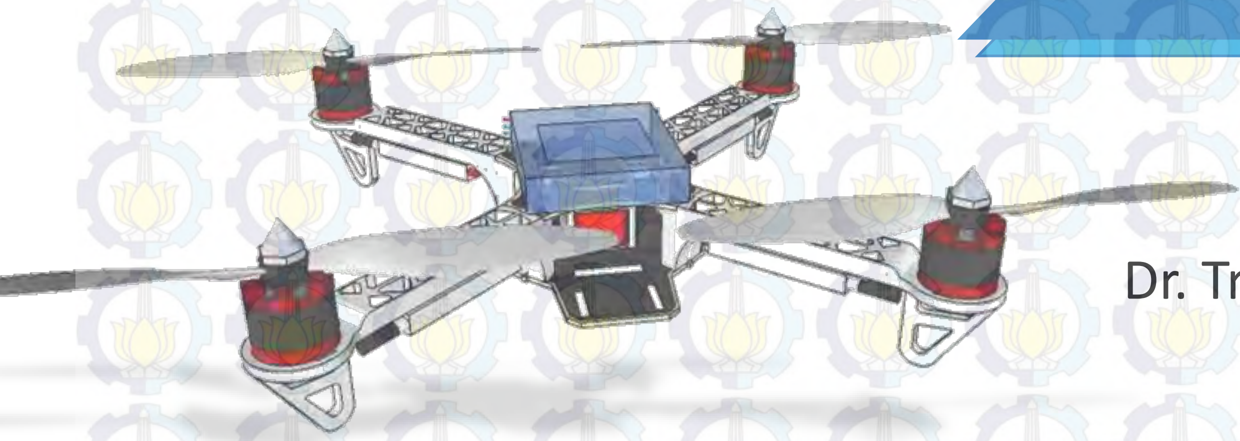
Kontrol Tracking Fuzzy Berbasis Performa Robust untuk Quadrotor

Tugas Akhir
TE 141599

Oleh :
Dinang Sohendri / 2212100097



Dosen Pembimbing :
Dr. Trihastuti Agustinah S.T., M.T.

Bidang Studi Teknik Sistem Pengaturan
Jurusan Teknik Elektro
Institut Teknologi Sepuluh Nopember

Pokok Bahasan

Pendahuluan

- Latar Belakang, Permasalahan, Tujuan

Perancangan Sistem

- Stabilisasi, Altitude, Tracking X,Y, Performa Robust

Hasil Pengujian

- Simulasi

Penutup

- Kesimpulan

Pendahuluan

Pendahuluan

Latar Belakang | Permasalahan | Tujuan

Kestabilan rendah

Rentan gangguan

Stabilisasi -> Fuzzy T-S
Tracking -> LQR (delay), Adaptif (rentan), SMC (chattering)

Pendahuluan

Latar Belakang | Permasalahan | Tujuan

- Merancang sistem kontrol untuk kestabilan sudut gerak Roll, Pitch, Yaw
- Merancang sistem kontrol untuk tracking posisi Quadrotor mengikuti referensi

Pendahuluan

Memperoleh sistem kontrol *tracking fuzzy* berbasis performa *robust* untuk mengatur gerak quadrotor

- Mampu mengikuti sinyal referensi
- Eror tracking minimal
- Tahan terhadap gangguan dari luar

Perancangan Sistem

Perancangan Sistem

Model Matematika Quadrotor

Vektor State

$$x_1 = X \qquad x_7 = \phi$$
$$x_2 = \dot{X} \qquad x_8 = \dot{\phi}$$
$$x_3 = Y \qquad x_9 = \theta$$
$$x_4 = \dot{Y} \qquad x_{10} = \dot{\theta}$$
$$x_5 = Z \qquad x_{11} = \psi$$
$$x_6 = \dot{Z} \qquad x_{12} = \dot{\psi}$$

Translasi

$$\begin{bmatrix} \dot{X} \\ \ddot{X} \\ \dot{Y} \\ \ddot{Y} \\ \dot{Z} \\ \ddot{Z} \end{bmatrix} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} x_2 \\ (s_{x11}s_{x7} + c_{x11}s_{x9}c_{x7})U_1 / m \\ x_4 \\ (-c_{x11}s_{x7} + s_{x11}s_{x9}c_{x7})U_1 / m \\ x_6 \\ -g + (c_{x9}c_{x7})U_1 / m \end{bmatrix}$$

Rotasi

$$\begin{bmatrix} \dot{\phi} \\ \ddot{\phi} \\ \dot{\theta} \\ \ddot{\theta} \\ \dot{\psi} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \dot{x}_7 \\ \dot{x}_8 \\ \dot{x}_9 \\ \dot{x}_{10} \\ \dot{x}_{11} \\ \dot{x}_{12} \end{bmatrix} = \begin{bmatrix} x_8 \\ ((J_{yy} - J_{zz})x_{10}x_{12} + U_2 l) / J_{xx} \\ x_{10} \\ ((J_{zz} - J_{xx})x_8 x_{12} + U_3 l) / J_{yy} \\ x_{12} \\ ((J_{xx} - J_{yy})x_8 x_{10} + U_4 d) / J_{zz} \end{bmatrix}$$

