

On the limiting form of the Kalmanbucy filter as measurement noise tends to zero (Part I,Finite Dimension)

T. Hamatsuka

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**ON THE LIMITING FORM
OF THE KALMAN-BUCY FILTER
AS MEASUREMENT NOISE
TENDS TO ZERO
(Part I, Finite Dimension)**

Teruo HAMATSUKA

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Institut National
de Recherche
en Informatique
et en Automatique

Domaine de Voluceau
Rocquencourt
BP 105
78153 Le Chesnay Cedex
France
Tel (3) 954 90 20

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INRIA

Domaine de Voluceau

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78153 LE CHESNAY CEDEX (France)

RESUME

On étudie dans ce papier le comportement asymptotique du filtre de Kalman lorsque le bruit sur l'observation tend vers zéro. On montre que sous des hypothèses assez générales la forme limite du filtre correspond à un observateur de Luenberger d'un système déterministe.

ABSTRACT

The purpose of this paper is to show that, under general circumstances, the Kalman-Bucy filter approaches a meaningful limit as measurement noise tends to zero. Moreover, it is shown that the limiting form corresponds to the so-called Luenberger observer in deterministic systems under suitable assumptions.

C O N T E N T S

1 - INTRODUCTION

2 - SERIES EXPANSION

3 - LIMITING FORM OF KALMAN-BUCY FILTER

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1 - INTRODUCTION

Let us consider the system

$$\frac{d}{dt} x(t) = Ax(t) + Bu(t) + D\xi(t)$$

(1)

$$x(0) = x_0 \quad E[x_0] = \bar{x}_0$$

$$(2) \quad y(t) = Cx(t) + \eta(t)$$

where $\xi(t)$ and $\eta(t)$ are independent Gaussian white noise processes such that

$$(3) \quad E [\xi(t) \xi'(\tau)] = Q\delta(t-\tau)$$

$$(4) \quad E [\eta(t) \eta'(\tau)] = R\delta(t-\tau)$$

Then the optimum minimum variance estimator $\hat{x}(t) = E [x(t) | y(\tau) \quad 0 \leq \tau \leq t]$ is given by the well-known Kalman-Bucy filter [8] :

$$(5) \quad \frac{d}{dt} \hat{x}(t) = A\hat{x}(t) + By(t) + P(t) C'R^{-1} [y(t) - C\hat{x}(t)]$$

with $P(t) = E [(x(t) - \hat{x}(t))(x(t) - \hat{x}(t))']$ being the solution to the matrix Ricatti equation

$$(6) \quad \frac{d}{dt} P(t) = AP(t) + P(t)A' - P(t)C'R^{-1} CP(t) + DQD'$$

$$(6) \quad P(o) = \Pi_o = E [(x_o - \bar{x}_o)(x_o - \bar{x}_o)']$$

under the assumption that the matrix R is positive definite.

If R is singular, however, the problem is much more complicated. One difficulty is that the gain $PC'R^{-1}$ of the filter becomes very large as the covariance matrix R of the noise η becomes small. In the case where $R = 0$, the nonsingularity of the matrix $CDQD'C'$ means that the new measurement vector $\frac{d}{dt} y(t)$ will contain a non-singular white noise component [2], [6]. Therefore, a standard Kalman-Bucy filter may be derived by using $\frac{d}{dt} y(t)$ instead of $y(t)$, and the need for the differentiation can be avoided by defining new filter state $Z_d(t) = \hat{x}(t) - P(t)C'R^{-1}y(t)$, [6].

This work is very closely related to the results of FRIEDLAND [2], MOYLAN [6], and KWANTNY [3]. Especially, FRIEDLAND [2], MOYLAN [6] proved that a known class of minimal order observers can be identified as limiting forms of Kalman-Bucy filters for the new filter state $Z_d(t)$ with vanishing observation noise under the assumption that $CDQD'C'$ is nonsingular.

The objective of this paper is to study the limiting form of Kalman-Bucy filter as R tends to zero under general circumstances, i.e. without assuming the regularity of $CDQD'C'$.

2 - SERIES EXPANSION

For the simplicity we consider the time invariant case, that is, $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$, $C \in \mathbb{R}^{r \times n}$, $D \in \mathbb{R}^{n \times \ell}$, $Q \in \mathbb{R}^{\ell \times \ell}$, $R \in \mathbb{R}^{r \times r}$. In this case, provided that the pair (C,A) is detectable, and the $2n \times 2n$ Hamiltonian matrix H defined by

$$H = \begin{bmatrix} A' & -C'R^{-1}C \\ -CDQD'C' & -A \end{bmatrix}$$

has no imaginary axis eigenvalues, $P(t)$ tends to a solution of the algebraic Riccati equation (ARE)

$$(7) \quad AP + PA' - PC'R^{-1}CP + GG' = 0$$

with $DQD' = GG'$ under suitable initial conditions, and $A - PC'C$ is stable [1]. Moreover, if (A,G) is stabilizable, the ARE (7) has an unique positive definite solution [7].

