Sustainable Design for Autonomous System

Shaopeng Jiang

Prof. Dr. Jamie Paik

Reconfigurable Robotics Laboratory

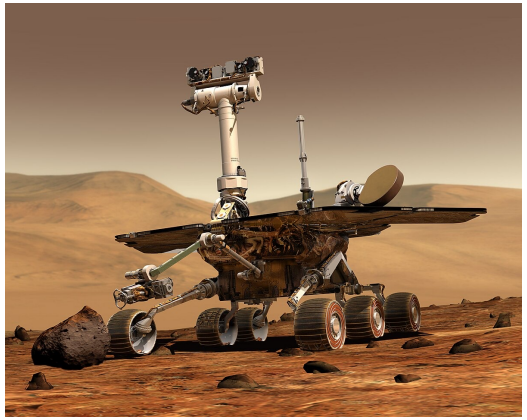
EPFL, Switzerland

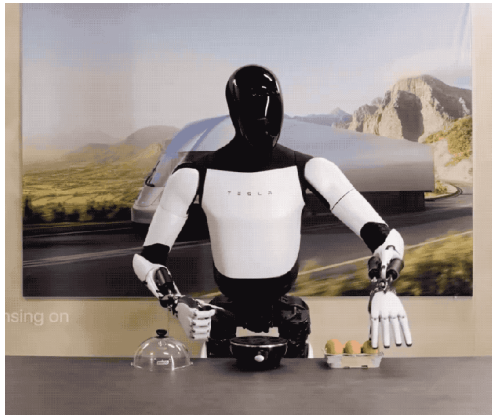
ME-420 Advanced design for sustainable future

Motivation - Sustainable Success

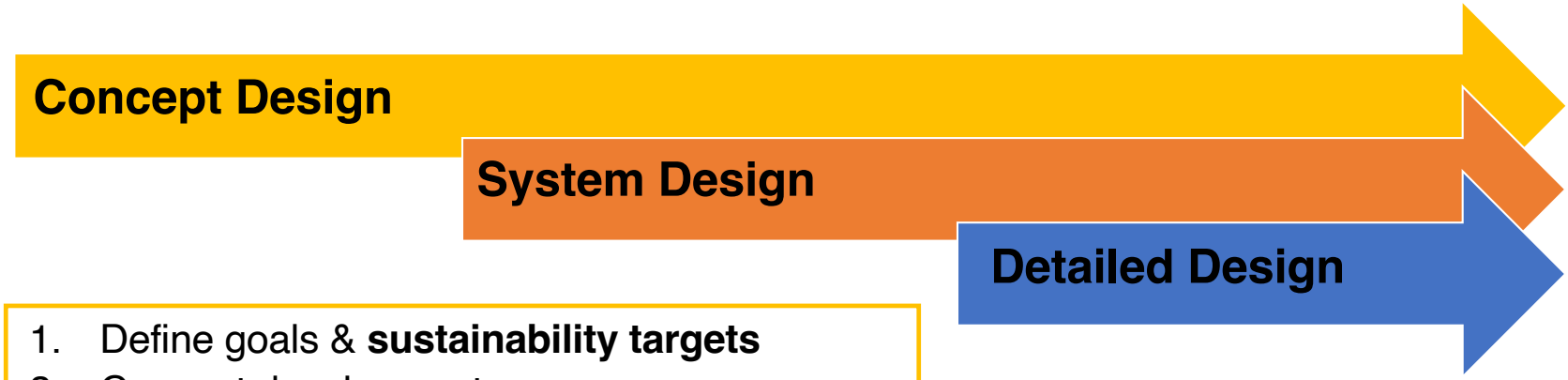
Autonomous System

- **Autonomous systems** refer to systems capable of operating in a **real-world environment** without any form of **external control** for extended periods of time.