Perancangan Sistem

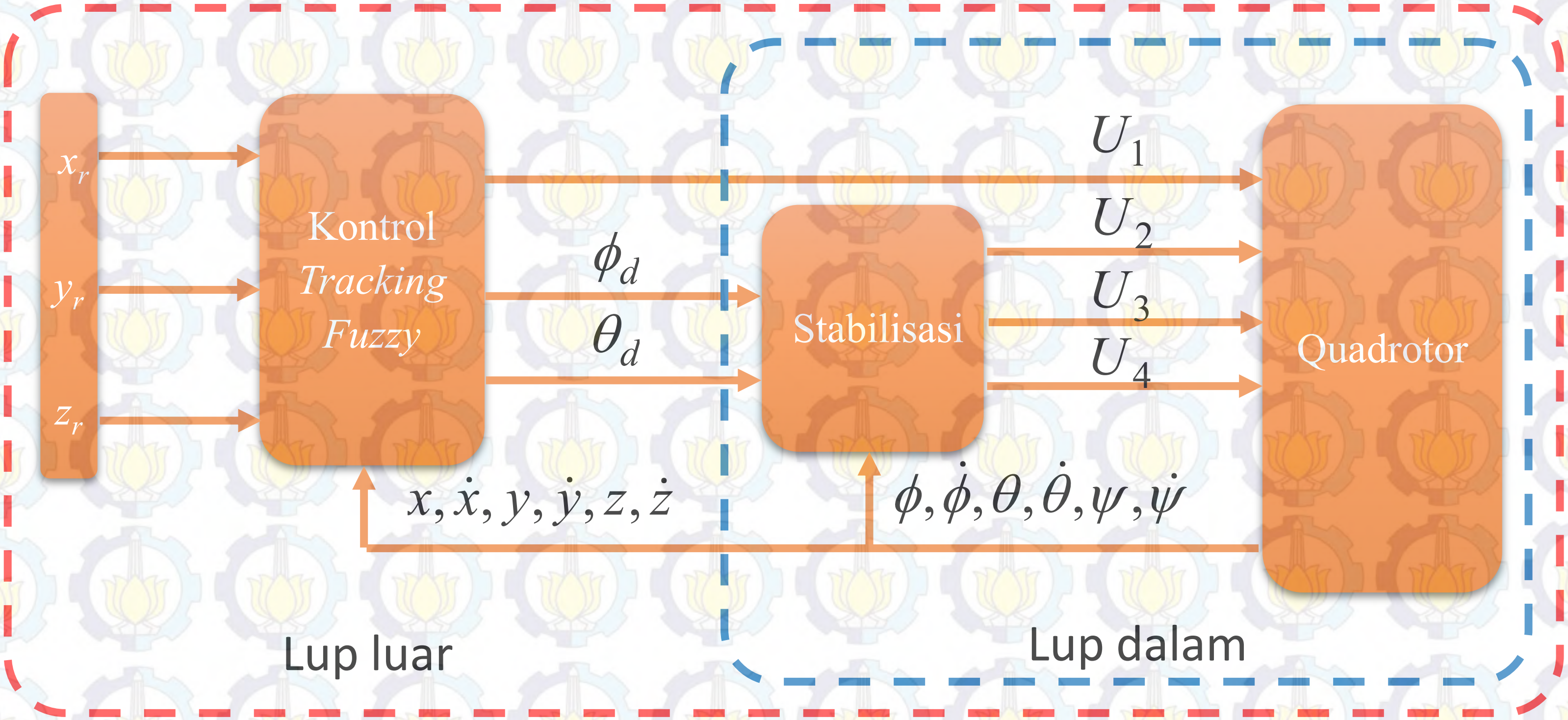
Sinyal kontrol Quadrotor

- Thrust $U_1 = F_1+F_2+F_3+F_4$
- Roll $U_2 = F_2-F_4$
- Pitch $U_3 = F_1-F_3$
- Yaw $U_4 = F_1-F_2+F_3-F_4$

Fi = Gaya tiap motor

Perancangan Sistem

Arsitektur Sistem Kontrol Quadrotor



Kontrol Stabilisasi Quadrotor

- Matriks sistem

$$A_{roll} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{roll} = \begin{bmatrix} 0 \\ 6.6667 \end{bmatrix}$$

$$A_{pitch} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{pitch} = \begin{bmatrix} 0 \\ 6.6667 \end{bmatrix}$$

$$A_{yaw} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{yaw} = 10^{-3}\begin{bmatrix} 0 \\ 0.7825 \end{bmatrix}$$

digunakan kontrol state-feedback dengan teknik pole placement

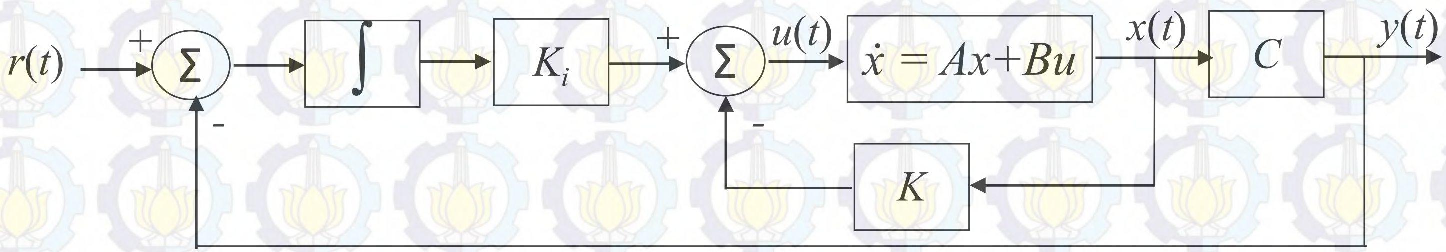
$$P\ roll = P\ pitch = P\ yaw = [-4 \quad -12]$$

$$K_{roll} = [7.2 \quad 2.4]$$

$$K_{pitch} = [7.2 \quad 2.4]$$

$$K_{yaw} = 10^{4}[6.1342 \quad 2.0447]$$

Kontrol Altitude (ketinggian) Quadrotor



Matiks Sistem

$$A_{Zi} = \begin{bmatrix} A_Z & 0 \\ -C & 0 \end{bmatrix}, \quad B_{Zi} = \begin{bmatrix} B_Z \\ 0 \end{bmatrix}$$

$$A_{Zi} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix}, \quad B_{Zi} = \begin{bmatrix} 0 \\ 0.2858 \\ 0 \end{bmatrix}$$

Dengan teknik pole placement

$$p = [-4 \ \ -12 \ \ -13]$$

$$K_z = 10^3[0.8957 \quad 0.1015]$$

$$K_{iz} = 10^3[-2.1834]$$

Perancangan Sistem

Kontrol Tracking X,Y menggunakan *fuzzy* Takagi-Sugeno

Aturan plant untuk gerak *X*

Aturan plant ke-1:

$$\begin{aligned} &If \quad x_9 \text{ is } M_1 \ (sekitar\ \ 0\, rad) \\ &Then \quad \dot{x} = A_{x1}x + B_{x1}\theta \\ &\qquad\qquad y = C_{x1}x + D_{x1}\theta \end{aligned}$$

Aturan plant ke-2:

$$\begin{aligned} &If \quad x_9 \text{ is } M_2 \ (\pm\ pi/9\, rad) \\ &Then \quad \dot{x} = A_{x2}x + B_{x2}\theta \\ &\qquad\qquad y = C_{x2}x + D_{x2}\theta \end{aligned}$$

Aturan kontroler untuk gerak *X*

Aturan kontroler ke-1:

$$\begin{aligned} &If \quad x_9 \text{ is } M_1 \ (sekitar\ \ 0\, rad) \\ &Then \quad \theta = K_1[x - x_r] \end{aligned}$$

Aturan kontroler ke-2:

$$\begin{aligned} &If \quad x_9 \text{ is } M_2 \ (\pm\ pi/9\, rad) \\ &Then \quad \theta = K_2[x - x_r] \end{aligned}$$

Perancangan Sistem

Aturan plant untuk gerak *Y*

Aturan plant ke-1:

$$\begin{aligned} &If && x_7 \; is \; M_1 \; (sekitar \;\; 0 \, rad) \\ &Then && \dot{x} = A_{y1} x + B_{y1} \phi \\ & && y = C_{y1} x + D_{y1} \phi \end{aligned}$$

Aturan plant ke-2:

$$\begin{aligned} &If && x_7 \; is \; M_2 \; (\pm \, pi/9 \, rad) \\ &Then && \dot{x} = A_{y2} x + B_{y2} \phi \\ & && y = C_{y2} x + D_{y2} \phi \end{aligned}$$

Aturan kontroler untuk gerak *Y*

Aturan kontroler ke-1:

$$\begin{aligned} &If && x_7 \; is \; M_1 \; (sekitar \;\; 0 \, rad) \\ &Then && \phi = K_1 [x - x_r] \end{aligned}$$

Aturan kontroler ke-2:

$$\begin{aligned} &If && x_7 \; is \; M_2 \; (\pm \, pi/9 \, rad) \\ &Then && \phi = K_2 [x - x_r] \end{aligned}$$

Perancangan Sistem

Keseluruhan sistem lup tertutup

$$\dot{x}(t) = \sum_{i=1}^{2}\sum_{j=1}^{2} h_i(x_z(t))h_j(x_z(t))[(A_i + B_i K_j)x(t) - B_i K_j x_r(t)] + w(t) \qquad (1)$$

dengan

$$h_j(x_z(t)) = \frac{\mu_i(x_z(t))}{\sum_{i=1}^{2}\mu_i(x_z(t))}, \qquad \mu_i(x_z(t)) = M_i(x_z(t))$$

Model Referensi

$$\dot{x}_r = A_r x_r + B_r r(t)$$

$$A_r = \begin{bmatrix} 0 & 1 \\ -8.5 & -7 \end{bmatrix}, \quad B_r = \begin{bmatrix} 0 \\ 8.5 \end{bmatrix}$$