Let

$$(8) \quad R = \epsilon^2 I$$

then the ARE (7) becomes

$$(9) \quad AP_{\epsilon} + P_{\epsilon}A' - \frac{1}{\epsilon}P_{\epsilon}C'CP_{\epsilon} + GG' = 0$$

Suppose P has the series expansion of the form such that

$$(10) \quad P_{\epsilon} = P_0 + \epsilon P_1 + \epsilon^2 P_2 + \dots$$

By substituting (10) into (9) and equating matrix coefficients of same powers of ϵ , we have

$$(11a) \quad CP_0 = 0$$

$$(11b) \quad AP_0 + P_0A' - P_1C'CP_1 + GG' = 0$$

$$(11c) \quad AP_1 + P_1A' - P_2C'CP_1 - P_1C'CP_2 = 0$$

$$(11d) \quad AP_2 + P_2A' - P_2C'CP_2 - P_1C'CP_3 - P_3C'CP_1 = 0$$

.....

Pre- and postmultiplying (11b) by C and C', it follows that

$$(12) \quad CP_1C' = (CGG'C')^{1/2}.$$

3 - LIMITING FORM OF KALMAN-BUCY FILTER

In this section we study the limiting forms of Kalman-Bucy filter in two cases, that is, $G = 0$ and $\text{rank } (CGG'C') \geq 1$.

Case 1 $G = 0$

In this case, equations (11) and (12) become

$$(11a') \quad CP_0 = 0$$

$$(11b') \quad AP_0 + P_0A' - P_1C'CP_1 = 0$$

$$(11c') \quad AP_1 + P_1A' - P_2C'CP_1 - P_1C'CP_2 = 0$$

$$(11d') \quad AP_2 + P_2A' - P_2C'CP_2 - P_1C'CP_3 - P_3C'CP_1 = 0$$

$$(12') \quad CP_1C' = 0$$

Let

$$X_c(A,B) = \sum_{i=0}^{n-1} A^i \text{ Range } B$$

(the controllable subspace of (A,B)),

$$X_{uo}(C,A) = \bigcap_{i=0}^{n-1} \text{Ker } CA^i$$

(the unobservable subspace of (C,A))

then we have the following lemma.

LEMMA 1

$$\text{Ker } P_0 \supset X_c(A',C')$$

$$\text{(or Range } P_0 \subset X_{uo}(C,A))$$

$$\text{Ker } CP_1 \supset X_c(A',C')$$

$$\text{(or Range } P_1C' \subset X_{uo}(C,A))$$

Proof . We prove this lemma by induction.

Premultiplying (11b') by C and using (11a), (12'),

$$(13) \quad CAP_0 = 0$$

Suppose

$$(14) \quad CA^i P_0 = 0$$

$$(15) \quad CA^i P_1 C' = 0$$

for $i = 0, 1, 2, \dots, k-1$. Premultiplication of (11b') by CA^{k-1} yields

$$(16) \quad CA^k P_0 + CA^{k-1} P_0 A' - CA^{k-1} P_1 C' CP_1 = 0.$$

Then, it follows from equations (14), (15) and (16) that

$$(17) \quad CA^k P_0 = 0.$$

By pre- and postmultiplying (11b') by CA^k and $A'^k C'$, we have

$$(18) \quad CA^{k+1} P_0 A'^k C' + CA^k P_0 A'^{k+1} - CA^k P_1 C' C P_1 A'^k C' = 0$$

Equations (17) and (18) give

$$CA^k P_1 C' = 0$$

This completes the proof. \square

THEOREM 1. Suppose the pair (C,A) is observable. Then

- (a) $P_0 = P_1 = 0$,
- (b) P_2 satisfies the ARE

$$(19) \quad AP_2 + P_2 A' - P_2 C' C P_2 = 0.$$

Furthermore, if A has no imaginary axis eigenvalues, then there exists a solution P_2 of ARE (19) such that $A - P_2 C' C$ is stable.