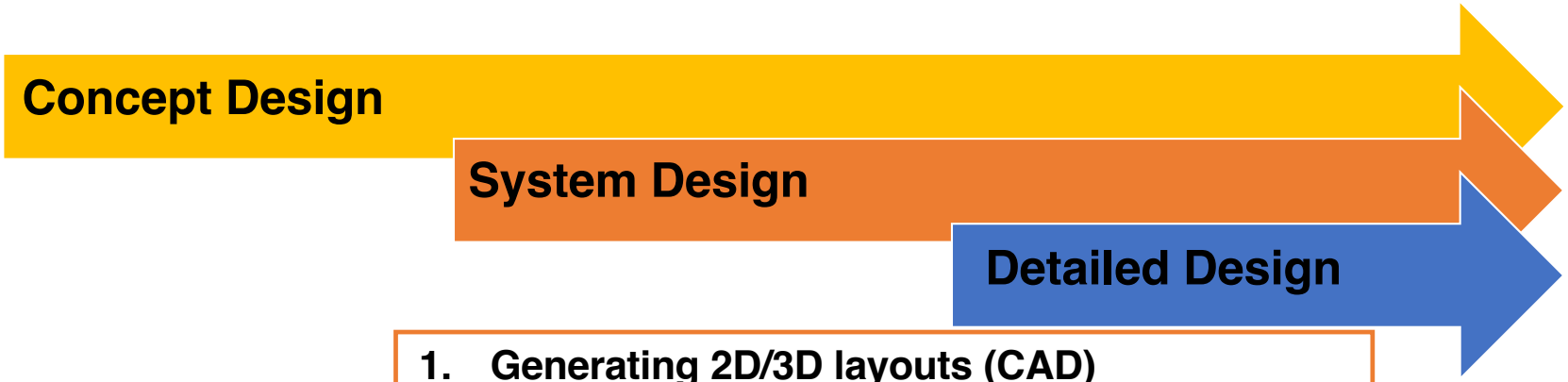


Autonomous System Design: Roadmap



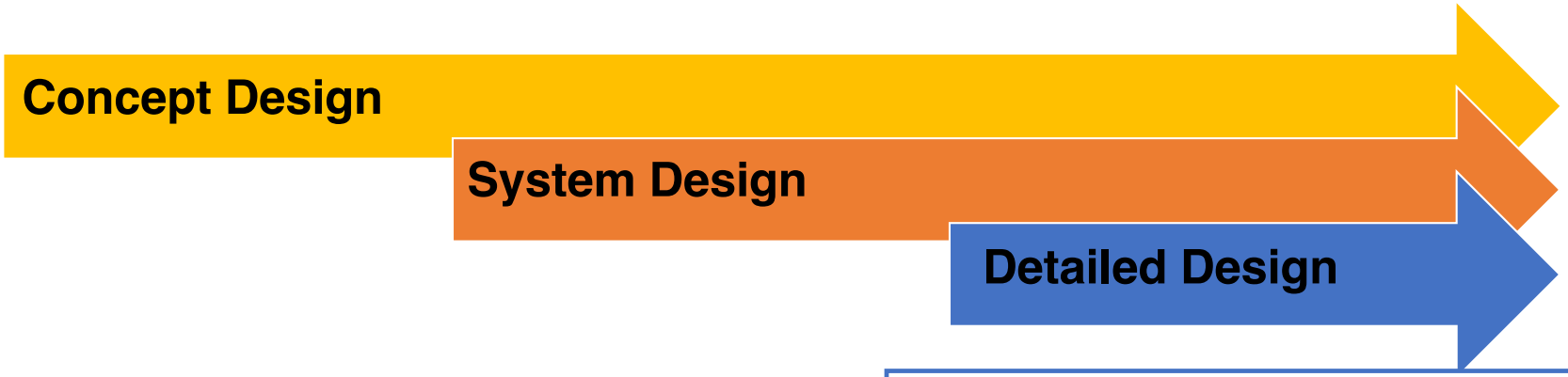
1. Define goals & **sustainability targets**
2. Concept development.
   - Payload, speed, energy, CO2 foot print?
   - Quantifiable target demonstrator
3. Concept evaluation
   - Engineering pre-analysis (related works)
   - Draw basic sketches
4. Material and process selection

Autonomous System Design: Roadmap



1. **Generating 2D/3D layouts (CAD)**
2. **Develop package and interface**
   - Mechanisms design (linkage, structure)
   - Elements design (sensor, actuator, motor, etc)
3. **Early stage prototyping**
   - Standardized components?
   - Light-weight design to optimize material?
   - Pick efficient drive parts?
   - Modularity?

Autonomous System Design: Roadmap



1. Details of each part (sensing, actuation, control unit)
2. Prototyping & iteration of System design
3. Finalize material & methods
4. Testing & Validation for the Concept Design

Autonomous System Elements

1. Design of sensing
   - Mechanical integration, measurement calibration, etc.
2. Design of actuators
   - Selection, transmission, etc.
3. Design of controllers
   - open/closed loop control
4. **Design of structure**

Autonomous System Design Essentials

Design of structure

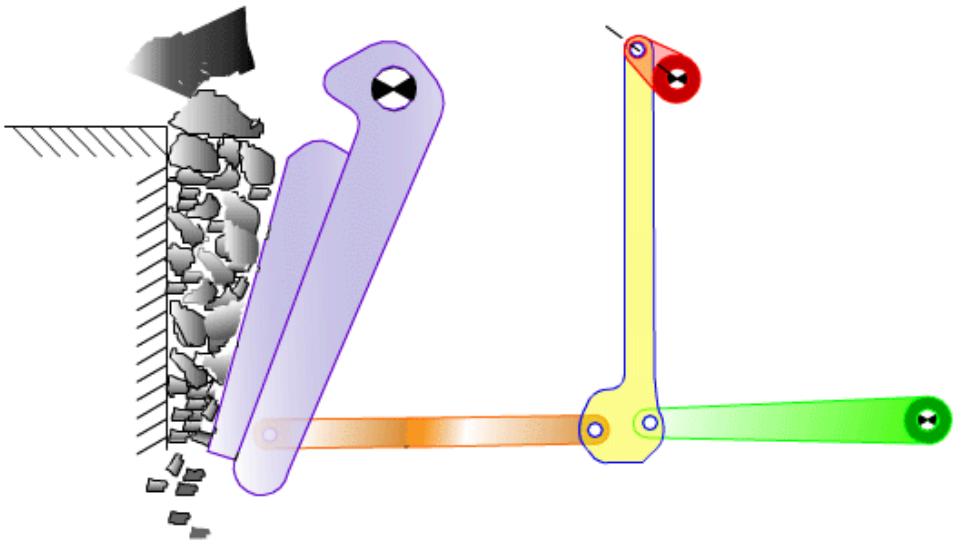
- **Mechanism Design**
  - Kinematic pair
  - Linkage
  - Degree-of-freedom
- **Modular Design**
  - Module decomposition strategies
  - Interface standardization & decoupling

Machine and Mechanism

- A **machine** structure is constructed to perform a particular task.

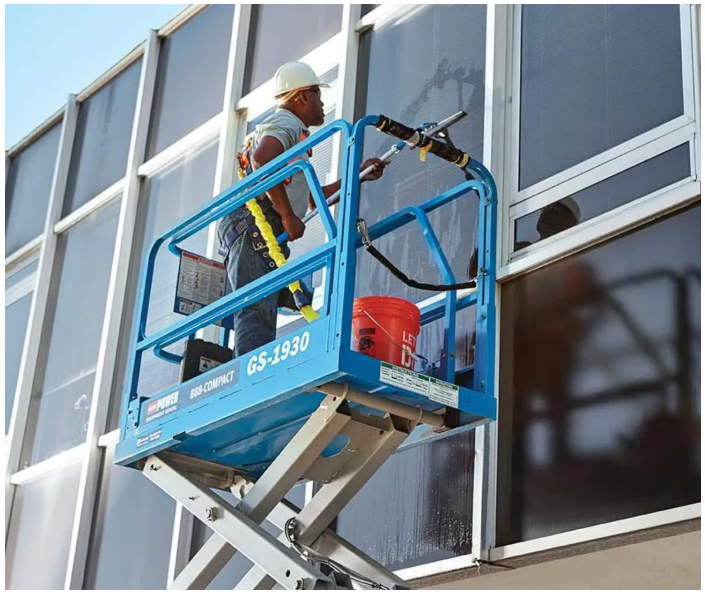
- A **mechanism** is a group of rigid bodies through the study of which we can understand the basic structure of any machine and can design machines that are not in existence.

