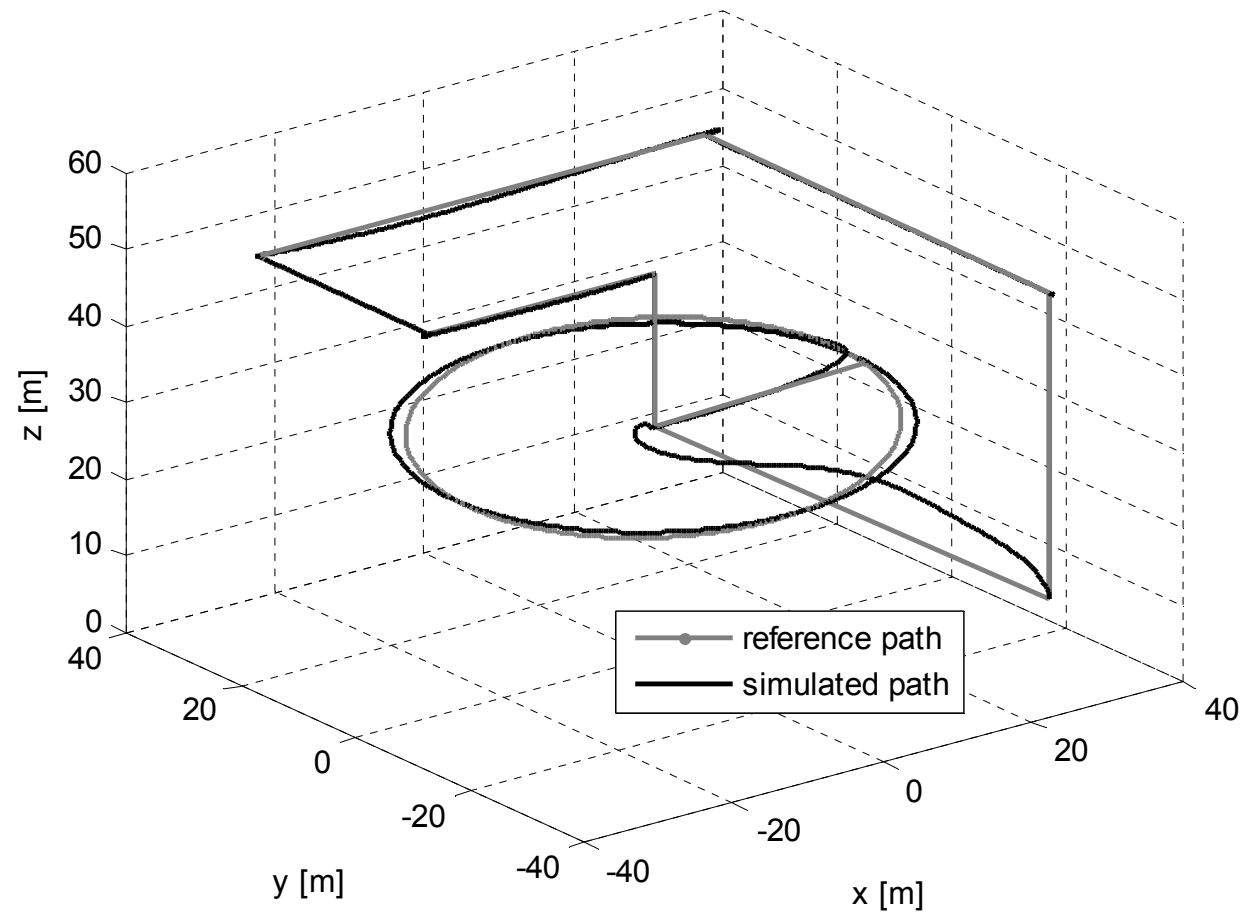
Niz naredbi

vert. gore=>unatrag=>lijevo=>naprijed=>

desno=>vert. dolje=>u polaznu točku=>

kružnica

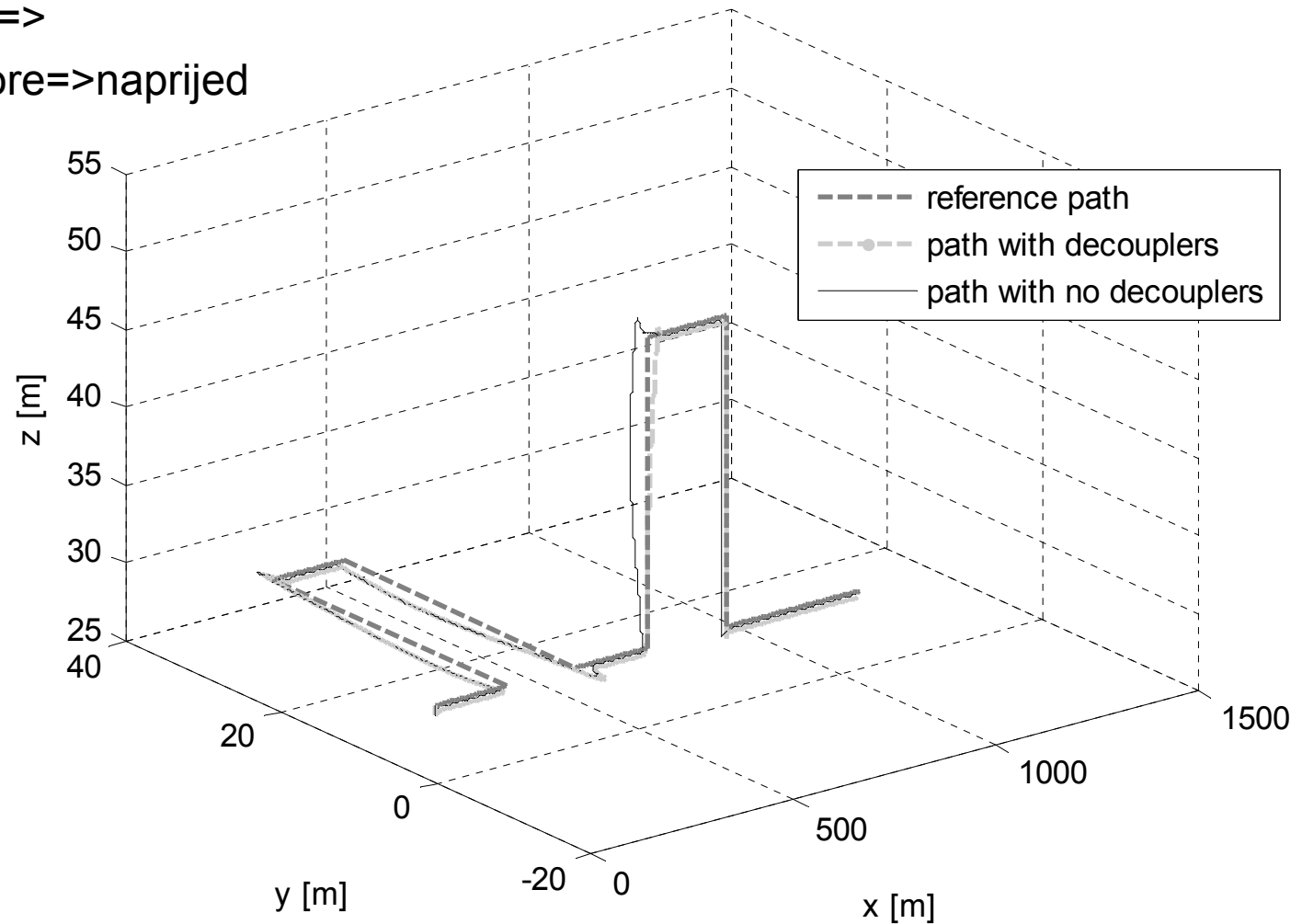
Controlled helicopter model accomplished path



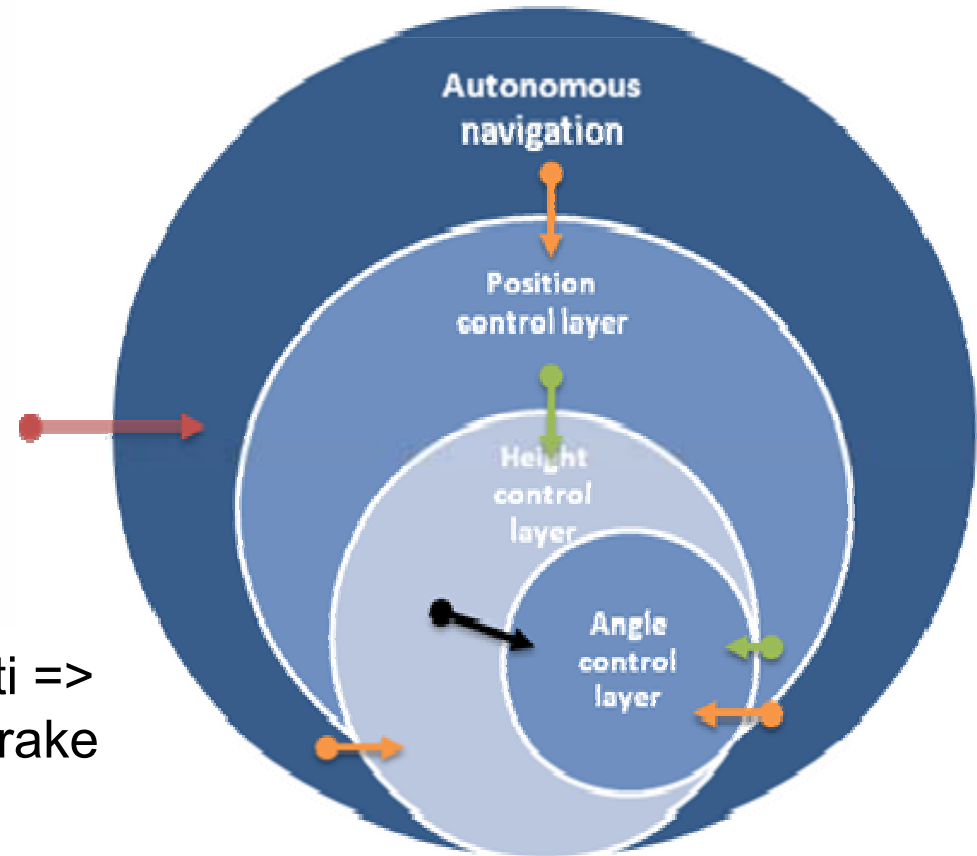
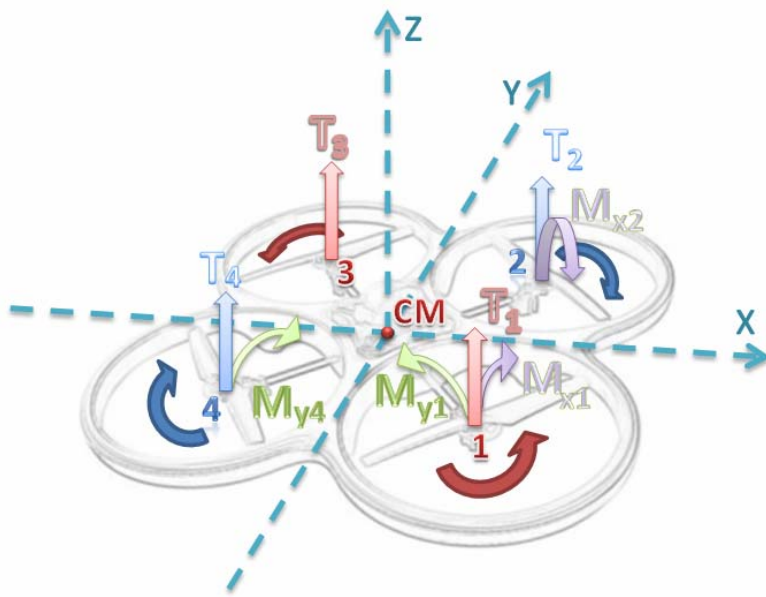


Niz naredbi (s raspresnim reg.)
naprijed=>lijevo=>naprijed=>
desno=>naprijed=>vert. gore=>naprijed
=>vert. dolje=>naprijed

Controlled helicopter model accomplished path



Upravljanje letjelicama - quadrotor



Ograničenje energije + nelinearnosti => manevar se razlaže na slijedeće korake

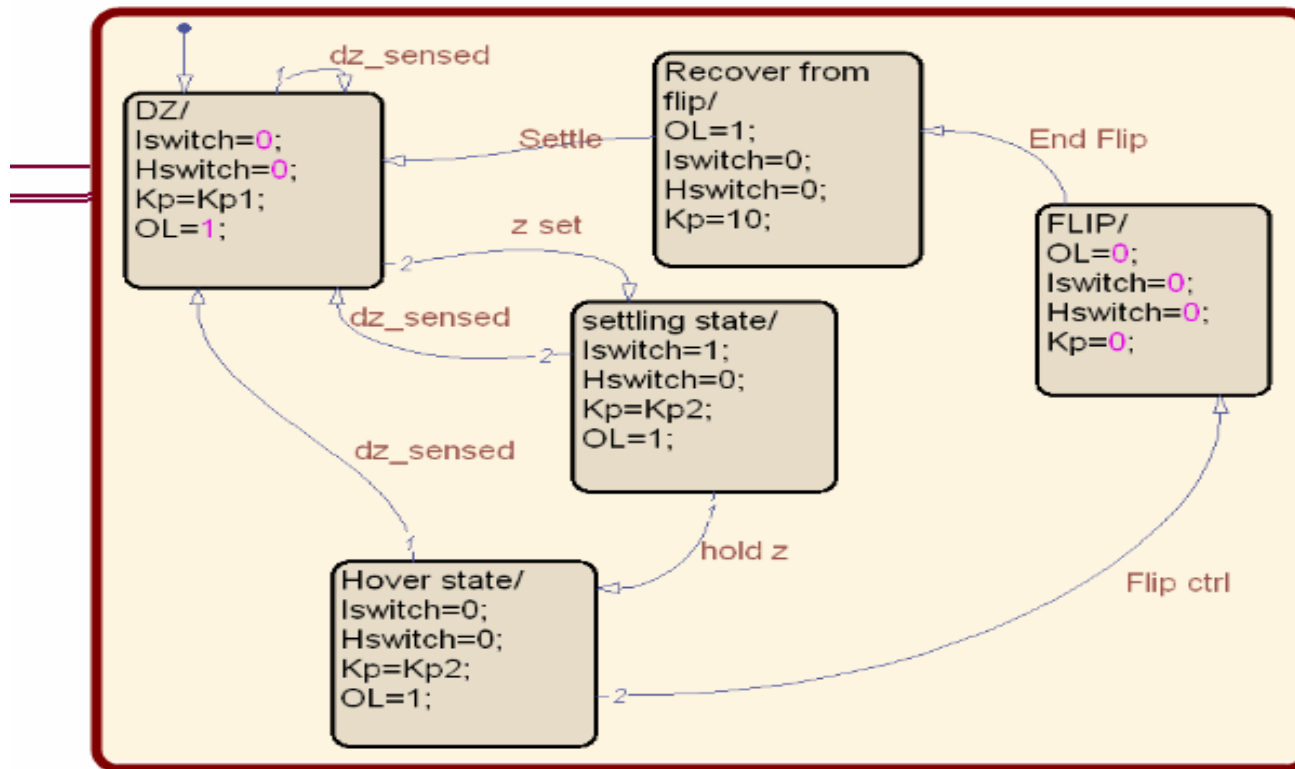
- 1) promjena visine,
- 2) promjena XY pozicije,
- 3) promjena kuta skretanja.