$x_r(t)$ = state referensi

A_r = Matriks stabil asimtotik

B_r = Matriks masukan

$r(t)$ = masukan referensi

Perancangan Sistem

- Augmented *fuzzy* sistem

$$\dot{x}(t) = \sum_{i=1}^{2}\sum_{j=1}^{2} h_i(x_z(t))h_j(x_z(t)) [\tilde{A}_{ij}\tilde{x}(t) + \tilde{E}\tilde{w}(t)] \qquad (2)$$

dengan

$$\tilde{A}_{ij} = \begin{bmatrix} A_i + B_i K_j & -B_i K_j \\ 0 & A_r \end{bmatrix}, \quad \tilde{E} = \begin{bmatrix} I & 0 \\ 0 & B_r \end{bmatrix}$$

$$\tilde{x}(t) = \begin{bmatrix} x(t) \\ x_r(t) \end{bmatrix}, \quad \tilde{w}(t) = \begin{bmatrix} w(t) \\ r(t) \end{bmatrix}$$

- Performa *tracking H*$_\infty$

$$\int_0^{t_f} \{[x(t) - x_r(t)]^T Q [x(t) - x_r(t)]\}dt = \int_0^{t_f} \tilde{x}(t)^T \tilde{Q}\tilde{x}(t)dt$$

$$\leq \tilde{x}(0)^T \tilde{P}\tilde{x}(0) + \gamma^2 \int_0^{t_f} \tilde{w}(t)^T \tilde{w}(t)dt \qquad (3)$$

dengan

$$\tilde{Q} = \begin{bmatrix} Q & -Q \\ -Q & Q \end{bmatrix}$$

$$\tilde{P} = \begin{bmatrix} P_{11} & 0 \\ 0 & P_{22} \end{bmatrix}$$

Perancangan Sistem

Jika $\tilde{P} = \tilde{P}^T > 0$ adalah solusi umum dari pertidaksamaan matriks

$$\tilde{A}_{ij}^T \tilde{P} + \tilde{P}\tilde{A}_{ij} + \frac{1}{\gamma^2} \tilde{P}\tilde{E}\tilde{E}^T \tilde{P} + \tilde{Q} < 0 \qquad (4)$$

untuk $i = j = 1, 2$, maka sistem lup tertutup adalah stabil dan performa *tracking* H_∞ adalah terjamin untuk nilai γ.

Pertidaksamaan diatas dapat dinyatakan sebagai berikut:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} < 0$$

$$S_{11} = (A_i + B_i K_j)^T P_{11} + P_{11}(A_i + B_i K_j) + \frac{1}{\gamma^2} P_{11} P_{11} + Q$$

$$S_{12} = S_{21}^T = -P_{11} B_i K_j - Q$$

$$S_{22} = A_r^T P_{22} + P_{22} A_r + \frac{1}{\gamma^2} P_{22} B_r B_r^T P_{22} + Q$$

$$\begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & P_{22} B_r \\ 0 & B_r^T P_{22} & -\gamma^2 I \end{bmatrix} < 0$$

$$H_{11} = S_{11}$$

$$H_{12} = H_{21}^T = -P_{11} B_i K_j - Q$$

$$H_{22} = A_r^T P_{22} + P_{22} A_r + Q$$

Perancangan Sistem

Persoalan kontrol *tracking* dapat diformulasikan sebagai persoalan minimisasi berikut:

$$\min_{P_{11},P_{22}} \gamma^2 \quad \text{dengan syarat}$$

- $P_{11} = P_{11}^T > 0$
- $P_{22} = P_{22}^T > 0$
- $\begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & P_{22}B_r \\ 0 & B_r^T P_{22} & -\gamma^2 I \end{bmatrix} < 0$

Prosedur Desain:

1. Pilih fungsi keanggotaan dan aturan *fuzzy*
2. Berikan tingkat pemelemahan awal γ^2.
3. Selesaikan LMI sehingga P_{11} , P_{22} dan K_j diperoleh.
4. Turunkan tingkat pelemahan γ^2 dan ulangi langkah 3-5 sampai solusi P_{11} dan P_{22} tidak definit positif.
5. Susun kontroler fuzzy

Perancangan Sistem

Parameter yang digunakan

1. $Q = 10^{-1} \times \begin{bmatrix} 4.8 & 0 \\ 0 & 1.8 \end{bmatrix}$
2. Tingkat pelemahan $\gamma = 0.85$

Matriks Stabilitas

$$P_{x1} = \begin{bmatrix} 1.5730 & 0.5745 \\ 0.5745 & 0.3371 \end{bmatrix} \quad P_{y1} = \begin{bmatrix} 1.5730 & 0.5745 \\ 0.5745 & 0.3371 \end{bmatrix}$$

$$P_{x2} = \begin{bmatrix} 0.7483 & 0.3977 \\ 0.3977 & 0.3537 \end{bmatrix} \quad P_{y2} = \begin{bmatrix} 0.7483 & 0.3977 \\ 0.3977 & 0.3537 \end{bmatrix}$$

Sehingga didapatkan

Gain Kontroler :

$$K_{x1} = [-1.2448 \quad -0.7130]$$
$$K_{x2} = [-1.3247 \quad -0.7588]$$
$$K_{y1} = [1.2448 \quad 0.7130]$$
$$K_{y2} = [1.3247 \quad 0.7588]$$

Eigenvalue lup tertutup

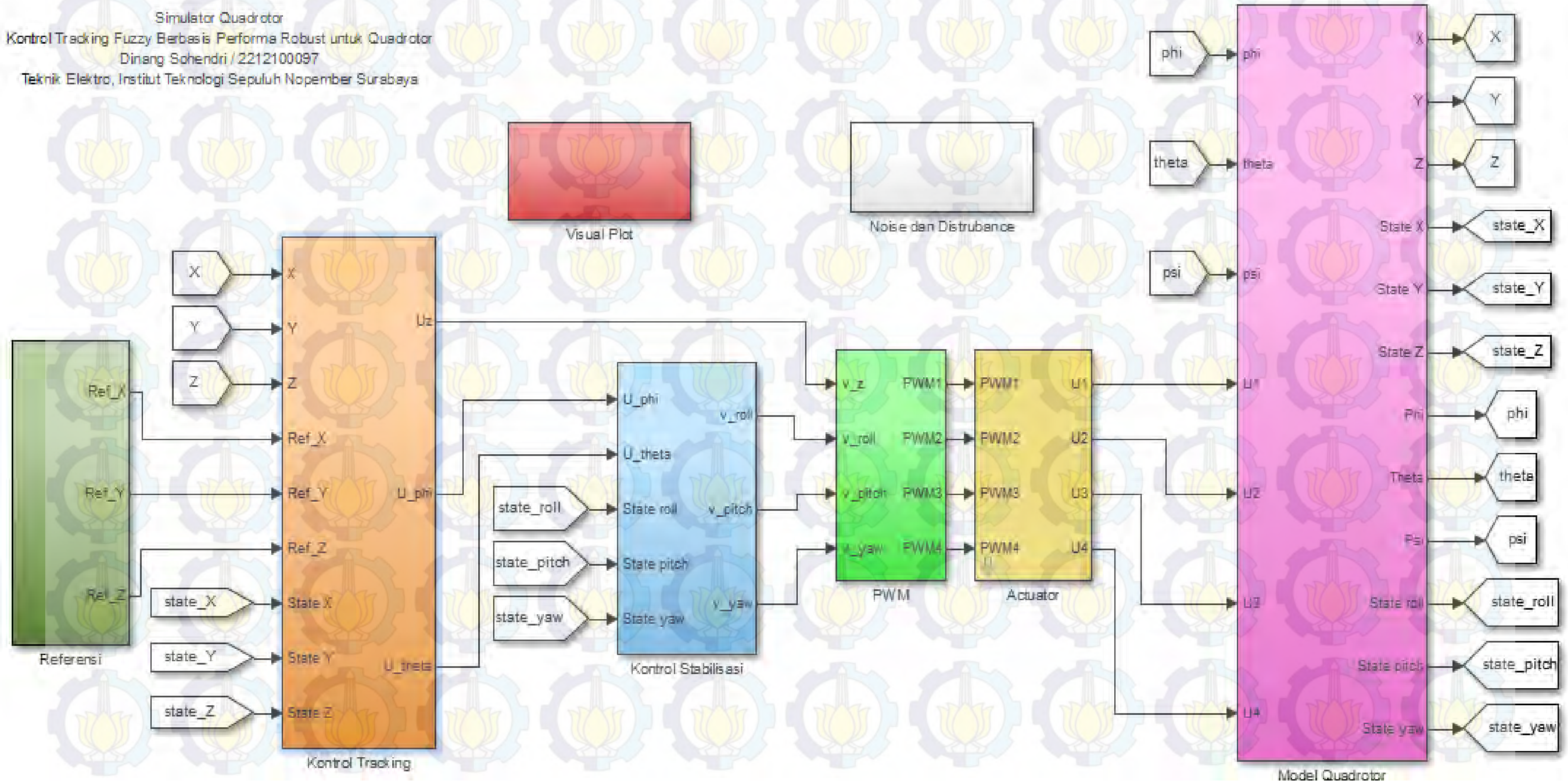
$$\det(\lambda I - (A_i + B_i K_j \quad -B_i K_j ; zeros(2,2) \quad Ar_i)) = 0$$

