Constrained LQR

Contact-aware Control, Lecture 13

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Constrained LTI

Consider equations in the form:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{c} \tag{1}$$

where $\mathbf{A}$ is the state matrix, $\mathbf{B}$ is the control matrix and $\mathbf{c}$ is the affine term of the affine dynamics model.

For systems with constraints the same linearization takes form:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{S}\lambda + \mathbf{c} \\ \mathbf{G}\dot{\mathbf{x}} = 0 \end{cases} \tag{2}$$

where $\mathbf{S}$ is linearized constraint Jacobian and $\mathbf{G} = \begin{bmatrix} \mathbf{F} & \mathbf{0} \\ \dot{\mathbf{F}} & \mathbf{F} \end{bmatrix}$.

Implicit (minimal) representation of a constrained system
Part 1

We can observe that constraint $\mathbf{G}\dot{\mathbf{x}} = 0$ implies that all feasible state velocities $\dot{\mathbf{x}}$ lie in the null space of $\mathbf{G}$. This means that we can introduce a new lower dimensional variable $\mathbf{z}$ to describe $\mathbf{x}$ (assuming initial value of $\mathbf{x}$ lies in the column space of $\mathbf{N}$):

$$\mathbf{N}\mathbf{z} = \mathbf{x} \tag{3}$$

where $\mathbf{N} = \text{null}(\mathbf{G})$ - orthonormal basis in the null space of $\mathbf{G}$.

Implicit (minimal) representation of a constrained system
Part 2

Let us re-express dynamics (2) in terms of $\mathbf{z}$ by multiplying it by $\mathbf{N}^\top$ on the left:

$$\mathbf{N}^\top \dot{\mathbf{x}} = \mathbf{N}^\top \mathbf{A}\mathbf{x} + \mathbf{N}^\top \mathbf{B}\mathbf{u} + \mathbf{N}^\top \mathbf{S}\lambda + \mathbf{N}^\top \mathbf{c} \tag{4}$$

We can prove that $\mathbf{N}^\top \mathbf{S} = 0$ for all mechanical systems (for example, by observing that mechanical constrains do not do work) or check that our particular $\mathbf{S}$ lies in the row space of our $\mathbf{G}$.

Noting that $\dot{\mathbf{z}} = \mathbf{N}^\top \dot{\mathbf{x}}$ and $\mathbf{x} = \mathbf{N}\mathbf{z}$ we get:

$$\dot{\mathbf{z}} = \mathbf{N}^\top \mathbf{A}\mathbf{N}\mathbf{z} + \mathbf{N}^\top \mathbf{B}\mathbf{u} + \mathbf{N}^\top \mathbf{c} \tag{5}$$

Defining $\mathbf{A}_N = \mathbf{N}^\top \mathbf{A}\mathbf{N}$, $\mathbf{B}_N = \mathbf{N}^\top \mathbf{B}$ and $\mathbf{c}_N = \mathbf{N}^\top \mathbf{c}$ we get:

$$\dot{\mathbf{z}} = \mathbf{A}_N \mathbf{z} + \mathbf{B}_N \mathbf{u} + \mathbf{c}_N \tag{6}$$

Implicit (minimal) representation of a constrained system
Part 3

Since we achieved that our constrained dynamics is written in the standard LTI form:

$$\dot{\mathbf{z}} = \mathbf{A}_N \mathbf{z} + \mathbf{B}_N \mathbf{u} + \mathbf{c}_N, \tag{7}$$

we can use standard LTI control methods on it, for example finding optimal feedback gains via pole placement or LQR:

$$\mathbf{K}_N = \mathrm{lqr}(\mathbf{A}_N, \mathbf{B}_N, \mathbf{Q}, \mathbf{R}) \tag{8}$$

where $\mathbf{Q}$ and $\mathbf{R}$ are matrices defining cost function for the LQR problem.