Hibridni regulator



Promjena visine

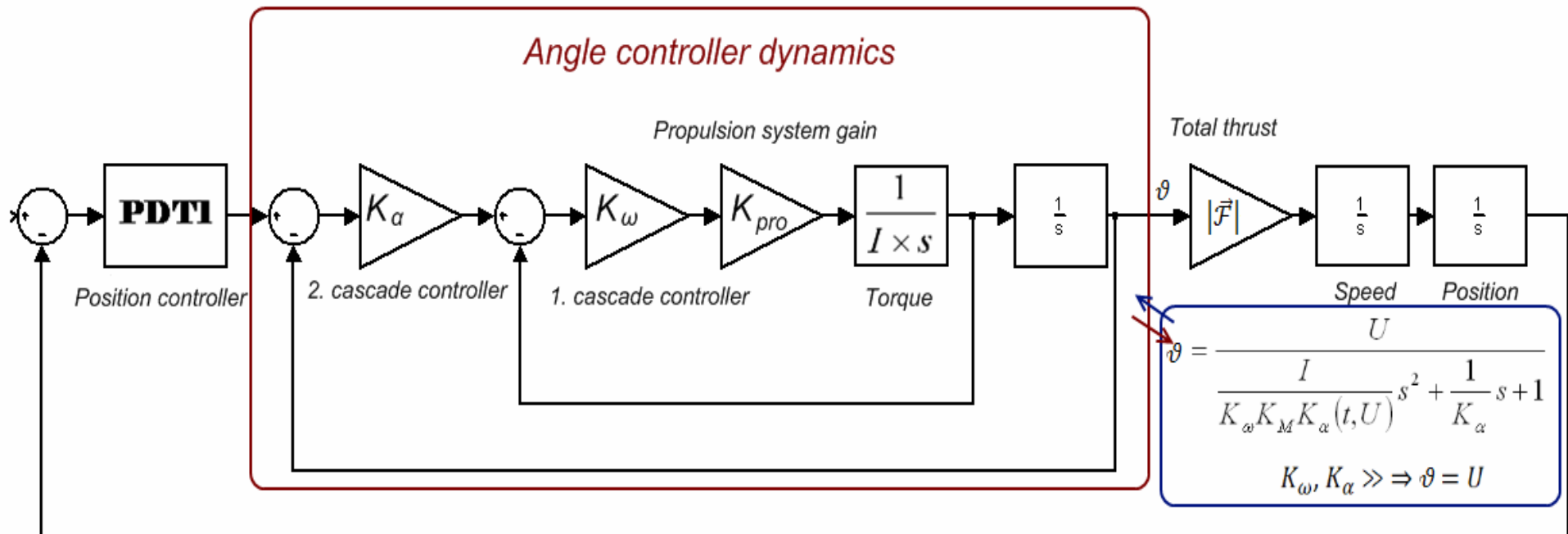
Automat s tri stanja – promjena pojačanja + uključenje integratora

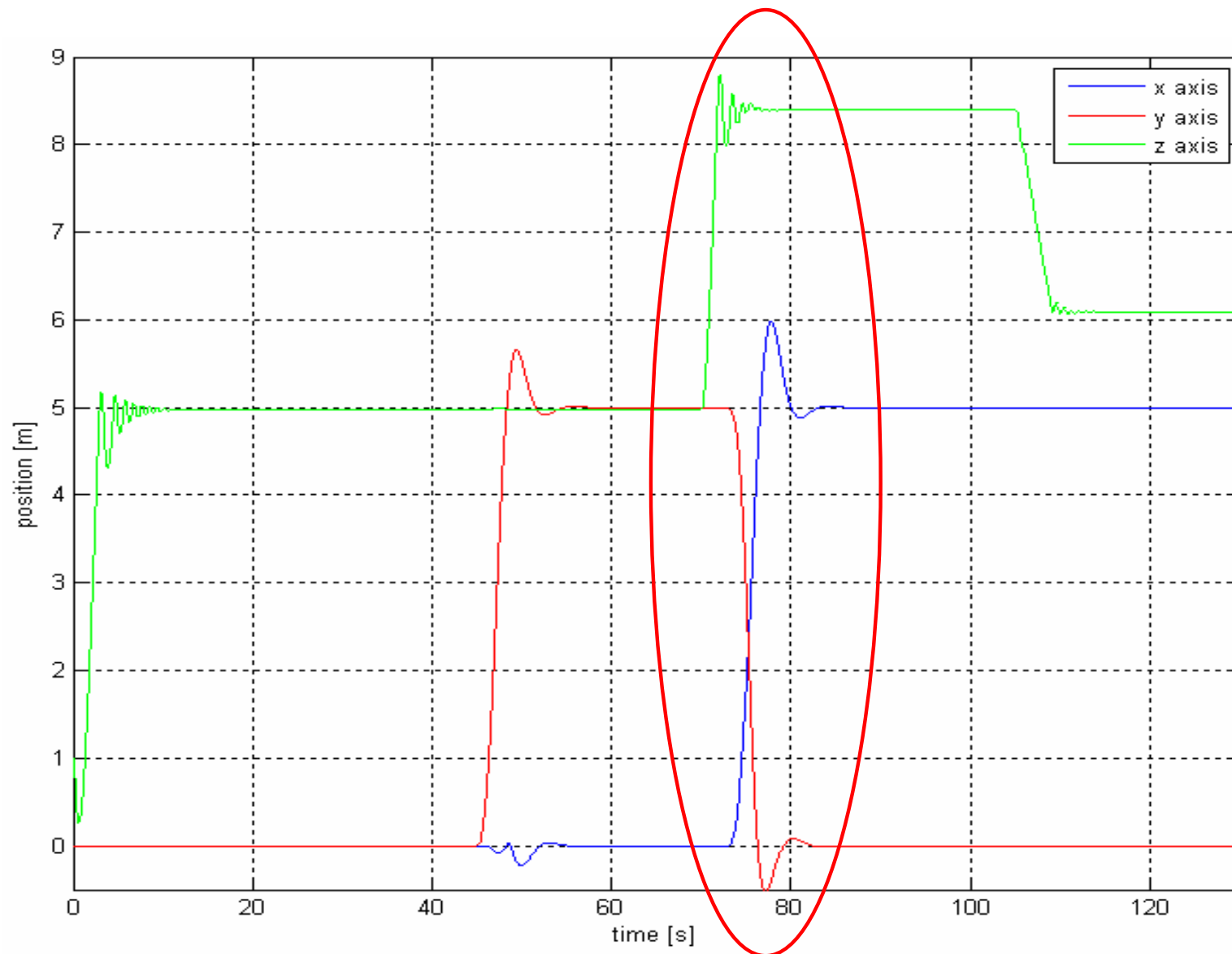


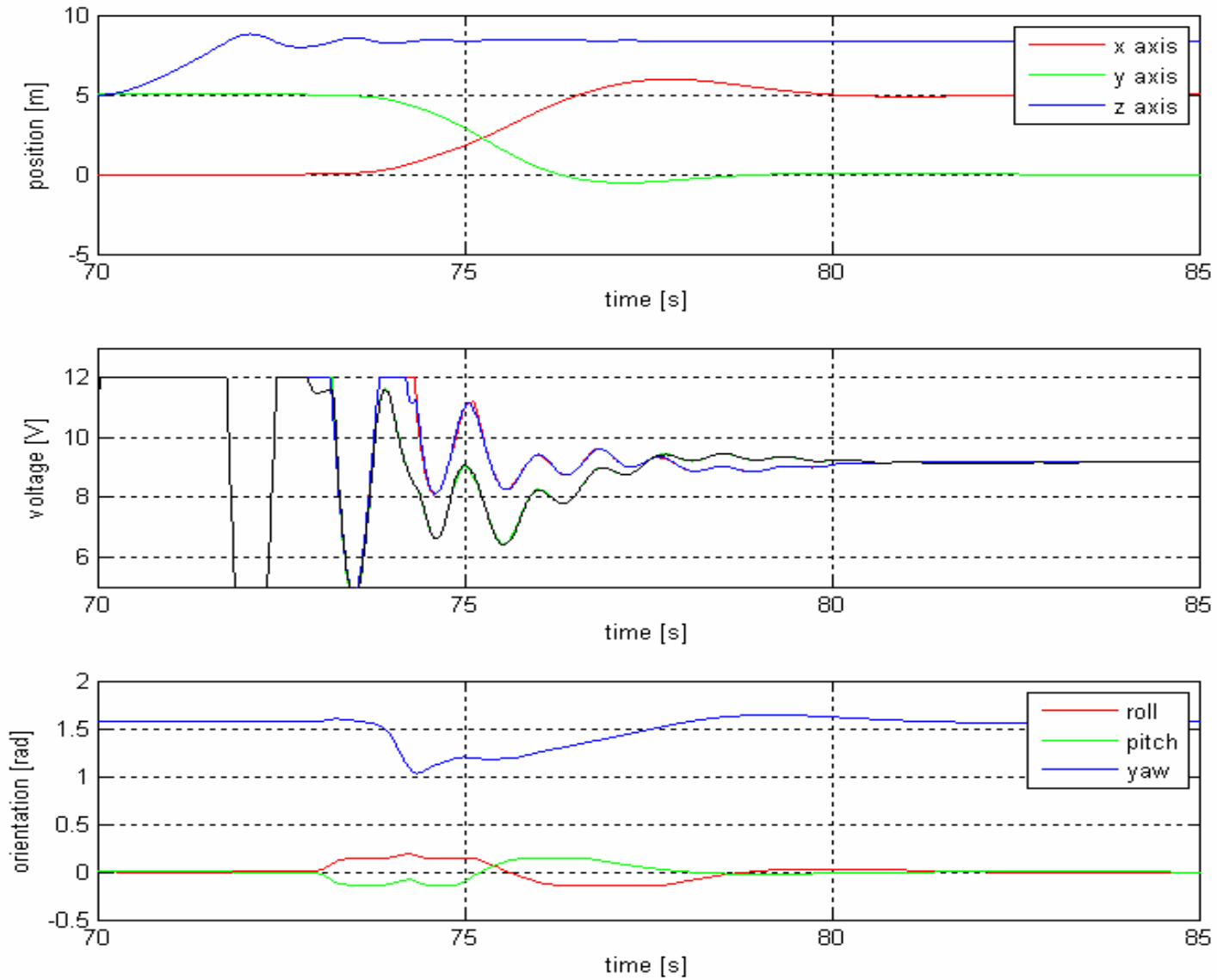


Promjena XY pozicije

Linearizirani sustav (male promjene kuteva) – kaskadno upravljanje









Navigacija – planiranje trajektorije (npr. pretraživanje prostora)

Ho-Cook metoda interpolacije (splines) + LQT optimalni regulator

$$\begin{aligned}\ddot{S}_1(0) &= \dot{S}_1(0) = 0 \\ \ddot{S}_{n-1}(\Delta t_{n-1}) &= \dot{S}_{n-1}(\Delta t_{n-1}) = 0 \\ S_i(\Delta t_i) &= S_{i+1}(0) \\ \dot{S}_i(\Delta t_i) &= \dot{S}_{i+1}(0) \\ \ddot{S}_i(\Delta t_i) &= \ddot{S}_{i+1}(0)\end{aligned}$$

$$J = \frac{1}{2} e'(t_f) S(t_f) e(t_f) + \frac{1}{2} \int_{t_0}^{t_f} [e(t)' Q(t) e(t) + u'(t) R(t) u(t)] dt ,$$