Example - Rock breaker



Toggle mechanism: <u>amplify force</u> to crush the rocks

Example - Lift Platform



Scissor-lift mechanism: amplify displacement and reach high

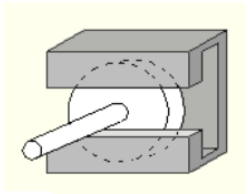
Mechanism Concepts

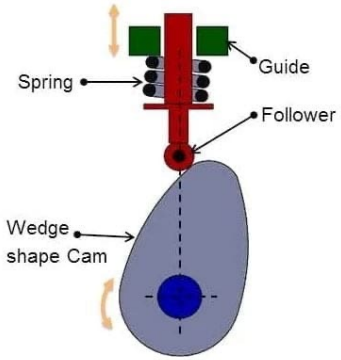
- **Kinematic element**, is that part of a rigid body which is used to connect it to another rigid body such that the relative motion between the two rigid bodies can occur.

- **Kinematic pair (i.e. joint)**, is the joining of two kinematic elements.

  - **Closed joint**

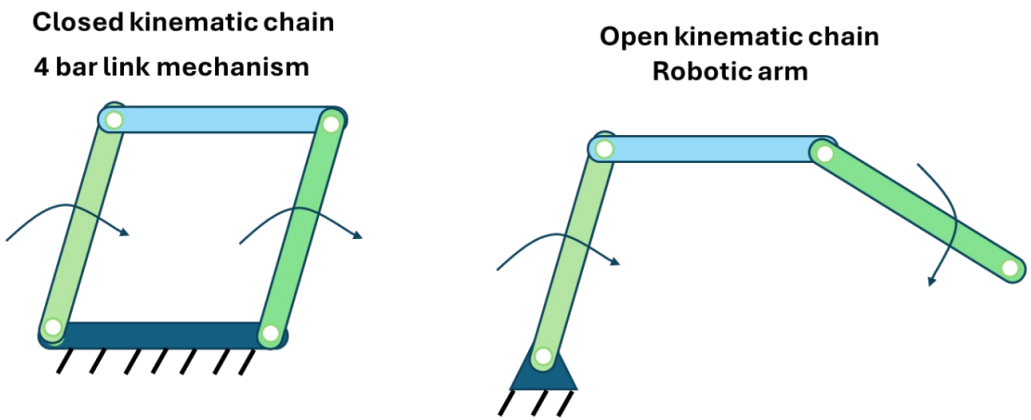
  - **Open joint**





Mechanism Concepts

- **Mechanical linkage:** If a rigid body contains at least two kinematic elements we shall call it a **link**.
- The links connected to each other by kinematic pairs will form a **kinematic chain.**
- If one of the links in a kinematic chain is fixed, then the system obtained is called a **mechanism.**



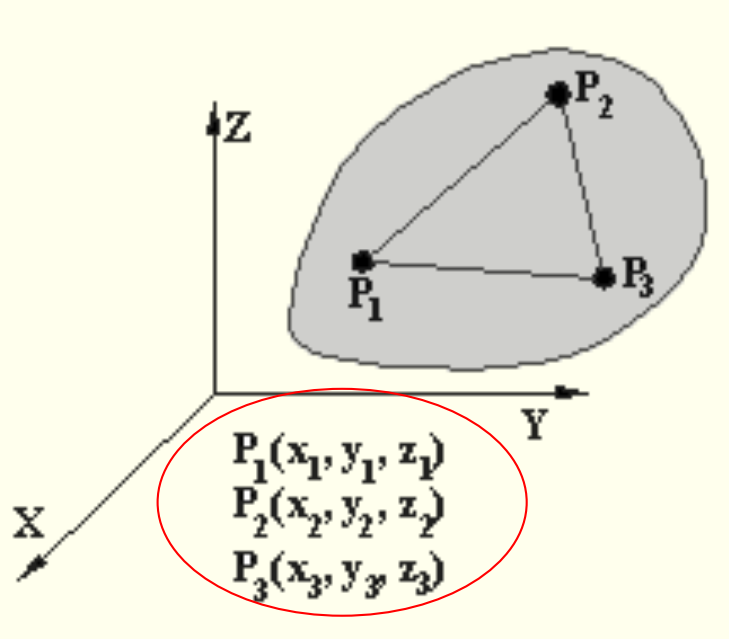
Degree of Freedom

- **The degree-freedom (DoF) of space** is the number of independent parameters to define the position of a rigid body in that space.

- Keywords to design system structure!

