上海科技大学
ShanghaiTech University

CS289: **Mobile Manipulation Fall 2024**

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ShanghaiTech Automation and Robotics Center · 上海科技大学自动化与机器人中心

STAR CENTER

Final

- Dec 3rd – next Tuesday!
  - 15:00 – 17:00 in 1D-106

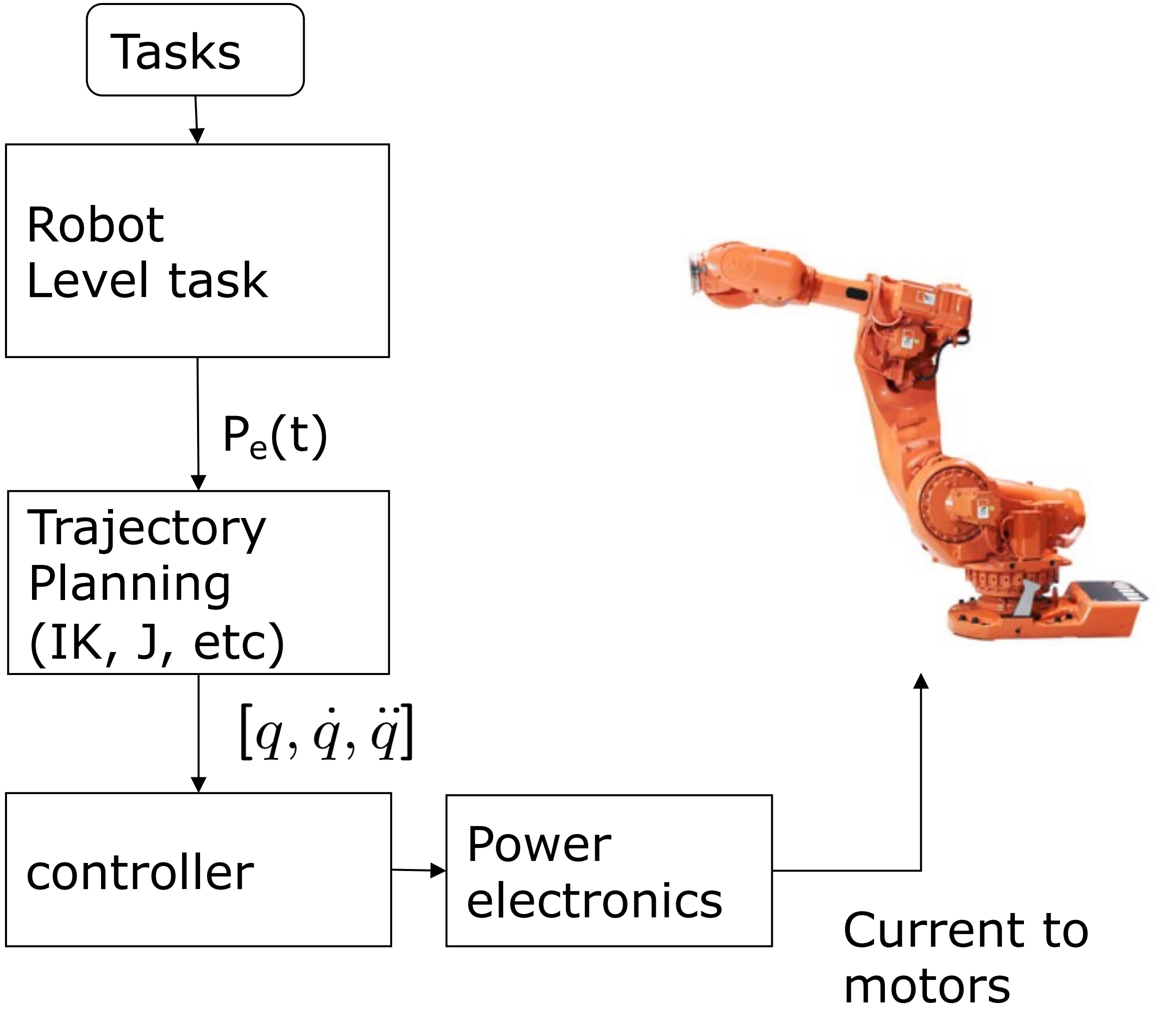
- Content:
  - All lectures
    - Take a look at facts, algorithms, concepts

- You are allowed to bring **3** A4 sheets (so 6 pages) of info to the exams. You can write/ print anything on those sheets. On top of **every page** (so 6 times) there needs to be your **name (pinyin), student ID and ShanghaiTech email** address. We will check every cheat sheet before the exam and **confiscate** every sheet without name or with a name that is not yours.

- No electronics/ calculator/ smartwatch allowed

Motivation & Overview

- We covered Kinematics, Planning, Perception, etc.
- How to make the robot actually move?
- **Control** the robot motion
  - Dynamics (forces, mass, inertia etc.) =>
  - Kinematics of speeds: Jacobian
  - Control Introduction
  - PID
- Hardware
  - PWM
  - Motor Drivers
  - Motor
  - Gears



Tasks

Robot Level task

$P_e(t)$

Trajectory Planning (IK, J, etc)

$[q, \dot{q}, \ddot{q}]$

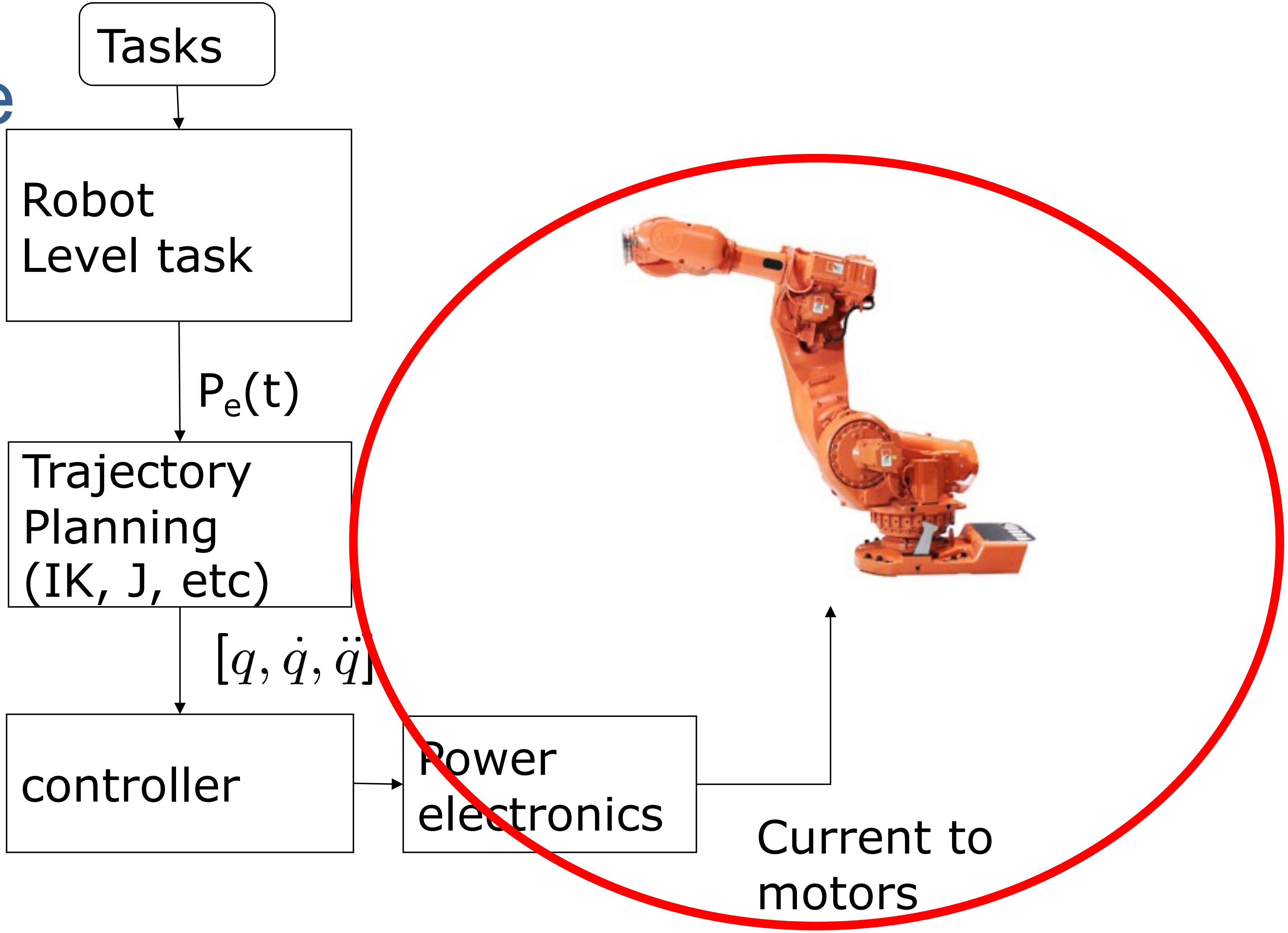
controller

Power electronics

Current to motors

HARDWARE

Hardware



Tasks

Robot
Level task

$P_e(t)$

Trajectory
Planning
(IK, J, etc)

$[q, \dot{q}, \ddot{q}]$

controller

Power
electronics

Current to
motors

Control Hierarchy

- Assume we have a goal trajectory
- Calculate needed joint speeds using Kinematics =>
- Desired joint speeds
  - Typically not just one joint =>
  - Many motor controllers, motors, encoders
- Motor control loop
- Pose control loop

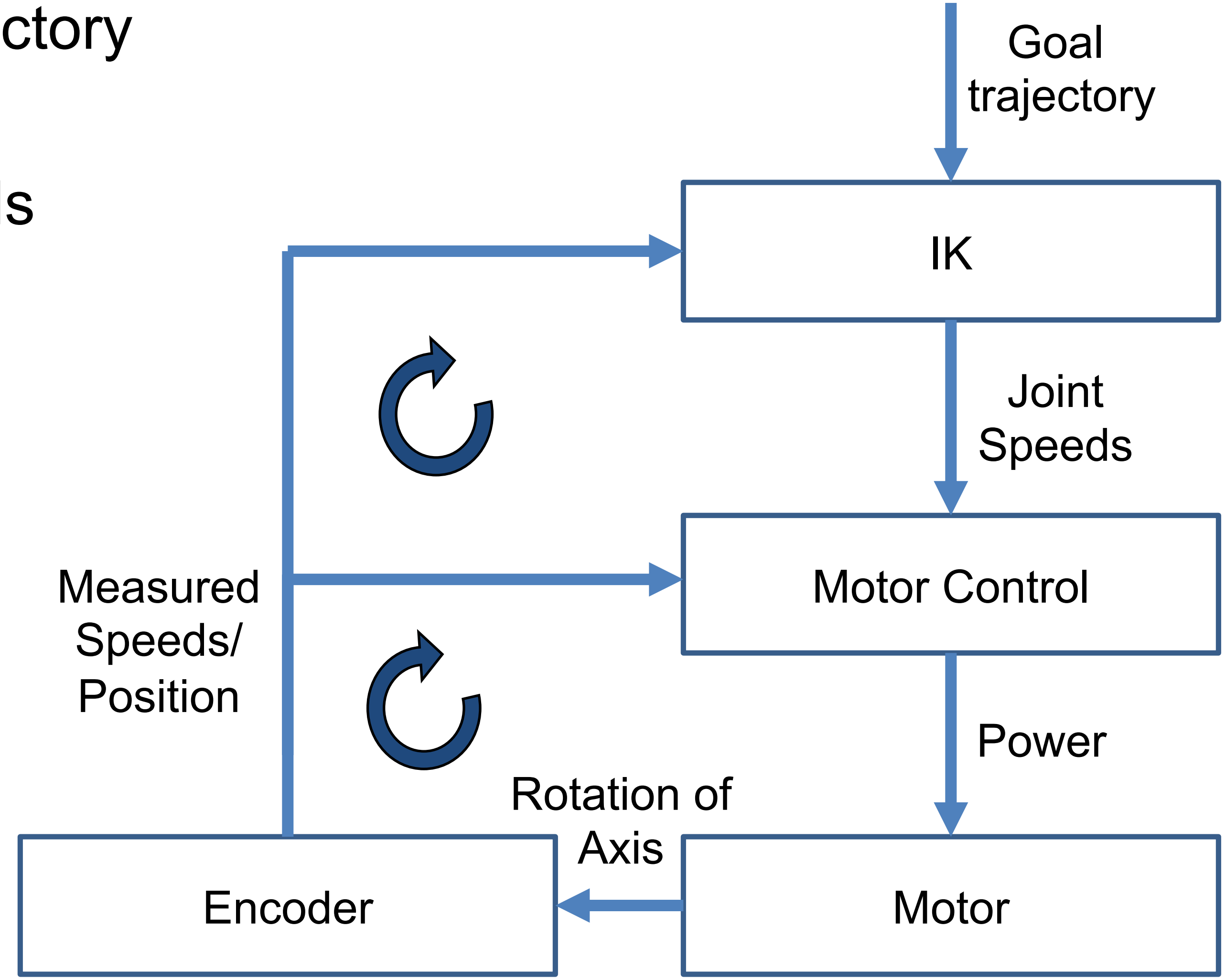
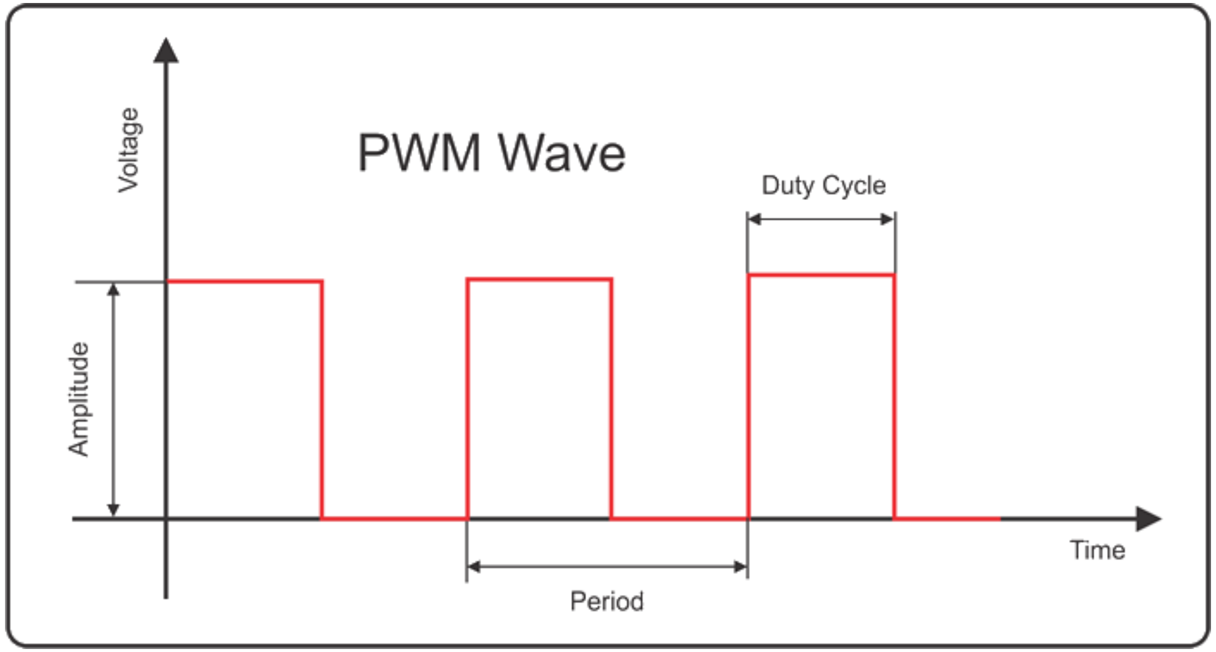


Image: zembedded.com

Pulse Width Modulation



- How can Controller control power?
  - Cannot just tell the motor “use more power”
  - Output of (PID) controller is a signal
  - Typical: Analogue signal
- Pulse Width Modulation (PWM)
  - Signal is either ON or OFF
  - Ratio of time ON vs. time OFF in a given interval: amount of power
  - Frequency in kHz (= period less than 1ms)
  - Very low power loss
- Signal (typica 5V or 3.3V) to Motor Driver
- Used in all kinds of applications:
  - electric stove; audio amplifiers, computer power supply (hundreds of kHz!)

