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Optimal Output Feedback Architecture for Triangular LQG Problems

Takashi Tanaka and Pablo A. Parrilo

Abstract—Distributed control problems under some specific information constraints can be formulated as (possibly infinite dimensional) convex optimization problems. The underlying motivation of this work is to develop an understanding of the optimal decision making architecture for such problems. In this paper, we particularly focus on the \(N\)-player triangular LQG problems and show that the optimal output feedback controllers have attractive state space realizations. The optimal controller can be synthesized using a set of stabilizing solutions to \(2N\) linearly coupled algebraic Riccati equations, which turn out to be easily solvable under reasonable assumptions.

Nomenclature

- \(G(s) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} := C(sI - A)^{-1}B + D\) represents a proper rational transfer function matrix.
- The space of matrix valued functions \(G\) such that \(\|G\| \triangleq \sqrt{\langle G, \bar{G} \rangle} < \infty\) is denoted by \(L_2\), where \(\langle G_1, G_2 \rangle \triangleq \frac{1}{2\pi} \int_{-\infty}^{\infty} tr(G_1(j\omega)\bar{G}_2(j\omega))d\omega\). \(L_2\) can be written as \(L_2 = H_2 \oplus \mathbb{H}_{\infty}^1\), where \(H_2\) is the subspace of functions \(G\) analytic in \(Re(s) > 0\). The \(H_2\) norm of a function \(G \in H_2\) can be computed using the same formula \(\|G\| \triangleq \sqrt{\langle G, \bar{G} \rangle}\).
- \(\mathbb{H}_{\infty}^1\) is the subspace of functions with \(n\) only (nonzero components only in the first \(n\) dimensional) convex optimization problems. The underlying spaces, Massachusetts Institute of Technology, Cambridge, MA, USA.

I. INTRODUCTION

It is widely recognized that tractability of distributed control problems greatly depends on the information structure underlying the problem. If the information structure is arbitrary, the problem can be hopelessly hard as demonstrated by an iconic example by Witsenhausen in 1968. In contrast, many tractability results initiated by Ho and Chu [1] suggest that distributed control problems seem much more accessible when decision makers form a hierarchy in terms of their ability to observe and control the physical system. Currently, a unification via the quadratic hierarchy (QH) introduced by [7] is known to capture a wide class of distributed control problems that can be formulated as (infinite dimensional) convex optimization problems. Unfortunately, the QI framework does not immediately lead us to an explicit form of the optimal solution, and as a result, state space realizations of the optimal controllers remain unknown for many QI optimal control problems. This paper derives a state space realization of the solution to the triangular LQG problem, which is a special case but an important instance of the QI optimal control problems.

The triangular LQG problem is formulated as follows. Suppose that the transfer function of the system to be controlled is given by

\[
G = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \triangleq \begin{bmatrix} A & W \\ F & 0 \end{bmatrix} \begin{bmatrix} B \\ 0 \end{bmatrix} \begin{bmatrix} C \\ V \end{bmatrix}.
\]

Matrices \(A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m}, C \in \mathbb{R}^{p \times n}\) are partitioned according to \(n = n_1 + \cdots + n_N, m = m_1 + \cdots + m_N, p = p_1 + \cdots + p_N\), and \(A, B, C \in I_{LBT}\) with respect to this partitioning. The injected noise \(w\), performance output \(z\), control input \(u\), and observation output \(y\) are related by \(\text{col}\{z, y\} = G\text{col}\{w, u\}\). A controller transfer function \(K \in I_{LBT}\) needs to be designed so that \(u = Ky\) minimizes the \(H_2\) norm of the closed loop transfer function from \(w\) to \(z\).

**Problem 1:** Find a state space realization of the optimal solution \(K_{opt}\) to the problem:

\[
\min \|G_{11} + G_{12}K(I - KG_{22})^{-1}G_{21}\|^2 \quad (1a)
\]

\[
\text{s.t. } K \in I_{LBT} \text{ and stabilizing.} \quad (1b)
\]

Problem [1] can be interpreted as a distributed control problem under a particular information constraint shown in Fig. 1.

We make some natural assumptions on system matrices \(A, B, C, F, H, W\) and \(V\) so that Problem [1] is well-posed.

**Assumption 1:** 1. For every \(i \in \{1, 2, \cdots, N\}\), \((A_{ii}, B_{ii})\) is stabilizable and \(H\) has full column rank.
Each row of $K$ can be seen as an independent controller, who observes local output and controls downstream subsystems. Another valid interpretation is to view $K \in T_{L, B, T}$ as a sum of local controllers $K_i \in T_{L, B, T}^i$, who observes upstream subsystems and controls downstream systems (the above figure).

Due to the quadratic invariance property [7], Problem [1] can be written as a convex optimization problem by introducing a particular re-parametrization [9]. It is also straightforward to see by vectorization [8] that Problem [1] admits a unique solution in this parameter domain, and hence that $K_{opt}$ is also rational. In this paper, we further show that the optimal controller has a fascinating state space structure, which can be easily synthesized by solving a set of linearly coupled Riccati equations. This work extends recent progress in the understanding of state space solutions to distributed control problems [2]–[4], [10], [12].

II. SUMMARY OF THE RESULT

Under Assumption [1] and 2 (the second assumption will be discussed later), a state space model of $K_{opt}$ can be constructed. This requires to determine $N$ controller gains $K_1, \ldots, K_N$ and $N$ observer gains $L_1, \ldots, L_N$ by finding a set of stabilizing solutions to algebraic Riccati equations:

\begin{align}
(1) \quad & X_1, K_1 = ARE_p(A, L_1 F, H) \\
(2) \quad & X_i, K_i = ARE_p(A + L_{i-1} C_{i-1}, B_i, \ldots, -H_i^{i-1} K_{i-1}, H_i^i), \quad i \in \{2, 3, \ldots, N\} \\
(3) \quad & Y_N, L_N = ARE_d(A, C, W, V) \\
(4) \quad & Y_i, L_i = ARE_d(A + B_i K_{i+1}, C_i, \ldots, -L_{i+1} V_{i+1}, V_i), \quad i \in \{1, 2, \ldots, N-1\}.
\end{align}

Notice that (2a) and (2c) can be solved independently since they require problem data $A, B, C, F, H, W$ and $V$ only, while the remaining $2N - 2$ Riccati equations (2b) and (2d) have dependencies on each other. By carefully looking at their substructures, we show that unknown variables can be sequentially determined as shown in Fig. 2.

Applying concepts of control and estimation are highly symmetric in this synthesis.

It is convenient to introduce $nN$ dimensional square incidence matrices $\zeta$ and $\mu$ to describe the architecture of $K_{opt}$. Define $\zeta$ by dividing it into $N \times N$ sub-blocks and setting its $(i, j)$-th sub-block to $I_{n_i}$ if $i \geq j$ and to zero otherwise. Matrix $\mu$ is defined as the inverse of $\zeta$.