Proof. It follows from Lemma 1 that $P_0 = 0$

$$(20) \quad CP_1 = 0,$$

since (C,A) is observable. By substituting (20) into (11b'), we have

$$(21) \quad AP_1 + P_1 A' = 0$$

Suppose now

$$(22) \quad CA^i P_1 = 0 \text{ for } i = 0, 1, 2, \dots, k-1.$$

Premultiplying (21) by CA^{k-1}

$$(23) \quad CA^k P_1 + CA^{k-1} P_1 A' = 0$$

Equations (22) and (23) mean $CA^k P_1 = 0$. Therefore, $P_1 = 0$ by induction. Equation (19) follows from (11c) and (20).

The fact that $A - P_2 C' C$ is stable is the well-known result of algebraic Riccati equation [7]. \square

REMARK 1. The ARE (19) has more than one symmetric positive semidefinite solution which form a lattice with common maximum and common minimum element. The maximal solution is the only stabilizing solution. $P_2 = 0$ is a solution of the ARE (19). It is the maximum (or minimum) solution if $\text{Re } \lambda(A) \leq 0$ (or ≥ 0), where $\lambda(A)$ denotes an arbitrary eigenvalues of A . Otherwise $P_2 = 0$ is an intermediate solution [7].

COROLLARY 1. Suppose the pair (C, A) is observable and A has no imaginary axis. Then the limiting form of Kalman-Bucy filter (5) as ϵ tends to zero is

$$(24) \quad \frac{d}{dt} \hat{x}(t) = (A - P_2 C' C) \hat{x}(t) + P_2 C' y(t) + Bu(t)$$

where P_2 is a maximal solution of the ARE (19). Furthermore (24) is an identity observer (in the sense of Luenberger) for the system

$$(25) \quad \frac{d}{dt} x(t) = Ax(t) + Bu(t)$$

$$(26) \quad y(t) = Cx(t)$$

Proof. Equation (24) is a direct result of Theorem 1. Let $e(t) = \hat{x}(t) - x(t)$, then from (24), (25) and (26) we have

$$\frac{d}{dt} e(t) = (A - P_2 C' C) e(t)$$

Therefore $e(t)$ tends to zero, since $A - P_2 C' C$ is stable. This completes the proof. \square

Case 2. $0 < \text{rank} (CGG'C') \leq r$.

From (11a), (11b) and (12), we have

$$(27) \quad (CGG'C')^{1/2} CP_1 = C(AP_0 + GG')$$

Let

$$q = \text{rank} (CGG'C')$$

then there exists an orthonormal matrix U such that

$$(28a) \quad CGG'C' = U' \Lambda^2 U$$

$$(28b) \quad \Lambda = \begin{bmatrix} \Lambda_q & 0 \\ 0 & 0 \end{bmatrix} \begin{matrix} q \\ r-q \end{matrix}$$

$$(28c) \quad \Lambda_q = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_q) \quad \lambda_i > 0, \quad i = 1, 2, \dots, q$$

Suppose equation (27) has a solution (which may be not unique), then

$$(29) \quad CP_1 = \Phi^+ C(AP_0 + GG') + Z$$

where Φ^+ is a pseudo-inverse of

$$(30) \quad \Phi = (CGG'C')^{1/2}$$

and Z is an arbitrary $r \times n$ matrix such that $\Phi Z = 0$ and $ZC' = 0$. Note that

$$(31) \quad \Phi^+ = U' \Lambda^+ U,$$

where

$$(32) \quad \Lambda^+ = \begin{bmatrix} \Lambda_q^{-1} & 0 \\ 0 & 0 \end{bmatrix} \begin{matrix} q \\ r-q \end{matrix}$$

Then

$$\begin{aligned}
 \Phi^+ Z &= U' \Lambda^+ U Z \\
 (33) \quad &= U' \left[I_q \mid 0_{q \times (r-q)} \right]' \Lambda_q^{-1} \left[I_q \mid 0_{q \times (r-q)} \right] U Z \\
 &= 0
 \end{aligned}$$

since $\Phi Z = 0$ implies $\left[I_q \mid 0_{q \times (r-q)} \right] U Z = 0$. Substituting (29) into (11b) and using (33), we have

$$\begin{aligned}
 (34) \quad & (I_n - GG'C'\Phi^{+2})AP_0 + P_0A'(I_n - GG'C'\Phi^{+2})' - P_0A'C'\Phi^{+2}CAP_0 + \\
 & + GG' - GG'C'\Phi^{+2}CGG' - Z'Z = 0
 \end{aligned}$$