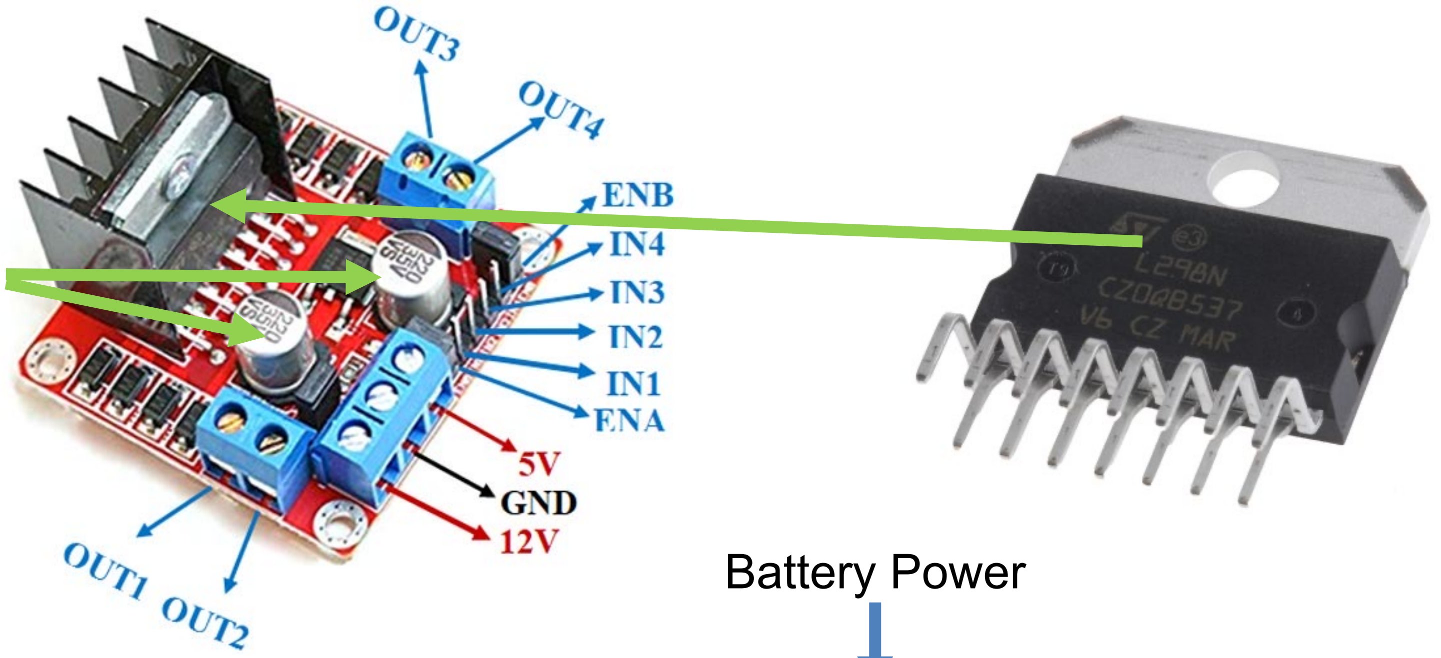
Motor Driver

- Motor Driver
  - Input:
    - PWM signal
    - Direction of rotation
    - Battery + & -
    - Optional: Enable =>
      - Emergency Stop
  - Output:
    - Two lines to the DC motor

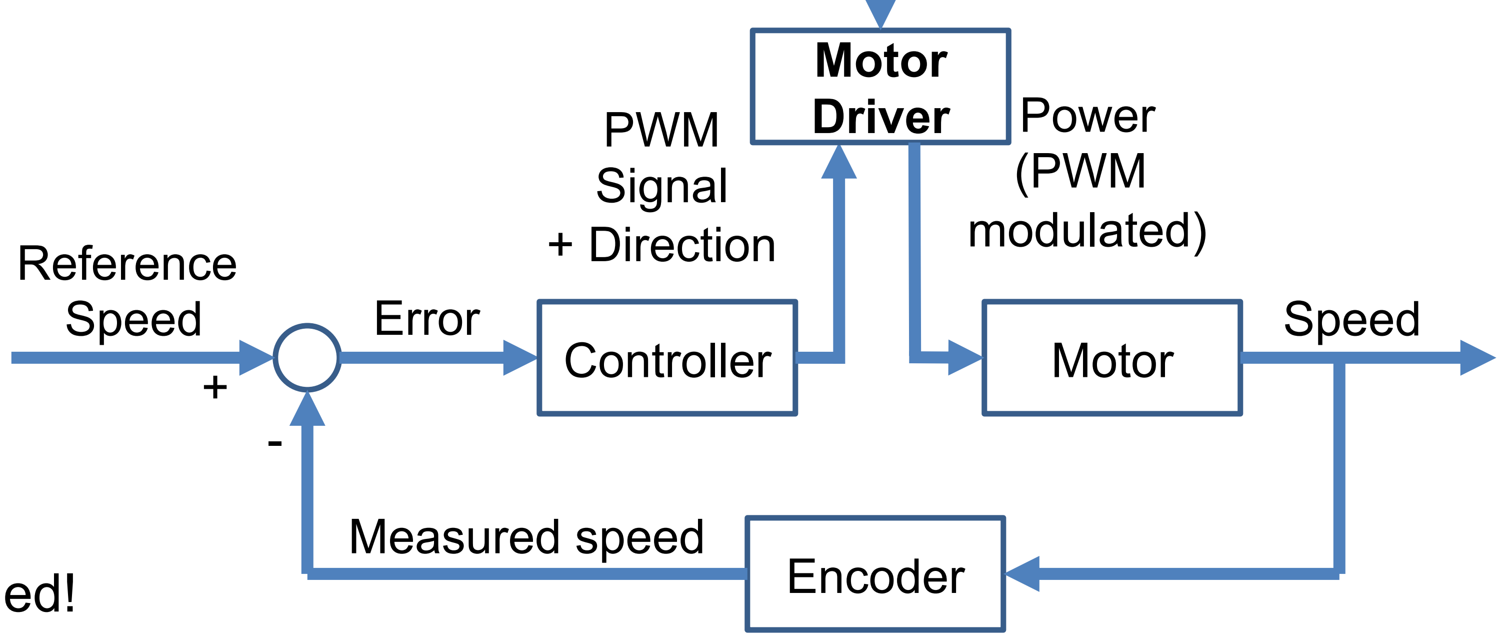
  - Popular: L298N dual motor driver
    - Up to 48V & 4A

  - High Efficiency (maybe 95%) – but still get‘s hot – cooling needed!

Capacitors to smooth output power



Battery Power



Motor Driver

PWM Signal + Direction

Power (PWM modulated)

Reference Speed

+

-

Error

Controller

Motor

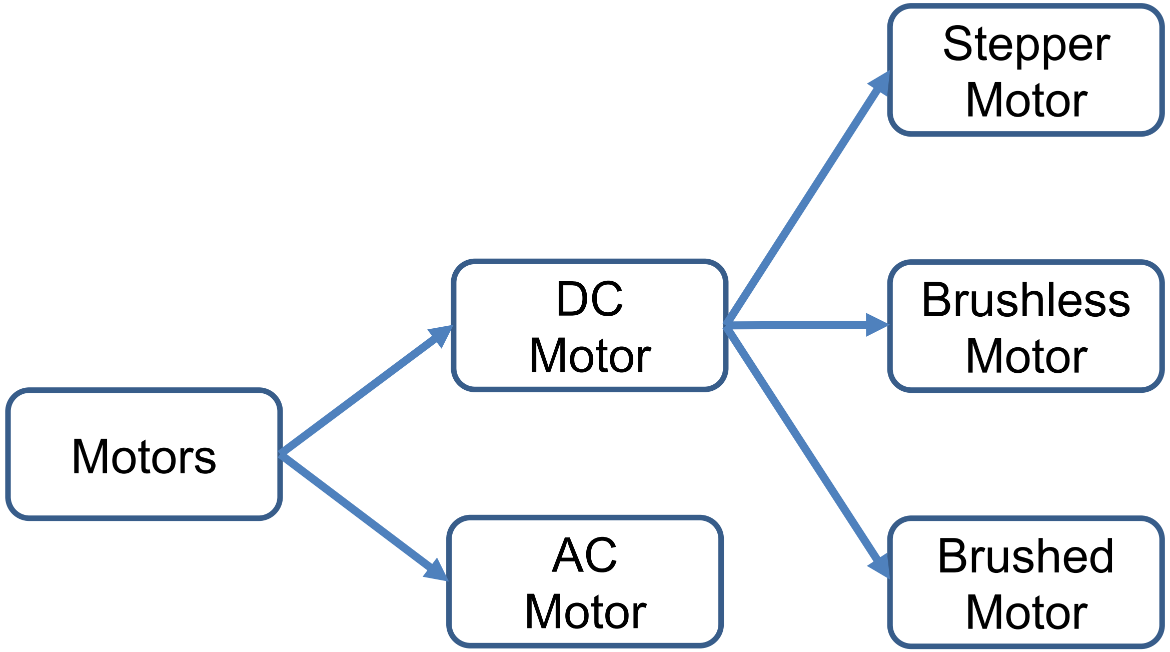
Speed

Measured speed

Encoder

Electrical Motor Types

- DC Motor: Direct Current Motor
- AC Motor: Alternating Current Motor
- Stepper motor:
  - Switching power steps one tooth/ coils forward
  - Open loop control: no encoder needed
  - Low resolution; open loop; torque must be well known
- Brushed motor:
  - Use brushes to power rotating coils => low efficiency and high wear
- Brushless (BL) motor:
  - Electronically control which coil to power => high efficiency low wear
  - Need dedicated controller


Motors

DC Motor

AC Motor

Stepper Motor

Brushless Motor

Brushed Motor

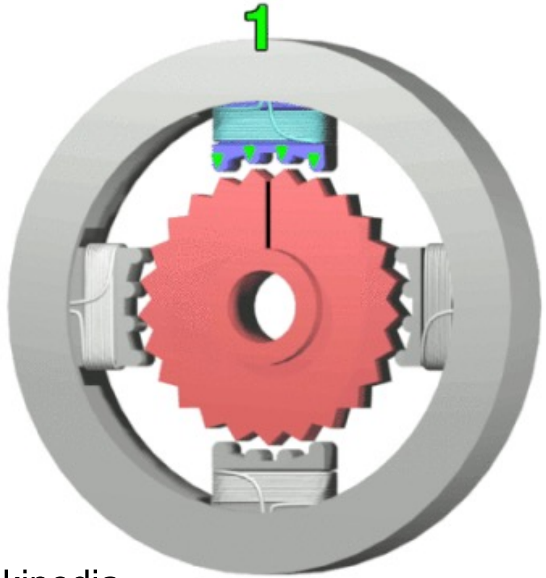
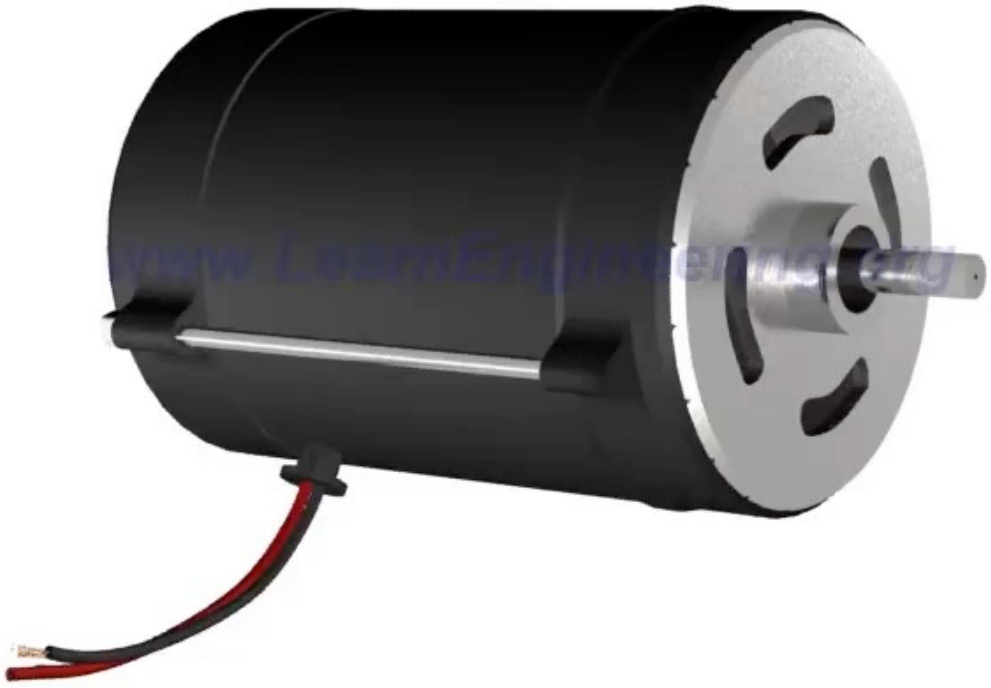


