Infrastructure Robotics

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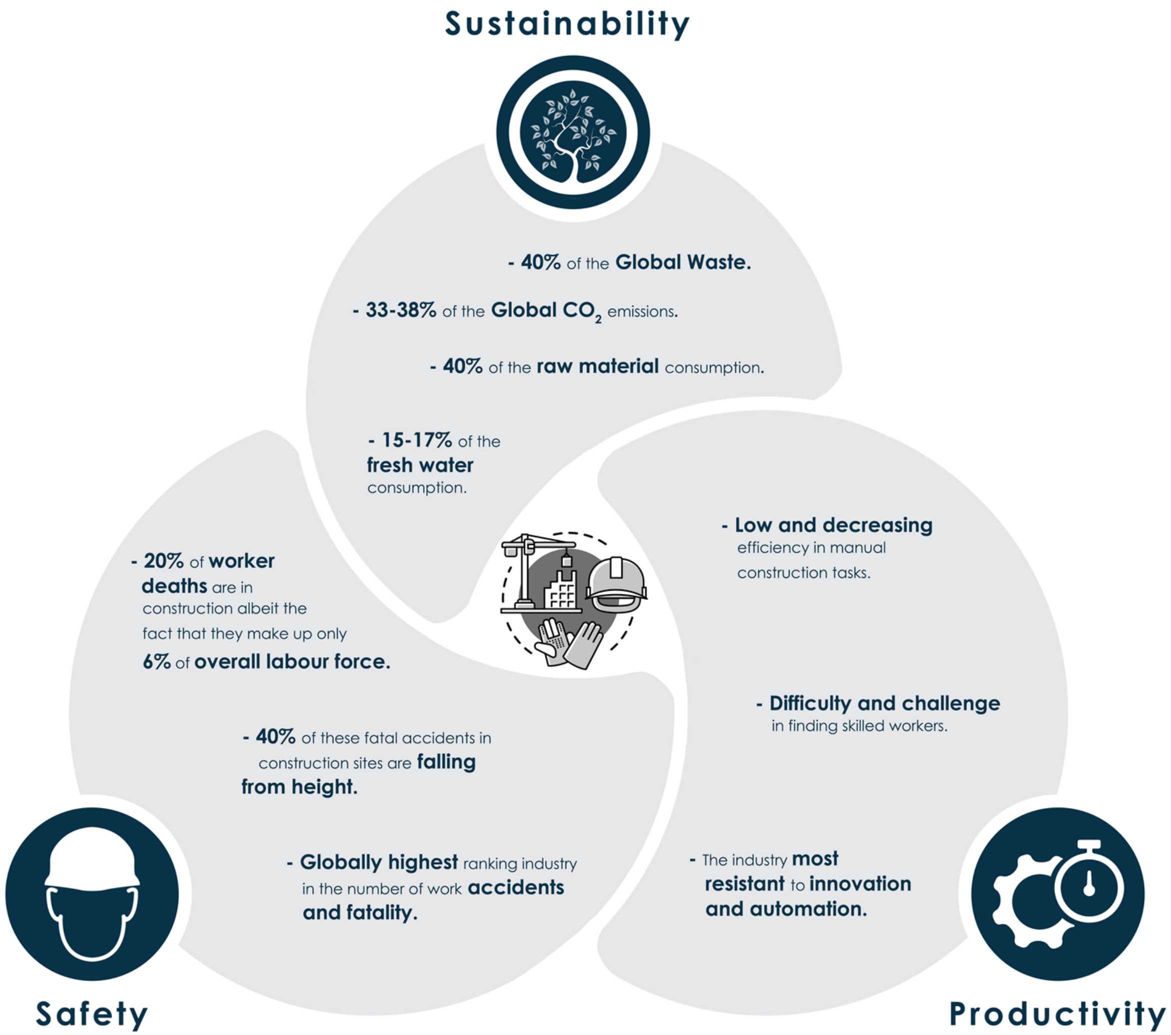
Lecture goals

- Understand the current state of the art in infrastructure robotics.
- Explore how different robotic systems can be used in csuch as aerial manipulators, perching drones, industrial climbers, and construction/landscaping robots.
- Learn the concept of robot degrees of freedom and how they relate to joint and task spaces.
- Develop an understanding of forward and inverse kinematics for robotic motion control.
- Identify and classify different types of robotic manipulators based on their structure and capabilities.

Motivation - Infrastructure



Main problems of the construction industry.

The construction chart book: The U.S. Construction Industry and its workers (2013). Silver Spring, MD: CPWR - The Center for Construction Research and Training.

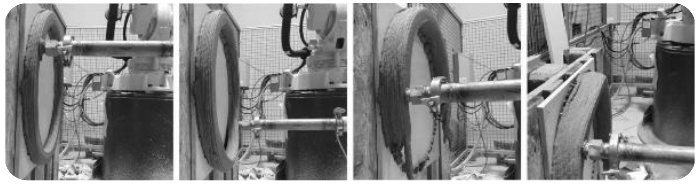
Illustration: Yusuf Furkan Kaya

Application – additive manufacturing

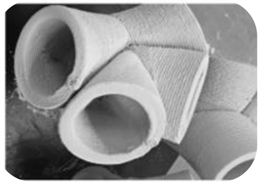
State-of-the-art Ground-based Robotic AM

© ICON 3D Concrete Printing

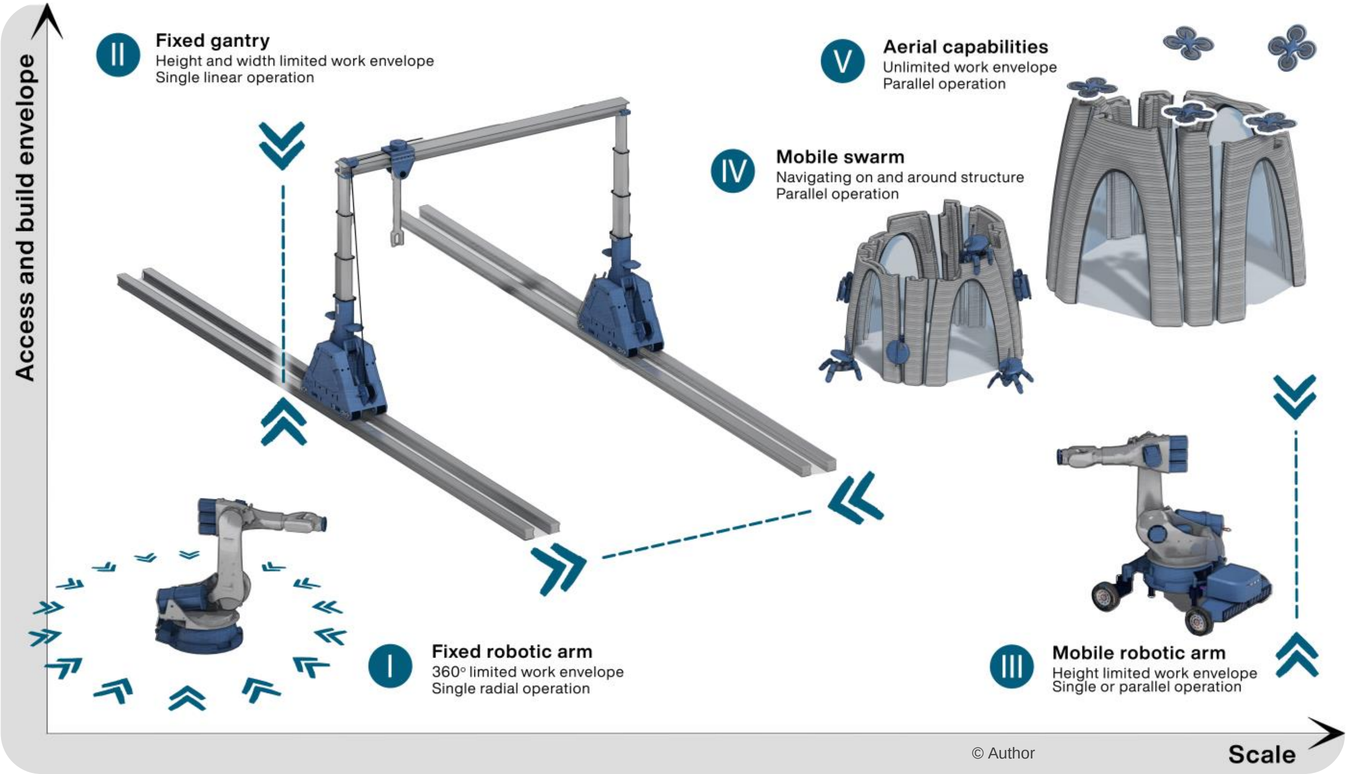
© CyBe Mobile Robot

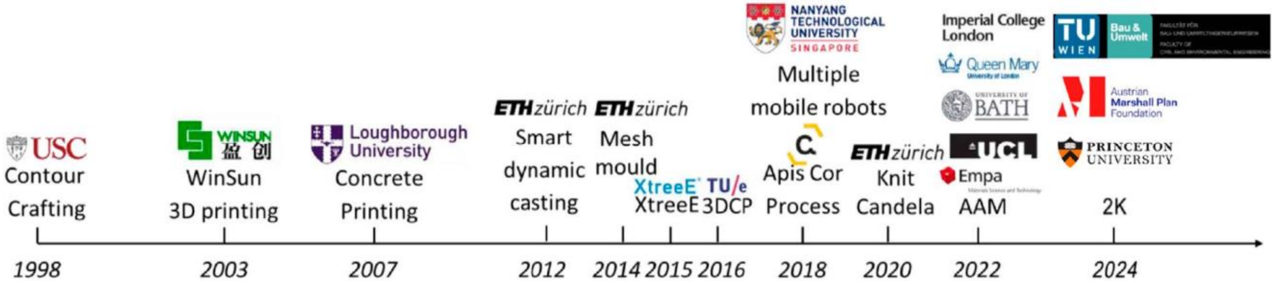


Carneau et al. Additive manufacturing of cantilever - From masonry to concrete 3D printing 2020.



Bhooshan et al. Function Representation for Robotic 3D Printed Concrete. 2019.





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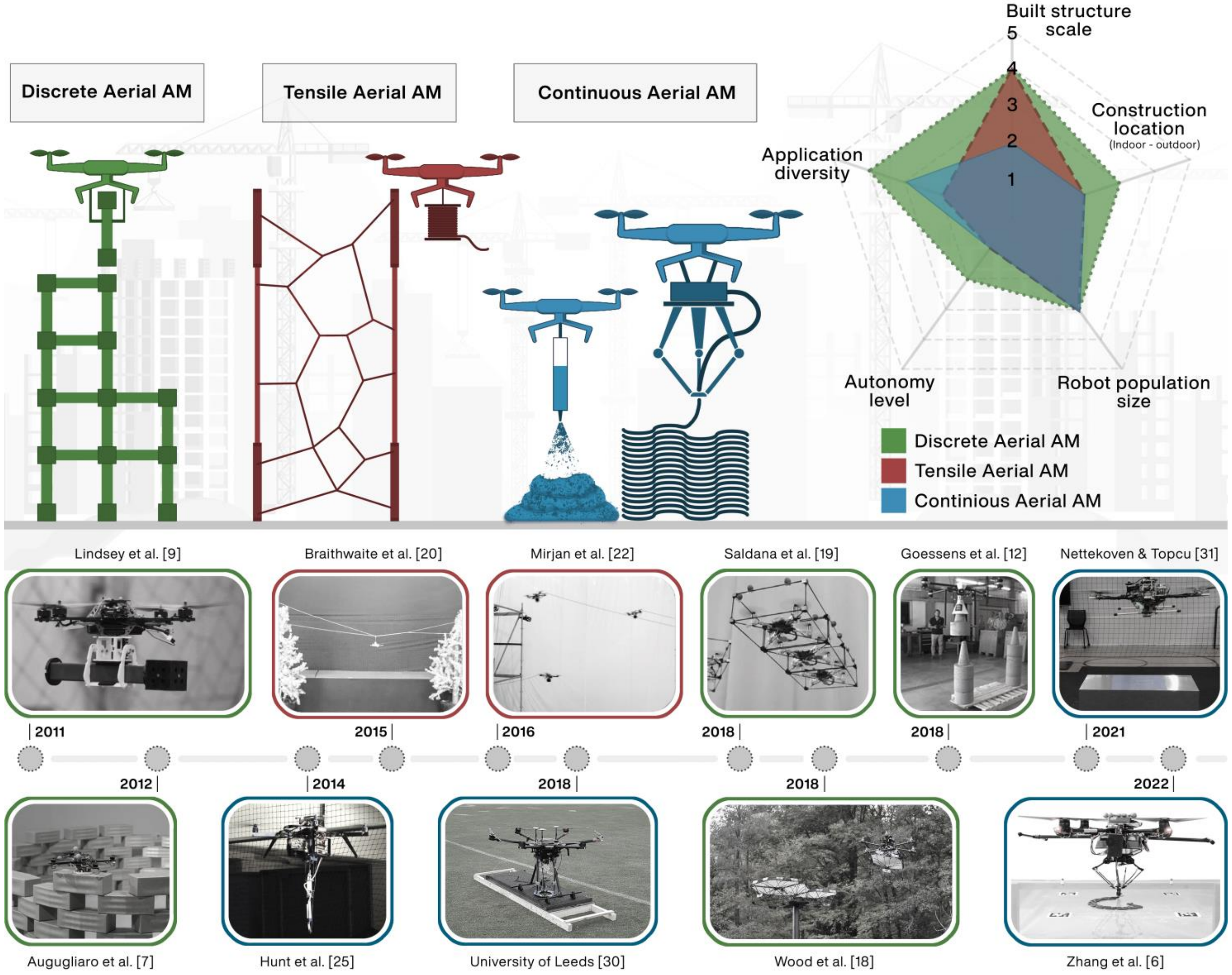
Dams B, Chen B, Kaya YF, Shepherd P, Kovac M and Ball RJ (2025) The rise of aerial additive manufacturing in construction: a review of material advancements. **Frontiers in Materials** 11:1458752. doi: 10.3389/fmats.2024.1458752

Aerial Additive Manufacturing (Aerial AM)



Conceptual representation of existing AAMs, the radar chart analysis of them, and their chronological representation.