Let us decompose UC into two blocks such that

$$(35a) \quad UC = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix}$$

where

$$(35b) \quad C_1 = \left[I_q \mid 0_{q \times (r-q)} \right] UC$$

$$(35c) \quad C_2 = \left[0_{(r-q) \times q} \mid I_{(r-q)} \right] UC,$$

then, noting that

$$\Phi^{+2} = U' \left[I_q \mid 0_{q \times (r-q)} \right]' \Lambda_q^{-2} \left[I_q \mid 0_{q \times (r-q)} \right] U$$

the algebraic Riccati equation (34) becomes

$$(36a) \quad (I_n - C_1^\# C_1) A P_0 + P_0 A' (I_n - C_1^\# C_1)' - P_0 A' C_1' \Lambda_q^{-2} C_1 A P_0 + M(Z) = 0$$

where

$$(36b) \quad C_1^\# = G G' C_1' \Lambda_q^{-2}$$

and

$$(36c) \quad M(Z) = G G' - G G' C_1' \Lambda_q^{-2} C_1 G G' - Z' Z$$

It can be easily shown from equations (28), (35) and (36b) that $C_1^\#$ is a right inverse of C_1 , that is

$$(37) \quad C_1 C_1^\# = I_q$$

and

$$(38) \quad C_2 C_1^\# = 0.$$

Let S_1 be an $n \times q$ selector matrix which selects q independent columns from C_1 , and let S_1^C be an $n \times (n-q)$ selector matrix which selects $n-q$ columns of C_1 such that S_1 does not select. Define an $n \times n$ nonsingular matrix T_1 by

$$(39a) \quad T_1 = \begin{bmatrix} C_1 \\ V_1 \end{bmatrix}$$

with

$$(39b) \quad V_1 = S_1^C (I_n - C_1^\# C_1)$$

then a simple calculation yields

$$(40a) \quad T_1^{-1} = [C_1^\# \quad V_1^\#]$$

where

$$(40b) \quad v_1^\# = s_1^C - s_1(C_1 S_1)^{-1} C_1 S_1^C$$

Furthermore

$$(41) \quad C_1 T_1^{-1} = [I_q \mid 0_{q \times (n-q)}]$$

$$(42) \quad T_1 C_1^\# = [I_q \mid 0_{q \times (n-q)}]'$$

$$(43) \quad T_1 C_1^\# C_1 T_1^{-1} = E_q$$

$$(44) \quad T_1 (I_n - C_1^\# C_1) T_1^{-1} = I_n - E_q$$

where

$$(45) \quad E_q = \begin{bmatrix} I_q & 0 \\ 0 & 0 \end{bmatrix} \begin{matrix} q \\ n-q \end{matrix}$$

Note that $CP_0 = 0$ if and only if

$$(46a) \quad C_1 P_0 = 0$$

and

$$(46b) \quad C_2 P_0 = 0$$

Note also that (27) has a solution (which may be not unique) if and only if

$$(47) \quad C_2 A P_0 = 0$$

since $C_2 G = 0$ from (28), (30), (31) and (35). From equations (39), (40) and (46a)

$$(48) \quad T_1 P_0 T_1' = \begin{bmatrix} 0 & 0 \\ 0 & \Pi_1 \end{bmatrix} \begin{matrix} q \\ n-q \end{matrix}$$

where

$$(49) \quad \Pi_1 = V_1 P_0 V_1'$$

Equations (39a), (40b) and (49) yield

$$(50) \quad P_0 = V_1^{\#} \Pi_1 V_1^{\#}$$

Moreover, it follows from (46b), (47) and (50) that

$$(51) \quad \begin{bmatrix} C_2 V_1^{\#} \\ C_2 A V_1^{\#} \end{bmatrix} \Pi_1 = 0$$

Suppose now

$$(52) \quad \text{rank} \begin{bmatrix} C_2 V_1^{\#} \\ C_2 A V_1^{\#} \end{bmatrix} = \ell < n-q$$

Let S_2 be an $\ell \times 2(r-q)$ selector matrix which selects ℓ independent rows from $C_2 V_1^{\#}$

and let S_3 be an $(n-q) \times \ell$ selector matrix which selects ℓ independent

columns from

$$(53) \quad \bar{C}_2 = S_2 \begin{bmatrix} C_2 V_1^{\#} \\ C_2 A V_1^{\#} \end{bmatrix}$$

Define an $(n-q) \times (n-q)$ nonsingular matrix T_2 by

$$(54a) \quad T_2 = \begin{bmatrix} \bar{C}_2 \\ V_2 \end{bmatrix}$$

with

$$(54b) \quad V_2 = S_3^C (I_{n-q} - \bar{C}_2^* \bar{C}_2)$$

where \bar{C}_2^* is an arbitrary right inverse of \bar{C}_2 and S_3^C is the $(n-q)$ $(n-q-\ell)$ selector matrix which selects $(n-q-\ell)$ columns of \bar{C}_2 such that S_3 does not select.

