Design of PI Observer for Descriptor System

디스크립터시스템에 대한 PI 관측기 설계

Hwan Seong Kim, Sang Bong Kim, and Shigeyasu Kawaji
(김 환 성, 김 상 봉, 川路 茂保)

요 약 : 디스크립터(Descriptor) 표현은 상태공간 표현을 확장시킨 일반적인 시스템의 기술방법으로 파라미터의 물리적인 구조를 보존하고 있으며, 임펄스를 포함한 현상을 기술할 수 있다. 또한, 대규모 시스템의 모델화가 용이하며, 프로퍼(Proper)이지 않은 시스템을 기술할 수 있고 구속조건을 가진 동적시스템의 기술이 가능하는 등의 특징을 지니고 있다. 그러나, 디스크립터 시스템의 해는 미분항을 포함하고 있으므로 노이즈 및 파라미터 변동에 대해서 매우 민감하여, 관측기설계시 강인(Robust)한 관측기설계가 요구된다. 본 논문에서는 디스크립터 시스템에 대해 로바스트 관측기의 일종인 비례적분(PI) 관측기의 설계에 대해서 논한다. 먼저, 디스크립터 시스템에 대한 PI 관측기의 존재조건을 유도하였으며, 체계적인 설계법을 보였다. 또한, PI 관측기의 존재조건이 Rosenbrock의 가관측 조건하에서 간단히 보여지며, 이것은 시스템 행렬의 Rank 조건에 의해 쉽게 구해질 수 있다.

Keywords : proportional integral(PI) observer, descriptor system, observability

I. Introduction

In practical system and control system design, many systems can be described in the mixture form of differential and algebraic equations, which is called as descriptor system (or singular system, generalized state space system etc.). The form of descriptor system also appears in many systems, such as engineering systems, social economic systems, network analysis systems, biological systems, and so on. So, the descriptor systems can contribute usefully in analysis of real and practical situations. As similar problem in regular systems, the problem of observing the states of descriptor system is very important. This problem is solved by using inverse matrix theory by El-Tohami et.al.[1] and Shafai and Carroll[2]. And nonrestrictive method by generalized inverse matrix is presented by Kawaji[6]. But, as it is well known, the solution of a descriptor system includes differential terms, that is, a descriptor system is very sensitive to slight changes of the inputs or system parameters[4]. Thus, to obtain the state vectors of the descriptor systems, the construc- tion of robust observer is required.

On the other hand, in attenuation problem of system's parameter variations and step disturbances, a proportional integral (PI) observer have remarkable attention in recently[3],[7]. Kawaji and Kim proposed a new systematic method to design the PI observer, and it was applied into the design of simultaneous recovery of loop transfer property (LTR) and disturbance attenuation property (DAPR)[7].

In this paper, based on the above systematic design method we propose a full-order PI observer to estimate the state vectors of descriptor systems.

The existence conditions of a PI observer for the linear descriptor system are derived. Furthermore, a necessary and sufficient condition for the existence of a PI observer is proposed in the sense of Rosenbrock's observability, and it is checked by a simple matrix rank condition from linear descriptor systems. A numerical example is shown to illustrate the PI observer for the linear descriptor systems.

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김 환 성 : 부경대학교 기계공학과, ERC-RCOID
김 상 봉 : 부경대학교 기계공학과
川路茂保 : 일본 Kumamoto Univ. 수리정보공학과

II. System and definition of observer

Consider a linear time-invariant descriptor system described by

$$\Sigma : \begin{cases} E\dot{x} = Ax+Bu \\ y = Cx \end{cases} \tag{1}$$

where $x \in R^n$ is the descriptor vector, $u \in R^m$ is the input vector, and $y \in R^p$ is the output. E, A, B, and C are known constant matrices of appropriate dimensions. Assume that $E \in R^{n \times n}$ and rank $E = r(\le n)$. Additionally, we also assume that

(i) System (1) is solvable, *i.e.*, there exists a scalar such that

$$\det(\lambda E - A) \neq 0.$$

(ii) System (1) is *R-observable*[8] (observable in the sense of Rosenbrock) if and only if

$$\text{rank}\begin{bmatrix} E \\ C \end{bmatrix} = n$$

$$\text{rank}\begin{bmatrix} \lambda E - A \\ C \end{bmatrix} = n, \quad \forall \lambda \in \mathrm{C},$$

where, **C** denotes the complex plane.