Degree of Freedom - Spatial

- **The degree-freedom (DoF) of space** is the number of independent parameters to define the position of a rigid body in that space.



$$(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 = a_1^2$$

$$(x_3 - x_1)^2 + (y_3 - y_1)^2 + (z_3 - z_1)^2 = a_2^2$$

$$(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2 = a_3^2$$

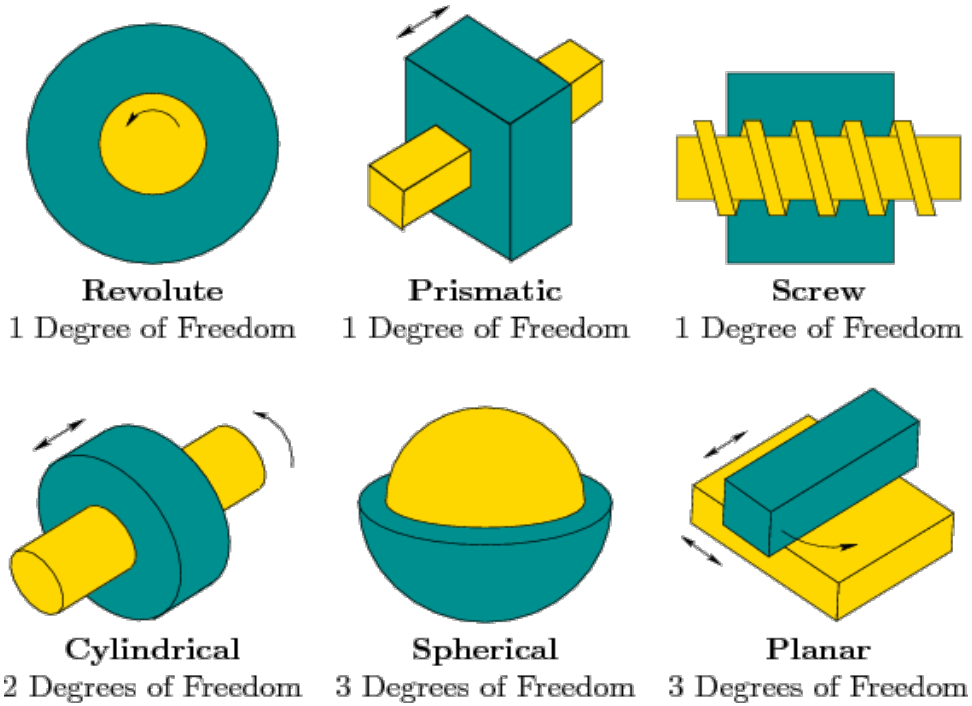
9 parameters (xi, yi, zi)

3 relations (a1, a2, a3)

Knowing 6 of the parameters solve all the rest!

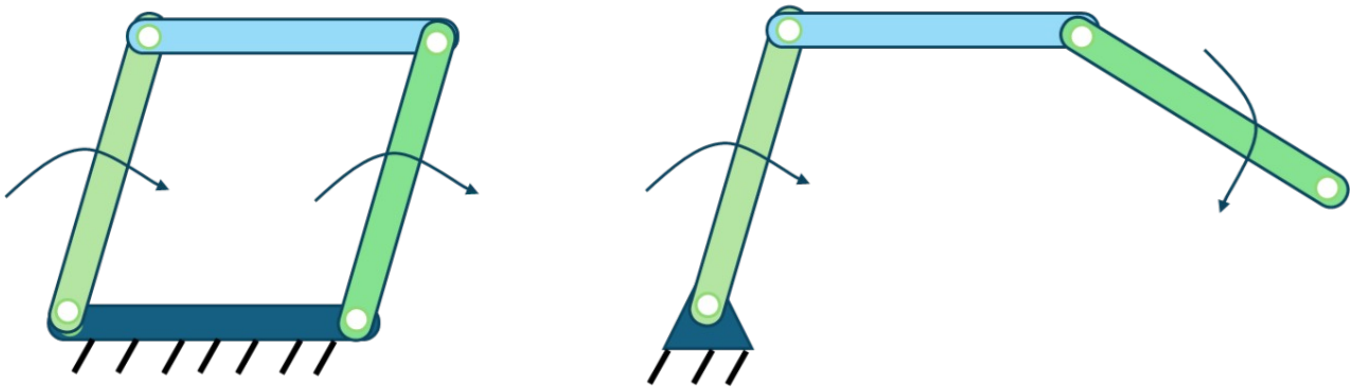
Degree of Freedom - Joints

- **DoF of a kinematic pair:** the number of independent parameters that is required to determine the relative position of one rigid body with respect to the other connected by the kinematic pair.



Degree of Freedom - Mechanism

- **The degree of freedom (DoF) of a mechanism** is the number of independent parameters required to define the position of every link in that mechanism.
- **Degree of freedom** is the theoretical lower bound on actuators for full independent system control.



How many actuators are required to make the system autonomous?

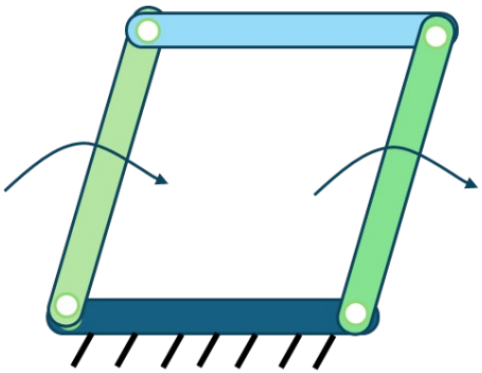
Degree of freedom – Formula

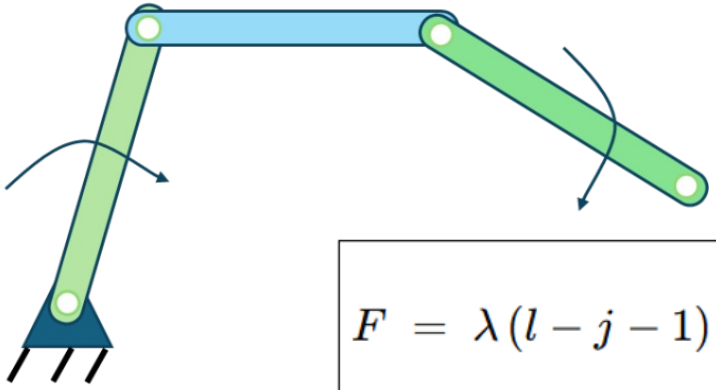
- λ: fixed parameter of **space** (λ = 3 for planar space ; λ = 6 for spatial space)
- l : The number of **links** in a mechanism (including the fixed link)
- j : The number of **joints** in a mechanism
- f_i : The degree of freedom of the ith **joint** in the mechanism
- F : **The degree of freedom of the mechanism**

$$F = \lambda(l - j - 1) + \sum_{i=1}^{j} f_i$$

General DoF Equation

Degree of Freedom - Mechanism





$$F = \lambda(l - j - 1) + \sum_{i=1}^{j} f_i$$

How many DoF do these structures have?