Then

$$(55a) \quad T_2^{-1} = [\bar{C}_2^* \mid V_2^*]$$

where

$$(55b) \quad V_2^* = S_3^C - S_3(\bar{C}_2 S_3)^{-1} \bar{C}_2 S_3^C$$

It follows from (51) and (54) that

$$(56) \quad T_2 \Pi_1 T_2' = \begin{bmatrix} 0 & 0 \\ 0 & \Pi_2 \end{bmatrix} \begin{matrix} \ell \\ n-q-\ell \end{matrix}$$

where

$$(57) \quad \Pi_2 = V_2 \Pi_1 V_2'$$

By a simple calculation

$$(58) \quad \Pi_1 = V_2^* \Pi_2 V_2^{* \prime}$$

The above procedure gives us one of the main results of this paper.

THEOREM 2

(a) If $\ell = n-q$, then $P_0 = 0$

(b) If $\ell < n-q$, then

$$(59) \quad P_0 = V_1^{\#} V_2^* \Pi_2 V_2^{* \prime} V_1^{\# \prime}$$

where Π_2 is an $(n-q-\ell) \times (n-q-\ell)$ matrix solution of the algebraic Riccati equation

$$(60) \quad (V_2 V_1 A V_1^{\#} V_2^*) \Pi_2 + \Pi_2 (V_2 V_1 A V_1^{\#} V_2^*)' - \Pi_2 (C_1 A V_1^{\#} V_2^*)' \Lambda_q^{-2} (C_1 A V_1^{\#} V_2^*) \Pi_2 + V_2 V_1 M(Z) V_1^{\#} V_2^* = 0$$

Proof. (a) is obvious from (51). It follows from (39) and (40) that

$$(61) \quad T_1 (I_n - C_1^{\#} C_1) A T_1^{-1} = \begin{bmatrix} 0 & 0 \\ V_1 A C_1^{\#} & V_1 A V_1^{\#} \end{bmatrix} \begin{matrix} q \\ n-q \end{matrix}$$

By noting $C_1 M(Z) = 0$, we have

$$(62) \quad T_1 M(Z) T_1' = \begin{bmatrix} 0 & 0 \\ 0 & V_1 M(Z) V_1^{\#} \end{bmatrix} \begin{matrix} q \\ n-q \end{matrix}$$

Pre- and postmultiplying (36a) by T_1 and T_1' , and using (48), (61) and (62) we obtain

$$(63) \quad (V_1 A V_1^{\#}) \Pi_1 + \Pi_1 (V_1 A V_1^{\#})' - \Pi_1 (C_1 A V_1^{\#})' \Lambda_q^{-1} (C_1 A V_1^{\#}) \Pi_1 + V_1 M(Z) V_1^{\#} = 0$$

Substitution of (58) into (63) yields (60). Equation (59) follows from (50) and (58). \square

REMARK 2. Theorem 2 is an extension of Theorem 1 in [3] to the case where $CGG'C'$ may be not invertible.

REMARK 3. It is easy to prove that the pair $(C_1 A V_1^{\#} V_2^*, V_2 V_1 A V_1^{\#} V_2^*)$ is observable if the pair (C_1, A) is observable.

REMARK 4. The condition $\ell = n-q$ implies $(n-r) < (r-q)$, i.e., $\text{rank } C_2 > n-r$.

REMARK 5. If $P_0 = 0$, then rank G must be less than or equal to r , since $P_1 C' C P_1 = G G'$. Moreover, by a simple calculation, we have

$$(64) \quad C_1 P_1 = \Lambda_q^{-1} C_1 G G'$$

$$(65) \quad C_2 P_1 = [0_{(r-q) \times q} \mid I_{(r-q)}] U Z$$

and

$$(66) \quad G G' = G G' G' \Lambda_q^{-2} C_1 G G'.$$

REMARK 6. Note that the solution of (60) depends on Z . Let $\Pi_2(Z)$ be a maximal solution of (60), then $\Pi_2(Z)$ is monotone with respect to $M(Z)$, that is, $\Pi_2(Z_1) \geq \Pi_2(Z_2)$ if $M(Z_1) \geq M(Z_2)$ [1]. Therefore, $\Pi_2^0 \geq \Pi_2(Z)$ with $\Pi_2^0 = \Pi_2(0)$, since $M(0) \geq M(Z)$ for all Z . In the following we assume that $Z = 0$, since the maximum of the maximal solutions of (60) has an interest for us.