To estimate the descriptor vector, we consider a PI observer

$$\Sigma_{PI} : \begin{cases} \dot{z} = \hat{A}z + \hat{B}y + \hat{J}u + \hat{H}\omega \\ \hat{x} = \hat{C}z + \hat{D}y \\ \dot{\omega} = y - C\hat{x} \end{cases} \tag{2}$$

where, $\hat{x}$ is estimated descriptor states, ω is integrated value of observation error output, and $\widehat{A}$, $\widehat{B}$, $\widehat{C}$, $\widehat{D}$, $\widehat{H}$, and $\widehat{J}$ are unknown matrices of appropriate dimensions. Especially, when matrix $\widehat{H}=0$, it is said to be the Luenberger observer. Our aim is to design the unknown matrices of the PI observer which asymptotically estimate the descriptor vector x.

Definition 1 : The system (2) is said to be a PI observer for the linear descriptor system (1) if and only if

$$\lim_{t\to\infty}[\hat{x}(t)-x(t)]=0, \quad \forall x(0_-), z(0_-), u(\cdot) \quad (3)$$

$$\lim_{t\to\infty}\omega(t)=0, \quad \forall \omega(0_-), z(0_-), u(\cdot). \quad (4)$$

To show the existence conditions of the PI observer for the system (1), let us define the estimate error as

$$\xi = z - UEx. \quad (5)$$

Then, the dynamics of this error is

$$\dot{\xi} = \widehat{A}\xi + (\widehat{A}UE + \widehat{B}C - UA)x + (\widehat{J} - UB)u + \widehat{H}\omega, \quad (6)$$

and $\hat{x}$ in the system (2) is rewritten by substituting z in (3)

$$\hat{x} = \widehat{C}\xi + (\widehat{C}UE + \widehat{D}C)x. \quad (7)$$

From (2), (6), and (7), the PI observer is summarized as

$$\dot{\xi} = \widehat{A}\xi + \widehat{H}\omega \quad (8)$$

$$\dot{\omega} = -C\widehat{C}\xi \quad (9)$$

$$\hat{x} = \widehat{C}\xi + x, \quad (10)$$

where

$$\widehat{A}UE + \widehat{B}C = UA$$

$$\widehat{J} = UB$$

$$\widehat{C}UE + \widehat{D}C = I_n.$$

From the above equations (8) and (9), the following augmented system can be constructed to satisfy the definition 1 as

$$\begin{bmatrix} \dot{\xi} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \widehat{A} & \widehat{H} \\ -C\widehat{C} & 0 \end{bmatrix} \begin{bmatrix} \xi \\ \omega \end{bmatrix}. \quad (11)$$

If (11) is stable, then the variables ξ and ω become zeros $(t\to\infty)$. So, the system (2) is an observer for the system (1). From the above statements, we obtain the following theorem.

Theorem 1 : The system (2) is a full-order PI observer for the linear descriptor system (1) if

$$\mathrm{Re}\ \lambda_i \begin{bmatrix} \widehat{A} & \widehat{H} \\ -C\widehat{C} & 0 \end{bmatrix} < 0, \quad i=1,\cdots,n+p \quad (12)$$

and if there exists a matrix $U \in R^{n\times n}$ such that

$$\widehat{A}UE + \widehat{B}C = UA \quad (13)$$

$$\widehat{J} = UB \quad (14)$$

$$\widehat{C}UE + \widehat{D}C = I_n \quad (15)$$

hold.

The design procedure of PI observer is presented by following statements. Let us assume $\widehat{C}=I_n$ for simplification. Substituting UE in (15) into (13), we get

$$\widehat{A} = UA - KC \quad (16)$$

where

$$K = \widehat{B} - \widehat{A}\widehat{D} \quad (17)$$

Substituting (16) into (17), we have

$$\widehat{B} = UA\widehat{D} + K(I_p - C\widehat{D}) \quad (18)$$

then, (12) becomes as

$$\mathrm{Re}\ \lambda_i \begin{bmatrix} UA-KC & \widehat{H} \\ -C & 0 \end{bmatrix} < 0, \quad i=1,\cdots,n+p \quad (19)$$

For stability of (19), it is necessary to design the matrices K and $\widehat{H}$ simultaneously. Its design problem is well known as that of conventional PI observer, and the observability of the observer is dependent on the observability of (C, UA) basically. Recently, its systematic design procedure is proposed by Kawaji and Kim[7]. The observability of PI observer is presented in Appendix A, and it is also dependent on the constructure of the matrix UA.

