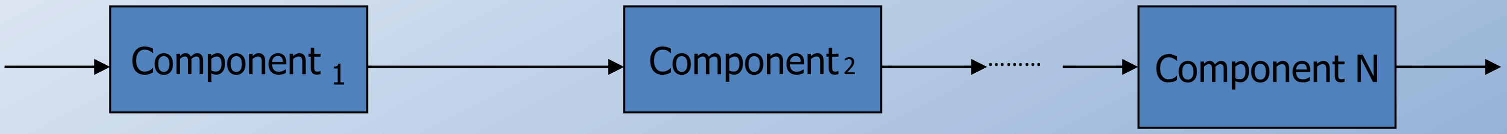
Why fault tolerant system ?

Non Fault-Tolerant System



The reliability block diagram of a series system-
each element of the system must operate correctly
for the system to operate correctly.

$$R_{series}(t) = R_1(t)R_2(t)\ldots R_N(t)$$

$$R_{series}(t) = \prod_{i=1}^{N} R_i(t)$$

$$R_{series}(t) = e^{-\lambda_1 t} e^{-\lambda_2 t} \ldots e^{-\lambda_N t}$$

So $\lambda_{system} = \lambda_1 + \lambda_2 + \ldots + \lambda_N$

The weakest component dictates overall failure rate

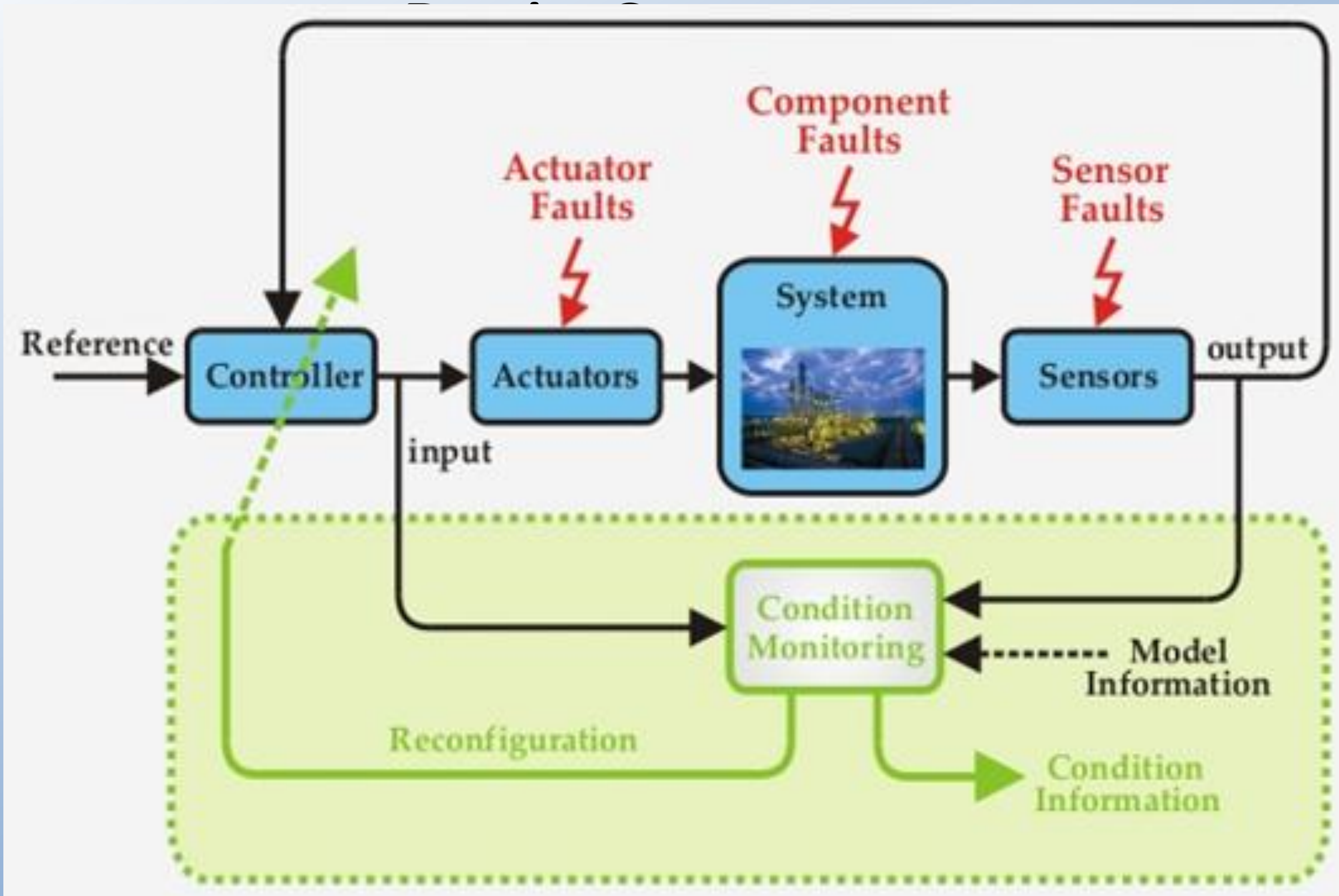
In an automobile tire=10^{-4} brakes=10^{-6}

so tires are the critical component.

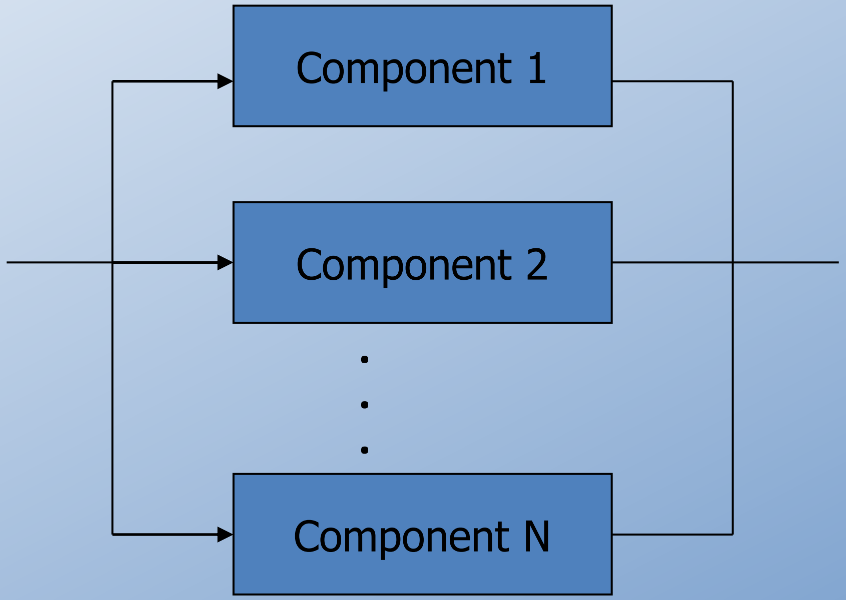
Motivation

- Current technologies need automation and accident prevention.
- Future technologies demand increased levels of reliability and safety.

DC-10 United Airlines Flight 232 accident, 19 July 1998.


Component
Faults
Actuator
Faults
Sensor
Faults
System
Reference
Controller
Actuators
Sensors
output
input
Condition
Monitoring
Model
Information
Reconfiguration
Condition
Information

Fault-Tolerant System



- All **N** component have to fail before the system fails
- The reliability block diagram of a parallel system only one of ***N*** components must operate correctly for the system to operate correctly
- System Survives if at least on component survives.

Failure probability = 1-R

Probability that system fails $F = (1-R_1(t))*(1-R_2(t))*\ldots*(1-R_N(t))$

Reliability $= 1-F = 1 - (1-R_1(t))*(1-R_2(t))*\ldots*(1-R_N(t))$

$$R_{system}(t) = R^6_s(t)R^3_{act}(T)R^3_c(t)R_{bus1}(t)R_{bus2}(t)$$

Because the failure rates can be added in a series system to obtain the failure rate of the system, we can write

$$\lambda_{system} = 6\lambda_s + 3\lambda_{act} + 3\lambda_c + \lambda_{bus2} + \lambda_{bus1}$$

Where λ_s is the failure rate of one sensor, λ_{act} is the failure rate of one actuator, λ_c is the failure rate of one computer, λ_{bus1} is the failure rate of the computer interconnection bus, λ_{bus2} is the failure rate of the primary Control bus, λ_{system} is the failure rate of the system.

