
EECS 16B Designing Information Devices and Systems II
 Fall 2019 Note: Stability

1 Overview

Given a discrete-time linear system, we now know how to determine its behavior by supplying inputs. We will now discuss the problem of *disturbance*, and how it affects our ability to both control a system and to move it to where we want.

2 Disturbance and Stability

Recall that we typically model the evolution of a linear system using the equation

$$\vec{x}(i+1) = A\vec{x}(i) + B\vec{u}(i).$$

In reality, though, these models never capture the full behavior of a system - errors, due to nonlinearities in the system or factors not taken into account when building the model, or just random noise, will always be present. We denote the error in our model as the disturbance \vec{w} , to obtain the full state equation

$$\vec{x}(i+1) = A\vec{x}(i) + B\vec{u}(i) + \vec{w}(i),$$

where \vec{w} is unobservable and varies arbitrarily at each time step.

At this point, a natural question to ask would be: if \vec{w} is unknown and varies arbitrarily, how can we possibly do anything with our system? We can apply control inputs and observe the system extremely carefully, only for everything to be thrown off by an arbitrarily large \vec{w} term! To address this, we will introduce the notion of *bounded disturbance*. Specifically, we are given that $\|\vec{w}\| \leq \varepsilon$ for some small nonzero constant ε .

Now, we will demonstrate that bounding the magnitude of \vec{w} is sufficient to guarantee the *stability* of our system. First, though, we need to define stability. For our purposes, we will call a system stable if, starting at $\vec{x}(0) = \vec{0}$ and supplying no input \vec{u} , the system can never move arbitrarily far from its initial state - in other words, for all discrete time t , $\|\vec{x}(t)\| \leq K$ for some (finite) constant K . This definition of stability is known as *bounded-input bounded output* stability.

3 Scalar Stability

First, we will consider the case of system stability in one dimension, so \vec{x} is in fact a scalar quantity x . Thus, our system's behavior can be modelled as

$$x(i+1) = \lambda x(i) + w(i).$$

The use of the symbol λ may remind you of eigenvalues - we'll see why that's the case shortly. We have $x(0) = 0$. Therefore, we have

$$\begin{aligned} x(0) &= 0 \\ \implies x(1) &= w(0) \\ \implies x(2) &= \lambda w(0) + w(1) \\ \implies x(3) &= \lambda^2 w(0) + \lambda w(1) + w(2) \\ &\vdots \\ \implies x(i) &= \lambda^{i-1} w(0) + \lambda^{i-2} w(1) + \dots + w(i-1). \end{aligned}$$

For now, let's assume that $\lambda \geq 0$. Recall that we have no control over the noise. For our system to be stable, $x(i)$ should be bounded no matter how w is chosen. In this scenario, it should make intuitive sense that $x(i)$ is maximized when we, in turn, maximize w , by setting it to ε every timestep. Therefore, we can write

$$x(i) = \varepsilon(1 + \lambda + \lambda^2 + \dots + \lambda^{i-1}).$$

Since the system should remain bounded after arbitrarily many timesteps, we can take the limit $i \rightarrow \infty$ (and abuse notation somewhat), to obtain

$$\lim_{i \rightarrow \infty} x(i) = x(\infty) = \varepsilon(1 + \lambda + \lambda^2 + \dots).$$

From our knowledge of geometric series, we know that this quantity converges to a finite value if and only if $|\lambda| < 1$. In other words, a scalar system where $\lambda \geq 0$ is stable exactly when $|\lambda| < 1$.

Unfortunately, the above analysis becomes somewhat more tricky when $\lambda < 0$, and breaks down entirely when λ is complex! However, it is still useful in that it has provided us with a conjecture - that a scalar discrete-time system is stable exactly when $|\lambda| < 1$. To prove this conjecture, we need to do two things: first, show that our system is stable when $|\lambda| < 1$, and second, show that it is unstable when $|\lambda| \geq 1$.