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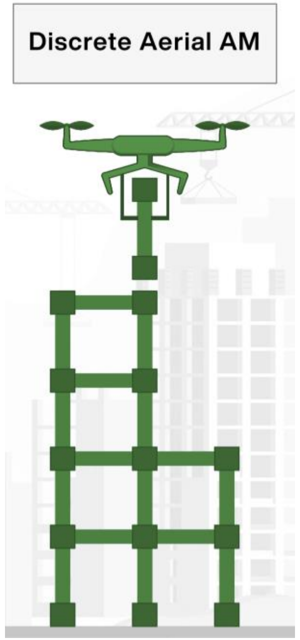
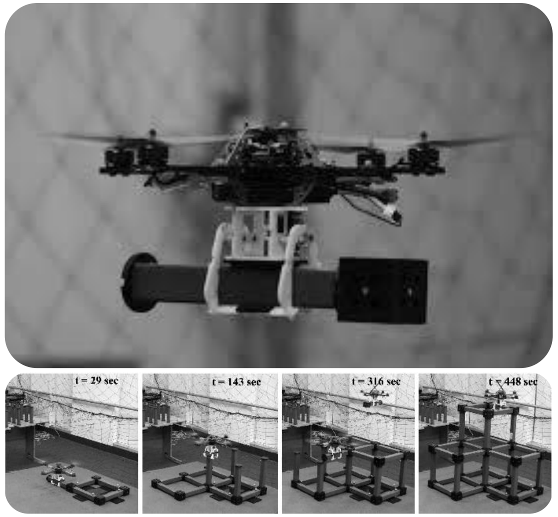
Kaya, Y. F., Orr, L., Kocer, B. B., Pawar, V., Stuart-Smith, R. and Kovac, M. Aerial Additive Manufacturing: Towards On-site Building Construction with Aerial Robots **(To appear | Science Robotics)**

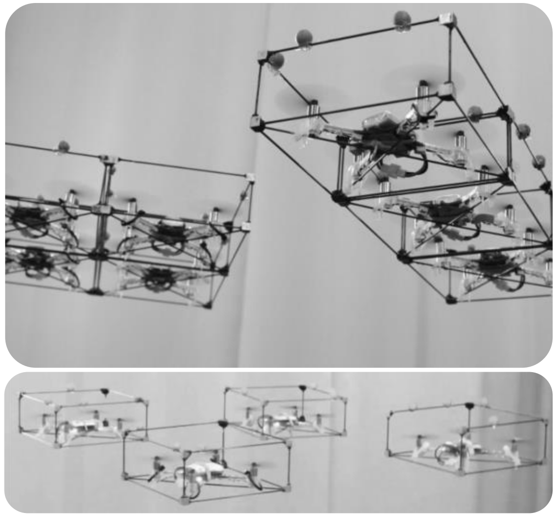
Discrete Aerial AM



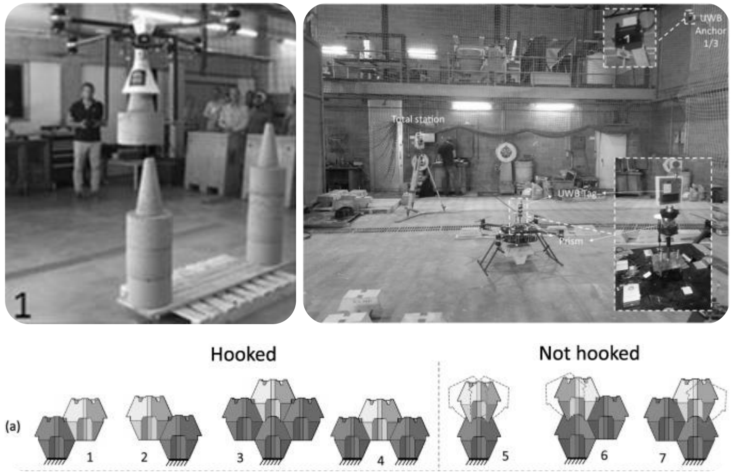
Lindsey et al. - Construction of Cubic Structures



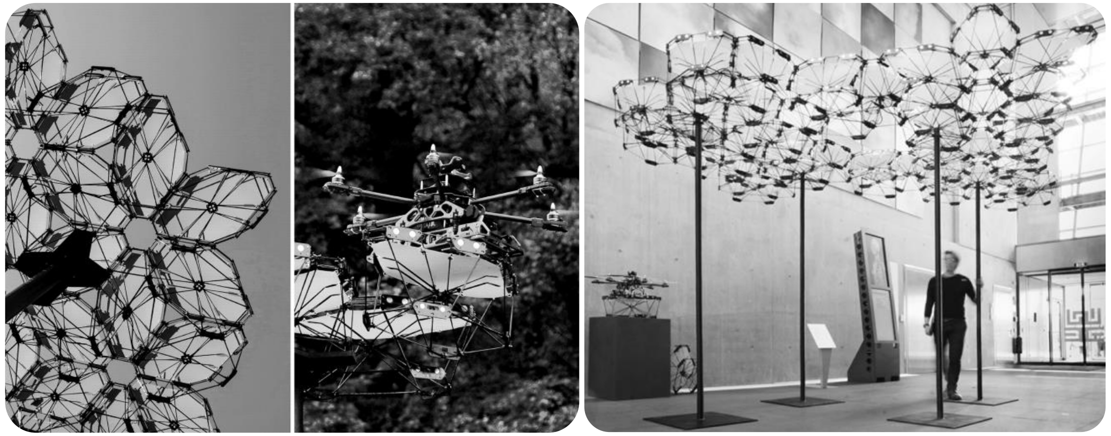
Saldana et al. - Modquad



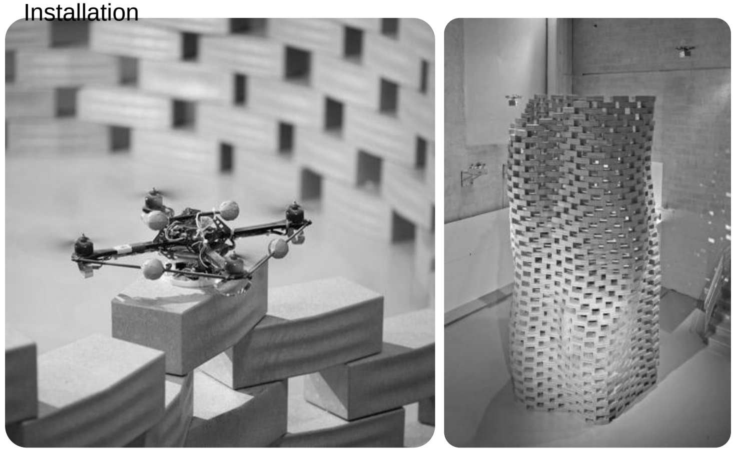
Goessens et al. – Feasibility Study of Drone-based Masonry



Wood et al. – Cyber Physical Macro Material as a UAV [re]Configurable Architectural System



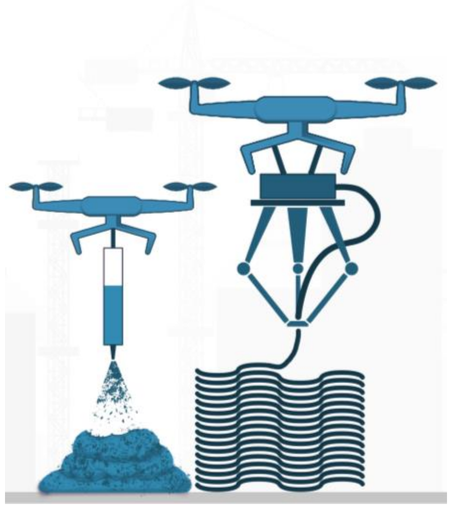
Augugliaro et al. – The Flight Assembled Architecture Installation



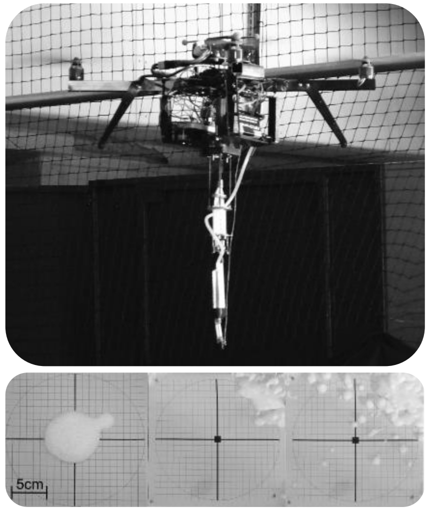
Kaya, Y. F., Orr, L., Kocer, B. B., Pawar, V., Stuart-Smith, R. and Kovac, M. Aerial Additive Manufacturing: Towards On-site Building Construction with Aerial Robots **(To appear | Science Robotics)**

