

Error dynamics and control of systems with constraints

Contact-aware Control, Lecture 6

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Trajectory tracking; desired trajectory

Trajectory tracking is a control problem that says:

Trajectory tracking

Find such *control law* $\mathbf{u} = \mathbf{u}(\mathbf{x}, t)$ that solution of the dynamical system $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t)$ converges to the *desired trajectory* $\mathbf{x}^* = \mathbf{x}^*(t)$.

For mechanical systems specifically we can write it as:

Trajectory tracking for mechanical systems

Find such control law $\mathbf{u} = \mathbf{u}(\mathbf{q}, \dot{\mathbf{q}}, t)$ that solution of the dynamical system $\mathbf{H}\ddot{\mathbf{q}} + \mathbf{c} = \mathbf{T}\mathbf{u}$ converges to the desired trajectory $\mathbf{q}^* = \mathbf{q}^*(t)$.

Desired trajectory and constraints

Assume your system is subject to constraints $\mathbf{g}(\mathbf{q}) = 0$, and you have desired trajectory $\mathbf{q}^* = \mathbf{q}^*(t)$. Then, unless $\mathbf{g}(\mathbf{q}^*(t)) = 0$, the desired trajectory is not valid.

You can find first two time derivatives of the desired trajectory: $\dot{\mathbf{q}}^*(t)$ and $\ddot{\mathbf{q}}^*(t)$. Defining $\mathbf{F} = \frac{\partial \mathbf{g}}{\partial \mathbf{q}}$ we can write first and second derivative of the constraint as: $\dot{\mathbf{g}}(\mathbf{q}) = \mathbf{F}\dot{\mathbf{q}}$ and $\ddot{\mathbf{g}}(\mathbf{q}) = \mathbf{F}\ddot{\mathbf{q}} + \dot{\mathbf{F}}\dot{\mathbf{q}}$. Therefor we can write implied conditions on the desired trajectory:

$$\dot{\mathbf{g}}(\mathbf{q}^*) = \mathbf{F}\dot{\mathbf{q}}^* = 0 \quad (1)$$

$$\ddot{\mathbf{g}}(\mathbf{q}^*) = \mathbf{F}\ddot{\mathbf{q}}^* + \dot{\mathbf{F}}\dot{\mathbf{q}}^* = 0 \quad (2)$$

Error dynamics

Definition

We can rewrite equations of dynamics in the normal form:

$$\ddot{\mathbf{q}} = \mathbf{H}^{-1}(\mathbf{T}\mathbf{u} - \mathbf{c}) \quad (3)$$

Let us define *control error* \mathbf{e} as follows:

$$\mathbf{e} = \mathbf{q}^* - \mathbf{q} \quad (4)$$

Then we can find its second derivative as: $\ddot{\mathbf{e}} = \ddot{\mathbf{q}}^* - \ddot{\mathbf{q}}$:

$$\ddot{\mathbf{e}} = \ddot{\mathbf{q}}^* - \mathbf{H}^{-1}(\mathbf{T}\mathbf{u} - \mathbf{c}) \quad (5)$$

If error dynamics is *stable*, it means the error will approach zero as the time approaches infinity. Is a good thing.

We can decide that we want error dynamics to have this form:

$$\ddot{\mathbf{e}} + \mathbf{K}_d \dot{\mathbf{e}} + \mathbf{K}_p \mathbf{e} = 0 \quad (6)$$

where \mathbf{K}_d and \mathbf{K}_p are diagonal positive-definite matrices.

Equation (6) is stable. So, if we achieve that our error dynamics takes this form, we make it stable.

Let us use (5) to re-write (6):

$$\ddot{\mathbf{q}}^* - \mathbf{H}^{-1}(\mathbf{T}\mathbf{u} - \mathbf{c}) + \mathbf{K}_d \dot{\mathbf{e}} + \mathbf{K}_p \mathbf{e} = 0 \quad (7)$$

Error dynamics

Computed torque controller

So, we have:

$$\ddot{\mathbf{q}}^* - \mathbf{H}^{-1}(\mathbf{T}\mathbf{u} - \mathbf{c}) + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e} = 0 \quad (8)$$

Now we can multiply it by \mathbf{H} (because it is invertible, so it's null space is trivial and we do not annihilate any part of the equation):

$$\mathbf{H}(\ddot{\mathbf{q}}^* + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e}) - (\mathbf{T}\mathbf{u} - \mathbf{c}) = 0 \quad (9)$$

...and then express \mathbf{u} out:

$$\mathbf{u} = \mathbf{T}^+(\mathbf{H}(\ddot{\mathbf{q}}^* + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e}) + \mathbf{c}) \quad (10)$$

This is called a *computed torque controller* (CTC), and it assumes that $(\mathbf{H}(\ddot{\mathbf{q}}^* + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e}) + \mathbf{c})$ is in the column space of \mathbf{T} .