Let's prove the former claim first. Clearly, it is the case that

$$x(t) = \sum_{i=0}^{t-1} \lambda^{t-i-1} w(i)$$

even in the complex case. We can upper-bound $|x(t)|$ to be

$$\begin{aligned} |x(t)| &= \left| \sum_{i=0}^{t-1} \lambda^{t-i-1} w(i) \right| \\ &\leq \sum_{i=0}^{t-1} |\lambda^{t-i-1} w(i)| \\ &= \sum_{i=0}^{t-1} |\lambda^{t-i-1}| |w(i)| \\ &\leq \varepsilon \sum_{i=0}^{t-1} |\lambda|^{t-i-1}, \end{aligned}$$

since $|\lambda^{t-i-1}| \geq 0$ and $|w(i)| \leq \varepsilon$ by the definition of bounded noise. Now, since $|\lambda| < 1$, we can apply the

geometric series formula (taking an upper-bound by summing to infinity, rather than stopping at $t - 1$), to obtain the final bound

$$|x(t)| \leq \varepsilon \left(1 + |\lambda| + |\lambda|^2 + \dots \right) = \frac{\varepsilon}{1 - |\lambda|},$$

which is a bounded quantity even as $t \rightarrow \infty$. Consequently, we have shown that our system is BIBO stable when $|\lambda| < 1$, even when λ is a complex number.

What if $|\lambda| \geq 1$? We'd like to show that our system is unstable. One way to do so would be to present a particular sequence of bounded $w(i)$ that take $|x(t)|$ to infinity over time, indicating that the state is unbounded. Looking at the special case of real, positive λ for inspiration, we might conjecture that

$$w(i) = \varepsilon$$

is one such sequence. Clearly, this candidate sequence of $w(i)$ is indeed bounded.

For this candidate sequence, we see that (when $\lambda \neq 1$)

$$\begin{aligned} x(t) &= \sum_{i=0}^{t-1} \lambda^{t-i-1} w(i) \\ &= \varepsilon(\lambda^0 + \lambda^1 + \dots + \lambda^{t-1}) \\ &= \varepsilon \frac{\lambda^t - 1}{\lambda - 1}, \end{aligned}$$

so

$$|x(t)| = \varepsilon \frac{|\lambda^t - 1|}{|\lambda - 1|}.$$

As $|\lambda^t| = |\lambda|^t$ goes to infinity when $|\lambda| > 1$, we have shown that our system is unstable when $|\lambda| > 1$.

Unfortunately, the above derivation forced us to exclude the case when $|\lambda| = 1$. For this case, we need to consider a new candidate sequence of noise. Some experimentation yields the candidate sequence

$$w(i) = \varepsilon \lambda^i.$$

Note that since $|\lambda| = 1$, $|w(i)| = \varepsilon 1^i = \varepsilon$, so the noise is still bounded. Now, plugging into our formula for $x(t)$, we find that

$$\begin{aligned} x(t) &= \varepsilon \sum_{i=0}^{t-1} \lambda^{t-i-1} \lambda^i \\ &= \varepsilon \sum_{i=0}^{t-1} \lambda^{t-1} \\ &= \varepsilon t \lambda^{t-1}, \end{aligned}$$

so

$$|x(t)| = t |\varepsilon|,$$

which goes to infinity over time. Thus, when $|\lambda| = 1$, we can supply bounded noise that still drives our system to infinity, so it is unbounded.

Putting everything together, we have shown that whenever the parameter λ of our scalar discrete-time linear system has magnitude less than 1, our system is stable, but that otherwise it is unstable.

4 Vector Stability

Now, we will look at the discrete-time vector case, with the state equation

$$\vec{x}(t+1) = A\vec{x}(t) + B\vec{u}(t) + \vec{w}(t).$$

We will assume that we start at the target state $\vec{x}(0) = \vec{0}$, and that we supply no inputs thereafter, so all $\vec{u} = \vec{0}$. Note that this means that B cannot affect the stability of our system, so we will disregard it.