$$\lambda_{x1} = \{-3.3576, -3.6371, -1.5635, -5.4365\}$$
$$\lambda_{x2} = \{-3.3576, -3.6371, -1.5635, -5.4365\}$$
$$\lambda_{y1} = \{-3.3576, -3.6371, -1.5635, -5.4365\}$$
$$\lambda_{y2} = \{-3.3576, -3.6371, -1.5635, -5.4365\}$$

Hasil Pengujian

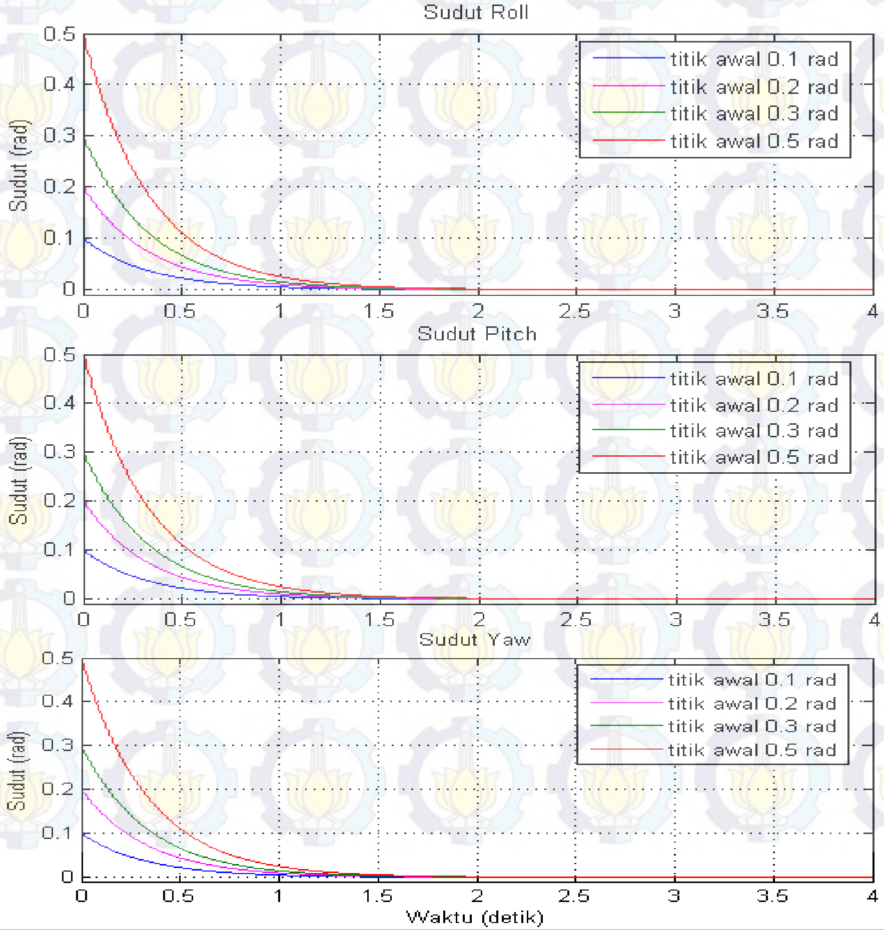
Hasil Simulasi

Stabilisasi | Altitude | Tracking X, Y | Uji Noise



Hasil Simulasi

Stabilisasi Roll, Pitch, dan Yaw dengan berbagai kondisi awal



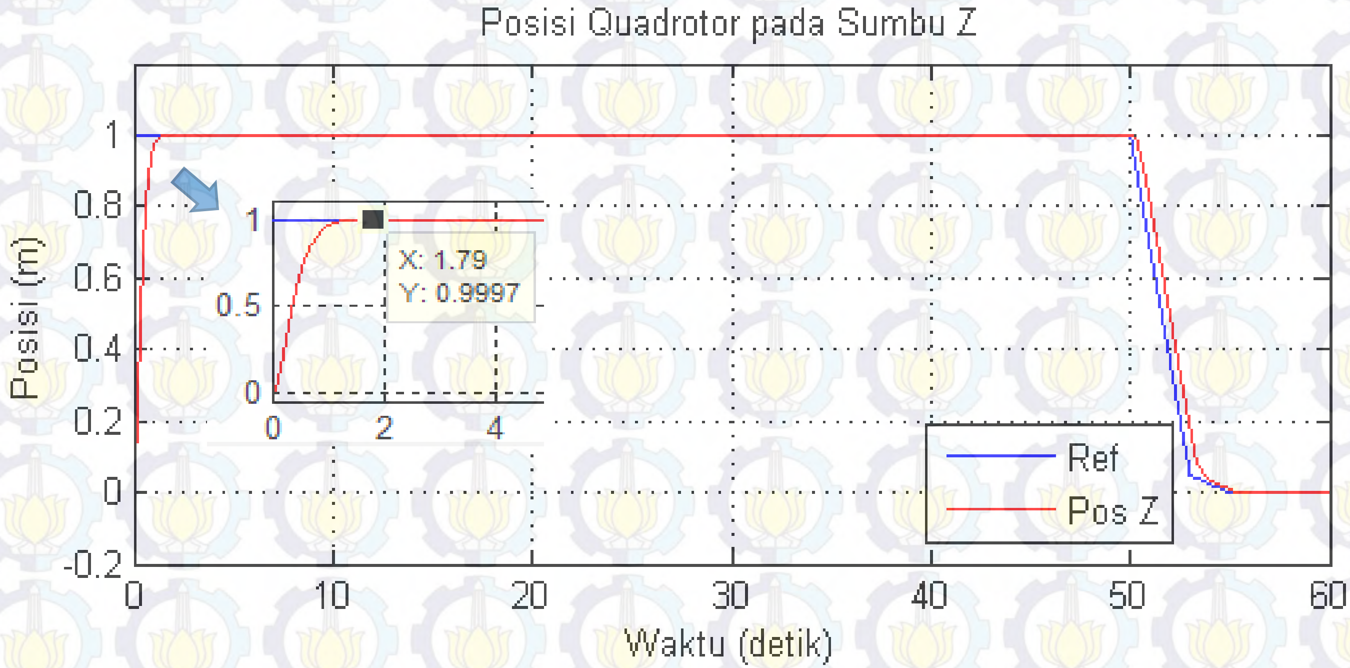
Waktu steady-state 1.75 detik

Ess = 0%

Hasil Simulasi

Stabilisasi | Altitude | Tracking X, Y | Uji Noise

Ketinggian Quadrotor (Sb Z)



