

Lecture 2: Inverse Kinematics

Iñigo Iturrate

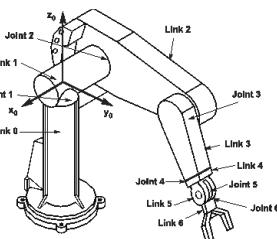
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About Me

- BEng Industrial Electronics & Automation



- MSc Robot Systems Engineering (SDU)
 - Student worker at Universal Robots for ~1 year



- Employed at Universal Robots (~4 years)
 - Software developer (½ year)
 - Industrial PhD with UR/SDU (3½ years)



- Postdoctoral Researcher at SDU (2019 – 2021)
- Assistant Professor at SDU (2021 – present)

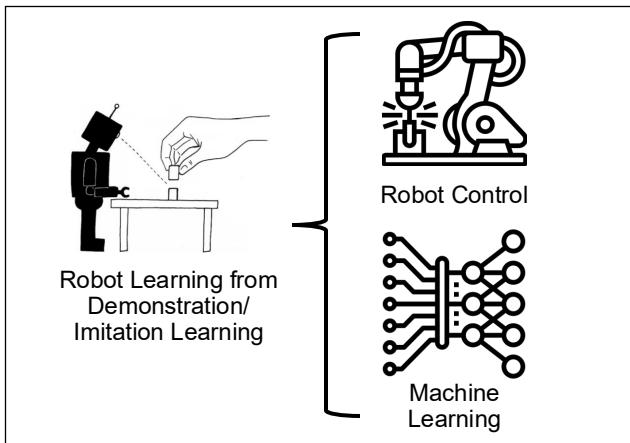


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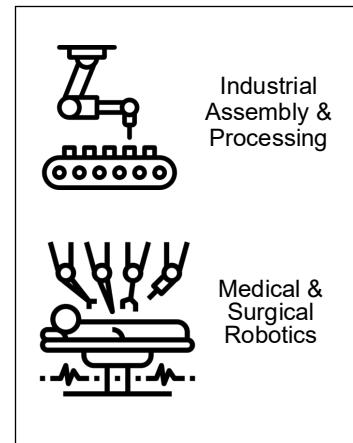


My Research

Methodology



Applications

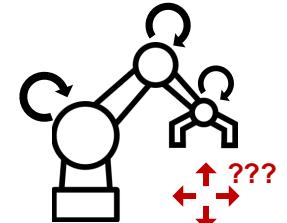


Previously you have seen/recapped...

We can describe a robot's **kinematic structure** using DH parameters.

Forward Kinematics describes how **motions of the joints** translate into motion of the end-effector:

- We can obtain the **Forward Kinematics from the DH parameters**.
- We can also derive the **forward kinematics from transformations** between frames.



forward için joint angle açıları varca tcp yani end pointi bulmak için kullanıyoruz

Today...

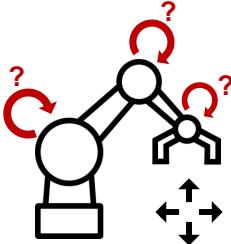
we know tcp so we want to find joint angle's

What if we want to do **the opposite**?

In most tasks, we will have a **defined task motion** that the robot needs to follow in Cartesian space, **not a defined joint space motion**.

The problem then becomes:

"Given a **target position and orientation** of the robot **end-effector**, what joint position values will **reach that target**?"



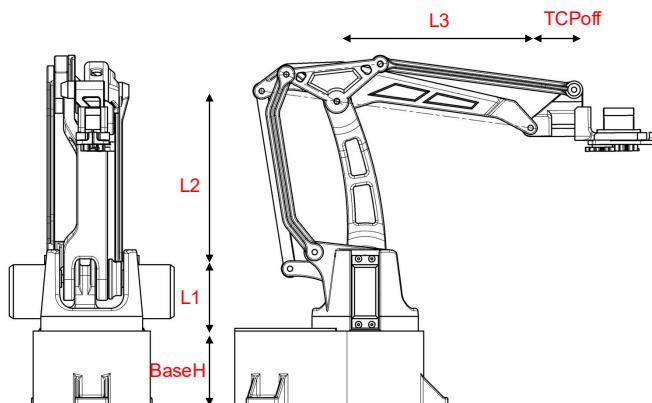
Let's start with a warming-up exercise

→ Derive the DK for the robot in the figure and implement it using the provided framework.

→ link lengths are:

- $L_1 = 0.054$
- $L_2 = 0.136$
- $L_3 = 0.148$
- $BaseH = 0.05$
- $TCPoff = 0.04$
- $q_0 = [\pi/2, \pi/2, \pi/2]$

20 min



Topics for Today

Part I: Joint and Cartesian Spaces

Part II: Analytical Inverse Kinematics

Part III: Practical Considerations

Part IV: Numerical Inverse Kinematics

Part I: Joint and Cartesian Spaces & Mapping between Them



Joint & Cartesian Spaces

In robotics, we are constantly working with **two different spaces**:

- **Joint (or Operational) space**

- The space where the robot actually operates.
- Defines **how its joints** (and their associated **motors**) **actually move**.
- It is the space **we have direct (low-level) control over**.