Now, recall that when we considered continuous-time systems with coupled differential equations, we were able to separate them into a set of decoupled differential equations by diagonalizing their state matrix.¹ We can do something similar here, by letting $A = V\Lambda V^{-1}$, and rearranging to obtain

$$\begin{aligned}\vec{x}(t+1) &= V\Lambda V^{-1}\vec{x}(t) + \vec{w} \\ \implies V^{-1}\vec{x}(t+1) &= \Lambda V^{-1}\vec{x}(t) + V^{-1}\vec{w} \\ \implies \tilde{\vec{x}}(t+1) &= \Lambda\tilde{\vec{x}}(t) + \tilde{\vec{w}},\end{aligned}$$

where $\tilde{\vec{x}} = V^{-1}\vec{x}$ and $\tilde{\vec{w}} = V^{-1}\vec{w}$. Clearly, if a single component of $\tilde{\vec{x}}$ is unbounded, then the system as a whole is unstable. So all we have to do is consider each of the components of $\tilde{\vec{x}}$, each of which gives us the scalar state equation

$$\tilde{x}_j(i+1) = \lambda_j \tilde{x}_j(i) + \tilde{w}_j.$$

It would seem that we can just apply the result from the previous section, to state that this component is stable exactly when $|\lambda_j| < 1$.

Recall, however, that that result only applied when the input noise was bounded - in other words, doing so would assume that $\|\tilde{\vec{w}}_j\| < \tilde{\epsilon}$ for some finite constant $\tilde{\epsilon}$. We were given that our original noise \vec{w} was bounded, so there existed some ϵ such that each component $\vec{w}_j < \epsilon$. But after applying V^{-1} , can we be certain that the transformed noise is still bounded? From our intuition of linear transformations, we should expect the answer to be yes. But for the sake of completeness, we will derive a proof here. Let

$$V^{-1} = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{n1} & v_{n2} & \cdots & v_{nn} \end{bmatrix},$$

and let m be the entry v_{ij} within V^{-1} with the largest magnitude. Thus,

$$\begin{aligned}V^{-1}\vec{w} &= \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{n1} & v_{n2} & \cdots & v_{nn} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \\ &= \begin{bmatrix} v_{11}w_1 + v_{12}w_2 + \dots + v_{1n}w_n \\ v_{21}w_1 + v_{22}w_2 + \dots + v_{2n}w_n \\ \vdots \\ v_{n1}w_1 + v_{n2}w_2 + \dots + v_{nn}w_n \end{bmatrix}.\end{aligned}$$

¹We will discuss the case when A is not diagonalizable later in the course.

Any given row of $\tilde{w} = V^{-1}\vec{w}$ is bounded by

$$v_{i1}w_1 + v_{i2}w_2 + \dots + v_{in}w_n \leq |m|(w_1 + w_2 + \dots + w_n).$$

Since $|m|$ is a constant that does not depend on \vec{w} , and $w_1 + w_2 + \dots + w_n$ is bounded since $\|\vec{w}\|$ is bounded, each element of \tilde{w} is also bounded by some finite constant. Therefore, we can indeed apply our original result in the eigenbasis. Consequently, our system as a whole is stable exactly when $|\lambda_j| < 1$ for all the eigenvalues λ_j of A .

5 Continuous-Time Systems

At this point, we will take a brief aside from our discussion of discrete-time systems to consider the stability of continuous time systems. First, consider a continuous-time scalar system whose behavior is described by the equation

$$\frac{d}{dt}x(t) = \lambda x(t) + u(t) + w(t),$$

where λ and $w(t)$ are possibly complex.

As before, we are interested to see, given bounded noise $|w(t)| \leq \epsilon$ and input $u(t) = 0$, whether $|x(t)|$ remains bounded over time. Initially, let's assume that $\lambda \neq 0$. Then, from our knowledge of differential equations, we know that we can solve for the state

$$x(t) = x(0)e^{\lambda t} + \int_0^t e^{\lambda(t-\theta)}w(\theta)d\theta.$$

Let's consider the leading term $x(t)e^{\lambda t}$ first. We know that $e^{\lambda t}$ behaves very differently for real and imaginary choices of λ . Thus, to study it, it makes sense to break λ up into real and imaginary components, as follows:

$$\lambda = \lambda_r + j\lambda_i.$$

Now, by Euler's identity, we can express

$$e^{\lambda t} = e^{\lambda_r t + j\lambda_i t} = e^{\lambda_r t}(\cos(\lambda_i t) + j \sin(\lambda_i t)).$$

Consequently, it is clear that

$$|e^{\lambda t}| = e^{\lambda_r t},$$

so it blows up as $t \rightarrow \infty$ if $\lambda_r > 0 \iff \text{Re}[\lambda] > 0$.

