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Constraint-based robot programming for advanced sensor-based applications and human-robot interaction

COBAROP – Bringing constraint-based robot programing to real-world applications

Workshop at IEEE/RSJ International conference on Robot and Systems (IROS 2020)

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ROBOTICS RESEARCH TEAM

Motivation

Introduction

From cages to human environments

KUKA, https://www.kuka.com/en-ch/industries/automotive

Traditional view on robotics:

- Robots are locked up in cages
- No humans around
- Highly conditioned environment

Introduction

From cages to human environments

New application areas where the traditional view isn't valid any more:

- Robots working in a human-like environment or with natural products:
  → **variability** and **uncertainty** in the environment or products
- **Human collaborators** close by
- **Humans physically interacting** with robots (jointly performing tasks)

Introduction

Seemingly conflicting goals when creating “robot apps”

1. Dealing with variations in the process
   - Production line is less conditioned
   - Product variations (natural, processes such as molding)
   - Human interference/interaction

   ➔ More complex and involved robot programming

2. Decreased development cost needed
   - Smaller production series
   - Rapid deployment

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Approach

Approach

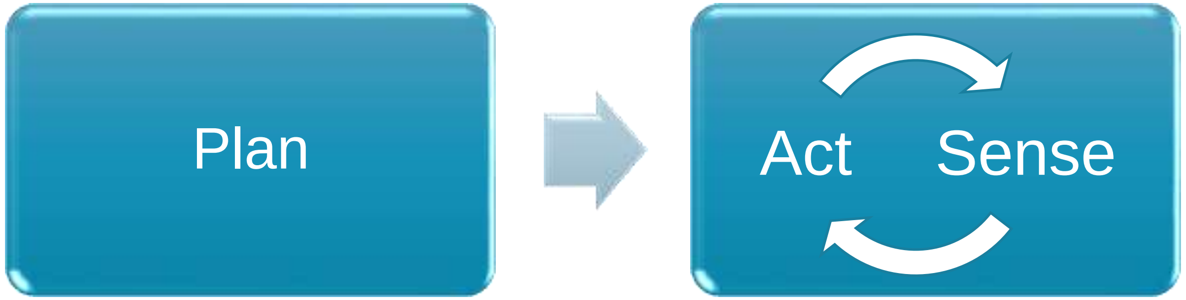
Traditional : Sense-Plan-Act

Models of
the environment

Trajectories

- Requires extensive calibration
- Once planned, there is no flexibility during execution.
  (or at least, much coarser)

Approach
Skill-based



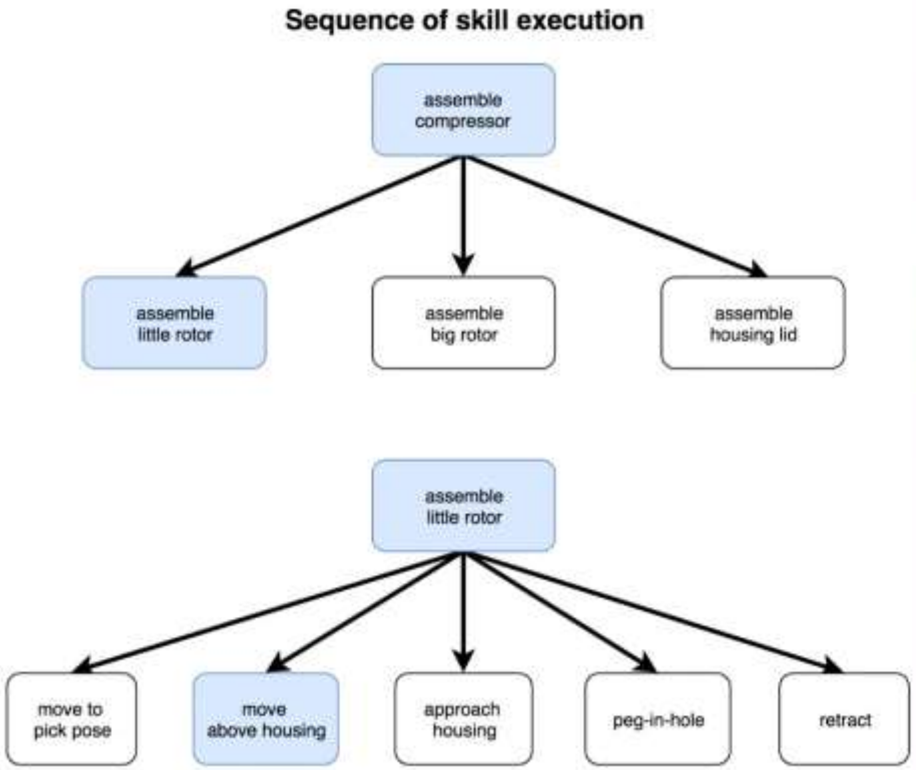
Behaviors
Skills

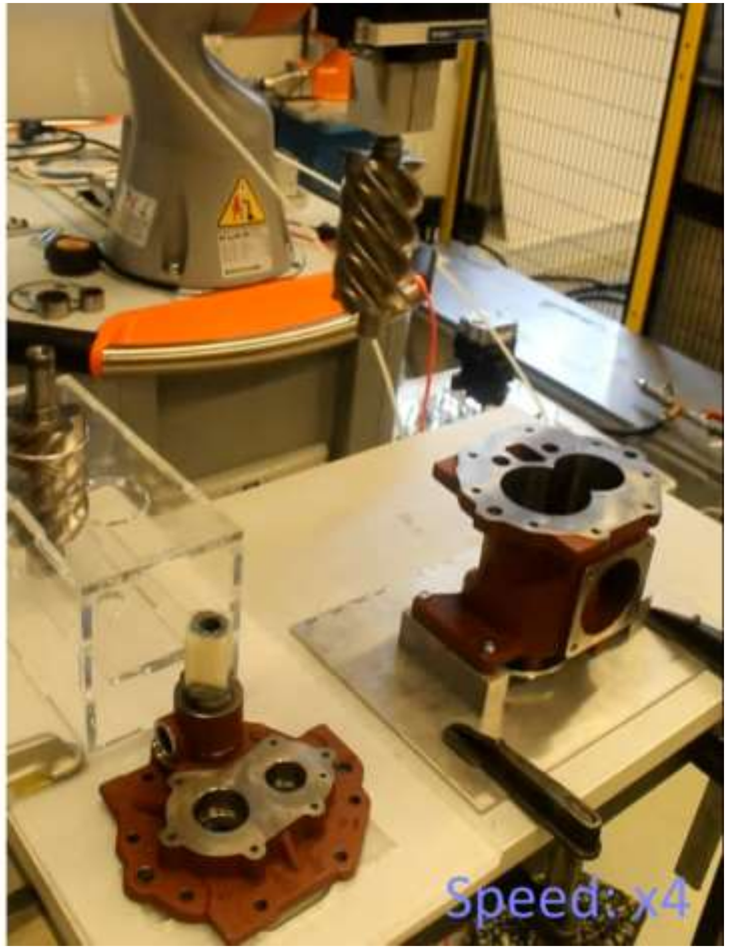
- Plan in terms of “**skills**” or behaviors
- **Reactive**
- Avoid calibration issues:
  - **Local** sensor measurements instead of **global**
  - Often more robust
  - Variable environments with human intervention/interaction

Example of skill-based approach

Force/Torque-based Assembly

Plan
Act Sense

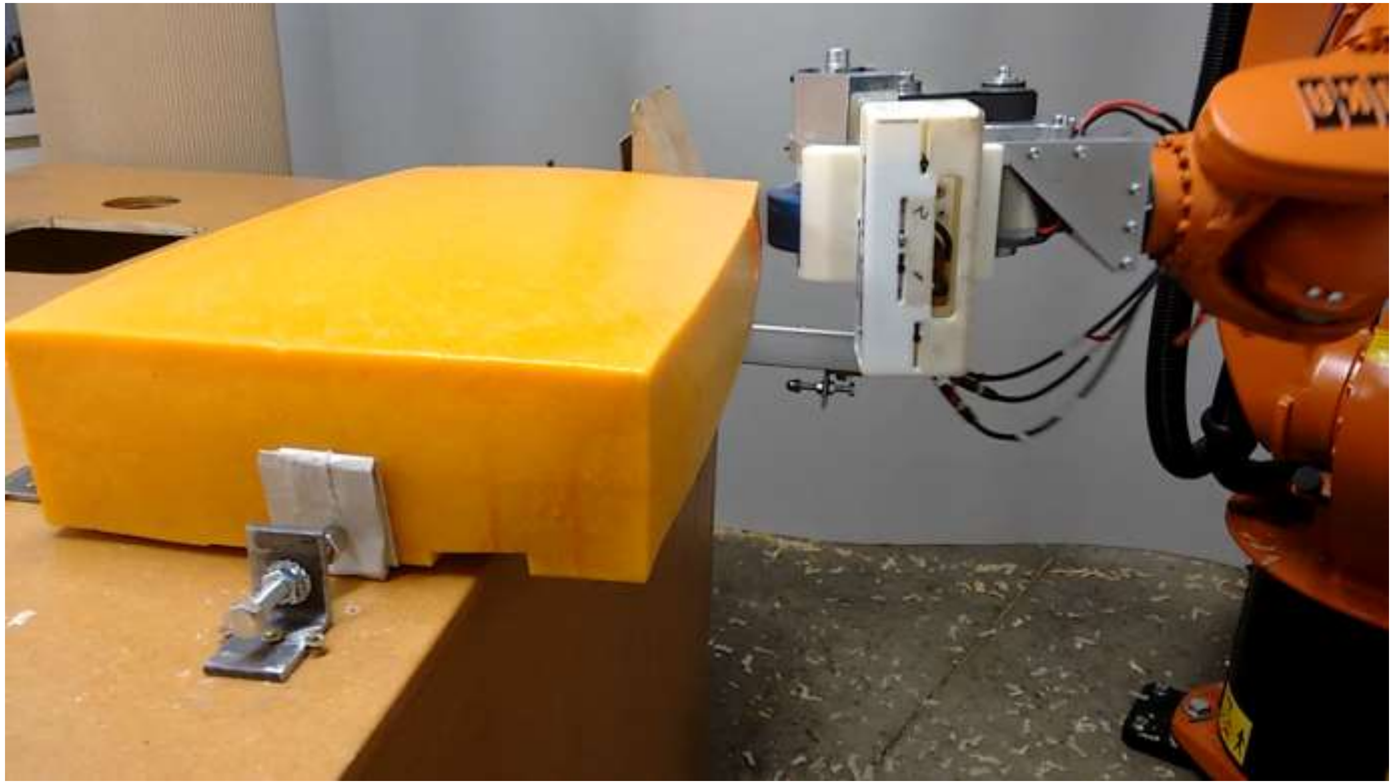




Example of skill-based approach

Cheese decrusting

Plan → Act Sense



- Cheese **decrusting** application
- A local measurement of 3 distances : (using laser distance sens.)
- High speed – high accuracy – avoiding calibration errors