Thus, the problem of designing the PI observer for the linear descriptor systems is reduced to find a matrix U such that the conditions of Theorem 1 is satisfied.

Ⅲ. Design of observer

In the previous section, a sufficient condition that a PI observer (2) can be qualified as an observer for the linear descriptor system (1) was derived. The observer design problem is to find a matrix U such that the conditions (12)-(15) must be satisfied when E, A, B and C matrices are given.

In this section, we will consider the existence condition of the PI observer and show the design procedure of the observer. Firstly, it is required from the condition (15) that

$$\mathrm{rank}\begin{bmatrix} E \\ C \end{bmatrix} = n, \quad (20)$$

which implies that the impulse modes and the purely static modes of system (1) must be observable[5].

When the condition (20) is satisfied, there exist two matrices $E^{\#} \in R^{n \times n}$ and $C^{\#} \in R^{n \times p}$ such that

$$[E^{\#} \ C^{\#}]\begin{bmatrix} E \\ C \end{bmatrix} = I_n \tag{21}$$

i.e., $[E^{\#} \ C^{\#}]$ is a generalized matrix inverse of $[E^T \ C^T]^T$.

Here we define a class

$$\Gamma = \{ (E^{\#}, C^{\#}) : \det E^{\#} \neq 0, \ E^{\#}E + C^{\#}C = I_n \} \tag{22}$$

Then we have the following lemma.

Lemma [6] : Γ is not empty.

Proof : Suppose two nonsingular matrices P_1 and P_2 such that

$$\begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix}\begin{bmatrix} E \\ C \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ C_1 \\ C_2 \end{bmatrix} \begin{matrix} \}r \\ \}n-r \\ \}n-r \\ \}p-n-r \end{matrix}$$

where

$$\text{rank } E_1 = r, \quad \text{rank} \begin{bmatrix} E_1 \\ C_1 \end{bmatrix} = n$$

Multiflying the right side

$$\begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix}\begin{bmatrix} E \\ C \end{bmatrix}\begin{bmatrix} I_n & M \\ 0 & I_p \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ C_1 \\ C_2 \end{bmatrix}\begin{bmatrix} I_n & M \\ 0 & I_p \end{bmatrix}$$

where

$$M = \begin{bmatrix} 0 & 0 \\ I_{n-r} & O_{p-n+r} \end{bmatrix}$$

then, we have

$$\begin{bmatrix} P_1 & MP_2 \\ 0 & P_2 \end{bmatrix}\begin{bmatrix} E \\ C \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 + C_1 \\ C_1 \\ C_2 \end{bmatrix}$$

So, we notify that

$$W = \begin{bmatrix} E_1 \\ E_2 + C_1 \end{bmatrix}$$

is nonsingular matrix.

Multiflying the right side

$$\begin{bmatrix} P_1 & MP_2 \\ 0 & P_2 \end{bmatrix}\begin{bmatrix} E \\ C \end{bmatrix}[W^{-1} \ 0] = \begin{bmatrix} E_1 \\ E_2 + C_1 \\ C_1 \\ C_2 \end{bmatrix}[W^{-1} \ 0]$$

then, we get

$$[W^{-1}P_1 \ \ W^{-1}MP_2]\begin{bmatrix} E \\ C \end{bmatrix} = I_n$$

Letting

$$E^{\#} = W^{-1}P_1$$
$$C^{\#} = W^{-1}MP_2$$

then,

$(E^{\#}, C^{\#}) \in \Gamma$. Therefore $\det E^{\#} \neq 0$. ■

An algorithm to find an element of Γ is given in Appendix B.