- **Cartesian (or Task) space**

- “Our world”, where we want the robot to actually act and perform a task.
- Defines **how the end-effector/tool** of the robot **should move**.
- We **cannot control it directly** (at a low level).

Cartesian (Task) Space

The **dimensionality** of the space **will depend on** the kind of task. Usually, we will work in a 3D environment.

For a 3D environment:

- **Poses** in Cartesian space are usually described by $\mathbf{x} \in \mathbb{R}^6$:

$$\mathbf{x} = \begin{bmatrix} \mathbf{p} \\ \boldsymbol{\phi} \end{bmatrix}$$

Where:

- $\mathbf{p} \in \mathbb{R}^3$ is a position vector $[p_x, p_y, p_z]^T$
- $\boldsymbol{\phi} \in \mathbb{R}^3$ or $\boldsymbol{\phi} \in SO(3)$ is an orientation vector $[\phi_x, \phi_y, \phi_z]^T$ (which can be in many representations)

- **Velocities** are usually given by $\dot{\mathbf{x}} \in \mathbb{R}^6$:

$$\dot{\mathbf{x}} = \mathbf{v} = \begin{bmatrix} \dot{\mathbf{p}} \\ \dot{\boldsymbol{\phi}} \end{bmatrix} \text{ or } \dot{\mathbf{x}} = \begin{bmatrix} \dot{\mathbf{p}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix}$$

Where:

- $\dot{\boldsymbol{\phi}} \in \mathbb{R}^3$ is the time-derivative of the orientation vector
- $\dot{\boldsymbol{\omega}} \in \mathbb{R}^3$ is an angular velocity

- **Accelerations** are usually given by $\ddot{\mathbf{x}} \in \mathbb{R}^6$:

$$\ddot{\mathbf{x}} = \mathbf{a} = \begin{bmatrix} \ddot{\mathbf{p}} \\ \ddot{\boldsymbol{\phi}} \end{bmatrix} \text{ or } \ddot{\mathbf{x}} = \begin{bmatrix} \ddot{\mathbf{p}} \\ \ddot{\boldsymbol{\omega}} \end{bmatrix}$$

Joint (Configuration) Space

The **dimensionality** of the space **will depend on the number and kind of joints** (i.e. DOF) in the robot.

For an n -DOF robot:

- **Positions** in joint space are given by $\mathbf{q} \in \mathbb{R}^n$:

$$\mathbf{q} = \begin{bmatrix} q_1 \\ \vdots \\ q_n \end{bmatrix}$$

Where each q_i is:

- An angle θ for revolute joints
- A displacement d for prismatic joints

- **Velocities** are given by $\dot{\mathbf{q}} \in \mathbb{R}^n$:

$$\dot{\mathbf{q}} = \begin{bmatrix} \dot{q}_1 \\ \vdots \\ \dot{q}_n \end{bmatrix}$$

- **Accelerations** are given by $\ddot{\mathbf{q}} \in \mathbb{R}^n$:

$$\ddot{\mathbf{q}} = \begin{bmatrix} \ddot{q}_1 \\ \vdots \\ \ddot{q}_n \end{bmatrix}$$

Note: Since we often work with robots with only revolute joints, joint positions are often denoted:

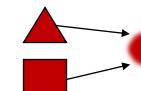
$$\boldsymbol{\theta} = \begin{bmatrix} \theta_1 \\ \vdots \\ \theta_n \end{bmatrix}$$

Different Cases with Mappings

One-to-one:



Many-to-one:



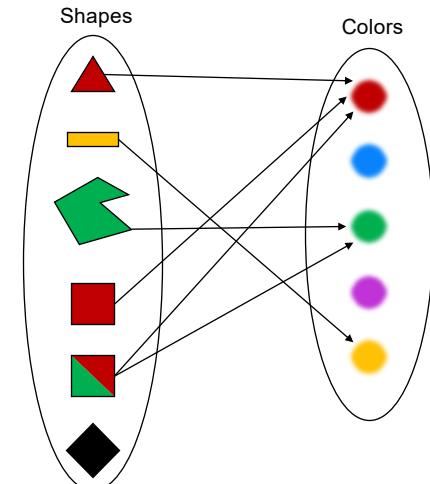
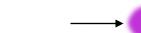
One-to-many:



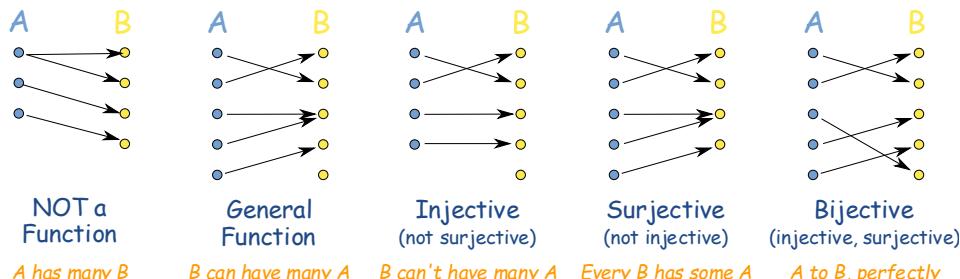
One-to-none:



None-to-one:



Different Cases with Mappings (More Formally)



Source: <https://www.mathsisfun.com/sets/injective-surjective-bijective.html>

Forward Kinematics (Joint → Cartesian)

Forward Kinematics is the name given to the **mapping** from joint space to Cartesian space.