For any LTI system, including the LTI form of a constrained system we saw previously, inverse dynamics can be solved precisely by a pseudo-inverse, as long as there exist a solution. The following condition verifies it:

$$(\mathbf{I} - \mathbf{B}\mathbf{B}^{+})(\dot{\mathbf{x}} - \mathbf{A}\mathbf{x} - \mathbf{c}) = 0, \tag{9}$$

The condition checks if vector $(\dot{\mathbf{x}} - \mathbf{A}\mathbf{x} - \mathbf{c})$ lies in the column space of $\mathbf{B}$. If it holds, precise solution to inverse kinematics can be found as:

$$\mathbf{u}_{ID} = \mathbf{B}^{+}(\dot{\mathbf{x}} - \mathbf{A}\mathbf{x} - \mathbf{c}). \tag{10}$$

For a constrained mechanical system we can solve inverse dynamics without the need for linearization. Consider the following dynamics:

$$\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g} = \mathbf{T}\mathbf{u} + \mathbf{F}^\top \lambda \tag{11}$$

We can represent constraint Jacobian $\mathbf{F}^\top$ as its QR decomposition: $\mathbf{F}^\top = \mathbf{Q}\begin{bmatrix}\mathbf{R} \\ \mathbf{0}\end{bmatrix}$, where $\mathbf{Q}^\top\mathbf{Q} = \mathbf{Q}\mathbf{Q}^\top = \mathbf{I}$ and $\mathbf{R}$ is convertible.

$$\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g} = \mathbf{T}\mathbf{u} + \mathbf{Q}\begin{bmatrix}\mathbf{R} \\ \mathbf{0}\end{bmatrix}\lambda \tag{12}$$

Let us multiply the equation by $\mathbf{Q}^\top$:

$$\mathbf{Q}^\top(\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g}) = \mathbf{Q}^\top\mathbf{T}\mathbf{u} + \begin{bmatrix}\mathbf{R} \\ \mathbf{0}\end{bmatrix}\lambda \tag{13}$$

Introducing switching variables (to divide upper and lower part of the equations) $\mathbf{S}_1 = \begin{bmatrix}\mathbf{I} & \mathbf{0}\end{bmatrix}$ and $\mathbf{S}_2 = \begin{bmatrix}\mathbf{0} & \mathbf{I}\end{bmatrix}$ and multiplying equations by one and the other we get two systems:

$$\begin{cases}\mathbf{S}_1\mathbf{Q}^\top(\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g}) = \mathbf{S}_1\mathbf{Q}^\top\mathbf{T}\mathbf{u} + \mathbf{R}\lambda \\ \mathbf{S}_2\mathbf{Q}^\top(\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g}) = \mathbf{S}_2\mathbf{Q}^\top\mathbf{T}\mathbf{u}\end{cases} \tag{14}$$

The main advantage we achieved is that now we can calculate both $\mathbf{u}$ and λ

Resulting expression for $\mathbf{u}$ is:

$$\mathbf{u} = (\mathbf{S}_2\mathbf{Q}^\top\mathbf{T})^+\mathbf{S}_2\mathbf{Q}^\top(\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g}) \tag{15}$$

Expression for λ is:

$$\lambda = \mathbf{R}^{-1}\mathbf{S}_1\mathbf{Q}^\top(\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g} - \mathbf{T}\mathbf{u}) \tag{16}$$

We can notice a pseudo-inverse, implying that the no-residual solution does not have to exist.

We can easily write inverse dynamics as a QP:

$$\begin{aligned}
&\underset{\mathbf{u},\lambda}{\text{minimize}} \quad ||\mathbf{u}||, \\
&\text{subject to} \quad \begin{cases} \mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{g} = \mathbf{T}\mathbf{u} + \mathbf{F}^{\top}\lambda \\ \mathbf{F}\ddot{\mathbf{q}} + \dot{\mathbf{F}}\dot{\mathbf{q}} = 0 \end{cases}
\end{aligned} \tag{17}$$

If there are some constraints or limits on the control input (torque limits, for instance) or the reaction forces are restricted (by friction cones, for instance), those can be directly added.

Read more

- Mason, S., Righetti, L. and Schaal, S., 2014, November. Full dynamics LQR control of a humanoid robot: An experimental study on balancing and squatting. In 2014 IEEE-RAS International Conference on Humanoid Robots (pp. 374-379). IEEE.
- Mason, S., Rotella, N., Schaal, S. and Righetti, L., 2016, November. Balancing and walking using full dynamics LQR control with contact constraints. In 2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids) (pp. 63-68). IEEE. - arxiv.org/pdf/1701.08179
- Mistry, M., Buchli, J. and Schaal, S., 2010, May. Inverse dynamics control of floating base systems using orthogonal decomposition. In 2010 IEEE international conference on robotics and automation (pp. 3406-3412). IEEE. - citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.212.3601&rep=re

Thank you!

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