By capital letters \hat{X} , \hat{U} , and Y we mean the Laplace transforms of x , \hat{u} and y , respectively. Upon Laplace transformation, the Kalman-Bucy filter (5) becomes

$$(67) \quad s \hat{X} = A \hat{X} + B \hat{U} + P C' \Gamma_\epsilon$$

with

$$(68) \quad \Gamma_\epsilon = \frac{1}{\epsilon^2} (Y - C \hat{X})$$

for $R = \epsilon^2 I$. Then, by using (67),

$$\begin{aligned} s \epsilon^2 \Gamma_\epsilon &= s Y - C s \hat{X} \\ &= s Y - C (A \hat{X} + B \hat{U} + P C' \Gamma_\epsilon) \end{aligned}$$

Therefore

$$(69) \quad \Gamma_\epsilon = (s \epsilon^2 I_r + C P C')^{-1} (s Y - C A \hat{X} - C B \hat{U}).$$

Premultiplying (69) by PC' and using the series expansion (10), we have

$$(70) \quad PC' \Gamma_{\epsilon} = (P_1 C' + \epsilon P_2 C' + O(\epsilon^2)) [CP_1 C' + \epsilon(CP_2 C' + sI) + O(\epsilon^2)]^{-1} \\ \times (sY - CA\hat{X} - CB\hat{U})$$

The following lemma will be useful.

LEMMA 2.

$$(a) \quad \lim_{\epsilon \rightarrow 0} P_1 C' [CP_1 C' + \epsilon(CP_2 C' + sI) + O(\epsilon^2)]^{-1} \\ = P_1 C' \phi^+$$

$$(b) \quad \lim_{\epsilon \rightarrow 0} \epsilon P_2 C' [CP_1 C' + \epsilon(CP_2 C' + sI) + O(\epsilon^2)]^{-1} \\ = 0$$

Proof. Using (29) and (31) with $Z = 0$,

$$P_1 C' [CP_1 C' + \epsilon(CP_2 C' + sI) + O(\epsilon^2)]^{-1} = [GG' + P_0 A'] \bar{C}' \Lambda^+ [\Lambda + \\ + \epsilon(\bar{C} P_2 \bar{C}' + sI) + O(\epsilon^2)]^{-1} U$$

where $\bar{C} = UC$.

Note that

$$\lim_{\epsilon \rightarrow 0} \Lambda^{1/2} [\Lambda + \epsilon(\bar{C} P_2 \bar{C}' + sI) + O(\epsilon^2)]^{-1} = (\Lambda^+)^{1/2},$$

since $\bar{C} P_2 \bar{C}'$ is symmetric nonnegative definite. Therefore, (71) becomes

$$\begin{aligned}
 & \lim_{\epsilon \rightarrow 0} P_1 C' [CP_1 C' + \epsilon(CP_2 C' + sI) + O(\epsilon^2)]^{-1} \\
 &= \lim_{\epsilon \rightarrow 0} [GG' + P_0 A'] \bar{C}' (\Lambda^+)^{3/2} \Lambda^{1/2} [\Lambda + \epsilon(\bar{C}P_2 \bar{C}' + sI) + O(\epsilon^2)]^{-1} U \\
 &= [GG' + P_0 A'] \bar{C}' (\Lambda^+)^2 U \\
 &= P_1 C \Phi^+
 \end{aligned}$$

For the proof of (b) it is enough to show that

$$(73) \quad \lim_{\epsilon \rightarrow 0} \epsilon P_2 \bar{C}' [\Lambda + \epsilon(\bar{C}P_2 \bar{C}' + sI) + O(\epsilon^2)]^{-1} U = 0$$

A simple calculation from (11c) yields that $\bar{C}P_2 \bar{C}'$ is a solution of

$$\bar{C}A P_1 \bar{C}' + \bar{C}P_1 A' \bar{C}' = (\bar{C}P_1 \bar{C}') \Lambda - \Lambda (\bar{C}P_2 \bar{C}')$$

and

$$(74) \quad \bar{C}P_2 = \Lambda^+ [\bar{C}A P_1 + \bar{C}P_1 A' + \bar{C}P_2 \bar{C}' \bar{C}P_1]$$

