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Machine Learning, Safety, and Industrial Robots

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What is Artificial Intelligence?

Breakthroughs in

- **visual perception,**
- **speech recognition, and**
- **semantic reasoning.**

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Challenges in

- **safe actuation**
- **physical manipulation**, and
- **physical human interaction**.

Future of Robotics: Breakthroughs & Challenges

Gary Kasparov vs. IBM Deep Blue, 1997.

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Future of Robotics: Breakthroughs & Challenges

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Future of Robotics: Breakthroughs & Challenges

Challenges in

- **safe actuation,**
- **physical manipulation**, and
- **physical human interaction**.

Data-driven Robotics

Machine learning for **perception**

Machine learning for **actuation**

Goal: No more programming required for industrial robots

Outline

Robot Learning

Deep reinforcement learning

Transfer learning with and without physics

Safe Human-Robot Interaction

Real-time motion planning

Real-time Robot Motion Planning and Control

Hybrid control

Generic Technology Readiness Levels

Level	Technology Readiness Level	Method Readiness Level (inspired by *M.F. Peeters, M. Robichaud, G. Guevremont, Analytical Process Certification for Gas Turbine Design, ISABE-2005-1203) Method capability	Applicability for design
TRL 9	Actual system “flight proven” through successful mission operations	Analysis method used for a long period of time and the method is validated by numerous measurements and tests of relevant components in engine environment and full requirement envelop. All input data are of highest quality. Fully coherent to other company specifications.	Used for design requirement verification without further testing or verification.
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)	Analysis method used for a long period of time and the method is measurements validated by and tests in relevant components in engine environment and full requirement envelop. Input data are of good quality. Coherent to other company specifications.	Suitable for component sizing in product development but requires system verification testing.
TRL 7	System prototype demonstration in a space environment	Analysis method used for a long period of time and the method is validated by measurements and tests in relevant components in engine environment. Input data are of good quality. Coherent to other company specifications.	Suitable for component sizing in product development but requires system verification testing. Service development programs necessary.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	Analysis method used for a period of time and the method is validated by measurements and tests of relevant components in subsystem environment. Input data are of good quality.	Suitable for component sizing in product development but requires component verification testing
TRL 5	Component and/or breadboard validation in relevant environment	Analysis method used for a period of time and the method is validated with a few measurements and tests of components. Input data are of reasonable quality.	Suitable for component sizing in product development but requires component verification testing
TRL 4	Component and/or breadboard validation in laboratory environment	Analysis method used for a period of time and the method is validated with a few measurements and tests. Input data are of reasonable quality.	Suitable for component sizing in technology development programs
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Some experience of the analysis method within the company but verification data and design criteria are limited. Input data are estimates and of poor quality	Suitable for component sizing in technology development programs
TRL 2	Technology concept and/or application formulated	Limited experience of the analysis method within the company and verification data and design criteria are very limited. Input data are estimates and of poor quality.	Suitable for technology component testing
TRL 1	Basic principles observed and reported	No experience of the analysis method within the company and no validation data are available.	Not used in product development

Learning Hand-Eye Coordination (TRL 2)

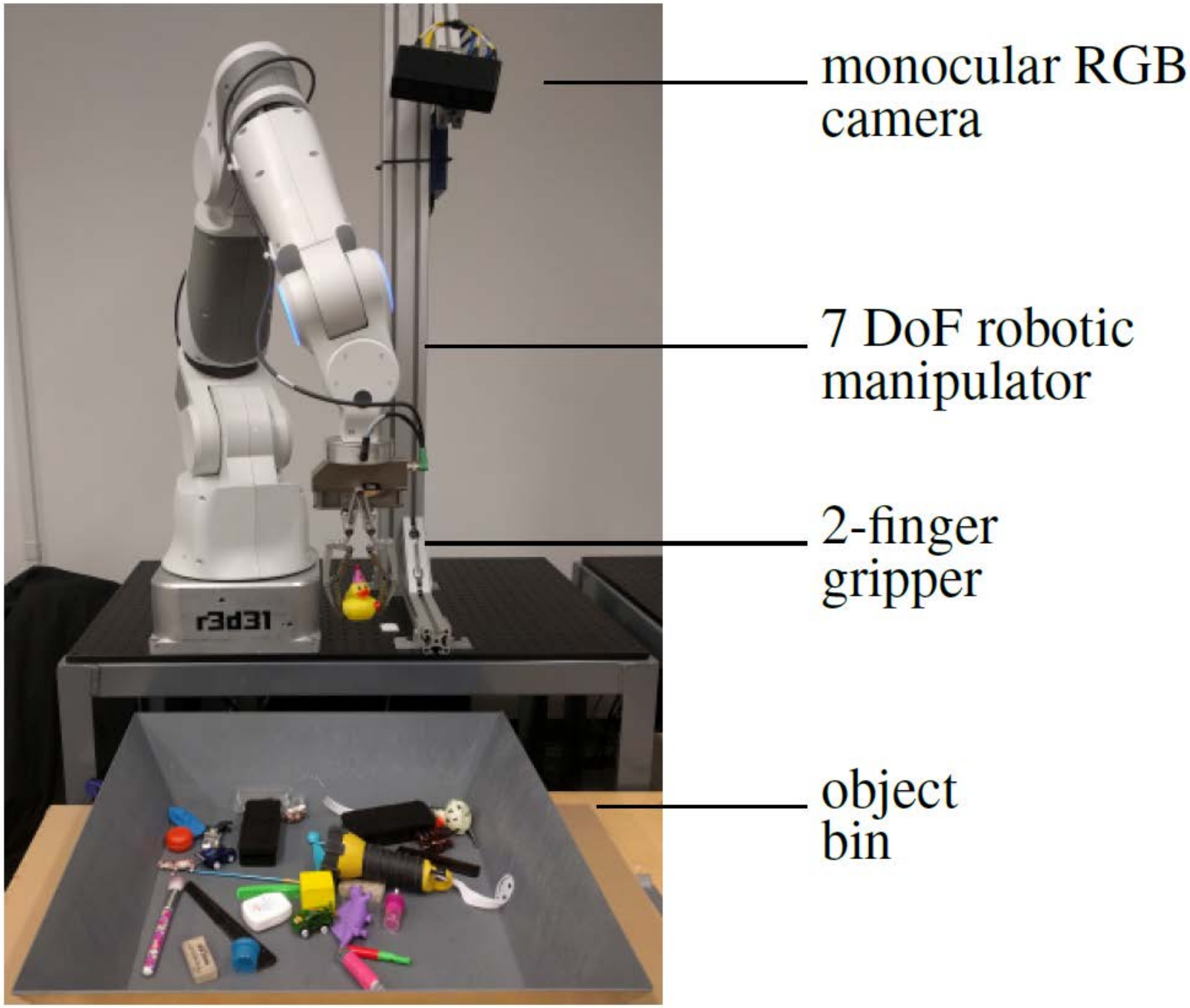
Input

512x512 pixels

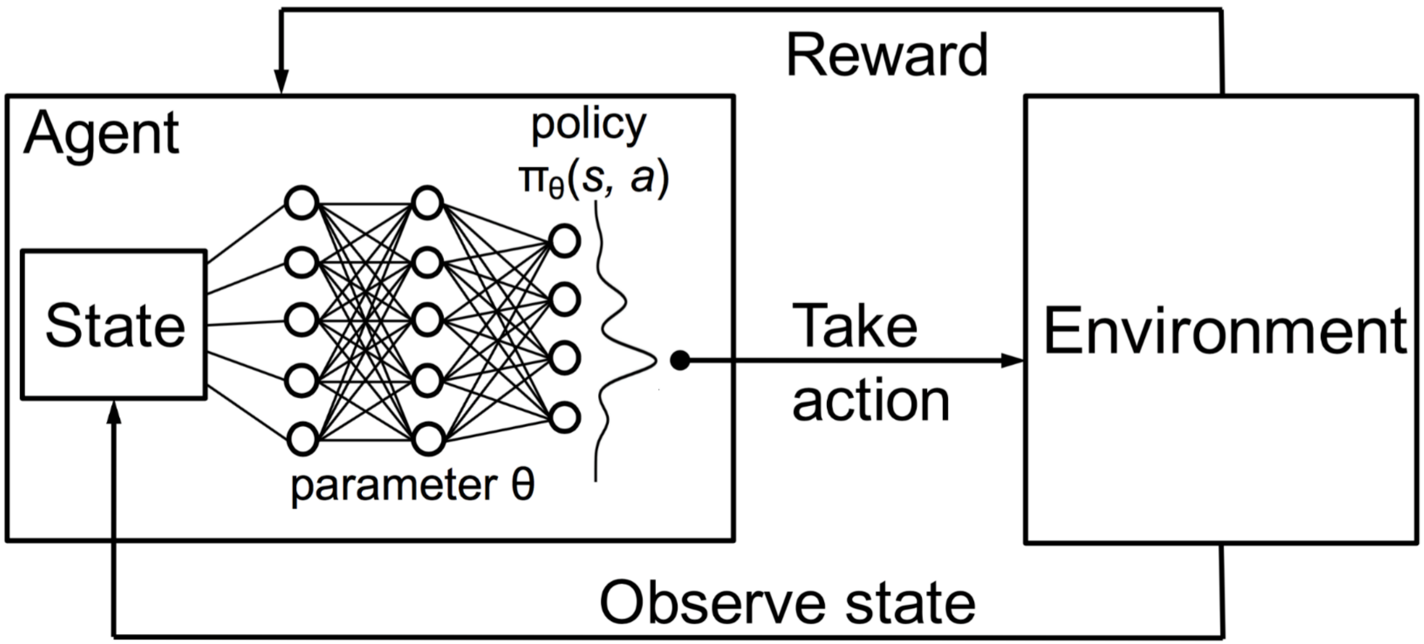
Finger position

Output

Task space gripper motion



Recap: Reinforcement Learning



Learning Hand-Eye Coordination (TRL 2)