Image: Wikipedia



www.LearnEngineering.org

https://www.youtube.com/watch?v=CWulQ1ZSE3c

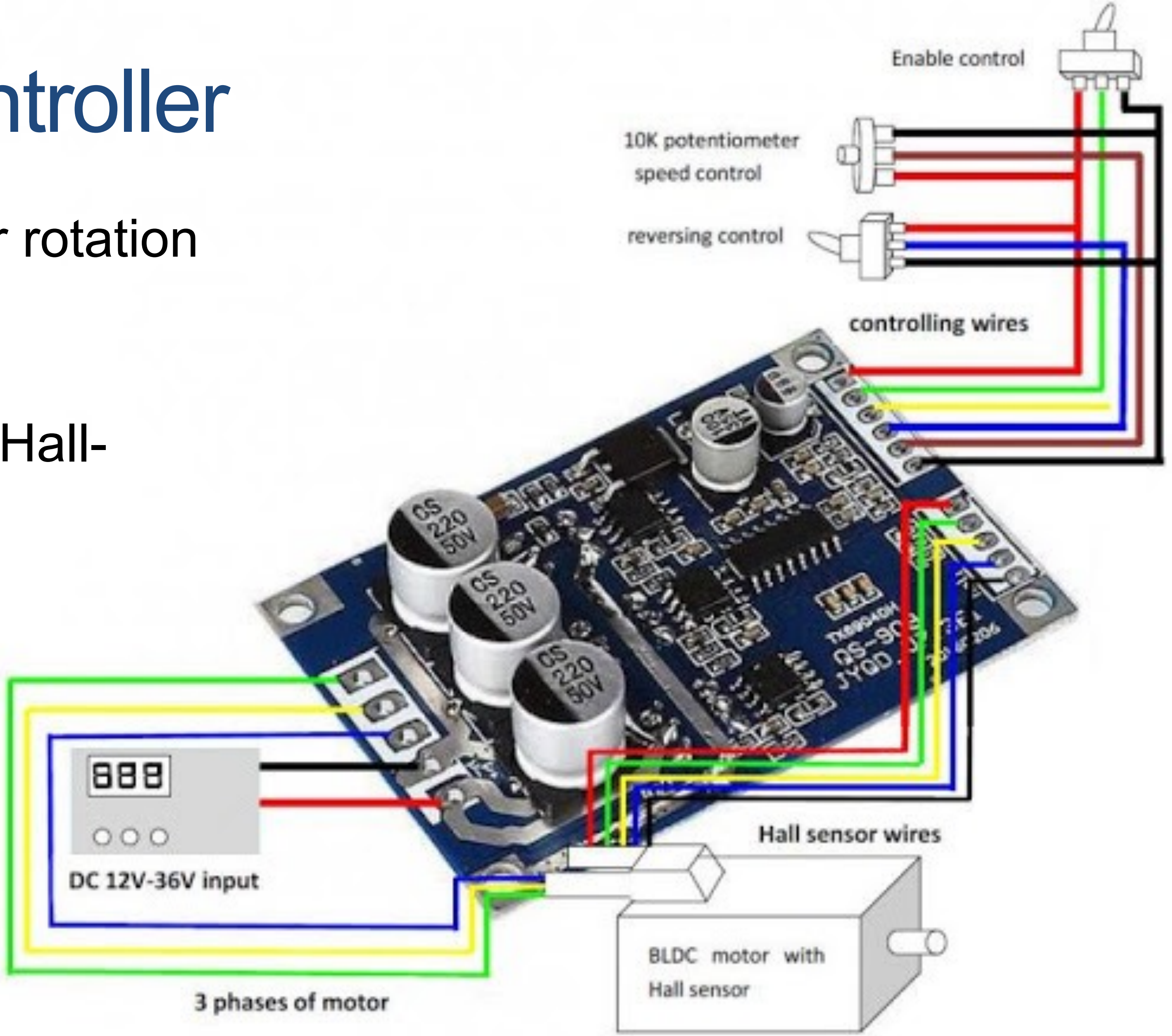
https://www.youtube.com/watch?v=bCEiOnuODac

Brushless Motor Controller

- Needs BLDC Controller
  - Does also the job of Motor Driver
- Sensorless BLDC motor:
  - Just apply power to coils in correct order
  - Motor might briefly turn backwards in the beginning
  - Works well for fast spinning motors (e.g. quadcopter)
  - May use the back-EMF (electromotive force) to estimate position

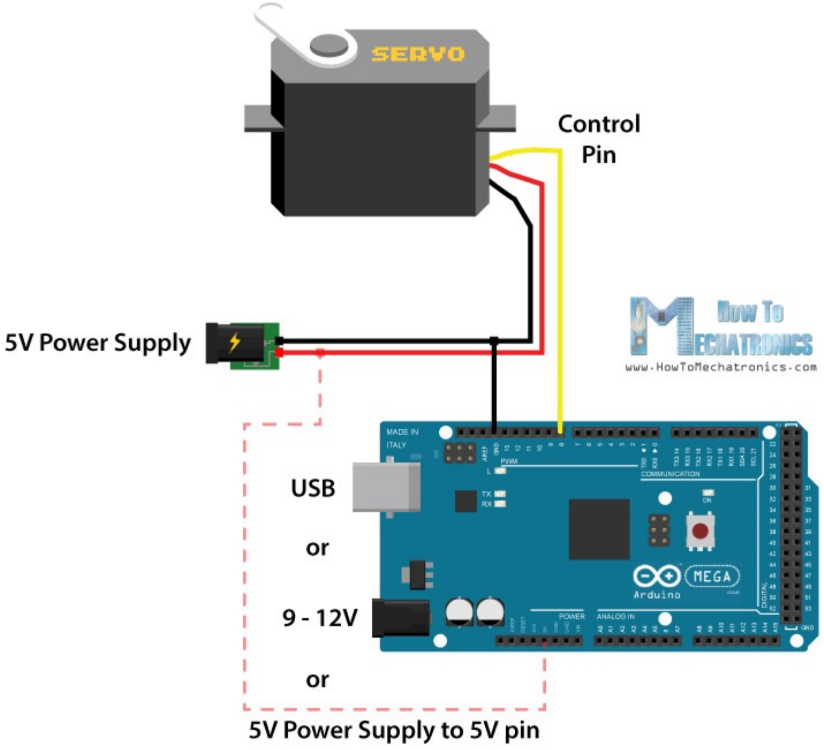
Brushless Motor Controller

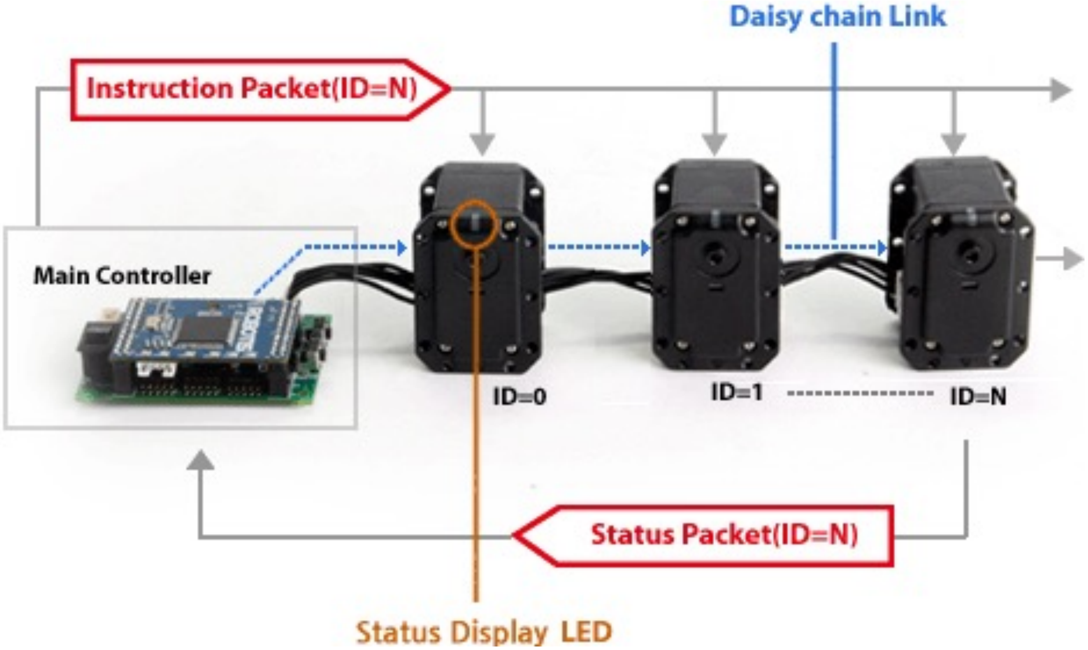
- Hall sensor only 3 positions per rotation
  - Quadrature encoder: up to 4096
- For high torque; low speeds: 3 Hall-effect sensors needed!
- External PID speed control may still be needed!
- Brushless: 20%-30% better efficiency



Servo Motor

- Combines Controller & Motor Driver in the motor
- Input may be analogue (e.g. PWM signal) or digital (e.g. Dynamixel)
- Input specifies a certain (angular) pose for the servo!
  - Servo moves and stays there.
- Continuous Rotation Servos: open loop, speed controlled motors

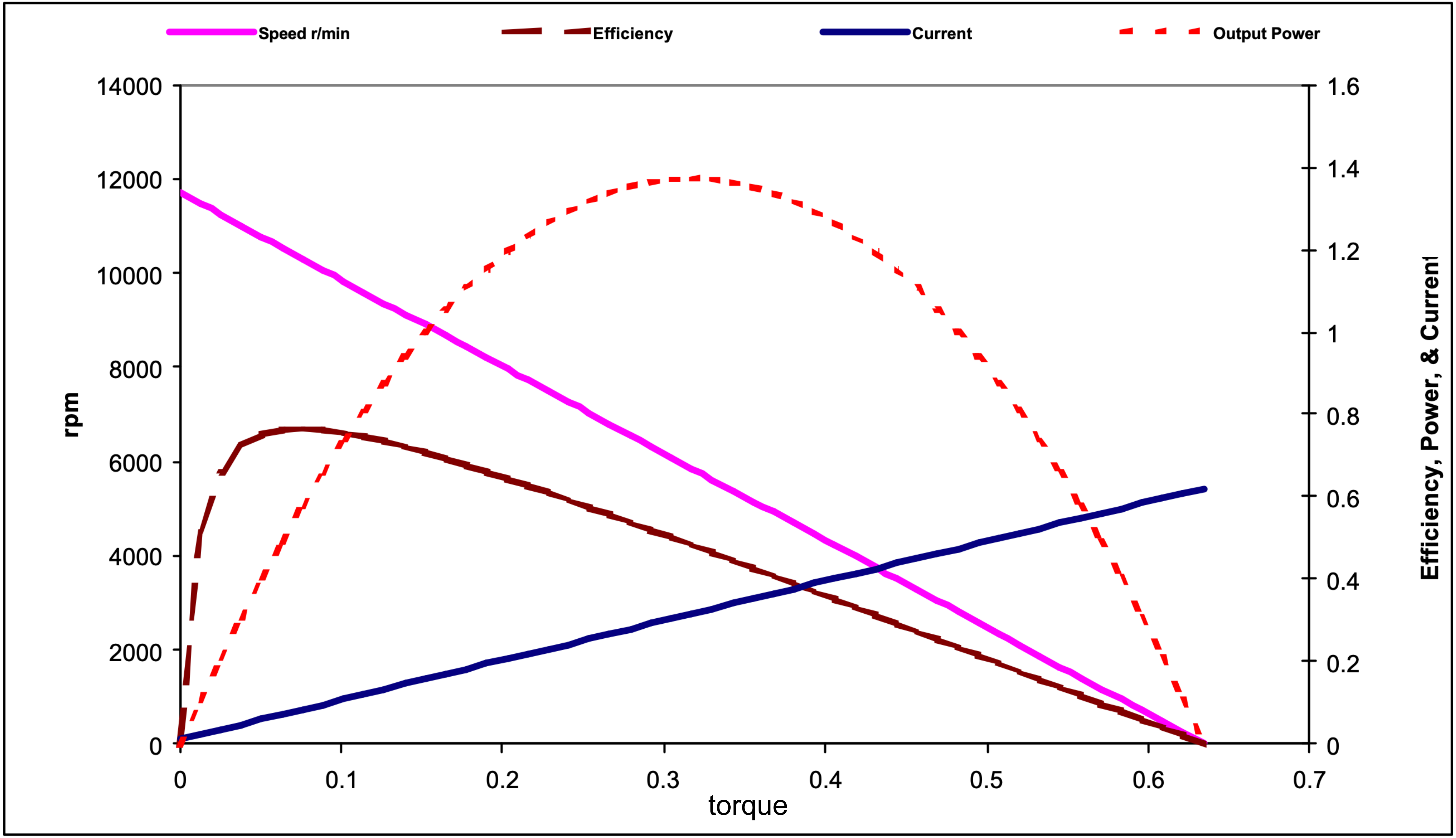




DC Motor Characteristics

- Torque: rotational equivalent to force (aka moment)
  - Measured in Nm (Newton meter)
  - Torque determines the rate of change of angular momentum
- Stall torque:
  - Maximum torque in a DC motor => maximum current => may melt coils
- Maximum energy efficiency:
  - At certain speed/ certain torque
- No-load-speed:
  - Maximum speed; little power consumption

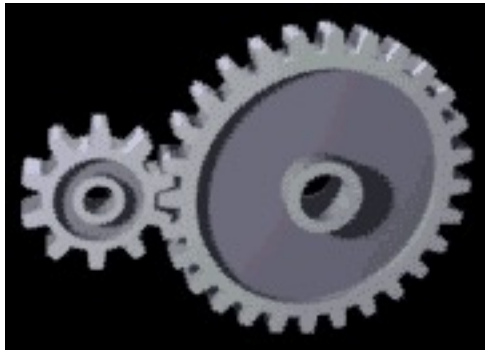
- High-power motors (e.g. humanoid robots) get very hot/ need cooling!


Speed r/min
Efficiency
Current
Output Power
14000
12000
10000
8000
6000
4000
2000
0
rpm
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
torque
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Efficiency, Power, & Current

GEARS

Gears

- Trade speed for torque
- See previous characteristic of DC motor: efficiency highest at high speeds
- Robotics: needs HIGH torque:
  - Inertia of mobile robot (high mass!)
  - Driving uphill
  - Robot arm: lift mass (object and robot arm) at long distances (lever!) – gravity!
- Most important property: Number of teeth => Gear Ratio $= \frac{DrivenGearTeeth}{DriveGearTeeth}$
- Torque = Motor Torque * Gear Ratio
- Speed = Motor Speed / Gear Ratio
- Teeth have same size =>
  gear diameter proportional to Number of teeth…



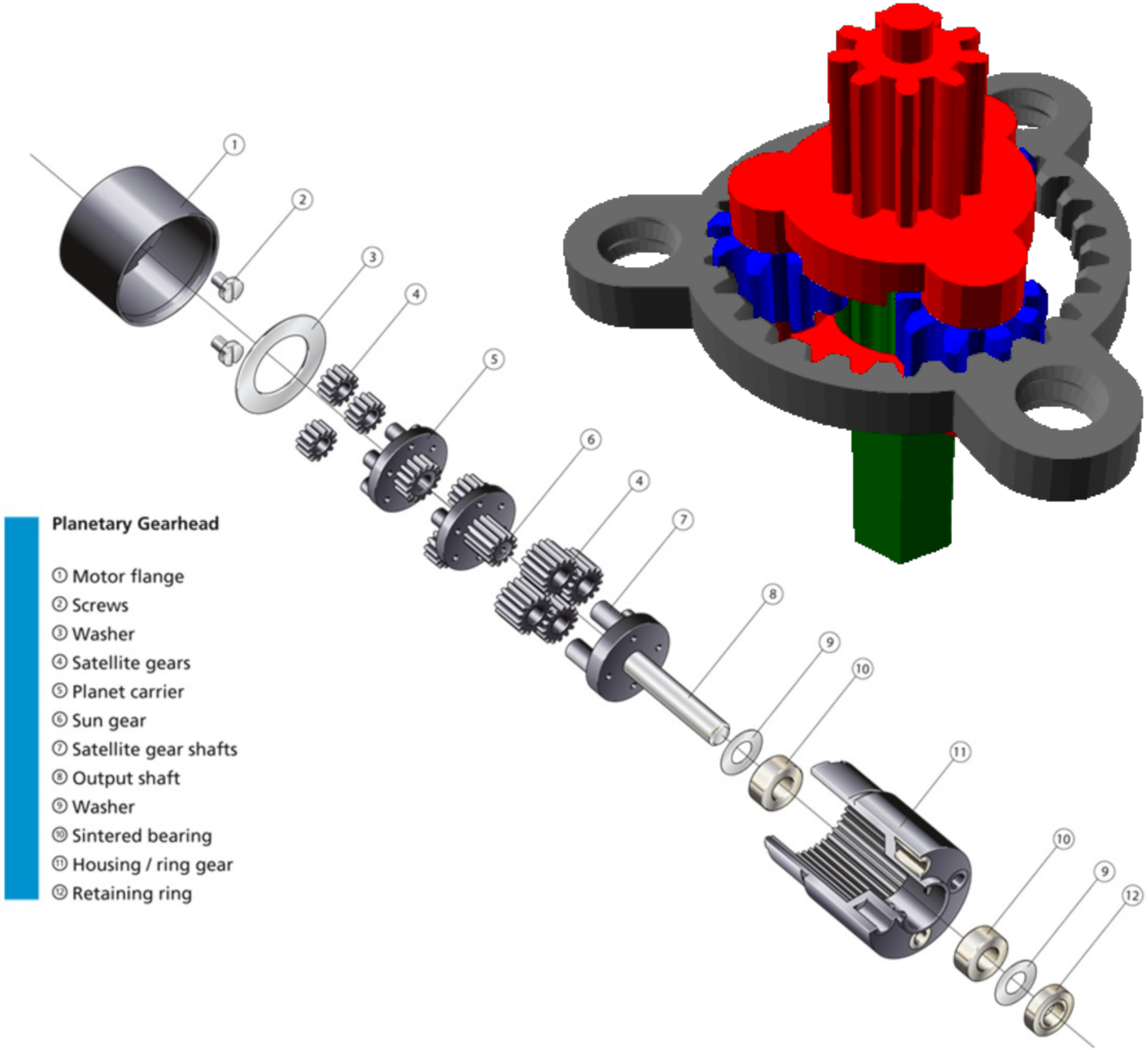
Gears

- Must be well designed to provide constant force transmission
  - Low wear/ low noise
- Back drivable: Can the wheel move the motor?
- Spur Gear reverses rotation direction!
- Backlash: when reversing direction: short moment of no force transmission => error in position estimate of wheel!