Going back to our expression for $x(t)$, we can now notice that the leading term $x(0)e^{\lambda t}$ will go to infinity when $\text{Re}[\lambda] > 0$, even if the noise $w = 0$ throughout, so long as $x(0) \neq 0$. What if $x(0) = 0$? Then we can simply apply some initial noise in order to perturb our state from 0, then set the noise to 0 and let the state blow up, so our system is unstable.

Thus, a necessary condition for stability is $\text{Re}[\lambda] \leq 0$. Is this condition sufficient? To find out, we now need to look at the effects of input on our state over time, by considering the second term in our above expression

for $x(t)$. Observe that, when $\text{Re}[\lambda] < 0$, we can present the upper bound

$$\begin{aligned}|x(t)| &= \left| x(0)e^{\lambda t} + \int_0^t e^{\lambda(t-\theta)} w(\theta) d\theta \right| \\ &\leq |x(0)e^{\lambda t}| + \left| \int_0^t e^{\lambda(t-\theta)} w(\theta) d\theta \right|\end{aligned}$$

We've just seen how the first term in the above sum is bounded when $\text{Re}[\lambda] < 0$. Focusing on the second term, we can rearrange it as

$$\begin{aligned}\left| \int_0^t e^{\lambda(t-\theta)} w(\theta) d\theta \right| &\leq \int_0^t |e^{\lambda(t-\theta)} w(\theta)| d\theta \\ &= \int_0^t |e^{\lambda(t-\theta)}| |w(\theta)| d\theta \\ &= \int_0^t e^{\lambda_r(t-\theta)} |w(\theta)| d\theta.\end{aligned}$$

Now, since $e^{\lambda_r(t-\theta)}$ is always a positive real number, it is clear that we can maximize the above expression by setting $|w(\theta)|$ to its maximum value ε , to obtain the bound

$$\begin{aligned}\left| \int_0^t e^{\lambda(t-\theta)} w(\theta) d\theta \right| &\leq \varepsilon \int_0^t e^{\lambda_r(t-\theta)} d\theta \\ &= \varepsilon e^{\lambda_r t} \left[-\frac{1}{\lambda_r} e^{-\lambda_r \theta} \right]_0^t \\ &= \frac{\varepsilon}{\lambda_r} e^{\lambda_r t} \left[e^{-\lambda_r \theta} \right]_t^0 \\ &= \frac{\varepsilon e^{\lambda_r t}}{\lambda_r} (1 - e^{\lambda_r t}).\end{aligned}$$

Since $\lambda_r < 0$, $e^{\lambda_r t}$ is bounded for all t , so is the above expression. Therefore, we have shown both terms in the closed-form of $x(t)$ to be bounded when $\text{Re}[\lambda] < 0$, so our system is stable when $\text{Re}[\lambda] < 0$.

Looking back at what we have shown, we know that our system is stable when $\text{Re}[\lambda] < 0$, and unstable when $\text{Re}[\lambda] > 0$. The only remaining case is when $\text{Re}[\lambda] = 0$, where $\lambda = j\lambda_j$. In this case, consider the bounded noise $w(t) = \varepsilon e^{j\lambda_j t}$. Observe that, even when we start with $x(0) = 0$, our state becomes

$$\begin{aligned}x(t) &= \int_0^t e^{\lambda(t-\theta)} w(\theta) d\theta \\ &= \int_0^t e^{\lambda(t-\theta)} \varepsilon e^{j\lambda_j \theta} d\theta \\ &= \varepsilon e^{j\lambda_j t} \int_0^t e^{-\lambda_j \theta + \lambda_j \theta} d\theta \\ &= \varepsilon e^{j\lambda_j t} \int_0^t 1 d\theta \\ &= \varepsilon t e^{j\lambda_j t}.\end{aligned}$$

Thus, $|x(t)| = \varepsilon t$, so it goes to infinity over time despite the noise being bounded by $|w(t)| = \varepsilon$ throughout. Consequently, when $\text{Re}[\lambda] = 0$, our system is still unstable.

Putting everything together, we ultimately see that continuous-time scalar systems are stable exactly when $\text{Re}[\lambda] < 0$.