800,000 attempts

14 robot arms

Two months

CNNs for deep reinforcement learning

Shared models

Data Driven Robotics (TRL 2)

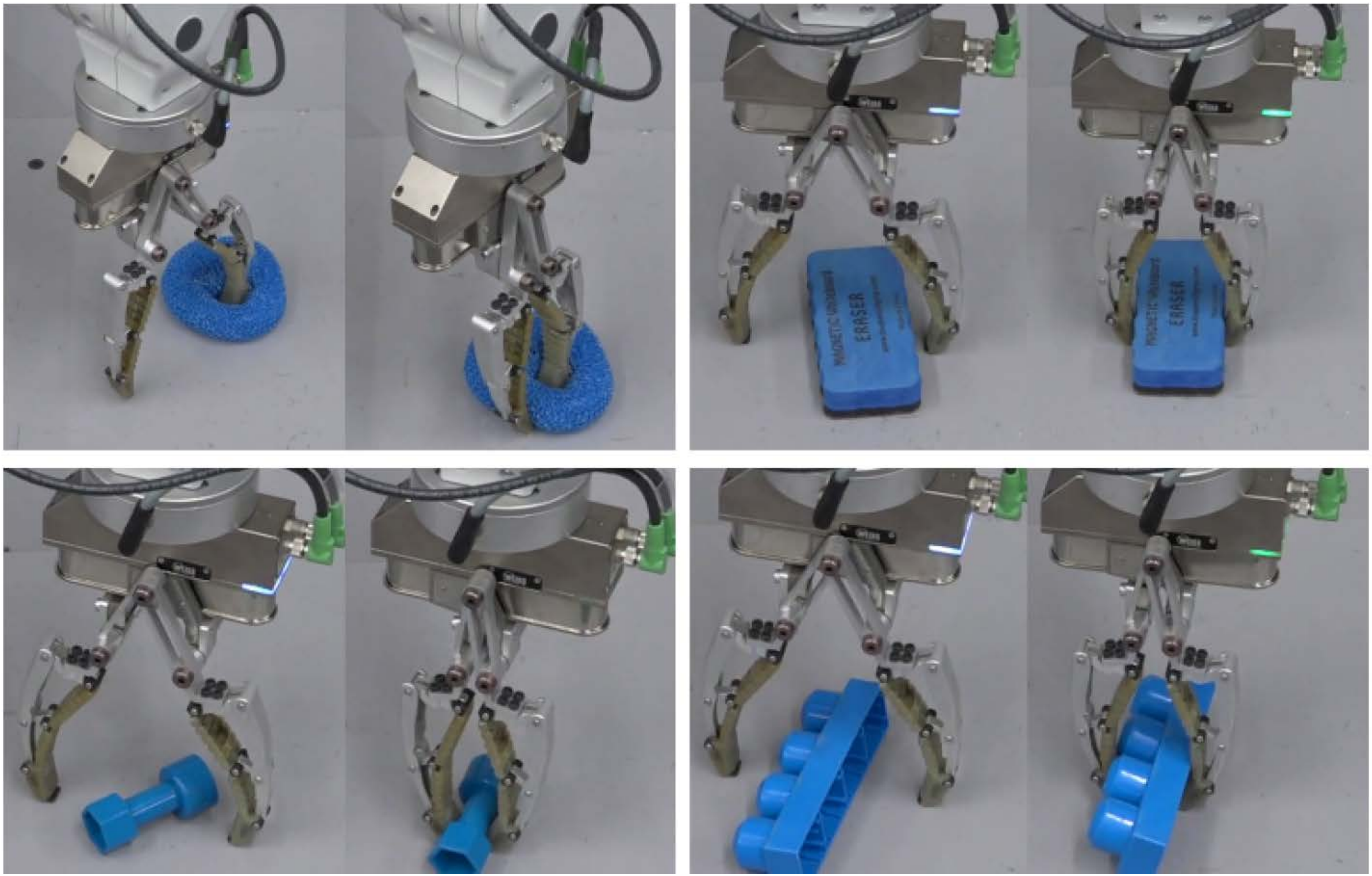
Video courtesy of Google, 2016.

Different Objects, Different Grasping Strategies (TRL 2)

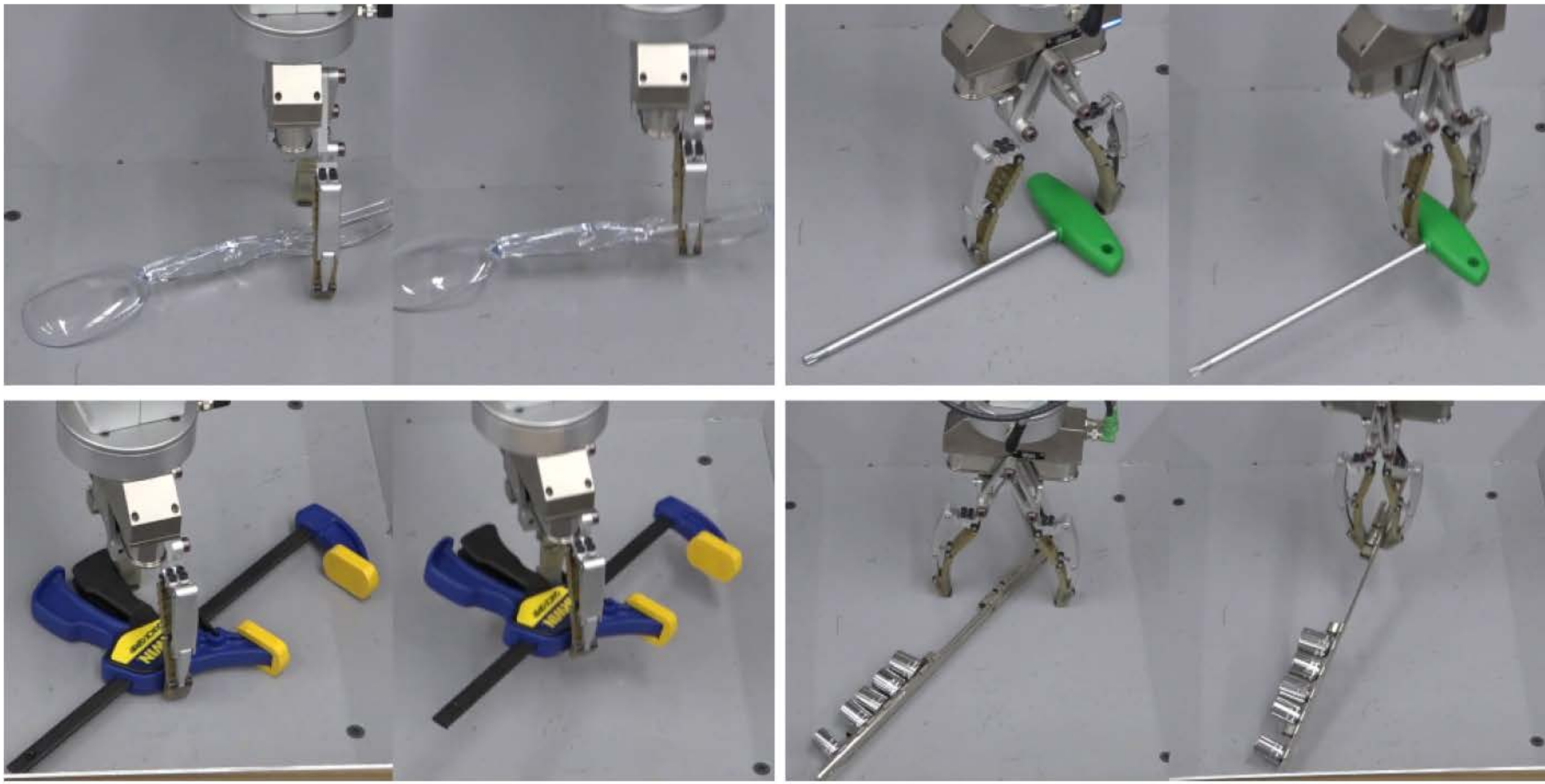
Video courtesy of Google, 2016.