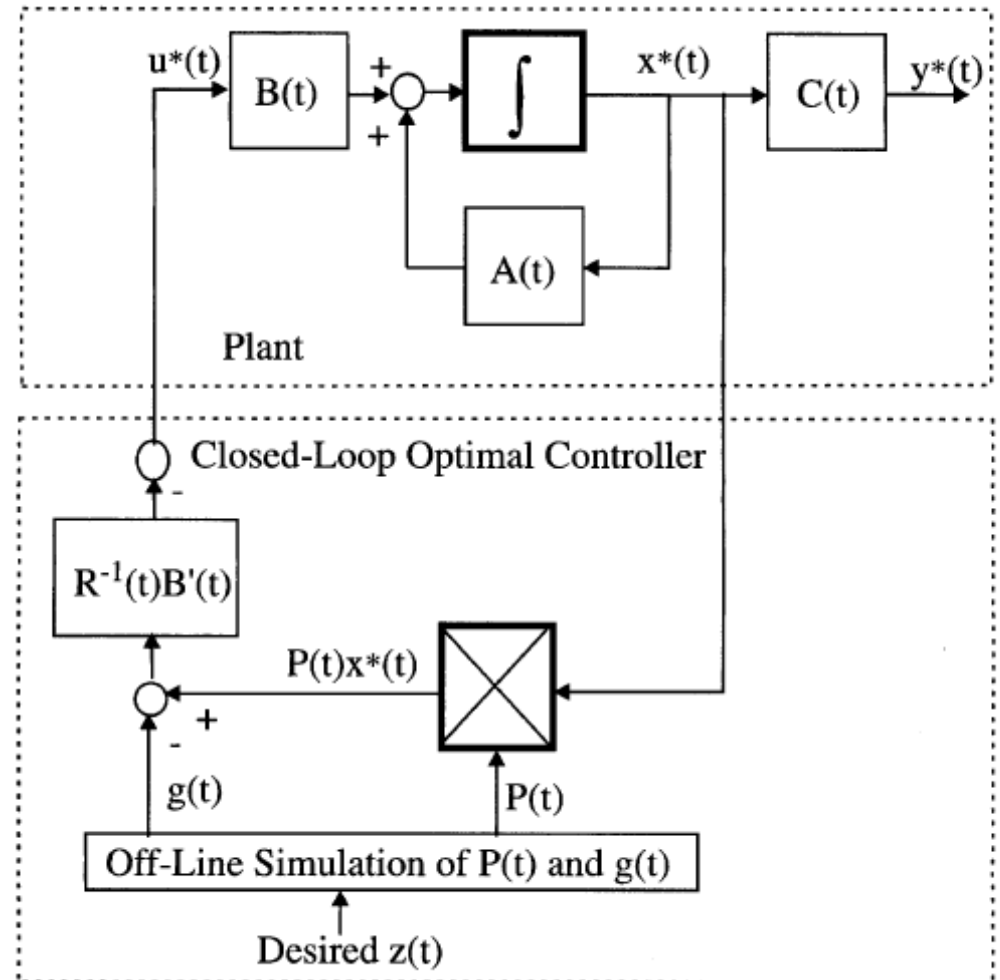


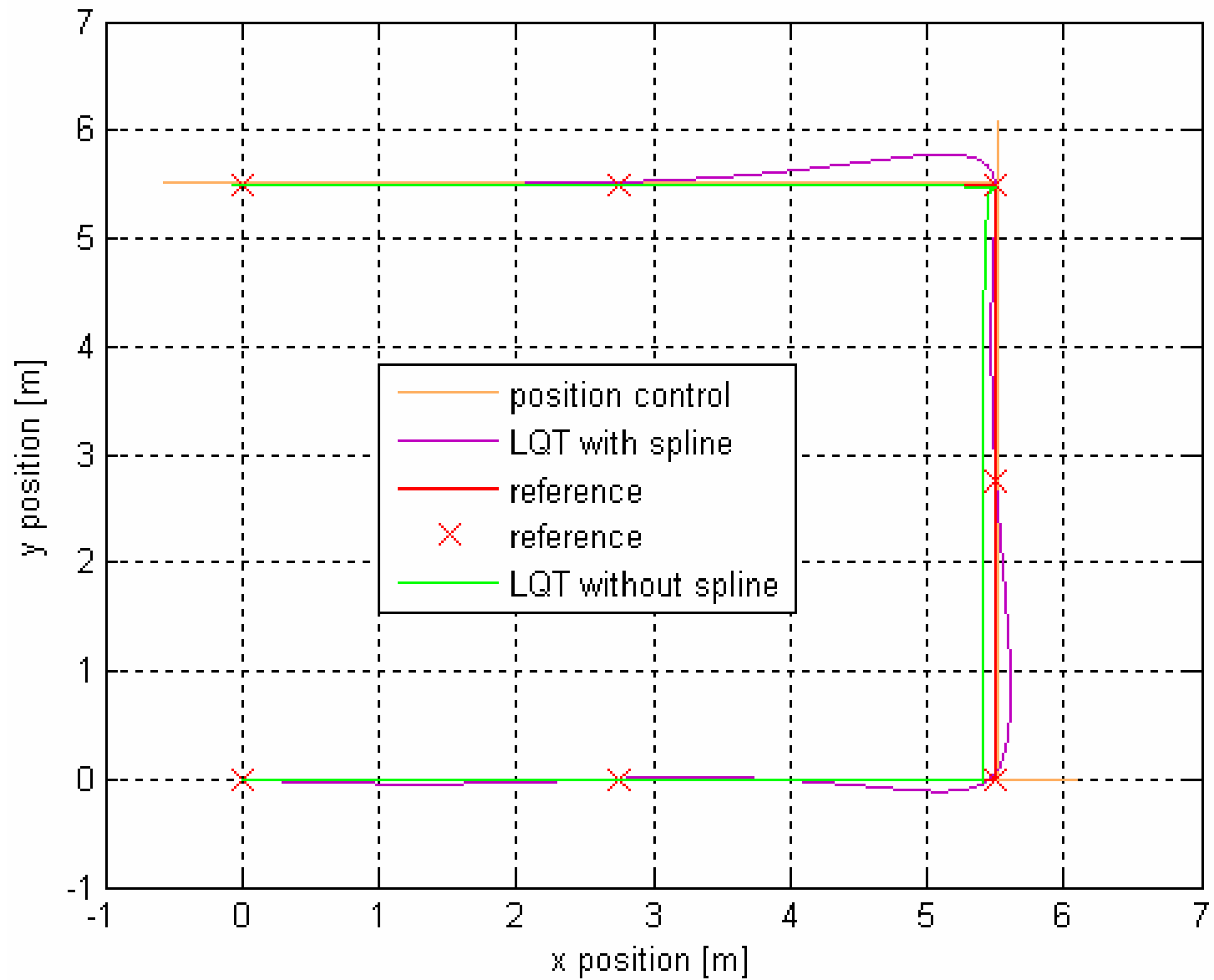
LQT optimalni regulator

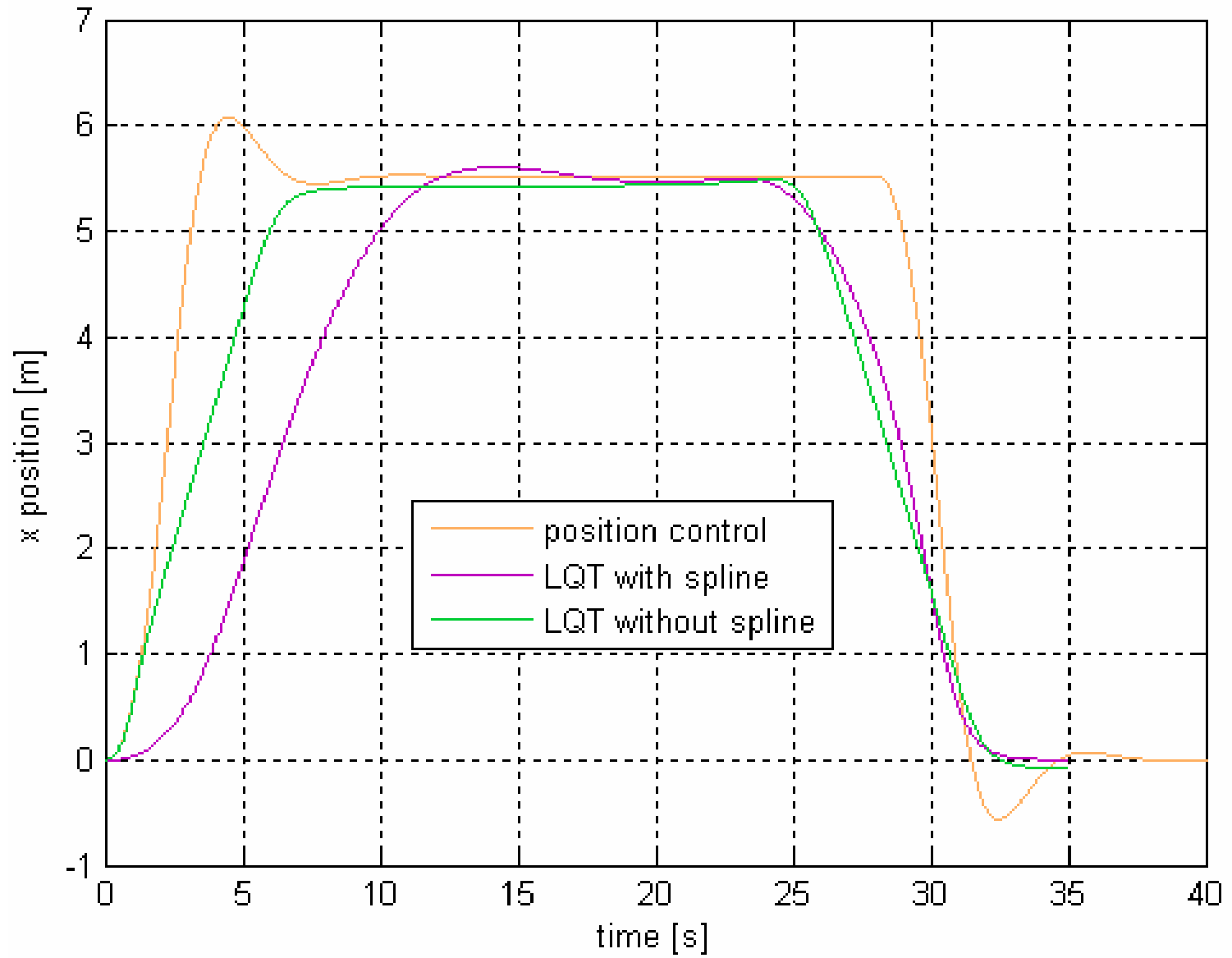
$$u^*(t) = -R^{-1}(t)B'(t)[P(t)x^*(t) - g(t)]$$

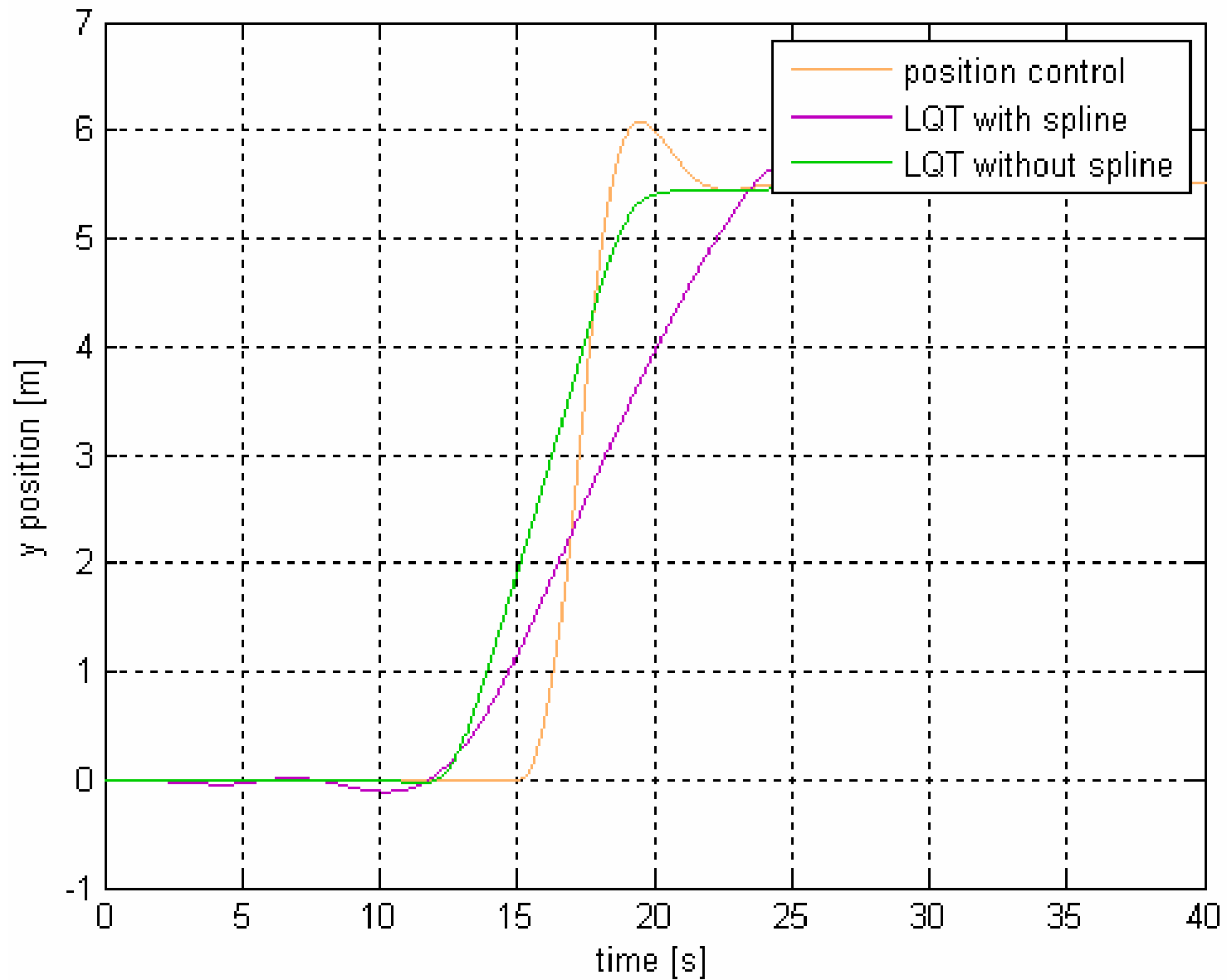
S, R, Q = ?