In other words, if we know the position of the joints, what is the position of the end-effector?

This is the easy problem.

Why? Because the mappings will be:

- One-to-one
 - Many-to-one
 - None-to-one
-
- The diagrams show the relationship between Joint Space and Cartesian Space:
- One-to-one:** A single yellow square in Joint Space maps to a single yellow circle in Cartesian Space.
 - Many-to-one:** Two red shapes (a triangle and a square) in Joint Space both map to a single red circle in Cartesian Space.
 - None-to-one:** A purple circle in Joint Space maps to no shape in Cartesian Space.

Inverse Kinematics (Cartesian → Joint)

Inverse Kinematics is the name given to the **mapping** from Cartesian space to joint space.

In other words, if we know the position of the end-effector, how should we place the joints?

This is the HARD problem.

Why? Because the mappings will be:

- One-to-one
 - One-to-many
 - One-to-none
-
- The diagram shows the relationship between Cartesian Space and Joint Space:
- One-to-one:** A single yellow circle in Cartesian Space maps to a single yellow square in Joint Space.
 - One-to-many:** Two red circles in Cartesian Space both map to two red shapes (a triangle and a square) in Joint Space.
 - One-to-none:** A purple circle in Cartesian Space maps to no shape in Joint Space.
- And this can be nasty!**

Part II: Analytical Inverse Kinematics

Inverse Kinematics as a Mathematical Problem

The forward kinematics of a robot are specified by a transformation matrix: ${}^{Base}T(\theta) = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Let's take a Universal Robots 6R manipulator as an example.

We can write a **system of 12 equations with 6 unknowns**¹:

$$\begin{bmatrix} r_{11} \\ r_{12} \\ \vdots \\ p_z \end{bmatrix} = \begin{bmatrix} \cos(\theta_6)(\sin(\theta_1)\sin(\theta_5) + \cos(\theta_2 + \theta_3 + \theta_4)\cos(\theta_1)\cos(\theta_5)) - \sin(\theta_2 + \theta_3 + \theta_4)\cos(\theta_1)\sin(\theta_6) \\ -\sin(\theta_6)*(\sin(\theta_1)*\sin(\theta_5) + \cos(\theta_2 + \theta_3 + \theta_4)\cos(\theta_1)*\cos(\theta_5)) - \sin(\theta_2 + \theta_3 + \theta_4)\cos(\theta_1)\cos(\theta_6) \\ \vdots \\ d_1 + d_5(\sin(\theta_2 + \theta_3)\sin(\theta_4) - \cos(\theta_2 + \theta_3)\cos(\theta_4)) + a_3\sin(\theta_2 + \theta_3) + a_2\sin(\theta_2) - d_6\sin(\theta_5)(\cos(\theta_2 + \theta_3)\sin(\theta_4) + \sin(\theta_2 + \theta_3)\cos(\theta_4)) \end{bmatrix}$$

Solving this for $[\theta_1, \theta_2, \dots, \theta_6]$ will give us the Inverse Kinematics.

Only 3 of the 9 equations for the rotation are independent → We end up with 6 equations/6 unknowns.



¹This comes from the FK, from combining the transformation matrices from the DH parameters.

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Exercise: IK of 2R Planar Manipulator

Objective: Obtain (q_1, q_2)

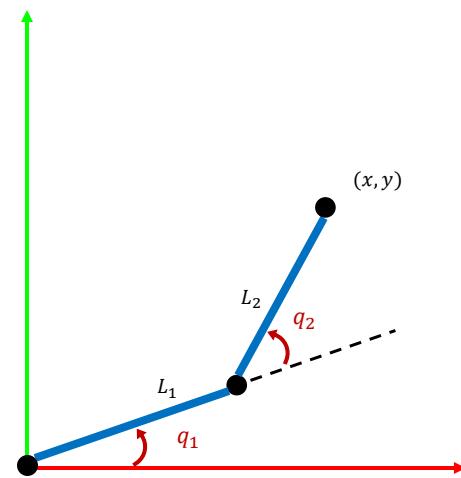
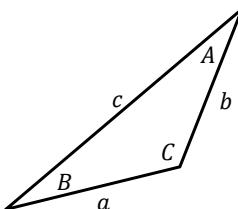
Given:

- End-effector position: (x, y)
- Length of links: L_1 and L_2

Exercise: 10-15 minutes

Hint: Use the rule of cosines:

$$\begin{aligned} a^2 &= b^2 + c^2 - 2bc \cos(A) \\ b^2 &= a^2 + c^2 - 2ac \cos(B) \\ c^2 &= a^2 + b^2 - 2ab \cos(C) \end{aligned}$$



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Closed-form vs. Numerical Solutions

Note that the equations IK are **non-linear and transcendental!**

There are **two main approaches** to solving the **inverse kinematics** problem:

- **Closed-form:** An analytical solution based on the forward kinematics transform equations.
 - + Fast to compute
 - + Exact
 - Does not exist for all robots
 - Can be complex to calculate
 - Needs to be calculated for each specific robot
- **Numerical:** A numerical solution based on an approximation and iterative attempts.
 - + Possible for all robots
 - + The same method can be used generally for any robot
 - Slow to compute
 - Inexact