Next Generation Arm Farm

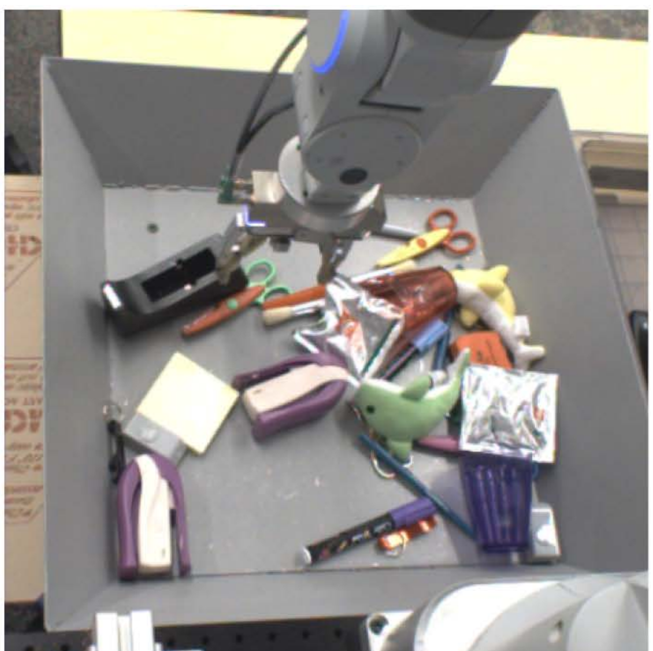
Different Objects, Different Grasping Strategies



Different Objects, Different Grasping Strategies



New (Unknown) Objects



Robotics and AI – Lessons Learned

1. Machine learning means learning from data; **AI is a buzzword**

2. Machine learning is about data and algorithms, **but mostly data**

3. Unless you have a lot of data, you should stick to **simple models**

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Robotics and AI – Lessons Learned

4. Machine learning can only be as good as the data you use to train it

5. Machine learning only works if your **training data is representative**

6. Most of the **hard work** for machine learning is data transformation

Robotics and AI – Lessons Learned

7. Machine learning is a revolutionary advance, but it isn't a magic bullet – **it is a tool.**

Nevertheless: There is a huge potential that will be unleashed within the next decade.

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Hybrid control

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Learning Robots

Step 1: Learning free space motions (**no** contact, **no** physics)

Step 2: Learning manipulation (contact, physics)

Goal: No more programming required for industrial robots

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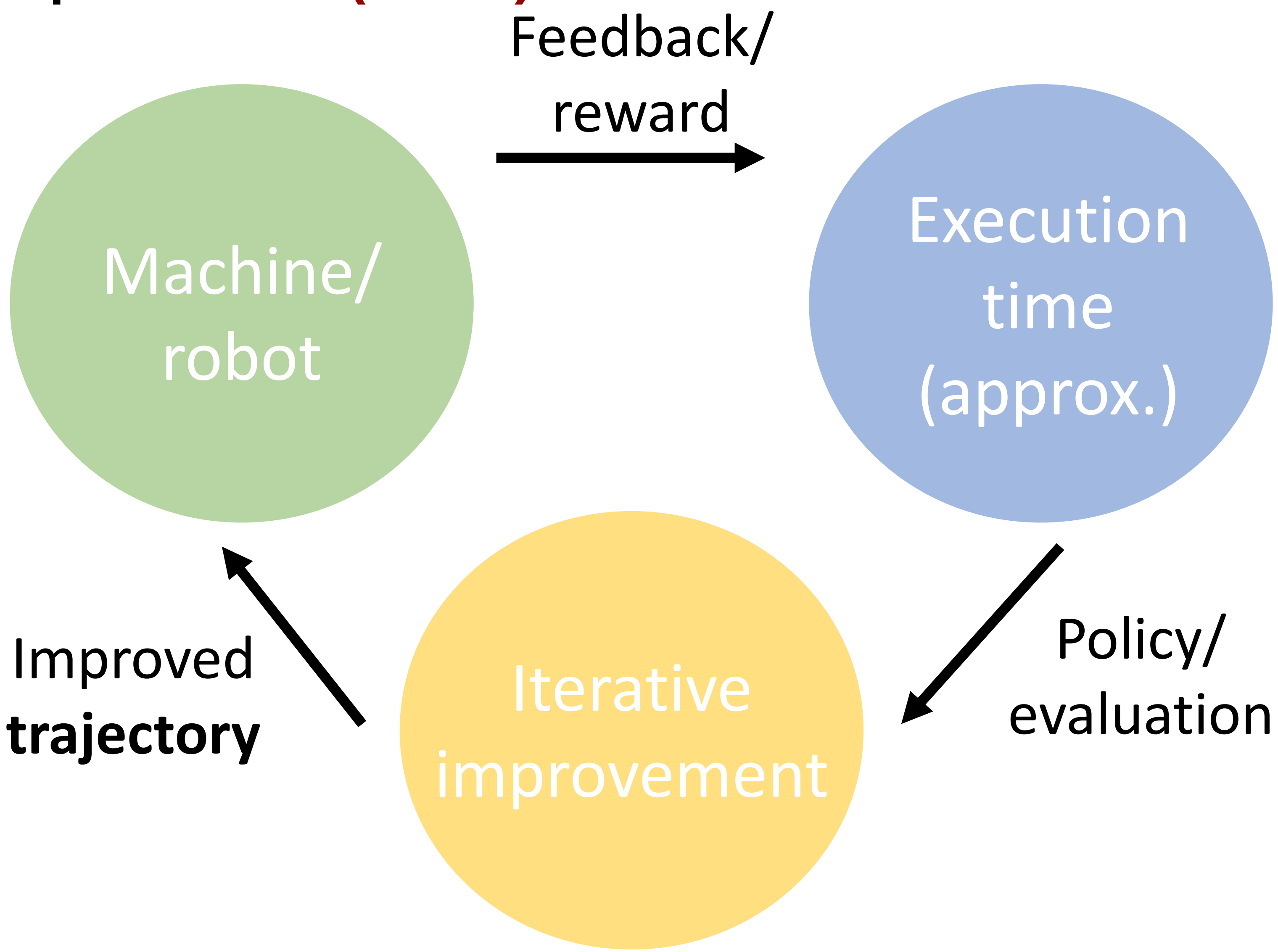
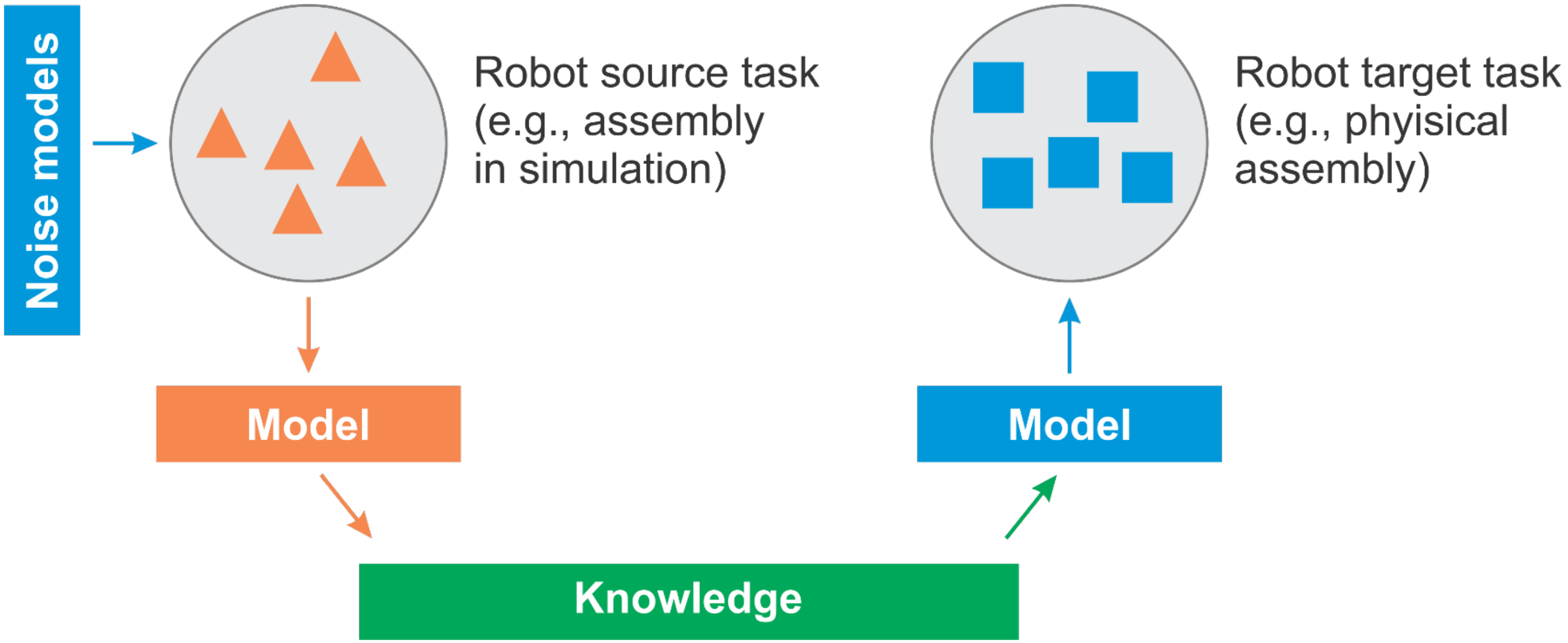
Common Topics