If the failure rates of the system are

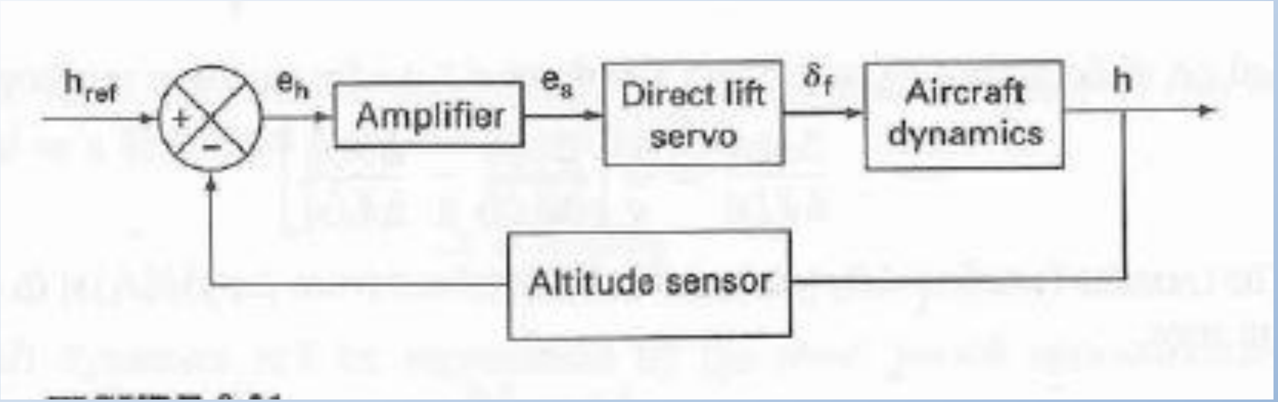
$\lambda_s = 1 * 10^{-6}$ failures per hour
$\lambda_{act} = 1 * 10^{-5}$ failures per hour
$\lambda_c = 4 * 10^{-4}$ failures per hour
$\lambda_{bus1} = 1 * 10^{-6}$ failures per hour
$\lambda_{bus2} = 2 * 10^{-6}$ failures per hour

then the system failure rate will be

$\lambda_{system} = 1.239 * 10^{-3}$ failures per hour
MTTF = 1000/1.239 = 800 hours

The reliability after five hours for this system is approximately

$R_{system}(5) = 0.995$



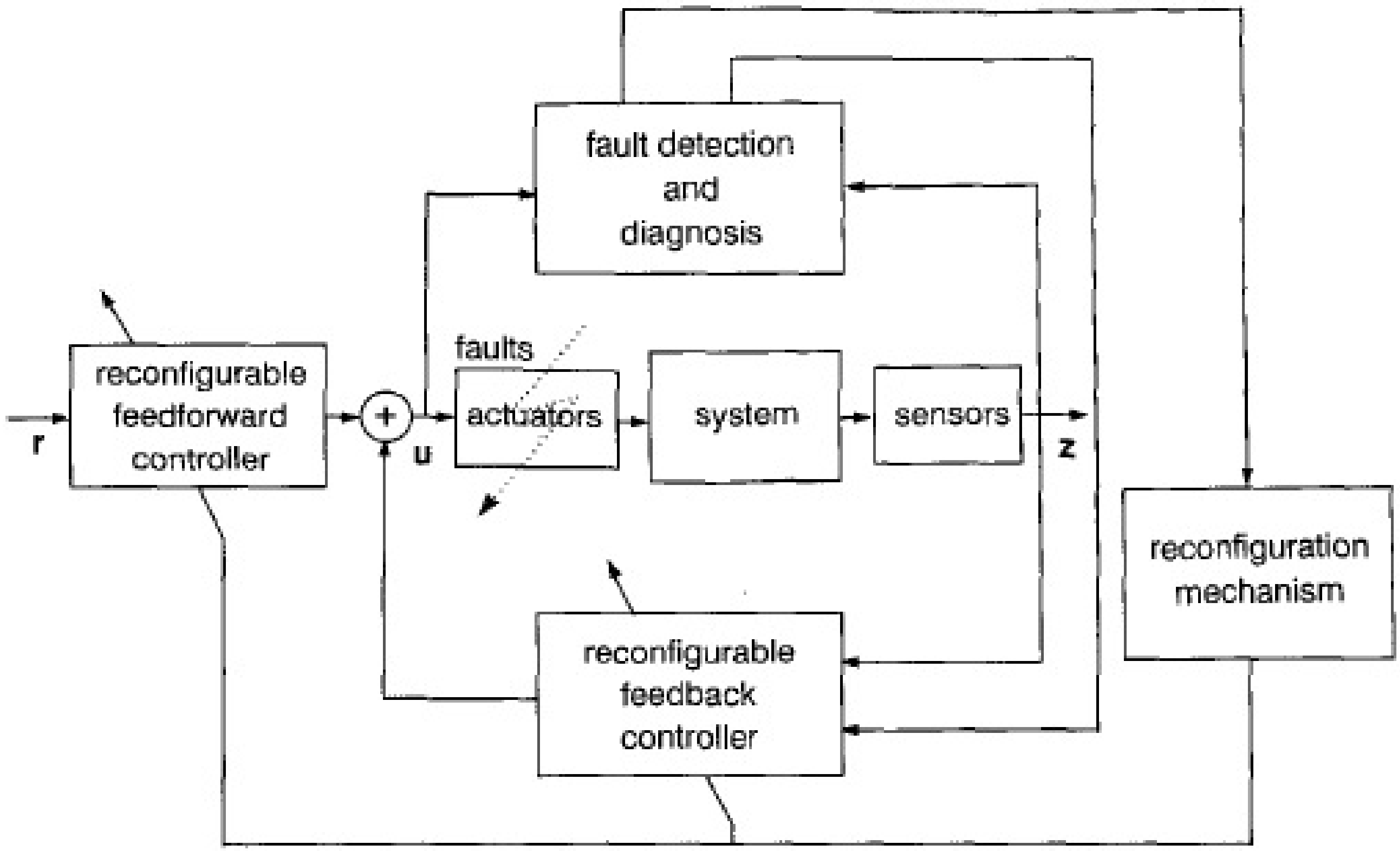
Why to actuators , Sensors ?

A failure to the structure of the aircraft , doesn't change the equation of motion, it may change the values of some parameters, however we can still control the aircraft