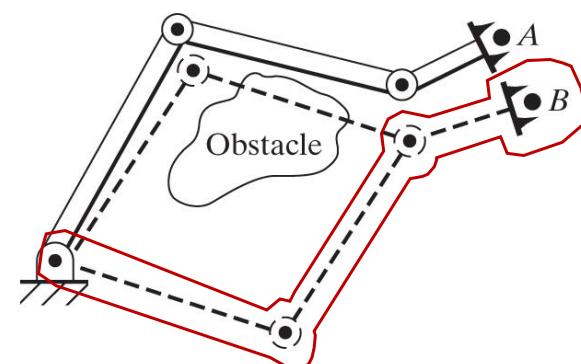
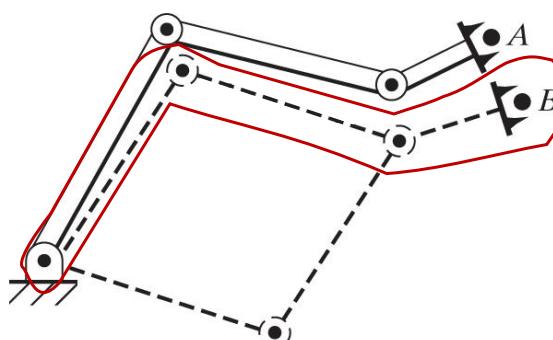


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Choice of IK Solutions

Notice in the previous slides that **there are multiple solutions** for the **same target pose**.

Different tasks will dictate a **different choice of IK solution**:



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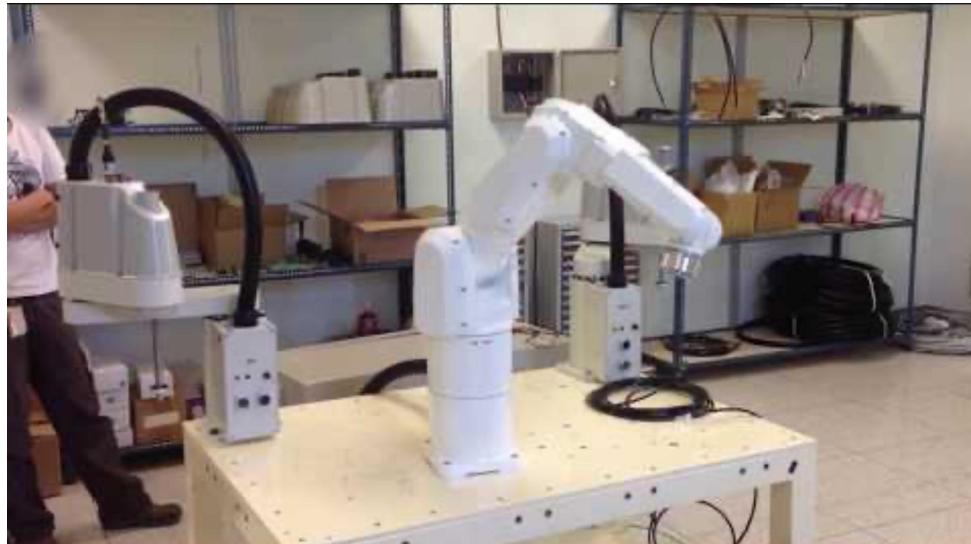
DOF and Number of IK Solutions

The number of **DOF** of the robot will greatly **affect the number of IK solutions**.

For a 3D Cartesian space with 3-DOF position + 3-DOF orientation and an n -DOF robot:

- $n < 6$: Will often run into the problem of not having a solution
- $n = 6$: Will (in theory) be the minimum to cover the entire space:
 - Some points will have **multiple solutions** (up to 8)
 - Some points will have a **single solution**
 - Some points will have **no solutions** (singularities)
- $n > 7$: Will be redundant (always multiple solutions).

Example: Multiple IK Solutions (7-DOF)



Example – Multiple IK Solutions: UR (6-DOF)

Pattern	Shoulder	Elbow	Wrist	Figure1 (Tool Down)
1	Left Side	Down	Tool Down: Outer	
2	Left Side	Down	Tool Down: Inner	
3	Left Side	UP	Tool Down: Outer	
4	Left Side	UP	Tool Down: Inner	

Pattern	Shoulder	Elbow	Wrist	Figure1 (Tool Down)
5	Right Side	UP	Tool Down: Inner	
6	Right Side	UP	Tool Down: Outer	
7	Right Side	Down	Tool Down: Inner	
8	Right Side	Down	Tool Down: Outer	

Part III: The Jacobian Matrix & Differential Kinematics

What do we want?

The **Forward Kinematics** allow us to relate joint positions to end-effector poses.

What if we want to relate joint velocities to end-effector velocities?

$$\dot{x} = \begin{bmatrix} ? & \dots & ? \\ \vdots & \ddots & \vdots \\ ? & \dots & ? \end{bmatrix} \dot{q}$$

Get end-effector velocity here Insert joint velocity vector here
Do some sorcery here
(This sorcery is called the Jacobian Matrix)

The Jacobian Matrix

The **Jacobian matrix** is a multidimensional form of the derivative. It is a **matrix of partial derivatives**.