- **Transfer learning**
  - Training in simulation
  - Noise models for dynamic model parameters
  - Progressive NNs to close the remaining gap
  - Execution on physical systems
- Combination with traditional models (engineering)
- Safety and machine learning
- Compliance with the law

Speed Optimization (TRL 3)



Data Generation for Reinforcement Learning



Learning in Task Space

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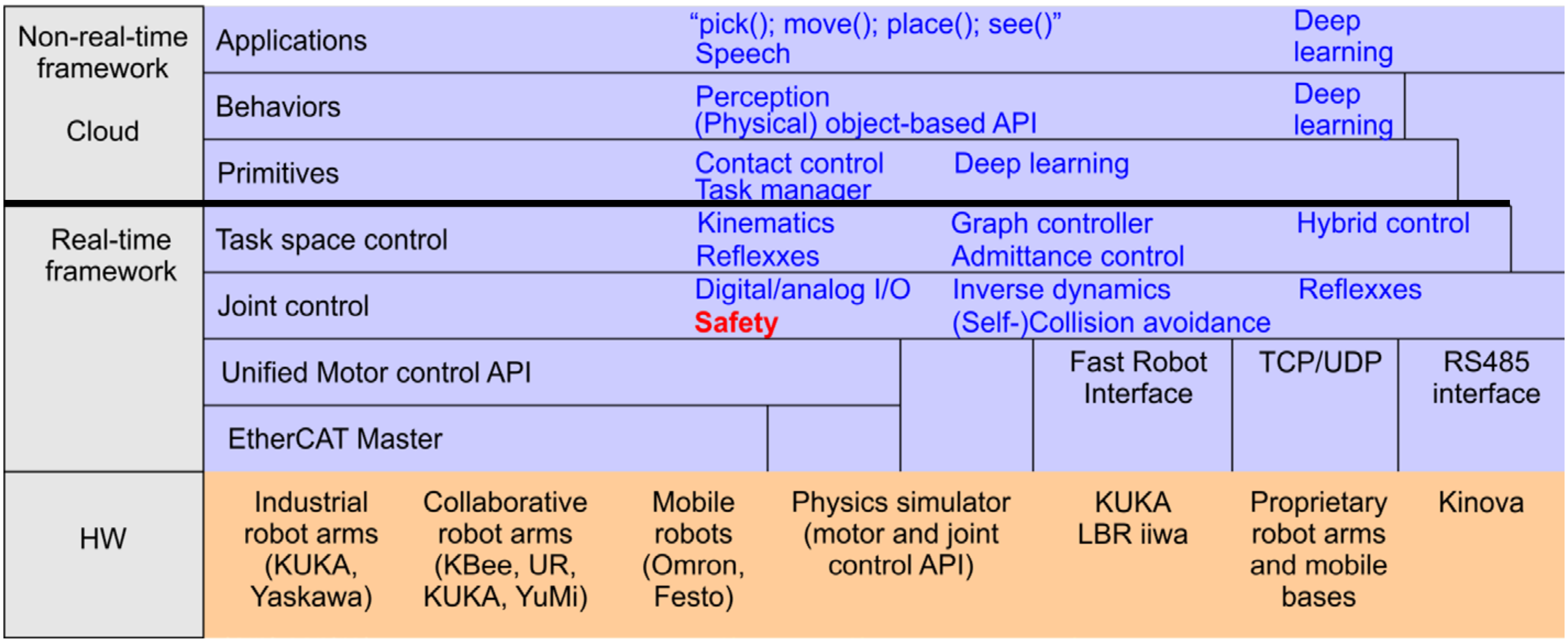

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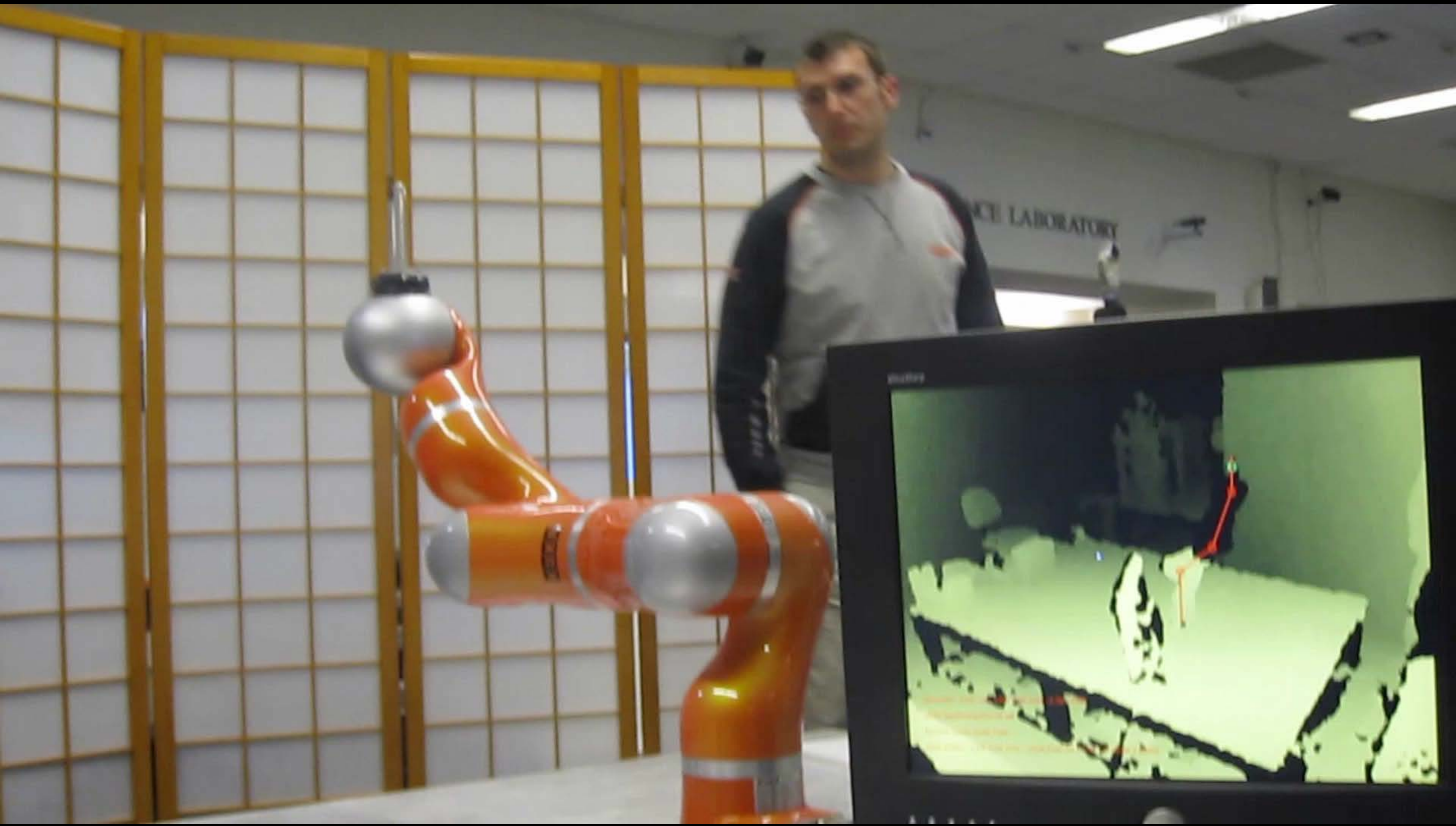
LABORATORY

Deterministic Collision Avoidance (TRL 5)

Collision avoidance algorithm, which

- is directly used in depth space
- deploys (safe) 3D sensors
- considers
  - multiple obstacles
  - whole robot body
- uses obstacle motions for prediction (fast)
- Reflexxes framework (smooth motions, instantaneous reactions, utilize the max. kinematic and dynamic robot capabilities)
- runs deterministically in real-time