Theorem 1: Under Assumption [1] and 2 (2) admits a unique set of solutions $(X_i, K_i), (Y_i, L_i), i = 1, 2, \ldots, N$ such that each of them is a stabilizing solution to the corresponding Riccati equation in (2). Using these solutions, the optimal controller to Problem 1 can be written as $K_{opt} = [A_K, B_K, C_K]$, where $A_K, B_K, C_K$ are defined by

\begin{align}
A_K &= I \otimes A + \text{diag}\{L_1 C_{11}, \ldots, L_N C_{NN}\} \\
B_K &= \zeta \text{diag}\{B_1 K_1, \ldots, B_N K_N\} \\
C_K &= \text{row}\{E_1 K_1, \ldots, E_N K_N\}.
\end{align}

Moreover, the optimal value of Problem [1] can be written as $J_{opt}^2 = J_{cnt}^2 + J_{d cnt}^2$ where

\begin{align}
J_{cnt}^2 &= tr W^T X_1 W + tr \Psi K_1 Y_N K_1^T \\
J_{d cnt}^2 &= \sum_{i=1}^{N-1} \text{tr}(H K_1 - H^{i+1} K_{i+1}) Y_i (H K_1 - H^{i+1} K_{i+1})^T.
\end{align}

Note that $J_{cnt}$ can be interpreted as the optimal cost when the controller is designed without information constraints (compare with the result of standard $H_2$ control). The price to pay to impose information constraints as in Fig. [1] is precisely given by $J_{d cnt}$. The optimal controller given in Theorem [1] turns out to be a certainty equivalent controller. That is, if $col\{x_1(t), \ldots, x_N(t)\}$ is the state of the optimal controller, then $x_i(t)$ can be interpreted as the least mean square estimate of $x(t)$ based on the observations of outputs of upstream subsystems (see Appendix C). Nevertheless, as Fig. [2] shows, controller and observer gain must be jointly designed when $N \geq 2$. The well-known separation principle holds only in an exceptional circumstance of $N = 1$, where controller and observer gains can be designed separately.

III. COUPLED RICCATI EQUATIONS

Since the proof of optimality of the proposed controller is closely related to the solvability of the set of Riccati equations [2], we study its solution procedure in this section. We introduce the following partitioning of unknown matrices $X_i, Y_i, K_i$ and $L_i$ for every $i \in \{1, 2, \ldots, N\}$:

\begin{align}
X_i &= \begin{bmatrix} \hat{X}_i^T & \tilde{X}_i \end{bmatrix}, \quad K_i = \begin{bmatrix} \hat{K}_i & \tilde{K}_i \end{bmatrix}, \\
Y_i &= \begin{bmatrix} \hat{Y}_i & \tilde{Y}_i \end{bmatrix}, \quad L_i = \begin{bmatrix} \hat{L}_i & \tilde{L}_i \end{bmatrix},
\end{align}

where $\hat{X}_i = (X_i)_{11}^i$, $\hat{Y}_i = (Y_i)_{11}^i$, $\hat{K}_i = K_i E_i^{i+1}$, $\hat{L}_i = E_i L_i$. In particular, $X_1 = \hat{X}_1, K_1 = \hat{K}_1$ and $Y_N = \hat{Y}_N, L_N = \hat{L}_N$. Matrices $\hat{K}_i$ and $\hat{L}_i$ are further partitioned as
This diagram illustrates the order in which controller/observer gains are determined when \( N = 3 \). Suppose \( K_{i,j} \) is the \( i \)-th player’s controller gain acting on his state estimate of \( x_j \) (i.e., \( K_i = \text{row}\{K_{1,i}, K_{2,i}, K_{3,i}\} \)). Similarly, suppose \( L_{i,j} \) is the \( i \)-th player’s estimator gain to update his state estimate of \( x_j \) (i.e., \( L_i = \text{col}\{L_{1,i}, L_{2,i}, L_{3,i}\} \)). The solution process starts by solving (2a) to generate \( K_{1,1}, K_{1,2}, K_{1,3} \). This recursively allows one to solve for \( K_{2,2}, K_{2,3} \) and then for \( K_{3,3} \). Estimator gains can be also found by first solving (2b) and then proceed backward on the chain. Finally, the remaining gains (in the dotted line) is computed at once by solving a system of linear equations. This procedure is a natural extension of the case of \( N = 2 \) reported in [4].

Equation (2b) can be written as

\[
\begin{align*}
A_{i,k-1}^{KL} &= A_i^{KL} + B_i^{KL} \hat{K}_i, \\
A^K &= A^{KL} + B^{KL} \hat{K}_i
\end{align*}
\]

where \( \Sigma_i = (H^{i+1}K_i - H^{i+1}K_i^{-1})^T (H^{i+1}K_i - H^{i+1}K_i^{-1}) \) and (2d) is rearranged as

\[
\begin{align*}
A_{i+1}^{KL}Y_i + Y_iA_{i+1}^{KL} + \Pi_i &= 0, \\
\Phi_i^{KL}L_i^T + C_iY_i - \Psi_i^{KL}L_i^T &= 0
\end{align*}
\]

where \( \Pi_i = (L_iV_i - L_iV_i^{-1}V_i)T (L_iV_i - L_iV_i^{-1}V_i) \). Now, all unknown variables can be determined by the following three-step procedure, which also visualized in Fig. 3.

**Step 1: Sequential solving of Riccati subequations**

In this step, sub-matrices indicated by “•” in (4) are determined. Notice that \( X_i, X_i, Y_i, L_i, L_i \) are directly obtained by solving (2a) and (2c). To compute \( \hat{K}_i, \hat{K}_i \) for \( i \in \{2, 3, \ldots, N\} \), focus on the lower-right (\( \Psi_i^{KL} \)) sub-block of (5a) and (\( \Delta_i^{HL} \)) sub-block of (5b). They are by themselves Riccati equations with respect to \( (\hat{X}_i, \hat{K}_i) \):

\[
(\hat{X}_i, \hat{K}_i) = ARE_p(A_i^{KL} + B_i^{KL} - H_i^{il-1}K_i^{il-1}, H_i^{il}).
\]

Since the right hand side contains \( \hat{K}_i^{il-1} \), these Riccati equations need to be solved in the forwarding (ascending) order on the chain. Similarly, \( \hat{Y}_i, \hat{L}_i \) for \( i \in \{1, 2, \ldots, N-1\} \)

\[
\begin{align*}
\hat{Y}_i, \hat{L}_i &= ARE_p(A_i^{KL} + B_i^{HL}K_i^{il-1}, H_i^{il}).
\end{align*}
\]

Since the right hand side contains \( \hat{K}_i^{il-1} \), these Riccati equations need to be solved in the forwarding (ascending) order on the chain. Similarly, \( \hat{Y}_i, \hat{L}_i \) for \( i \in \{1, 2, \ldots, N-1\} \)

\[
\begin{align*}
\hat{Y}_i, \hat{L}_i &= ARE_p(A_i^{KL} + B_i^{HL}K_i^{il-1}, H_i^{il}).
\end{align*}
\]
When \( N = 2 \), it is shown in [4] that the linear system \( \mathcal{L} \) admits a unique solution under Assumption [1] and thus Assumption [2] is unnecessary. It must be addressed in the future whether this generalizes to \( N > 2 \). Our numerical studies indicate that, when problem data is randomly generated to satisfy Assumption [1][9] is usually a well-conditioned linear system.