Accurate layer of crust removed

Echord++ 3DSSC : KULeuven / FRS-Flexible Robotic Systems

A constraint-based approach

Task function $e(q, t) \to 0$

First order $$\frac{de}{dt} = -k\ e$$

Second order $$\frac{\mathrm{d}^2 e}{\mathrm{d}t^2} = -2\zeta\omega_0 \frac{\mathrm{de}}{\mathrm{d}t} - \omega_0^2 e$$

A constraint-based approach

First order

$$\frac{de}{dt} = -k\,e$$

$$\frac{\partial e}{\partial q}\dot{q} + \frac{\partial e}{\partial t} = -k\,e$$

$$J\dot{q} = -k\,e - \frac{\partial e}{\partial t}$$

Jacobian

Feedback term

Feedforward term

A constraint-based approach

First order

$$\frac{de}{dt} \leq -k\ e$$

$$\frac{\partial e}{\partial q}\dot{q} + \frac{\partial e}{\partial t} \leq -k\ e$$

$$J\dot{q} \leq -k\ e\ - \frac{\partial e}{\partial t}$$

Jacobian

Feedback term

Feedforward term

A constraint-based approach

$$\underset{\dot{q}}{minimum} \quad \sum_i w_i \varepsilon_i^2 \quad + \lambda \sum_l v_l \dot{q}_l^2$$

Subject to:

$$\vdots$$

$$J_i \dot{q} = -k e_i - \frac{\partial e_i}{\partial t} + \varepsilon_i$$

$$\vdots$$

eTaSL

eTaSL

expression graph based Task Specification Language

Constraint-based task specification and control framework to describe these **reactive** skills (behaviors)

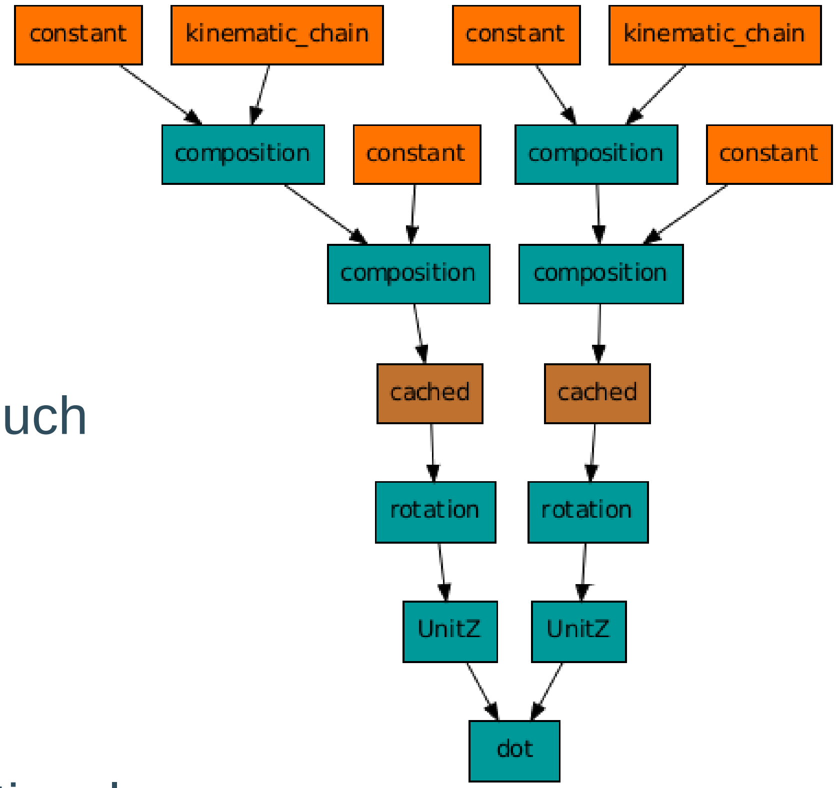
- at each sample time (100 Hz→250 Hz), it **optimizes** the **control velocity** of each robot joint **subject to** a number of **constraints**
- **instantaneous optimization**: we do not (yet) look ahead in time
- only considers **kinematical model** of the robot
  → we can still achieve high performance!

More information: https://etasl.pages.mech.kuleuven.be/ and E. Aertbeliën and J. De Schutter, **Etasl/eTC: A Constraint-Based Task Specification Language and Robot Controller Using Expression Graphs**, IEEE/RSJ International Conference on Intelligent Robots and Systems, 2014

eTaSL

expression graph based Task Specification Language

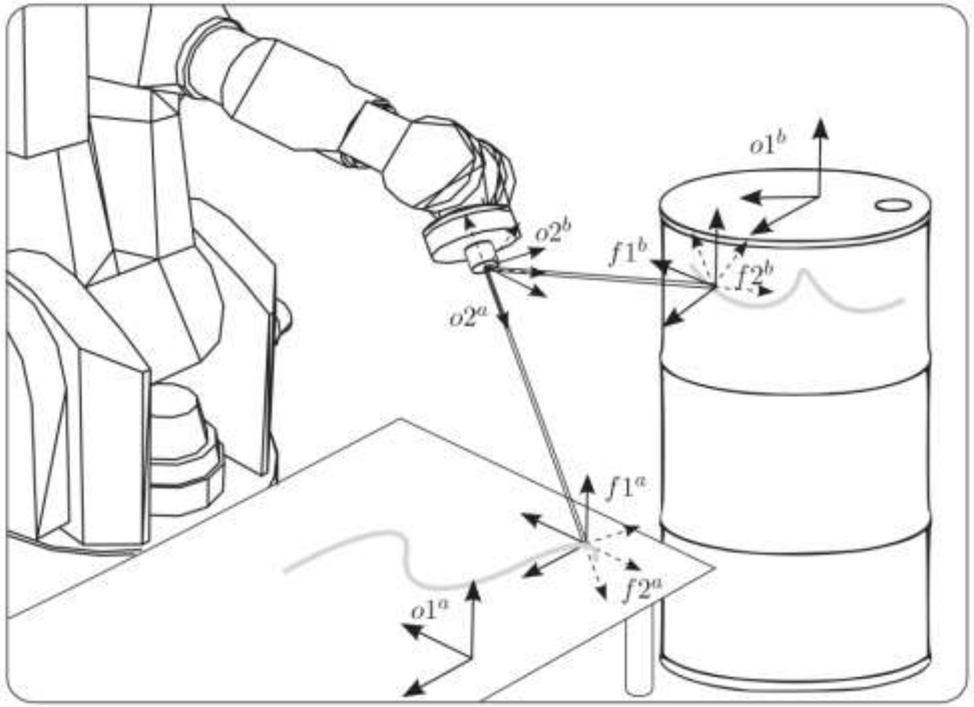
- Constraints are described using **expression graphs**:
  - Symbolic, graph-structure
  - **Not only scalar** expressions
  - **Robot** is described as a function of its joint variables
  - **Trajectory** as a function of time
  - Expressions can relate to **sensor-input**
  - **Simple language** (LUA-based) where you can write down such expressions



- Controller is automatically generated:
  - Evaluation
  - Introspection
  - Automatic differentiation for Jacobians (avoiding representational singularities)

Variables & Feature variables

iTaSC (*)



(*) J. De Schutter et al., “Constraint-based task specification and estimation for sensor-based robot systems in the presence of geometric uncertainty,” *The Int. Journal of Robotics Research*, vol. 26, no. 5, pp. 433–455, 2007.

Variables & Feature variables

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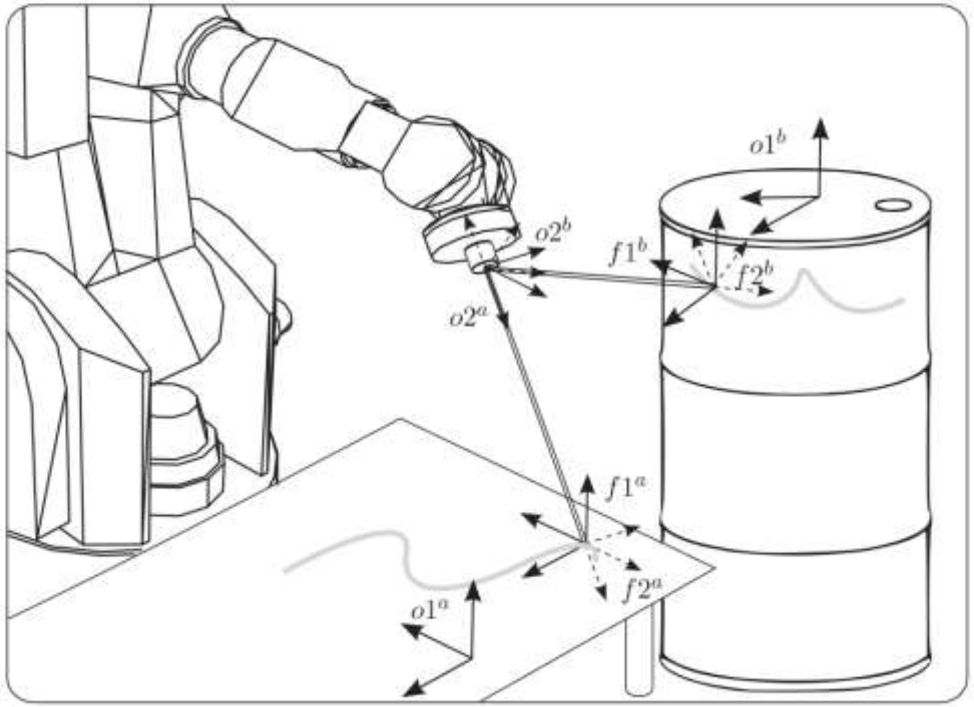
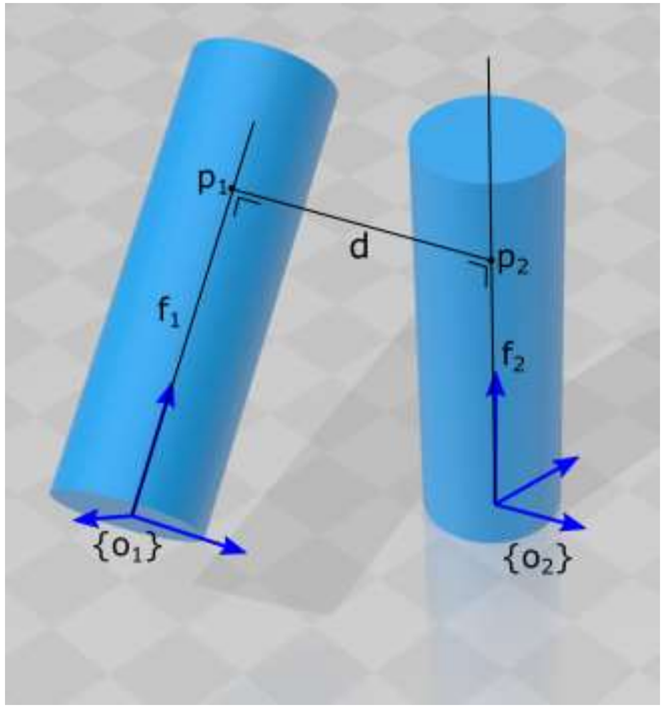


eTaSL



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eTaSL

expression graph based Task Specification Language

Constraints can be related to:

