1 Definitions

Consider a discrete time LTI system:

\[ x_{n+1} = Ax_n + Bu_n, \quad x_0 = \xi. \]

Now suppose that we do not measure \( x_n \). Instead, consider a model in which we measure \( u_n \) and

\[ y_n = Cx_n + Du_n, \]

where \( C \in \mathbb{R}^{m \times p} \) and \( D \in \mathbb{R}^{m \times q} \); this equation is often called a read-out equation. Note that we assume that \( A \in \mathbb{R}^{p \times p}, B \in \mathbb{R}^{p \times q}, C \in \mathbb{R}^{m \times p}, \) and \( D \in \mathbb{R}^{m \times q} \) are known. We have two related definitions. The LTI system with pair \((C,A)\) is:

1. **observable** if and only if given values of \( u_n \) and \( y_n \) for \( n = 0, \ldots, p - 1 \), we can uniquely determine \( x_0 \);

2. **detectable** if and only if given values of \( u_n \) and \( y_n \) for \( n = 0, \ldots, p - 1 \), we can determine an estimate \( \hat{x}_n \) such that \( \|x_n - \hat{x}_n\| \to 0 \).

These definitions are related because if an LTI system is observable, then it is also detectable. The converse is not true: There are detectable LTI systems that are not observable. Also not that we made these definitions only with respect to the pair \((C,A)\) and not \( B \) or \( D \). We can remove the effect of \( D \) by considering a model \( \tilde{y}_n = y_n - Du_n = Cx_n \). And because \( x_n = A^n x_0 + \sum_{k=0}^{n-1} A^{n-k-1} Bu_k \), we can subtract out the \( B \) by defining \( \tilde{y}_n = \tilde{y}_n - C \sum_{k=0}^{n-1} A^{n-k-1} Bu_k = CA^n x_0 \). Lastly, note that these definitions do not say anything about boundedness of the states. We could in fact have that \( \|x_n\| \to \infty \).

2 Conditions

There is a duality between controllability (stabilizability) and observability (detectability). A pair \((C,A)\) is observable if and only if the pair \((A',C')\) is controllable. Similarly, a pair \((C,A)\) is detectable if and only if the pair \((A',C')\) is stabilizable.
3 Linear Observer

The concepts of observability and detectability are important because of the following result: An LTI system \((C, A)\) is detectable if and only if there exists a constant matrix \(L \in \mathbb{R}^{p \times m}\) such that \(A + LC\) is stable. To understand why this is relevant, suppose that we choose the following estimate

\[
\hat{x}_{n+1} = A\hat{x}_n + Bu_n + L(\hat{y}_n - y) , \quad \hat{x}_0 = \phi
\]

\[
\hat{y}_n = C\hat{x}_n + Du_n.
\]

Now if we define the estimation error as \(e_n = \hat{x}_n - x_n\), then we have

\[
e_{n+1} = \hat{x}_{n+1} - x_{n+1} = A\hat{x}_n + Bu_n + L(C\hat{x}_n + Du_n - Cx_n + Du_n) - Ax_n - Bu_n
\]

\[
= (A + LC)(\hat{x}_n - x_n) = (A + LC)e_n,
\]

meaning that \(\|e_n\| = \|\hat{x}_n - x_n\| \to 0\) because \(A + LC\) is stable.

The condition of observability is even more powerful. Let \(\lambda_1, \lambda_2, \ldots, \lambda_p \in \mathbb{C}\) be fixed complex numbers. If \((C, A)\) is observable, then there exists an \(L\) such that the eigenvalues of \(A + LC\) are precisely the \(\lambda_1, \lambda_2, \ldots, \lambda_p\) that were chosen.

4 Steady State Kalman Filter

Consider the following LTI system with noise:

\[
x_{n+1} = Ax_n + v_n
\]

\[
y_n = Cx_n + w_n
\]

where \(v_n \sim \mathcal{N}(0, Q)\) is process noise (or state noise) and \(w_n \sim \mathcal{N}(0, R)\) is measurement noise. The initial condition to this system is \(x_0 \sim \mathcal{N}(\mu, \Sigma_0)\). For simplicity, we will assume that \(Q > 0\) and \(R > 0\).

Based on this system, consider the following optimization problem

\[
\lim_{n \to \infty} \min_n \mathbb{E}[\left(\hat{x}_{n+1} - x_{n+1}\right)\left(\hat{x}_{n+1} - x_{n+1}\right)']
\]

s.t. \(x_{k+1} = Ax_k + v_k\)

\[
y_k = Cx_k + w_k
\]

\[
v_k \sim \mathcal{N}(0, Q)
\]

\[
w_k \sim \mathcal{N}(0, R)
\]

Note that this minimum may not be finite unless we impose additional restrictions.

In particular, suppose that \((C, A)\) is detectible. Then the minimizer is given by \(\hat{x}_{n+1} = A\hat{x}_n + L(\hat{y}_n - y)\) (i.e., linear observer with constant gain), where

\[
L = -APC'(R + CPC')^{-1}
\]
and $P > 0$ is the unique solution to the discrete time algebraic Riccati equation (DARE)

$$P = Q + A(P - PC'(R + CPC')^{-1}CP)A'.$$

If $K$ is the feedback gain for the infinite horizon LQR problem with pair $(A', C')$, then we actually have that $K = L'$; in other words, there is a duality between the infinite horizon LQR problem and the steady-state Kalman filter gain.

5 Separation Principle

Suppose we have an LTI system in which $(A, B)$ is stabilizable and $(C, A)$ is detectable. And imagine that we do not have access to measurements of $x_n$, rather we only measure $u_n$ and $y_n$. An interesting question to what happens if we use an observer to produce estimates $\hat{x}_n$, and then uses these estimates with a linear feedback to control the system? Is the resulting closed-loop system stable? It turns out that the answer is yes, and the answer lets us separate the observer design from the controller design.

In particular, consider an output-feedback controller

$$\hat{x}_{n+1} = A\hat{x}_n + Bu_n + L(C\hat{x}_n + Du_n - y_n)$$

$$u_n = K\hat{x}_n,$$

where $K, L$ are any matrices such that $(A+BK)$ and $(A+LC)$ are stable. Note that the closed-loop system is given by

$$\begin{bmatrix} x_{n+1} \\ \hat{x}_{n+1} \end{bmatrix} = \begin{bmatrix} A & BK \\ -LC & A + BK + LC \end{bmatrix} \begin{bmatrix} x_n \\ \hat{x}_n \end{bmatrix}.$$

Next consider a change of variables

$$\begin{bmatrix} x_n \\ e_n \end{bmatrix} = \begin{bmatrix} I & 0 \\ -I & I \end{bmatrix} \begin{bmatrix} x_n \\ \hat{x}_n \end{bmatrix}.$$

Then the dynamics in this new coordinate system are given by

$$\begin{bmatrix} x_{n+1} \\ e_{n+1} \end{bmatrix} = \begin{bmatrix} I & 0 \\ -I & I \end{bmatrix} \begin{bmatrix} A & BK \\ -LC & A + BK + LC \end{bmatrix} \begin{bmatrix} I & 0 \\ -I & I \end{bmatrix}^{-1} \begin{bmatrix} x_n \\ e_n \end{bmatrix} = \begin{bmatrix} A + BK & 0 \\ -LC - A & A + LC \end{bmatrix} \begin{bmatrix} x_n \\ e_n \end{bmatrix}.$$

The eigenvalues of this block matrix are precisely the eigenvalues of $A + BK$ and $A + LC$, and so the closed-loop system as long as $A + BK$ and $A + LC$ are both individually stable.