C. Step 3: Solving Lyapunov equations

Finally, \( \tilde{X}_i \) for \( i \in \{2, 3, \ldots, N\} \) and \( \tilde{Y}_i \) for \( i \in \{1, 2, \ldots, N-1\} \) are computed by looking at \( (\mathcal{L})_i^{N-1} \) sub-block of (5a) and \( (\mathcal{L})_{i+1}^{N+1} \) sub-block of (6a).

\[
\tilde{A}^L_i T \tilde{X}_i + \tilde{X}_i \tilde{A}^L_i + \tilde{A}^L_{i-1} T \tilde{X}_i + \tilde{X}_i \tilde{A}^L_{i-1} - \tilde{K}_i T \tilde{K}_i^T + \text{row}(\tilde{K}_{i-1}, \tilde{K}_i^a) \tilde{K}_i^{-1} \text{row}(\tilde{K}_{i-1}, \tilde{K}_i^a) = 0
\]

\[
\hat{K}^+ \hat{Y}_i + \hat{Y}_i \hat{K}^+ T + \tilde{K}^+ \hat{Y}_i + \hat{Y}_i \tilde{K}^+ T - \hat{L}_i \hat{L}_i^T + \text{col}(\hat{L}_{i-1} \hat{L}_i^T) \hat{L}_i^T \text{col}(\hat{L}_{i-1} \hat{L}_i^T) = 0
\]

Since all other quantities are known by the previous step, these are Lyapunov equations with respect to \( \tilde{X}_i \) and \( \tilde{Y}_i \), which can be easily solved. Since \( \tilde{A}^K \) and \( \tilde{A}^L \) are Hurwitz stable (guaranteed by Proposition [1]), they admit a unique solution.

**Proposition 2:** Under Assumption [1] and [2] the set of algebraic Riccati equations (2) admit a unique tuple of positive semidefinite solutions \( X_i, Y_i \), \( i \in \{1, 2, \ldots, N\} \). Moreover, they are stabilizing solutions.

**Proof:** It is clear from Theorem [5] that (2a) and (2c) admit unique positive semidefinite solutions which are stabilizing. To see why solutions constructed in Step 1, 2 and 3 above are positive semidefinite, notice that under Assumption [1] and [2] the algorithm produces a unique set of variables satisfying (5a) and (6a). Furthermore, notice that

\[
A_{i,i-1}^{KL} = \begin{bmatrix} A_i^L & A_i^{-1} & B_i^T K_i & C_i^T L_i^{-1} & 0 \\ A_i^{-1} & B_i^T K_i & C_i^T L_i^{-1} & 0 & A_i \\ \end{bmatrix}
\]

is a stable matrix since its diagonal blocks are stable. Hence, due to the inertia property of a Lyapunov equation, \( X_i \) and \( Y_i \) must be positive semidefinite. They are indeed stabilizing solutions since \( A_{i,i-1}^{KL} \) is a stable matrix.

IV. DERIVATION OF MAIN RESULT

A. Stability

Notice that the closed-loop transfer function is given by

\[
G^c = \begin{bmatrix} G_{11}^c & G_{12}^c \\ G_{21}^c & G_{22}^c \end{bmatrix} = \begin{bmatrix} A & W \\ F & 0 \\ 0 & H \end{bmatrix} = \begin{bmatrix} A_K & B_K C \\ B_K & 0 \\ 0 & 0 \end{bmatrix}.
\]

\[
S_{0,1} \subset S_{0,2} \subset \cdots \subset S_{0,N} \subset S_{0,N+1} \quad \in \quad \cup \quad \cup \quad \cup \quad \cup 
\]

\[
S_{1,1} \subset S_{1,2} \subset \cdots \subset S_{1,N} \subset S_{1,N+1} \quad \in \quad \cup \quad \cup \quad \cup \quad \cup 
\]

\[
S_{2,2} \subset \cdots \subset S_{2,N} \subset S_{2,N+1} \quad \in \quad \cup \quad \cup \quad \cup \quad \cup 
\]

\[
\vdots
\]

\[
S_{N,N} \subset S_{N,N+1} \quad \in \quad \cup \quad \cup \quad \cup \quad \cup 
\]

To see that \( K_{opt} \) is a stabilizing controller, we need to verify that \( \mathcal{A} \) is a stable matrix. Let \( \zeta \) be an \( n(N+1) \)-dimensional square matrix whose \((i,j)\)-th sub-block is \( I_n \) if \( i \geq j \) and is zero otherwise. Also define \( \mu = \zeta^{-1} \). One can easily check that a similarity transformation gives

\[
\mu A \mu = \begin{bmatrix} A_{1,0}^{KL} & * & * & * \\ A_{2,1}^{KL} & * & * & * \\ \vdots & \ddots & \ddots & \ddots \\ A_{N,N-1}^{KL} & * & * & A_{N,N+1,1}^{KL} \end{bmatrix}.
\]

This is a block upper-triangular matrix. Moreover, all diagonal blocks are stable matrices as we saw in the proof of Proposition [2]. This shows the stability of \( \mathcal{A} \).

B. Optimal Controller Characterization

If \( K_{opt} \) is the optimal solution to Problem [1] then any perturbation \( K = K_{opt} + K' \) such that \( K' \in \mathcal{I}_{LB} \) only degrades control performance. Due to the uniqueness of the rational solution to Problem [1] it is sufficient for us to show that \( K' = 0 \) is the optimal solution to the modified \( H_2 \) optimal control problem

\[
\min \| G_{11}^c + G_{12}^c K' (I - G_{22}^c K')^{-1} G_{21}^c \| \\
\text{s.t. } K' \text{ is stabilizing and } K' \in \mathcal{I}_{LB}.
\]

Since \( G_{22}^c \in H_2 \cap \mathcal{I}_{LB} \), the subspace \( \mathcal{I}_{LB} \) is quadratically invariant under \( G_{22}^c \). This means that all stabilizing controllers are parametrized by the structured Youla parameter \( \mathcal{Q} = -K' (I - G_{22}^c K')^{-1} \in H_\infty \cap \mathcal{I}_{LB} \). Hence, the above statement is equivalent to that \( \mathcal{Q} = 0 \) is the optimal solution to the model matching problem

\[
\min \| G_{11}^c - G_{12}^c \mathcal{Q} G_{21}^c \| \\
\text{s.t. } \mathcal{Q} \in H_2 \cap \mathcal{I}_{LB}.
\]