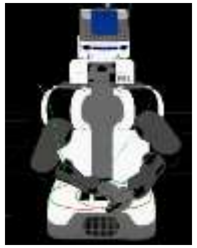
- the **task:** desired trajectory, speed, contact force, distance, etc.
- the **robot platform** and its limitations in terms of reachable/allowable joint positions velocities

  (specified using URDF)
- the **environment:** e.g. avoiding collisions and self collisions
- interaction with **humans** (physcial or cognitive)

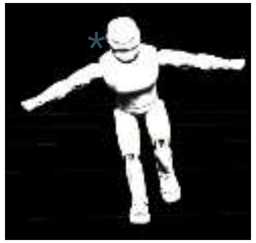
7 dof

*

8 dof



20 dof



33 dof

100 dof

eTaSL

expression graph based Task Specification Language

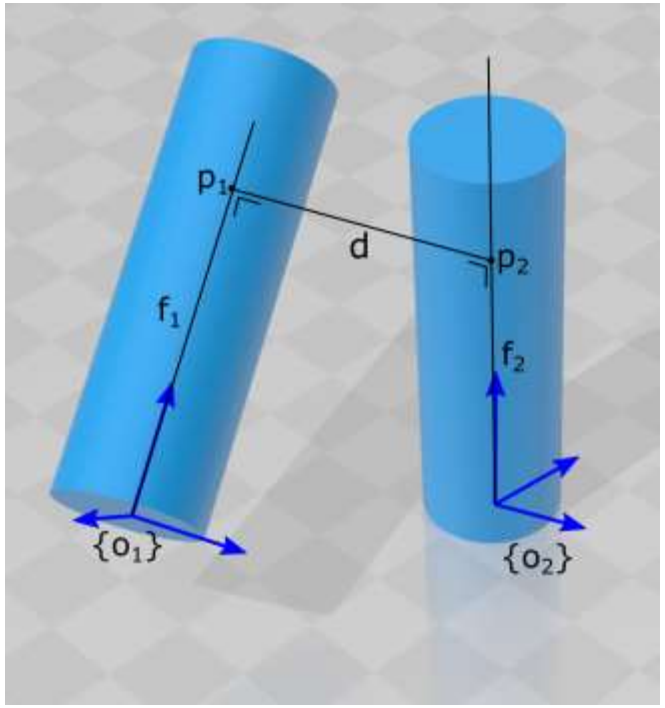
- constraints can be **conflicting**:
  - priorities
  - soft constraints & weights
- and can be **equality** or **inequality** constraints (e.g. collision constraint)
- **explicit time**
  - task function expressions within the constraints:
  - a trajectory can be specified a mix of trajectories with time-varying weights
  - eTaSL perfectly deals with tracking errors
    (**automatically generates feedforward control term!**)

Geometric constraints

Geometric constraints

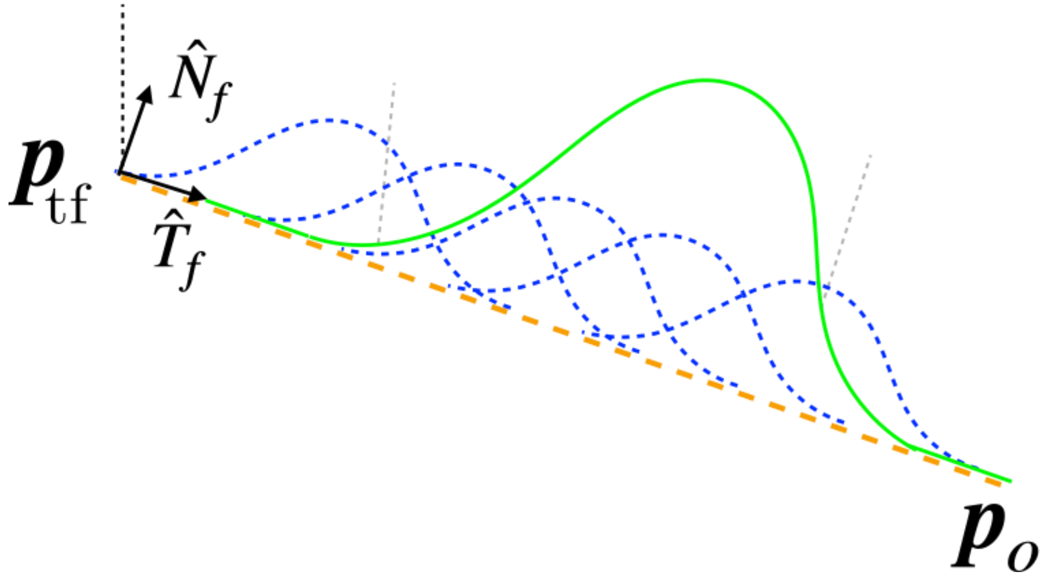
Tools to model geometric constraints:

- Facilitated by the use of feature variables
- Distances between convex objects using the GJK-algorithm (*)
- Library for typical geometrical distances and angles.



(*) Gilbert, E. G., Johnson, D. W., & Keerthi, S. S. (1988). A fast procedure for computing the distance between complex objects in three-dimensional space. *IEEE Journal on Robotics and Automation*, *4*(2), 193-203.

Flexible trajectories



- Linear combination of basis functions B_i (in function of feature variabels f_i and progress s)

$$T(s, f_1, \dots, f_n) = T_{mean}(s) + \sum_i f_i B_i(s)$$

- Basis functions can be
  - Pre-defined (Gaussians, B-splines,…)
  - Generated by programming-by-demonstration

- Soft constraints on the feature variables

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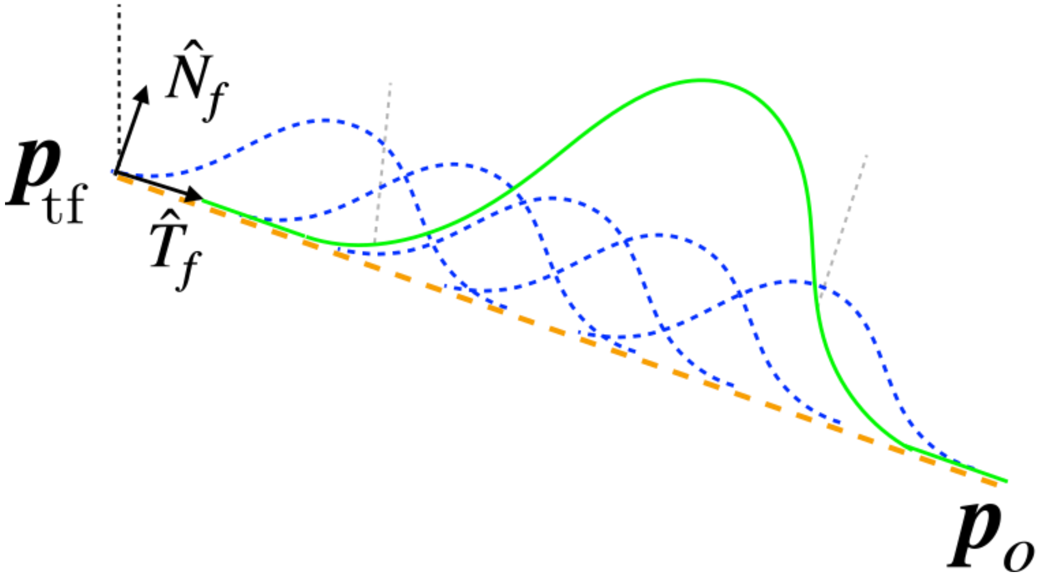
Flexible trajectories

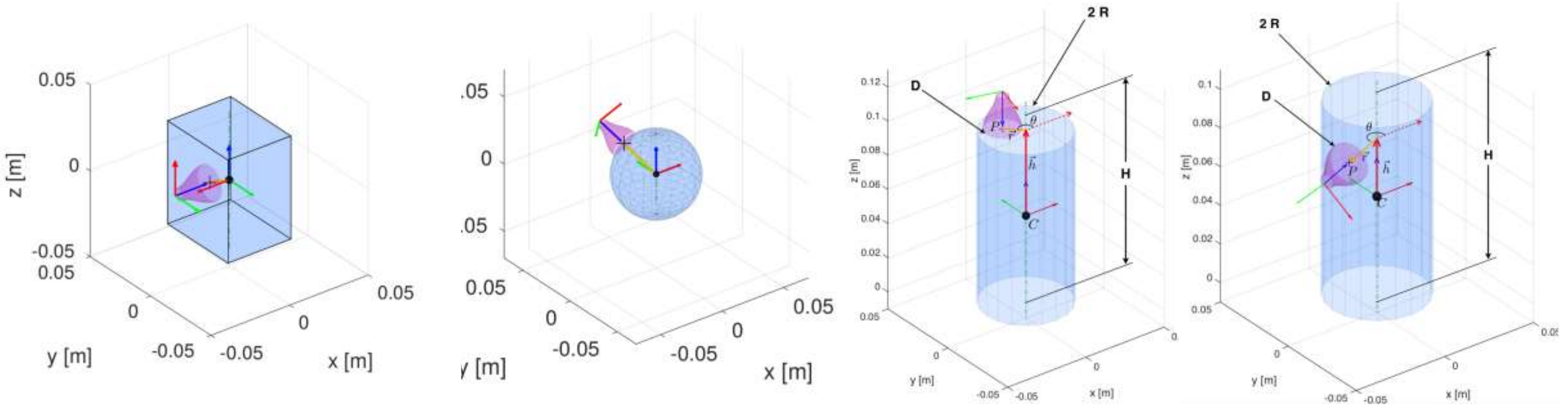


- Linear combination of basis functions B_i (in function of feature variabels f_i and progress s)