If we have, e.g. 6 functions of 6 variables each:

$$\left. \begin{array}{l} y_1 = f_1(x_1, x_2, x_3, x_4, x_5, x_6) \\ y_2 = f_2(x_1, x_2, x_3, x_4, x_5, x_6) \\ \vdots \\ y_6 = f_6(x_1, x_2, x_3, x_4, x_5, x_6) \end{array} \right\} \text{Which we can re-write: } y = F(x)$$

And we want to **calculate the differentials** of each function based on the input:

$$\left. \begin{array}{l} \delta y_1 = \frac{\partial f_1}{\partial x_1} \delta x_1 + \frac{\partial f_1}{\partial x_2} \delta x_2 + \dots + \frac{\partial f_1}{\partial x_6} \delta x_6 \\ \delta y_2 = \frac{\partial f_2}{\partial x_1} \delta x_1 + \frac{\partial f_2}{\partial x_2} \delta x_2 + \dots + \frac{\partial f_2}{\partial x_6} \delta x_6 \\ \vdots \\ \delta y_6 = \frac{\partial f_6}{\partial x_1} \delta x_1 + \frac{\partial f_6}{\partial x_2} \delta x_2 + \dots + \frac{\partial f_6}{\partial x_6} \delta x_6 \end{array} \right\} \text{Which we can re-write: } \delta y = J(x) \delta x$$

$$J(x) = \begin{bmatrix} \frac{\partial f_1}{\partial x_1}(x) & \frac{\partial f_1}{\partial x_2}(x) & \dots & \frac{\partial f_1}{\partial x_6}(x) \\ \frac{\partial f_2}{\partial x_1}(x) & \frac{\partial f_2}{\partial x_2}(x) & \dots & \frac{\partial f_2}{\partial x_6}(x) \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_6}{\partial x_1}(x) & \frac{\partial f_6}{\partial x_2}(x) & \dots & \frac{\partial f_6}{\partial x_6}(x) \end{bmatrix}$$

The Forward Velocity Kinematics Equation

Now let us put this in the **context of our robotics problem**:

From the **definition** of Jacobian:

$$\frac{\partial x}{\partial q} = J(q)$$

By applying the **chain rule**:

$$\frac{\partial x}{\partial q} \frac{dq}{dt} = J(q) \frac{dq}{dt}$$

Re-arranging:

$$\frac{dx}{dt} = J(q) \frac{dq}{dt}$$

$$\dot{x} = J(q) \dot{q}$$



Exercise: Jacobian for a 2R Planar manipulator

Remember: the forward kinematics of a 2R manipulator are given by:

$$\begin{aligned} x &= L_1 \cos(q_1) + L_2 \cos(q_1 + q_2) \\ y &= L_1 \sin(q_1) + L_2 \sin(q_1 + q_2) \end{aligned}$$

Objective: Calculate $J(q_1, q_2)$

Exercise: 5 minutes

Hint: By definition, the Jacobian is:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial q_1} & \frac{\partial x}{\partial q_2} \\ \frac{\partial y}{\partial q_1} & \frac{\partial y}{\partial q_2} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}$$

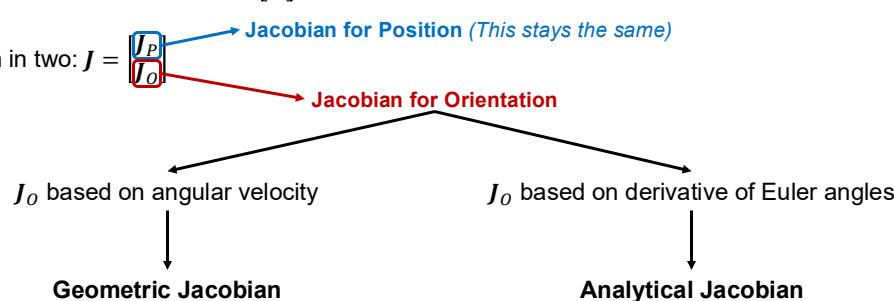
The Two Jacobians in Robotics

What about orientation?

Remember that we can describe Cartesian-space velocity in (at least) **two ways**, depending on how we describe **rotational velocity**:

- Using **angular velocity**: $\dot{x} = \begin{bmatrix} \dot{p} \\ \omega \end{bmatrix}$
- Using the **derivative of Euler angles**: $\dot{x} = v = \begin{bmatrix} \dot{p} \\ \dot{\phi} \end{bmatrix}$

We can split the Jacobian in two: $J = \begin{bmatrix} J_P \\ J_O \end{bmatrix}$



Calculating the Positional Jacobian Analytically

The **positional part** of the Jacobian, J_{Pi} , can instead be **calculated analytically**.