Since the non-rectangular constraint \( \mathcal{I}_{LB} \) is inconvenient to work with, we use an alternative characterization of the same statement using rectangular blocks \( \mathcal{I}_{LB}^i, i \in \{1, 2, \ldots, N\} \).

\[\text{The condition } \mathcal{Q} \in H_\infty \cap \mathcal{I}_{LB} \text{ can be replaced by } \mathcal{Q} \in H_2 \cap \mathcal{I}_{LB} \text{ without loss of generality. Recall that under Assumption [1] } H \text{ has full column rank, } V \text{ has full row rank, and } G_{21}^c \in H_2. \text{ This means that } \mathcal{Q} \text{ must be in } H_2 \text{ so that the value of (18) is bounded.} \]
projection step can be associated with one of
tions is convenient in the following presentation, since each
using an “orthonormal” basis. Recall that a rational function
According to Fig. 4, Theorem 2 suggests that
π
\[ \pi_i \equiv \text{row}(0, \ldots, 0, E^{i+1}_1 K_{i+1} - E^{i+1}_i K_i, \ldots, E^{i+1}_N K_N - E^{i+1}_N K_{N-1}, -E^{i+1}_N K_N , \ldots, -E^{i+1}_i K_i) \] (13)
\[ \mathcal{L}_j \equiv \text{col}(L_j E^{(j-1)}_1, \ldots, L_j E^{(j-1)}_i, \ldots, L_j E^{(j-1)}_j, L_j E^{(j-1)}_j) \} E^{(j)}_j \] (14)
\[ \tilde{\mathbf{J}}_i \equiv \text{row}(0, \ldots, 0, \mathbf{I}, \ldots, 0, \mathbf{I}) \} \] (15)

Proposition 3: \( Q = 0 \) is the optimal solution to (18) if
and only if for every \( i \in \{1, 2, \ldots, N\} \), \( Q_i = 0 \) is the optimal solution to the model matching problem
\[
\min_{Q_i} \| G_{i1}^{cl} - G_{i2}^{cl} Q_i G_{21}^{cl} \| 
\] s.t. \( Q_i \in H_2 \cap T_{i1}^{cl} \). (19)

One approach to find a solution to the model matching problem [19] is to apply the projection theorem [5]. Define subspaces \( S_{i,j} \) of \( H_2 \) for the projections
\[ S_{i,j} \equiv \{ G_{i2}^{cl} E_i^{cl} Q E_j^{cl} G_{21}^{cl} : Q \in H_2 \}. \] (20)

Proposition 3 implies that, in order to infer that \( K_{opt} \) is the optimal controller, it suffices to prove that \( Q = 0 \) is the minimizer of \( \| G_{i1}^{cl} - G_{i2}^{cl} E_i^{cl} Q E_j^{cl} G_{21}^{cl} \| \) over \( Q \in H_2 \) for every \( i \in \{1, 2, \ldots, N\} \). Equivalently, it needs to be shown that \( \pi_{S_{i,j}}(G_{i1}^{cl}) = 0 \) for every \( i \in \{1, 2, \ldots, N\} \), where \( \pi_{S_{i,j}} : H_2 \rightarrow S_{i,j} \) is the projection operator.

C. Nested Projections

It is clear that the inclusion relations in Fig. 4 hold among subspaces defined by (20). We are going to exploit this diagram to find an explicit representation of \( \pi_{S_{i,j}}(G_{i1}^{cl}) \). Recall the following fact:

Theorem 2: (Nested Projections, see e.g., [6]) Let \( S_1, S_2, \ldots, S_N \) be subspaces of a Hilbert space such that \( S_N \subset S_{N-1} \subset \cdots \subset S_2 \subset S_1 \). Then \( \pi_{S_N} = \pi_{S_{N-1}} \circ \cdots \circ \pi_{S_2} \circ \pi_{S_1} \).

According to Fig. 4, Theorem 2 suggests that \( \pi_{S_{i,j}} \) can be computed as, for instance,
\[
\pi_{S_{i,j}} = \pi_{S_{i,1}} \circ \pi_{S_{i+1,2}} \cdots \circ \pi_{S_{N-i,N}} \pi_{S_{i-N,1}} \cdots \circ \pi_{S_{1,N}}. \] (21)

Understanding \( \pi_{S_{i,j}} \) as a composition of stepwise projections is convenient in the following presentation, since each projection step can be associated with one of 2N Riccati equations in [2]. To be precise, we consider writing \( S_{i,j} \) using an “orthonormal” basis. Recall that a rational function
\[ U \in H_\infty \] is said to be inner if \( U^* U = I \) and co-inner if \( U U^* = I \). It turns out that each subspace can be written as
\[ S_{i,j} = \{ U_1 \cdots U_i M_i^{-1} Q N_j^{-1} V_j \cdots V_N : Q \in H_2 \} \] (22)
where the explicit form of inner functions \( U_1, \cdots, U_N \), co-inner functions \( V_1, \cdots, V_N \) and other necessary quantities are given in (13)-(17). The above expression is obtained by repeated applications of a particular type of spectral factorizations (Lemma 3 in Appendix D). Each application of the factorization requires a solution to one of the Riccati equations in (2).

Writing \( S_{i,j} \) in the form of (22) makes nested projections easier. Suppose that the projection of \( G_{i1}^{cl} \) onto \( S_{i,j} \) can be written in the form of
\[ \pi_{S_{i,j}}(G_{i1}^{cl}) = U_1 \cdots U_i \tilde{\mathbf{P}}_i V_j \cdots V_N \in S_{i,j} \] for some \( \tilde{\mathbf{P}}_i \). Then it is easy to check that the subsequent projection is given by
\[ \pi_{S_{i+1,j}}(G_{i1}^{cl}) = U_1 \cdots U_i \tilde{\mathbf{P}}_i V_j \cdots V_N \in S_{i+1,j} \] where \( \tilde{\mathbf{P}}_{i+1} \) is chosen to satisfy the optimality condition
\[ \left\langle U_{i+1}^* \tilde{\mathbf{P}}_i - \tilde{\mathbf{P}}_{i+1}, M_i^{-1} Q N_j^{-1} V_j \cdots V_N \right\rangle = 0 \] \( \forall Q \in H_2 \).