Continuous Aerial AM

Continuous Aerial AM

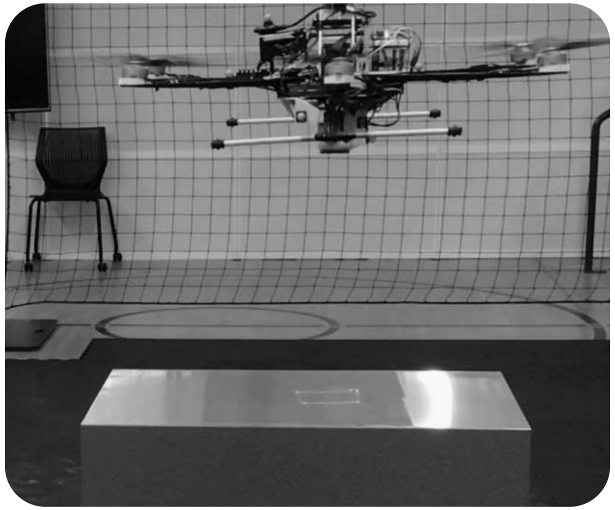


Hunt et al. - 3D Printing with Flying Robots

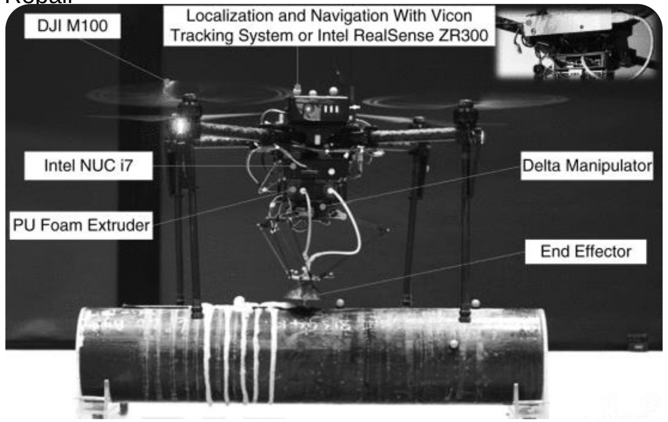


Eskandari et al. – Self-repairing Cities

Nettekoven and Topcu – A 3d Printing Hexacopter



Chermprayong et al. – An Integrated Delta Manipulator for Aerial Repair



Zhang et al. – Aerial Additive Manufacturing

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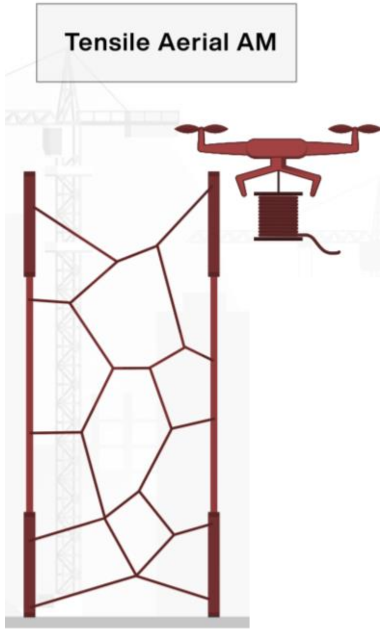
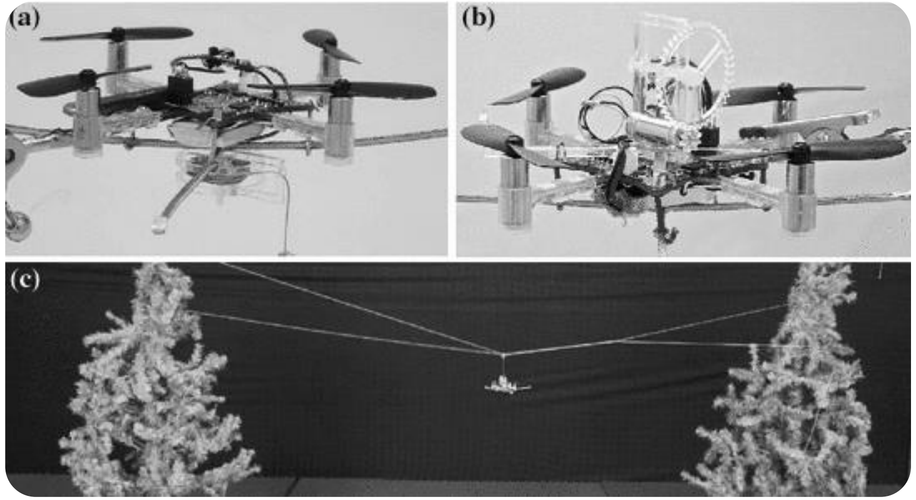
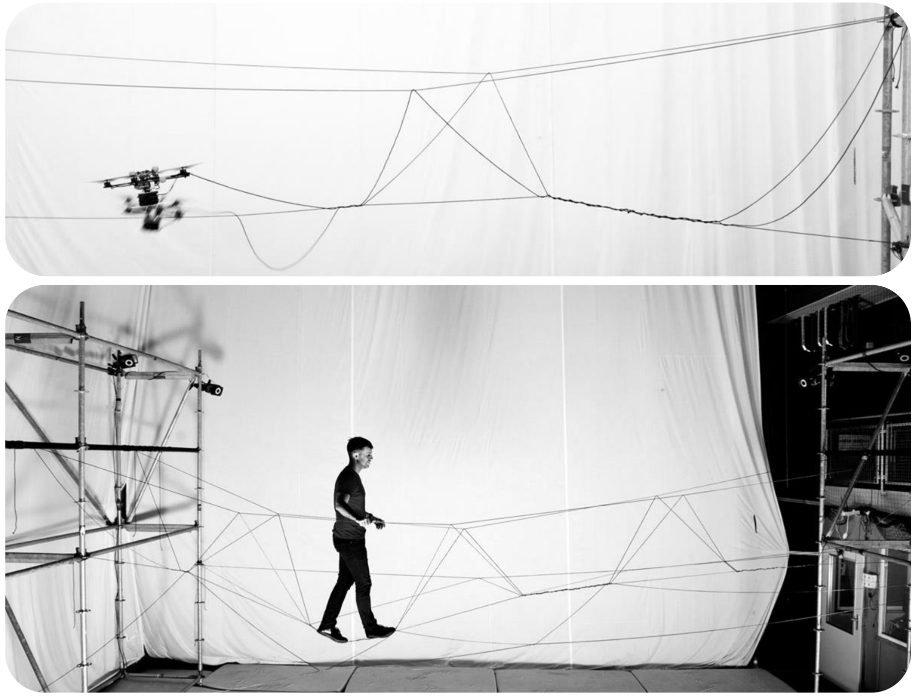
Tensile Aerial AM



Braithwaite et al. - Tensile Web Construction and Perching



Mirjan et al. – Building a Tensile Bridge with Flying Vehicles



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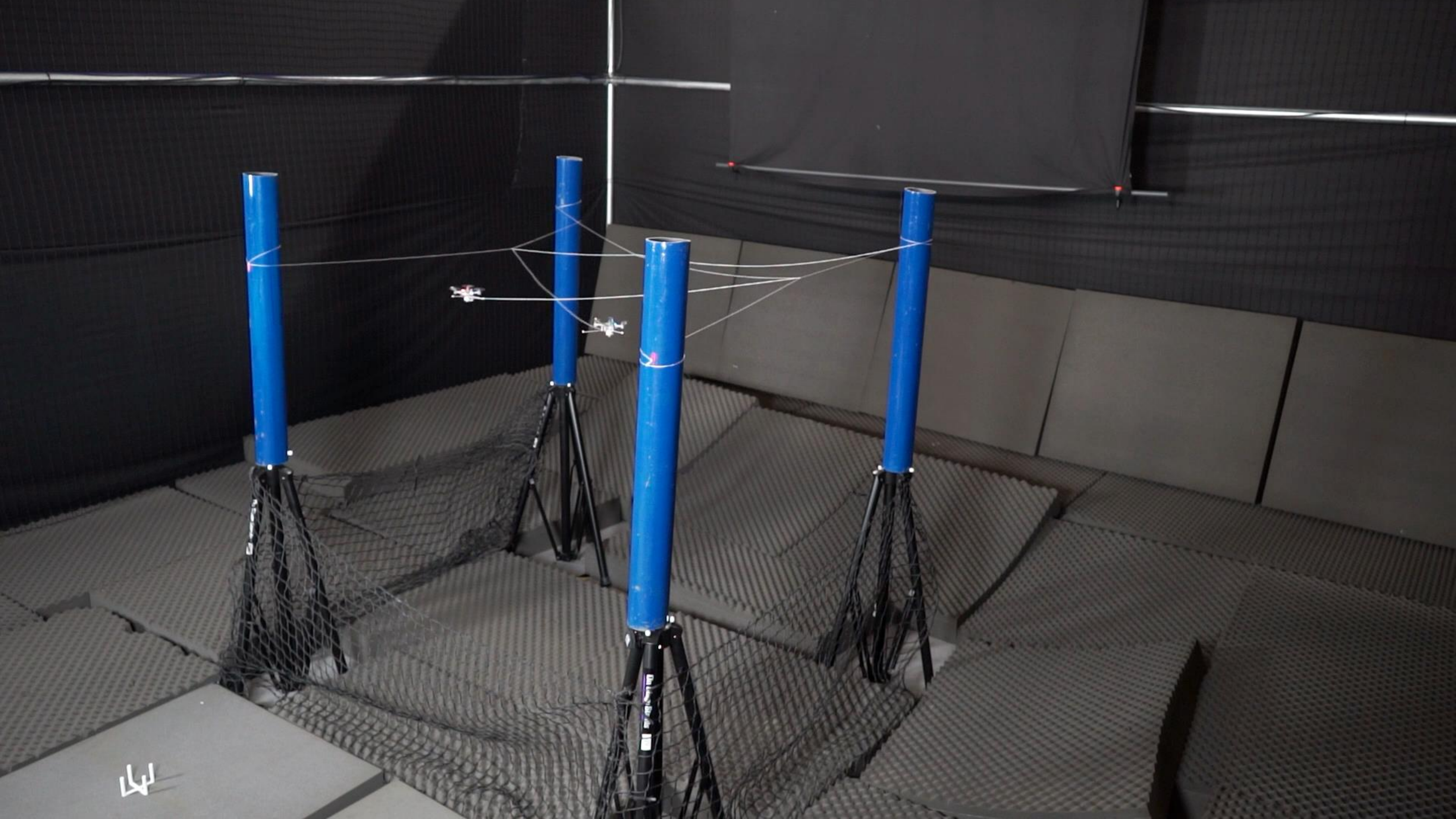
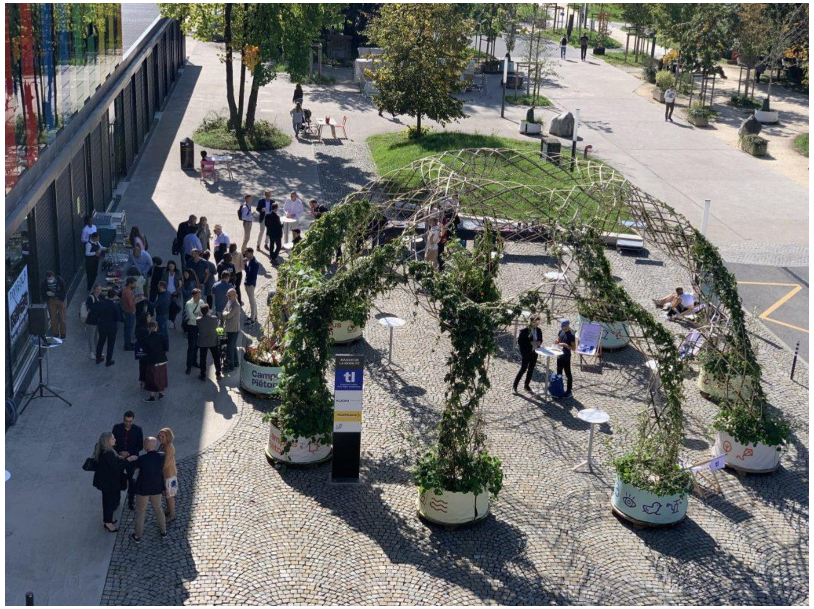
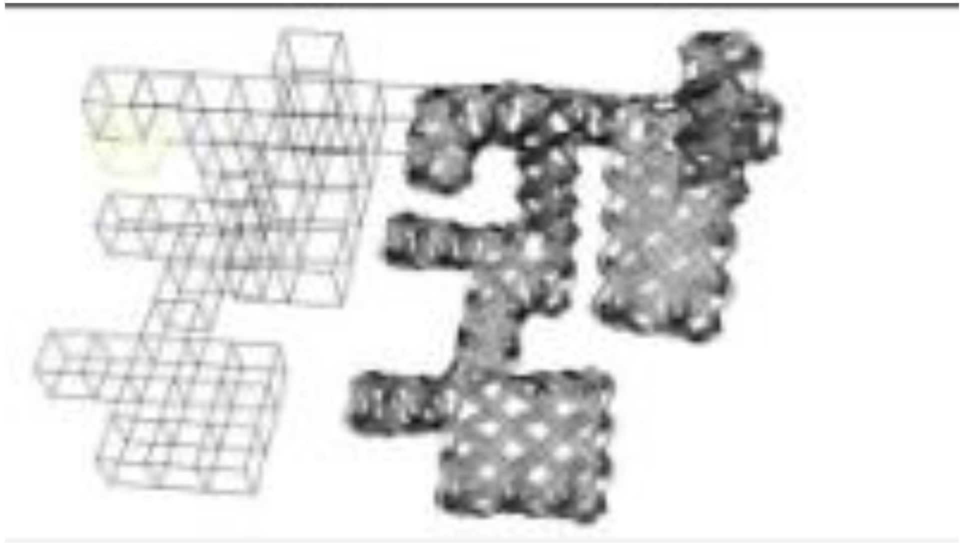