$$T(s, f_1, \ldots, f_n) = T_{mean}(s) + \sum_i f_i\, B_i(s)$$

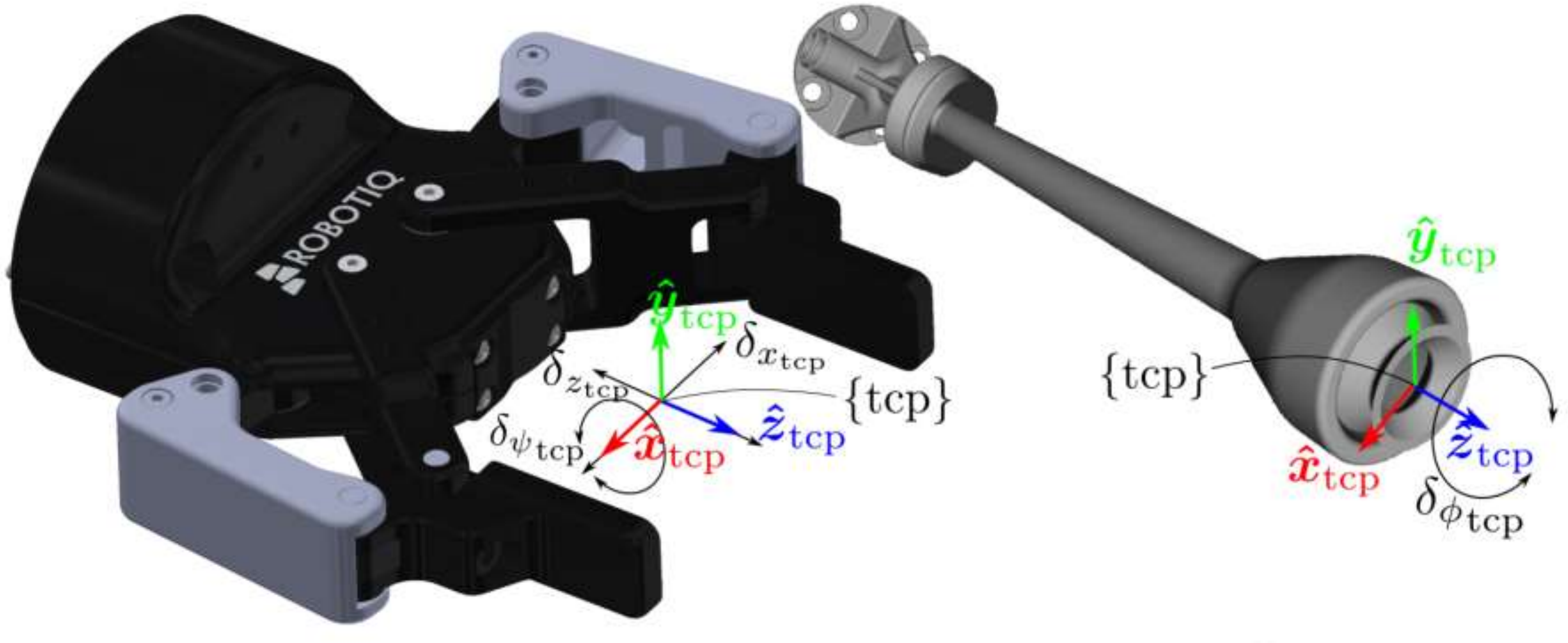
- The progress s is modeled separately and is related to time via a soft position or velocity constraint

Reactively modeling grasp and contact

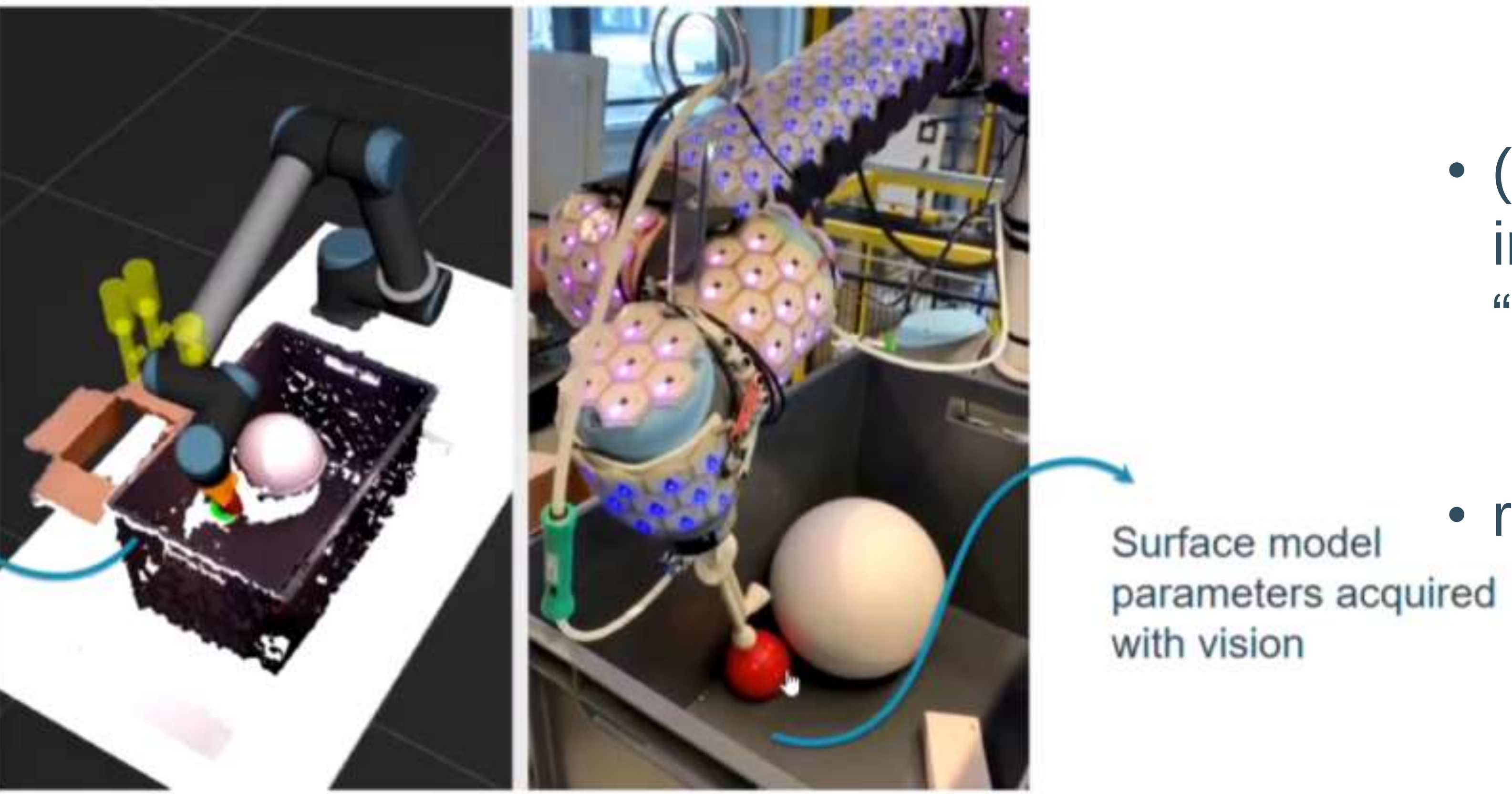


C. Vergara, S. Iregui et al. Generating Reactive Approach Motions Towards Allowable Manifolds using Generalized Trajectories from Demonstrations, IROS 2020

Reactively modeling grasp and contact



Flexible trajectories & grasp modeling



- Impose constraints "in the future"
- (local) collisions can be implemented by adding virtual "tools"
- reactive

Sensor related constraints

Sensor-related constraints

Admittance constraints

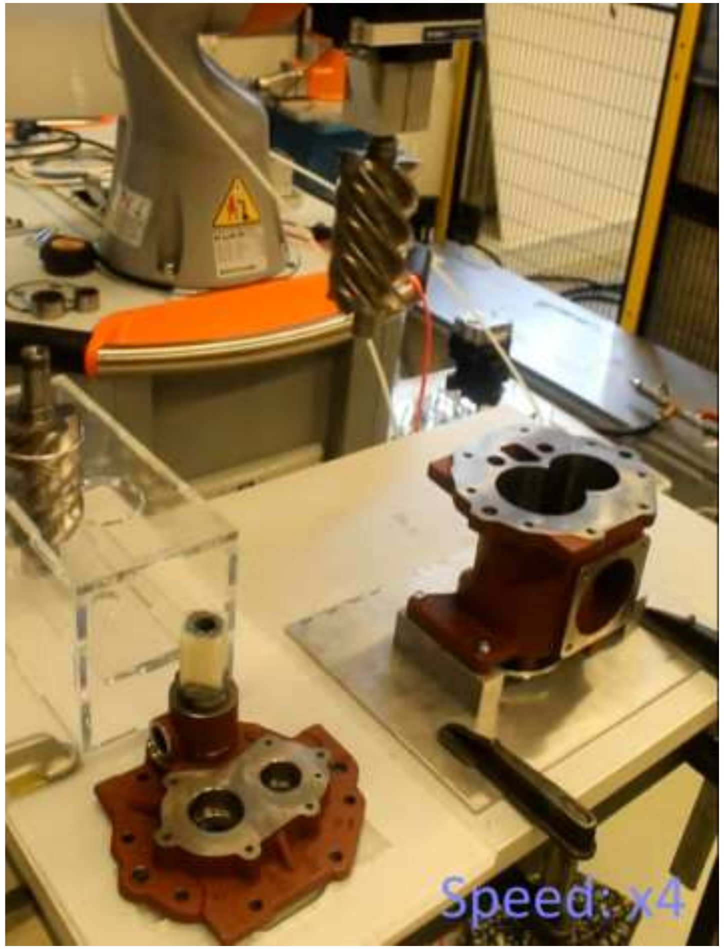
A generalized way to include sensors using a admittance control strategy:

- **model** of the sensor measurement
- sensor **measurement**
- **target** value

$$\underbrace{\mathbf{J}(\tilde{\mathbf{q}})}_{\frac{\partial}{\partial \tilde{\mathbf{q}}}\text{model}} \; \dot{\tilde{\mathbf{q}}} = -K \underbrace{(e(\tilde{\mathbf{q}}))}_{\text{meas - target}} - \underbrace{\frac{\partial e}{\partial t}(\tilde{\mathbf{q}})}_{\frac{\partial e}{\partial t}\text{model}} + \epsilon$$