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Interfaces and Software APIs

Robot arm with real-time joint control **API** (read/write)

- Joint positions (e.g., FRI/RSI)
- Joint velocities (optional)
- Joint torques (optional)

Safe **3D Camera** with point cloud **API** (read)

- Point cloud
- 3D shape

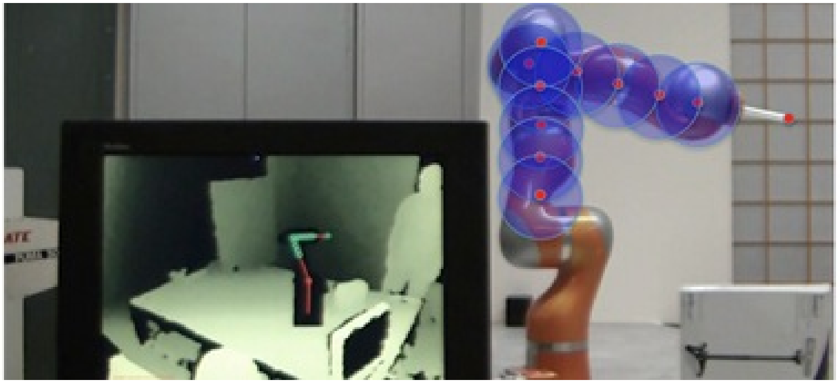
Deterministic motion planning and collision avoidance algorithm

Motion Planning and Control (TRL 5)

- End effector

  repulsive vector → repulsive velocity

- Collision avoidance for the robot body



Repulsive vector

Cartesian constraints

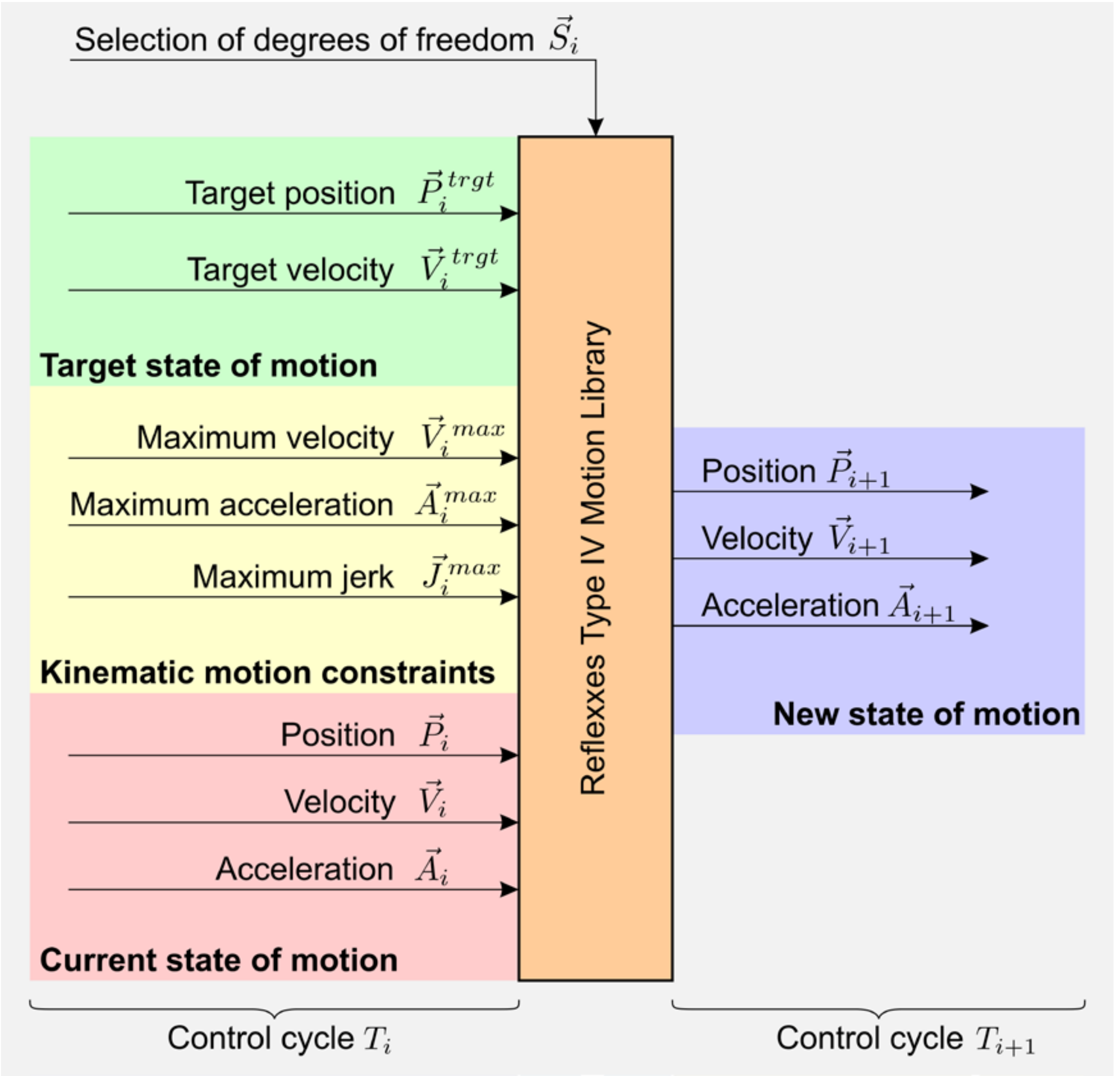
Joint velocity limit

- Smooth, jerk limited motions →

Deterministic real-time motion planning →

Utilizing the maximum kinematic and dynamic capabilities (max. joint torques and speeds)

Reflexxes Motion Libraries



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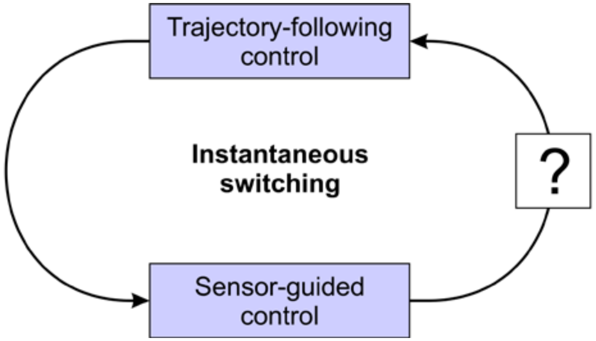
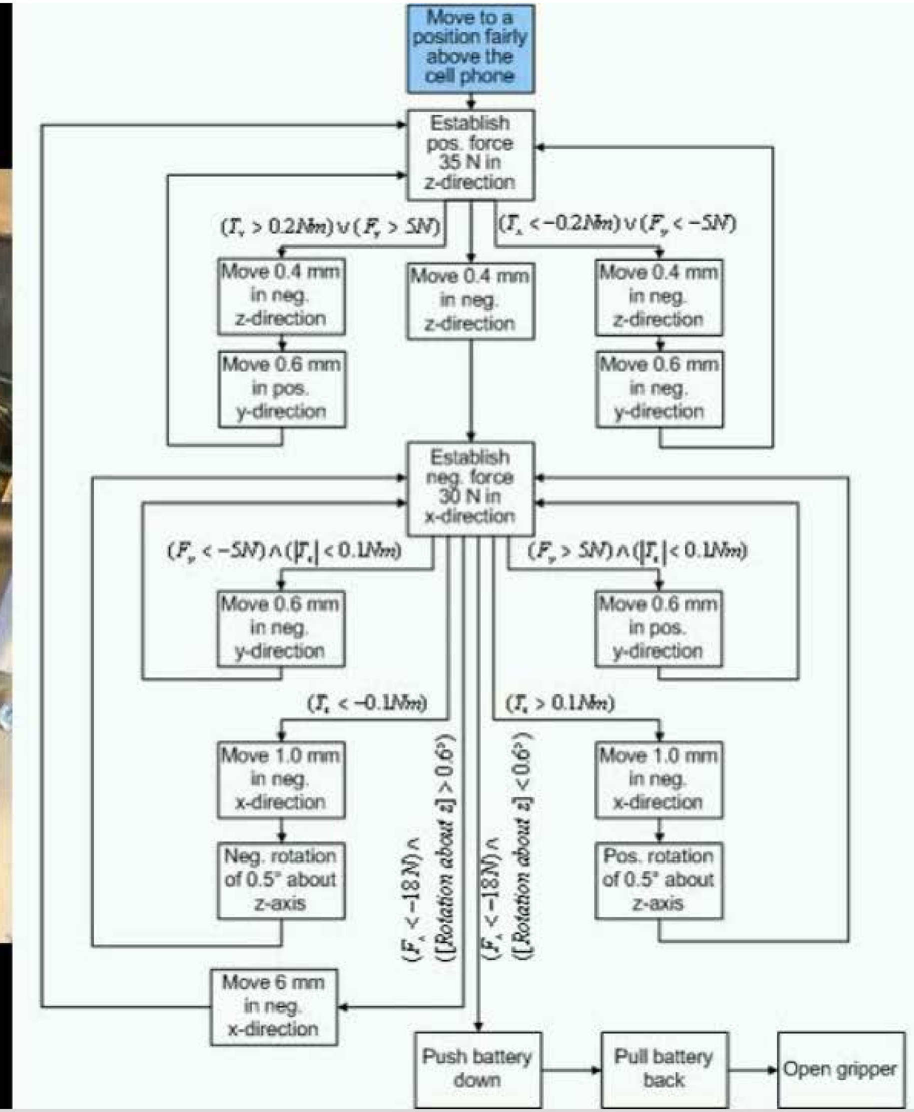
Robots, Sensors, and Programming

- Programming robot in “free space” is **expensive**.
- **Sensor integration** on different motion control levels belongs to one of the keys for future advancements of **robot systems**.
- In general, we distinguish between:
  1. Trajectory-following motions
  2. Sensor-guided motions
     - Force/torque control
     - Visual servo control
     - …



- This makes programming even **more expensive**.