Details can be found in Lemma 3 in Appendix D. Also, notice that every projection generates a “residual term” as
\[ \pi_{S_{i,j}}(G_{i1}^{cl}) = \pi_{S_{i,j}}(G_{i1}^{cl}) + U_1 \cdots U_i R_{i,(i+1)} \cdots R_{(i+1),j} V_j \cdots V_N \]
\[ \pi_{S_{i,j}}(G_{i1}^{cl}) = \pi_{S_{i,j}}(G_{i1}^{cl}) + U_1 \cdots U_i R_{(i+1),(i+1)} \cdots R_{(i+1),j} V_j \cdots V_N \]

The \( H_2 \) norm of residual terms will be used later to compute the optimal value of Problem 1. Finally, all the above operations can be performed at the state space level, as summarized in Lemma 1.
Lemma 1: The projection of $G_{11}^{cl}$ onto any subspace $S_{i,j}$ in Fig. 2 is given by $\pi_{S_{i,j}}(G_{11}^{cl}) = U_i U_2 \cdots U_{i-1} V_j \cdots V_{N-1} V_N$ where

$$P'_{i,j} = \begin{bmatrix} A & \Lambda_j \end{bmatrix} \Gamma_i$$

(25)

$$\Gamma_i = \begin{cases} \mathcal{F} & \text{if } i = 0 \\
\Psi_{i+1}^{2} & \text{if } 1 \leq i \leq N-1 \\
l_{2,i} & \text{if } i = N \\N \end{cases}, \quad \Lambda_j = \begin{cases} \mathcal{W} & \text{if } j = N+1 \\
\tilde{L}_2 & \text{if } 1 \leq j \leq N \\N \end{cases}$$

Moreover,

$$R_{(i-1,j)\rightarrow(i,j)} = \begin{bmatrix} A_{KL}^{i+1,i} & -\tilde{J}_i \Lambda_j \\
\tilde{V}_i & \tilde{G}_i \end{bmatrix}$$

$$R_{(i,j+1)\rightarrow(i+1,j)} = \begin{bmatrix} A_{KL}^{i+1,i} & B_{V_N} \\
\tilde{V}_i & \tilde{G}_i \end{bmatrix}$$

Proof: See Appendix D.

V. Conclusion and Future Work

In this paper, we have presented a state-space realization of the optimal output feedback controller for the $N$-player triangular LQG problem. We have derived a set of algebraic Riccati equations to be solved to construct the optimal controller. Solvability of Riccati equations, namely non-singularity of the linear system (9), must be verified in the future work.

References


A. Quadratic Invariance and Convexity

This section gives a brief review of the notion of Quadratic Invariance and how an optimal control problem can be formulated as an infinite dimensional convex optimization problem. For brevity, our discussion here is rather informal; for a thorough introduction, readers are referred to [7]. The $H_2$ optimal control formulated in Problem 1 is a nonconvex optimization problem respect to $K$. A natural approach is to introduce the Youla parametrization, which has been historically used to convexify central control problems. Youla parameterization is particularly simple if $G$ is stable, and is given by $Q = -K(I - G_{22}K)^{-1}$. The inverse in this expression is guaranteed to exist on the domain of stabilizing spaces. Suppose that $Q_{\text{stabilizing}}$ is translated in the new domain as the requirement $Q$, and is given by $Q = -K(I - G_{22}K)^{-1}$. The inverse in this expression is guaranteed to exist on the domain of stabilizing $K$ by the generalized Nyquist criterion [11]. Conversely, the corresponding controller $K$ can be recovered from $Q$ by $K = -(I - QG_{22})^{-1}Q$. The objective function is expressed as $\|G_{11} - G_{12}QG_{21}\|_2^2$, which is clearly convex with respect to the new parameter $Q$. Moreover, the requirement that $K$ is stabilizing is translated in the new domain as the requirement that $Q$ is stable (i.e., $Q \in H_\infty^2$) which is also a convex constraint. The information constraint $K \in \mathcal{I}$, however, results in a nonconvex constraints on the $Q$ domain, unless $\mathcal{I}$ is quadratically invariant under $G_{22}$.

**Definition 1:** (Quadratic Invariance) Let $\mathcal{U}, \mathcal{Y}$ be vector spaces. Suppose $G$ is a linear mapping from $\mathcal{U}$ to $\mathcal{Y}$ and $\mathcal{I}$ is a set of linear maps from $\mathcal{Y}$ to $\mathcal{U}$. Then $\mathcal{I}$ is called quadratically invariant under $G$ if $K \in \mathcal{I} \Rightarrow KG \in \mathcal{I}$.

The significance of $\mathcal{I}$ being quadratically invariant is that, the condition $K \in \mathcal{I}$ can be translated to $Q \in \mathcal{I}$ on the new domain, which is a convex constraint.

Since we are considering triangular LQG problems in this paper, $G_{22}$ has a lower block triangular structure ($G_{22} \in \mathcal{I}_{LBT}$), while the information constraint on the controller implies that the controller transfer function is also lower block triangular ($K \in \mathcal{I}_{LBT}$). It is easy to verify that the space of transfer function matrices with sparsity pattern $\mathcal{I}_{LBT}$ is indeed quadratically invariant under $G_{22}$. Therefore, Problem 1 can be recast as the following infinite dimensional convex optimization problem.

$$\min \|G_{11} - G_{12}QG_{21}\|_2^2 \quad \text{s.t.} \quad Q \in H_\infty \cap \mathcal{I}_{LBT}. \quad (26a)$$

An optimization problem of this form is called the model matching problem.

This fact can be understood from the following informal observation: if $K \in \mathcal{I}$ and $\mathcal{I}$ is QI under $G_{22}$, the Neumann series expansion gives

$$Q = -K(I - G_{22}K)^{-1} = -K - KG_{22}K - K(G_{22}K)^2 - \cdots.$$

Since we can inductively show that every term in the last expression belongs to $\mathcal{I}$, $Q \in \mathcal{I}$.

If $G_{22}$ is not stable, Youla parameter must be constructed using coprime factors of $G_{22}$ [13]. In this case, parametrization of stabilizing controllers subject to the information constraint is more involved. Nevertheless, if $\mathcal{I}$ is quadratically invariant under $G_{22}$, the information constraints can be recast as linear constraints on the Youla parameter [9]. Therefore, even in this case, the optimal $H_2$ control problem subject to information constraints can be reformulated as a convex optimization problem.

B. Centralized $H_2$ Optimal Control

Assume that $A$ is a Hurwitz matrix and that $G_{11} \in H_2$. In this case, the optimal solution $Q$ to the $H_2$ model matching problem (26) must be in $H_2$, since otherwise $\|G_{11} - G_{12}QG_{21}\|$ is unbounded under Assumption 1. Hence the centralized $H_2$ optimal control problem can be cast as a simple $H_2$ model matching problem

$$\min \|G_{11} - G_{12}QG_{21}\| \quad \text{s.t.} \quad Q \in H_2. \quad (27a)$$

One approach to find a solution to the model matching problem is to apply the projection theorem [5]. Let $H$ be a Hilbert space and $S$ be a closed nonempty subspace of $H$. If $a \in H$, then there exists an element $x_0 \in S$ such that $\|a - x_0\| \leq \|a - x\|$ for all $x \in S$. Such an element $x_0$ is called a projection of $a$ onto $S$, and is denoted by $x_0 = \pi_S(a)$. It can be shown that $x_0 = \pi_S(a)$ if and only if $x_0 \in S$ and $\langle a - x_0, x \rangle = 0$ for all $x \in S$.