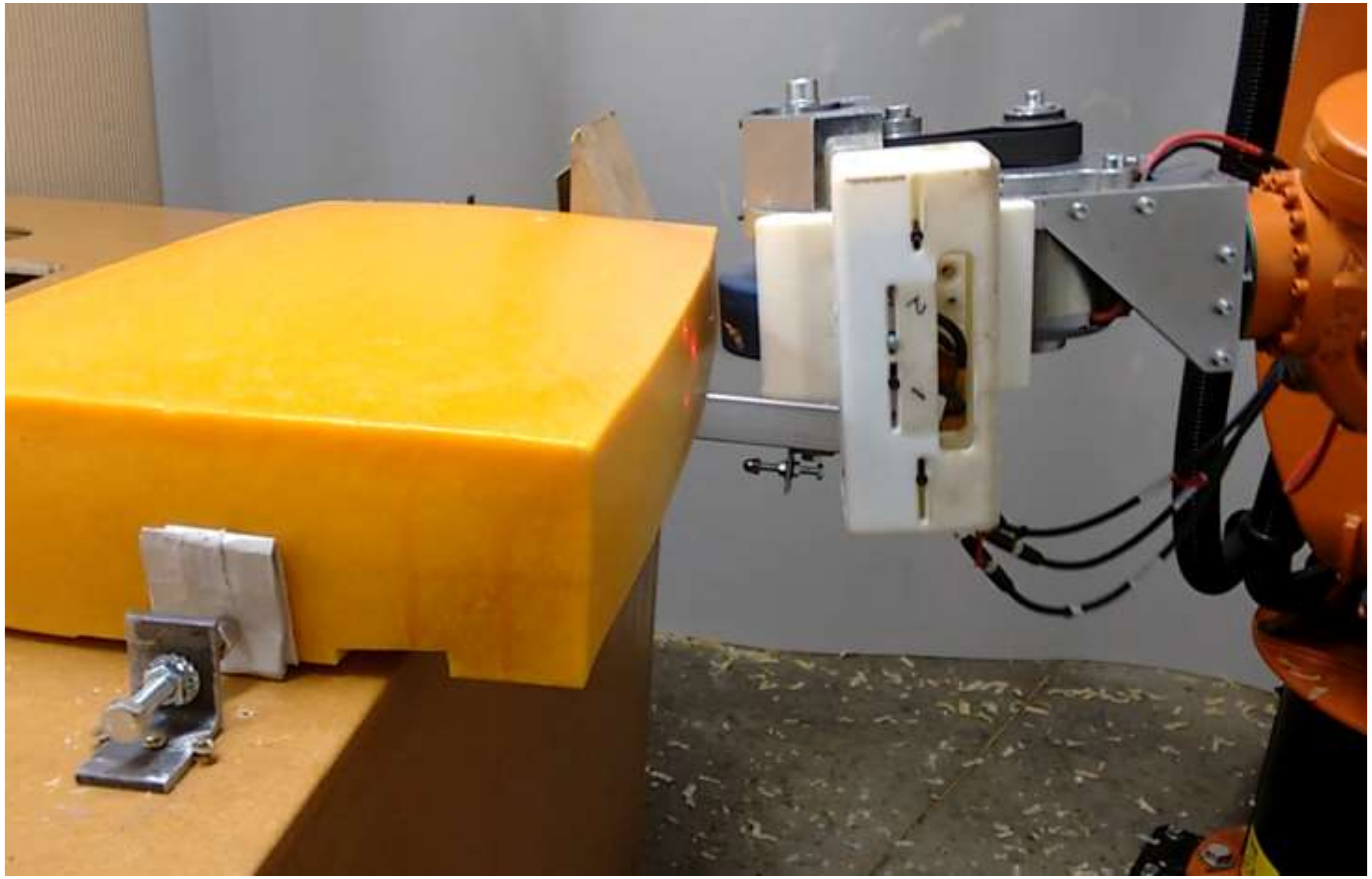
Sensor-related constraints

Force/Torque for assembly

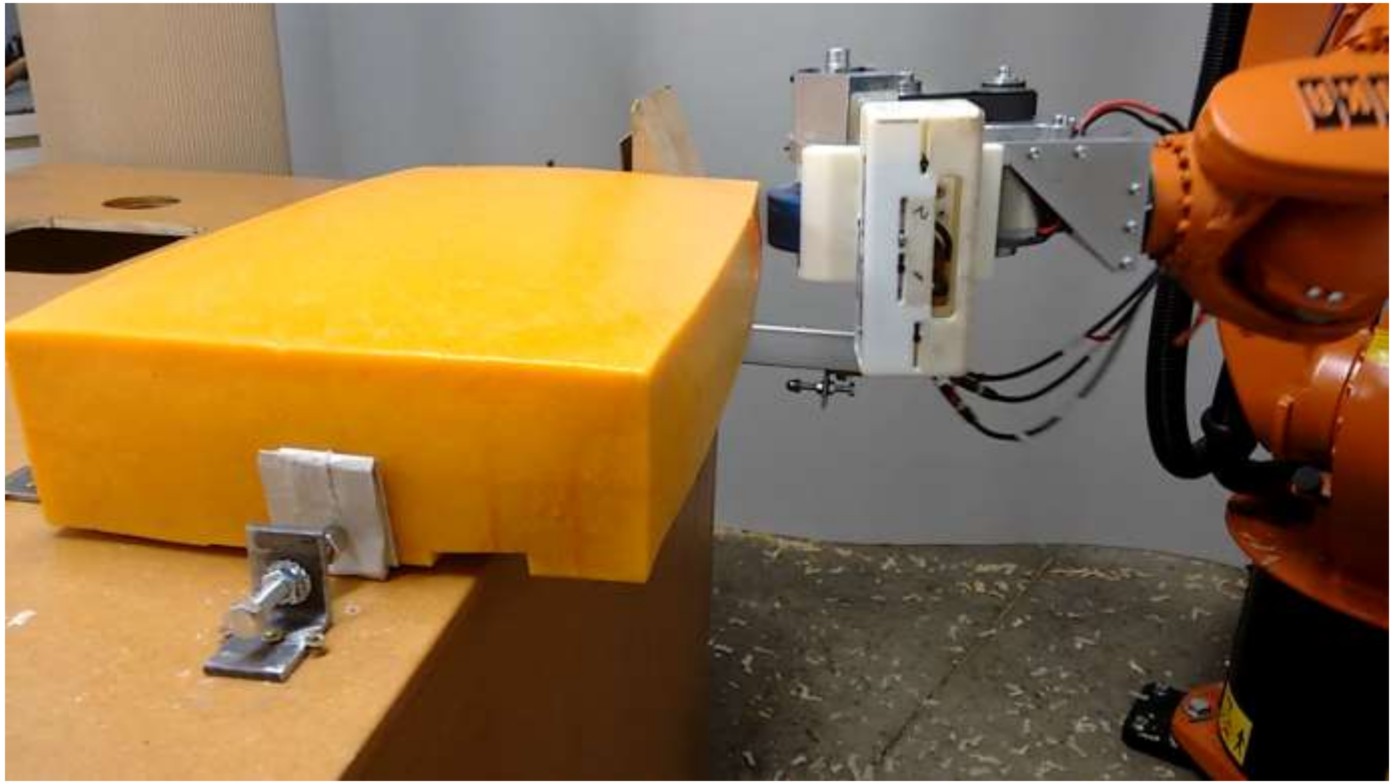


Sensor-related constraints

distance sensors



Combining constraints



Echord++ 3DSSC : KULeuven / FRS-Flexible Robotic Systems

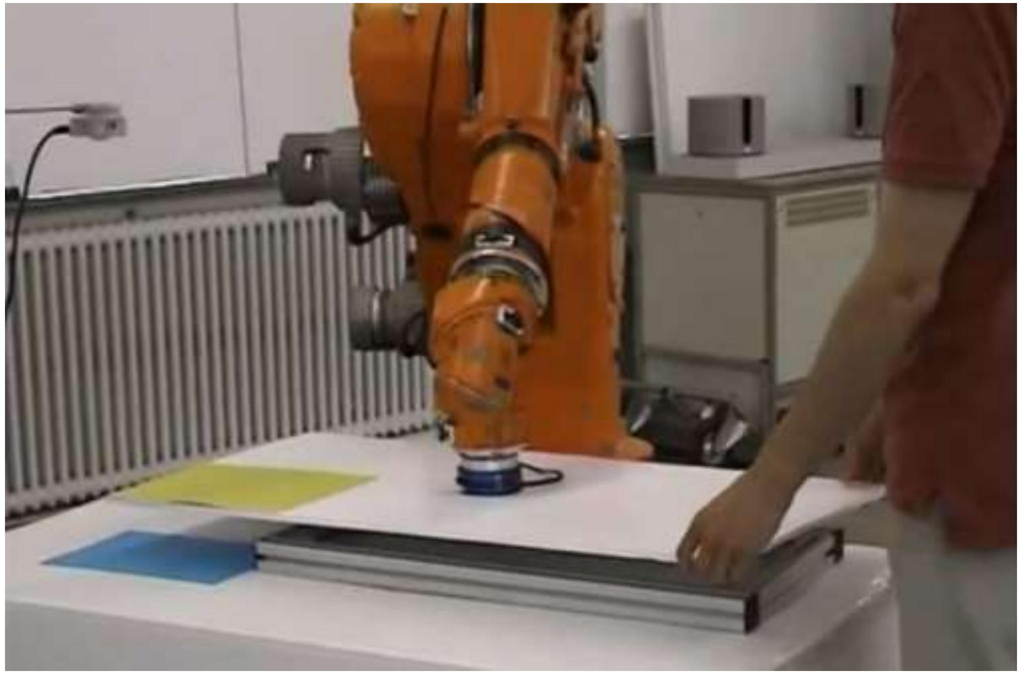
Added value of eTaSL:

- generating robot trajectory based on model built from sensor readings
- trajectory control (feedback + feedforward)
- automatic pitch control to keep laser sensor measurements within range
- compensation of time delays in control loop
- automatic speed reduction to keep joint velocities within limits
- smooth and fast transition between approach/retract and cutting trajectory