Manipulation Primitives

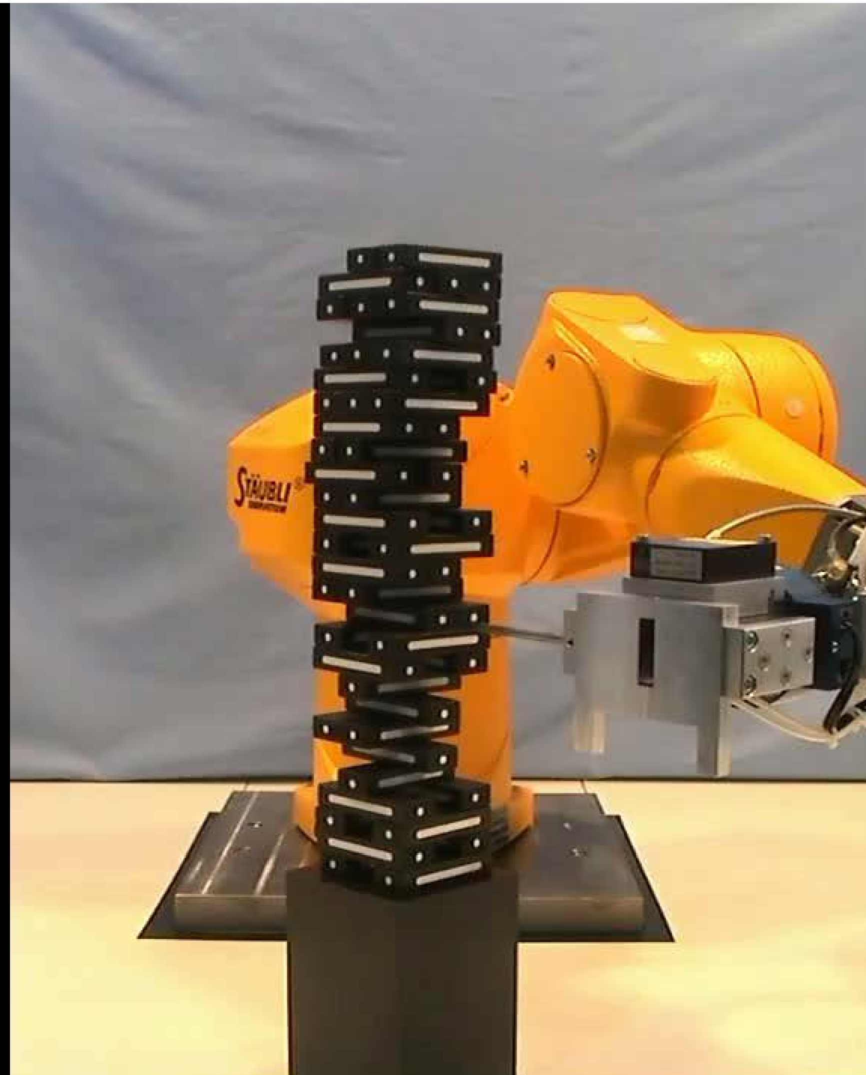


Robot Programing with Primitives

Sensor-based motions

- Low-level programming APIs
  - Complex
  - Expert knowledge required
- Graphical programming interfaces
  - Simple
  - Little to no expertise required
  - Limitation of applications
- Automated based on CAD data and task descriptions
  - Not yet generic
  - Not yet robust
  - Little to no sensor integration (e.g., force/torque, distance, vision)

A Robot Playing Jenga (2005)



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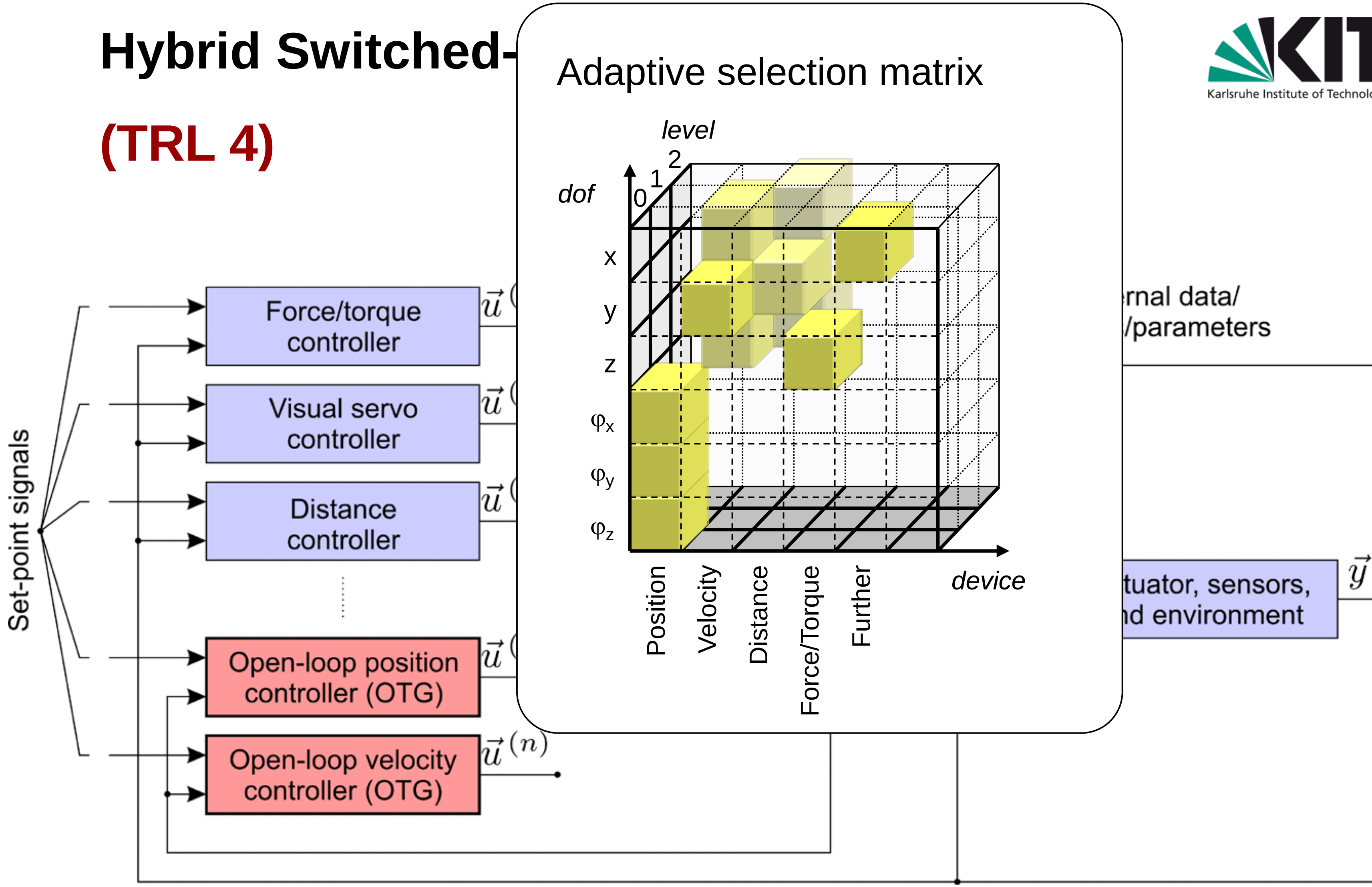
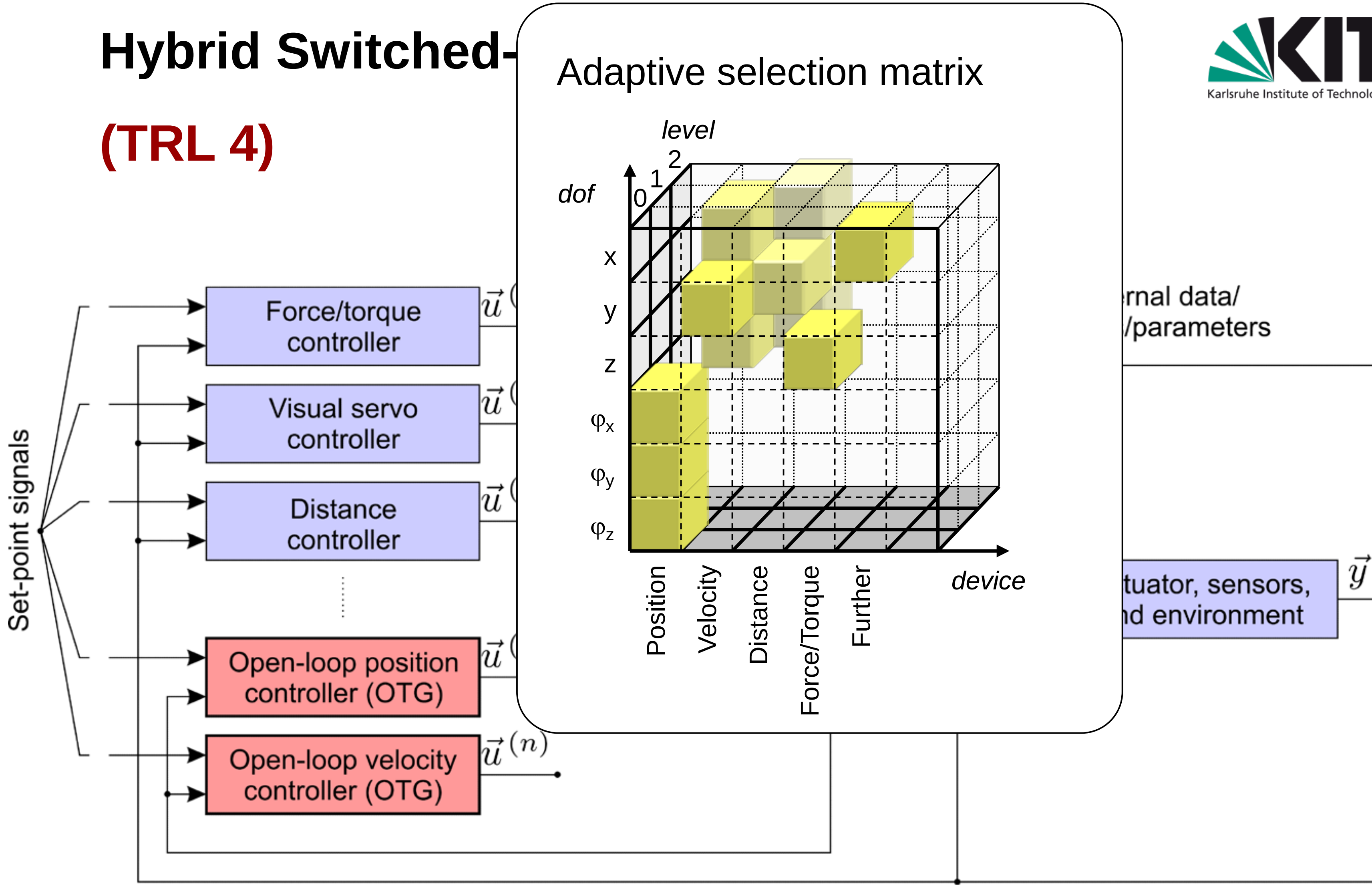
Hybrid Switched-