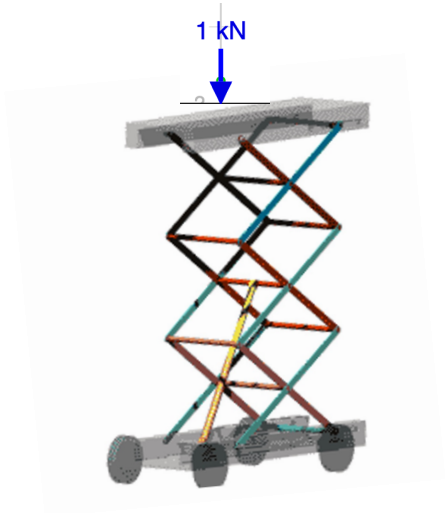
$\lambda = 3$
$l = 4$
$j = 4$
$f_i = 1$

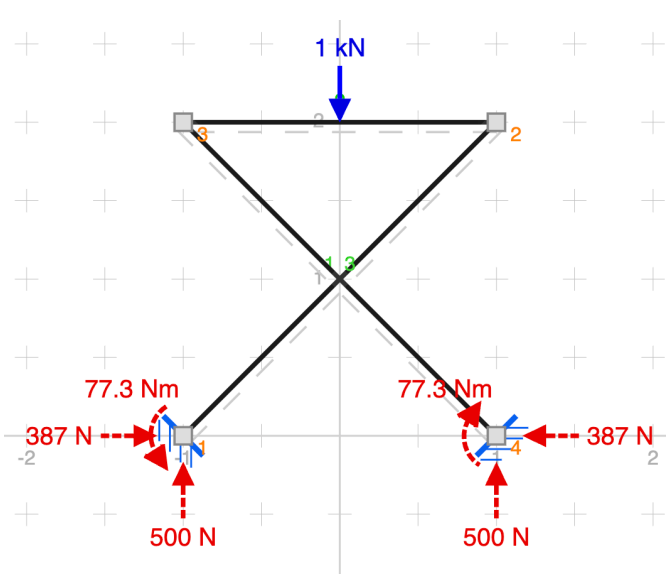
F = 1

$\lambda = 3$
$l = 4$
$j = 3$
$f_i = 1$

F = 3

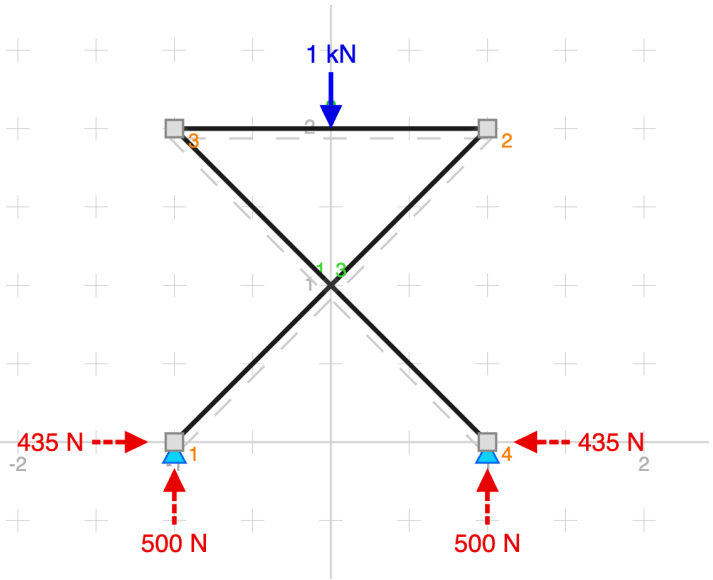
Further: Force/Torque Analysis





Fixed joint

- Motor torque selection



Revolute joint

Bearing or hinge design

Utilize simulation software! –SolidWorks, ANSYS, etc.