Vines – living infrastructure

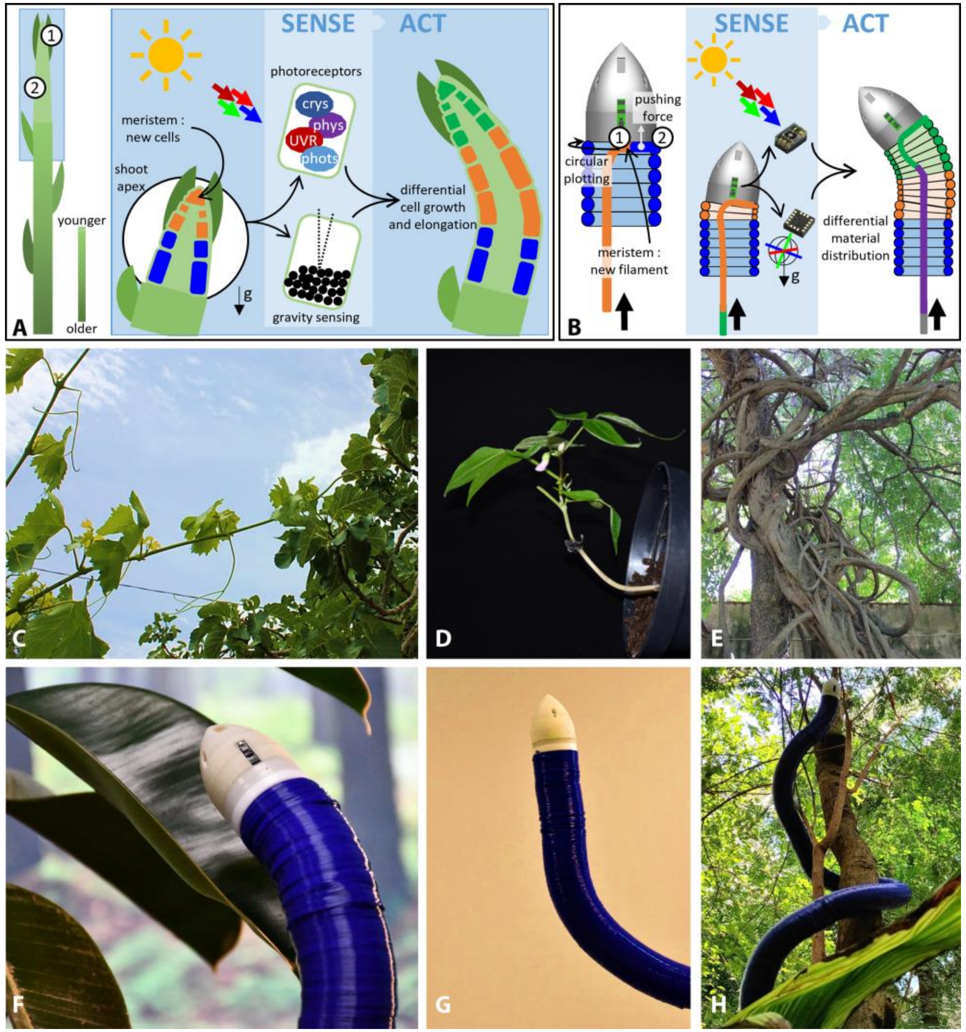


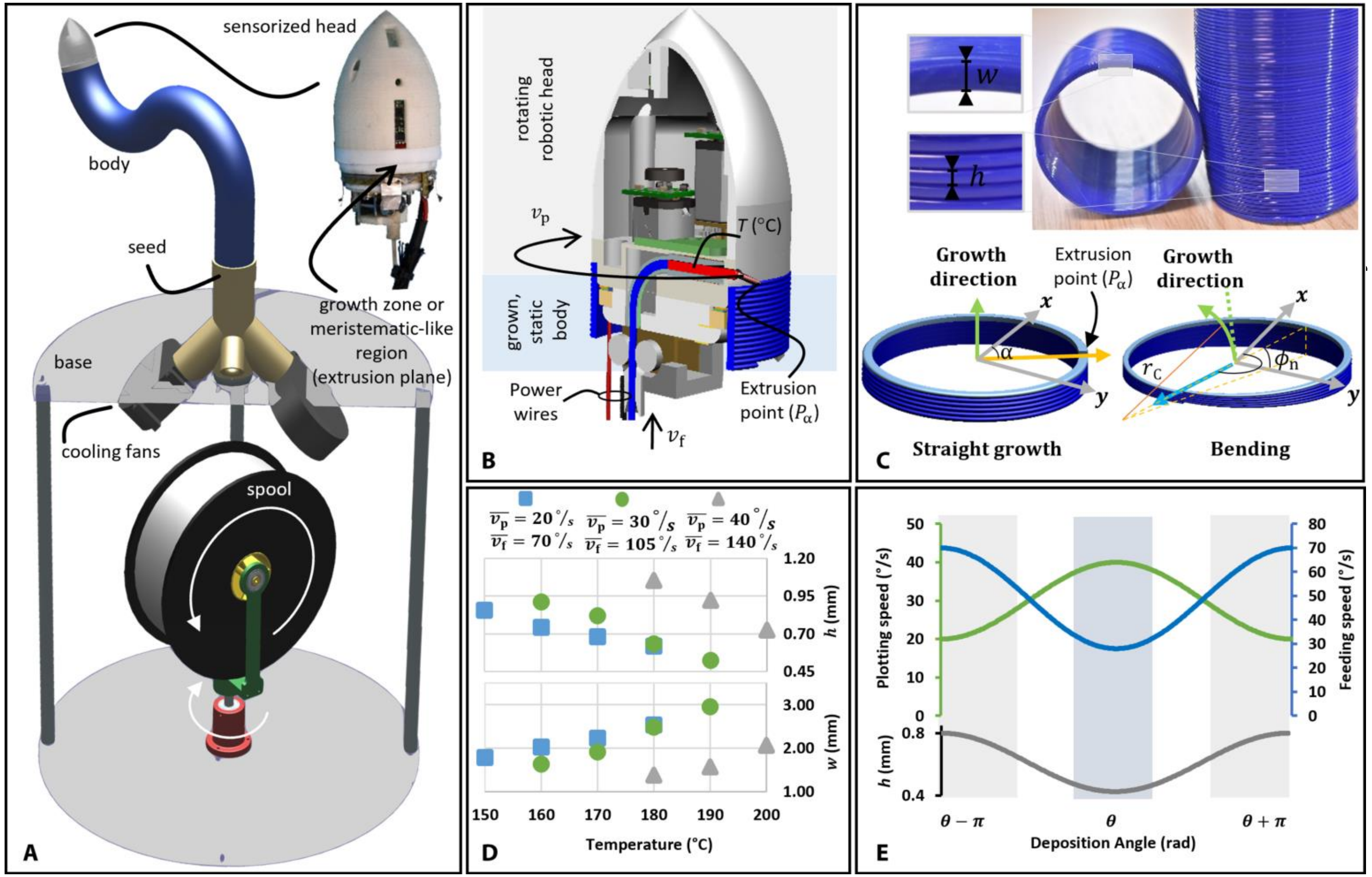


Modular & reconfigurable

Climbing robots for additive manufacturing

Climbing robots for additive manufacturing





https://www.science.org/doi/full/10.1126/scirobotics.adi5908

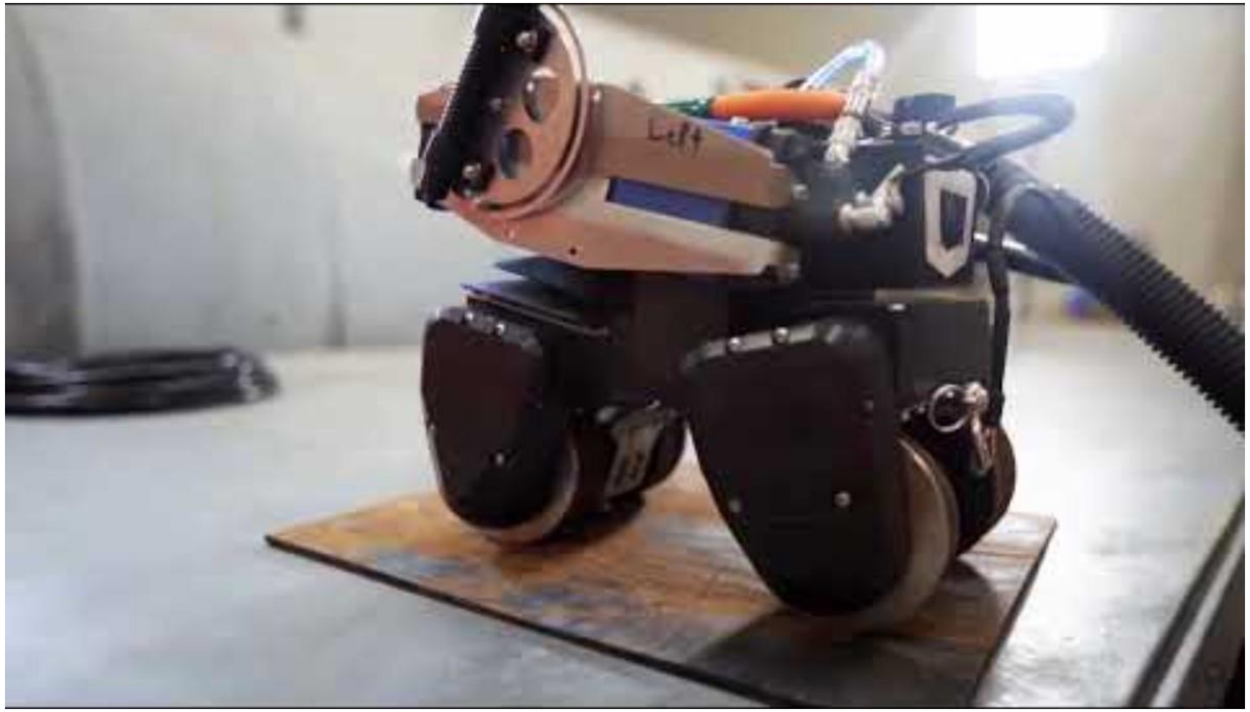
Surface inspection

Silo inspection – Gecko Robotics

Ship Derusting – ROBOT++

Multi-dimensional inspecting

Steel Bridge Inspection



Pipe Inspection (Waygate Technologies)

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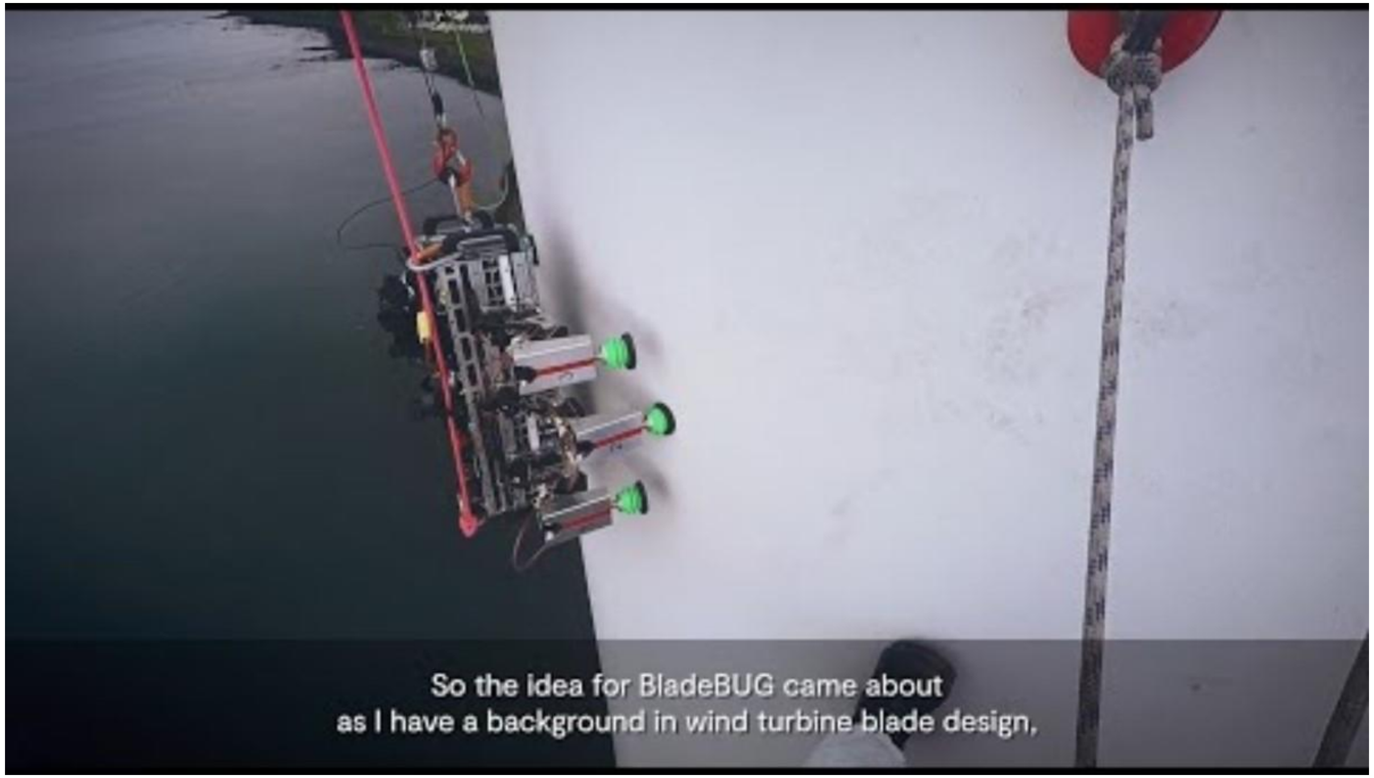
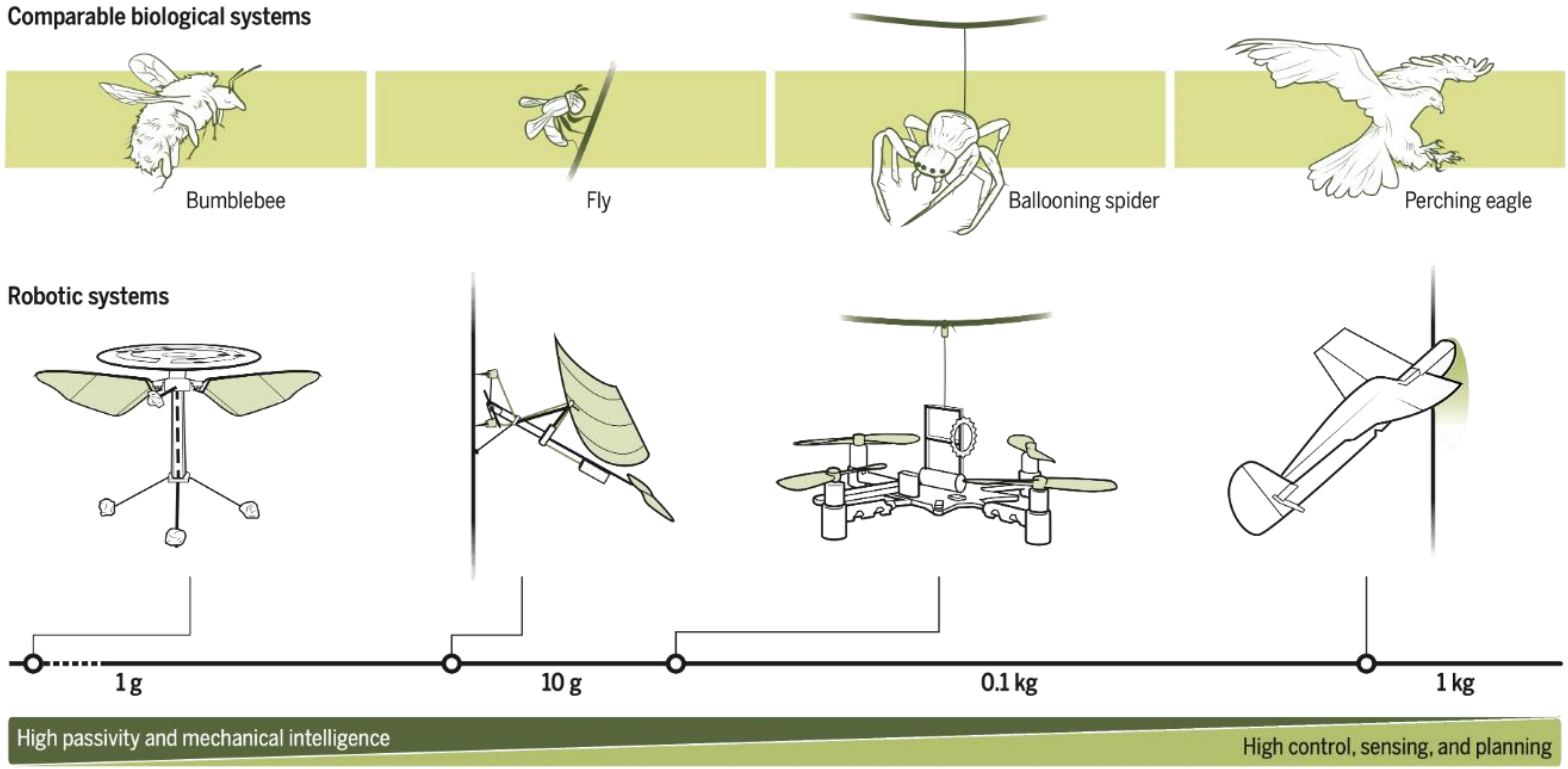
Wind turbine inspection