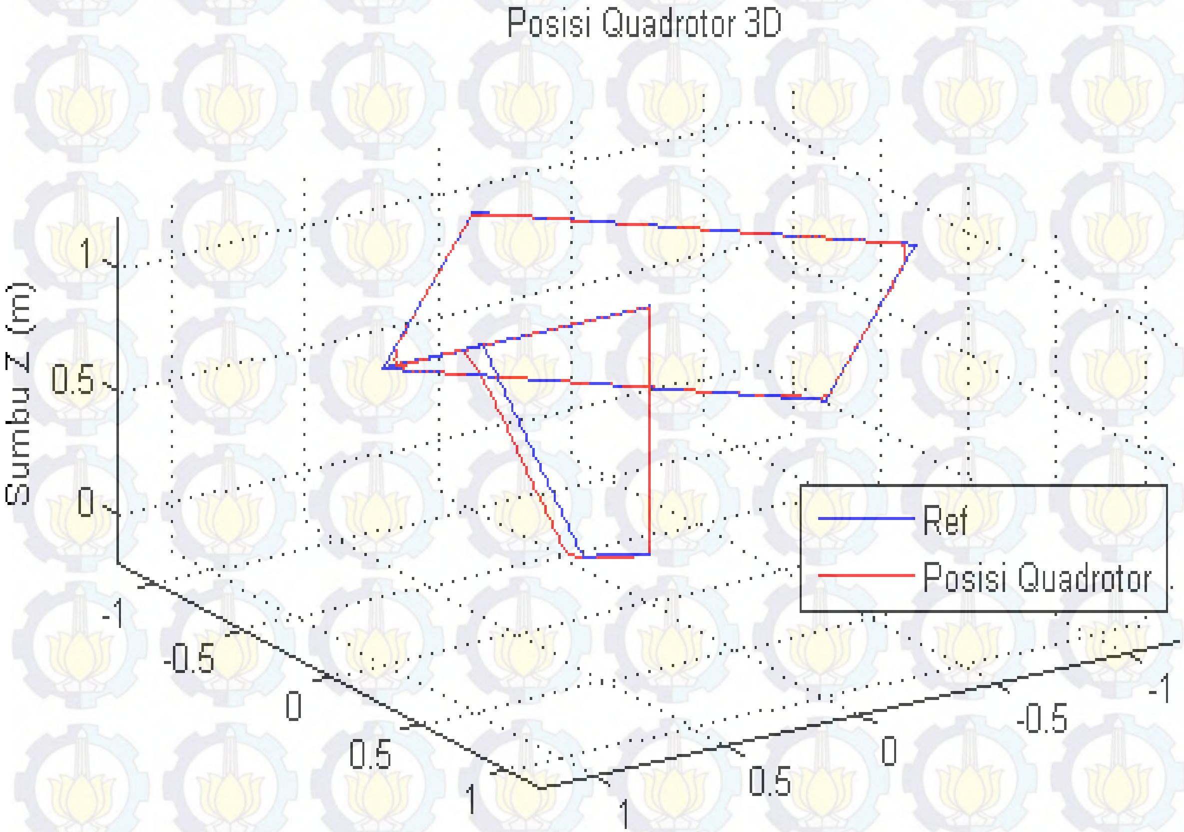
Waktu steady-state 1.8 detik

Ess = 0%

Hasil Simulasi

Stabilisasi | Altitude | Tracking X, Y | Uji Noise

Tracking Sb X dan Y

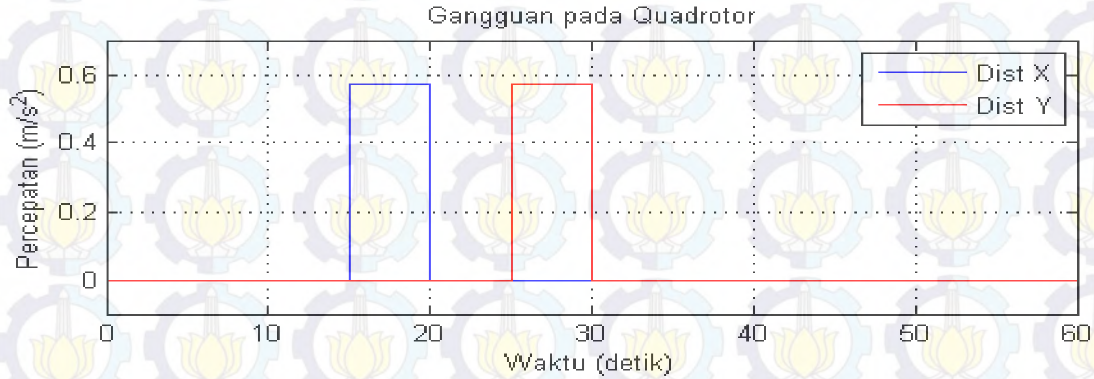


IAB Sb X 0.1149
IAB Sb Y 0.0617
Beda fasa 0.78 detik

Hasil Simulasi

Stabilisasi | Altitude | Tracking X, Y | Uji Noise

Tracking Sb X dan Y dengan gangguan



Nilai γ divariasikan untuk memperoleh gamma optimal

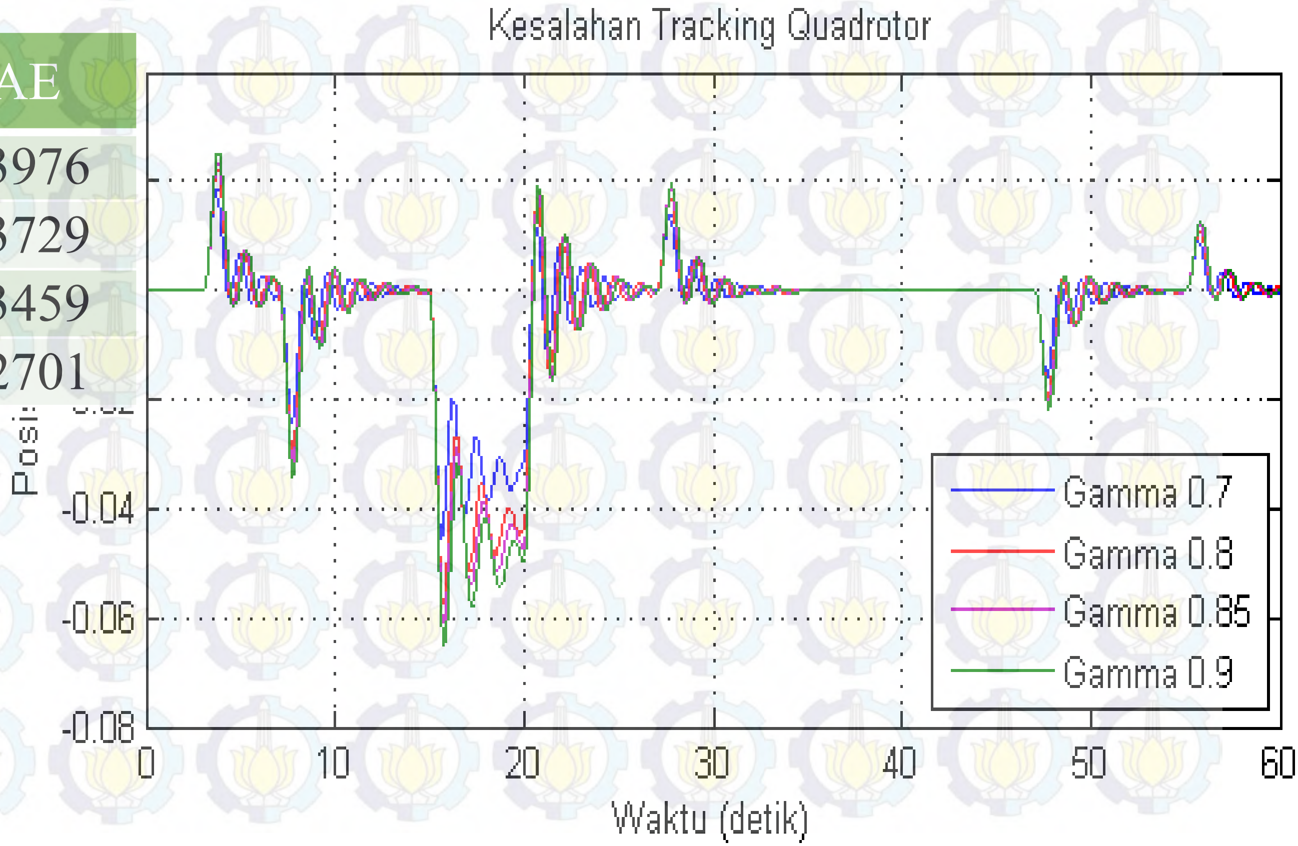
γ	K_{x1}	K_{x2}	$\|T_{z,w}(s)\| = \gamma^*$
0.9	[−1.1678 −0.6751]	[−1.2428 −0.7184]	0.8535
0.85	[−1.2448 −0.7130]	[−1.3247 −0.7588]	0.8007
0.8	[−1.3371 −0.7572]	[−1.4229 −0.8058]	0.7454
0.7	[−1.6935 −0.9303]	[−1.8022 −0.9900]	0.5883