Error dynamics

Feedback and feedforward

Thus CTC has the form: $\mathbf{u} = \mathbf{T}^+(\mathbf{H}(\ddot{\mathbf{q}}^* + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e}) + \mathbf{c})$

We can separate feedback part \mathbf{u}_{FB} and feedforward part \mathbf{u}_{FF} :

$$\mathbf{u} = \mathbf{u}_{FB} + \mathbf{u}_{FF} \quad (11)$$

$$\mathbf{u}_{FB} = \mathbf{T}^+\mathbf{H}(\mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e}) \quad (12)$$

$$\mathbf{u}_{FF} = \mathbf{T}^+(\mathbf{H}\ddot{\mathbf{q}}^* + \mathbf{c}) \quad (13)$$

Notice that feedback part is just a PD (proportional-derivative) controller with varying gains, while the feedforward part is just \mathbf{u} expressed out of the robot's dynamics $\mathbf{H}\ddot{\mathbf{q}} + \mathbf{c} = \mathbf{T}\mathbf{u}$; the latter - finding \mathbf{u} directly from the dynamics - is called *inverse dynamics*.

Control and constraints

Part 1

Dynamical system with constraints can be written as:

$$\begin{cases} \mathbf{H}\ddot{\mathbf{q}} + \mathbf{c} = \mathbf{T}\mathbf{u} + \mathbf{F}^\top \lambda \\ \mathbf{F}\ddot{\mathbf{q}} + \dot{\mathbf{F}}\dot{\mathbf{q}} = 0 \end{cases} \quad (14)$$

How do we apply the ideas about stable error dynamics here?

One naive approach is to define a new variable $\mathbf{v} = \mathbf{T}\mathbf{u} + \mathbf{F}^\top \lambda$ and rewrite the first equation in the system (14) as:

$$\mathbf{H}\ddot{\mathbf{q}} + \mathbf{c} = \mathbf{v} \quad (15)$$

Here it seems we can apply CTC directly. But we need to study how (and when) it will work.

We are considering equation $\mathbf{H}\ddot{\mathbf{q}} + \mathbf{c} = \mathbf{v}$. CTC for this case will take form:

$$\mathbf{v} = \mathbf{H}(\ddot{\mathbf{q}}^* + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e}) + \mathbf{c} \quad (16)$$

But remember that $\mathbf{v} = \mathbf{T}\mathbf{u} + \mathbf{F}^\top\lambda$. We can always try to do our best to find such \mathbf{u} that it holds, but what about λ ?

On the value of λ

We should always keep in mind that λ is uniquely determined for any given \mathbf{u} . So, while we can't assign λ arbitrarily, as long as we assigned \mathbf{u} , we did in fact determined what value λ will take.

Control and constraints

Part 3: calculating control input expressing reaction forces out

We remember from the previous lecture, that if we define

$\mathbf{M} = \begin{bmatrix} \mathbf{H} & -\mathbf{F}^\top \\ \mathbf{F} & \mathbf{0} \end{bmatrix}$, then assuming \mathbf{L} is a left inverse of \mathbf{M} , then we can write expressions for both $\ddot{\mathbf{q}}$ and λ in terms of its components:

$$\begin{cases} \ddot{\mathbf{q}} = \mathbf{L}_{11}(\mathbf{T}\mathbf{u} - \mathbf{c}) - \mathbf{L}_{12}\dot{\mathbf{F}}\dot{\mathbf{q}} \\ \lambda = \mathbf{L}_{21}(\mathbf{T}\mathbf{u} - \mathbf{c}) - \mathbf{L}_{22}\dot{\mathbf{F}}\dot{\mathbf{q}} \end{cases} \quad (17)$$

We can try to use this naive way of finding relation between λ and the control input \mathbf{u} , or one of the many more sophisticated ones. The idea would be to substitute the expression into the equation $\mathbf{v} = \mathbf{T}\mathbf{u} + \mathbf{F}^\top \lambda$, giving, in this case:

$$\mathbf{v} = \mathbf{T}\mathbf{u} + \mathbf{F}^\top (\mathbf{L}_{21}(\mathbf{T}\mathbf{u} - \mathbf{c}) - \mathbf{L}_{22}\dot{\mathbf{F}}\dot{\mathbf{q}}) \quad (18)$$

Control and constraints

Part 4: calculating control input, accelerations and reaction forces simultaneously