BladeBUG

Soft sensing

Perching robots



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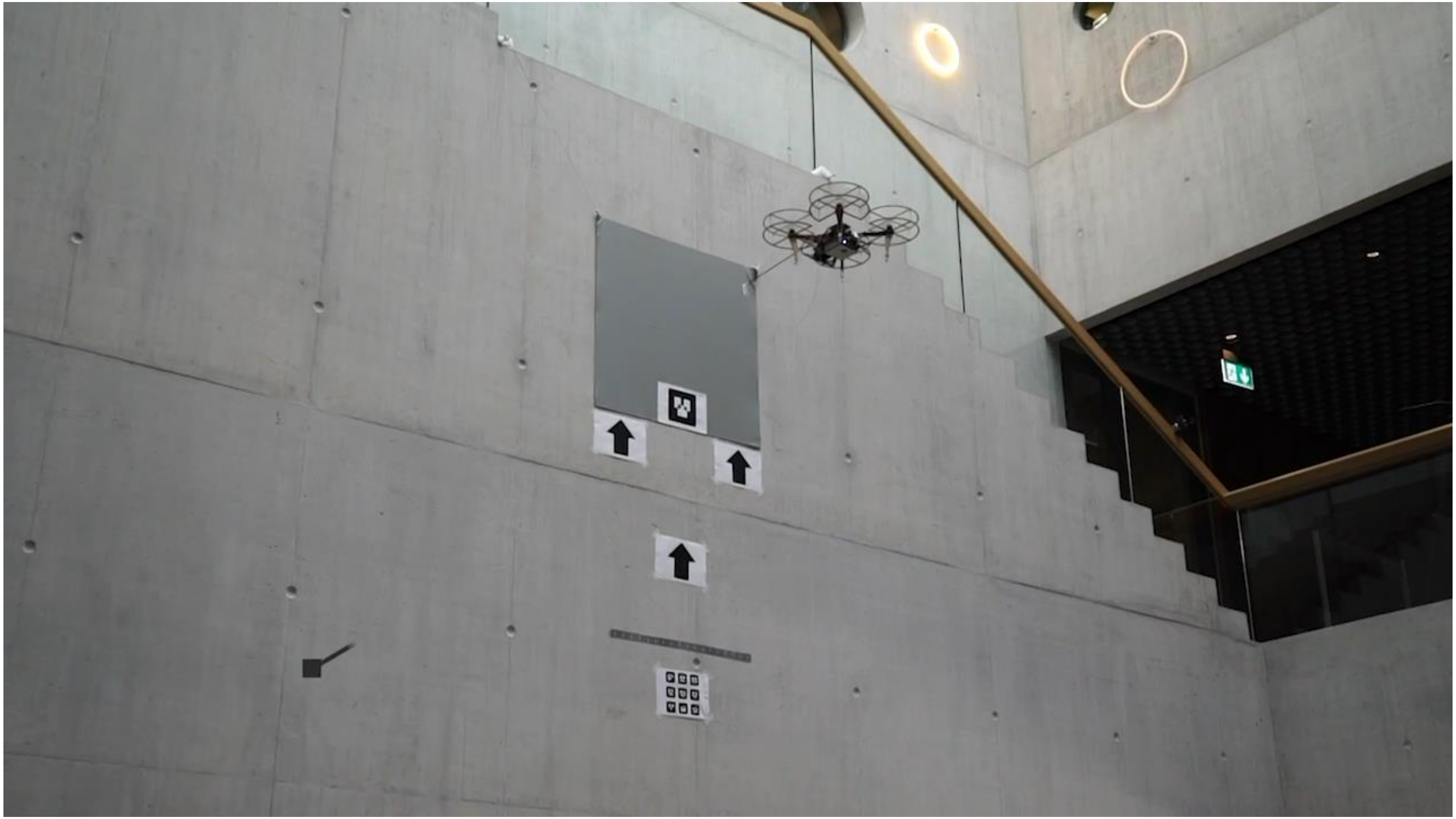
Tensile perching



Sensor placement and aerial drilling

Section - Robot manipulation

Motivation

- *Why are organisms designed the way they are, how are limbs coordinated, and how do we perform complex tasks?*

- In order to operate a robot we must:
  - Develop methods to convert a desired task to a sequence of commands to the robot's actuators
  - Understand the limitations of the chosen configuration

Key terms

- **configuration**: a specification of the positions of all points of a mechanism
- **End-effector:** a component that interacts with objects or performs tasks in the surrounding world
- **degrees of freedom** (DoF): How many variabled are required to describe a configuration
- How many DoF does an object moving in 2D have?
  - **3**
- How many in 3D?
  - **6**

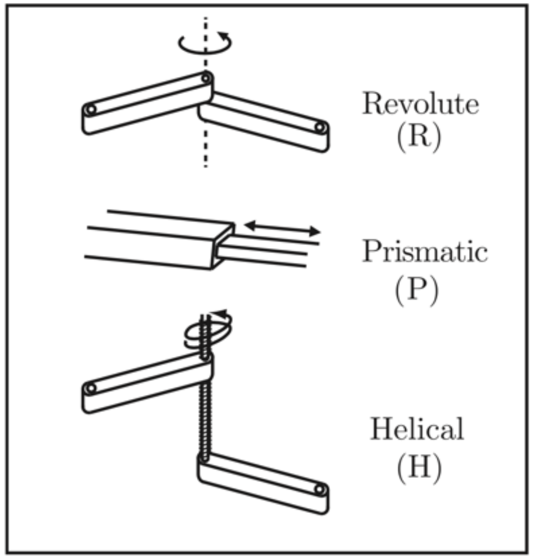
Vector spaces

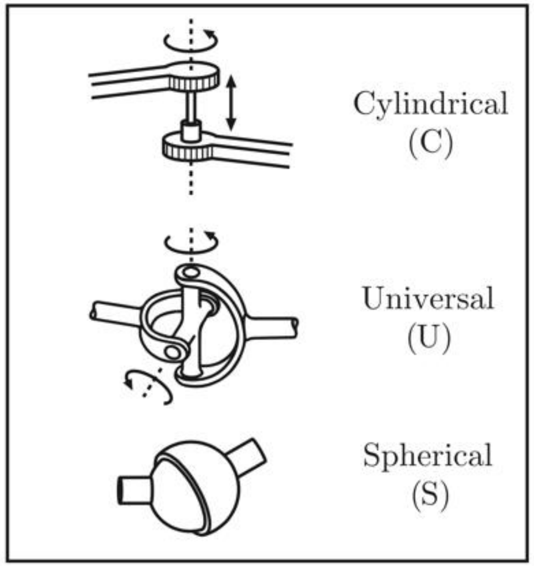
- **configuration space** (C-space): the dof-dimension space of all configurations (sometimes referred to as joint space)

- The **task space** is the space in which a task is most naturally represented. It is independent of a robot.

- How do we convert between joint angles (C-space) and task space?

Types of joints



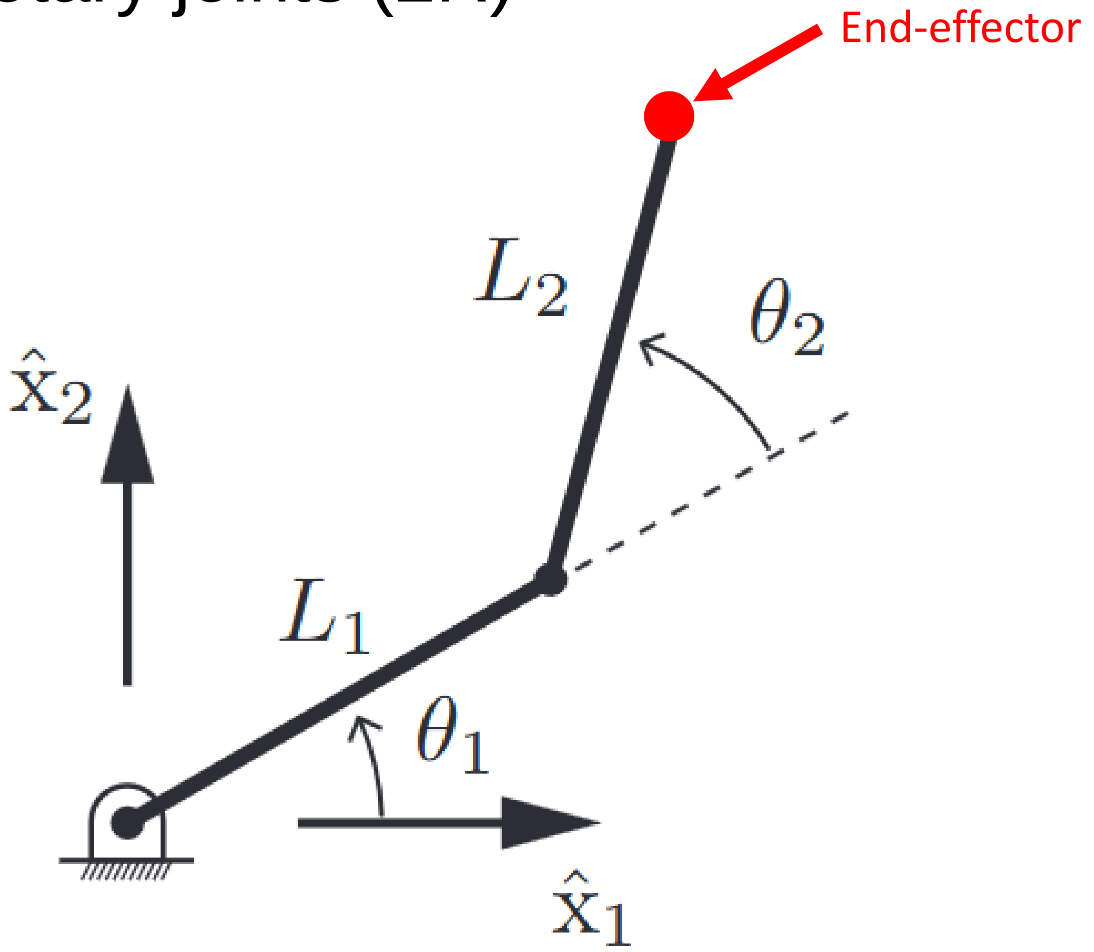


Joint type	dof f	Constraints c between two planar rigid bodies	Constraints c between two spatial rigid bodies
Revolute (R)	1	2	5
Prismatic (P)	1	2	5
Helical (H)	1	N/A	5
Cylindrical (C)	2	N/A	4
Universal (U)	2	N/A	4
Spherical (S)	3	N/A	3

Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

The 2R planar robot

- Minimal example to explain concepts.
- 2 linkages with 2 rotary joints (2R)