(TRL 4)

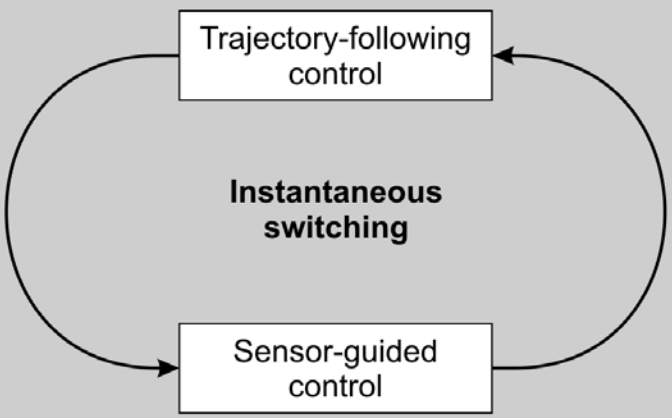


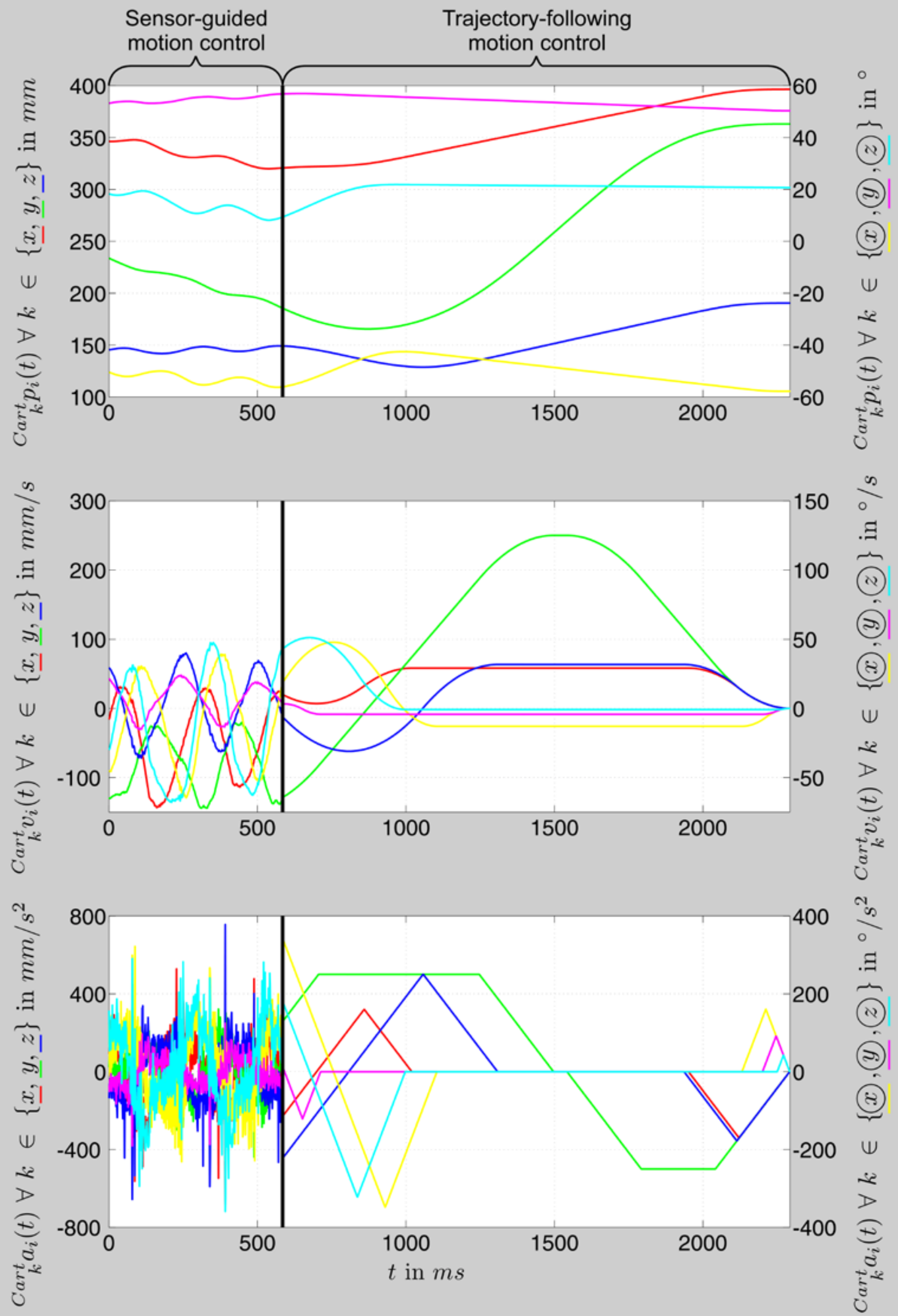
Hybrid Switched-

(TRL 4)