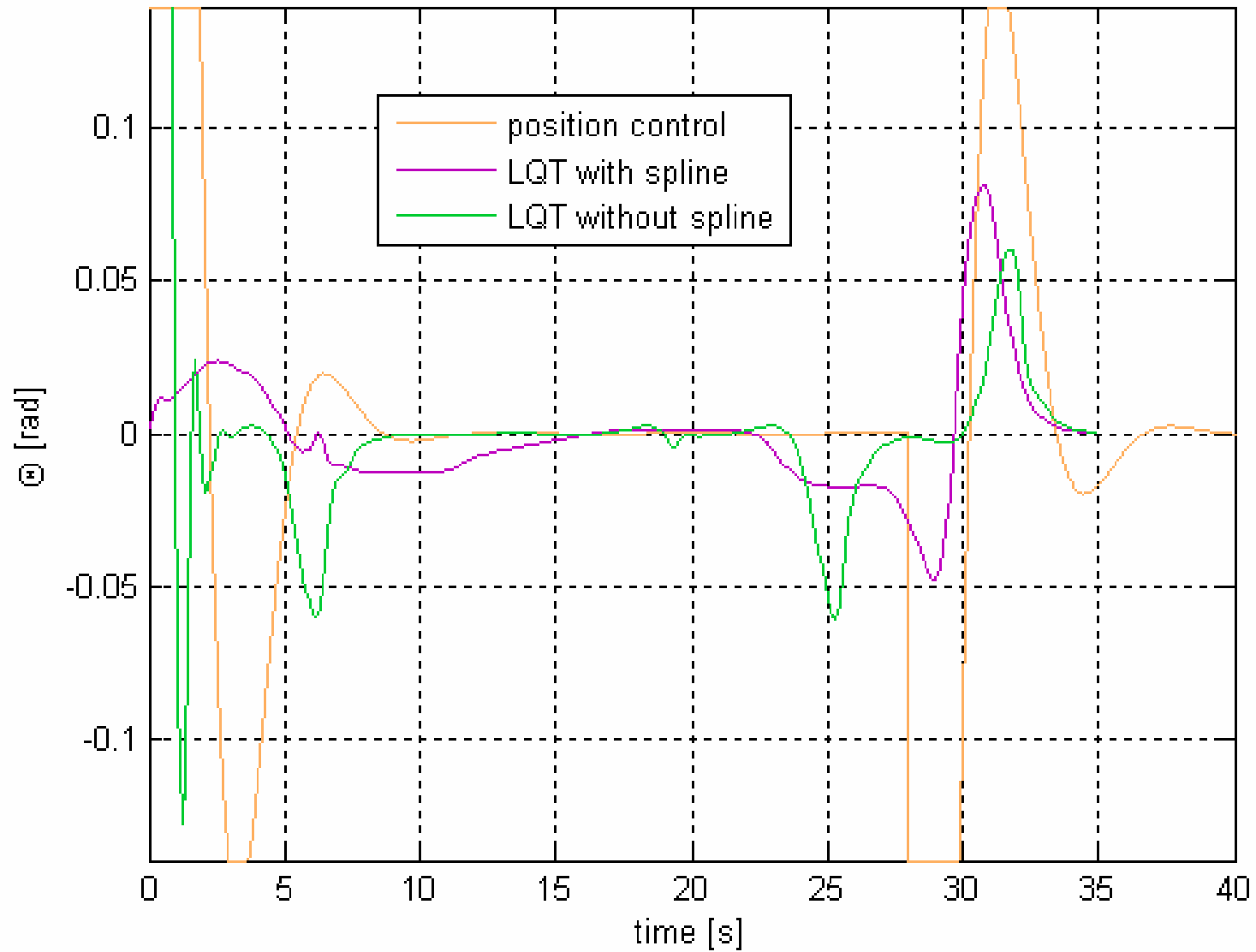
npr. Brysonova metoda

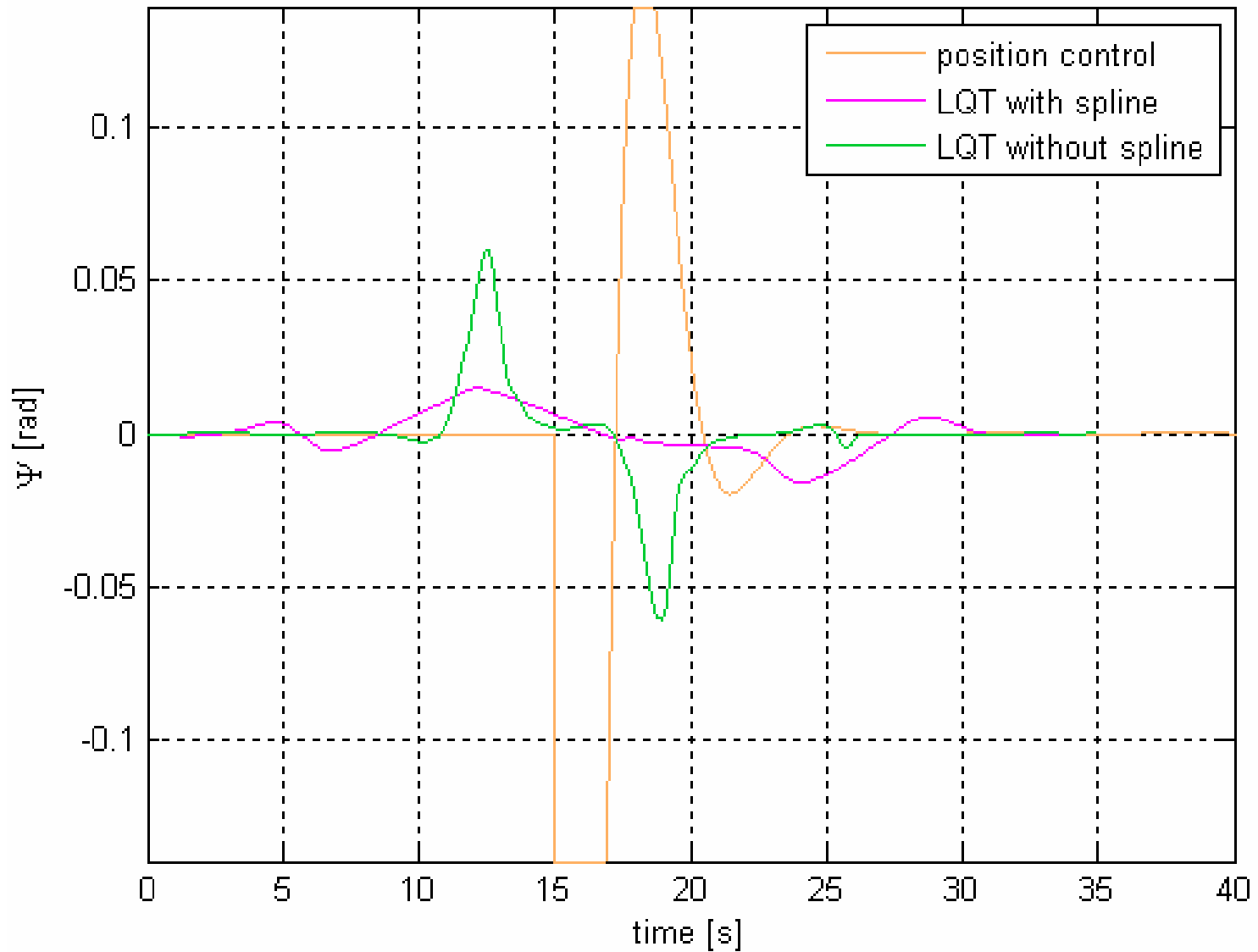








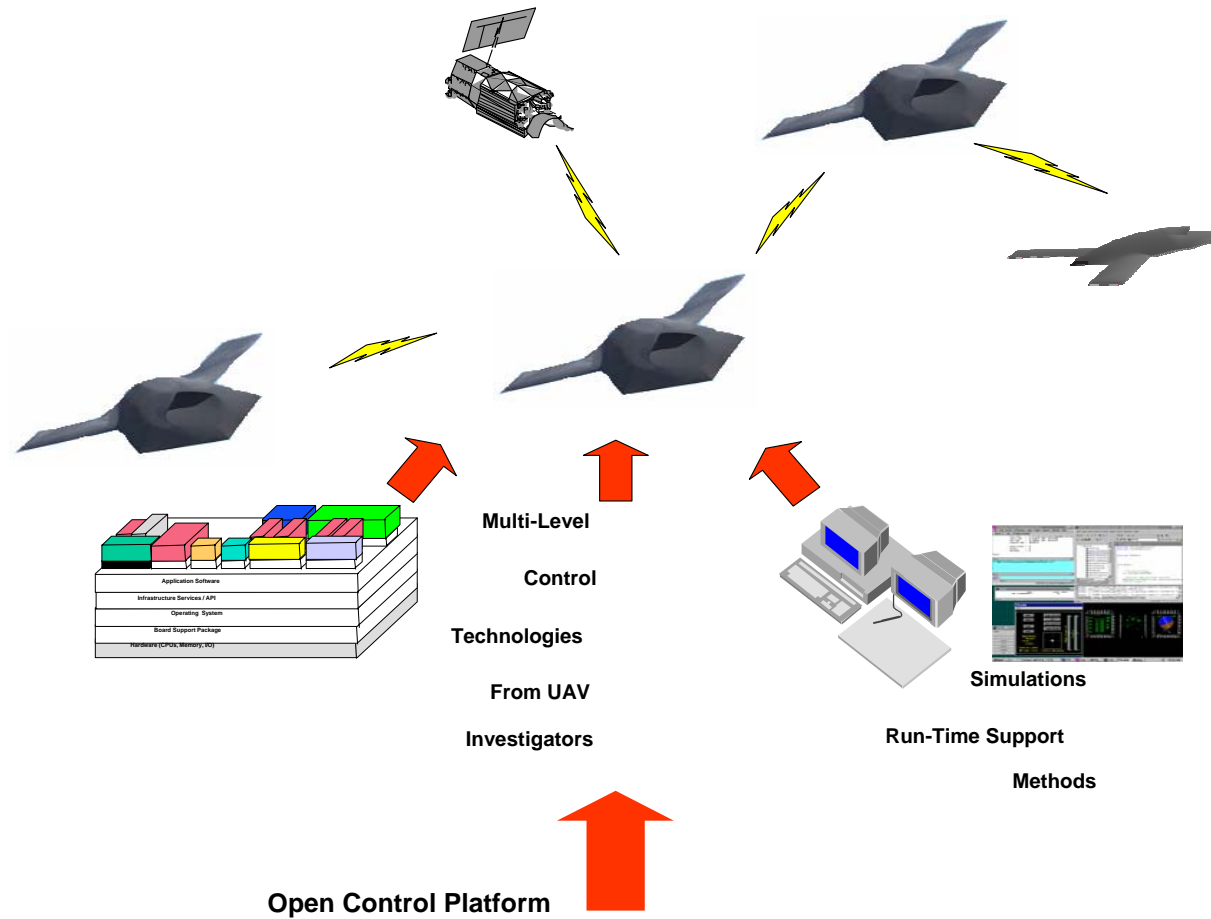






Upravljanje formacijama

Coordinated Operation of Highly Autonomous UAVs





- Dinamička mreža (dynamic network)
 - “A dynamic network is characterized by a spatially **distributed** set of dynamic **nodes** which are **coordinated** (or integrated) by the mission objectives and possible dynamic coupling between the nodes. The mission objectives are to be obtained in the presence of **large uncertainties** due largely to a hostile environment. Within this context, nodes may fail at various levels, measurements may be highly corrupted and communication channels may be severely limited due to jamming.”

S. Banda, J. Doyle, R. Murray, J. Paduano, J. Speyer, and G. Stein. Research needs in dynamics and control for uninhabited aerial vehicles (uavs). Draft available at <http://www.cds.caltech.edu/murray/notes/uav-nov97.html>, November 10 1997.



Dinamičke mreža – svuda oko nas!

- Mapiranje i pretraživanje
- Transport
- Komunikacije
- Mobilni senzori
- Klasteri satelita
- Jata
- Formacijsko letenje



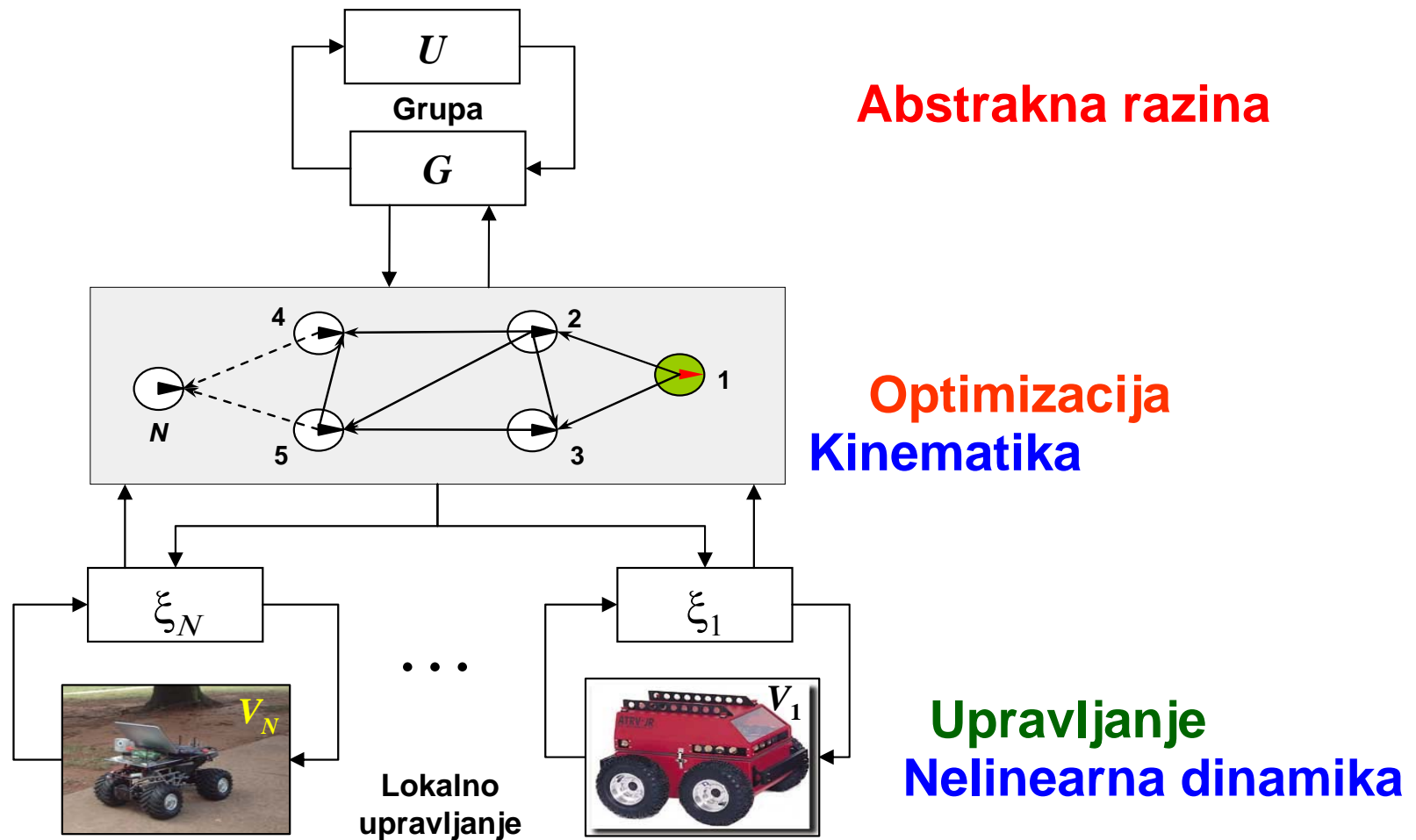
Pristupi rješavanju problema

- Linearizacija po povratnoj vezi,
- Teorija grafova,
- Teorija jata,
- Različiti oblici prediktivnog upravljanja,
- Virtualni potencijali,



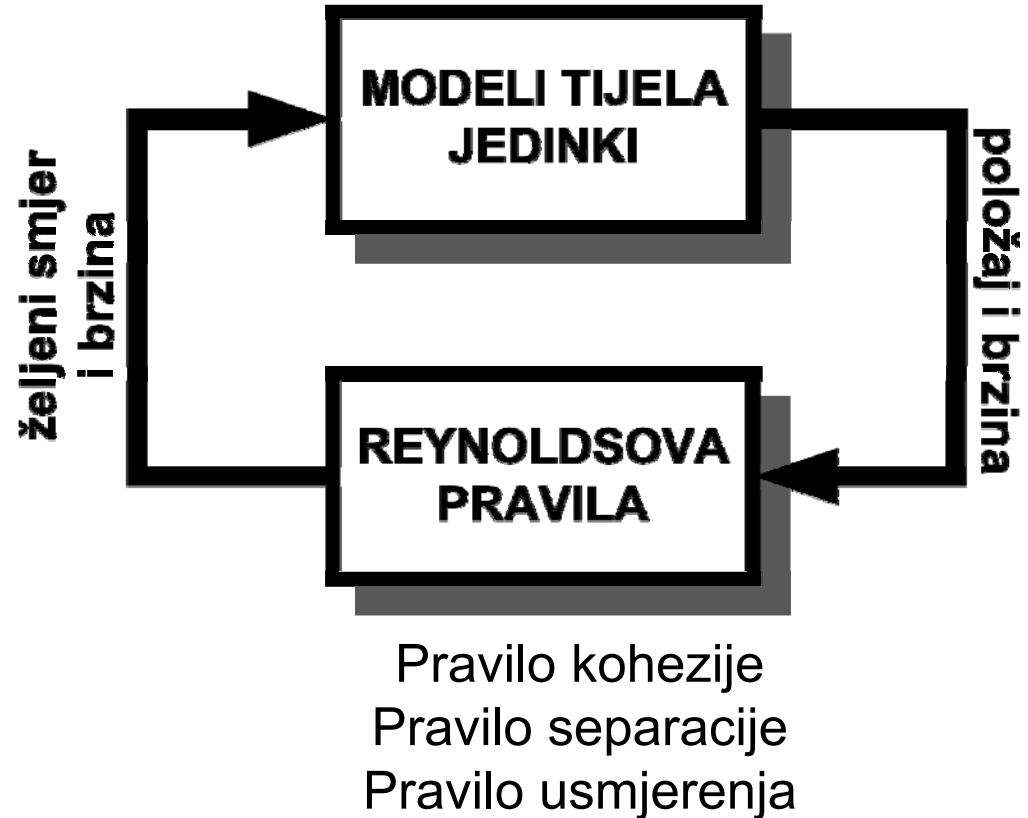


Razine upravljanja formacijom



Reynoldsov model – najjednostavniji model

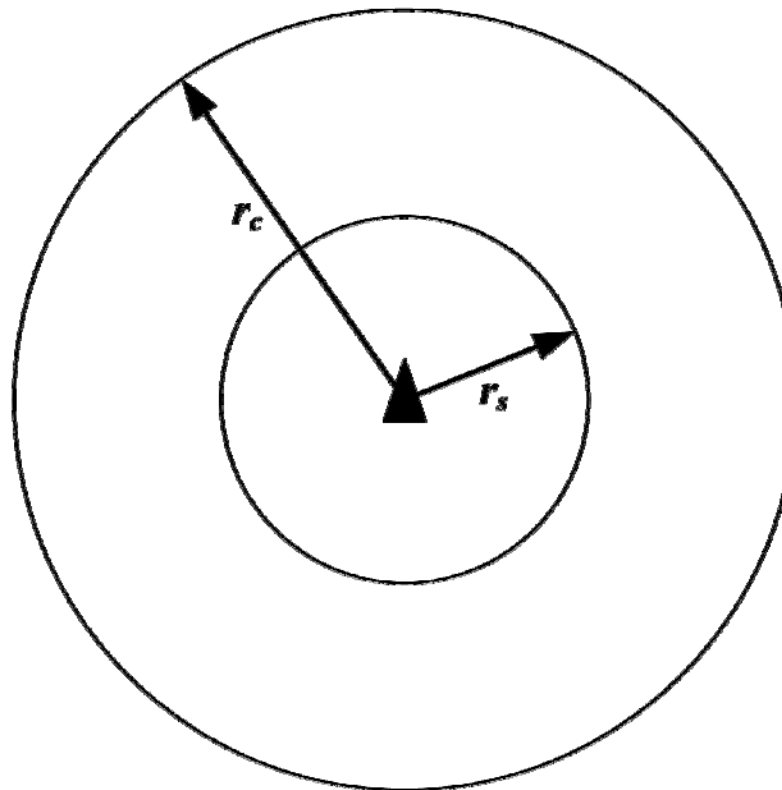
- Definiraju se lokalna (Reynoldsova) pravila koja vrijede za svaku jedinku
- Skup jedinki modeliran na ovaj način predstavlja samoorganizirajući višeagentni sustav