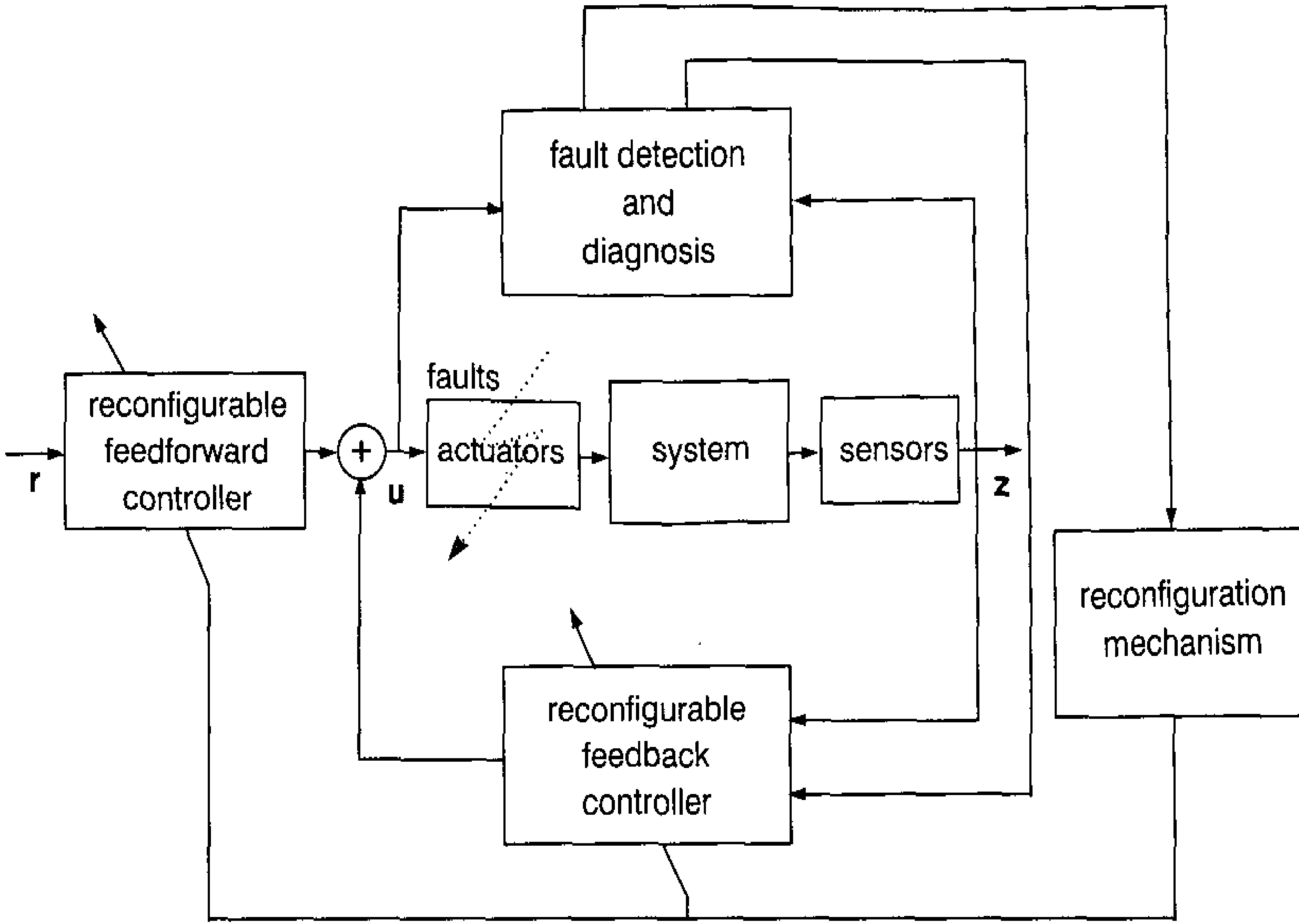
A faultier in the actuator means we lost control on that actuator, and therefore we lost control of the aircraft

- fault- tolerant control (FTC) for constrained linear systems subject to partial actuator failures.
- An active fault-tolerant control scheme based on adjustable gain control and fault detection and isolation (FDI) was proposed.

- The FDI module using a two-stage Kalman filtering algorithm provides simultaneous control parameter and state estimation, which are used to modify the forward and backward gain formulation to accommodate partial actuator failures
- The most important advantage of the scheme is that partial actuator failures and input constraints can be dealt with simultaneously


fault detection
and
diagnosis
faults
r
reconfigurable
feedforward
controller
+
u
actuators
system
sensors
z
reconfiguration
mechanism
reconfigurable
feedback
controller

- The adaptive control is achieved by estimating both the system states and the control effectiveness factors .


fault detection
and
diagnosis
faults
reconfigurable
feedforward
controller
r
u
actuators
system
sensors
z
reconfiguration
mechanism
reconfigurable
feedback
controller

$$\mathbf{x}_{k+1} = A\mathbf{x}_k + B\mathbf{u}_k + \mathbf{w}_k^{\mathbf{x}}$$

$$\mathbf{y}_k = C_r\mathbf{x}_k$$

$$\mathbf{z}_k = C\mathbf{x}_k + \mathbf{v}_k \,.$$

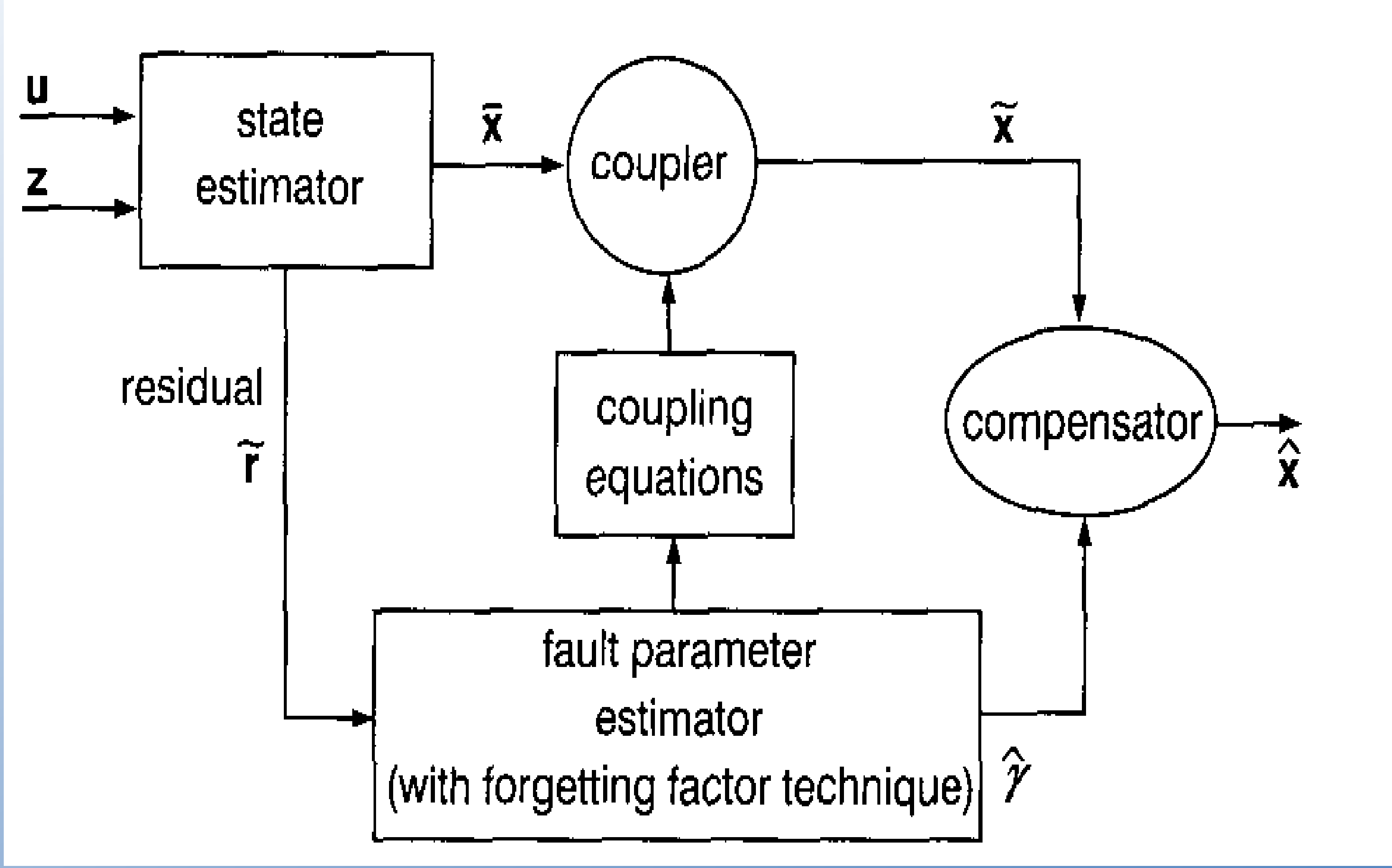
$$\mathbf{x}_{k+1} = A\mathbf{x}_k + B\mathbf{u}_k + D_k(\mathbf{u}_k)\gamma_k + \mathbf{w}_k^{\mathbf{x}}$$

$$\gamma_{k+1} = \gamma_k + \mathbf{w}_k^{\gamma}$$

$$\mathbf{y}_k = C_r\mathbf{x}_k$$

$$\begin{cases} \gamma_k = 0, k < k_F \\ \gamma_k \neq 0, k \geq k_F \end{cases}$$

$$\mathbf{z}_k = C\mathbf{x}_k + \mathbf{v}_k$$



u
z
state estimator
$\bar{x}$
coupler
$\tilde{x}$
residual
$\tilde{r}$
coupling equations
compensator
$\hat{x}$
fault parameter estimator (with forgetting factor technique)
$\hat{\gamma}$