https://www.youtube.com/watch?v=8s4zm_ajxAA

Planetary Gear

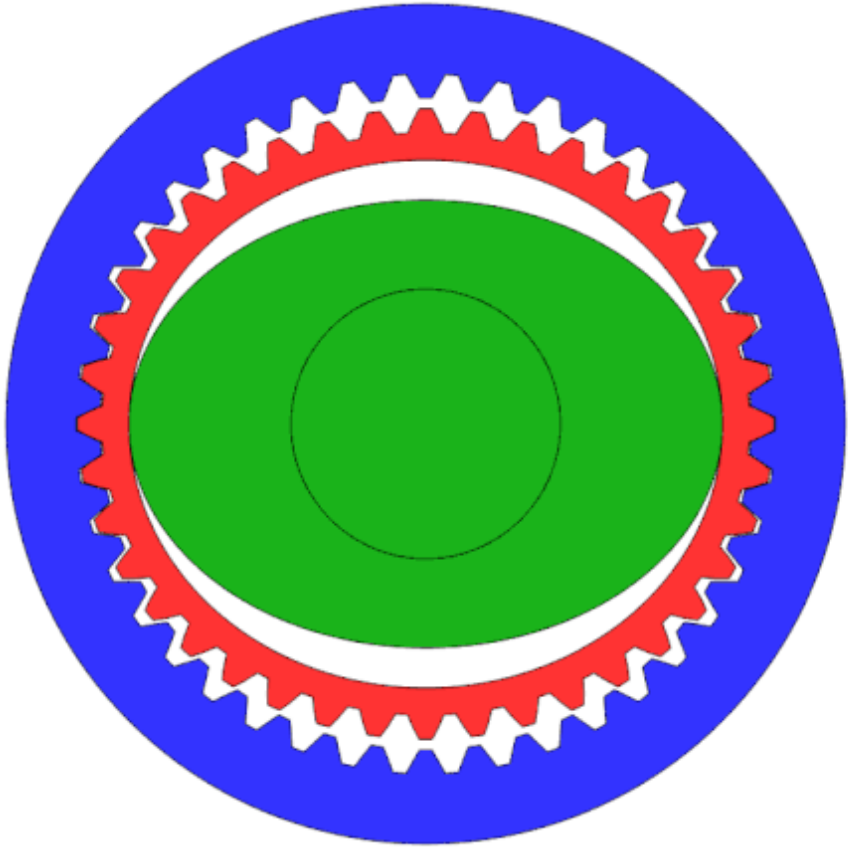
- Aka epicyclic gear train
- Quite common!
- Ratios: 3:1 … 1526:1
- Typical setup:
  - Sun (green) to motor
  - Carrier (red) output
  - Planets (blue): support
  - Ring (black): constraints the planets
  - => Ratio = $1:(1 + N_{Ring}/N_{Sun})$



Harmonic Drive

- High reduction in small volume (30:1 to 320:1)
- No backlash
- Light weight

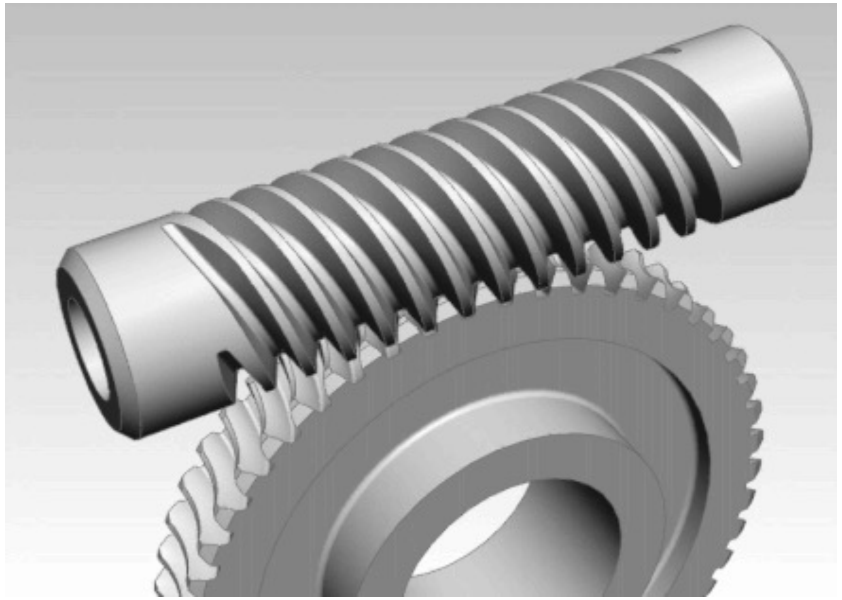
- Used in robotics, e.g. robotic arms (e.g. our Schunk arm!)



$$\text{reduction ratio} = \frac{\text{flex spline teeth} - \text{circular spline teeth}}{\text{flex spline teeth}}$$

More Gears

- Rack and pinion
  - linear drive

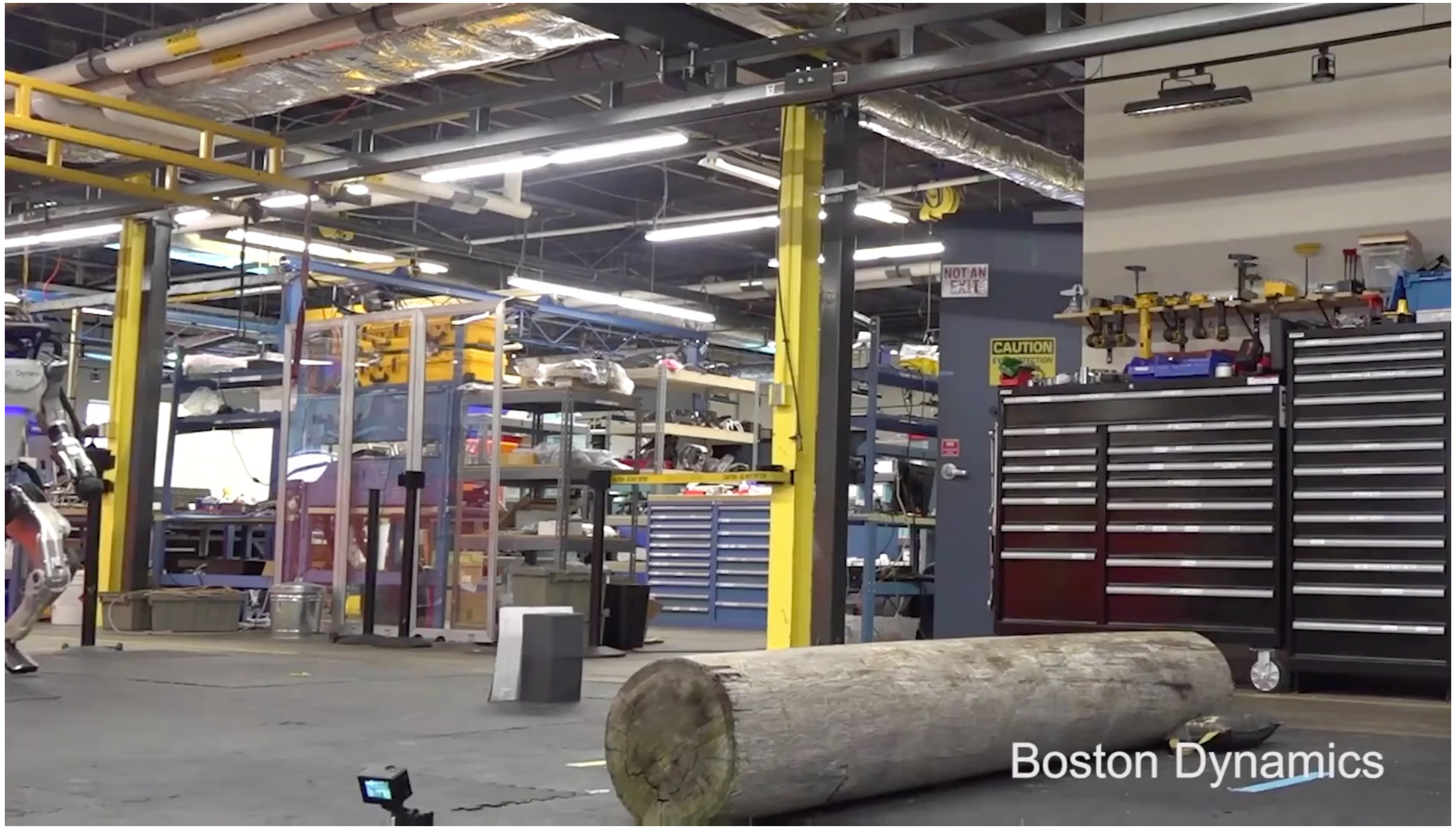


- Worm drive
  - Very high torque
  - Ratio: $N_{Wheel} : 1$
  - Locking (not back-drivable) gear)

- Bevel gear
  - Mainly to change direction

ALTERNATIVES

Hydraulics



- 28 Hydraulic actuated joints
- Why?
  - Compact actuators with high torque – do not get hot!
  - Low mass
  - One central, highly efficient motor to pressurize the hydraulic fluid
- Actuation controlled via controlling valves

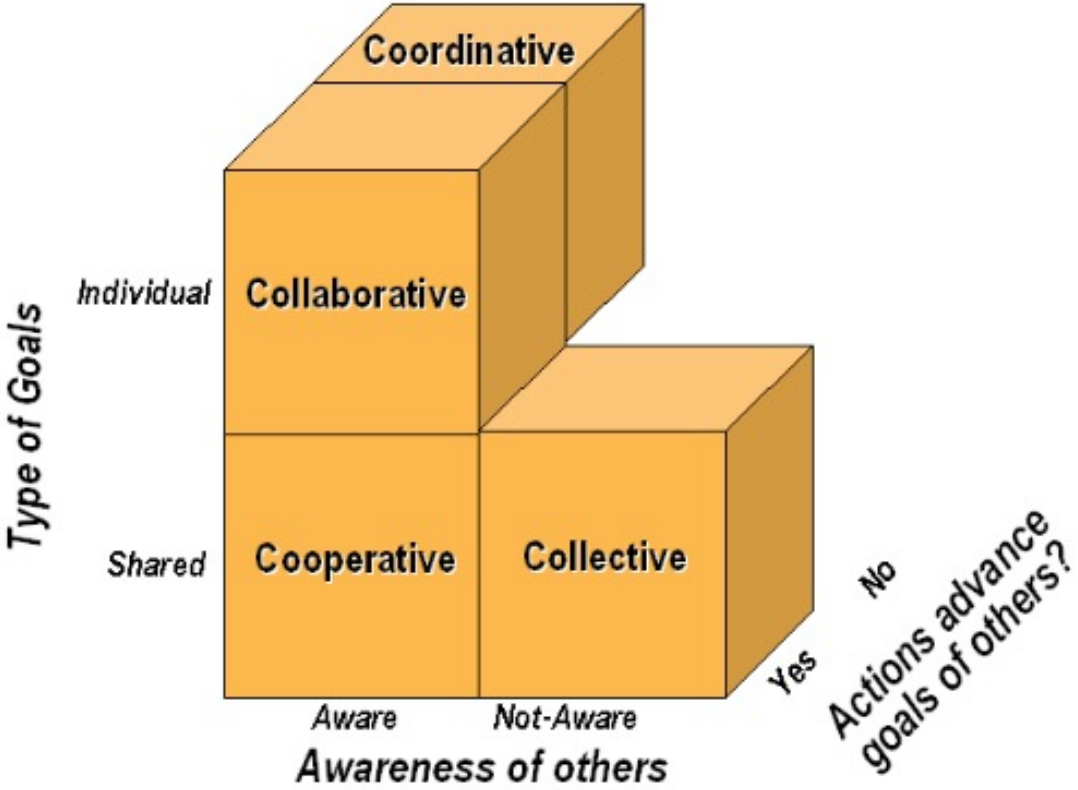
Synthetic Muscles

- Electroactive polymer: Apply voltage => change shape by 30% OR: …

MULTIPLE MANIPULATORS

Multi-Robot & Human-Robot Co*****

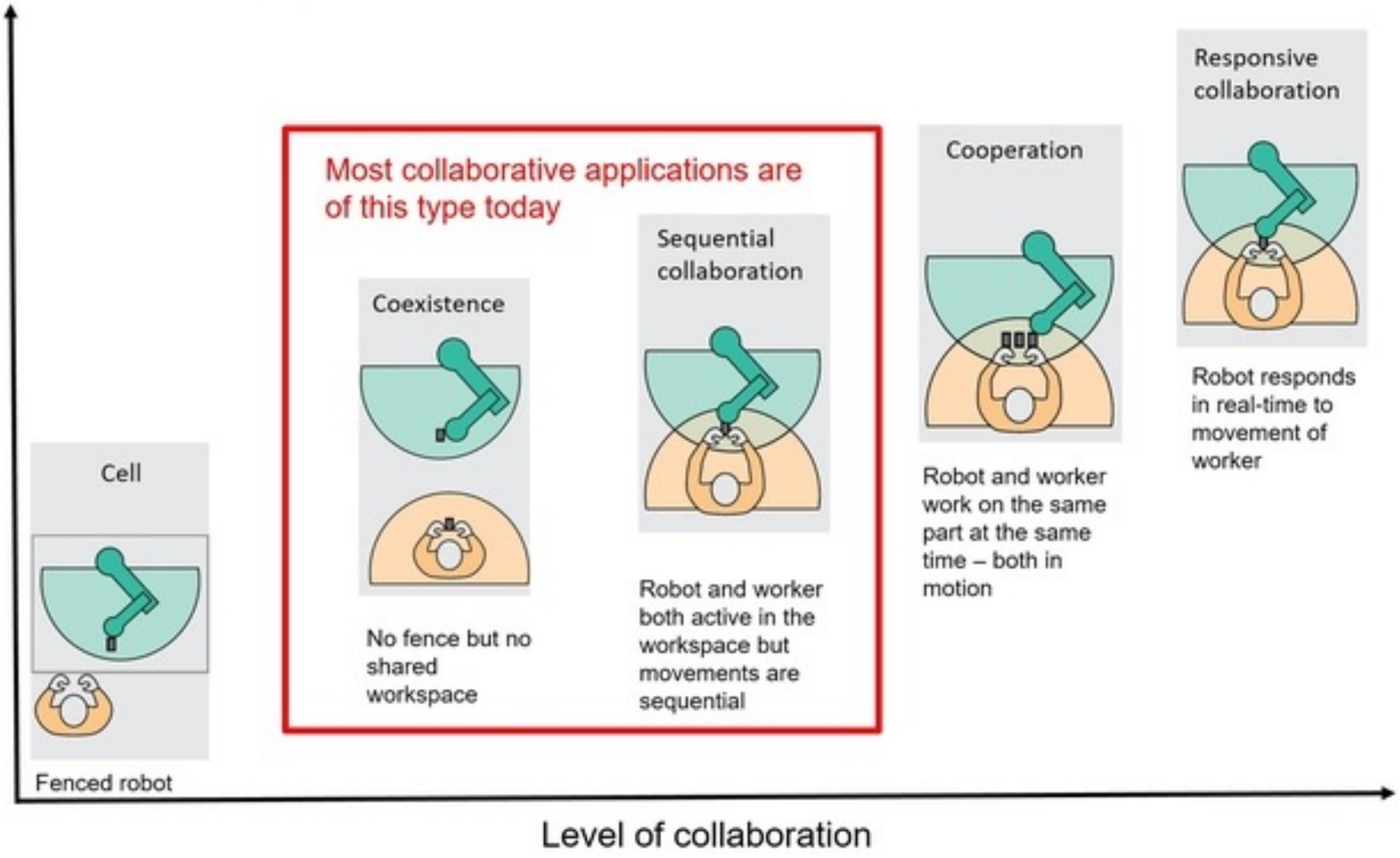
- Often in terms of task and mission planning
  - E.g.: tidy up the room together, cook together, build a house together, search together, …



- Sometimes: Perception and/ or Control problem:
  - Typically when manipulating the same object (at the same time)
  - E.g.: two agents carrying a heavy object together, shaking hands, throwing & catching ball, …

Parker, L. E. (2007, November). Distributed Intelligence: Overview of the Field and its Application in Multi-Robot Systems. In *AAAI fall symposium: regarding the intelligence in distributed intelligent systems* (pp. 1-6).