Hasil Simulasi

Stabilisasi | Altitude | Tracking X, Y | Uji Noise

Error Posisi Sb X

γ	Error	IAE
0.9	± 0.065	0.3976
0.85	± 0.061	0.3729
0.8	± 0.057	0.3459
0.7	± 0.045	0.2701



Hasil Simulasi

Stabilisasi | Altitude | Tracking X, Y | Uji Noise

Nilai γ divariasikan untuk memperoleh gamma optimal

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Hasil Simulasi

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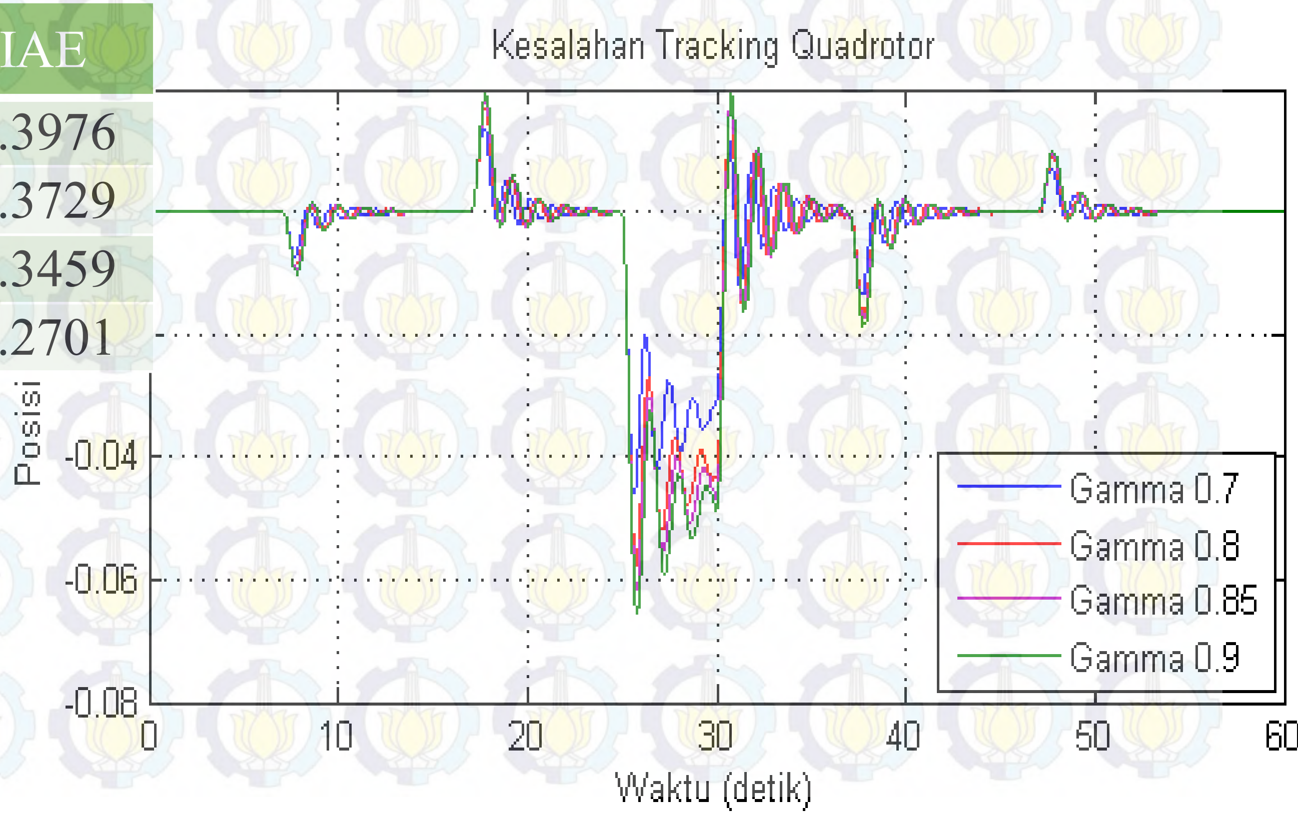
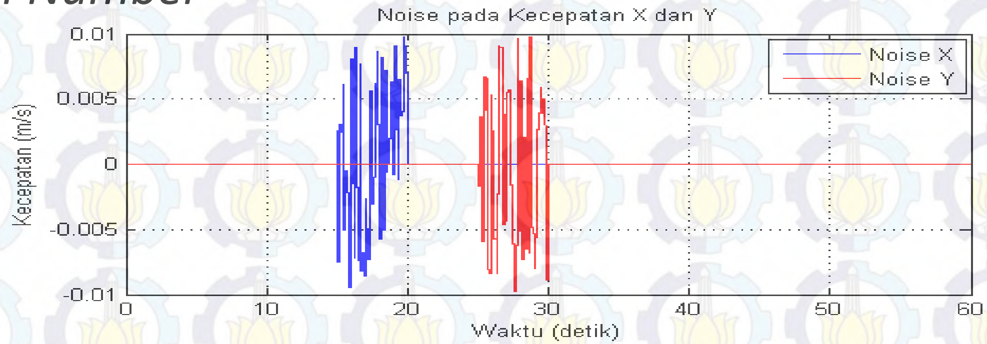


Hasil Simulasi

Stabilisasi | Altitude | Tracking X, Y | Uji Noise

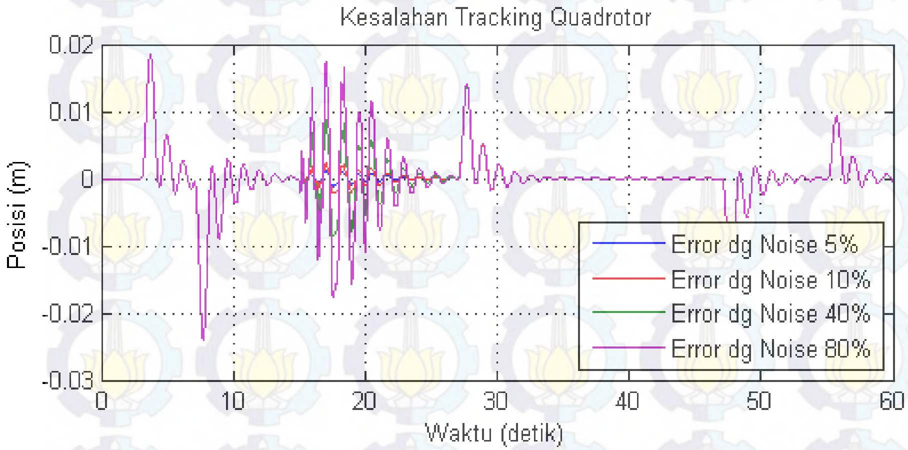
Uji Noise yang diberikan pada sensor kecepatan dimodelkan dengan *Uniform Random Number*