Sensor-related constraints

Conflicting admittance and position constraints

- Impedance = conflicting **position** and **force** constraint

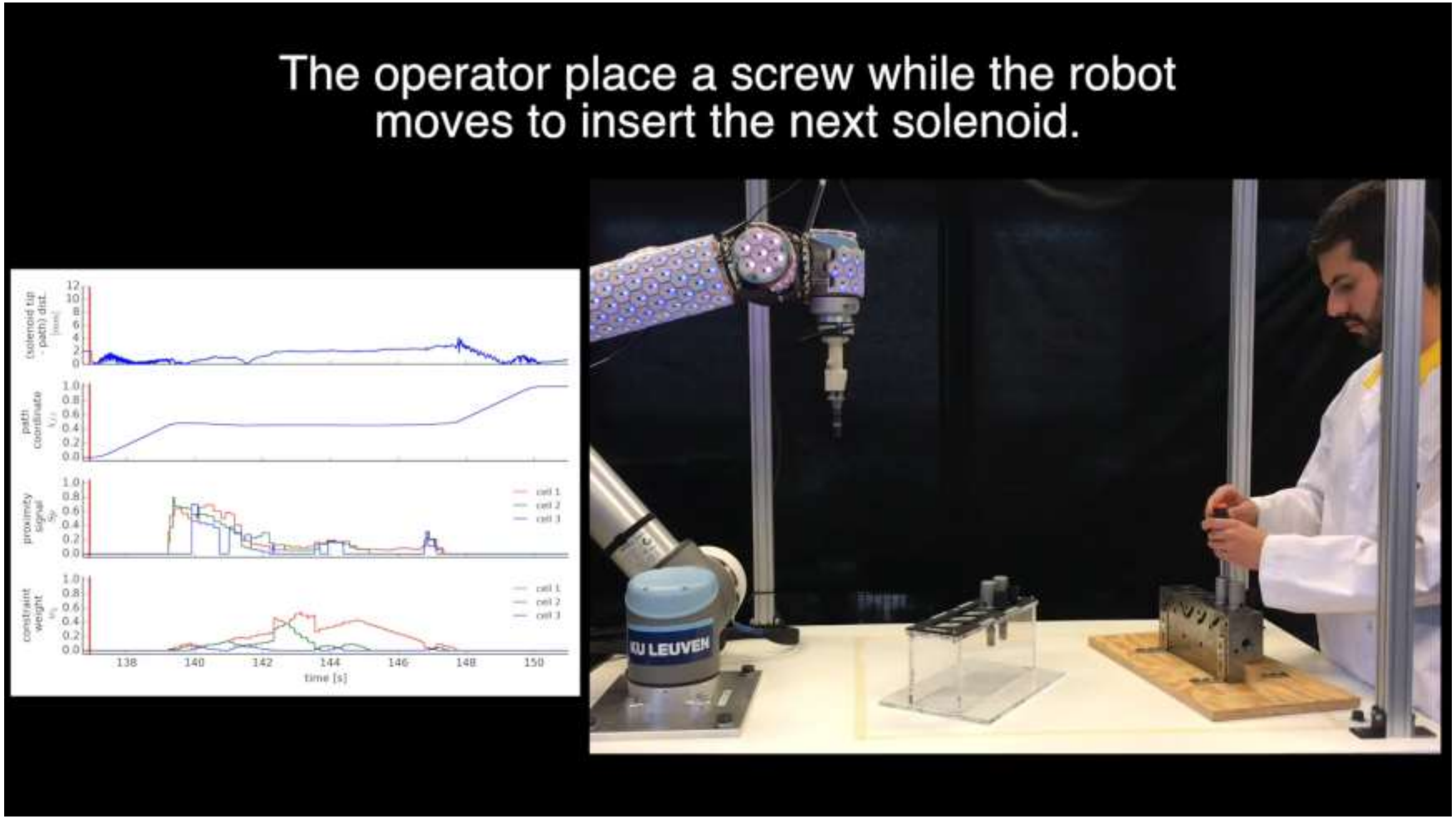


* Need **not** necessarily the same **reference** point!

* Often used in **shared** control

Sensor-related constraints

Skin



- Skin with 400 cells that measure both distance and force.
- Defined behavior along a trajectory and away from that trajectory.
- Trajectory adapts itself to the information from vision.

Sensor-related constraints

Force/Torque for contour following

Movie by Flexible Robotic systems (FRS, https://www.frsrobotics.com/

No pre-programmed positions, the robot is automatically adapting to the contour.

A constraint formulation similar to the task frame formalism (*)

Can still be combined with other Non-task frame related constraints

H. Bruyninckx and J. De Schutter, "Specification of force-controlled actions in the "task frame formalism"-a synthesis," in IEEE Transactions on Robotics and Automation, vol. 12, no. 4, pp. 581-589, 1996

Modeling human motion

Modeling human motion

Why?

- For use in **programming-by-demonstration:**
  $\Rightarrow$ For rapid deployment

- To **anticipate** and **predict** human motion in the neighborhood of the robot

- For **shared control**

➡ a modeling approach for **reactive** control and **constraints**.

Demonstration of tasks

Demonstrate task segments

while recording:
- poses
- wrenches

Kinesthetic teaching
- ensure feasibility
- less calibration efforts needed
- use previous demonstrations to facilitate
- more disturbance forces

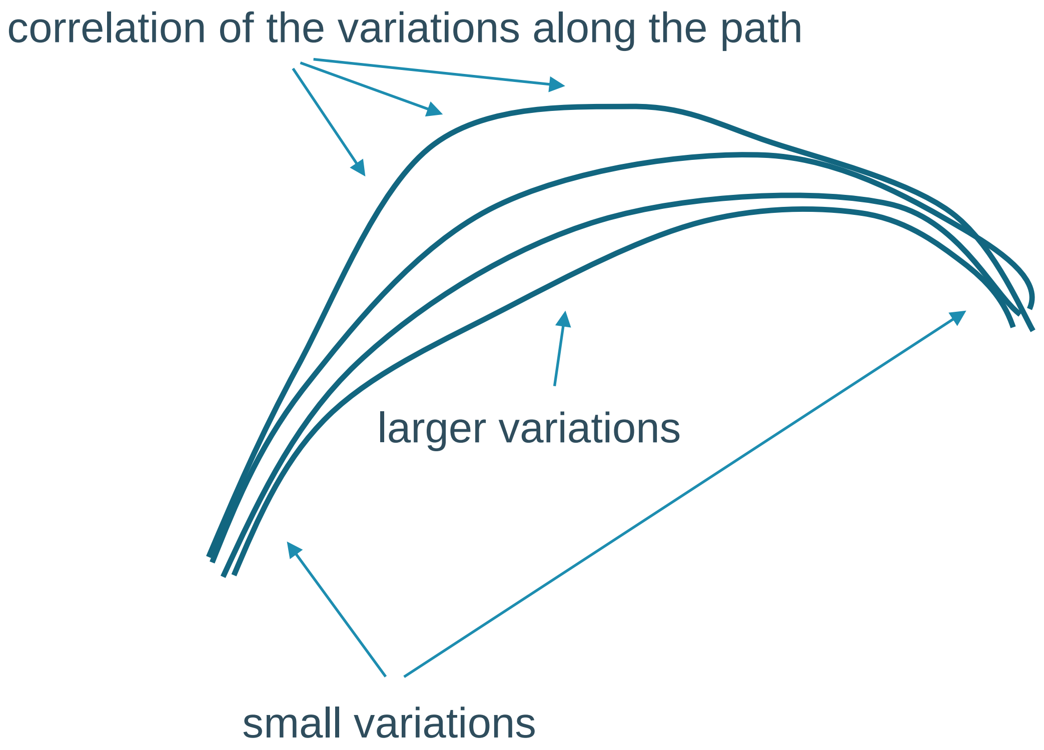
Passive observation:
- feasibility is not guaranteed
- less disturbed demonstrations

Programming by demonstration

and combining this with constraint-based task specification

- we learn a **trajectory** and its **allowable variations** from demonstrations using a generative probabilistic approach: **Probabilistic Principal Component Analysis (PPCA)**

- combine with (model-based) constraint-based task specification
  - to support the **demonstration**
  - to add constraints for the **task execution**



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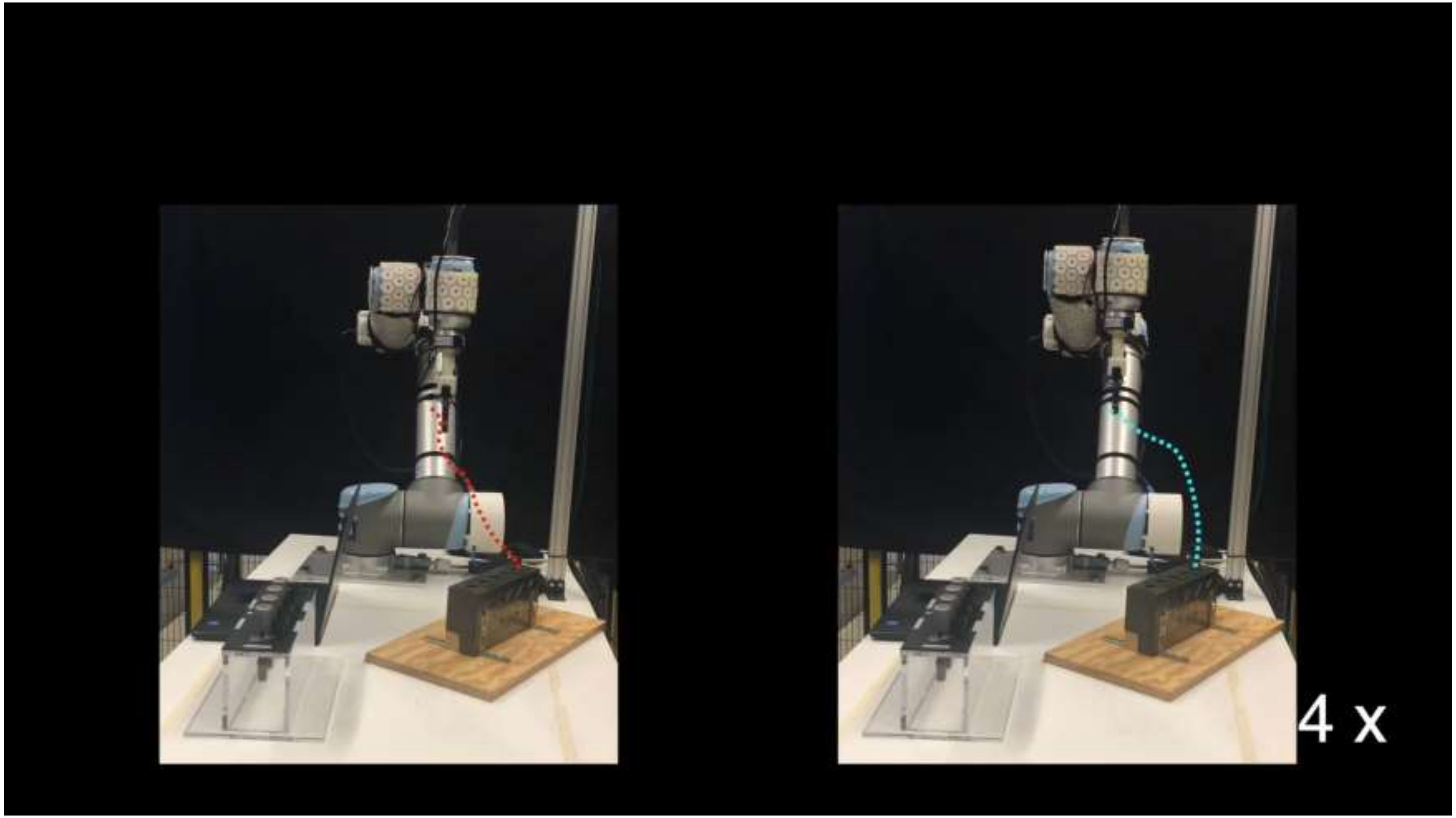
PbD for the assembly of solenoids: demonstrations