For system (1), choosing an any $(E^{\#}, C^{\#}) \in \Gamma$ and letting

$$\hat{C} = I_n, \ U = E^{\#}, \ \hat{D} = C^{\#} \tag{23}$$

we get

$$\hat{C}UE + \hat{D}C = E^{\#}E + C^{\#}C = I_n \tag{24}$$

The remainding problem is the determination of the paramenter U in such a way that a stable observer obtained. For this, in (19), $(C, E^{\#}A)$ must be observable. That is,

$$\text{rank}\begin{bmatrix} \lambda I_n - E^{\#}A \\ C \end{bmatrix} = n, \ \forall \lambda \in \mathrm{C} \tag{25}$$

is necessary. Noticing $(E^{\#}, C^{\#}) \in \Gamma$

$$\begin{bmatrix} \lambda I_n - E^{\#}A \\ C \end{bmatrix} = \begin{bmatrix} E^{\#} & \lambda C^{\#} \\ 0 & I_p \end{bmatrix}\begin{bmatrix} \lambda E - A \\ C \end{bmatrix}, \tag{26}$$

and rank $E^{\#} = n$. Therfore we have

$$\text{rank}\begin{bmatrix} \lambda E - A \\ C \end{bmatrix} = n, \ \forall \lambda \in \mathrm{C}, \tag{27}$$

which implies that the exponential modes of system (1) must be observable[5]. Thus we come to the theorem giving a sufficient condition for the existence of a PI obsrever.

Theorem 2 : For the linear descriptor system (1), the full-order PI observer (2) exists if and only if

(i) $\text{rank}\begin{bmatrix} \lambda E - A \\ C \end{bmatrix} = n, \ \forall \lambda \in \mathrm{C}$

(ii) $\text{rank}\begin{bmatrix} E \\ C \end{bmatrix} = n.$

When the algorithm of designing the PI observer in Appendix A is used to obtain the matrices K and $\hat{H}$, it is necessary to satisfy the condition of Theorem A.2. Also, the matrix $E^{\#}$ should be designed such that the pair $(C, E^{\#}A)$ is observable.

Thus, the matrices of PI observer can be obtained as

$$\hat{A} = E^{\#}A - KC \tag{28}$$

$$\hat{B} = E^{\#}A\hat{D} + K(I - C\hat{D}) \tag{29}$$

$$\hat{J} = E^{\#}B \tag{30}$$

where $\hat{C} = I_n$. Therefore, we obtained the full-order PI observer for the linear descriptor systems.

Ⅳ. Numerical example

We consider the following system[9].

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \dot{x} = \begin{bmatrix} -1 & 2 & 1 \\ -1 & -1 & -1 \\ 1 & -1 & 1 \end{bmatrix} x + \begin{bmatrix} 1 \\ -1 \\ -1 \end{bmatrix} u$$

$$y = [\,2 \; -1 \; 1\,]\,x$$

This system satisfy the condition (i) of Theorem 2 as

$$\text{rank}\begin{bmatrix} sE-A \\ C \end{bmatrix} = \text{rank}\begin{bmatrix} s+1 & -2 & -1 \\ 1 & s+1 & 1 \\ -1 & 1 & -1 \\ 2 & -1 & 1 \end{bmatrix} = 3, \; \forall s \in \mathbb{C} \tag{31}$$

So, one can know that the system is observable. Thus, the full-order PI observer for descriptor systems can be designed by Theorem 1.

Step 1 : Calculate $E^{\#}$ and $C^{\#}$ by using Appendix B.

$$E^{\#} = U = \begin{bmatrix} 1.000 & 0.000 & 0.000 \\ 0.000 & 1.000 & 1.000 \\ -2.000 & 1.000 & 2.000 \end{bmatrix},$$

$$C^{\#} = \hat{D} = \begin{bmatrix} 0.000 \\ 0.000 \\ 1.000 \end{bmatrix}. \tag{32}$$

Matrices P_1 and P_2 are selected as

$$P_1 = \begin{bmatrix} 1.000 & 0.000 & 0.000 \\ 0.000 & 1.000 & 1.000 \\ 0.000 & 0.000 & 1.000 \end{bmatrix}, \quad P_2 = 1.$$

Step 2 : By using Appendix A, the PI observer gains K and $\hat{H}$ are designed by using pole assignment method, where the desired pole is { -1.1, -1.2, -1.3, -2.4 }.

$$K = \begin{bmatrix} -0.2440 \\ -0.0924 \\ 2.3955 \end{bmatrix}, \quad \hat{H} = \begin{bmatrix} 0.2353 \\ -0.1177 \\ 0.1177 \end{bmatrix} \tag{33}$$