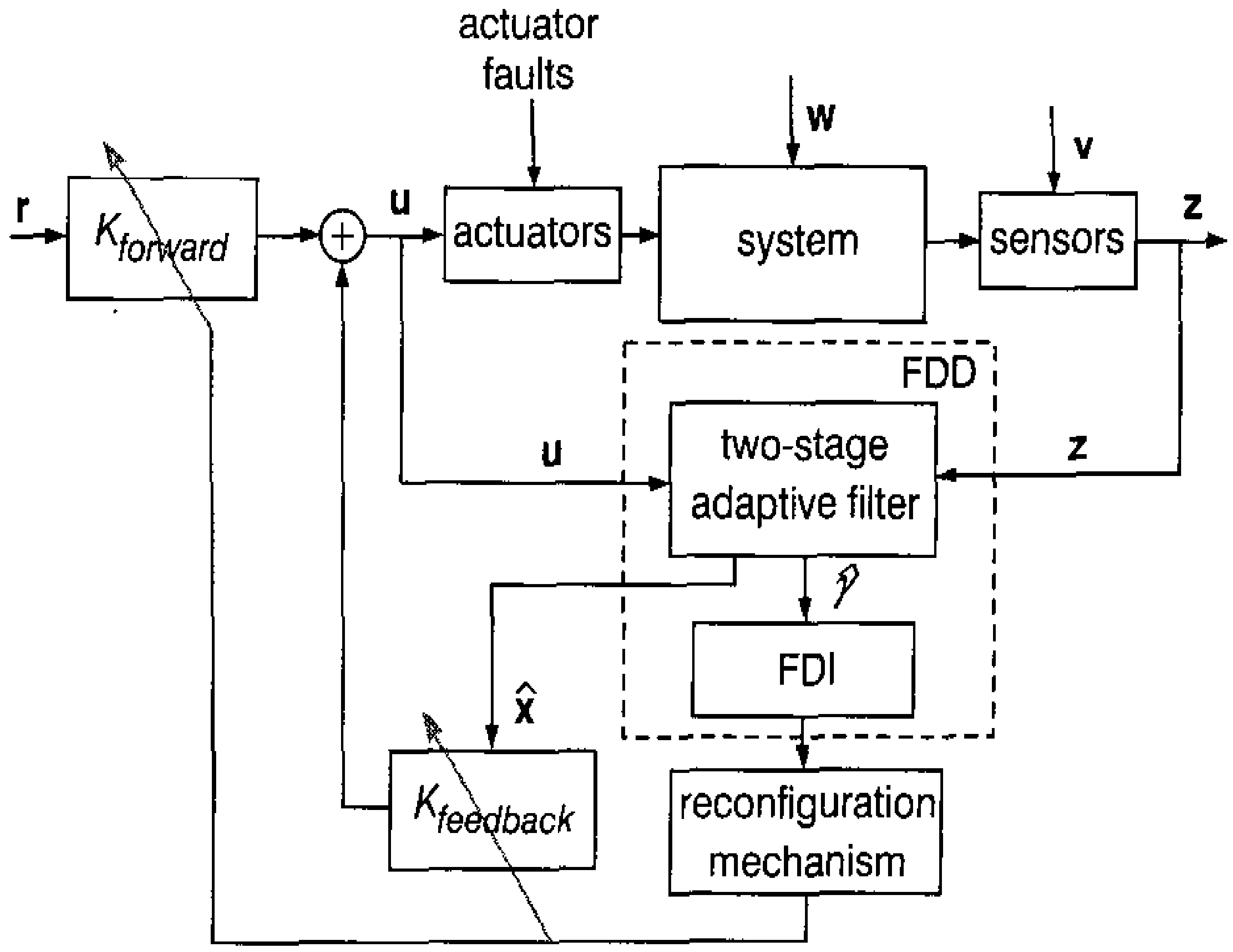
$$d_k^i = \frac{\sigma^2_{\hat{\gamma}_k^i I}}{\sigma^2_{\hat{\gamma}_0^i}} - \ln \frac{\sigma^2_{\hat{\gamma}_k^i II}}{\sigma^2_{\hat{\gamma}_0^i}} - 1, \quad i = 1, \ldots, l$$

$$\lambda_i^f = \lambda(A + \hat{B}_k^f K_{feedback}) = \lambda_i = \lambda(A + BK_{normal})$$

$$\Phi = \begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{bmatrix} = \begin{cases} \begin{bmatrix} A - I & B \\ C_r & 0 \end{bmatrix}^{-1} & \text{fault-free} \\ \begin{bmatrix} A - I & \hat{B}_k^f \\ C_r & 0 \end{bmatrix}^{-1} & \text{with fault} \end{cases}$$

$$\mathbf{u}_k = \underbrace{(\Phi_{22} - K_{feedback}\Phi_{12})\mathbf{r}_k}_{\text{feedforward}} + \underbrace{K_{feedback}\mathbf{x}_k}_{\text{feedback}}$$