Given the **forward kinematics** transformation matrix:

$$_eT(\theta) = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Take the first three rows of the last column:

$${}_eP(\theta) = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \rightarrow J_P = \frac{\partial P}{\partial q} = \begin{bmatrix} \frac{\partial p_x}{\partial q_1} & \dots & \frac{\partial p_x}{\partial q_n} \\ \frac{\partial p_y}{\partial q_1} & \dots & \frac{\partial p_y}{\partial q_n} \\ \frac{\partial p_z}{\partial q_1} & \dots & \frac{\partial p_z}{\partial q_n} \end{bmatrix}$$

Do NOT do this by hand!
If you have the FK in symbolic MATLAB, call:
`J = jacobian(P)`

<https://se.mathworks.com/help/symbolic/sym.jacobian.html>

Building a Geometric Jacobian

We first **split the matrix** into (3×1) column vectors, J_{Pi} and J_{Oi} , where each element i represents the **contribution of a single joint q_i to either the position or orientation**:

$$J = \begin{bmatrix} J_{P1} & \dots & J_{Pn} \\ J_{O1} & \dots & J_{On} \end{bmatrix}$$

Then, for each joint i :

- Revolute:** $J_{Pi} = {}^0\hat{Z}_i \times ({}^0P_e - {}^0P_i)$
 $J_{Oi} = {}^0\hat{Z}_i$
 - Prismatic:** $J_{Pi} = {}^0\hat{Z}_i$
 $J_{Oi} = 0$
- ${}^0\hat{Z}_i = {}^0R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$
- 0P_e is the position of the end-effector
- 0P_i is the position of the origin of frame $\{i\}$

Forward and Inverse Differential Kinematics

Given the **forward differential kinematics** equation, and assuming that the **inverse of the Jacobian exists**, we can obtain the inverse differential kinematics equation:

$$\dot{x} = J(q)\dot{q} \longleftrightarrow \dot{q} = J^{-1}(q)\dot{x}$$

This is a **very important result in robotics**.

As we will see, the forward/inverse velocity kinematics equations are the **basis of numerical IK methods**.

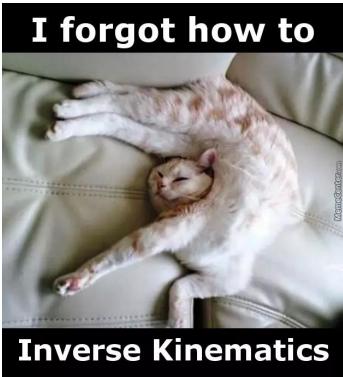
The Problem with the Jacobian Inverse

Consider the inverse velocity kinematics equation:

$$\dot{q} = J^{-1}(q)\dot{x}$$

Do you see any potential issues here?

Not all matrices have an inverse...
This does not always exist!



So... what happens then?

Singularities: Non-existence of inverse

When does the inverse of a matrix not exist?

Due to a **non-square** matrix:

- Example: **a redundant robot** (e.g. 7-DOF in a 3D space)

$$\dot{x} = J(q)\dot{q}$$



$$\begin{bmatrix} \dot{p} \\ \omega \end{bmatrix} = \begin{bmatrix} J_{P1} & \dots & J_{P7} \\ J_{O1} & \dots & J_{O7} \end{bmatrix} \begin{bmatrix} q_1 \\ \vdots \\ q_7 \end{bmatrix}$$

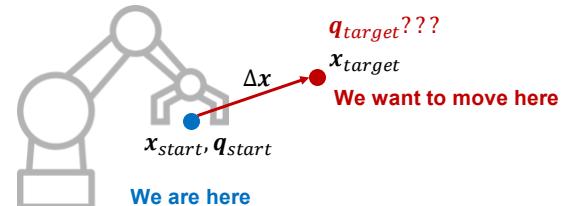
(6 × 1) (6 × 7) (7 × 1)

Due to a **rank-deficient square matrix** (**singularities!**) You will study this in detail in the coming lectures.

Part IV: Numerical Inverse Kinematics

Numerical Inverse Kinematics: Conceptually

1. We know: $x_{start}, q_{start}, x_{target}$
2. We want to find: q_{target}
3. We can calculate: $\Delta x = x_{target} - x_{start}$
4. We take Δx and split it in smaller segments:



5. We make a very small step in the direction of Δx :
 $dq(t) = J^{-1}(q)dx(t)$
 $q(t + dt) = q(t) + dq(t)dt$

What happens if, in step 5, the step size is not small enough?

What assumptions are we making (mathematically)?

Formally: Numerical IK using Newton-Raphson

Let us reformulate the IK as a **nonlinear optimization problem**. We have:

- A desired Cartesian space pose, x_d
- The desired IK solution, a set of joint angles, θ_d
- A **nonlinear** vector function that computes the FK, $f(\theta_d)$, where $f: \mathbb{R}^n \rightarrow \mathbb{R}^m$

We want: $x_d - f(\theta_d) = 0$ (*this is our objective function*)

We first apply Taylor expansion:

$$x_d = f(\theta_d) = f(\theta_0) + \left. \frac{\partial f}{\partial \theta} \right|_{\theta_0} (\theta_d - \theta_0) + \text{higher order terms}$$

$J(\theta_0)$

$$J(\theta_0)\Delta\theta = x_d - f(\theta_0) \quad \rightarrow \quad \Delta\theta = J^{-1}(\theta_0)(x_d - f(\theta_0))$$

By ignoring these, we are linearizing around θ_0

If we use this to take a **new step**: $\theta_1 = \theta_0 + \Delta\theta$, then this is **guaranteed to be closer to the solution**.