Step 3 : Calculate the other matrices by (28)-(30)

$$\hat{A} = \begin{bmatrix} -0.5120 & 1.7560 & 1.2440 \\ 0.1849 & -2.0924 & 0.0924 \\ -1.7911 & -4.6045 & -3.3955 \end{bmatrix}$$

$$\hat{B} = \begin{bmatrix} 1.0000 \\ 0.0000 \\ -1.0000 \end{bmatrix}, \quad \hat{J} = \begin{bmatrix} 1.0000 \\ -2.0000 \\ -5.0000 \end{bmatrix}$$

The results of simulation are shown by Fig. 1-3. These figures show the real state of descriptor system and estimated state by PI observer, respectively. In this simulation, the input is $u = -1$, and sampling time is 0.02[sec].

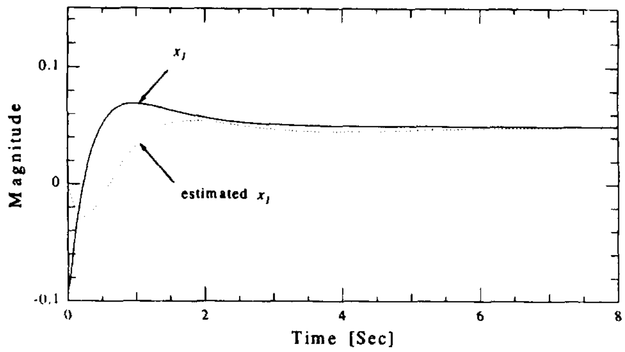

Fig. 1. Estimated state $\hat{x}_1$.

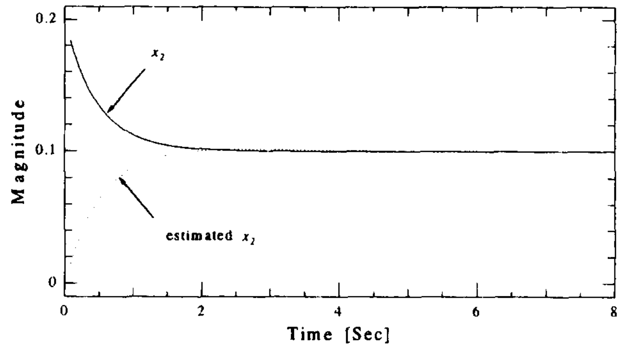

Fig. 2. Estimated state $\hat{x}_2$.

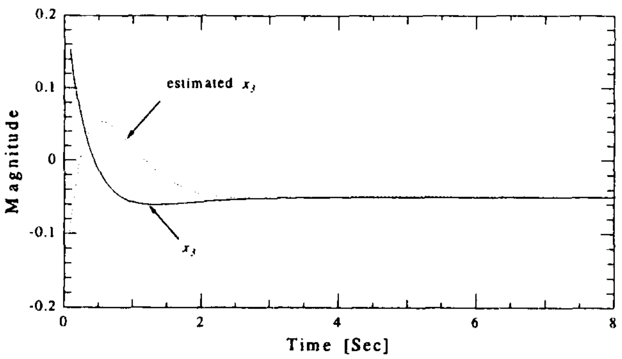

Fig. 3. Estimated state $\hat{x}_3$.

V. Conclusion

In this paper, we have proposed a nonrestrict design method of full-order PI observer for linear descriptor systems. The existence conditions of the PI observer for the linear descriptor system are proposed. Furthermore, a necessary and sufficient condition for the existence of a PI observer is proposed in the sense of Rosenbrock's observability.

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Appendix A

Consider a linear time-invariant system described by

$$\dot{x} = Ax + Bu \quad (34a)$$

$$y = Cx \quad (34b)$$

where $x \in R^n$ is the state vector, $u \in R^m$ is the input vector, and $y \in R^p$ is the output. A, B and C are known constant matrices of appropriate dimensions. Assume that (C, A) is observable and rank $C = p$.

Let us consider a linear time-invariant system[3] (PI observer)

$$\dot{\hat{x}} = \hat{A}\hat{x} + Ky + Bu + H\omega \quad (35a)$$

where, $\hat{x} \in R^n$ and $\omega \in R^p$ are vectors, respectively.

Given the PI observer (2), the following theorem depicts the realizability of the observer.