Types of collaboration with industrial robots



Requirement for intrinsic safety features vs. external sensors

Cell

Fenced robot

Most collaborative applications are of this type today

Coexistence

No fence but no shared workspace

Sequential collaboration

Robot and worker both active in the workspace but movements are sequential

Cooperation

Robot and worker work on the same part at the same time – both in motion

Responsive collaboration

Robot responds in real-time to movement of worker

Level of collaboration

Green area: robot's workspace; yellow area: worker's workspace

Source: IFR (classification), adapted and modified from Bauer et al. (2016).

Industrial vs. Collaborative Robot Arms

Industrial Arms

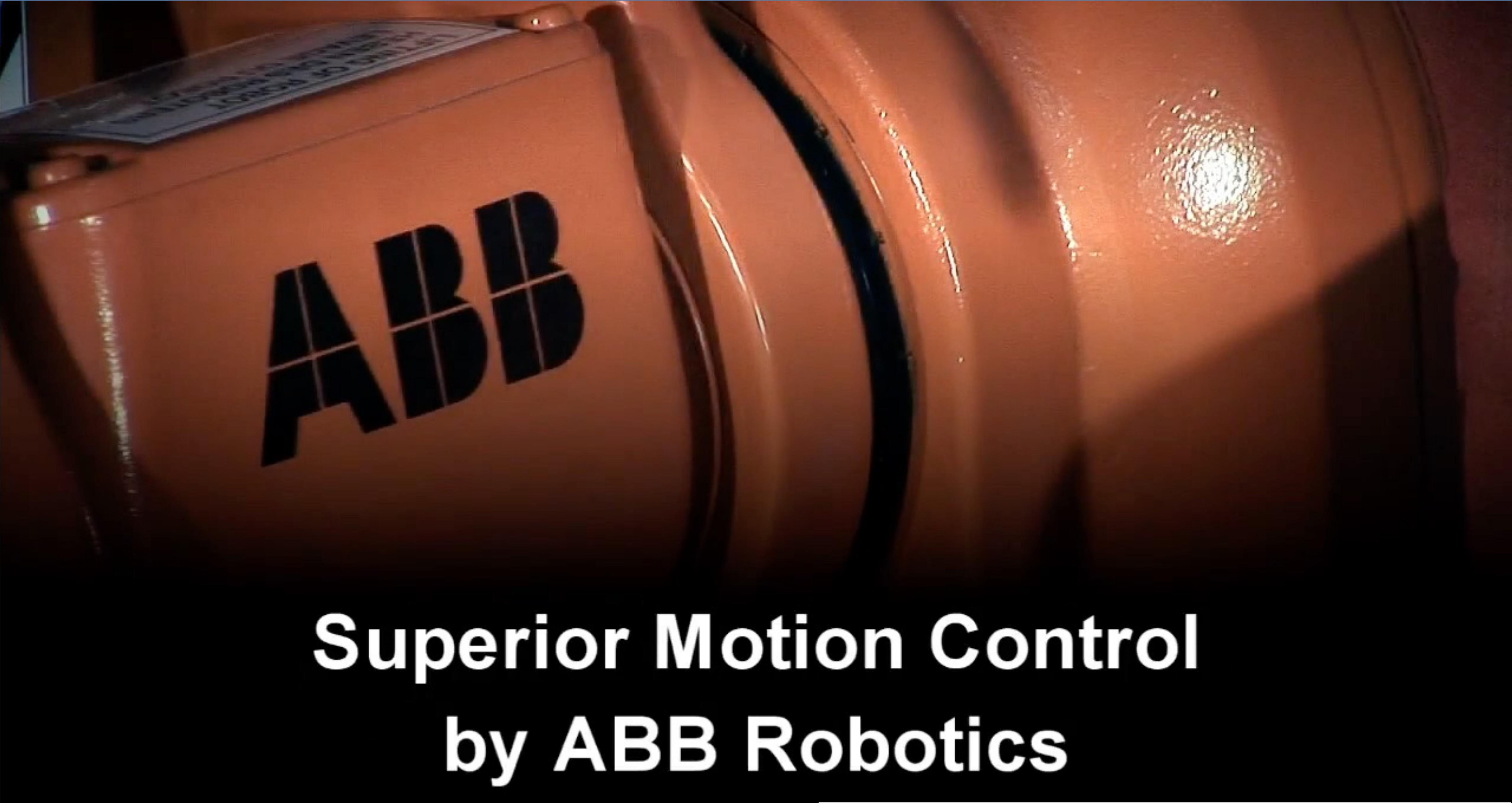
- Can be very precise (up to sub-mm)
- Can be very fast
- Can have very high payload
- May smack you over if you get in the way…

Collaborative Robots

- Often related to soft robotics (to a certain degree) because:
  - Inherent safety due to softness
- Often made compliant (you can move against them) – steer them
  - Also for teaching them easily
- Often less precise, slower, less payload

https://www.youtube.com/watch?v=ArBxq3mOt2s

MULTI-ROBOT KINEMATIC CONTROL

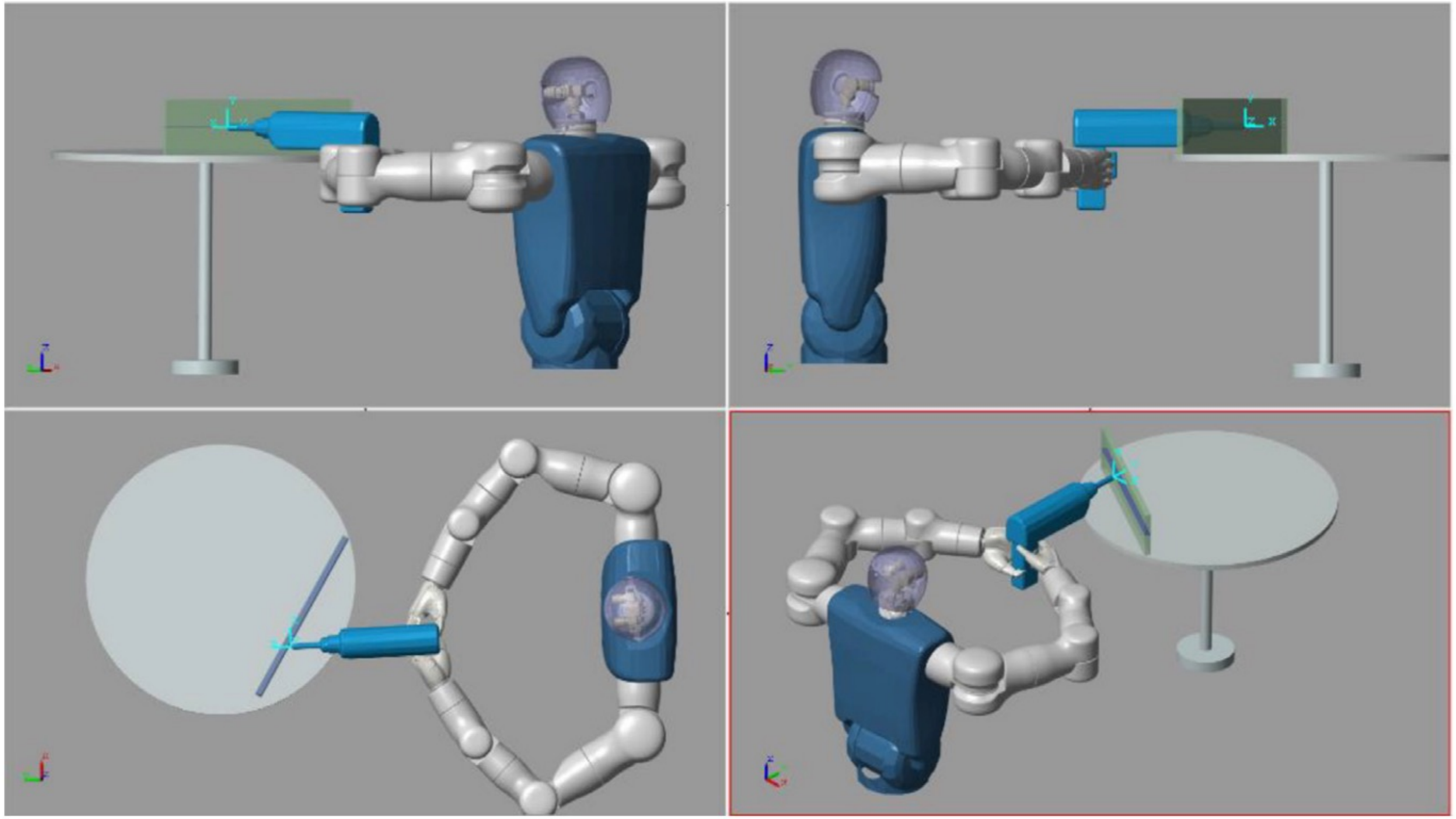


Superior Motion Control
by ABB Robotics

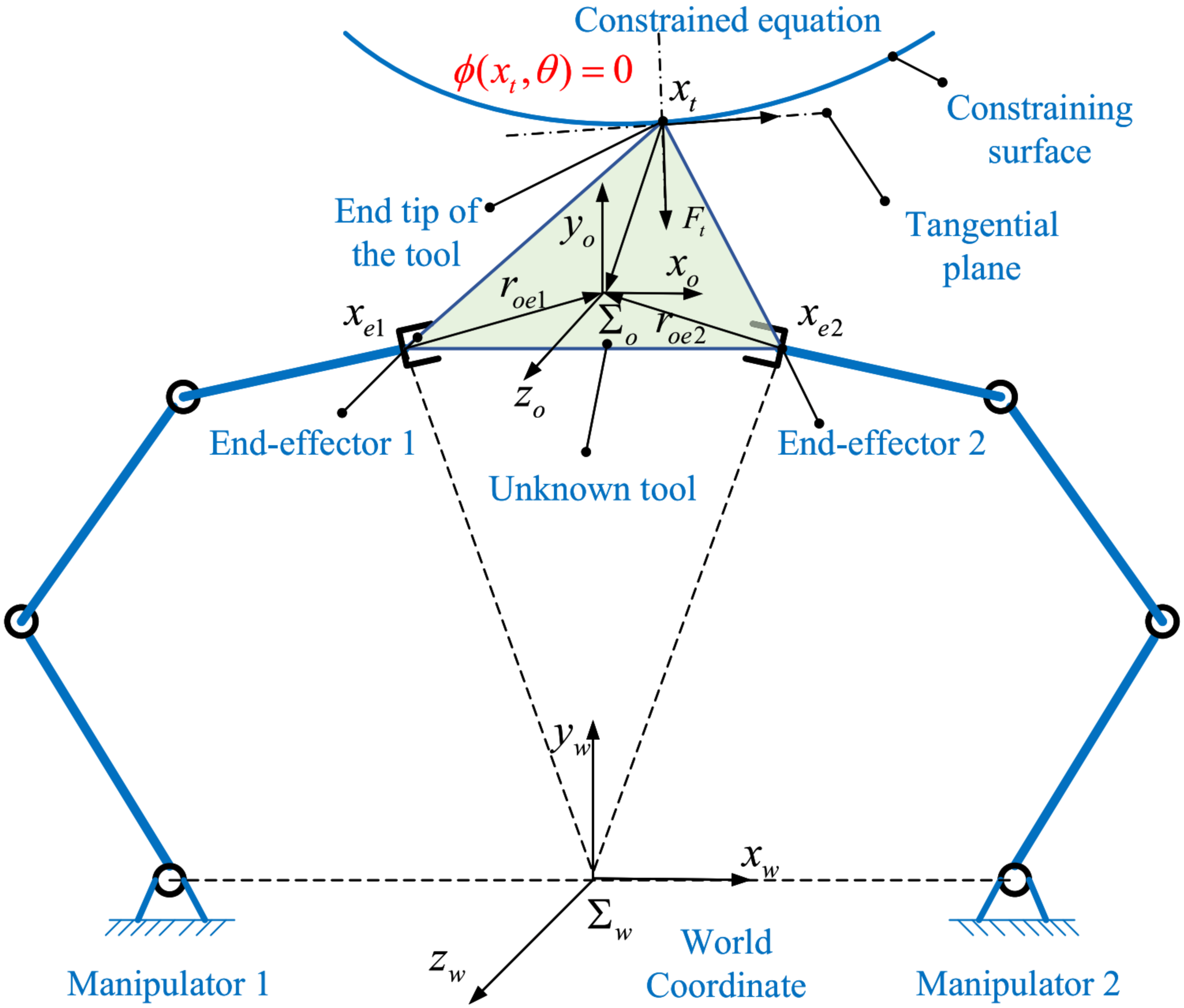
https://www.youtube.com/watch?v=SOESSCXGhFo

DUAL-ARM FORCE CONTROL

Adaptive hybrid position/force control of dual-arm cooperative manipulators with uncertain dynamics and closed-chain kinematics.