On the other hand

$$\begin{aligned}
 & \lim_{\epsilon \rightarrow 0} \epsilon \Lambda^+ [\Lambda + \epsilon(\bar{C}P_2 \bar{C}' + sI) + O(\epsilon^2)]^{-1} \\
 &= \lim_{\epsilon \rightarrow 0} \epsilon (\Lambda^+)^{3/2} \Lambda^{1/2} [\Lambda + \epsilon(\bar{C}P_2 \bar{C}' + sI) + O(\epsilon^2)]^{-1} \\
 (75) \quad &= \lim_{\epsilon \rightarrow 0} \epsilon (\Lambda^+)^{3/2} + \lim_{\epsilon \rightarrow 0} \Lambda^{1/2} [\Lambda + \epsilon(\bar{C}P_2 \bar{C}' + sI) + O(\epsilon^2)]^{-1} \\
 &= 0
 \end{aligned}$$

Equations (74) and (75) mean (73). This completes the proof. \square

From (67), (70) and Lemma 2, we have

$$(76) \quad s(\hat{X} - P_1 C' \Phi^+ Y) = (I_n - P_1 C' \Phi^+ C') (\hat{A} \hat{X} + \hat{B} U)$$

Let

$$(77) \quad W = X - P_1 C' \Phi^+ Y$$

then (76) becomes

$$(78) \quad sW = (I - P_1 C' \Phi^+ C') [A(W + P_1 C' \Phi^+ Y) + \hat{B}U]$$

Define another right inverse of C_1 by

$$(79) \quad C_1^* = C_1^\# + P_0 A' C_1 \Lambda_q^{-2}$$

Then, it follows from (29), (31) and (36b) that

$$(80) \quad \begin{aligned} P_1 C' \Phi^+ &= (GG' + P_0 A') \bar{C}' (\Lambda^+)^2 U \\ &= (GG' + P_0 A') [C_1' \Lambda_q^{-1} \mid 0_{n \times (r-q)}] U \\ &= [C_1^\# + P_0 A' C_1 \Lambda_q^{-2} \mid 0_{n \times (r-q)}] U \\ &= [C_1^* \mid 0_{n \times (r-q)}] U \end{aligned}$$

Equations (77), (78) and (80) yield

$$(81) \quad \hat{x}(t) = w(t) + [C_1^* \mid 0_{n \times (r-q)}] U y(t)$$

and

$$(82) \quad \begin{aligned} \frac{d}{dt} w(t) &= (I_n - C_1^* C_1) A w(t) \\ &\quad + (I_n - C_1^* C_1) A [C_1^* \mid 0_{n \times (r-q)}] U y(t) + (I_n - C_1^* C_1) B u(t) \end{aligned}$$

Let us define an $n \times n$ nonsingular matrix T_3 by

$$(83a) \quad T_3 = \begin{bmatrix} C_1 \\ V_3 \end{bmatrix}$$

with

$$(83b) \quad V_3 = S_1^c (I_n - C_1^* C_1)$$

Then, easily we have

$$(84) \quad T_3^{-1} = [C_1^* \quad V_1^\#]$$

Furthermore

$$(85) \quad T_3(I_n - C_1^* C_1)T_3^{-1} = \begin{bmatrix} 0 & 0 \\ 0 & I_{(n-q)} \end{bmatrix} \begin{matrix} q \\ n-q \end{matrix}$$

$q \quad n-q$

Let

$$(86a) \quad W_1 = [I_q \mid 0_{q \times (n-q)}] T_3 W$$

and

$$(86b) \quad W_2 = [0_{(n-q) \times q} \mid I_{(n-q)}] T_3 W$$

Then, noting that

$$(87) \quad T_3 A T_3^{-1} = \begin{bmatrix} C_1 A C_1^* & C_1 A V_1^\# \\ V_3 A C_1^* & V_3 A V_1^\# \end{bmatrix}$$

equations (82) becomes

$$(88) \quad \frac{d}{dt} W_1(t) = 0$$

and

$$\begin{aligned}
 \frac{d}{dt} W_2(t) &= V_3 A C_1^* W_1(t) + V_3 A V_1^\# W_2(t) \\
 (89) \quad &+ [V_3 A C_1^* \mid 0_{(n-q) \times (r-q)}] U y(t) \\
 &+ V_3 B u(t)
 \end{aligned}$$

By summarizing the above results we have

THEOREM 3. The limiting form of Kalman-Bucy filter (5) as measurement noise tends to zero is as follows

$$(90) \quad \hat{x}(t) = V_1^\# W_2(t) + [C_1^* \mid 0_{n \times (r-q)}] U y(t)$$

$$\begin{aligned}
 \frac{d}{dt} W_2(t) &= (V_3 A V_1^\#) W_2(t) \\
 (91) \quad &+ [V_3 A C_1^* \mid 0_{(n-q) \times (r-q)}] U y(t) \\
 &+ V_3 B u(t)
 \end{aligned}$$