https://structural-analyser.com/domains/www/online-free-structural-analysis.html

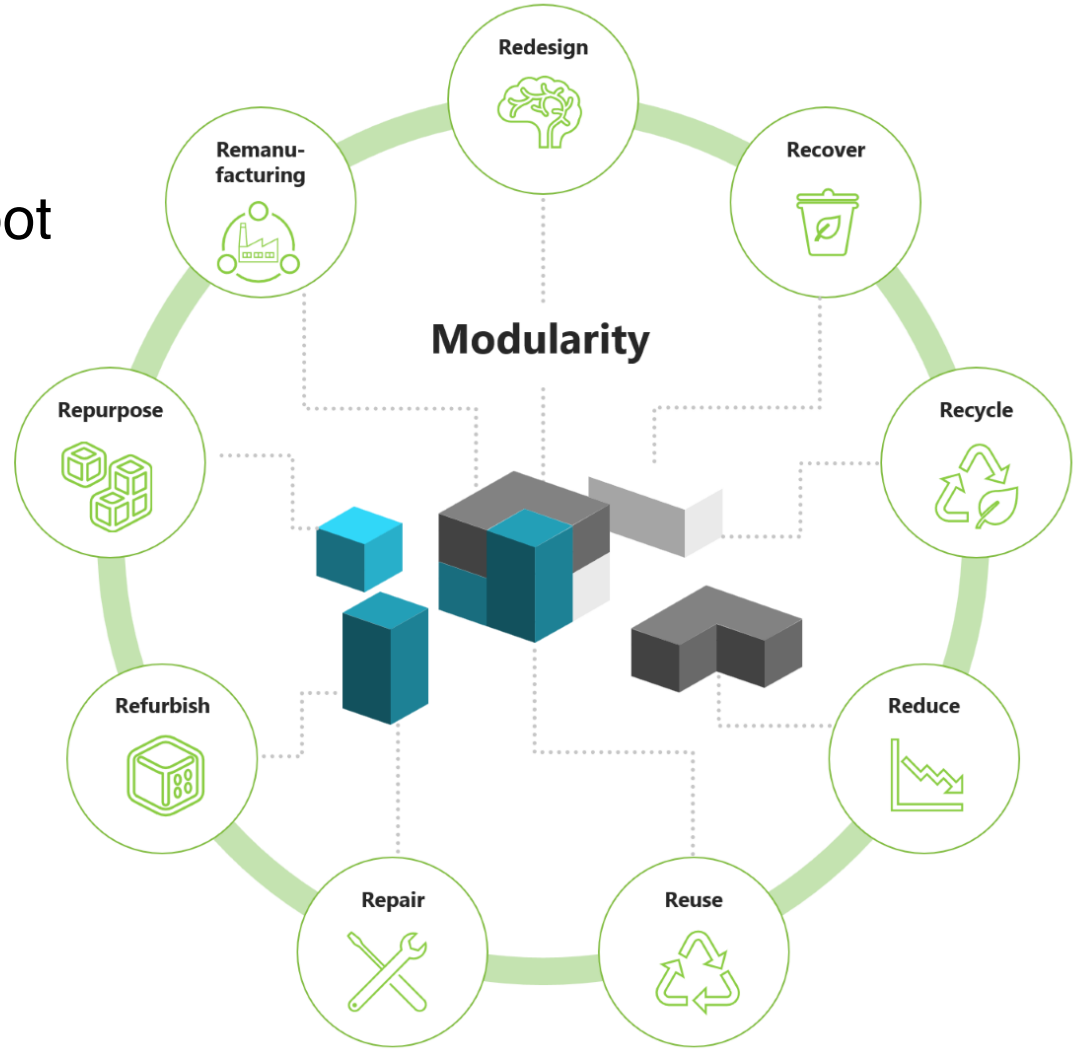
Autonomous System – Modularity

Autonomous system to export solar energy to the grid

Modular Design

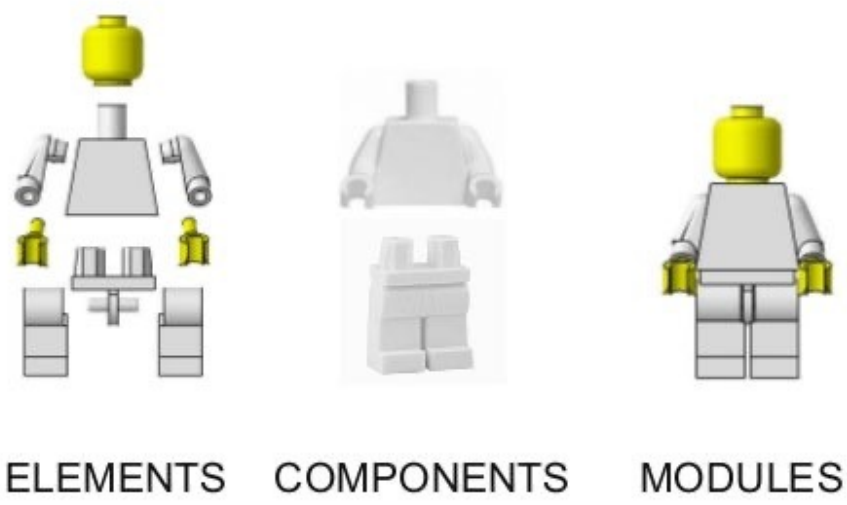
- **Modularity**: Divide the robot into interchangeable, well-defined modules.
  - rapid upgrades, parallel development, simplified maintenance, etc.

- **Sustainability**:
  - Repair
  - Reduce
  - Rethink



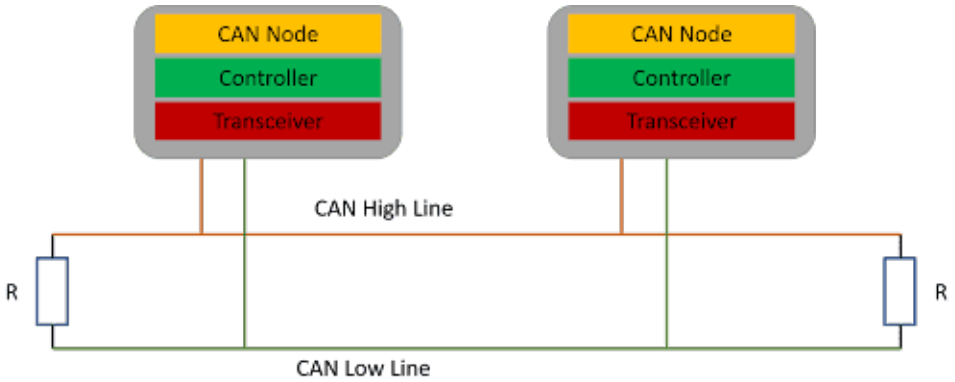
Module Decomposition Strategies

- **Functional decomposition** breaks the system into “what it does”.
- **Physical decomposition** groups by “where it lives” on the robot.