But what about continuous-time vector systems? By performing diagonalization in an analogous manner to what we did earlier for discrete-time systems, it can easily be seen that (diagonalizable) vector systems are stable exactly when $\text{Re}[\lambda_i] < 0$ for all the eigenvalues λ_i of the state matrix A . Thus, we now have derived a necessary and sufficient condition for the stability of diagonalizable continuous-time systems.

6 Closed-Loop Control

Now, we know (at least to some extent) when a system is stable in the absence of input. That is to say, we can determine when a system is such that any bounded perturbations when applied over time can never lead to unbounded deviations from the stable state. However, many real-world systems are not stable in this manner, instead relying on continuous monitoring and intervention to keep them near a desired state. We will now begin to explore how we may choose inputs that achieve our goal of stability, returning to discrete-time systems for simplicity.

In particular, imagine choosing inputs that linearly depend on the state vector. Specifically, let

$$\vec{u}(i) = K\vec{x}(i)$$

where K is a matrix that we can adjust. Then, our state equation becomes

$$\begin{aligned}\vec{x}(i+1) &= A\vec{x}(i) + B\vec{u}(i) + \vec{w}(i) \\ &= A\vec{x}(i) + BK\vec{x}(i) + \vec{w}(i) \\ &= (A + BK)\vec{x}(i) + \vec{w}(i).\end{aligned}$$

In essence, it is as if we have replaced our original state matrix A with the new matrix $A + BK$, and continue to apply no other input. Ideally, we'd be able to choose a K that would move the eigenvalues of the state transition matrix $A + BK$ into the regime of stability. We will derive the general condition for the existence of such a K in future lectures. Right now, however, we will examine a few special cases. Consider the scalar case, with the system

$$x(t+1) = ax(t) + bu(t) + w(t).$$

If $|a| \geq 1$ (for instance, if $a = 3$), we know that this system will be unstable in the absence of input. But now, imagine that we choose $u(t) = kx(t)$ for a constant k to be determined. Substituting into the state equation, we obtain

$$x(t+1) = (a + bk)x(t) + w(t).$$

Thus, when $b \neq 0$, we can choose k to set our system's eigenvalues to whatever we want! In particular, by setting $k = -a/b$, we obtain

$$x(t+1) = w(t),$$

minimizing the system's eigenvalues and ensuring that noise cannot accumulate geometrically. Now, we will look at a simple 2D case, with the state equation

$$\vec{x}(t+1) = \begin{bmatrix} 0 & 1 \\ 3 & 2 \end{bmatrix} \vec{x}(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \vec{u}(t) + \vec{w}(t).$$

Notice that with no input, the eigenvalues of our state matrix are 3 and -1 , so this system is definitely

unstable in the absence of input. Notice also that the input only affects the second state directly, so we have no direct way of manipulating the first state. This is in contrast to our scalar example, where our input could affect the entire (one-dimensional) state. With that in mind, let our unknown K be

$$K = \begin{bmatrix} k_1 & k_2 \end{bmatrix},$$

so we obtain the state equation

$$\vec{x}(i+1) = \left(\begin{bmatrix} 0 & 1 \\ 3 & 2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} k_1 & k_2 \end{bmatrix} \right) \vec{x}(i) + \vec{w}.$$

We are interested in minimizing the magnitudes of both eigenvectors of our state transition matrix, which may be reexpressed as

$$A + BK = \begin{bmatrix} 0 & 1 \\ 3 & 2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ k_1 & k_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 3+k_1 & 2+k_2 \end{bmatrix}$$

Computing the eigenvalues λ , we see that they must satisfy the characteristic polynomial

$$(-\lambda)(2+k_2-\lambda) - (3+k_1) = 0 \implies \lambda^2 - (k_2+2)\lambda - (k_1+3) = 0.$$

Notice that we have full control over both coefficients of the characteristic polynomial, even though we can't fully control the state matrix. Therefore, we can place the state matrix's eigenvalues wherever we like, so we can still choose a feedback control law to make our system stable. In the future, we will explore the condition that determines whether a K that stabilizes a system exists.

Contributors:

- Rahul Arya.
- Anant Sahai.
- Jaijeet Roychowdhury.