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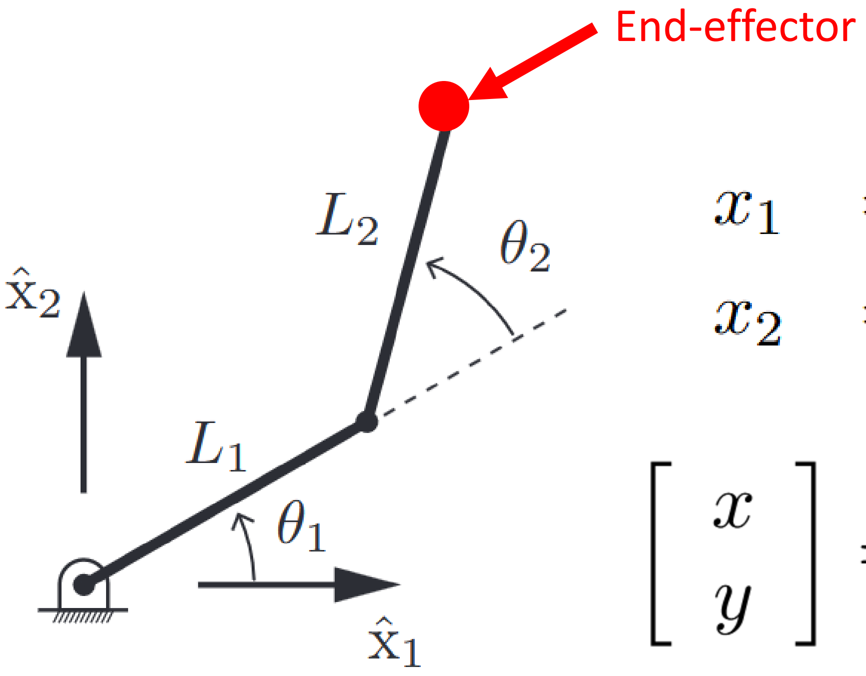
Forward Position Kinematics (FPK)

Determine position and orientation of a robot's end-effector (x) from its joint coordinates (θ)

Forward Position Kinematics - Example



$$x_1 = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)$$
$$x_2 = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2).$$

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \\ L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) \end{bmatrix}$$

Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

Inverse Position Kinematics (IPK)

Determine the required joint coordinates (θ) to achieve a desired end-effector state (x)

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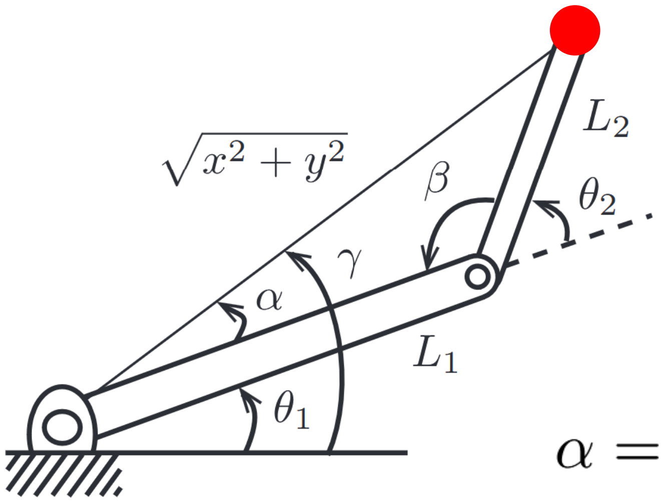
Inverse Position Kinematics - Example



- Cosine rule: $c^2 = a^2 + b^2 - 2ab\cos C$
- Solve for alpha, beta & gamma:

$$L_1^2 + L_2^2 - 2L_1L_2\cos\beta = x^2 + y^2$$

$$\alpha = \cos^{-1}\left(\frac{x^2+y^2+L_1^2-L_2^2}{2L_1\sqrt{x^2+y^2}}\right) \qquad \beta = \cos^{-1}\left(\frac{L_1^2+L_2^2-x^2-y^2}{2L_1L_2}\right)$$

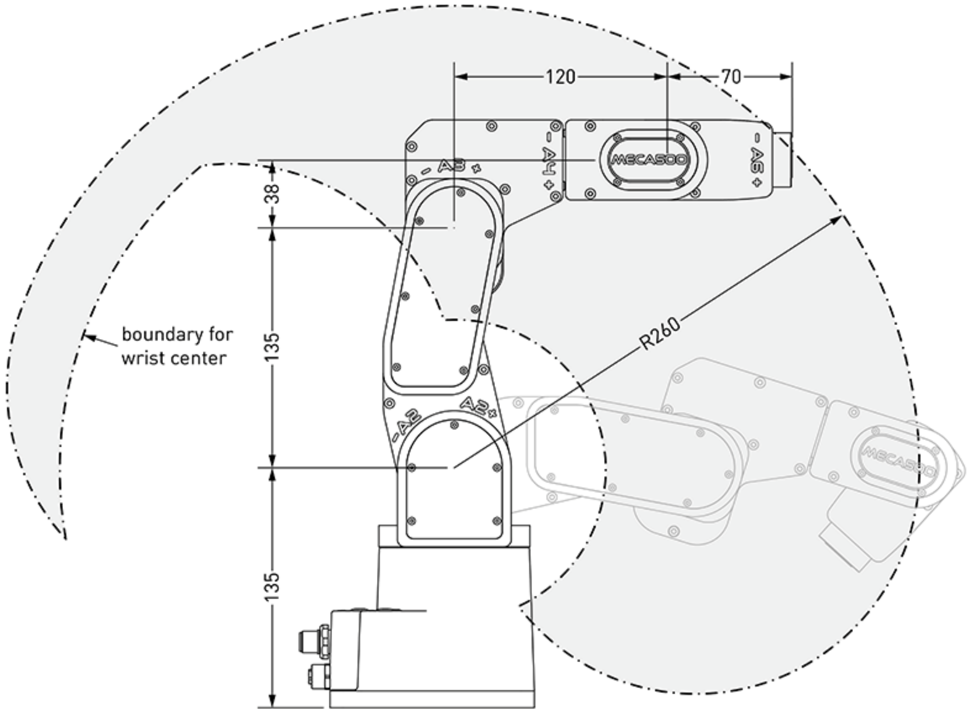
$$\gamma = \tan^{-1}\frac{y}{x} \qquad \theta_1 = \gamma - \alpha, \qquad \theta_2 = \pi - \beta$$

(note that most configurations have multiple solutions)

Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

Workspace

- The **workspace** is usually a specification of the reachable space by a robot (or its wrist, or end-effector).
  - Often defined in terms of (x,y,z) translational positions only.
  - Sometimes the **dexterous workspace** is the set of translational positions that can be reached with arbitrary orientation.



Cross section of workspace for a 6R robot respecting joint limits (Mecademic Meca500)

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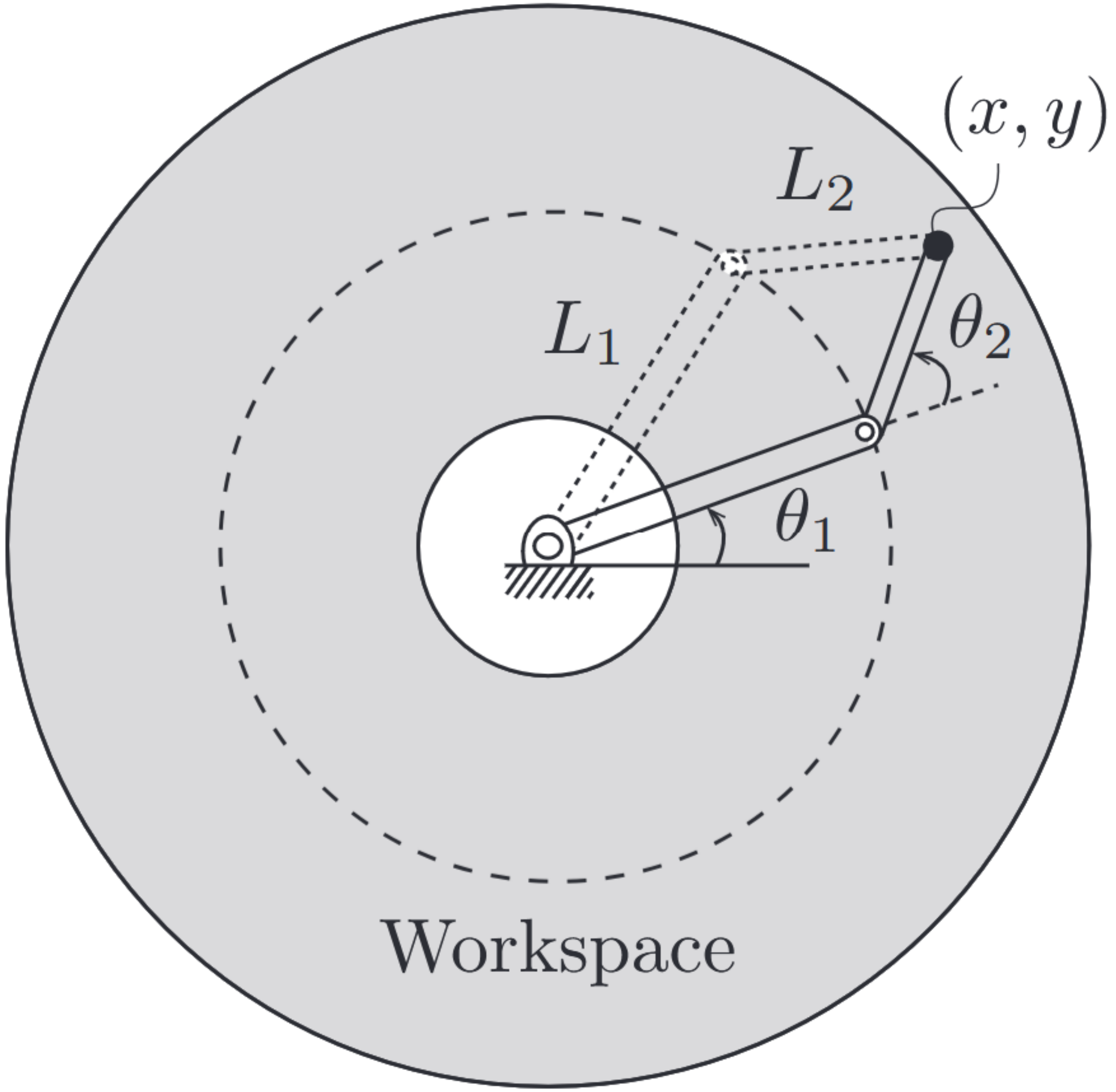
Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

Workspace - Example

- What is the workspace of the 2R planar robot?



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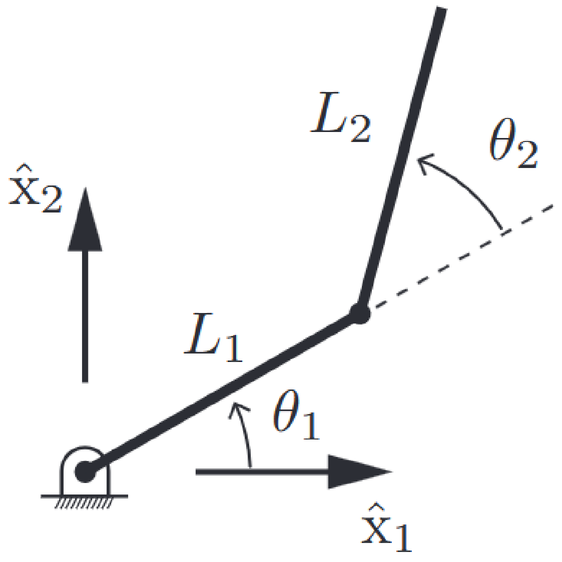
Velocity kinematics



- Determine end effector velocity as a function of joint velocities

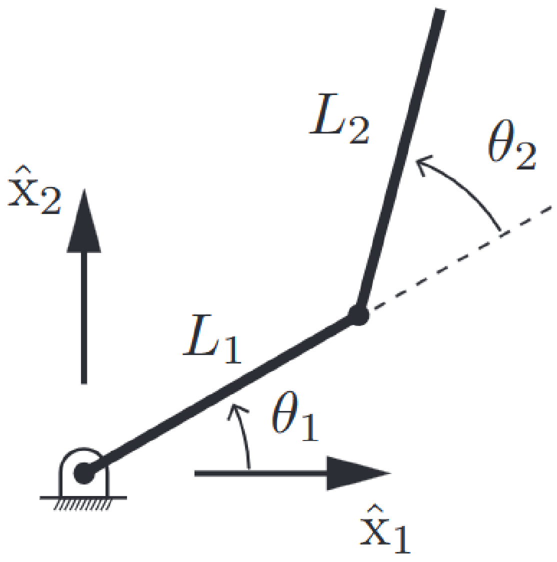
- In general: $x(t) = f(\theta(t)),$

  Using the chain rule:

$$\dot{x} = \frac{\partial f(\theta)}{\partial \theta}\frac{d\theta(t)}{dt} = \frac{\partial f(\theta)}{\partial \theta}\dot{\theta}$$
$$= J(\theta)\dot{\theta},$$

Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

Velocity kinematics - Example



Previous FPK solution:

$$
\begin{aligned}
x_1 &= L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \\
x_2 &= L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2).
\end{aligned}
$$

Take derivative (using chain rule):

$$
\begin{aligned}
\dot{x}_1 &= -L_1\dot{\theta}_1 \sin\theta_1 - L_2(\dot{\theta}_1 + \dot{\theta}_2)\sin(\theta_1 + \theta_2) \\
\dot{x}_2 &= L_1\dot{\theta}_1 \cos\theta_1 + L_2(\dot{\theta}_1 + \dot{\theta}_2)\cos(\theta_1 + \theta_2),
\end{aligned}
$$

Matrix representation:

$$
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -L_1 \sin\theta_1 - L_2 \sin(\theta_1 + \theta_2) & -L_2 \sin(\theta_1 + \theta_2) \\ L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) & L_2 \cos(\theta_1 + \theta_2) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}
$$

Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

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Jacobian Matrix

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} -L_1 \sin\theta_1 - L_2 \sin(\theta_1+\theta_2) & -L_2 \sin(\theta_1+\theta_2) \\ L_1 \cos\theta_1 + L_2 \cos(\theta_1+\theta_2) & L_2 \cos(\theta_1+\theta_2) \end{bmatrix}}_{\dot{x} = J(\theta)\dot{\theta}} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}$$

$J(\theta)$ is the **Jacobian matrix** of the system

The Jacobian matrix represents: *“the linear sensitivity of the end-effector velocity ˙x to the joint velocity ˙θ”*

Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

Robot singularities

- Singularities occur when Jacobean matrix becomes **non-invertible** (i.e. det(J) = 0)

- Non-invertible means that there is no solution to the inverse velocity kinematics (ie. A case where we cannot solve a set of joint velocities to achieve a desired end effector speed).