Reynoldsov model

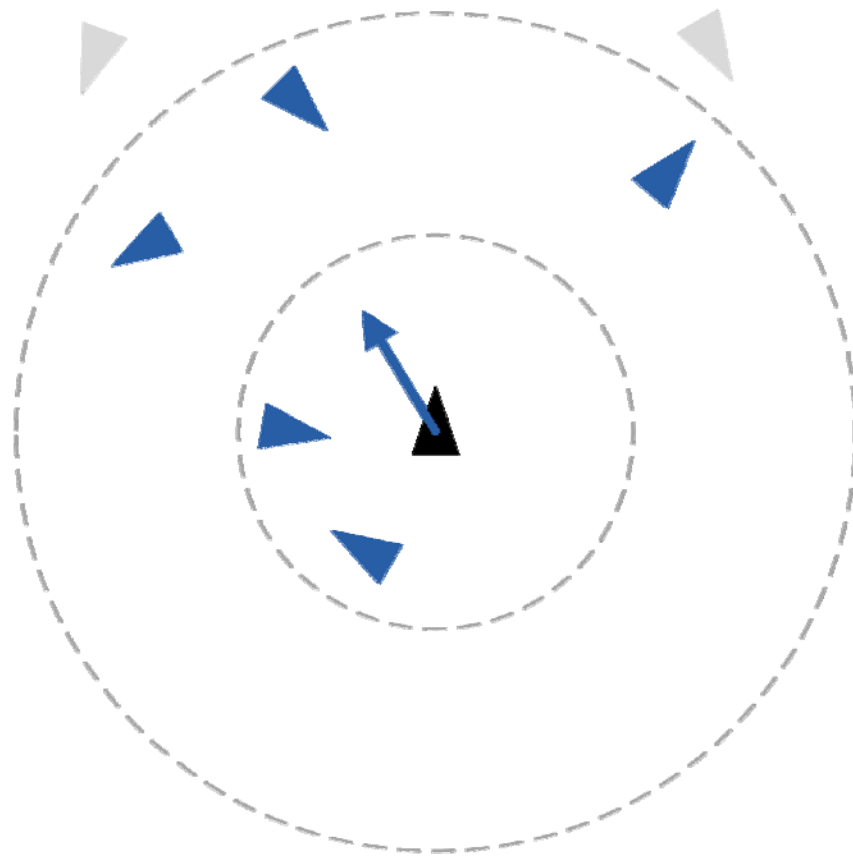
- ograničena percepcija okoline





Pravilo kohezije (*cohesion*)

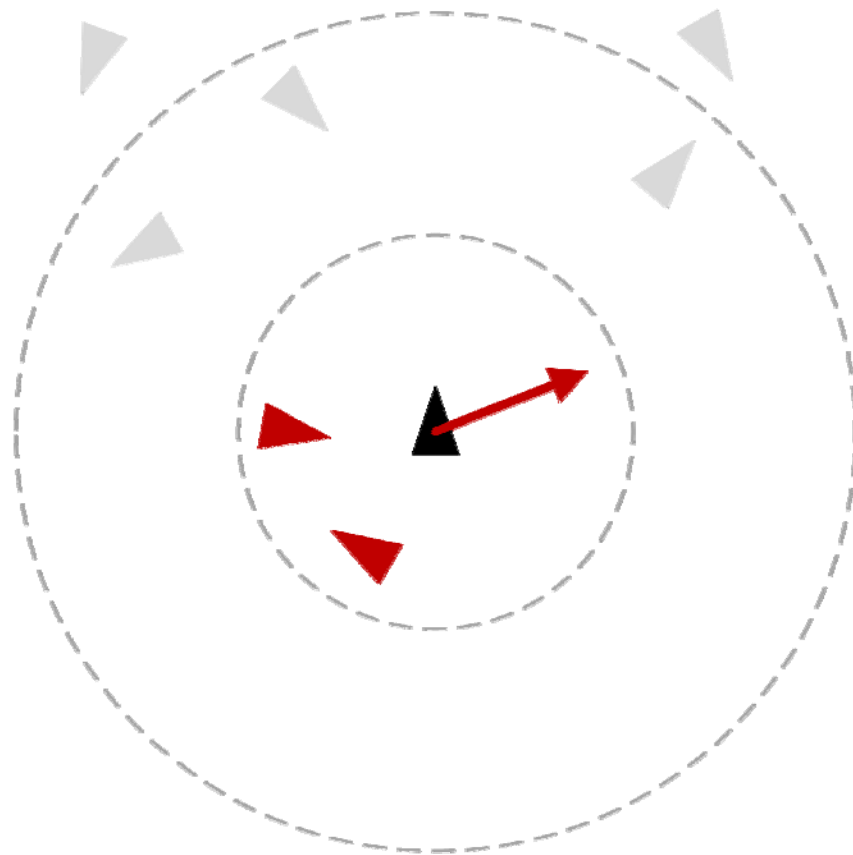
Nastojanje jedinice da se nalazi u blizini drugih jedinki u jatu.





Pravilo separacije (*separation*)

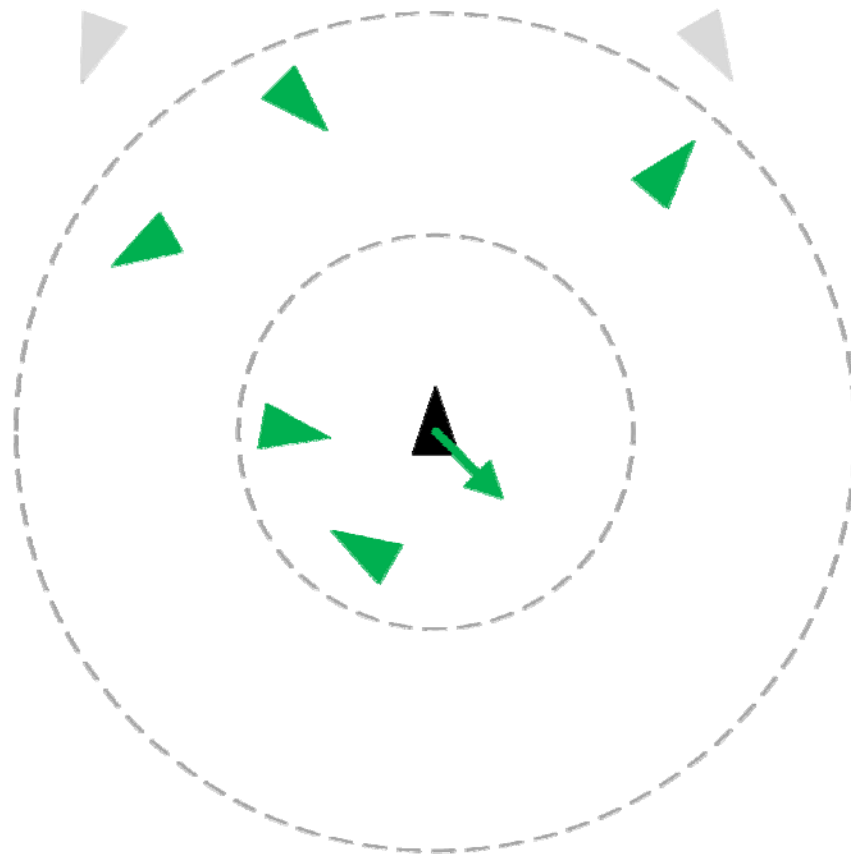
Nastojanje jedinice da održi određeni razmak od drugih jedinki u jatu.





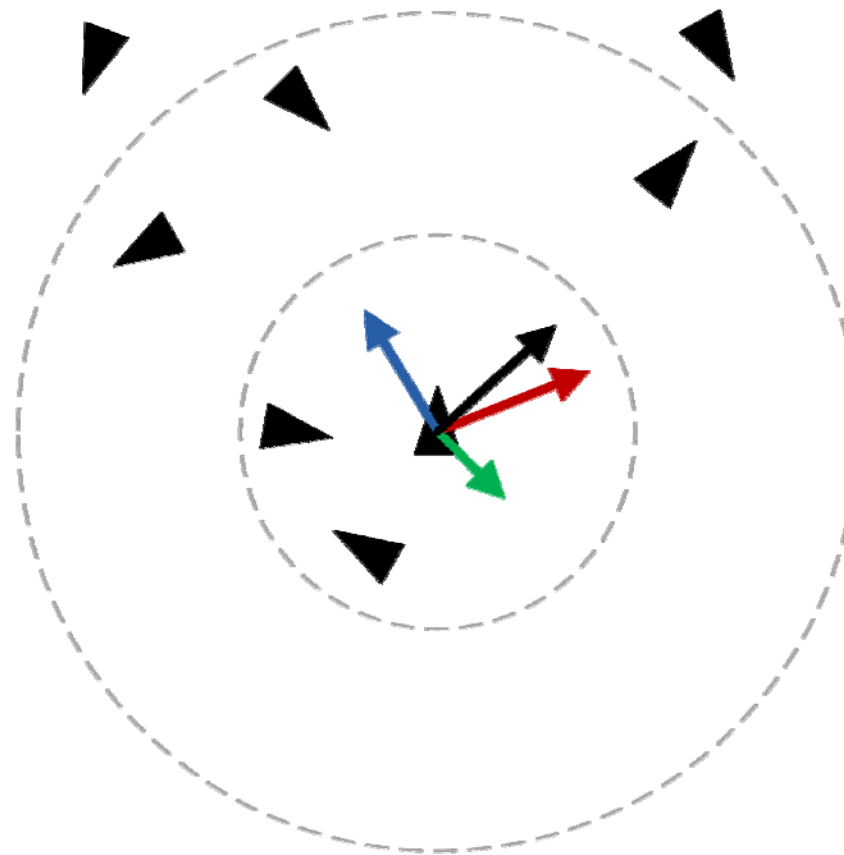
Pravilo usmjerenja (*alignment*)

Nastojanje jedinice da smjer i brzinu gibanja uskladi s drugim jedinkama u jatu.




Ukupni vektor gibanja

$$v_{Ri} = C \cdot v_{ci} + S \cdot v_{si} + A \cdot v_{ai}$$



Utjecaj C, S i A 

Utjecaj dinamike 

Veliko jato 

Vektor migracije 



Formacija – položaj jedinice unutar grupe definiran

$$\mathbf{q}_T = [q_{1T} \ q_{2T} \ \dots \ q_{nT}]^T \quad - \text{ zadana formacija}$$

$$\mathbf{q}_0 = [q_{10} \ q_{20} \ \dots \ q_{n0}]^T \quad - \text{ početni položaj}$$

Zadatak algoritma upravljanja - formirati i potom održati formaciju

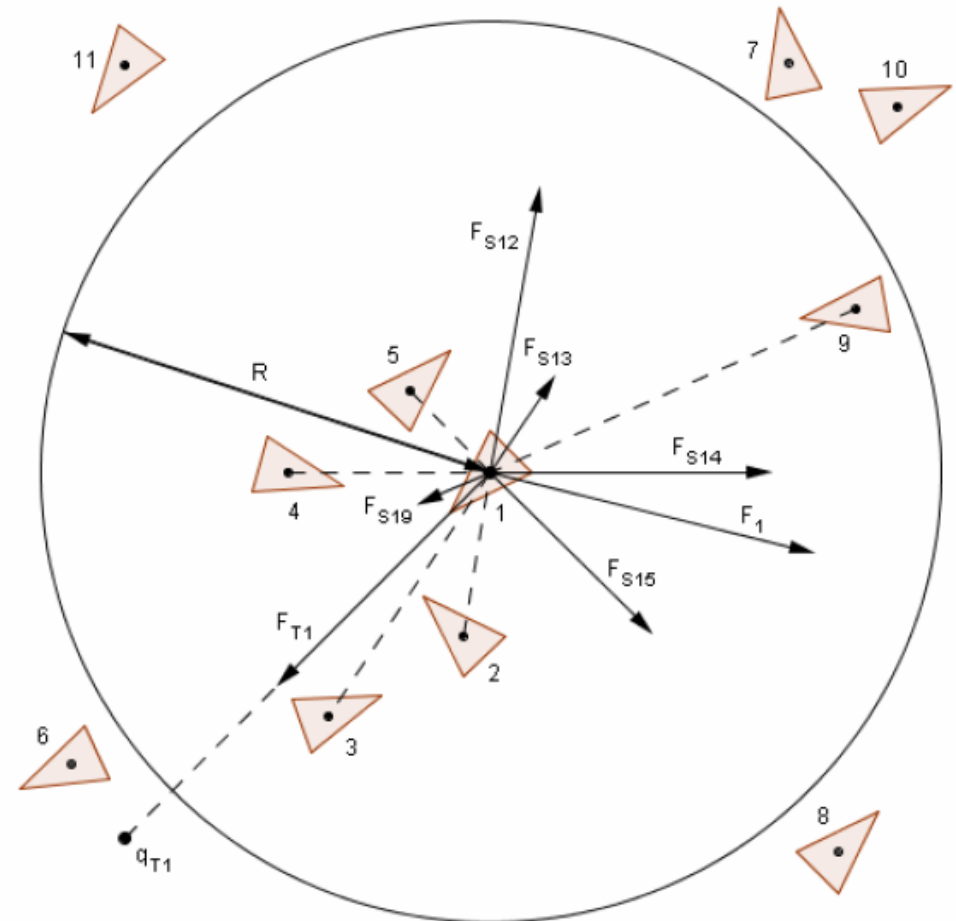
Upravljanje metodom privlačne i odbojne sile

$$F_{Ai} = \begin{cases} k_{Ai} d_i & \text{for } d_i \leq \bar{d} \\ \bar{F}_{Ai} & \text{for } d_i > \bar{d} \end{cases}$$