Interface Standardization & Decoupling

- **Mechanical Interfaces:** quick-change couplers, unified mounting patterns
- **Power/Signal Interfaces:** Standard power buses, I2C, CAN-bus
- **Decoupling & Debugging:** Test and validate each module independently



Resources

1. Sustainable mechanical engineering guide: https://project.me.tudelft.nl/Duurzaam-ontwerpen/green-me/en/res/GuideV4.02.pdf
2. Mechanisms: https://blog.metu.edu.tr/eresmech/mechanisms/
3. Online mechanical linkage simulation: https://structural-analyser.com/
4. Modularity perspective: https://www.modularmanagement.com/blog/modularization-paving-the-way-for-a-circular-economy
5. Book: Self-Reconfigurable Robots: An Introduction, https://mitpress.mit.edu/9780262013710/self-reconfigurable-robots/

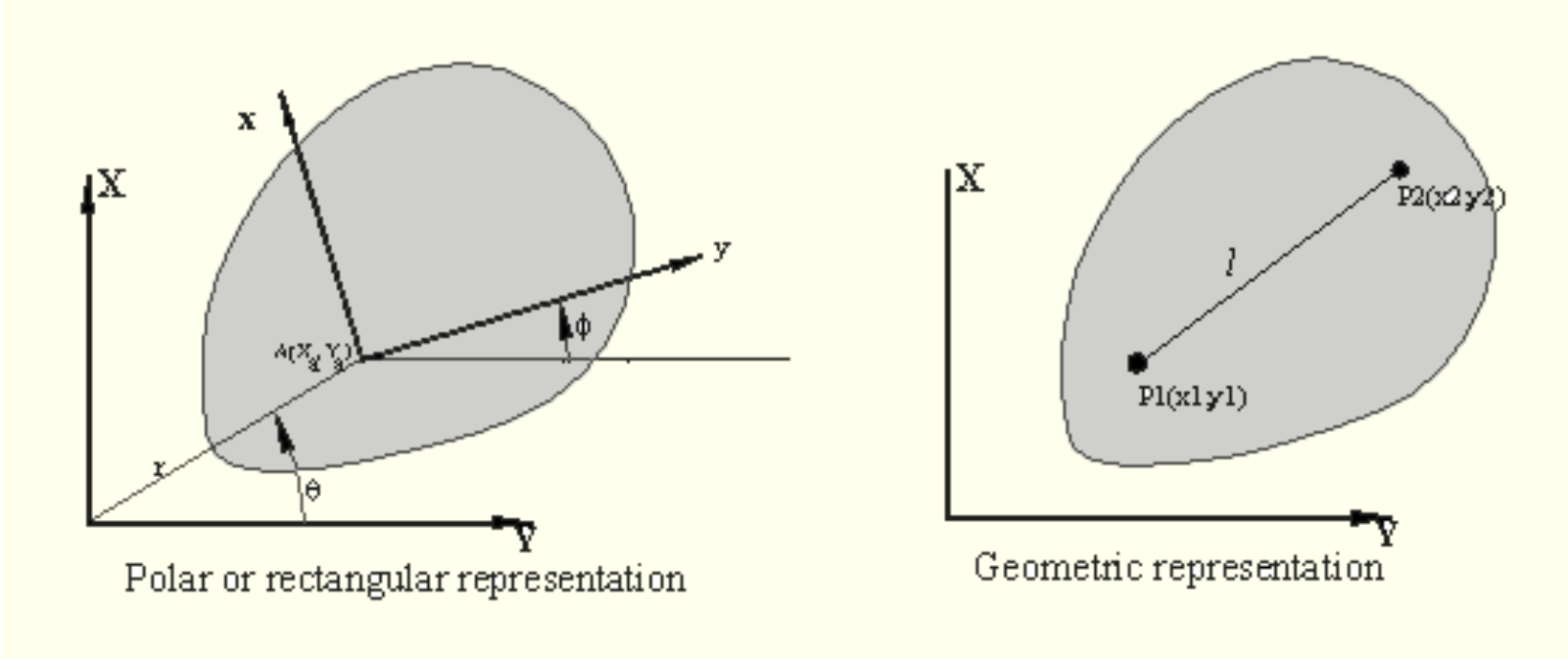
Summary & Takeaways

- Select mechanisms based on your real needs.

- Mechanisms and modular design serve as a bone or basic architecture for autonomous system design.

  Of course autonomous system is more than these. You will get necessary knowledge for other lectures, from sensing, actuating to control.