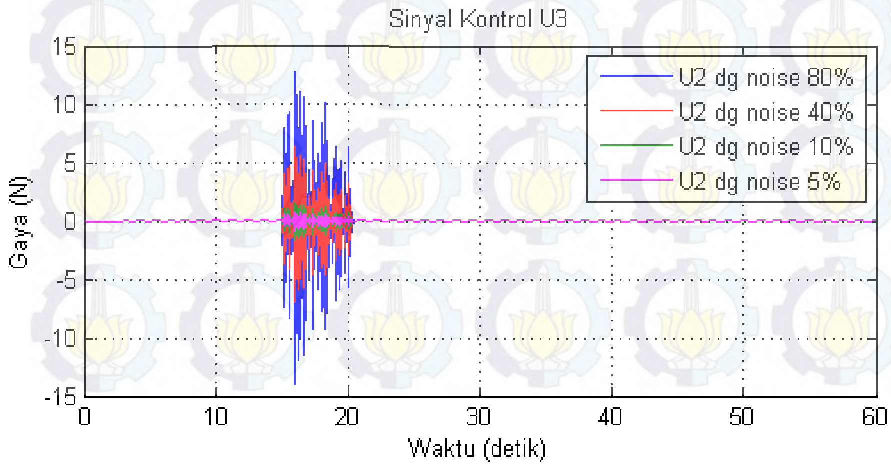


No	Besar Noise	Deviasi Posisi X (m)	Deviasi Posisi Y (m)	U2 (N)	U3 (N)	IAE Sb X	IAE Sb Y
1	5%	0.001	0.001	0.5	0.5	0.0866	0.0492
2	10%	0.002	0.002	1	1	0.0901	0.0536
3	20%	0.005	0.005	2	2	0.0972	0.0624
4	40%	0.01	0.01	4	4	0.1114	0.0801
5	80%	0.02	0.02	8	8	0.1398	0.1152

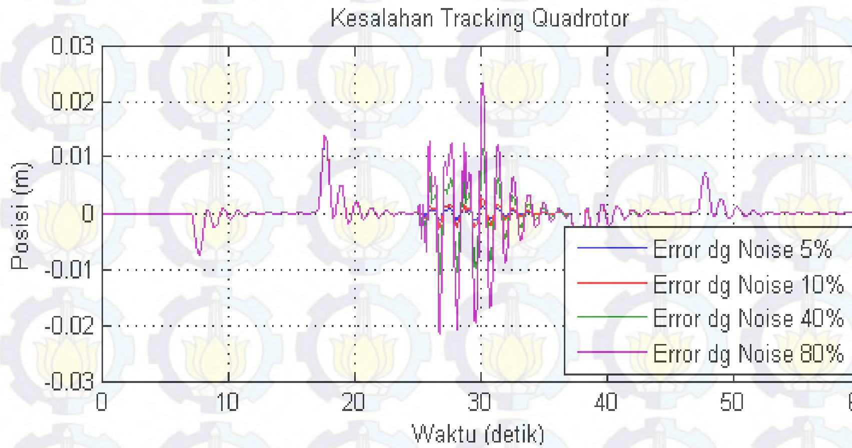
Hasil Simulasi

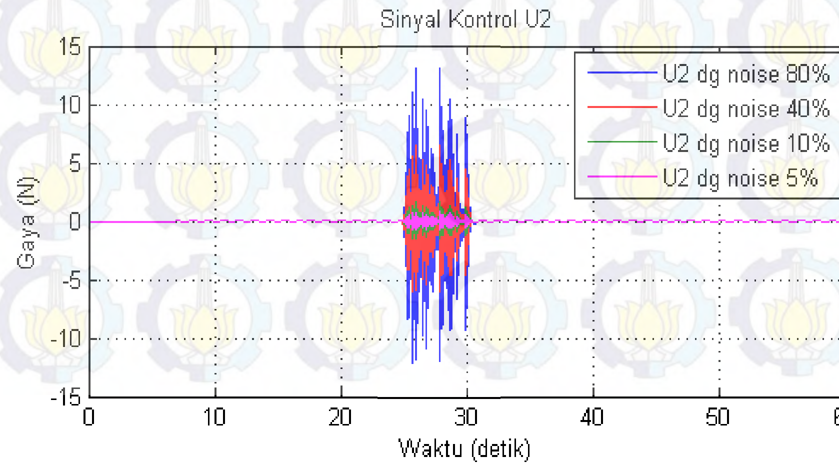
Sumbu X





Sumbu Y





Penutup

Penutup

Kesimpulan   Saran

Kesimpulan

- Metode kontrol *fuzzy* Takagi-Sugeno bekerja dengan baik untuk mengendalikan gerak quadrotor dengan nilai *Integral Absolute Error* (IAE) 0.1149 pada sumbu X dan 0.06171 pada sumbu Y
- Kontrol *tracking fuzzy* yang dirancang memiliki performa *robust* dengan tingkat pelemahan gangguan terhadap performa keluaran kurang dari γ yang ditentukan.

Saran

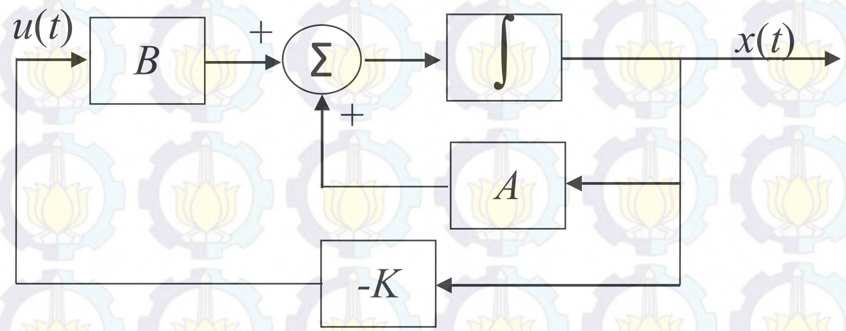
- Saat uji noise, sinyal kontrol mengalami *chattering* dengan amplitude besar, sehingga perlu dibatasi untuk menghemat energi.