$$\mathbf{u}_k = K_{forward}\mathbf{r}_k + K_{feedback}\hat{\mathbf{x}}_{k|k}$$

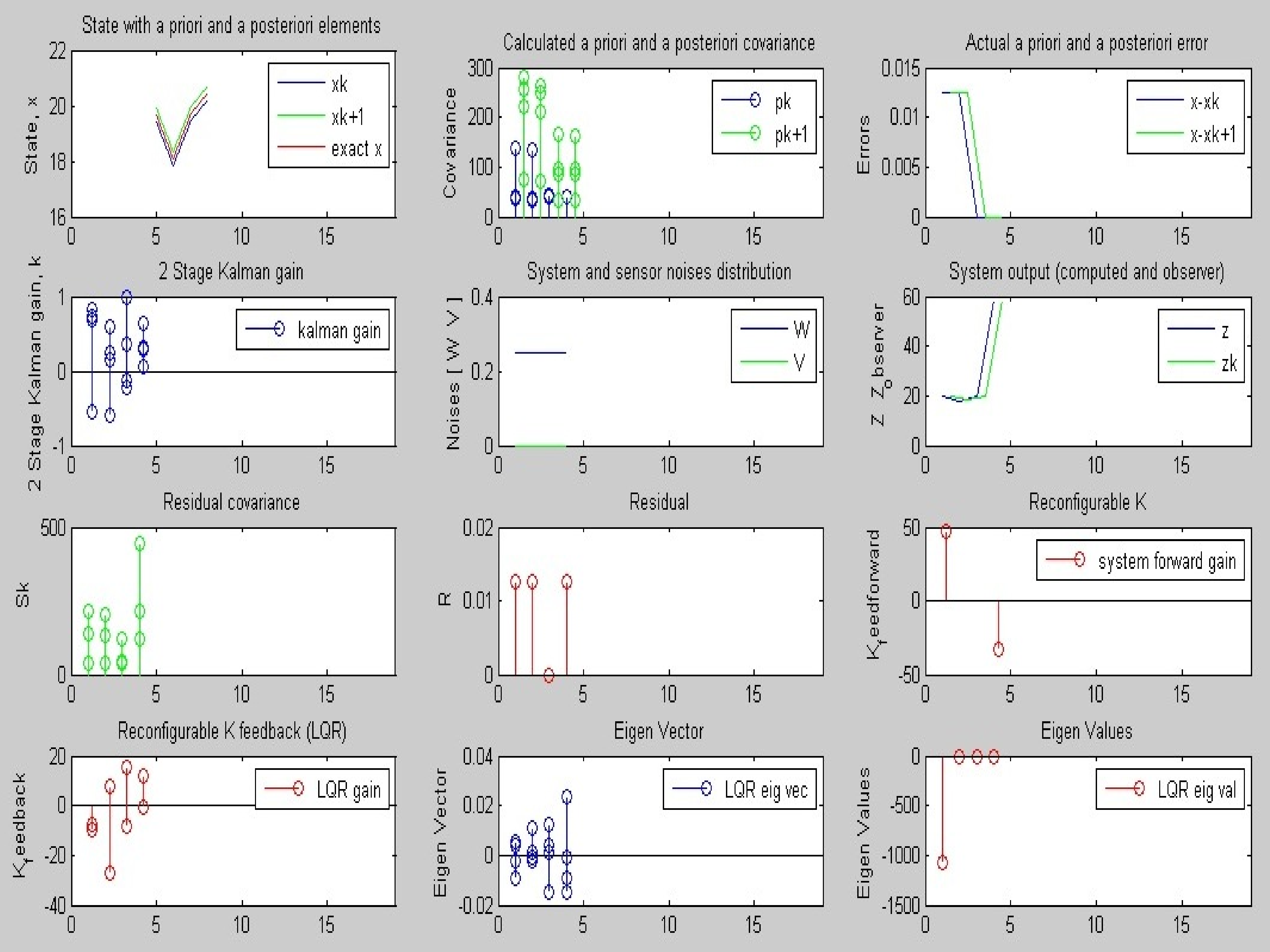

actuator
faults
w
v
r
$K_{forward}$
u
actuators
system
sensors
z
FDD
u
two-stage
adaptive filter
z
$\hat{x}$
FDI
$K_{feedback}$
reconfiguration
mechanism

Pseudocode Steps

- Initialization
- Coupling equations
- Reference model computations
- Cost minimization
- Gamma and threshold
- Prediction
- Correction
- Feedback controller settings
- Feedforward controller settings
- Plotting samples
- Root locus and system judge

System stages

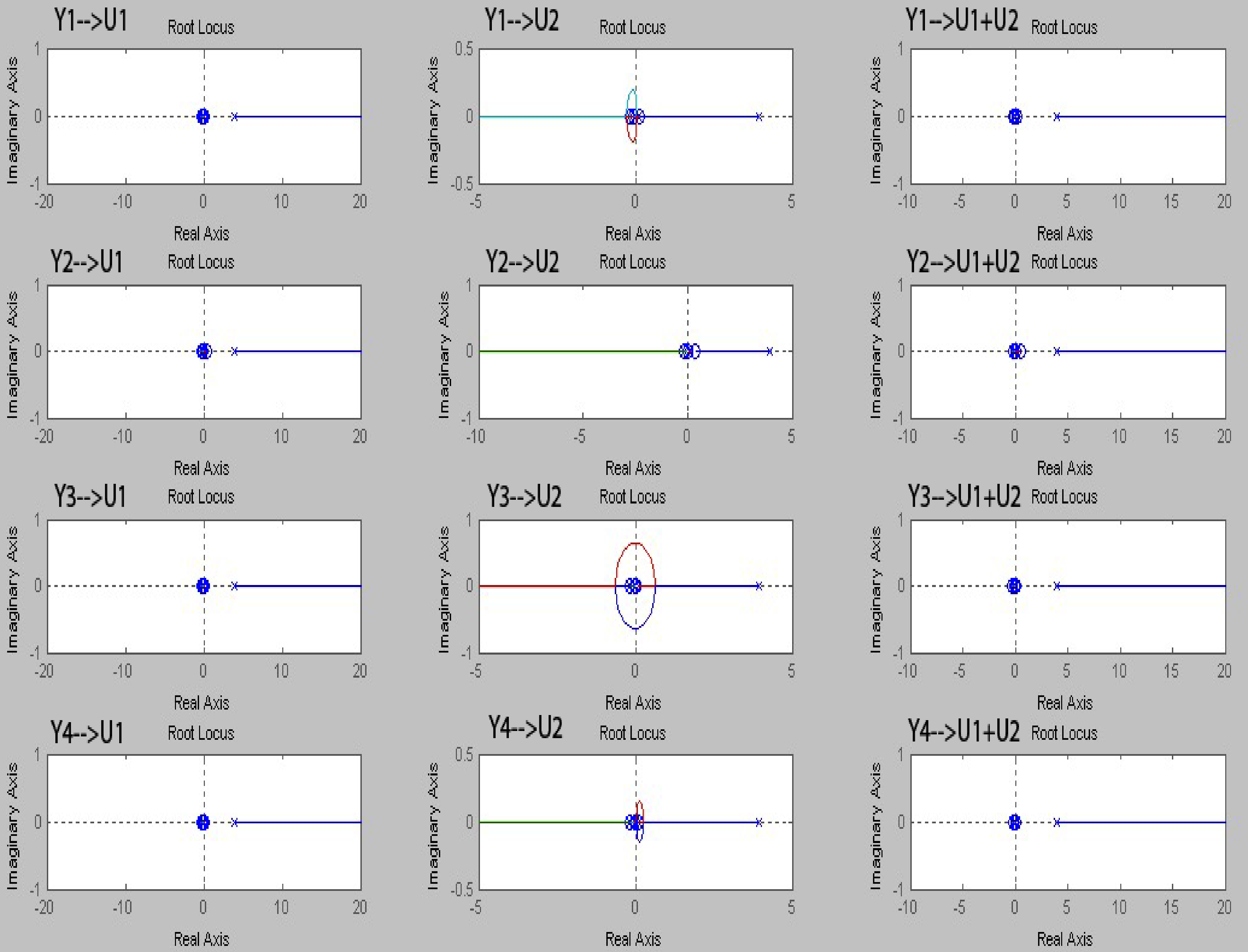
- Free fault
- Faulty
- Kalman
- Eigen vector
- Feedback
- Feedforward