In the model matching problem (27), a set $S \setminus \{G_{12}QG_{21} : Q \in H_2\}$ defines a closed nonempty subspace of $H_2$. Hence the optimal solution to (27) can be found by computing a projection of $G_{11}$ onto $S$. To this end, a coprime factorization technique of rational functions, particularly the inner-outer factorization, is useful. We first recall the following facts. Proofs can be found in [14].

**Theorem 3:** Suppose $(A, B)$ is stabilizable, $H$ has full column rank, and

$$[A - j\omega I \quad B \quad F \quad H]$$

has full column rank for all $\omega \in \mathbb{R}$. Then algebraic Riccati equation $(X, K) = ARE_p(A, B, F, H)$ has a unique positive semidefinite solution. Moreover, it is stabilizing (that is, $A_{cl} \equiv A + BK$ is a Hurwitz stable matrix).

**Theorem 4:** (Right Inner-Outer Factorization)

Assume $G_{12} = [A \quad B \quad F \quad H]$ is stabilizable and

$$[A - j\omega I \quad B \quad F \quad H]$$

has full column rank for all $\omega \in \mathbb{R}$. Then there exists a right coprime factorization $G_{12} = UM^{-1}$ such that $U$ is inner and $M$ is stably invertible. A particular realization of such factorization is

$$U = [A + BK \quad B \Psi^{-\frac{1}{2}} \quad F + HK \quad H\Psi^{-\frac{1}{2}}], \quad M^{-1} = [A \Psi^{-\frac{1}{2}} K \quad B \Psi^{-\frac{1}{2}}]$$

where $\Psi = H^TH$ and $(X, K) = ARE_p(A, B, F, H)$.

(2). (Left Inner-Outer Factorization)
Assume \( G_{21} = \begin{bmatrix} A & W \\ C & V \end{bmatrix} \) is detectable and
\[
\begin{bmatrix}
A - j\omega I & W \\
C & V
\end{bmatrix}
\]
has full row rank for all \( \omega \in \mathbb{R} \). Then there exists a left coprime factorization \( G_{21} = N^{-1}_i V \) such that \( V \) is co-inner and \( N \) is stably invertible. A particular realization of such factorization is
\[
V = \begin{bmatrix} A + LC & W + LV \\ \Phi^{-\frac{1}{2}}C & \Phi^{-\frac{1}{2}}V \end{bmatrix}, \quad N^{-1} = \begin{bmatrix} A & -L\Phi^{-\frac{1}{2}} \\ C & \Phi^{-\frac{1}{2}} \end{bmatrix}
\]
where \( \Phi = VV^T \) and \( (Y, L) = ARE_p(A, C, W, V) \).

Using \( U \) and \( V \), the subspace \( S \) can be expressed as
\( S = \{UPV : P \in H_2\} \), where \( P = M^{-1}QN^{-1} \) is a new parameter. Since \( M \) and \( N \) are stably invertible, requiring that \( Q \in H_2 \) is equivalent to requiring \( P \in H_2 \).

Suppose the projection of \( G_{11} \) onto \( S \) can be written as \( UPV \). By the optimality condition \( \langle G_{11} - UPV, UPV \rangle = 0 \) \( \forall P \in H_2 \), one obtains
\[
U^*G_{11}V^* = P' \in H_2^+. \quad \text{Hence it must be that} \quad P' = \pi_{H_2}(U^*G_{11}V^*).
\]
Moreover, straightforward state space manipulations show that
\[
P' = \pi_{H_2}(U^*G_{11}V^*) = \begin{bmatrix} A & -L\Phi^{-\frac{1}{2}} \\
-\Phi^{-\frac{1}{2}}K & 0 \end{bmatrix}.
\]
From this result, one can recover the optimal centralized \( H_2 \) controller.

\[
K_{opt} = \begin{bmatrix} A + BK + LC & -L \\ K & \end{bmatrix}.
\]

It is also possible to show that the optimal control performance is
\[
J_{cent} = \text{tr}(W^TW) + \text{tr}(\Psi KYK^T).
\]

C. Proof of Proposition \cite{1}

By Theorem 3 \( (X_1, \hat{K}_1) = ARE_p(A, B, F, H) \) has a unique positive semidefinite solution that is also stabilizing; in particular \( A^{1+i} + B^{1+i}\hat{K}_1 \) is stable. Thus it suffices to show that if \( A^{1+i} + B^{1+i}\hat{K}_1 \) is stable for some \( i \in \{1, 2, \cdots, N-1\} \), then the algebraic Riccati equation
\[
\tilde{X}_{i+1}, \hat{K}_{i+1} = ARE_p(A^{1+i+1}, B^{1+i+1}, -H^{1+i}\hat{K}_i, H^{1+i+1})
\]
has a unique positive semidefinite solution that is also stabilizing. Since \( (A^{1+i+1}, B^{1+i+1}) \) is stabilizable by Assumption \[1\] by Theorem 3 the only way that \( (30) \) fails to have a unique positive semidefinite solution is that
\[
\begin{bmatrix} A^{1+i+1} - j\omega I & B^{1+i+1} \\
-H^{1+i}\hat{K}_i & H^{1+i+1} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = 0
\]
for some \( \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \neq 0 \). Notice that \( z_1 \) cannot be zero as this implies \( z_2 \) is also zero due to the assumption that \( H^{1+i+1} \) has full column rank. Introducing \( \tilde{z}_1 = \begin{bmatrix} 0 \\ z_1 \end{bmatrix} \), \( \tilde{z}_2 = \begin{bmatrix} 0 \\ z_2 \end{bmatrix} \), we have
\[
\begin{bmatrix} A^{1+i} - j\omega I & B^{1+i} \\
-H^{1+i}\hat{K}_i & H^{1+i} \end{bmatrix} \begin{bmatrix} \tilde{z}_1 \\ \tilde{z}_2 \end{bmatrix} = 0. \quad \text{Left-multiplied by}
\]
\[
\begin{bmatrix} I & -B^{1+i}(\Psi_{i+1}^{-1})H^{1+i} \end{bmatrix}, \quad \text{this reduces to}
\]
\[
\begin{bmatrix} A^{1+i} + B^{1+i}\hat{K}_i \end{bmatrix} \tilde{z}_1, \quad \tilde{z}_1 \neq 0. \quad \text{However, this contradicts that stability of}
\]
\[
A^{1+i} + B^{1+i}\hat{K}_i. \quad \text{This shows that} \quad \text{has a unique positive}
\]
semidefinite and stabilizing solution for all \( i \in \{2, \cdots, N\} \). A similar argument can be applied to \( \hat{K}_i \) as well.