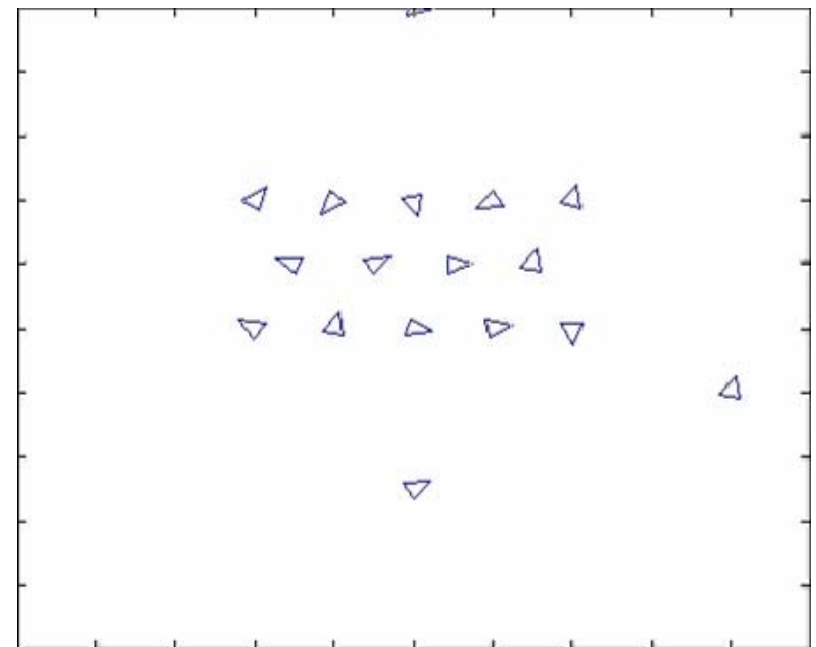
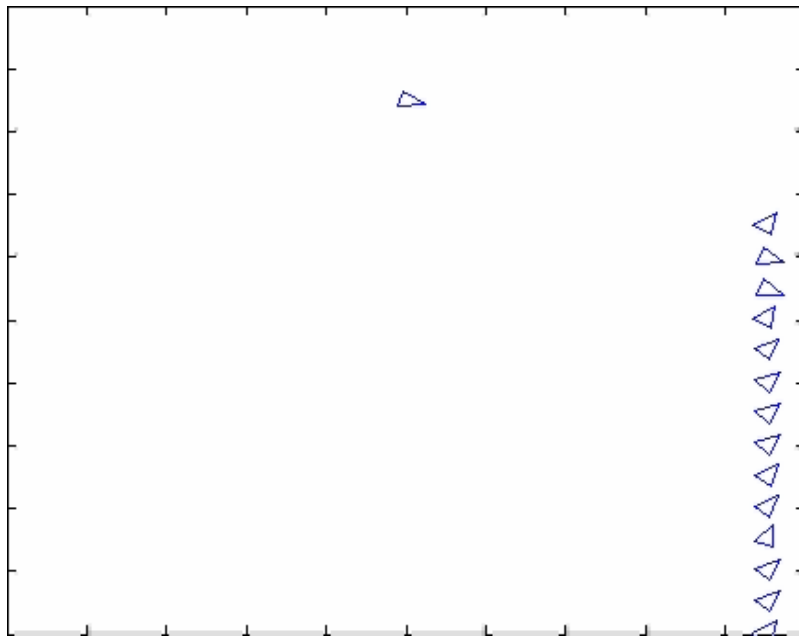
$$d_i = \|q_i - q_{iT}\|$$

$$F_{Rij} = k_{Ri} l_{ij}^p \Rightarrow F_{Ri} = \sum_{j=1}^p F_{Rij}$$

$$l_{ij} = \|q_i - q_j - R_i\|$$

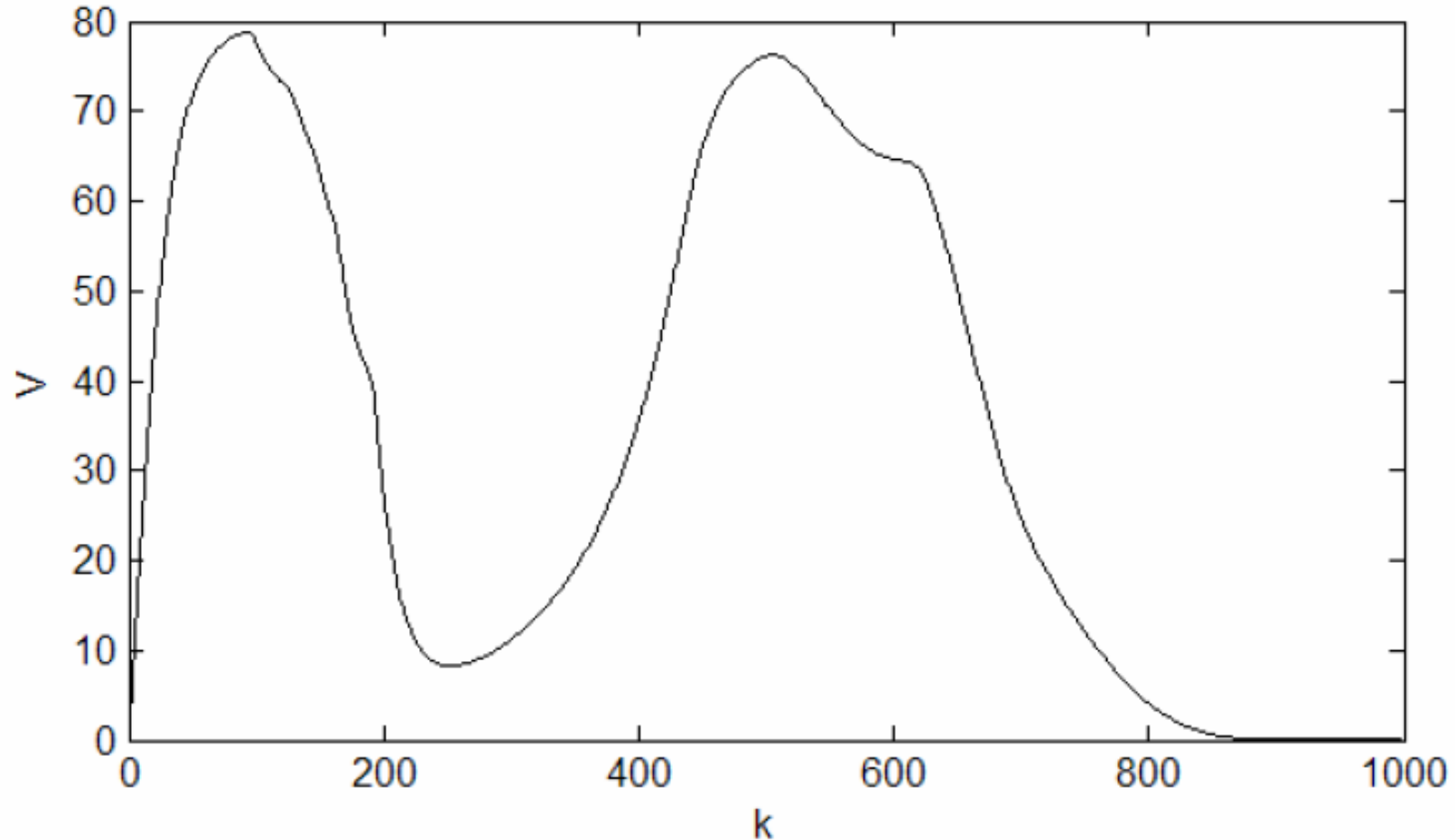


$$\vec{F}_i = \vec{F}_{Ai} + \vec{F}_{Ri}$$

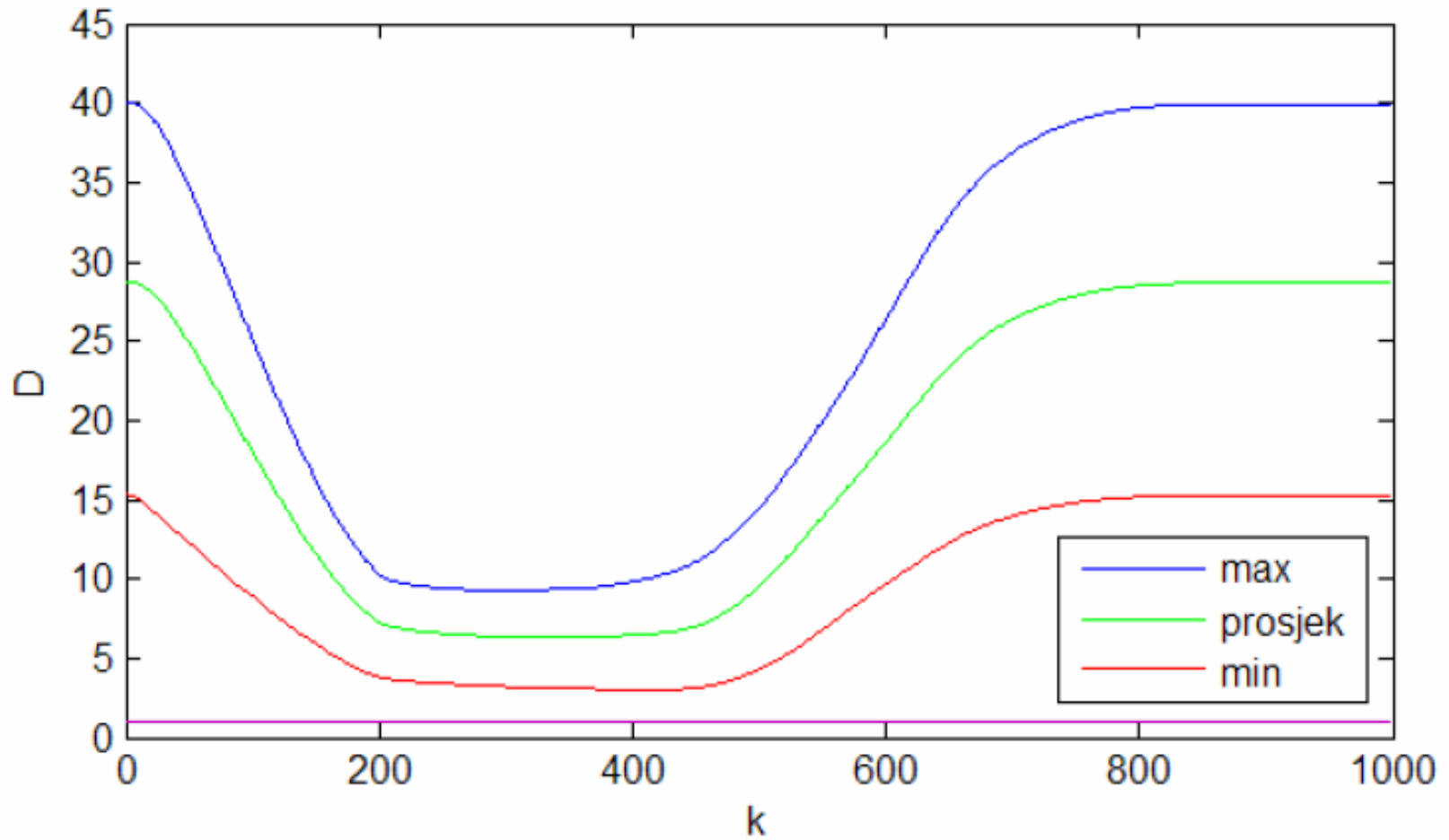




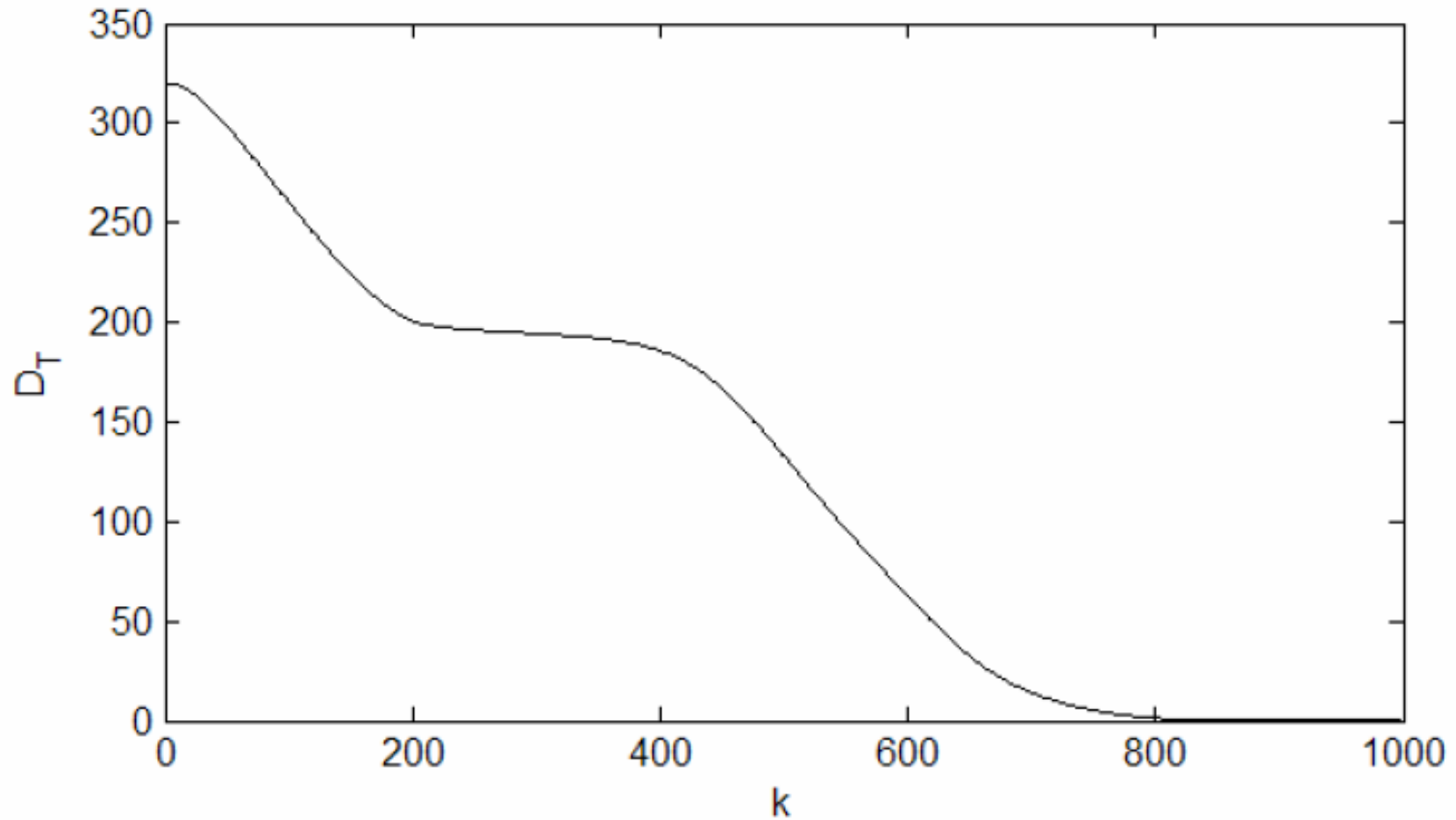
Pokazatelji kvalitete – situacija zamjene mjesta u kružnoj formaciji



Zbroj brzina gibanja svih jedinki



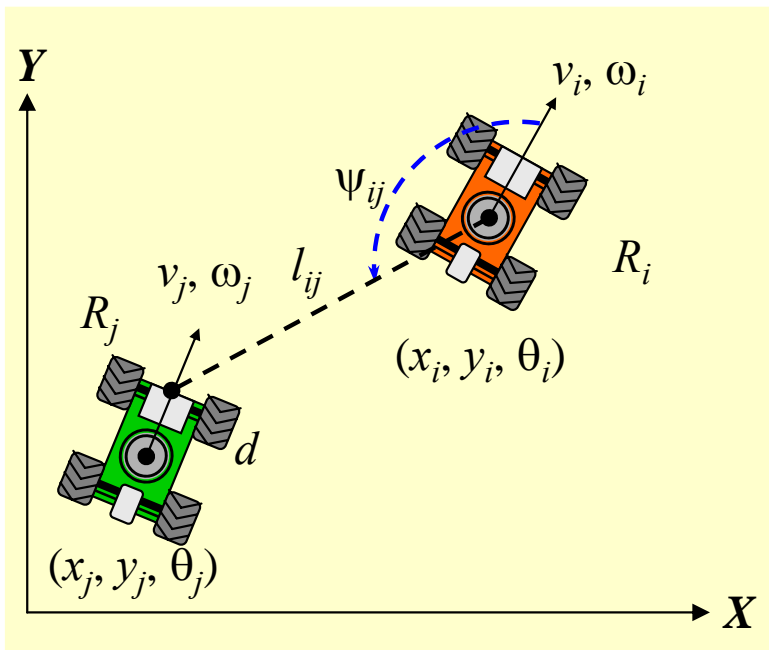
Udaljenost među jedinkama



Ukupna udaljenost od zadane formacije

Upravljanje metodom linearizacije po povratnoj vezi

“leader-follower” konfiguracija



$$\dot{x}_i = v_i \cos \theta_i, \quad \dot{y}_i = v_i \sin \theta_i, \quad \dot{\theta}_i = \omega_i$$