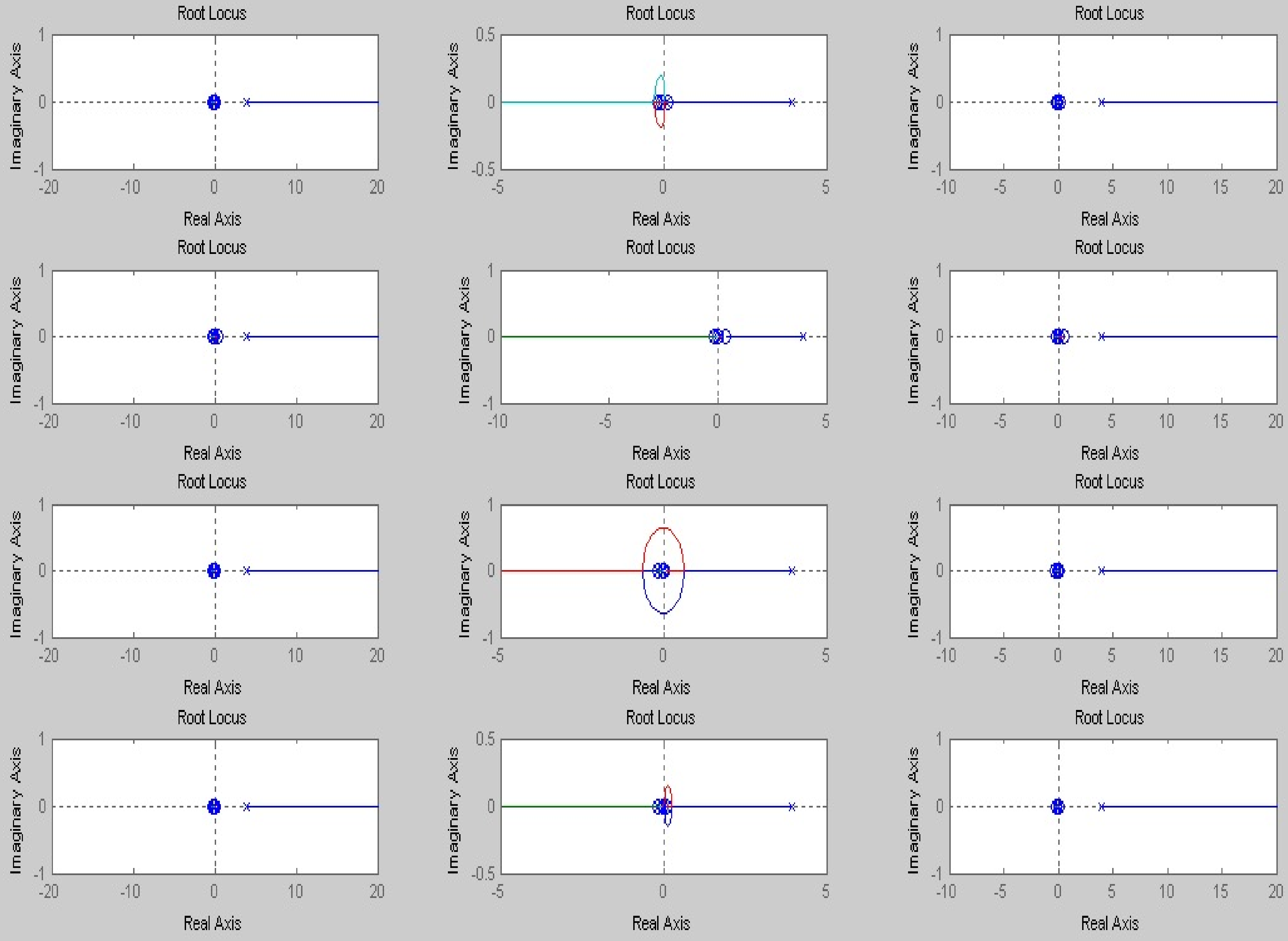


State with a priori and a posteriori elements
State, x
xk
xk+1
exact x
Calculated a priori and a posteriori covariance
Covariance
pk
pk+1
Actual a priori and a posteriori error
Errors
x-xk
x-xk+1
2 Stage Kalman gain
2 Stage Kalman gain, k
kalman gain
System and sensor noises distribution
Noises [W V]
W
V
System output (computed and observer)
Z Z observer
z
zk
Residual covariance
Sk
Residual
R
Reconfigurable K
K feedforward
system forward gain
Reconfigurable K feedback (LQR)
K feedback
LQR gain
Eigen Vector
Eigen Vector
LQR eig vec
Eigen Values
Eigen Values
LQR eig val

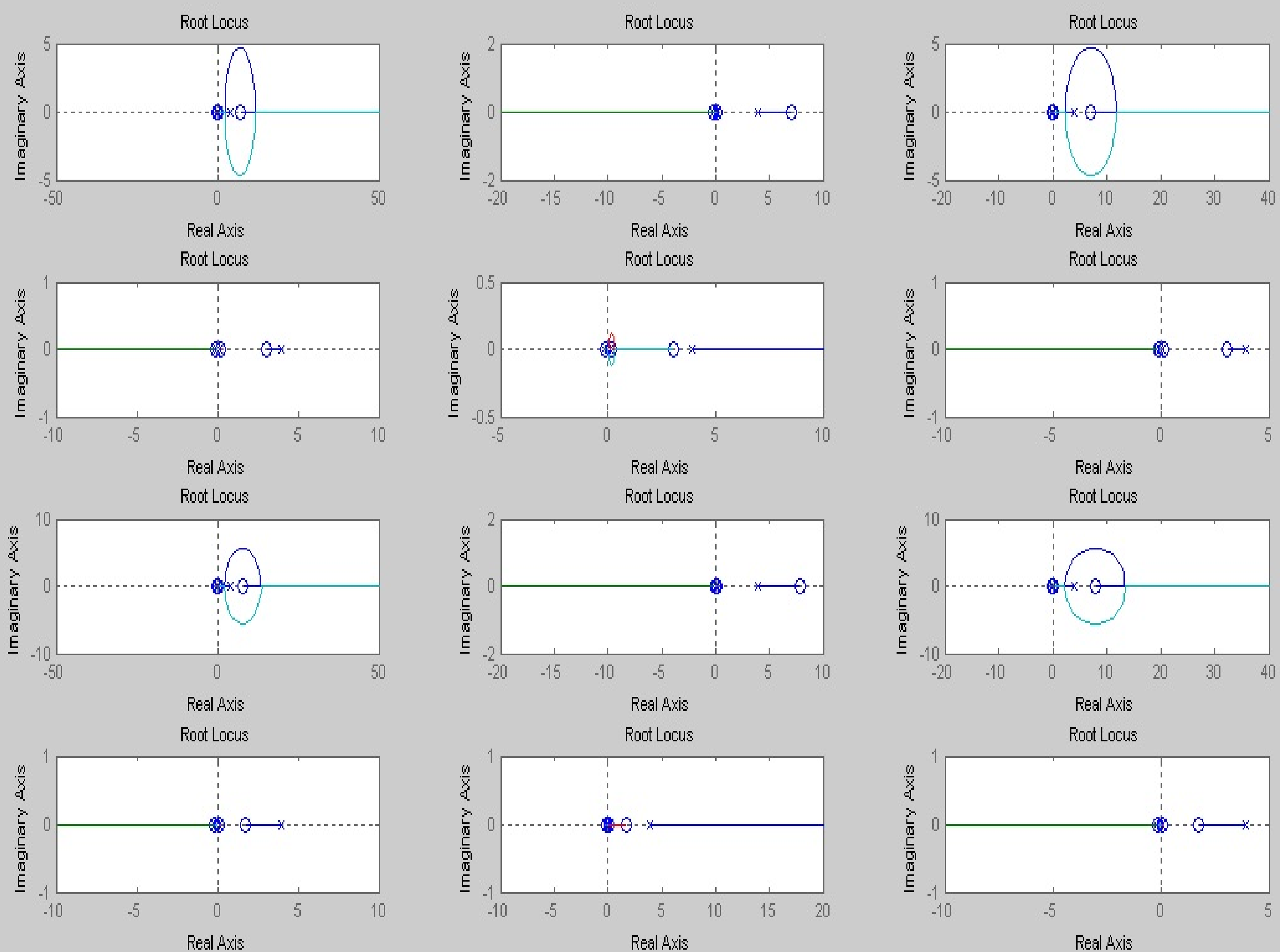
- -44.34 -5.804 0.8882 0.06702
- 25.05 2.751 -0.5238 -0.02707
- 1 -3.832 -0.4522 0.06912 0.001892
- -43.99 9.624 3.271 0.01937
- 24.27 -3.662 -1.683 -0.0219
- 1 -3.832 -0.4522 0.06912 0.001892
- -44.93 -11.27 -0.2208 -1.016e-016
- 25.48 5.43 0.1088 3.49e-017
- 1 -3.832 -0.4522 0.06912 0.001892
- -133.3 -13.94 2.2 0.01698
- 74.77 8.355 -1.216 -0.0203
- 1 -3.832 -0.4522 0.06912 0.001892

- -9.966e014 4.561e033 2.858e047 2e048
- 1.26e016 2.961e033 4.629e047 -1.197e048
- 1 1.839e017 2.789e031 3.91e032 1.105e033
- 9.588e016 1.893e033 3.4e047 -1.696e048
- 3.125e016 3.613e033 5.456e047 2.641e048
- 1 1.839e017 2.789e031 3.91e032 1.105e033
- -9.969e014 3.978e033 2.367e047 -3.409e048
- 9.926e015 2.39e033 3.75e047 7.901e048
- 1 1.839e017 2.789e031 3.91e032 1.105e033
- 1.462e017 6.908e033 2.184e047 -3.769e048
- 2.613e016 2.096e033 3.457e047 1.601e048
- 1 1.839e017 2.789e031 3.91e032 1.105e033


Y1-->U1
Root Locus
Y1-->U2
Root Locus
Y1-->U1+U2
Root Locus
Y2-->U1
Root Locus
Y2-->U2
Root Locus
Y2-->U1+U2
Root Locus
Y3-->U1
Root Locus
Y3-->U2
Root Locus
Y3-->U1+U2
Root Locus
Y4-->U1
Root Locus
Y4-->U2
Root Locus
Y4-->U1+U2
Root Locus
Imaginary Axis
Real Axis