Ren, Y., Chen, Z., Liu, Y., Gu, Y., Jin, M., & Liu, H. (2017). Adaptive hybrid position/force control of dual-arm cooperative manipulators with uncertain dynamics and closed-chain kinematics. Journal of the Franklin Institute, 354(17), 7767-7793. https://doi.org/10.1016/j.jfranklin.2017.09.015


Constrained equation
$\phi(x_t,\theta)=0$
x_t
Constraining surface
Tangential plane
End tip of the tool
y_o
F_t
x_o
r_{oe1}
x_{e1}
Σ_o
r_{oe2}
x_{e2}
z_o
End-effector 1
Unknown tool
End-effector 2
y_w
x_w
Σ_w
z_w
Manipulator 1
World Coordinate
Manipulator 2

Kinematics

$$x_e = [x_{e1}^T \quad x_{e2}^T]^T \in R^{2m\times 1}$$

Pose vector of two end-effectors

$$\dot{x}_e = J_D \dot{q}_D$$

$$q_D = [q_1^T, q_2^T]^T \in R^{(n_1+n_2)\times 1}$$

Joint angles vector

$$J_D = \text{blockdiag}[J_1, J_2] \in R^{2m\times(n_1+n_2)}$$

Jacobian Matrix

$$\dot{x}_e = Y_k(q_D, \dot{q}_D)\theta_k \qquad \theta_k = [\theta_{k1}, \theta_{k2}, \ldots, \theta_{kj}]^T \in R^{j}$$

Kinematic parameters, e.g. joint offsets & link lengths

$$\dot{x}_e = J_o \dot{x}_o$$

$x_o \in R^p$ Object's center of mass

J_o Grasp matrix

$$\dot{x}_o = \mathcal{R}(x_t)\dot{x}_t$$

Velocity of the tip of tool

$\mathcal{R}(x_t)$ Mapping matrix from the task space to object space

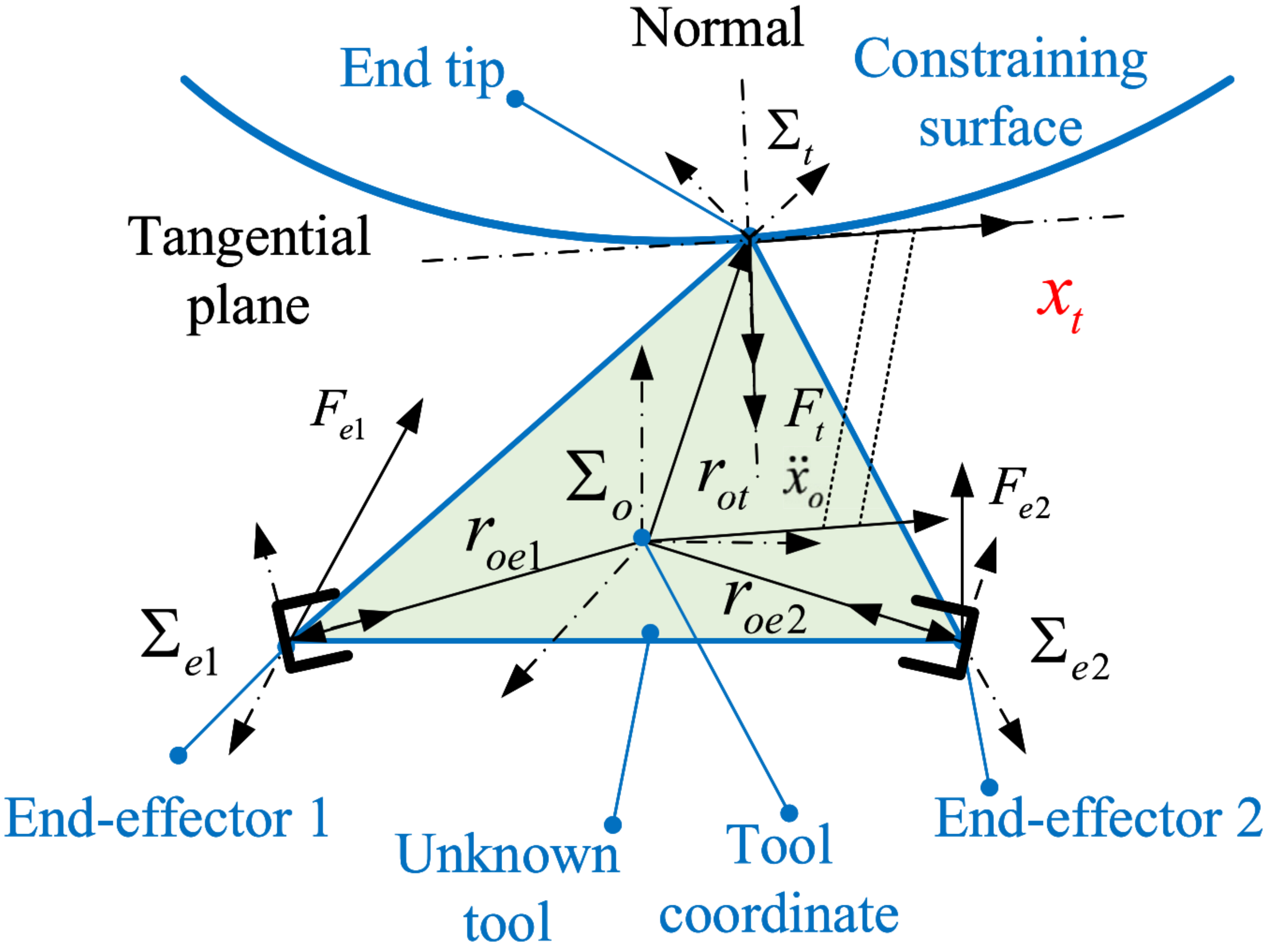


Fig. 2. Sketch of the forces acting on the unknown tool.

Dynamics

$\tau \in R^{(n_1+n_2)}$ Applied joint torques

$F_e = [F_{e1}^T \quad F_{e1}^T]^T \in R^{2m\times 1}$ Interacting forces on object

$$M_D(q_D)\ddot{q}_D + C_D(q_D, \dot{q}_D)\dot{q}_D + g_D(q_D) = \tau - J_D^T F_e$$

$M_D(q_D) = \text{blockdiag}[M_1(q_1), M_2(q_2)] \in R^{(n_1+n_2)\times(n_1+n_2)}, \;\; M_i(q_i) \in R^{n_i \times n_i}$ Inertial matrix

$C_D\dot{q}_D = [(C_1\dot{q}_1)^T, (C_2\dot{q}_2)^T]^T \in R^{(n_1+n_2)\times 1}$ Coriolis & Centrifugal forces

$g_D = [g_1^T \quad g_2^T]^T \in R^{(n_1+n_2)\times 1}$ Gravitational forces

Hybrid position/ force control: velocities & accelerations

Reference joint velocities

$$\dot{q}_r = \hat{J}_D^{\dagger}\left(J_o\mathcal{R}\dot{x}_{tr} + \kappa N_{J_o^{\dagger}}\mathcal{F}^T\lambda_{FI}\right) + \left(I - \hat{J}_D^{\dagger}\hat{J}_D\right)\psi$$

$$= \hat{J}_D^{\dagger}J_o\mathcal{R}\left[\underbrace{\dot{x}_{td} + \alpha(x_{td} - x_t)}_{\text{Tip position term}} - \underbrace{\beta R_t J_t^T \Delta\lambda_{Ft}}_{\text{Contact force term}}\right] + \underbrace{\kappa \hat{J}_D^{\dagger} N_{J_o^{\dagger}}\mathcal{F}^T\Delta\lambda_{FI}}_{\text{Internal force term}} + \left(I - \hat{J}_D^{\dagger}\hat{J}_D\right)\psi$$

Reference joint accelerations

$$\ddot{q}_r = \left(I - \hat{J}_D^{\dagger}\hat{J}_D\right)\dot{\psi} - \frac{d\left(\hat{J}_D^{\dagger}\hat{J}_D\right)}{dt}\psi + \frac{d\left(\hat{J}_D^{\dagger}J_o\mathcal{R}\right)}{dt}\left[\dot{x}_{td} + \alpha(x_{td}-x_t) - \beta R_t J_t^T\Delta\lambda_{Ft}\right]$$

$$+\hat{J}_D^{\dagger}J_o\mathcal{R}\left[\ddot{x}_{td} + \alpha(\dot{x}_{td} - \dot{x}_t) - \beta\left(R_tJ_t^T\Delta\lambda_t + \frac{d(R_tJ_t^T)}{dt}\Delta\lambda_{Ft}\right)\right]$$

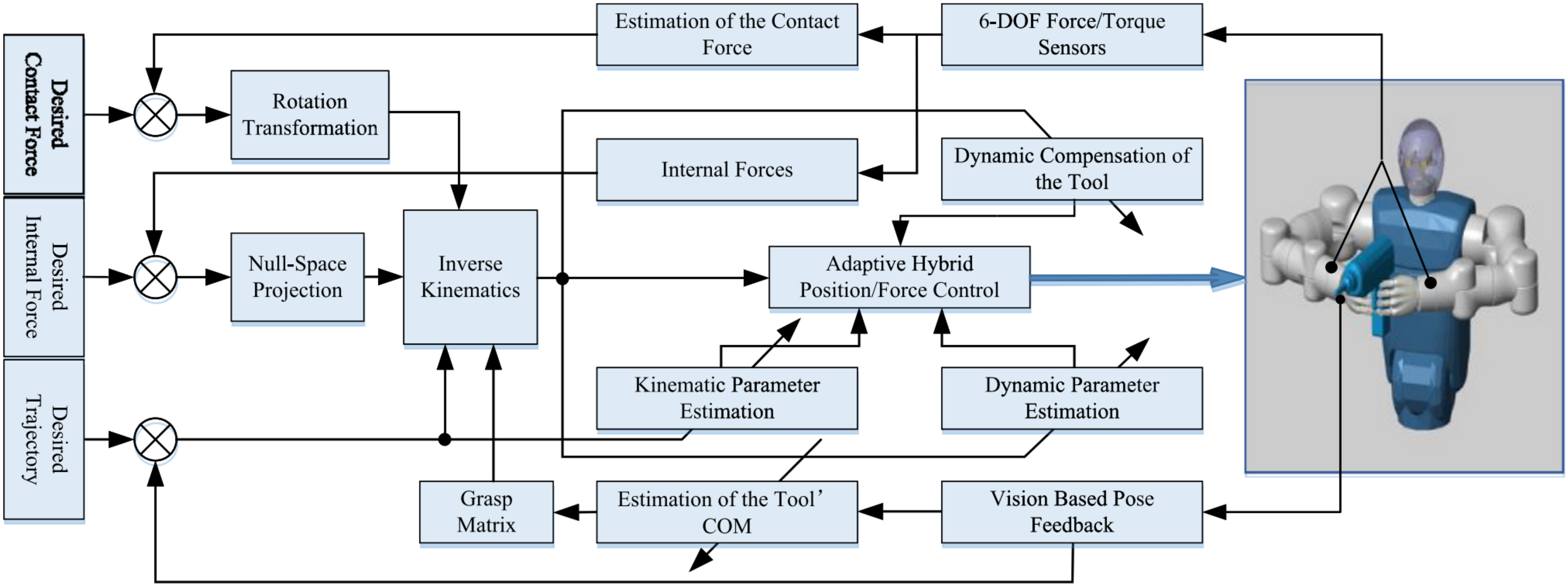
$$+\kappa\frac{d\left(\hat{J}_D^{\dagger}N_{J_o^{\dagger}}\mathcal{F}^T\right)}{dt}\Delta\lambda_{FI} + \kappa\hat{J}_D^{\dagger}N_{J_o^{\dagger}}\mathcal{F}^T\Delta\lambda_I$$

Hybrid position/ force control: Adaptive torque controller

$$\tau = K_p s + \underbrace{Y_{mdr}\hat{\theta}_{mdr} + Y_{Jod}\hat{\theta}_{Jod} - Y_{ft}\hat{\theta}_{ft}\lambda_t + Y_{fI}\hat{\theta}_{fI}\lambda_I}_{\text{Dynamic compensation}} + \underbrace{\hat{J}_D^T \mathcal{F}^T (\Delta\lambda_I + \gamma\,\Delta\lambda_{FI})}_{\text{Internal force control}}$$

$$+\left(\mathcal{R}^- J_o^\dagger \hat{J}_D\right)^T \left\{ \underbrace{K\left(\Delta\hat{\dot{x}}_t + \alpha\tilde{x}_t\right)}_{\text{Tip position control}} - \underbrace{R_t J_t^T (\Delta\lambda_t + \gamma\,\Delta\lambda_{Ft})}_{\text{Contact force control}} \right\}$$