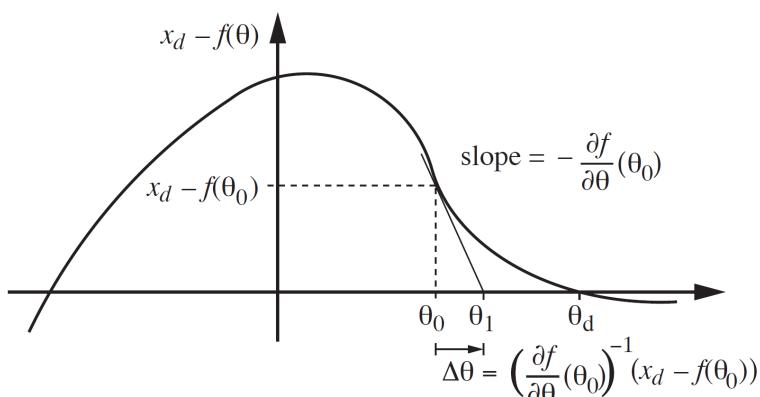
We can therefore **apply this recursively** until we are "close enough", i.e. $x_d - f(\theta_d) < \epsilon$.

Convergence to Different Solutions

Newton-Raphson is a **locally optimal** method.

It will **converge** to the solution **closest to the initial guess**.

It is therefore **highly-dependent on the initial guess**.



IK: Newton Raphson Algorithm

Algorithm 1 Newton-Raphson method for numerical IK

Require: θ , $x^* = f(\theta)$, x_d and $x_d \approx x^*$

Compute $\Delta x = x_d - x^*$

while $\|\Delta x\| > \epsilon$ do

 Compute $J(\theta)$

 Solve $J(\theta)\Delta\theta = \Delta x$ for $\Delta\theta$

$\theta := \theta + \Delta\theta$

 Compute $x^* = f(\theta)$

 Compute $\Delta x = x_d - x^*$

end while

What if the Jacobian is NOT square?

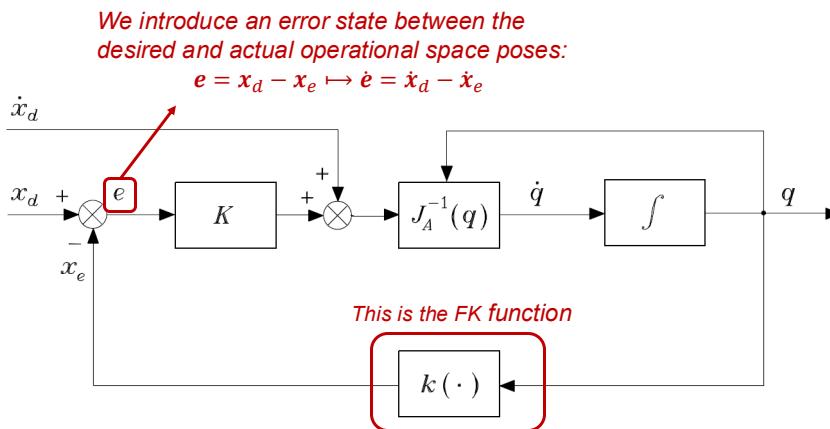
What do we do with robots whose Jacobians are not square, e.g. redundant robots?

- **Jacobian Transpose:** $\dot{q} = \alpha J^T \dot{x}$ (for some small $\alpha > 0$)
 - This is can behave "close enough" to the inverse assuming a small enough α .
We will see this in the coming slides
- **Jacobian (Moore-Penrose) Pseudoinverse:** $\dot{q} = J^\dagger \dot{x}$ (where \dagger is the pseudoinverse)
 - This is a generalization of the concept of inverse for non-square matrices: $J^\dagger = (JJ^T)^{-1}$
 - If J has full row rank, then $(JJ^T)^{-1}$ will always exist.

In MATLAB, J^\dagger can be calculated using `pinv()`:
https://se.mathworks.com/help/matlab/ref/pinv.html?s_tid=doc_ta

IK as a Control Problem

We can also reformulate inverse kinematics as a **control problem**:



Jacobian Transpose

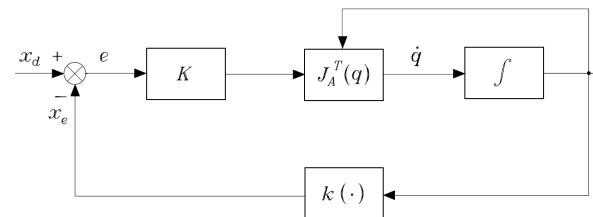
We may want a **computationally simpler** algorithm that **does not require linearization**.

This means that the **equations for the system will be non-linear**.

The joint velocities are given by:
 $\dot{q} = J_A^T(q)K\dot{e}$,

Using a **Lyapunov function**¹ we can prove that, if K is positive definite:

- For a constant reference, $\dot{x}_d = 0$, the system converges ($e = 0$).
- There is a case where the robot can stop before having converged with $e \neq 0$, but this only happens when the desired pose is unreachable.



Jacobian Inverse

Using differential kinematics, we re-write:
 $\dot{e} = \dot{x}_d - \dot{x}_e = \dot{x}_d - J_A(q)\dot{q}$

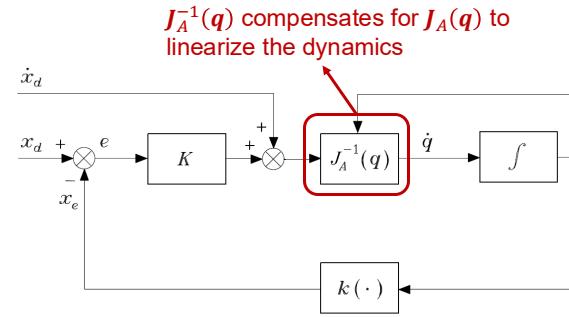
We relate \dot{q} to the e , to obtain a differential equation that describes the evolution of the error dynamics over time.