D. Proof of Lemma \cite{7}

Lemma 2: (1). For every \( i \in \{1, 2, \cdots, N\} \), \( U_i \) is an inner function and \( G_{21}^{cr}E^{1+i} = U_iU_{i+1} \cdots U_iM_i^{-1} \). (2). For every \( j \in \{1, 2, \cdots, N\} \), \( V_j \) is a co-inner function and \( E_{2j}G_{2j}^{cr} = N^{-1}_jV_jV_{j+1} \cdots V_N \).

Proof: (1). When \( i = 1 \),
\[
U_iM_i^{-1} = \begin{bmatrix} A_{i,i-1}^{KL} & -B^{1+i}\hat{K}_i & B^{1+i} \\ 0 & A & \Psi_{i-1}^{1+i}E^{1+i}K_i \\ C_{i,1} & 0 & 0 \end{bmatrix}
\]
\[
= \begin{bmatrix} A_{i,i-1}^{KL} & 0 & 0 \\ 0 & A & B^{1+i} \\ C_{i,1} & -\Psi_{i-1}^{1+i}K_{i-1} & \Psi_{i-1}^{1+i}E^{1+i} \\ 0 & A & \Psi_{i-1}^{1+i}E^{1+i} \\ 0 & 0 & 0 \end{bmatrix} = M_{i-1}^{-1}E^{1+i}_i.
\]

From the first to the second expression, a similarity transformation was applied by multiplying the state space “A” matrix by
\[
\begin{bmatrix} I & \tilde{J}_i \\ 0 & I \end{bmatrix}
\]
from the left and by its inverse from the right.

The fact that \( K_1 \) is a solution to \( (28) \) is exploited to obtain “0” at the upper-right corner of the state space “A” matrix.

The last step was obtained by eliminating uncontrollable states. When \( i \in \{2, 3, \cdots, N\} \),
\[
U_iM_i^{-1} = \begin{bmatrix} A_{i,i-1}^{KL} & -B^{1+i}\hat{K}_i & B^{1+i} \\ 0 & A & \Psi_{i-1}^{1+i}E^{1+i}K_i \\ 0 & A & 0 \end{bmatrix}
\]
\[
= \begin{bmatrix} A_{i,i-1}^{KL} & 0 & 0 \\ 0 & A & B^{1+i} \\ 0 & \Psi_{i-1}^{1+i}K_{i-1} & \Psi_{i-1}^{1+i}E^{1+i} \\ 0 & A & \Psi_{i-1}^{1+i}E^{1+i} \\ 0 & 0 & 0 \end{bmatrix} = M_{i-1}^{-1}E^{1+i}_i.
\]

From the first to the second expression, a similarity transformation was applied by multiplying by
\[
\begin{bmatrix} I & \tilde{J}_i \\ 0 & I \end{bmatrix}
\]
from the left and by its inverse from the right. Combining the above results, one obtains \( G_{21}^{cr}E^{1+i} = U_iU_{i+1} \cdots U_iM_i^{-1} \). To see that \( U_i \) is inner, notice that
\[
A_{i,i-1}^{KL}T_{i-1}X_i + X_iA_{i,i-1}^{KL} + CT_{i-1}C_iU_i = 0
\]
\[
D_i^TU_{i-1}C_i + B_i^TX_i = 0
\]
follows from \( (5) \). Since \( D_i^T, D_i = I \), by Corollary 13.30 in [14], \( U_i \) is an inner function.

(2). When \( j = N \),
\[
N^{-1}_NV = \begin{bmatrix} A & -LNC & -LNC \\ 0 & A_{N-1,N} & W + LN \end{bmatrix}
\]
\[
= \begin{bmatrix} A & 0 & 0 \\ 0 & A_{N-1,N} & W + LN \end{bmatrix} = G_{21}^{cr}.
\]

From the first to the second expression, a similarity transformation was applied by multiplying the state space “A” matrix
by \[ \begin{bmatrix} I & \tilde{J}_N \\ 0 & I \end{bmatrix} \] from the left and by its inverse from the right. The last step was obtained by eliminating unobservable states. When \( j \in \{1, 2, \cdots, N-1\} \),

\[
N_j^{-1}V_j = \begin{bmatrix}
A & -L_j C_{t,j} & -L_j E_{t,j} E_{t,j+1}^T \phi_{t,j+1} + \frac{1}{2} E_{t,j} E_{t,j+1}^T  \\
0 & A_{KL,j} & 0  \\
C_{t,j} & C_{t,j} & E_{t,j} E_{t,j+1}^T \phi_{t,j+1} + \frac{1}{2} E_{t,j} E_{t,j+1}^T
\end{bmatrix}
\]

\[
= \begin{bmatrix}
A & 0 & 0  \\
-\phi_{t,j+1} E_{t,j} & A_{KL,j} & 0  \\
0 & E_{t,j} E_{t,j+1}^T & E_{t,j+1}^T
\end{bmatrix}
\]

\[
= E_{t,j} E_{t,j+1}^T N_{i+1}^{-1}.
\]

From the first to the second expression, a similarity transformation was applied by multiplying by \[ \begin{bmatrix} I & J_j \\ 0 & I \end{bmatrix} \] from the left and by its inverse from the right. Combining the above results, one obtains \( E_{t,j}V_j \Sigma_j N_{i+1}^{-1} V_{j+1} \cdots V_N \). To see that \( V_j \) is co-inner, or equivalently that \( V_j^T \) is inner, notice that

\[
A_{j+1,j} Y_j + Y_j A_{j+1,j}^T + B_{V_j} B_{V_j}^T = 0
\]

follows from (6). Since \( D_{V_j} D_{V_j}^T = I \), \( V_j \) is a co-inner function.

**Lemma 3:** Let \( \Gamma_i \) and \( \Lambda_j \) be given as in Lemma 1 while \( \Gamma \) and \( \Lambda \) be any matrices. Let \( 0 \leq i < j \leq N + 1 \).

1. If \( F = U_1 \cdots U_i \tilde{P}_i V_j \cdots V_N \in S_{i,j} \) where

\[
\tilde{P}_j \triangleq \begin{bmatrix} A & \Lambda_1 \\ \Gamma & 0 \end{bmatrix},
\]

then \( \pi_{S_{i+1,j}} (F) = U_1 \cdots U_{i+1} \tilde{P}_{i+1} V_j \cdots V_N \).

2. If \( F = U_1 \cdots U_j \tilde{P}_j V_j \cdots V_N \in S_{i,j} \) where

\[
\tilde{P}_j \triangleq \begin{bmatrix} A & \Lambda_j \\ \Gamma & 0 \end{bmatrix},
\]

then \( \pi_{S_{i,j-1}} (F) = U_1 \cdots U_{i+1} \tilde{P}_{i+1} V_{j-1} \cdots V_N \).