Proof. We may assume $W_1(0) = 0$, then $W_1(t) = 0$ from (88). Therefore, (81) and (89) become (90) and (91), respectively. \square

REMARK 7. A simple calculation shows that

$$(92) \quad V_2 V_3 A V_1^\# V_2^* = V_2 V_1 A V_1^\# V_2^* - \Pi_2 (C_1 A V_1^\# V_2^*)' \Lambda_q^{-2} (C_1 A V_1^\# V_2^*)$$

where Π_2 is a maximal solution of (60), if $\ell < n-q$. Moreover, if the pair (C_1, A) is observable, then $V_2 V_3 A V_1^\# V_2^*$ is asymptotically stable, since the observability of (C_1, A) implies the observability of $(C_1 A V_1^\# V_2^*, V_2 V_1 A V_1^\# V_2^*)$ by Remark 3. We have also

$$(93) \quad V_3 A V_1^\# = V_1 A V_1^\# - \Pi_1 (C_1 A V_1^\#)' \Lambda_q^{-2} (C_1 A V_1^\#)$$

where Π_1 is given by (58) and is a maximal solution of (63) with constraints (51).

THEOREM 4. Suppose $V_3AV_1^\#$ is asymptotically stable, then the system (90) and (91) is an observer of the system

$$(94a) \quad \frac{d}{dt} x(t) = Ax(t) + Bu(t)$$

$$(94b) \quad y(t) = Cx(t)$$

Proof. Recall that the p-dimensional system

$$(95a) \quad \frac{d}{dt} \psi(t) = F \psi(t) + Ky(t) + SBu(t)$$

$$(95b) \quad \hat{x}(t) = N_1\psi(t) + N_2y(t)$$

is an observer for the system (94) if and only if

(i) F is asymptotically stable

(ii) $SA - FS = KC$

(iii) $N_1S + N_2C = I_n$

[4], [5].

Let $p=n-q$, $F = V_3AV_1^\#$, $K = [V_3AC_1^{*-} \mid 0_{(n-q) \times (r-q)}]U$, $S = V_3$, $N_1 = V_1^\#$, and $N_2 = [C_1^* \mid 0_{n \times (r-q)}]U$. Then obviously condition (i) holds. Condition (ii) follows from the fact that

$$SA - FS = V_3A(I_n - V_1^\#V_3) = V_3AC_1^*C_1 = KC.$$

Also

$$N_1S + N_2C = V_1^\#V_3 + C_1^*C_1 = I_n$$

This completes the proof.

REMARK 8. Suppose $\ell < n-q$. Then by Remark 7, $V_2V_3AV_1^\#V_2^*$ is asymptotically stable, however, this fact doesn't always imply that $V_3AV_1^\#$ is asymptotically stable. A sufficient condition which guaranties the asymptotic stability of $V_3AV_1^\#$ is

$$(96a) \quad \bar{C}_2 V_1 A V_1^\# = 0$$

and

$$(96b) \quad \bar{C}_2 V_1 A V_1^\# C_2^* \text{ is asymptotically stable,}$$

since

$$(97) \quad T_2 V_3 A V_1^\# T_2^{-1} = \begin{bmatrix} \bar{C}_2 V_1 A V_1^\# C_2^* & \bar{C}_2 V_1 A V_1^\# V_2^* \\ V_2 V_3 A V_1^\# C_2^* & V_2 V_3 A V_1^\# V_2^* \end{bmatrix}$$

REMARK 9. Suppose $\ell = n-q$, then $C_1^* = C_1^\#$ and $V_3 = V_1$, since $P_0 = 0$. This case we have no guarantee that $V_3 A V_1^\# (= V_1 A V_1^\#)$ is asymptotically stable except in the case where $V_1 A V_1^\#$ itself is asymptotically stable.

REMARK 10. Theorem 4 is an extension of the results in [2] to the case where $CGG'C'$ is singular.

4 - CONCLUSION

This paper has considered the limiting form of Kalman-Bucy filter as measurement noise tends to zero. By introducing the pseudo-inverse of $CGG'C'$, we derived the $(n-q-\ell) \times (n-q-\ell)$ dimensional Riccati equation for $q = \text{rank } CGG'C'$ and

$\ell = \text{rank} \begin{bmatrix} C_2 V_1^\# \\ C_2 A V_1^\# \end{bmatrix}$. It has also shown that, under suitable conditions, the

limiting form corresponds to an observer of order $n-q$ for deterministic systems.

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