We want to choose a relationship between \dot{q} and e that ensures the error converges to 0.

If J_A is square and non-singular:
 $\dot{q} = J_A^{-1}(q)(\dot{x}_d + Ke)$

This leads to an equivalent linear system:
 $\dot{e} + Ke = 0 \rightarrow \dot{e} = -Ke$

If K is positive definite, the system is asymptotically stable.



If $\dot{x}_d = 0$, this is the same as the Newton-Raphson method

Second-Order Algorithm (I)

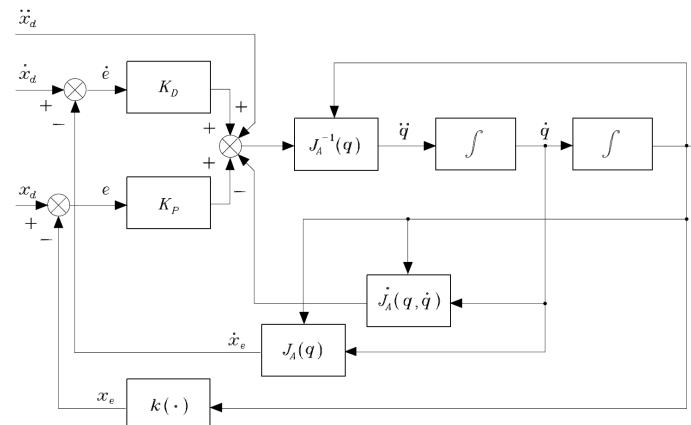
It might be necessary to **include accelerations** in the motion specification.

We can then specify the IK problem as a **second-order system**.

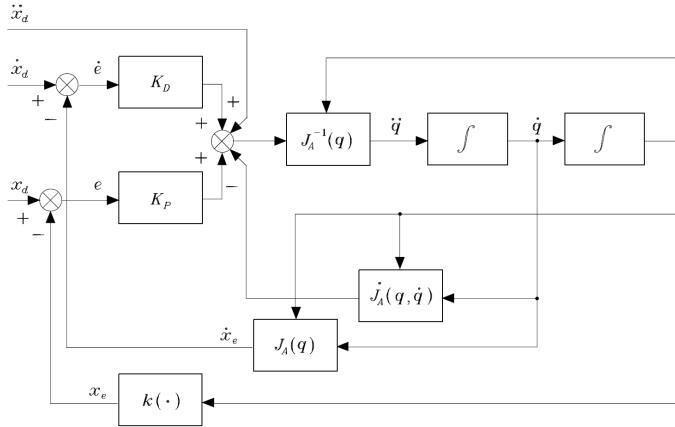
This is **related to the dynamical model**¹ of the manipulator which is also specified as a second-order system.

By differentiating $\dot{x}_e = J_A(q)\dot{q}$ we get:
 $\ddot{x}_e = J_A(q)\ddot{q} + \dot{J}_A(q,\dot{q})\dot{q}$

If $J_A(q)$ is invertible, then:
 $\ddot{q} = J_A^{-1}(q)(\ddot{x}_e - \dot{J}_A(q,\dot{q})\dot{q})$



Second-Order Algorithm (II)



Integrating \dot{q} numerically will lead to **drift**.

We consider the **acceleration error**:

$$\begin{aligned}\dot{e} &= \ddot{x}_d - \ddot{x}_e \\ \ddot{e} &= \ddot{x}_d - J_A(q)\ddot{q} - J_A(q, \dot{q})\dot{q}\end{aligned}$$

leading to the choice of **control law**:

$$\ddot{q} = J_A^{-1}(q)(\ddot{x}_d + K_D\dot{e} + K_P e - J_A(q, \dot{q})\dot{q})$$

Substituting, the **error dynamics** become:

$$\ddot{e} + K_D\dot{e} + K_P e = 0 \quad \boxed{\ddot{e} = -K_D\dot{e} - K_P e}$$

If K_D and K_P are **positive definite**, the system is **asymptotically stable**.

Recap: What have we learned today?

1. While FK is a relatively straightforward problem, IK is **more complicated**, as the mapping:
 - May have **multiple solutions**.
 - May have **no solutions**.
2. There exist **analytical** (exact, only exist for some robots) **and numerical** (approximation, exist for all robots) **solutions to the IK problem**.
3. The **Jacobian maps joint velocities to Cartesian-space velocities**. There exist two types:
 - **Geometric**: The orientational part is expressed as **angular velocities** (i.e. not the derivative of the orientation).
 - **Analytical**: The orientational part is **directly differentiated** from, e.g. Euler angles.
4. There are **multiple algorithms for numerical IK**, all of which **use the Jacobian**:
 - **Newton-Raphson**
 - **Jacobian (Pseudo-)Inverse**
 - **Jacobian Transpose**
 - **Second-Order Algorithms**

Thank you for today.

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