Alternatively, we can try to simultaneously calculate generalized accelerations $\ddot{\mathbf{q}}$, control inputs \mathbf{u} and reaction forces λ . This allows us to bring in the constraint equation $\mathbf{F}\ddot{\mathbf{q}} + \dot{\mathbf{F}}\dot{\mathbf{q}} = 0$:

$$\begin{cases} \mathbf{H}\ddot{\mathbf{q}} + \mathbf{c} = \mathbf{v} \\ \mathbf{T}\mathbf{u} + \mathbf{F}^\top \lambda = \mathbf{v} \\ \mathbf{F}\ddot{\mathbf{q}} + \dot{\mathbf{F}}\dot{\mathbf{q}} = 0 \end{cases} \quad (19)$$

where unknowns are $\ddot{\mathbf{q}}$, \mathbf{u} and λ . This is solved as a simple linear system:

$$\begin{bmatrix} \ddot{\mathbf{q}} \\ \mathbf{u} \\ \lambda \end{bmatrix} = \begin{bmatrix} \mathbf{H} & 0 & 0 \\ 0 & \mathbf{T} & \mathbf{F}^\top \\ \mathbf{F} & 0 & 0 \end{bmatrix}^+ \begin{bmatrix} \mathbf{v} - \mathbf{c} \\ \mathbf{v} \\ -\dot{\mathbf{F}}\dot{\mathbf{q}} \end{bmatrix} \quad (20)$$

Algebra recap

Fundamental subspaces

Column space

All possible outputs of a linear operator \mathbf{A} are called *column space* of \mathbf{A} .

Null space

Null space of \mathbf{A} is the set of all vectors \mathbf{x} that \mathbf{A} maps to 0

Now we can find all solutions to the system of equations $\mathbf{A}\mathbf{x} = \mathbf{0}$ by using functions that generate an orthonormal *basis* in the null space of \mathbf{A} . In MATLAB it is function `null()`.

In MATLAB it can be constructed by calling function `orth()`. Both `orth()` and `null()` (as well as `rank()` and `pinv()`) simply call `svd()` and perform minimal computations on the resulting decomposition. You can check it by typing `open orth` in MATLAB command window.

We can project any vector onto a subspace using a *projector*.

Definition 1

For linear space $\mathcal{L} \subset \mathbb{R}^n$, an orthogonal projector \mathbf{P} onto it has properties:

- $\forall \mathbf{x} \in \mathbb{R}^n, \mathbf{P}\mathbf{x} \in \mathcal{L}$
- $\forall \mathbf{x} \in \mathcal{L}, \mathbf{P}\mathbf{x} = \mathbf{x}$
- $\forall \mathbf{y} \in \mathcal{L}, \mathbf{y}^\top (\mathbf{I} - \mathbf{P})\mathbf{x} = 0$

Projector \mathbf{P}_c onto the column space of an operator \mathbf{A} can be found as:

$$\mathbf{P}_c = \mathbf{A}\mathbf{A}^+ \quad (21)$$

Control and constraints

Part 5: feasibility conditions

Last expression suggests a simple feasibility condition for the existence of the control input that will generate the desired \mathbf{v} , namely that the left-hand-side vector of the linear system should lie in the column space of the matrix of the linear system:

$$\left(\mathbf{I} - \begin{bmatrix} \mathbf{H} & 0 & 0 \\ 0 & \mathbf{T} & \mathbf{F}^\top \\ \mathbf{F} & 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{H} & 0 & 0 \\ 0 & \mathbf{T} & \mathbf{F}^\top \\ \mathbf{F} & 0 & 0 \end{bmatrix}^+ \right) \begin{bmatrix} \mathbf{v} - \mathbf{c} \\ \mathbf{v} \\ -\dot{\mathbf{F}}\mathbf{q} \end{bmatrix} = 0 \quad (22)$$

Control and constraints

Part 6: feasibility conditions, simpler

We can make a simple set of necessary conditions. Remember that $\mathbf{v} = \mathbf{T}\mathbf{u} + \mathbf{F}^\top \lambda$. Therefore, vector \mathbf{v} should lie in the column space of the matrix $[\mathbf{T} \ \mathbf{F}^\top]$:

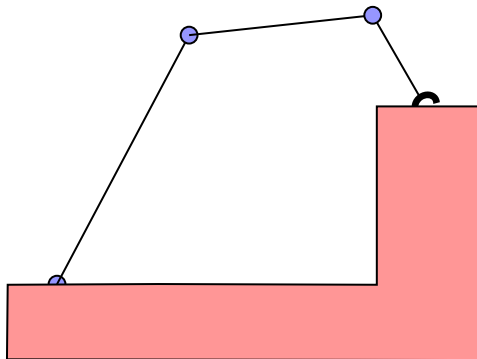
$$\left(\mathbf{I} - [\mathbf{T} \ \mathbf{F}^\top] [\mathbf{T} \ \mathbf{F}^\top]^\dagger \right) \mathbf{v} = 0 \quad (23)$$

You can read more at:

- Slotine, J.J.E. and Li, W., 1987. *On the adaptive control of robot manipulators. The international journal of robotics research*, 6(3), pp.49-59 - learn more about error dynamics and similar techniques, is very interesting!

Homework

Write a tracking controller for this robot (description of the robot is given in the previous lectures).



Lecture slides are available via Moodle.

You can help improve these slides at:

github.com/SergeiSa/Contact-Aware-Control-Slides-Fall-2020

Check Moodle for additional links, videos, textbook suggestions.