Terima Kasih

Parameter Quadrotor yang digunakan

No	Parameter	Simbol	Nilai
1	Massa	m	3,499 kg
2	Gravitasi	g	9,81 kg/m^2
3	Moment Inersia pada sumbu X	Jxx	0.03 $kg.m^2$
4	Moment Inersia pada sumbu Y	Jyy	0.03 $kg.m^2$
5	Moment Inersia pada sumbu Z	Jzz	0.04 $kg.m^2$
6	Jarak rotor dari pusat massa	l	0.2 m
7	Gaya drag	d	$3,13x10^{-5}$
8	Gaya trust	b	$7,5x10^{-7}$
9	Bandwith aktuator	ω	15 rad/s
10	Konstanta gaya dorong	K	120 N

Kontrol State-Feedback



Orde-1

$$\tau = \frac{Ts}{4}, \quad Ts(2\%) = 4\tau$$

$$G = \frac{1}{\tau s + 1} = \frac{1}{\frac{Ts}{4}s + 1}$$

$$s = -\frac{4}{Ts}$$

Jika diinginkan Ts = 1 detik maka

$$p = [-4 \quad -12]$$

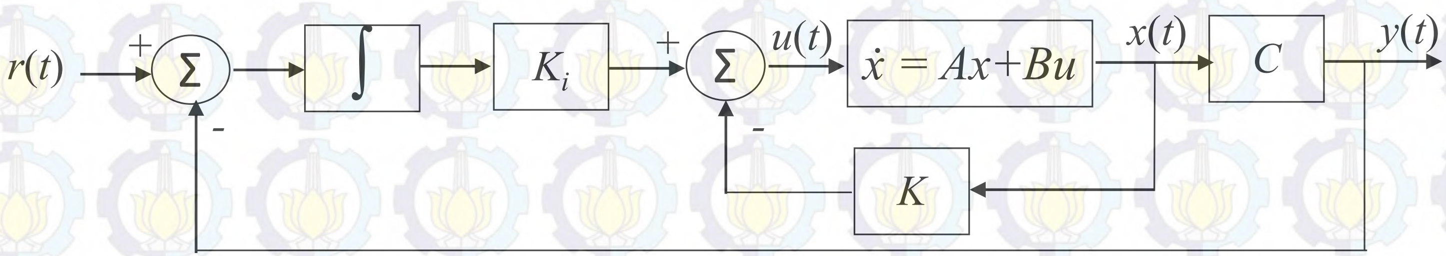
$$K_{roll} = [7.2 \quad 2.4]$$

$$K_{pitch} = [7.2 \quad 2.4]$$

$$K_{yaw} = 10^4[6.1342 \quad 2.0447]$$

Perancangan Sistem

Kontrol Altitude (ketinggian) Quadrotor



Matiks Sistem

$$A_{Zi} = \begin{bmatrix} A_Z & 0 \\ -C & 0 \end{bmatrix}, \quad B_{Zi} = \begin{bmatrix} B_Z \\ 0 \end{bmatrix}$$

$$A_{Zi} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix}, \quad B_{Zi} = \begin{bmatrix} 0 \\ 0.2858 \\ 0 \end{bmatrix}$$

Jika diinginkan Ts = 1 detik maka

$$p = [-4 \quad -12 \quad -13]$$

$$K_z = 10^3[0.8957 \quad 0.1015]$$

$$K_{iz} = 10^3[-2.1834]$$

Kontrol Tracking X,Y menggunakan fuzzy Takagi-Sugeno

- Matriks Sistem Sumbu X

$$A_{xi} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{xi} = \begin{bmatrix} 0 \\ (c_{x11} c_{x9} c_{x7}) U_1 / m \end{bmatrix}$$

$$A_{x1} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{x1} = \begin{bmatrix} 0 \\ 9.81 \end{bmatrix}$$ linierisasi θ sekitar 0 rad

$$A_{x2} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{x2} = \begin{bmatrix} 0 \\ 9.2184 \end{bmatrix}$$ linierisasi $\theta \pm$ pi/9 rad

Perancangan Sistem

Kontrol Tracking X,Y menggunakan fuzzy Takagi-Sugeno

- Matriks Sistem Sumbu Y

$$A_{yi} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{yi} = \begin{bmatrix} 0 \\ (-c_{x11}c_{x7})U_1 / m \end{bmatrix}$$

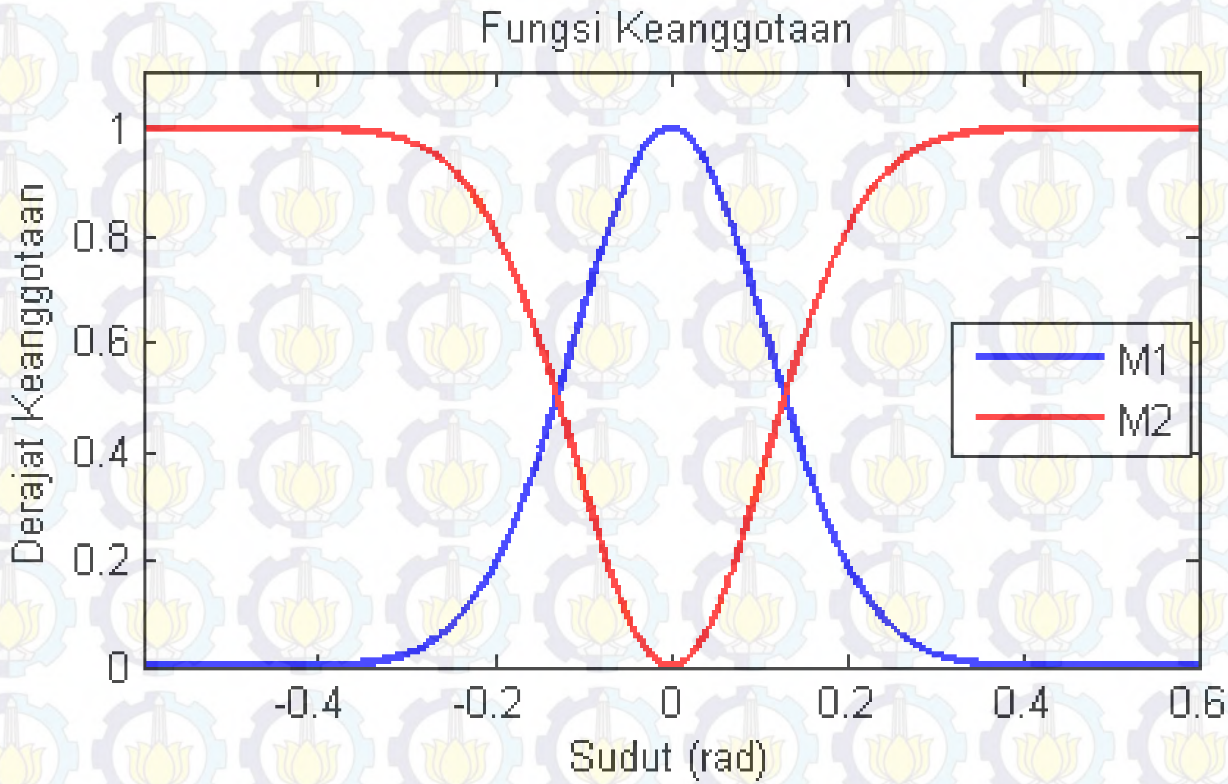
$$A_{y1} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{y1} = \begin{bmatrix} 0 \\ -9.81 \end{bmatrix}$$ linierisasi ϕ sekitar 0 rad

$$A_{y2} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_{y2} = \begin{bmatrix} 0 \\ -9.2184 \end{bmatrix}$$ linierisasi $\phi \pm$ pi/9 rad

Perancangan Sistem

Model Quadrotor | Stabilisasi | Altitude Z | Tracking X, Y

- Membership function untuk Aturan plant dan Kontroler



Perancangan Sistem

LMI diselesaikan dengan 2 langkah

Langkah pertama: menyelesaikan LMI berikut sehingga $Y_{11} = P_{11}^{-1}$ dan $X_j = K_j Y_{11}$ diperoleh.

$$\begin{bmatrix} Y_{11}A_i^T + A_iY_{11} + B_iX_j + (B_iX_j)^T + \frac{1}{\gamma^2}I & Y_{11} \\ Y_{11} & -Q^{-1} \end{bmatrix} < 0$$

Langkah kedua

Substitusi P_{11} dan K_j ke $\begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & P_{22}B_r \\ 0 & B_r^T P_{22} & -\gamma^2 I \end{bmatrix} < 0$ untuk mendapatkan P_{22}