Root Locus
Imaginary Axis
Real Axis
1
0
-1
-20
-10
0
10
20
Root Locus
Imaginary Axis
Real Axis
0.5
0
-0.5
-5
0
5
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
10
15
20
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-20
-10
0
10
20
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
10
15
20
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-20
-10
0
10
20
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-5
0
5
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
10
15
20
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-20
-10
0
10
20
Root Locus
Imaginary Axis
Real Axis
0.5
0
-0.5
-5
0
5
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
10
15
20



Root Locus
Imaginary Axis
Real Axis
5
0
-5
-50
0
50
Root Locus
Imaginary Axis
Real Axis
2
0
-2
-20
-15
-10
-5
0
5
10
Root Locus
Imaginary Axis
Real Axis
5
0
-5
-20
-10
0
10
20
30
40
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
10
Root Locus
Imaginary Axis
Real Axis
0.5
0
-0.5
-5
0
5
10
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
Root Locus
Imaginary Axis
Real Axis
10
0
-10
-50
0
50
Root Locus
Imaginary Axis
Real Axis
2
0
-2
-20
-15
-10
-5
0
5
10
Root Locus
Imaginary Axis
Real Axis
10
0
-10
-20
-10
0
10
20
30
40
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5
10
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
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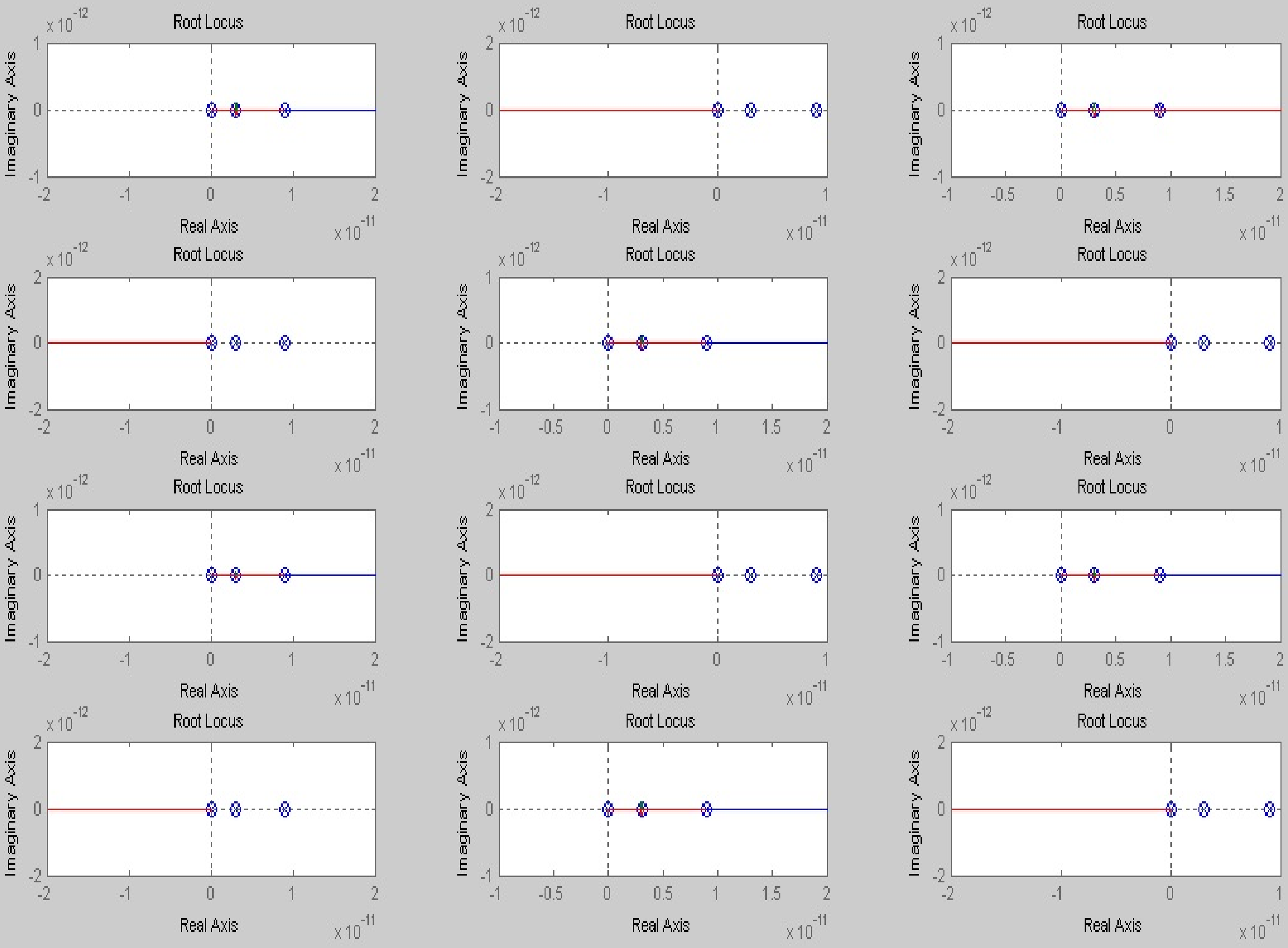
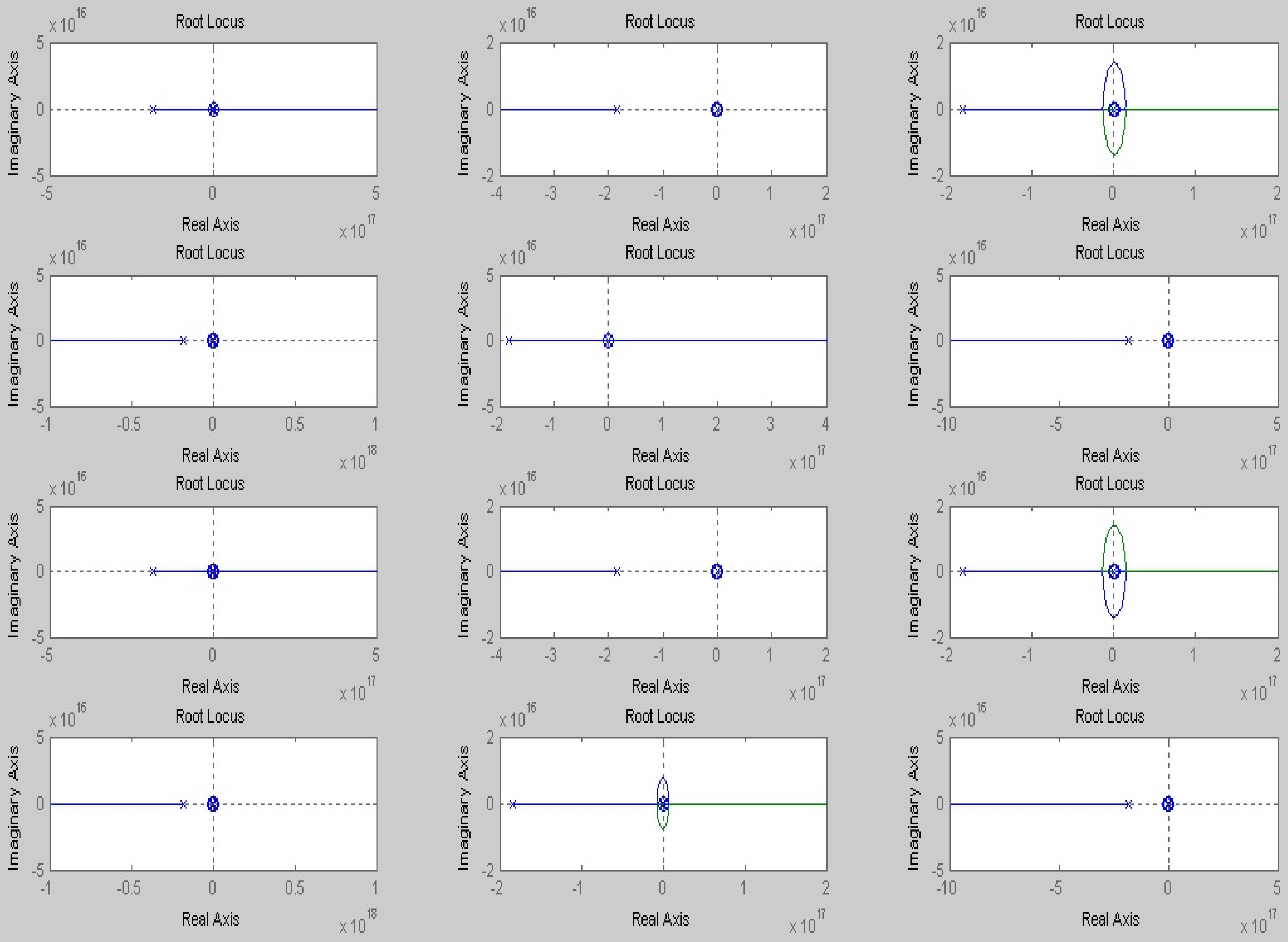
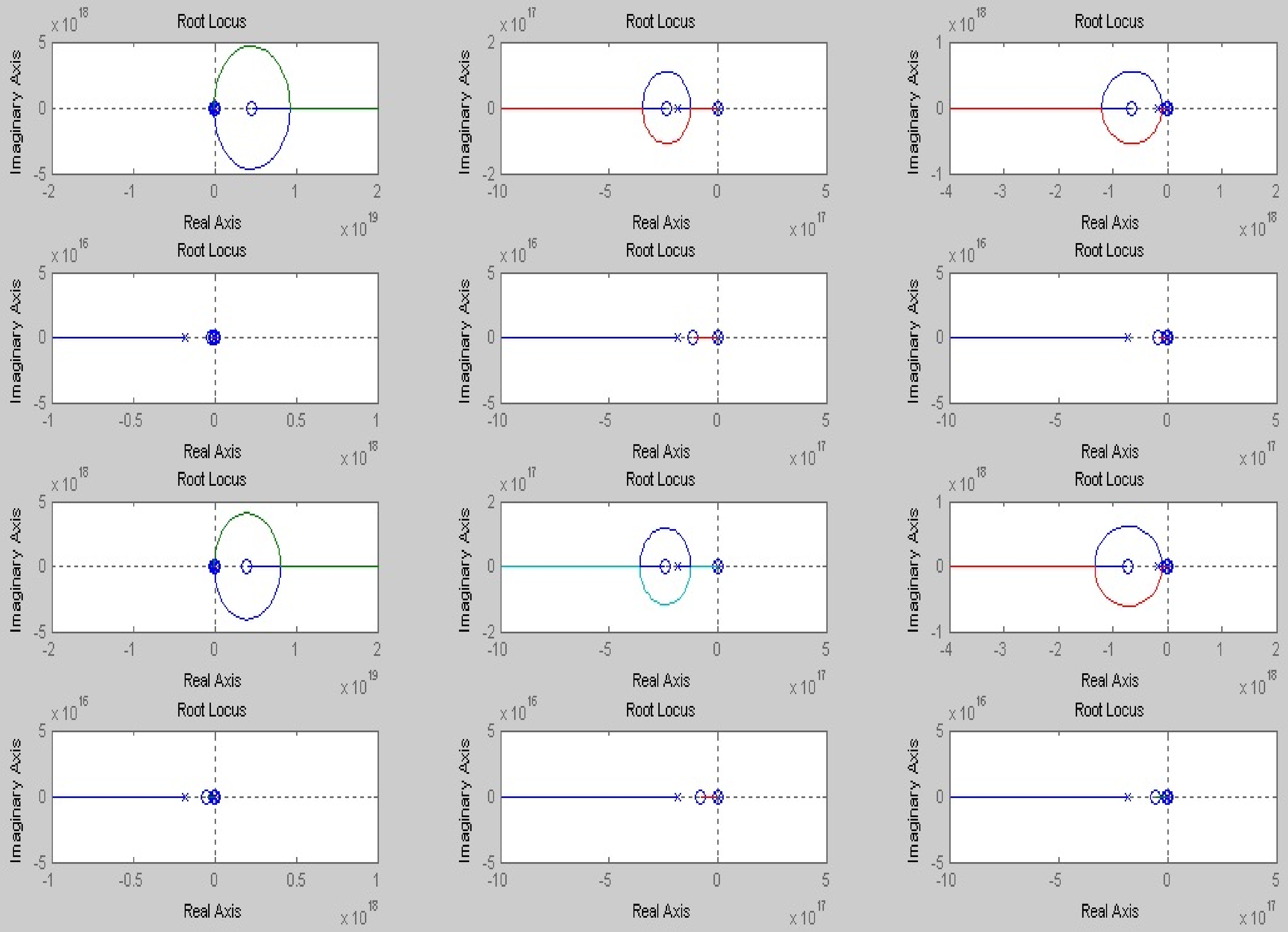
15
20
Root Locus
Imaginary Axis
Real Axis
1
0
-1
-10
-5
0
5