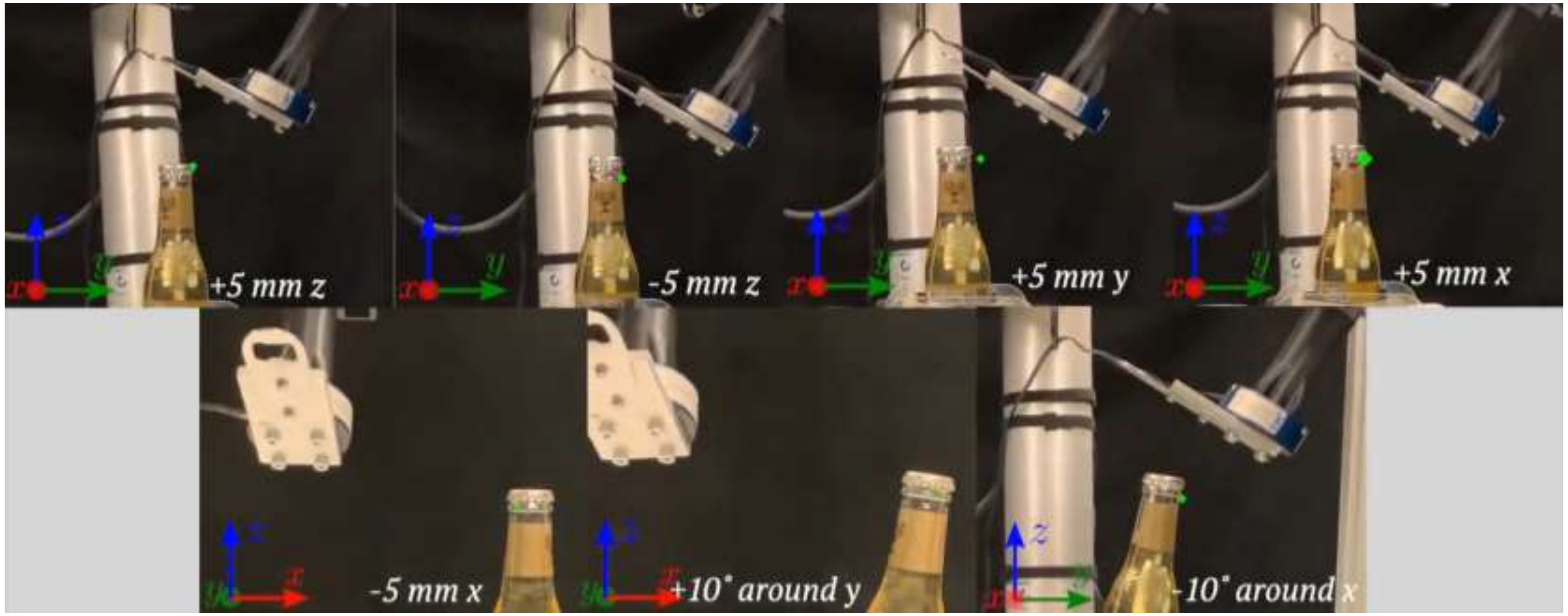
PbD for the assembly of solenoids: guided demonstrations

PbD for the assembly of solenoids : execution



Tasks with an approach & contact-phase: bier opening

Tasks with an approach & contact phase: contour following



Tasks with an approach & contact phase: contour following

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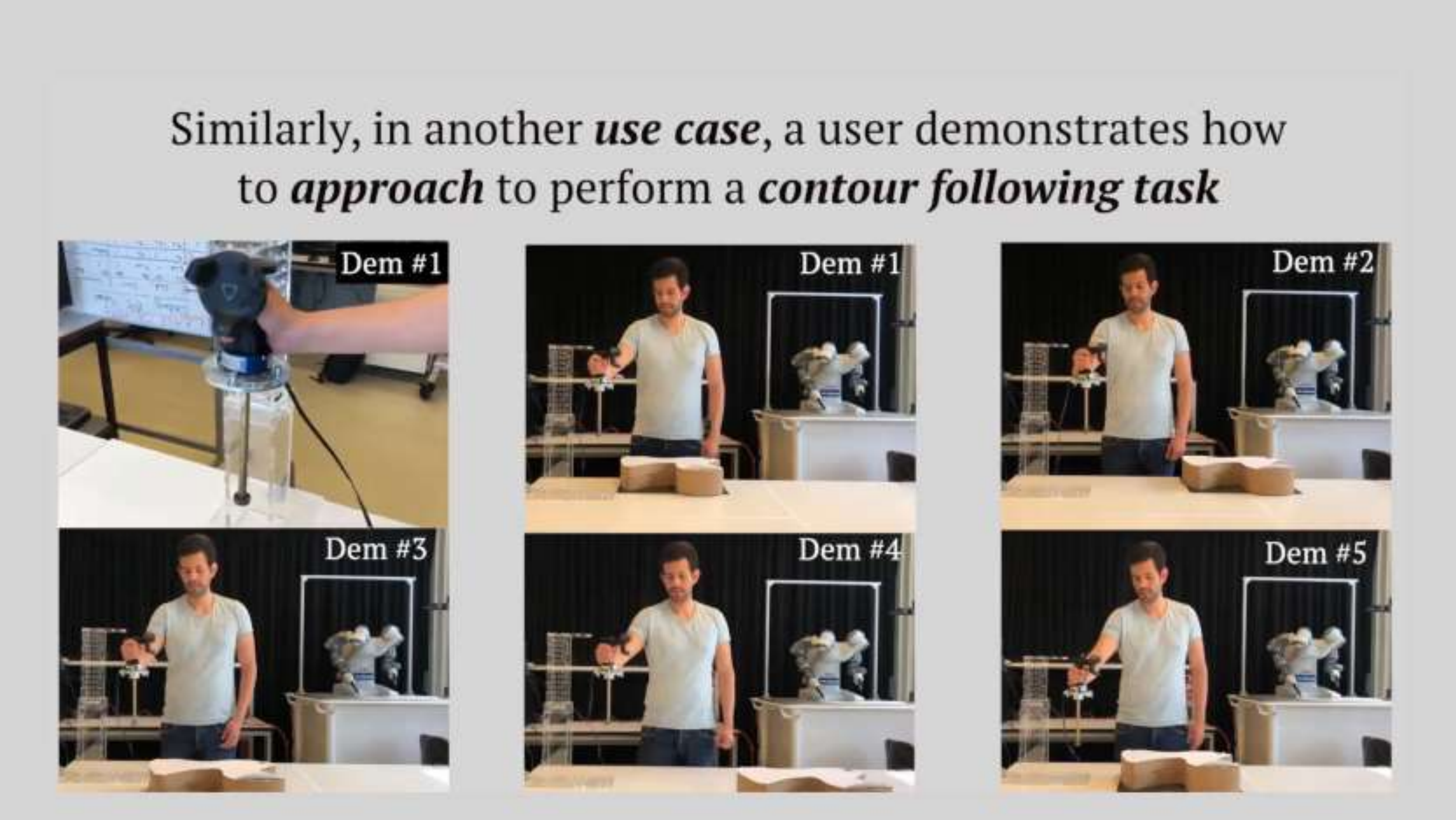
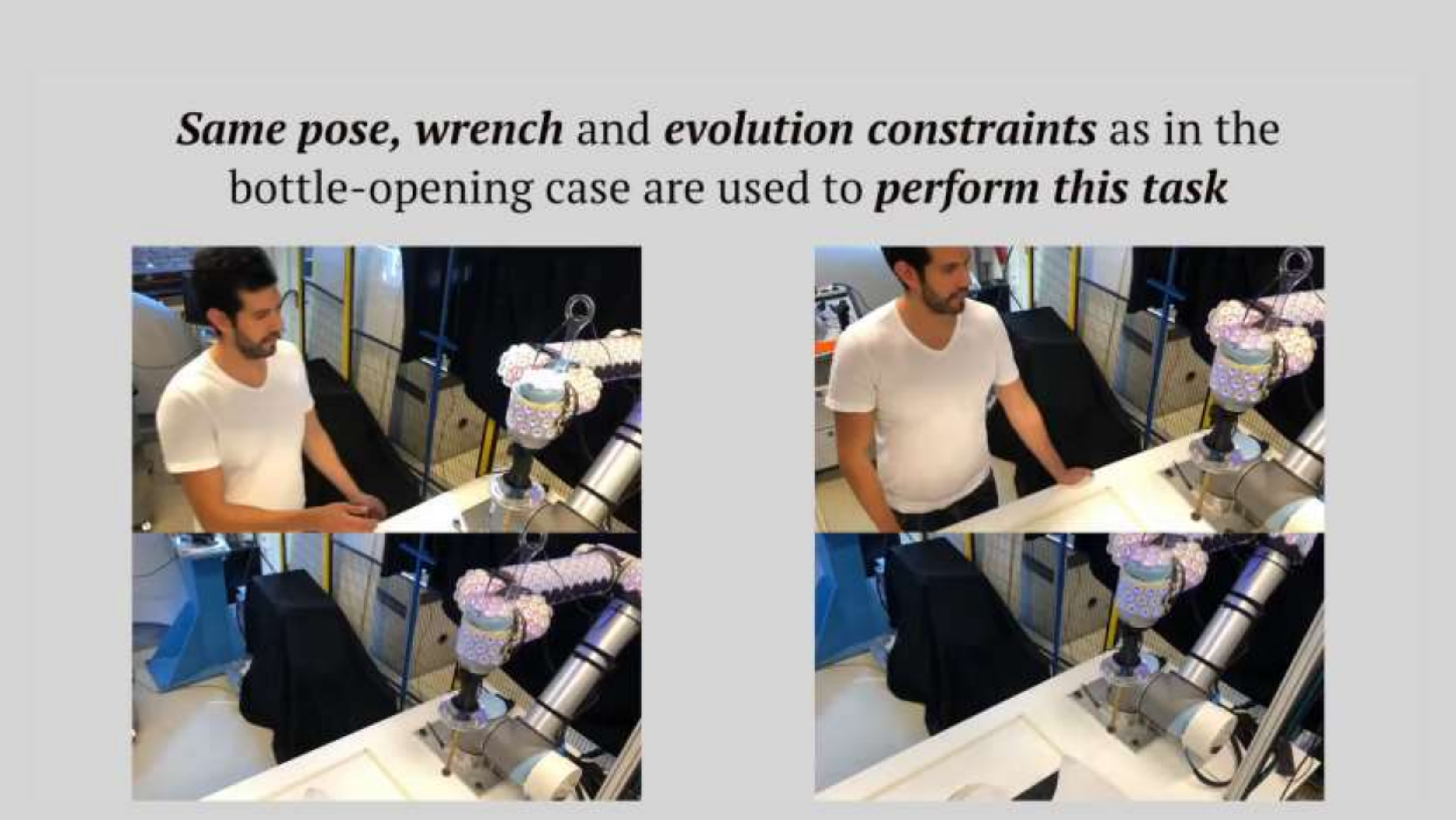