**Proof:** (1). We show that if \( \tilde{P}_j \) is in the assumed form, then so is \( \tilde{P}_{i+1} \). By the optimality condition, \( \pi_{S_{i+1,j}} (F) \) satisfies

\[
\langle F - \pi_{S_{i+1,j}} (F), U_1 \cdots U_{i+1} M_{i+1}^{-1} Q_{i+1,j} N_{i}^{-1} V_j \cdots V_N \rangle = 0
\]

for all \( Q_{i+1,j} \in H_2 \). Hence \( \tilde{P}_{i+1} \) must satisfy

\[
\langle U_{i+1}^* \tilde{P}_{i+1} - \tilde{P}_{i+1}, M_{i+1}^{-1} Q_{i+1,j} N_{i}^{-1} \rangle = 0 \quad \forall Q_{i+1,j} \in H_2.
\]

Such \( \tilde{P}_{i+1} \) is given by \( \tilde{P}_{i+1} = \pi_{H_2} (U_{i+1}^* \tilde{P}_i) \), since in this case, the inner product of \( U_{i+1}^* \tilde{P}_i - \tilde{P}_{i+1} \in H_2 \) and \( M_{i+1}^{-1} Q_{i+1,j} N_{i}^{-1} \in H_2 \) is zero. The projection \( \pi_{H_2} (U_{i+1}^* \tilde{P}_i) \) is computed as follows. For every \( i \in \{0, 1, \cdots, N - 1\} \),

\[
U_{i+1}^* \tilde{P}_i = \begin{bmatrix} -A_{KL,i}^T & C_{\Gamma_{i+1,j}} & \Gamma_i \\ 0 & A & \Lambda \end{bmatrix}
\]

To obtain the last expression, a similarity transformation is applied to the state space matrices by left-multiplying by \[ \begin{bmatrix} I & -X_{j+1} \tilde{J}_N \\ 0 & I \end{bmatrix} \] and right-multiplying by its inverse. Notice that the Riccati equation (2a) or (2b) appears on the upper right block of the state space “\( A \)’’ matrix, and hence this component is zero. Moreover, since \( A \) is stable and \( -A_{1,0}^T \) is anti-stable, its projection onto \( H_2 \) is given by

\[
\tilde{P}_{i+1} = \pi_{H_2} (U_{i+1}^* \tilde{P}_i) = \begin{bmatrix} A & \Lambda \\ \Gamma_{i+1,j} & 0 \end{bmatrix}.
\]

(2). Similarly, we show that if \( \tilde{P}_j \) is in the assumed form, then so is \( \tilde{P}_{j-1} \). From the optimality condition, it is possible to infer that \( \tilde{P}_{j-1} = \pi_{H_2} (\tilde{P}_j V_{j-1}) \). For every \( j \in \{1, 2, \cdots, N + 1\} \),

\[
\tilde{P}_j V_{j-1}^* = \begin{bmatrix} A & \Lambda_j B_{V_{j-1}}^T \\ 0 & -A_{j,j-1}^T - C_{V_{j-1}}^T \end{bmatrix}.
\]

A similarity transformation is applied to state space matrices by left-multiplying by \[ \begin{bmatrix} I & -J_{j-1} Y_{j-1} \\ 0 & I \end{bmatrix} \] and right-multiplying by its inverse. Since \( -A_{j,j-1}^T \) is anti-stable, its projection onto \( H_2 \) is \( \tilde{P}_{j-1} = \pi_{H_2} (\tilde{P}_j V_{j-1}^*) = \begin{bmatrix} A & \Lambda_{j-1} \\ \Gamma & 0 \end{bmatrix} \).

**Proof of Lemma 1** is by induction. When \( i = 0 \) and \( j = N + 1 \), the identity (25) clearly holds since \( P_{0,N+1}^* = G_{11}^T \). So suppose (25) holds for some \( (i,j) \) such that \( 0 \leq i < j \leq N + 1 \). By the nested projection, \( \pi_{S_{i+1,j}} (G_{11}^T) = \pi_{S_{i,j+1}} (G_{11}^T) \), where

\[
F = \pi_{S_{i+1,j}} (G_{11}^T) = U_1 \cdots U_i \tilde{P}_i \cdots V_j \cdots V_N.
\]

Applying Lemma 3 (1), we have that \( \pi_{S_{i+1,j}} (G_{11}^T) = U_1 \cdots U_{i+1} \tilde{P}_{i+1} \tilde{P}_j \cdots V_j \cdots V_N \). Hence, we have verified that (25) holds for \((i+1,j)\). Similarly, by the nested projection, \( \pi_{S_{i,j+1}} (G_{11}^T) = \pi_{S_{i+1,j}} (F) \).

Applying Lemma 3 (2), we have that \( \pi_{S_{i,j+1}} (G_{11}^T) = U_1 \cdots U_i \tilde{P}_{i,j-1} \tilde{P}_j \cdots V_j \cdots V_N \). Hence, we have verified that (25) holds for \((i,j-1)\). This proves that the identity (25) holds for every subspace in Fig. 3. Finally, state space expressions for \( R_{(i,j)} \) and \( R_{(i+1,j)} \) are obtained by straightforward state space manipulations.
E. Certainty Equivalence

We verify that $x^{K_i}(t)$ can be interpreted as the least mean square estimate of $x(t)$ conditioned on the observations of outputs of upstream subsystems. In other words, if $H_{y_j} : w \mapsto y_{tj}$ and $F : w \mapsto x$ are given, a transfer function $Q_{x_j} : y_{tj} \mapsto x^{K_j}$ defined by the proposed controller minimizes $\| F - Q_{x_j} H_{y_j} \|$ over $H_2$. Notice that $H_{y_j} = E_{tj} G_{21}^c$.

$$Q_{x_j} H_{y_j} = Q_{x_j} N_j^{-1} V_j \cdots V_N$$

$$= \begin{bmatrix} A & -L_j \Phi_{tj}^{1/2} \\ \text{row}(E_j, 0) & 0 \end{bmatrix} V_j \cdots V_N.$$

To see $Q_{x_j} H_{y_j} = Q_{x_j} N_j^{-1} V_j \cdots V_N$, notice that

$$\hat{P}_j - Q_{x_j} H_{y_j} = \begin{bmatrix} A & -L_j \Phi_{tj}^{1/2} \\ \text{row}(-E_j, 0) & 0 \end{bmatrix} = \begin{bmatrix} \mu A \zeta & -\mu L_j \Phi_{tj}^{1/2} \\ \text{row}(-E_j, I) \zeta & 0 \end{bmatrix}. \quad (31)$$

The upper right block of (31) has nonzero matrices only on the first $j$ subblocks, while the first $j$ subblocks of the lower left block of (31) are all zero matrices. Since $\mu A \zeta$ is upper-triangular as observed in (12), all controllable states are not observable and (31) is identically zero. This proves $\pi_{S_{0,j}}(F) = Q_{x_j} H_{y_j}$. 

$$\text{F} = \begin{bmatrix} A & \mathcal{W} \\ \text{row}(0, \cdots, 0, I) & 0 \end{bmatrix}, \quad Q_{x_j} = \begin{bmatrix} A_K & B_K E_{tj}^{\top} \\ E_j & 0 \end{bmatrix}.$$