Izlazni vektor:
$$z_j = \begin{bmatrix} l_{ij} \\ \psi_{ij} \end{bmatrix}$$

$$\dot{z}_j = G_1(z_j)u_j + F_1(z_j, u_j),$$

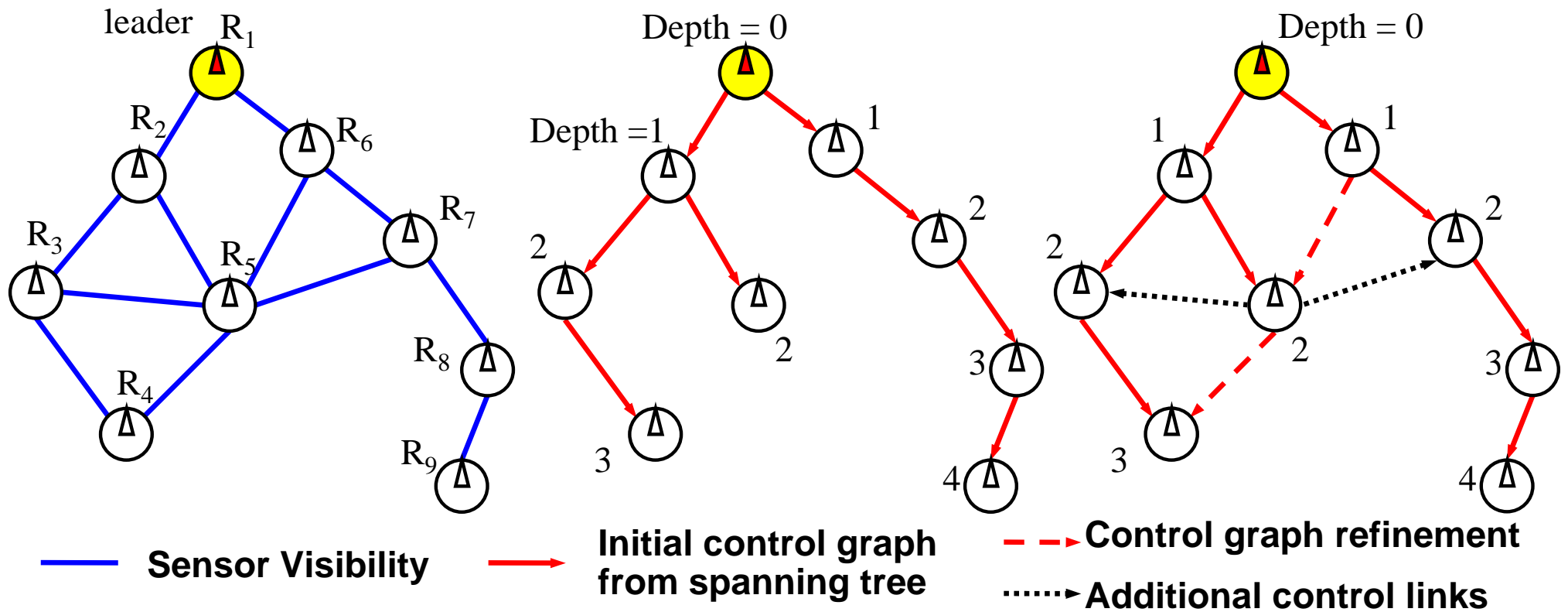
$$\dot{\theta}_j = \omega_j$$

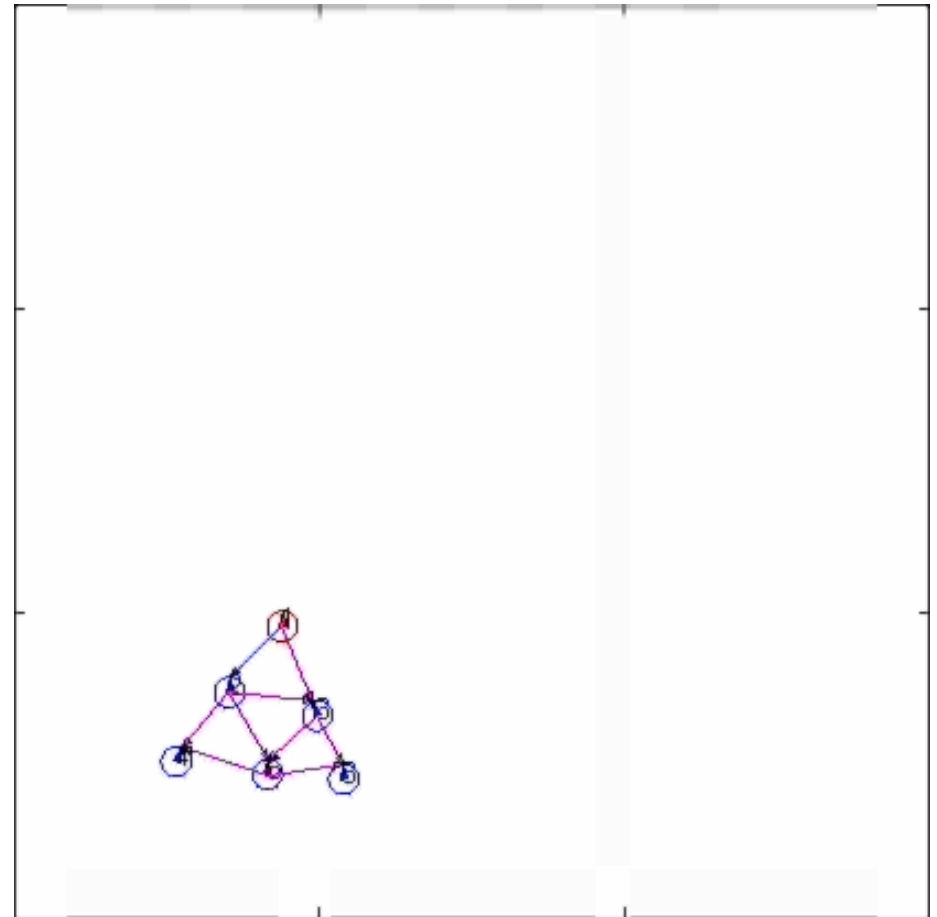
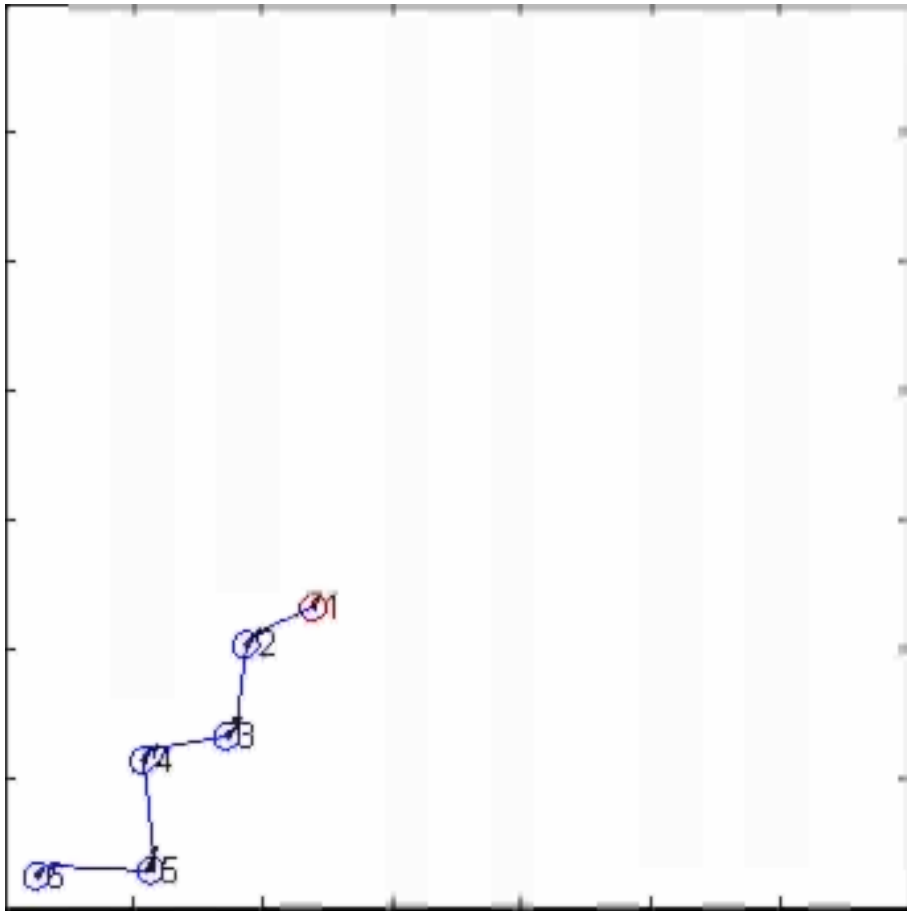
$$u_j = G_1^{-1} [k(z_j^d - z_j) - F_1]$$

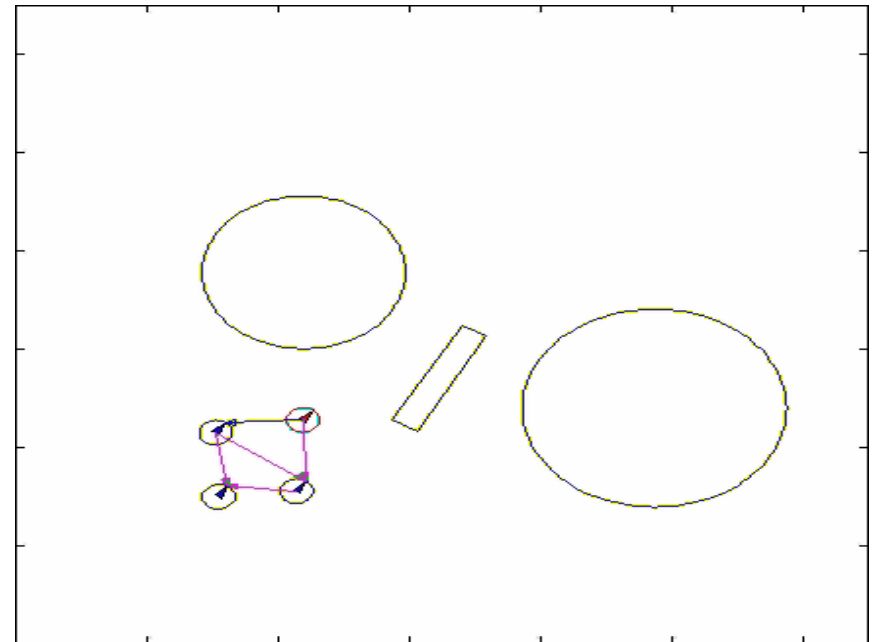
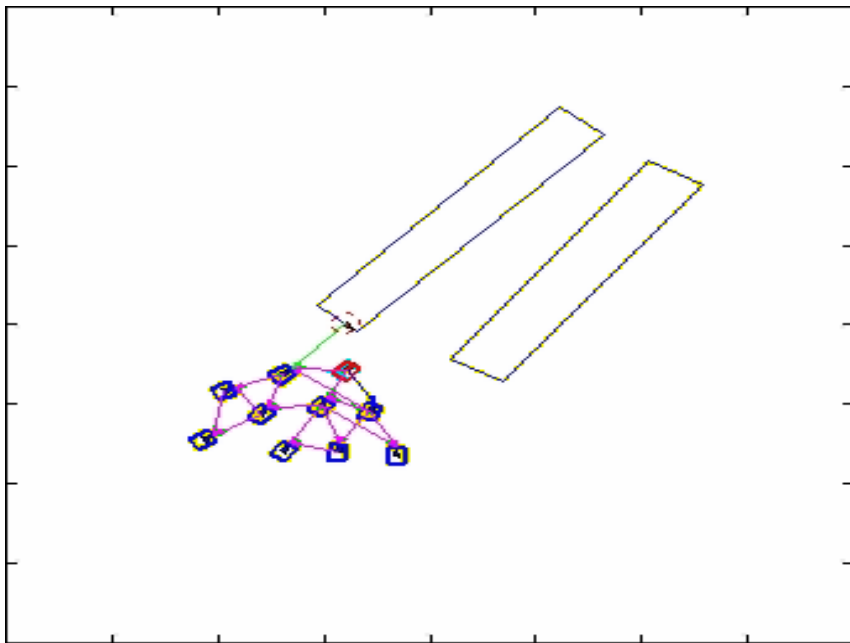
$$\begin{aligned} \dot{l}_{ij} &= k_1(l_{ij}^d - l_{ij}) \\ \dot{\psi}_{ij} &= k_2(\psi_{ij}^d - \psi_{ij}) \\ \dot{\theta}_j &= \omega_j \end{aligned}$$