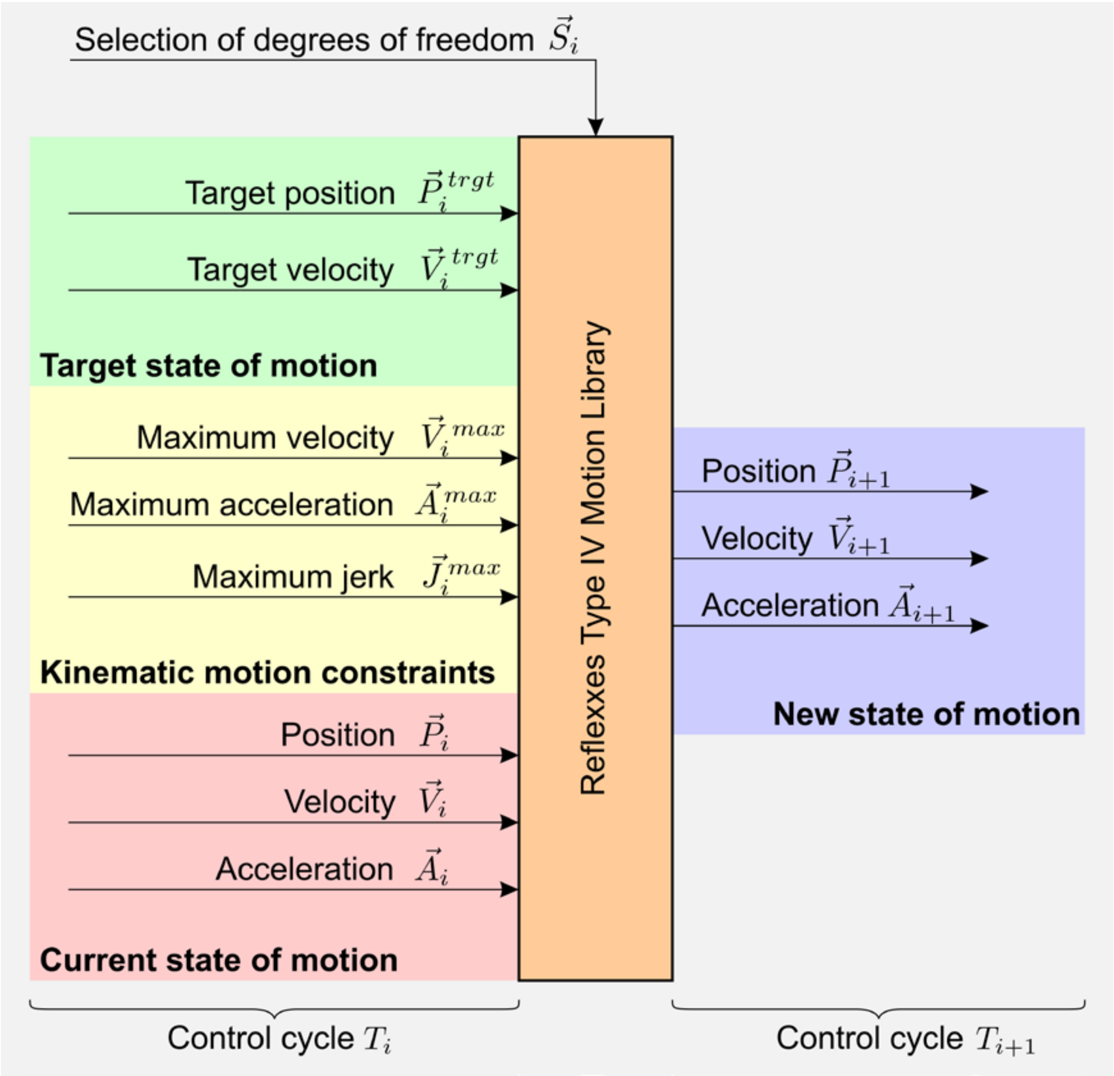


Switching from sensor-guided to trajectory-following robot motion control





Reflexxes Motion Libraries (TRL 8)



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Reflexxes Motion Libraries (TRL 8)

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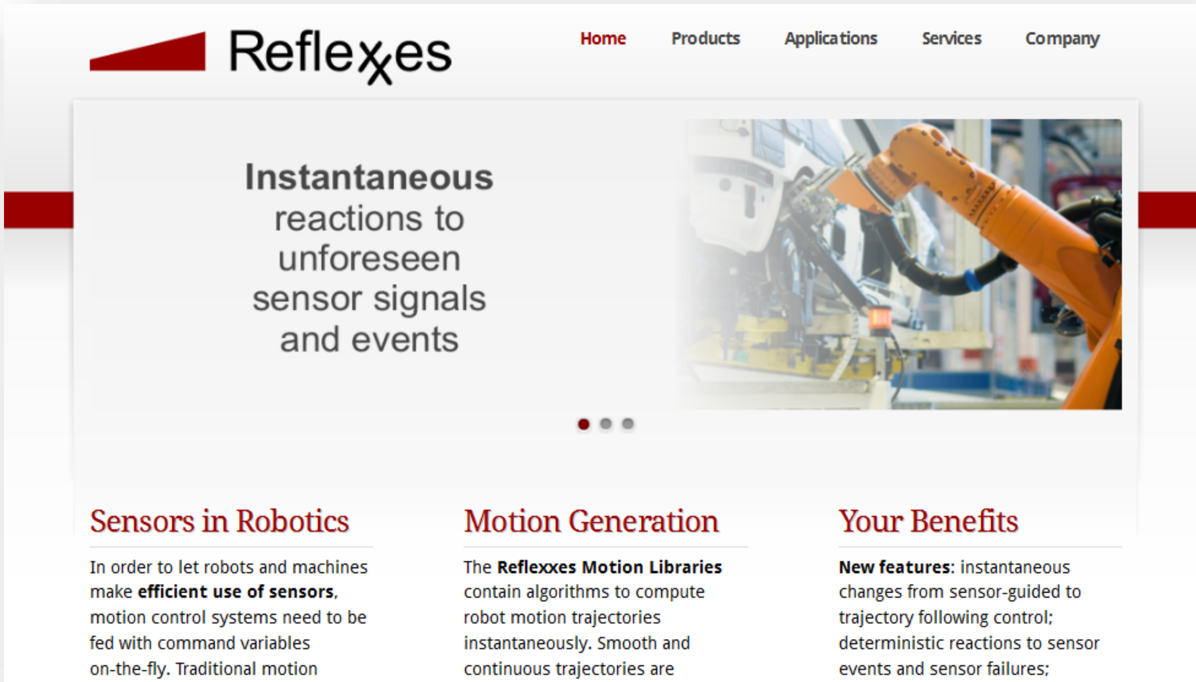
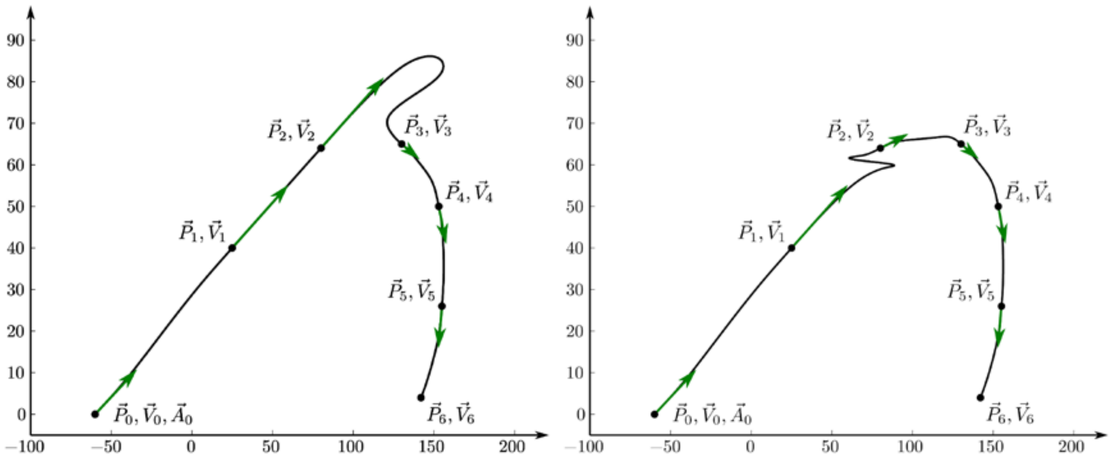
Open source software, tutorials, examples…



www.reflexxes.com

Outlook

- Asymmetric kinematic constraints **(TRL 5)**
  - Dynamic constraints
- Connection to (real-time) path planning **(TRL 2)**



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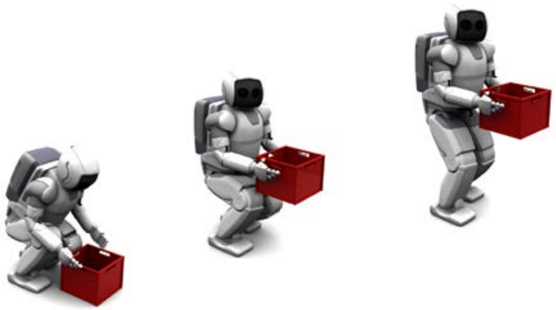


Thank you!

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