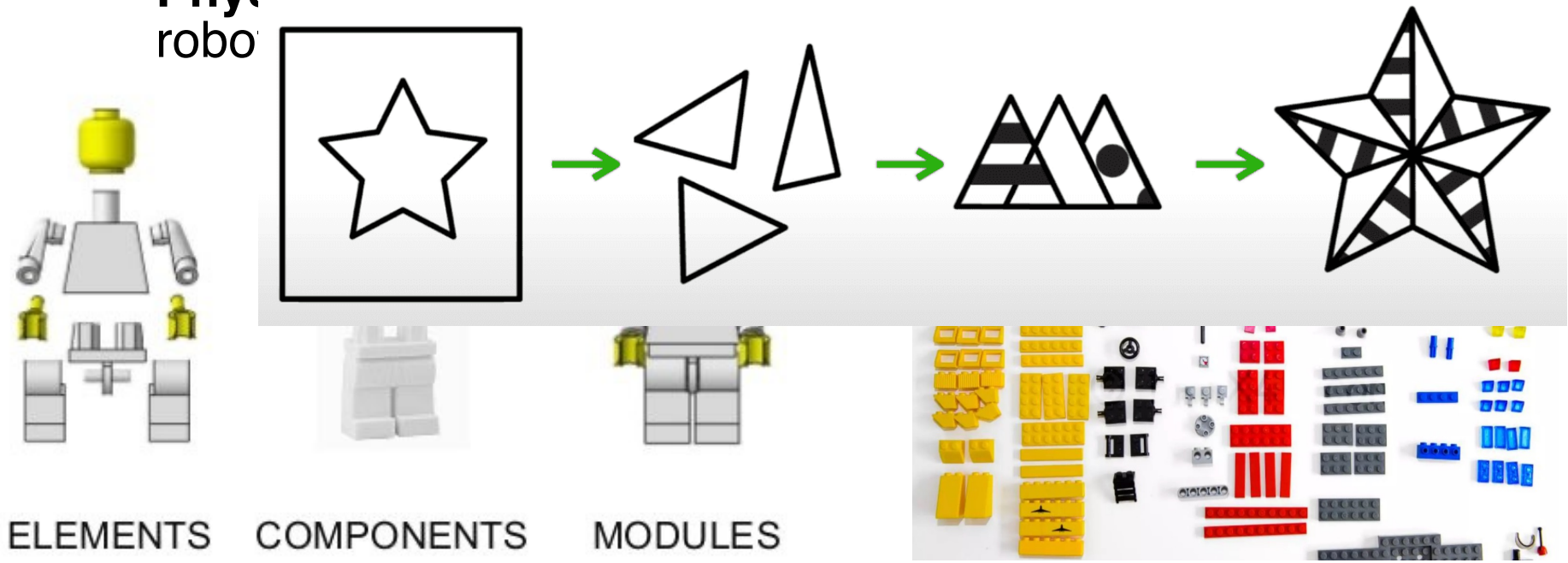
Appendix



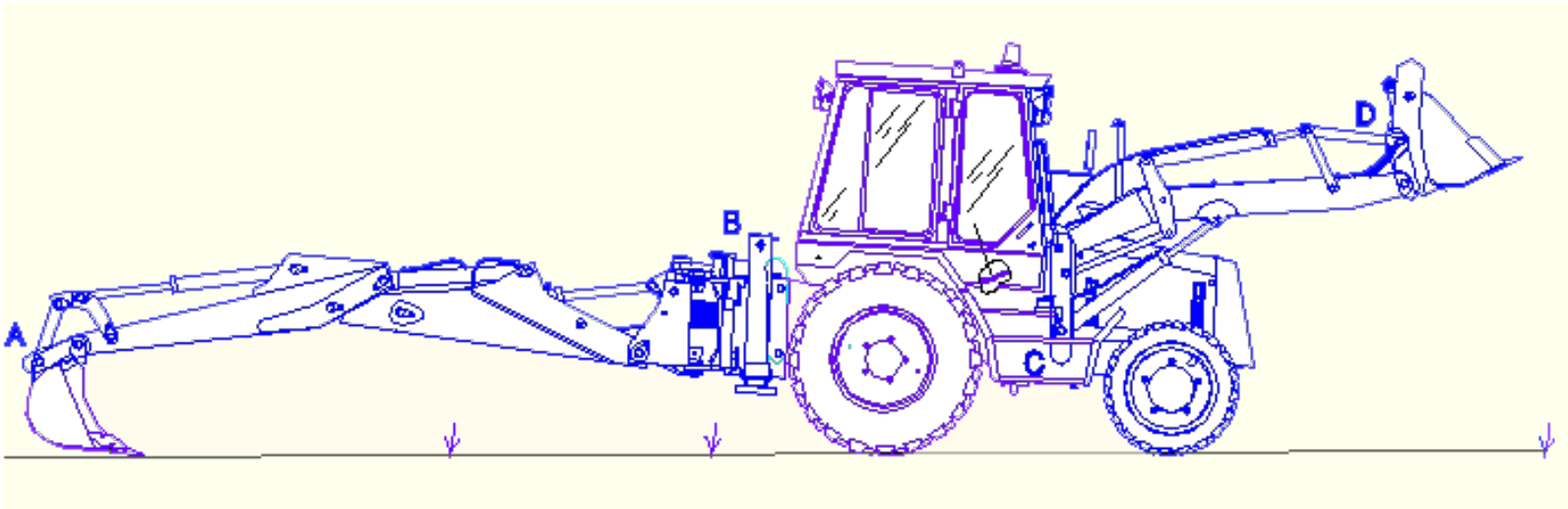
Spatial: 6 degree-of-freedom
Planar: 3 degree-of-freedom

Module Decomposition Strategies

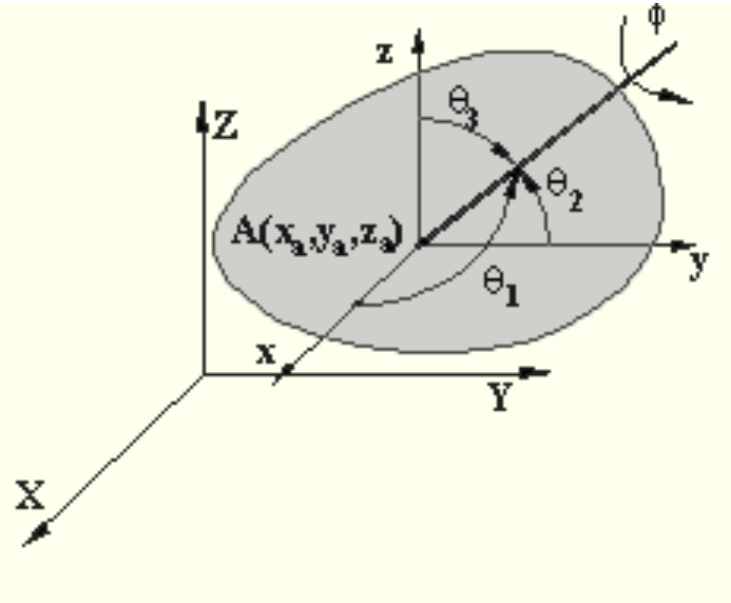
- **Functional decomposition** breaks the system into “what it does”
- **Phys**
  robo



Backhoe-Loader



Degree of Freedom - Spatial



- Parameters are not unique

Autonomous System - Mechanism

Autonomous system for photovoltaic tracking