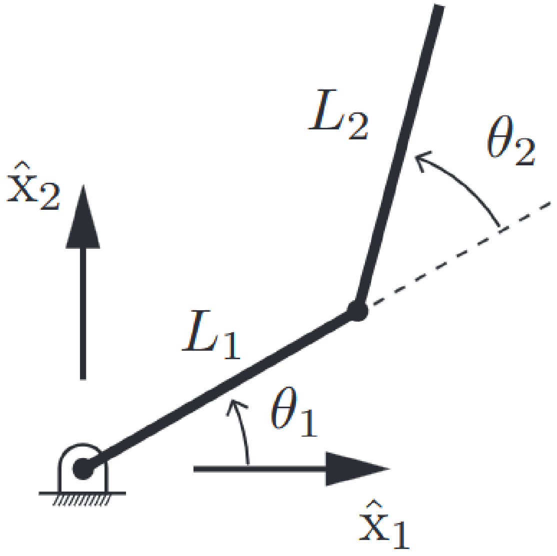
  - Robot tip becomes unable to generate velocities in certain directions

  - Why avoid singularities?
    - Low precision near singular positions
    - Difficult to produce smooth motion at constant velocity
    - Actuator velocities may become excessively high while performing a motion close to this position

Robot singularities - Example

Where are the singular positions of the 2R planar robot?

$$J(\theta) = \begin{bmatrix} -L_1 \sin\theta_1 - L_2 \sin(\theta_1 + \theta_2) & -L_2 \sin(\theta_1 + \theta_2) \\ L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) & L_2 \cos(\theta_1 + \theta_2) \end{bmatrix}$$

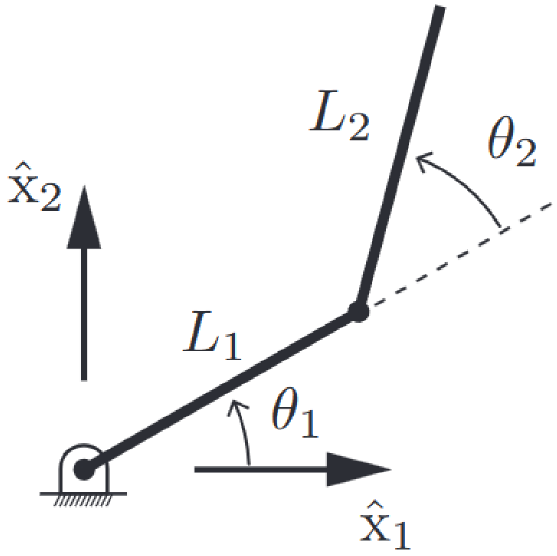


$\det(J) = ad - bc$, where $J = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$

$$= -L_2\cos(\theta_1 + \theta_2)[L_1\sin\theta_1 + L_2\sin(\theta_1 + \theta_2)]$$
$$+ L_2\sin(\theta_1 + \theta_2)[L_1\cos\theta_1 + L_2\cos(\theta_1 + \theta_2)]$$

Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

Robot singularities - Example



$$\det(J) = -L_2\cos(\theta_1+\theta_2)[L_1\sin\theta_1 + L_2\sin(\theta_1+\theta_2)] + L_2\sin(\theta_1+\theta_2)[L_1\cos\theta_1 + L_2\cos(\theta_1+\theta_2)]$$

Recall that $\cos\theta = \sin(180+\theta)$,

$$\det(J) = \sin(\theta_1+\theta_2)\sin(\theta_1+180) - \sin(\theta_1)\sin(\theta_1+\theta_2+180)$$

When is the determinant zero?: $\boldsymbol{\theta_2} = \mathbf{0° \text{ or } 180°}$ (for $0^0 \leq \theta < 360^0$)

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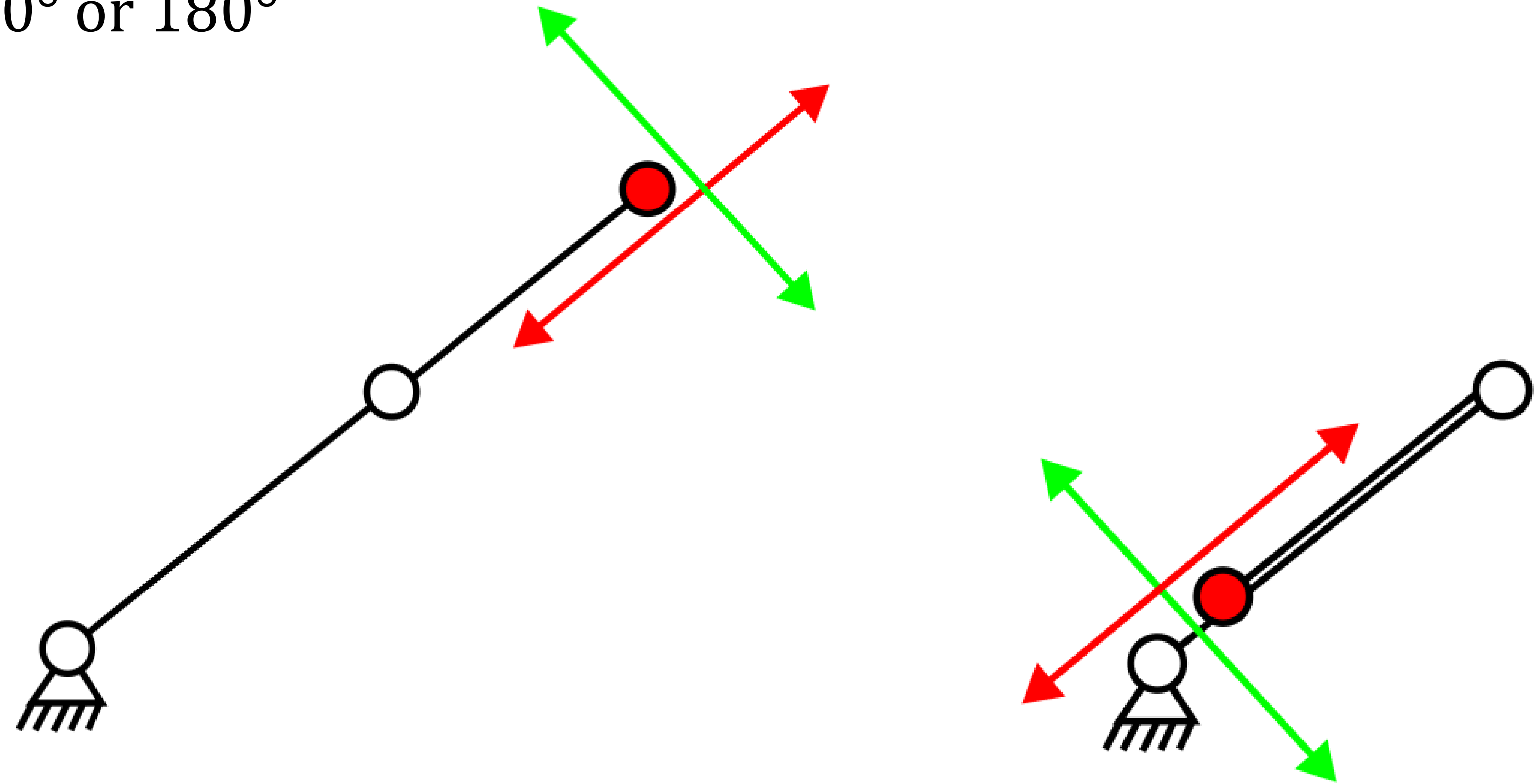
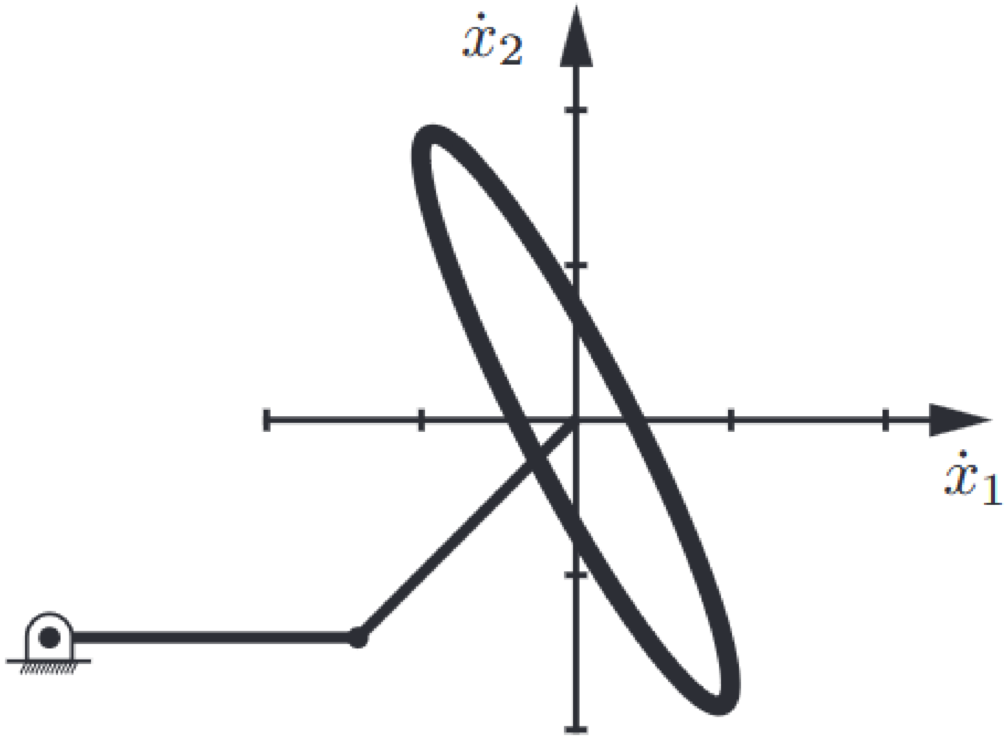
Robot singularities - Example

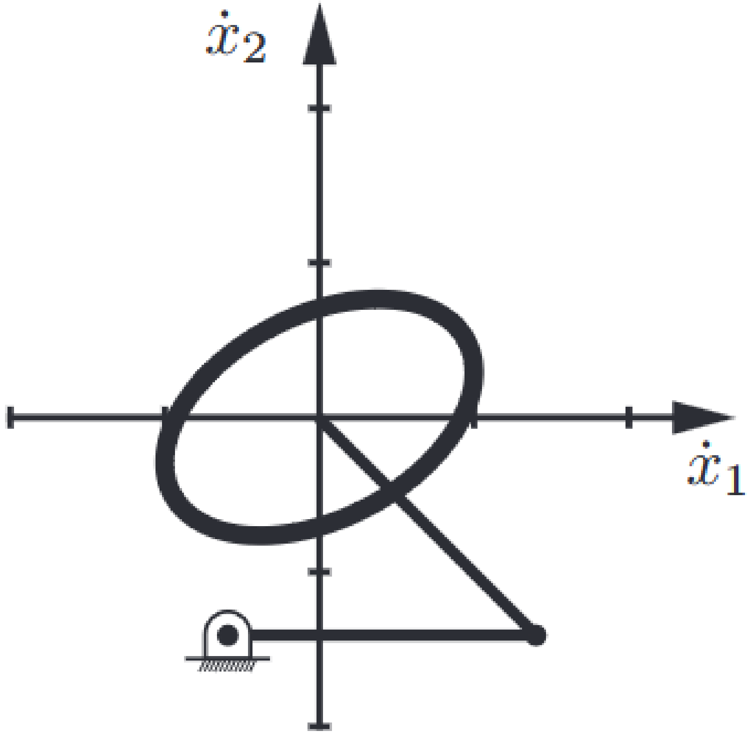
$\theta_2 = 0° \text{ or } 180°$



Manipulability ellipsoid

- *How do we quantify how the arm can move when close to singular positions?*
- The Jacobean maps how fast the end-effector can move for given actuator speed limits.