Theorem A1[3] : The system (35) is a full-order PI observer for the system (34) if and only if all the eigenvalues of the matrix

$$R = \begin{bmatrix} A - KC & H \\ -C & 0 \end{bmatrix}$$

have negative real parts.

For Theorem A1, there does not exist any systematic methods to calculate the parameters K and H by the eigenvalues assignment or the optimal control methods. As a method solving the problem, recently a new method is proposed by Kawaji and Kim as following[7].

< Design algorithm of PI observer >

Step 1 : Check the C matrix

(A1) $C = [\, C_m \;\; 0_{p\times(n-p)}\,]$

where C_m is nonsingular matrix and $O_{n\times m}$ is matrix of demension $n\times m$ with 0's($I_{n\times m}$ is $I_{n\times m}$ demension matrix with 1's on the diagonal of $\min(n,m)$ and 0's elsewhere). If the C matrix is not a form of (A1), then matrices A and C should be reconstructed with

$$A = (V_c^*)^{-1} A V_c \text{ and } C = CV_c$$

where V_c^* is obtained by singular value decomposition (SVD) of C matrix as $C = U_c \Psi_c V_c^*$ and superscript * denotes the complex-conjugate transpose.

Step 2 : Construct augmented matrices as

$$A_e = \begin{bmatrix} A & I_{n\cdot p} \\ I_{p\cdot n} & 0_p \end{bmatrix}, \quad C_e = [\, C \;\, 0_p]$$

Step 3 : Design a matrix L_e with assumption of observability of (C_e, A_e) by conventional pole assignment, LQG, or etc.

$$\det\,[\, A_e - L_e C_e \,] = 0$$

where $$L_e = \begin{bmatrix} L_1 \\ L_2 \end{bmatrix}$$

Step 4 : Calculate the matrices K and H

$$K = L_1$$

$$H = I_{n\cdot p}(L_2 - I_{p\cdot n} C^+)$$

where $$C^+ = C^T (CC^T)^{-1}.$$

Step 5 : If the transformation matrix is used in Step 1, then the real matrices K and H are calculated as

$$K = V_c^* K, \text{ and } H = V_c^* H$$

However, even if (C, A) is observable, the observability of (C_e, A_e) would not be proved directly in Step 3.

Theorem A2[7] : The system (C_e, A_e) is observable, if (C, A) is observable.

Appendix B

< Algorithm for $(E^\#, C^\#) \in \Gamma$ >

Step 1 : Find two nonsingular matrices P_1 and P_2 such that

$$\begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} E \\ C \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ C_1 \\ C_2 \end{bmatrix} \begin{matrix} \}r \\ \}n-r \\ \}n-r \\ \}p-n-r \end{matrix}$$

where

$$\text{rank } E_1 = r, \quad \text{rank} \begin{bmatrix} E_1 \\ C_1 \end{bmatrix} = n.$$

Step 2 : Let

$$W=\begin{bmatrix} E_1 \\ E_2+C_1 \end{bmatrix},$$

$$M=\begin{bmatrix} 0 & 0 \\ I_{n-r} & O_{p-n+r} \end{bmatrix}.$$

Step 3 : $E^{\#}$ and $C^{\#}$ are given as

$$E^{\#}=W^{-1}P_1,$$

$$C^{\#}=W^{-1}MP_2.$$

김 환 성

1991년 부경대학교 기관공학과 졸업, 동대학원 기계공학과 석사(1993), 일본 Kumamoto Univ. 공학박사 (1996), 1996년 ~ 현재 부경대학교 Post- Doc.. 관심분야는 디스크립터 시스템 및 관측기설계, 로바스트제어, 고장진단 등.

김 상 봉

1978년 부경대학교 기관공학과 졸업, 동대학원 동학과 석사(1980), 일본동경공업대학 공학박사(1988), 현재 부경대학교 공과대학 기계공학과 부교수. 관심분야는 로바스트제어, 크레인제어 등.

川路 茂保

1969년 일본 Kumamoto Univ. 전기공학과 졸업, 同年 조교수를 거쳐 현재 수리정보공학과 교수. 공학박사(동경공업대학). 1994년 Berkely Univ., Havard Univ. 등의 객원연구원으로 1년간체재. 관심분야는 로바스트 제어이론 및 메카니칼시스템의 응용, 지능형제어계 구축 등.