Hybrid position/ force control: Block Diagram



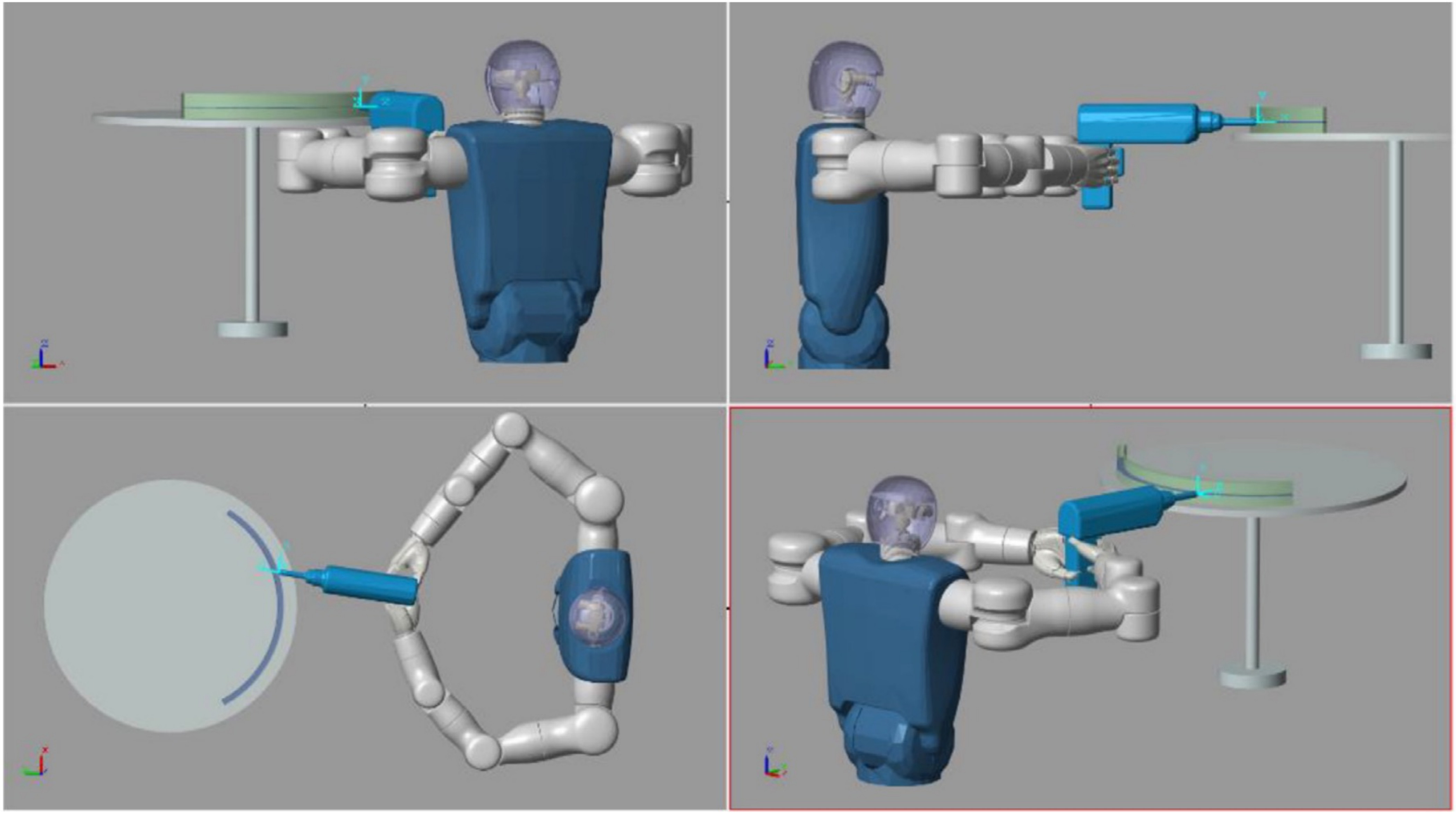
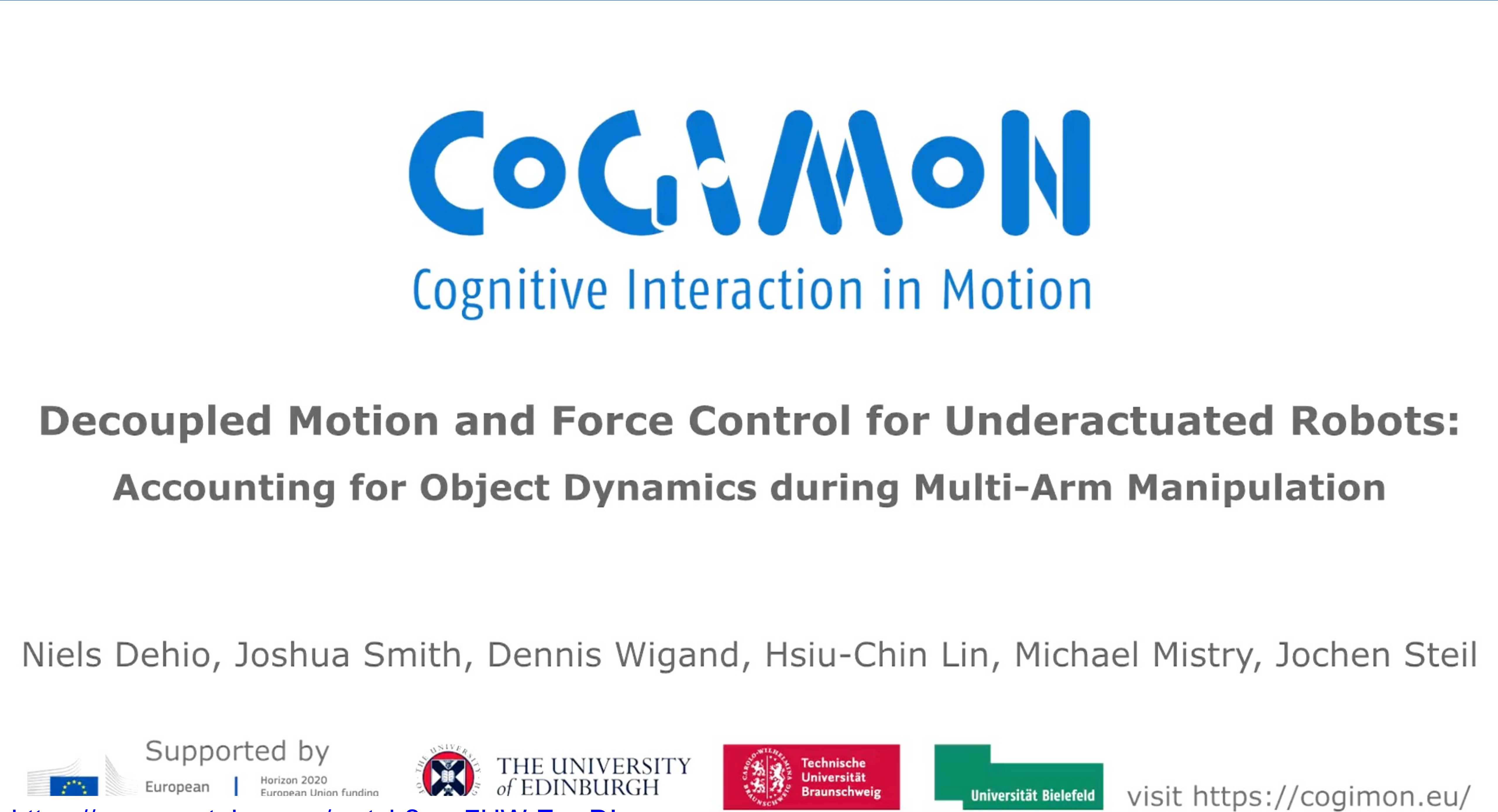


Fig. 8. Snapshot of the curved contact simulation.



CoGiMoN

Cognitive Interaction in Motion

Decoupled Motion and Force Control for Underactuated Robots:

Accounting for Object Dynamics during Multi-Arm Manipulation

Niels Dehio, Joshua Smith, Dennis Wigand, Hsiu-Chin Lin, Michael Mistry, Jochen Steil

Supported by

European | Horizon 2020 European Union funding

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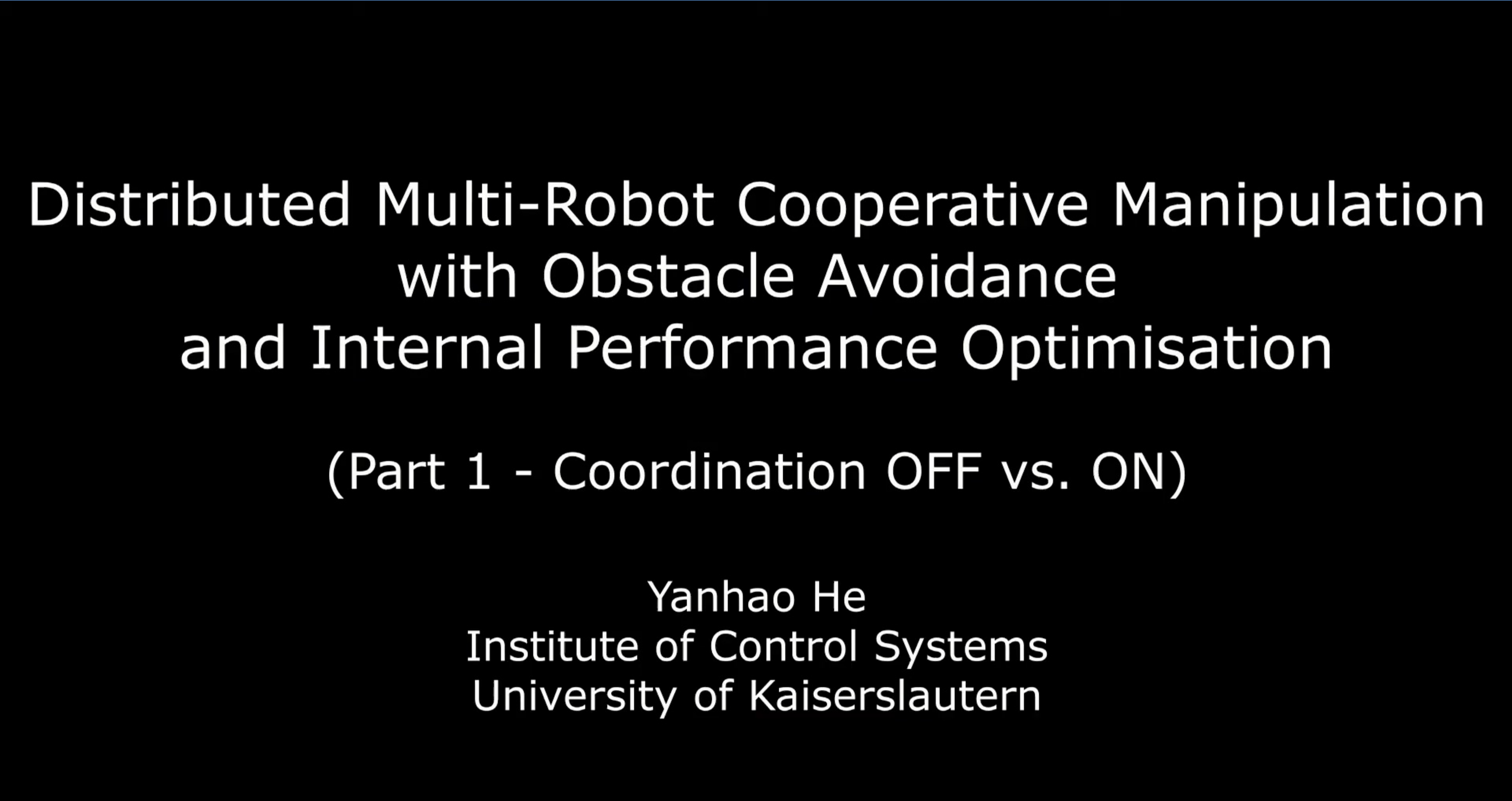
Technische Universität Braunschweig

Universität Bielefeld

visit https://cogimon.eu/

https://www.youtube.com/watch?v=z7HWrE-urDI

DISTRIBUTED COOPERATION



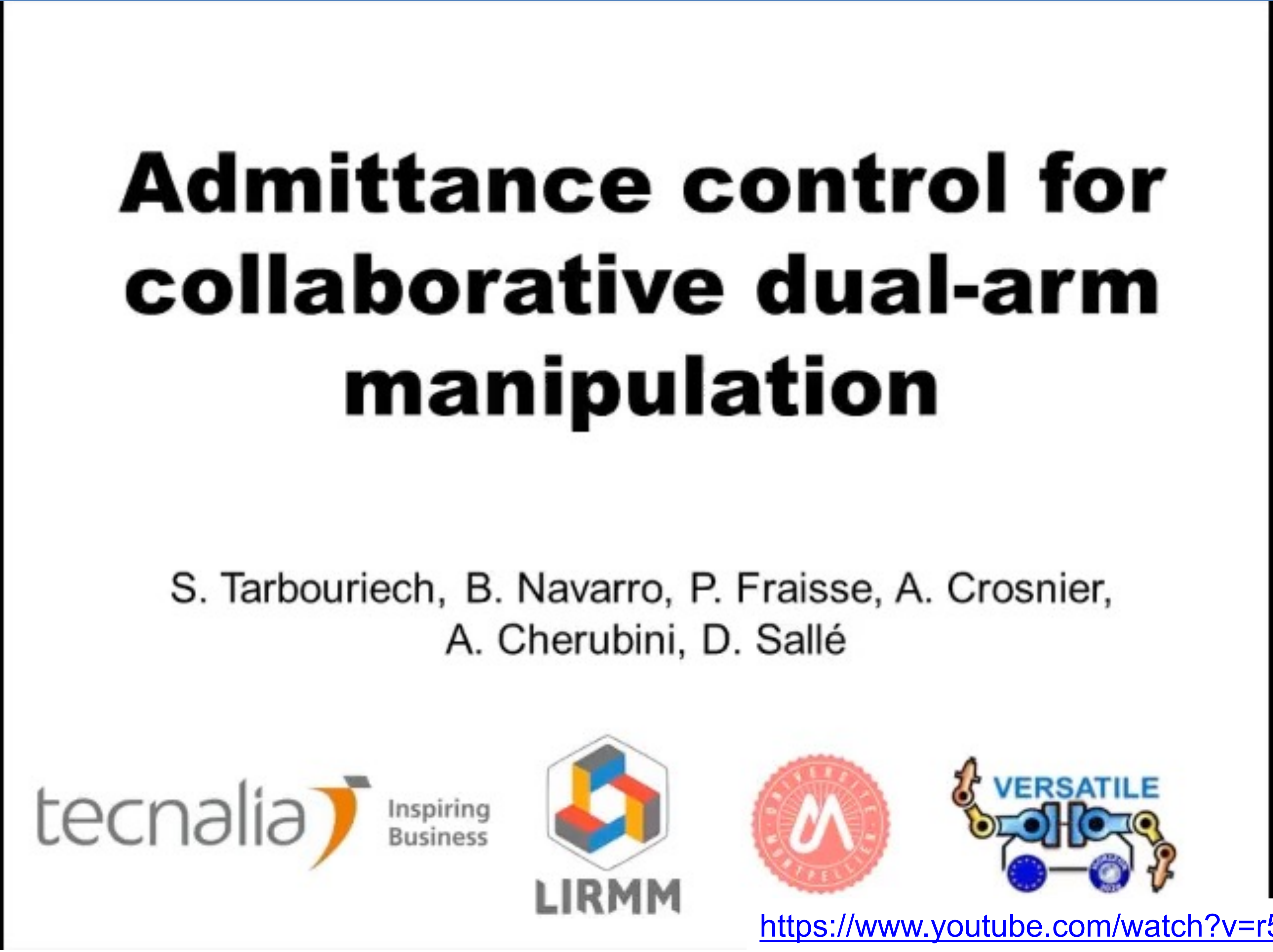
Distributed Multi-Robot Cooperative Manipulation with Obstacle Avoidance and Internal Performance Optimisation

(Part 1 - Coordination OFF vs. ON)

Yanhao He
Institute of Control Systems
University of Kaiserslautern

https://www.youtube.com/watch?v=8PN7bQok8_w

COLLABORATIVE CONTROL



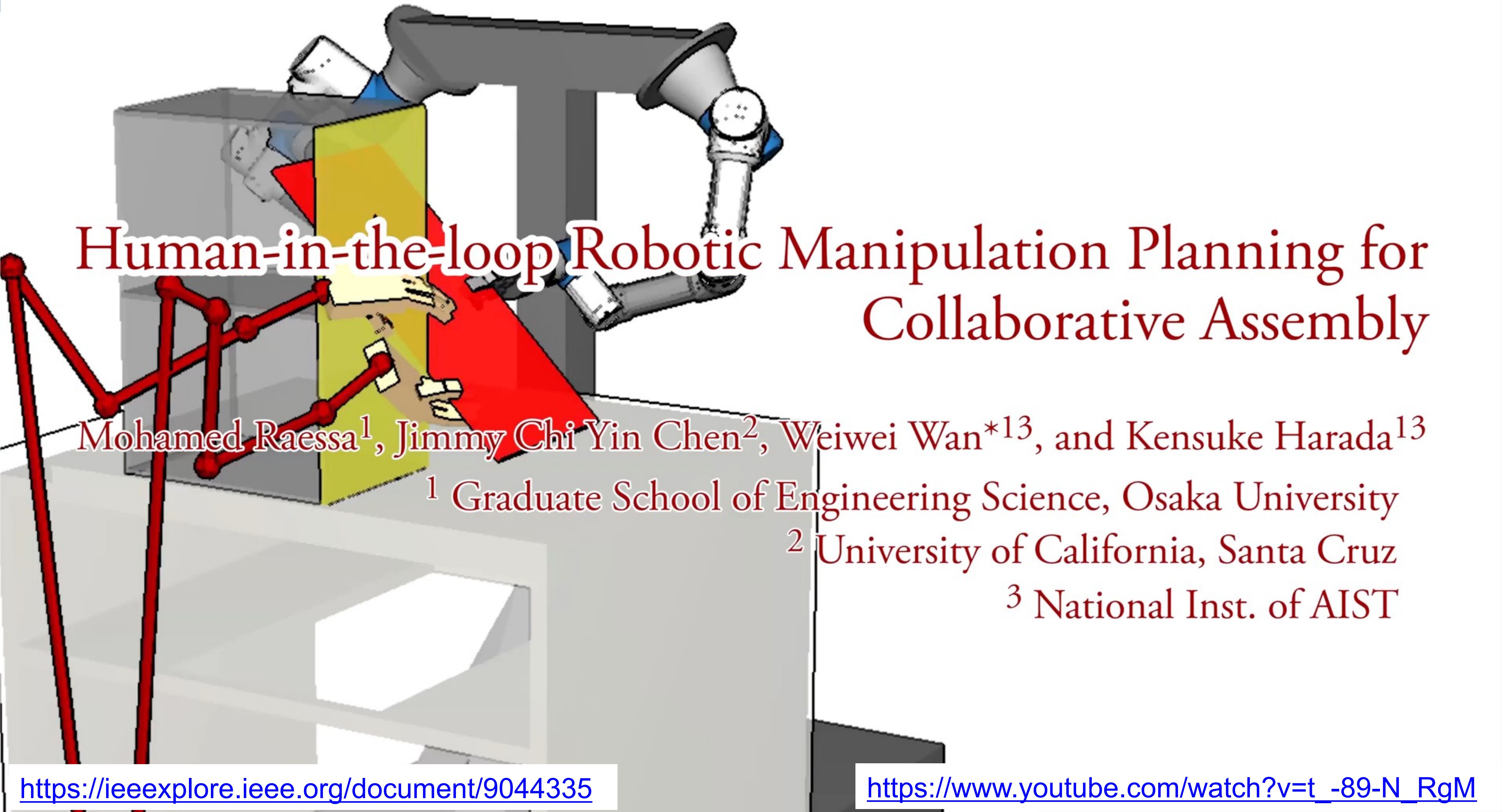
Admittance control for collaborative dual-arm manipulation