Root Locus
Imaginary Axis
Real Axis
x 10^-12
x 10^-11
1
0
-1
2
-2
-0.5
0.5
1.5


x 10^16
Root Locus
Imaginary Axis
5
0
-5
-5
0
5
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
2
0
-2
-4
-3
-2
-1
0
1
2
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
2
0
-2
-2
-1
0
1
2
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
5
0
-5
-1
-0.5
0
0.5
1
Real Axis
x 10^18
x 10^16
Root Locus
Imaginary Axis
5
0
-5
-2
-1
0
1
2
3
4
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
5
0
-5
-10
-5
0
5
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
5
0
-5
-5
0
5
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
2
0
-2
-4
-3
-2
-1
0
1
2
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
2
0
-2
-2
-1
0
1
2
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
5
0
-5
-1
-0.5
0
0.5
1
Real Axis
x 10^18
x 10^16
Root Locus
Imaginary Axis
2
0
-2
-2
-1
0
1
2
Real Axis
x 10^17
x 10^16
Root Locus
Imaginary Axis
5
0
-5
-10
-5
0
5
Real Axis
x 10^17



Root Locus
x 10^18
Imaginary Axis
5
0
-5
-2
-1
0
1
2
Real Axis
x 10^19
Root Locus
x 10^17
Imaginary Axis
2
0
-2
-10
-5
0
5
Real Axis
x 10^17
Root Locus
x 10^18
Imaginary Axis
1
0
-1
-4
-3
-2
-1
0
1
2
Real Axis
x 10^18
Root Locus
x 10^16
Imaginary Axis
5
0
-5
-1
-0.5
0
0.5
1
Real Axis
x 10^18
Root Locus
x 10^16
Imaginary Axis
5
0
-5
-10
-5
0
5
Real Axis
x 10^17
Root Locus
x 10^16
Imaginary Axis
5
0
-5
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-5
0
5
Real Axis
x 10^17
Root Locus
x 10^18
Imaginary Axis
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-2
-1
0
1
2
Real Axis
x 10^19
Root Locus
x 10^17
Imaginary Axis
2
0
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0
5
Real Axis
x 10^17
Root Locus
x 10^18
Imaginary Axis
1
0
-1
-4
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1
2
Real Axis
x 10^18
Root Locus
x 10^16
Imaginary Axis
5
0
-5
-1
-0.5
0
0.5
1
Real Axis
x 10^18
Root Locus
x 10^16
Imaginary Axis
5
0
-5
-10
-5
0
5
Real Axis
x 10^17
Root Locus
x 10^16
Imaginary Axis
5
0
-5
-10
-5
0
5
Real Axis
x 10^17

Challenges

- Choosing the parameters , like Activation of reconfiguration process , LQR , cost function
- Tracking errors and simulation
- It is reality control systems have an associated set of constraints; for example, inputs always have maximum and minimum values and states are usually required to lie within certain ranges
- When some actuators fail, to achieve the control objectives such as tracking more demands are placed on other healthy actuators, which can lead to actuator saturations and state limit violations

Suggestions

- Performance estimation , track more history
- Added hardware for faster response and complete redundancy