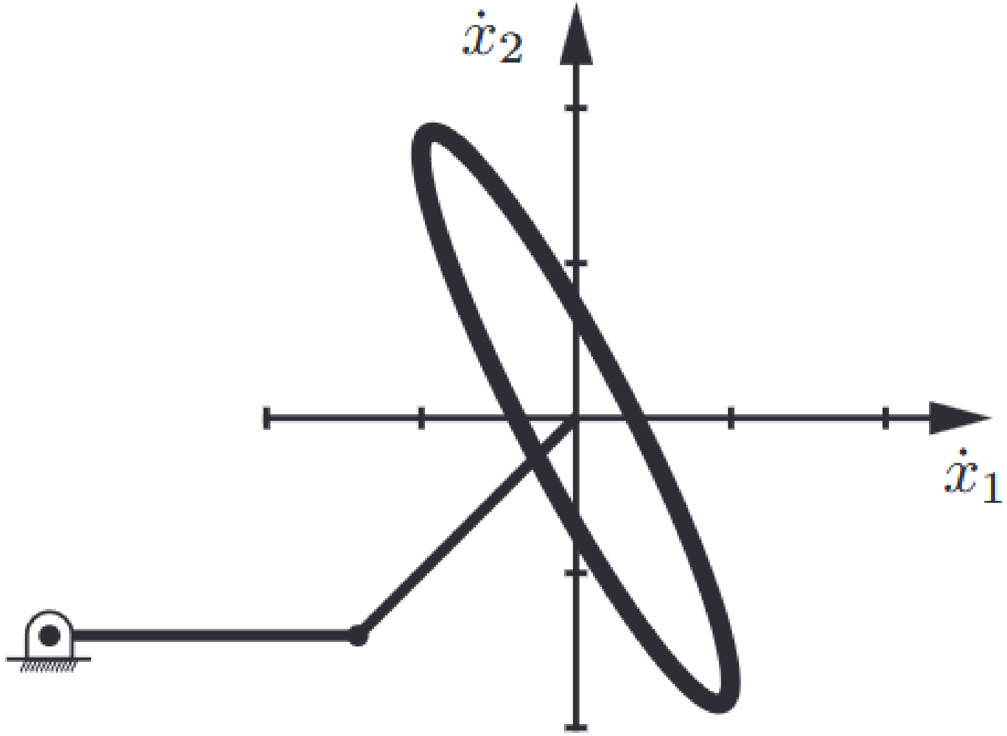


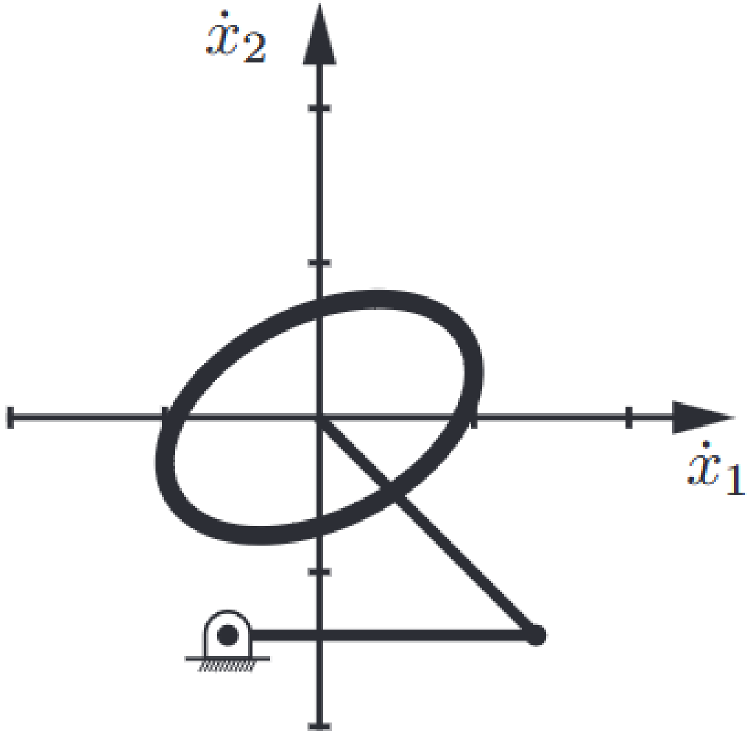


Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

Manipulability ellipsoid

- The principle axes of the ellipse are the eigenvectors of JJ^T
- The magnitude of the axes are the square roots of the corresponding eigenvalues (see Modern Robotics page 197 for derivation)





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Parallel mechanisms

- Any kinematic chain that contains one or more loops is called a **closed chain**
- Manipulators that exploit closed chains are called **parallel manipulators**
- Examples:

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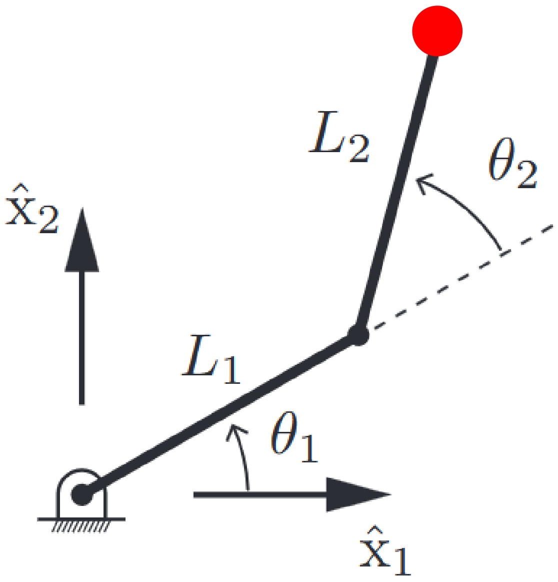
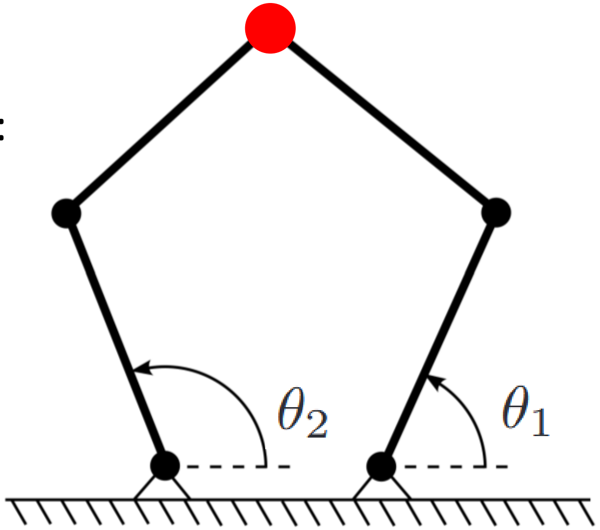
Open vs. Closed kinematic chains

2R planar robot:



5 bar linkage:



Open chains	Closed chains
Simple analytical FPK	Analytical solutions to FPK are only feasible in simple cases
Numerical IPK – high numbers of joints lead to infinite solutions	Analytical IPK is typically possible
Singularities within workspace limits	Singularities at outer limits of workspace (typically)
Actuators mounted on moving parts	Actuators mounted at base
Large workspace & ability to navigate around obstacles	Limited workspace

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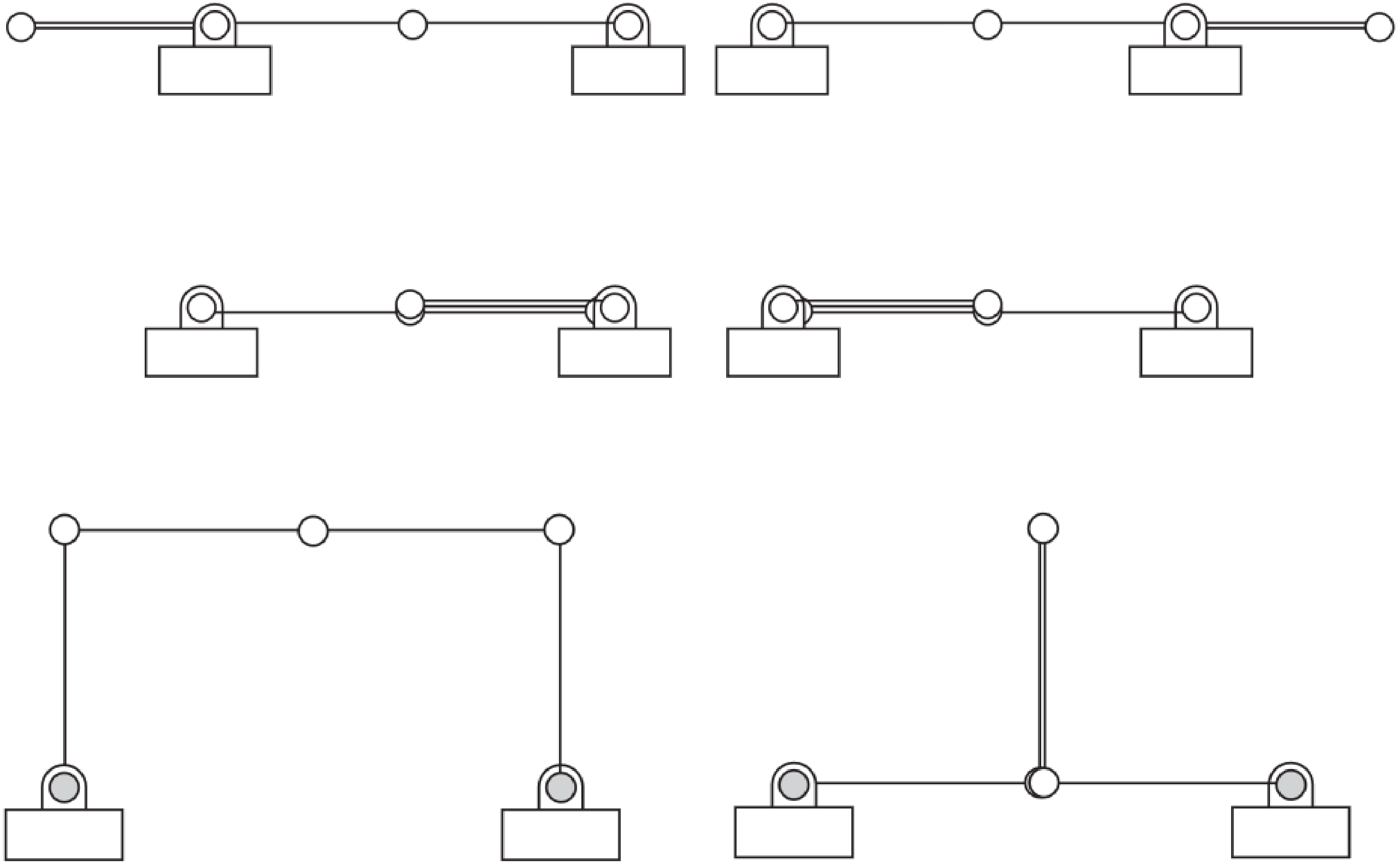
5 bar linkage singularities



Modern Robotics: Mechanics, Planning, and Control," Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017

More complex examples

- 2R planar robot is a very simple example where forward/inverse kinematics can be solved analytically
- Additional constraints:
  - Collisions with environment
  - Joint limits
  - Visibility (keep end effector within visibility cone of a sensor)
- Software such as *MoveIt* contains libraries for motion planning with collision avoidance and numerical kinematics – however only for open chains.

Summary

- Automation is needed in the construction industry
- Aerial Additive Manufacturing
- Climbing Robots
- Perching and sensor placement

- Configuration & Task space
- Forward/Inverse kinematics
- Velocity kinematics & robot singularities
- Parallel vs Serial manipulators

Further reading

- **Modern Robotics: Mechanics, Planning, and Control**, Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017 (free preprint: https://hades.mech.northwestern.edu/images/2/25/MR-v2.pdf)

- **Infrastructure Robotics: Methodologies, Robotic Systems and Applications,** Dikai Liu, Carlos Balaguer, Gamini Dissanayake, Mirko Kovac, Wiley Online Library, 2023 (https://onlinelibrary.wiley.com/doi/book/10.1002/9781394162871)

- **Aerial additive manufacturing with multiple autonomous robots,** Ketao Zhang, … Mirko Kovac, Nature, 2022 (https://www.nature.com/articles/s41586-022-04988-4**)**