S. Tarbouriech, B. Navarro, P. Fraisse, A. Crosnier,
A. Cherubini, D. Sallé

tecnalia Inspiring Business
LIRMM
VERSATILE

https://www.youtube.com/watch?v=r5FeUCIPwfw

COLLABORATION: TASK PLANNING



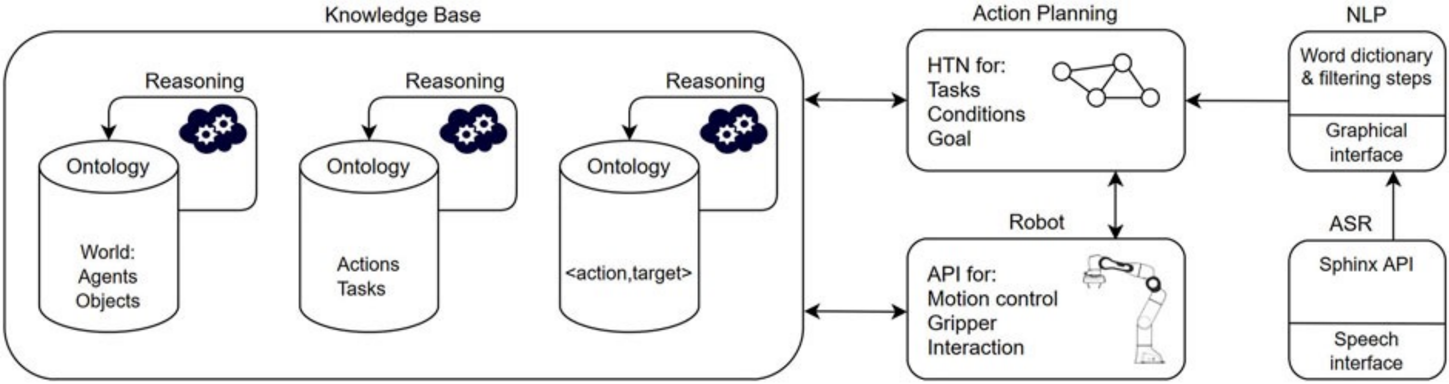
Human-in-the-loop Robotic Manipulation Planning for Collaborative Assembly

Mohamed Raessa[1], Jimmy Chi Yin Chen[2], Weiwei Wan*[13], and Kensuke Harada[13]
[1] Graduate School of Engineering Science, Osaka University
[2] University of California, Santa Cruz
[3] National Inst. of AIST

https://ieeexplore.ieee.org/document/9044335

https://www.youtube.com/watch?v=t_-89-N_RgM

Coordinating Shared Tasks in Human-Robot Collaboration by Commands



- Knowledge-based system architecture: supports reasoning, planning and knowledge integration
- Shared task coordination by human commands, either by a graphical interface or by speech
- Hierarchical Task Networks (HTN): another symbolic AI planning approach – can often be translated to PDDL

Action	Pre-conditions	Signature	Semantics	Format	Explanation
moveTo	isWithinReach isReady	Object	Come Go	move action	Move robot end-effector
graspObject	gripperEmpty isReady holdsObject	Object Robot	Pick Take	motion action gripper action	Grasps object
placeObject	isWithinReach isReady	Object Robot	Place Deposit	motion action gripper action	Places object
handOver	isWithinReach isReady humanPresent	Object Robot Human	Give Hand	motion action gripper action	Hand-over object
kitParts	isWithinReach isReady	Object Robot	Kit Stock	motion action gripper action	Pick and place objects
Target					
Parts	isWithinReach canBeGrasped	Object Robot Human	Bolt Bolts Tool	3D Pose	Location of parts
Box	isWithinReach isReady isEmpty	Object Robot	Box Kit Container	3D Pose	Location of box
Table	isWithinReach isReady isEmpty	Object Robot	Storage Kit_store Back	3D Pose	Pose on table
Human	isWithinReach isReady humanPresent	Object Human	Here Me	3D Pose	Human hand-over pose

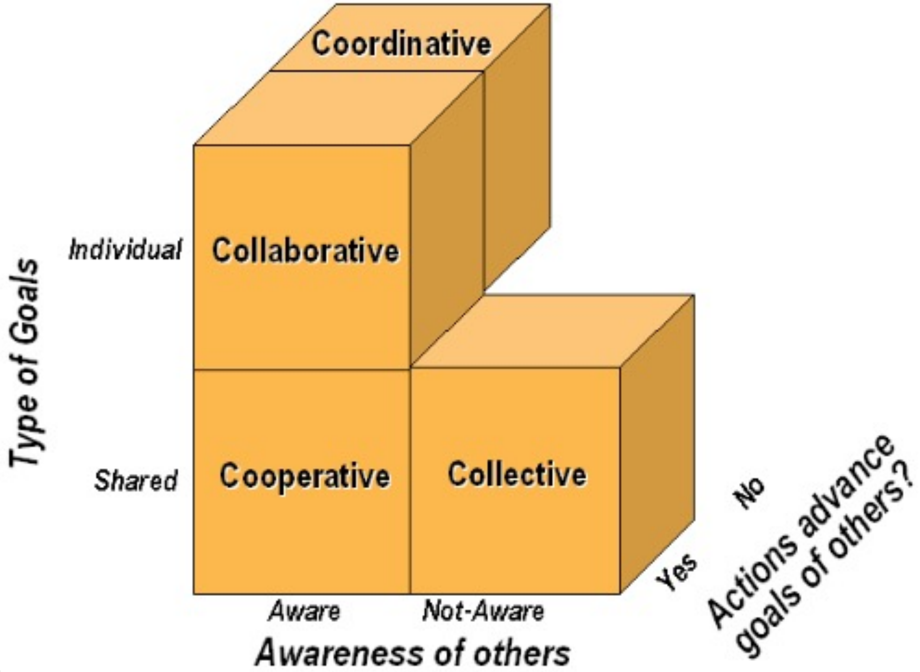
Integrating new knowledge =>

Action	Format	Modality	Explanation
Primitive	Robot action	Software integration Python and ontology	Primitive robot actions can be included by function call from ontology to action library
Task	List of robot actions	Software integration Python and ontology	Higher level tasks can be included by defining a list of robot actions
Target			
Pose/object	3D pose	Robot hand-guiding	New targets are defined by hand-guiding the robot to a desired pose. This target is then recorded in the ontology
Other			
Reasoning rule	SWRL	Software integration Python and ontology	New reasoning rules are defined in the SWRL language and integrated to update the ontology
Synonym	Words	Ontology population	Synonyms to all actions and targets can be included by creating new ontology instances

Angleraud, A., Mehman Sefat, A., Netzev, M., & Pieters, R. (2021). Coordinating shared tasks in human-robot collaboration by commands. Frontiers in Robotics and AI, 8, 734548.

Summary Multi Manipulator Manipulation

- Force Control (e.g. carry a heavy load together)
  - Centralized
  - De-centralized -> multi-agent control -> collaboration
  - Distributed Cooperation: share some information
- Position Control
  - Precisely follow pre-programmed trajectories
  - Motion planning: on-the-fly plan new trajectories for cooperation
- Sequential manipulation
- Task level coordination, collaboration & cooperation

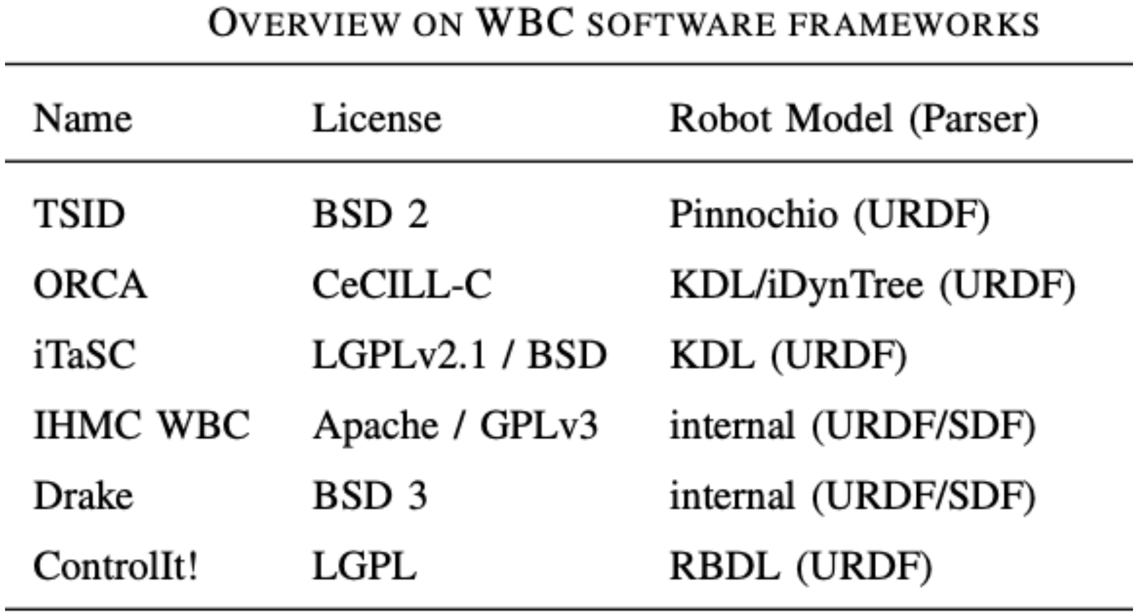


- Whole-body control (e.g. dual-arms & mobile base)

WHOLE-BODY CONTROL

Whole-Body Control

- Plan & control for combined motion of manipulator and mobile base
- Particular popular for legged, especially humanoid robots
  - Tree-like kinematic structure – no loops!
- Also needed for aerial, underwater, surface vehicles and space robots:
  - Manipulation forces move the mobile base!
- Ground vehicles: non-holonomic kinematics restricts possible motions -> difficult and unpopular
  - Alternative: holonomic ground robots!
- MPC popular
- Reinforcement Learning very popular



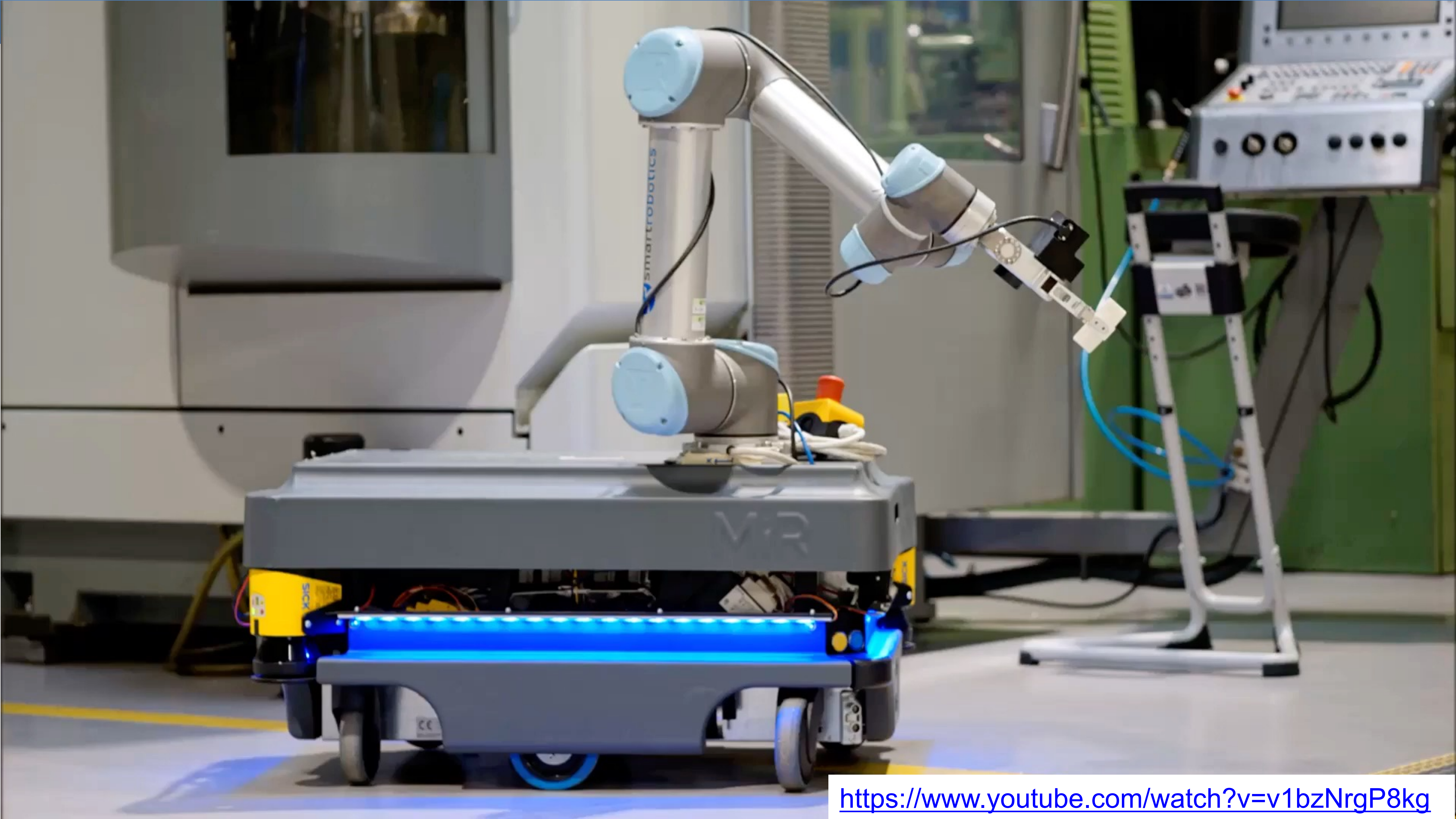
OVERVIEW ON WBC SOFTWARE FRAMEWORKS

Name	License	Robot Model (Parser)
TSID	BSD 2	Pinnochio (URDF)
ORCA	CeCILL-C	KDL/iDynTree (URDF)
iTaSC	LGPLv2.1 / BSD	KDL (URDF)
IHMC WBC	Apache / GPLv3	internal (URDF/SDF)
Drake	BSD 3	internal (URDF/SDF)
ControlIt!	LGPL	RBDL (URDF)

Mronga, D., Kumar, S., & Kirchner, F. (2022, May). Whole-body control of series-parallel hybrid robots. In *2022 International Conference on Robotics and Automation (ICRA)* (pp. 228-234). IEEE.

Fig. 3: (left) HRP-4 holding a large box with a human while walking (Agravante et al. (2019)) (right) HRP-2 pivoting a furniture (Murooka et al. (2017)).

Stasse, O., & Righetti, L. (2020). Whole-body manipulation. *Encyclopedia of Robotics*, 1-9.



https://www.youtube.com/watch?v=v1bzNrgP8kg