Opis formacije grafom

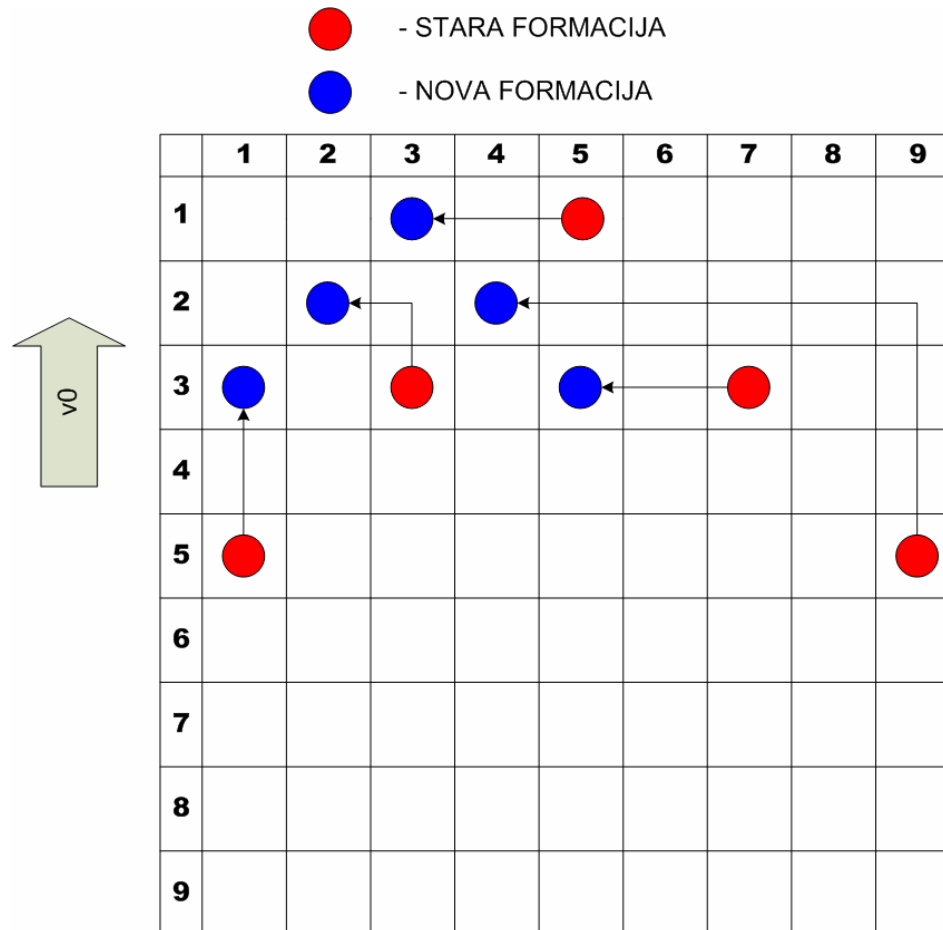






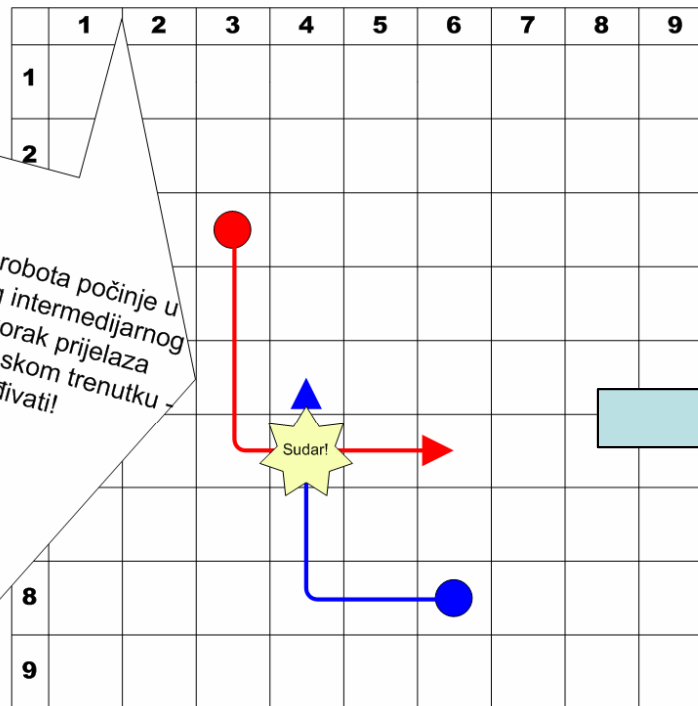


Upravljanje metodom rastera





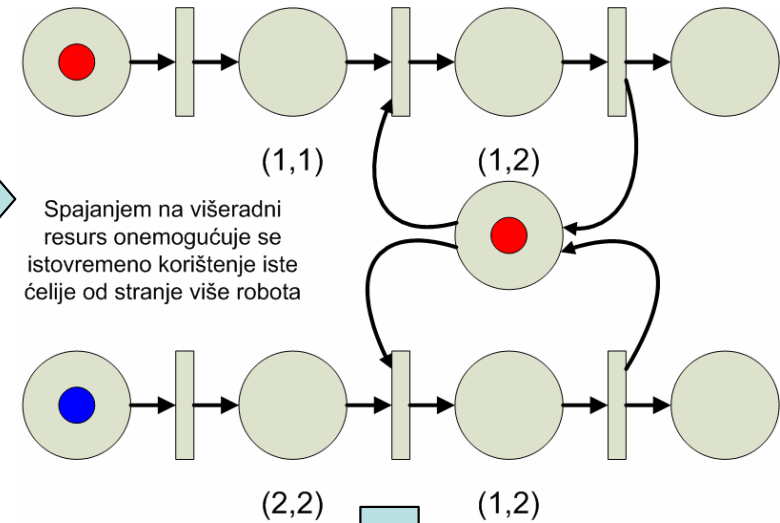
● - ROBOT1
● - ROBOT2



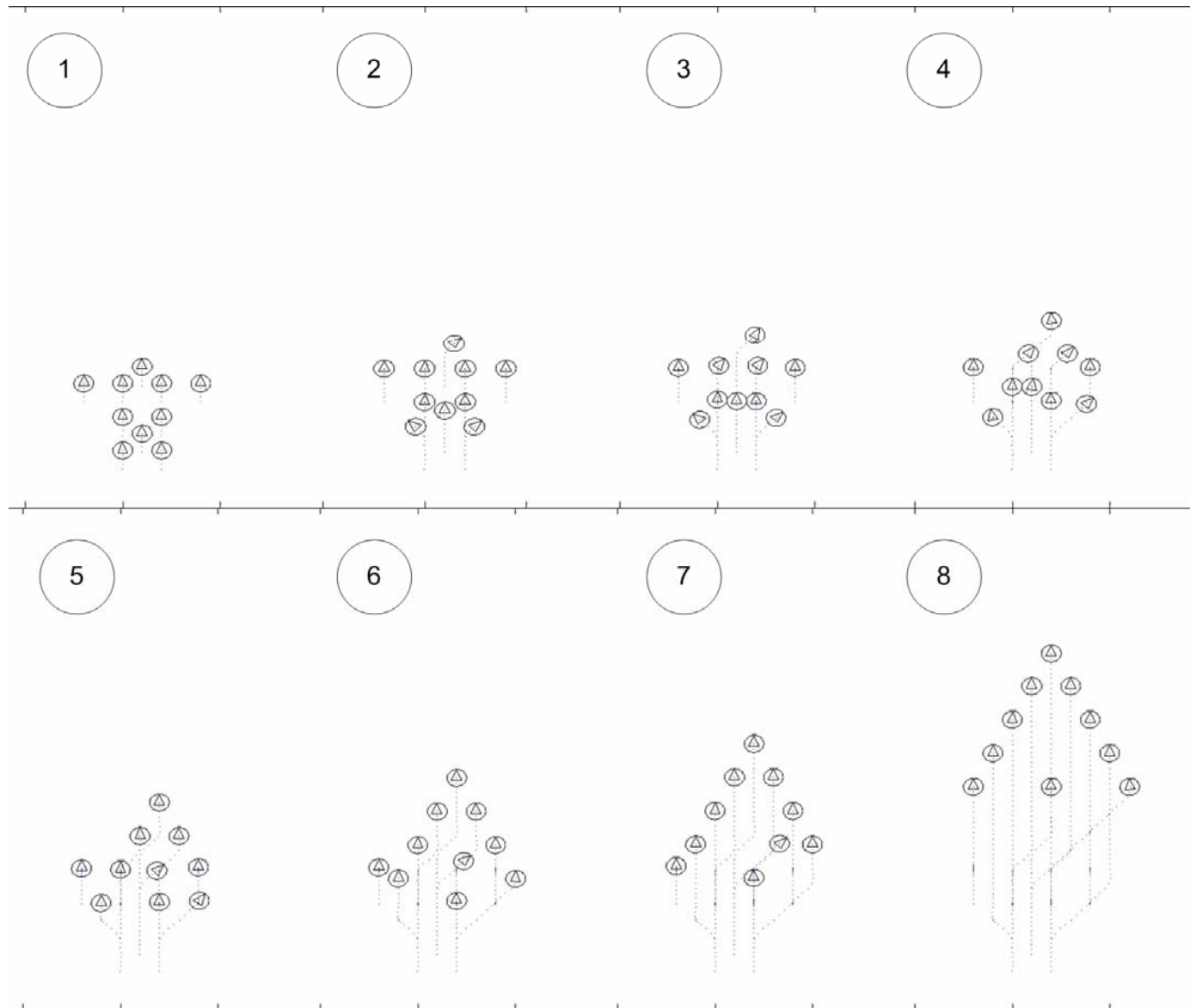
Pod pretpostavkom da tranzicija svih robota počinje u istom trenutku i da svi prijelazi iz jednog intermedijarnog polja u drugo traju jednako dugo, i-ti korak prijelaza predstavlja položaj robota u i-tom vremenskom trenutku - položaji robota mogu se uspoređivati!

Zbog toga što će se u petom koraku roboti nalaziti u istoj ćeliji, dolazi do sudara!

put{1}=[3 4 5 6 6 6;
3 3 3 3 4 5 6];
put{2}=[8 8 8 7 6 5;
6 5 4 4 4 4];



DES kontroler





Upravljanje metodom potencijalnog polja

$$\ddot{q}_i + b\dot{q}_i + \nabla_i U(\mathbf{q}, \mathbf{q}_T) = 0, \quad b > 0, \quad \nabla_i = \frac{\partial}{\partial q_i}$$

$$U(\mathbf{q}, \mathbf{q}_T) = -\sum_{i,j} u(d_{ij}, \sigma) + \sum_{i < j} \left[u(r_{ij}, \sigma) + u_A(r_{ij}, \sigma_A) \right]$$

- elementarna funkcija potencijala (zvonoliki oblik)

$$u(\rho, \sigma) = u\left(\frac{\rho^2}{\sigma}\right)$$

$$u: \mathbb{R}^2 \times \mathbb{R}^+ \rightarrow \mathbb{R}^+,$$

$$u(x) < u(0); \forall x \neq 0,$$

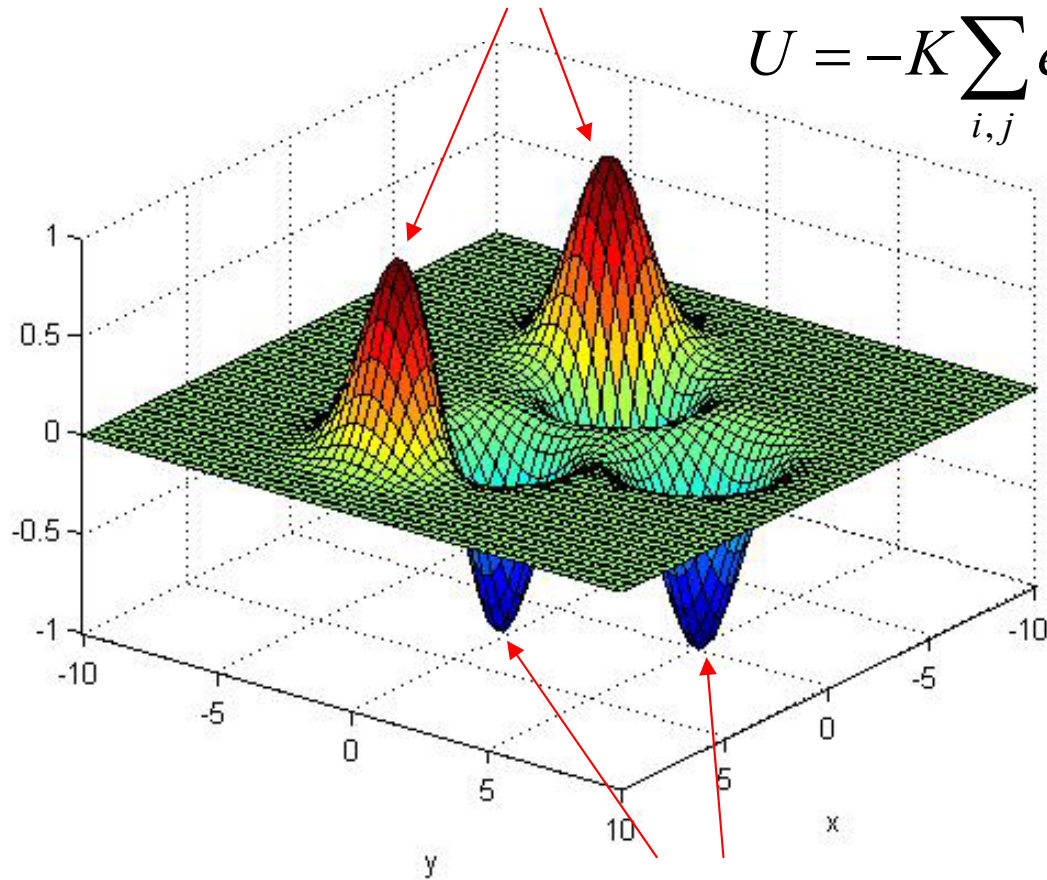
$$\nabla u(0) = 0.$$



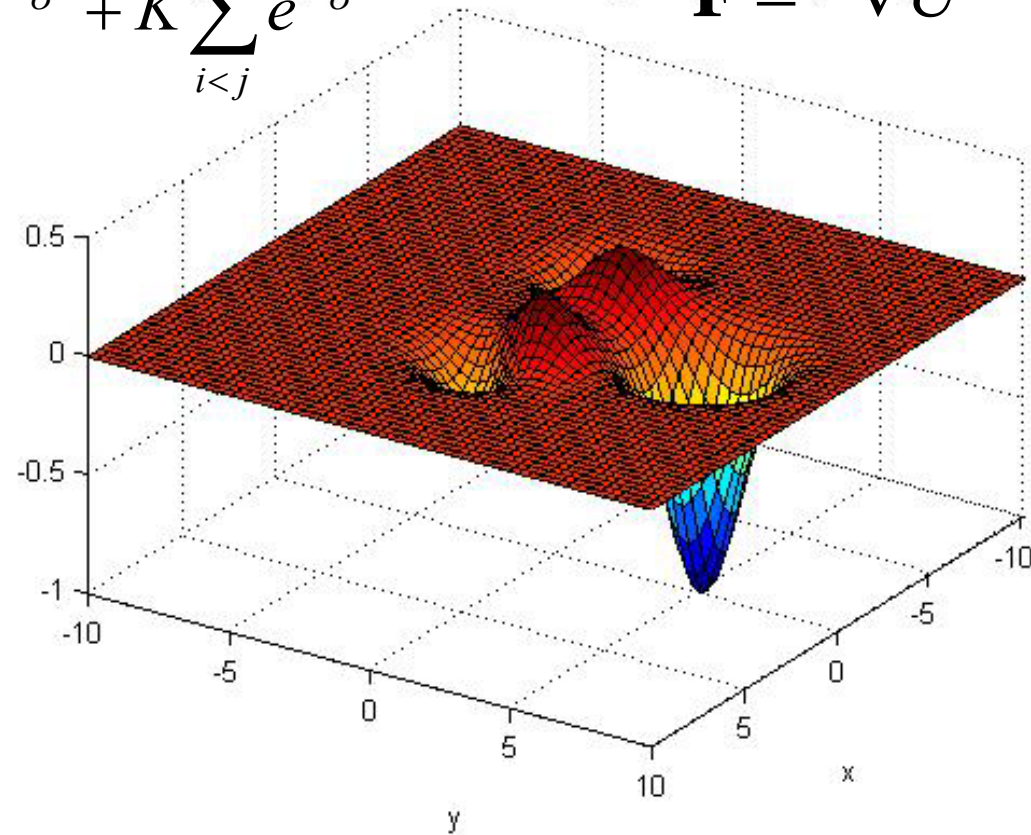
Potencijal jedinki

$$U = -K \sum_{i,j} e^{-\frac{d_{ij}^2}{\sigma}} + K \sum_{i < j} e^{-\frac{r_{ij}^2}{\sigma}}$$

$$\mathbf{F} = -\nabla U$$



Potencijal zadane formacije



σ - parametar upravljanja



Sustav je stabilan zbog oblika funkcije potencijala.

Odrediti vrijednost parametra σ tako da vrijedi $Q = Q_T \Big|_{t \rightarrow \infty}$ gdje su

$$Q = \{q_1, q_2, \dots, q_N\}$$

$$Q_T = \{q_{T1}, q_{T2}, \dots, q_{TN}\}$$

Adaptacija parametra σ

$$\|\dot{\mathbf{q}}\| \leq \varepsilon_1,$$

$$\|\mathbf{F}\| \leq \varepsilon_2,$$

$$h(Q, Q_T) \geq \varepsilon_3.$$

$$\longrightarrow \sigma_k = (1 + p)\sigma_{k-1}$$

$$1 \geq p > 0$$

$$h(Q, Q_T) = \max_{q_i \in Q} \left[\min_{q_{jT} \in Q_T} (d_{ij}) \right] \quad \text{- Hausdorff distance}$$