Tasks with an approach & contact phase: contour following



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Conclusion

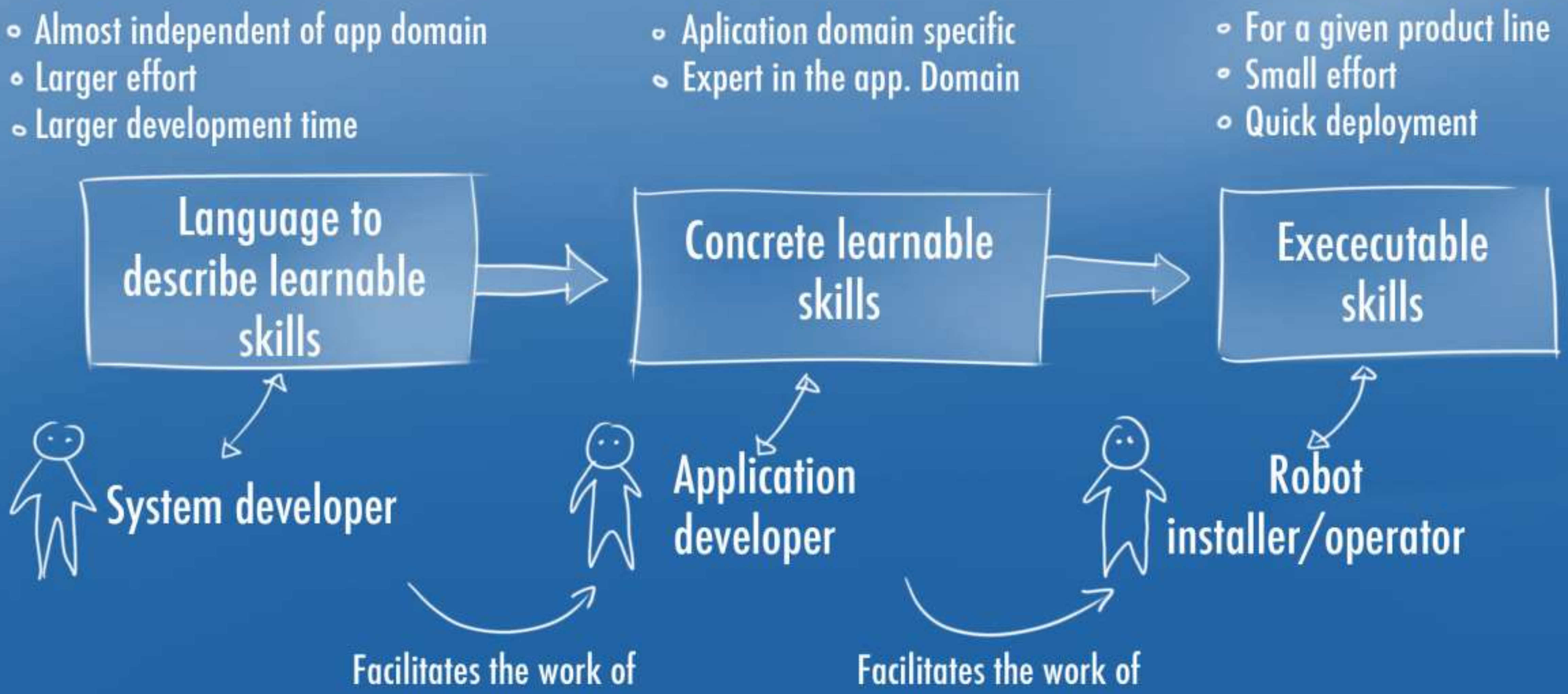
Conclusion

Seemingly conflicting goals when creating “robot apps”

1. Dealing with variations in the process
   - Production line is less conditioned
   - Product variations (natural, processes such as molding)
   - Human interference/interaction

   ➔ More complex and involved robot programming

2. Decreased development cost needed
   - Smaller production series
   - Rapid deployment


• Almost independent of app domain
• Larger effort
• Larger development time
• Aplication domain specific
• Expert in the app. Domain
• For a given product line
• Small effort
• Quick deployment
Language to describe learnable skills
Concrete learnable skills
Exececutable skills
System developer
Application developer
Robot installer/operator
Facilitates the work of
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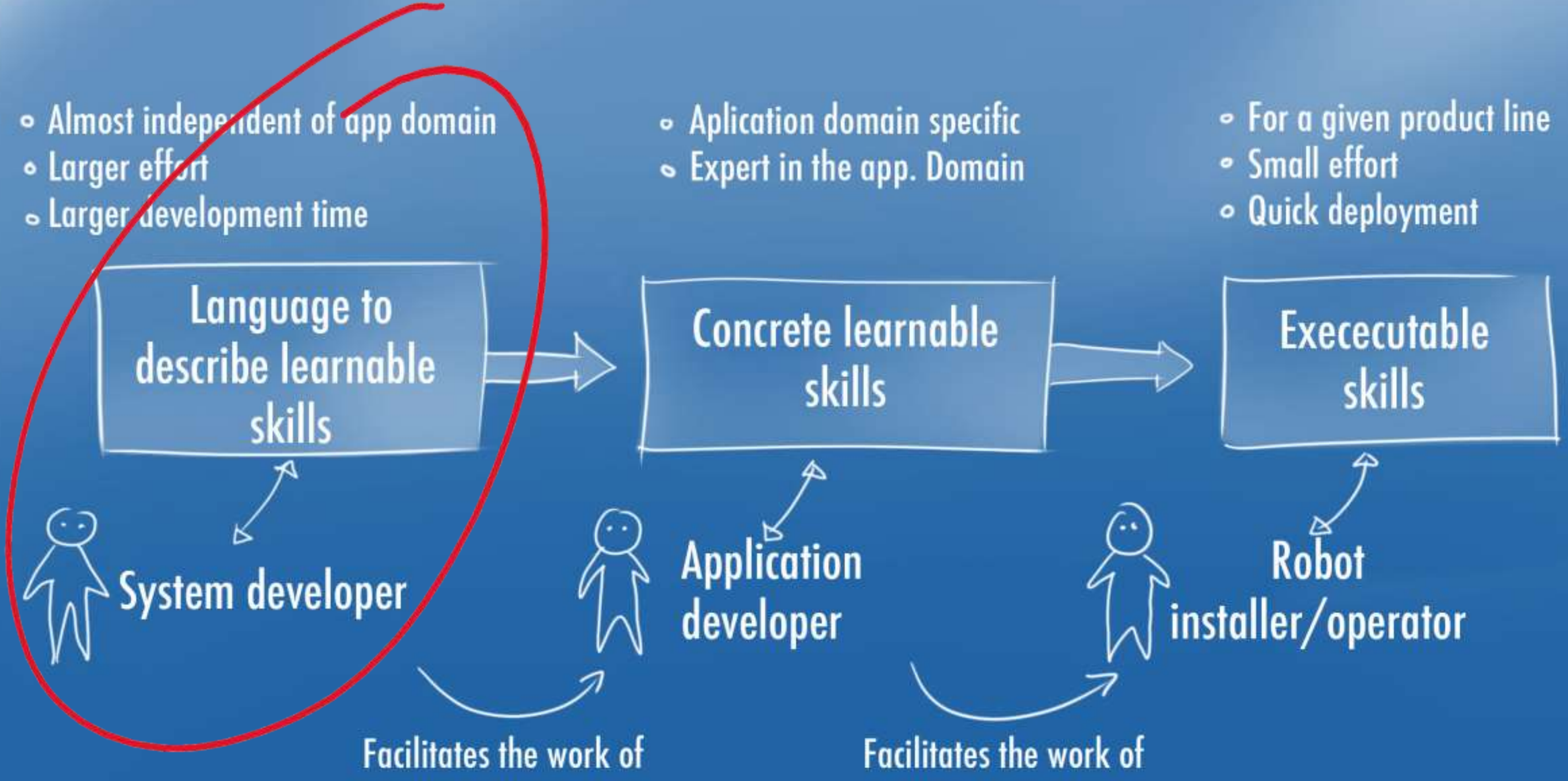

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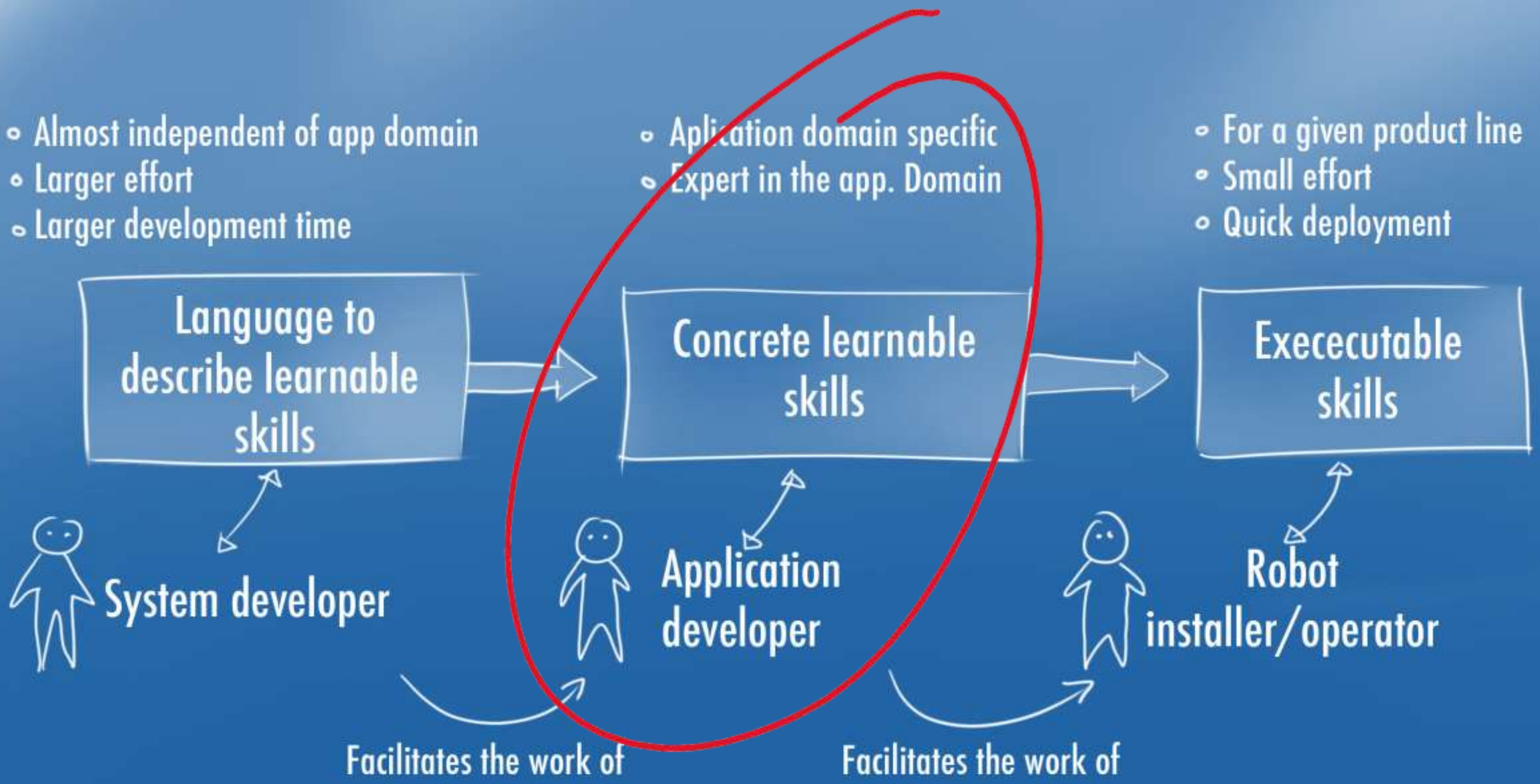

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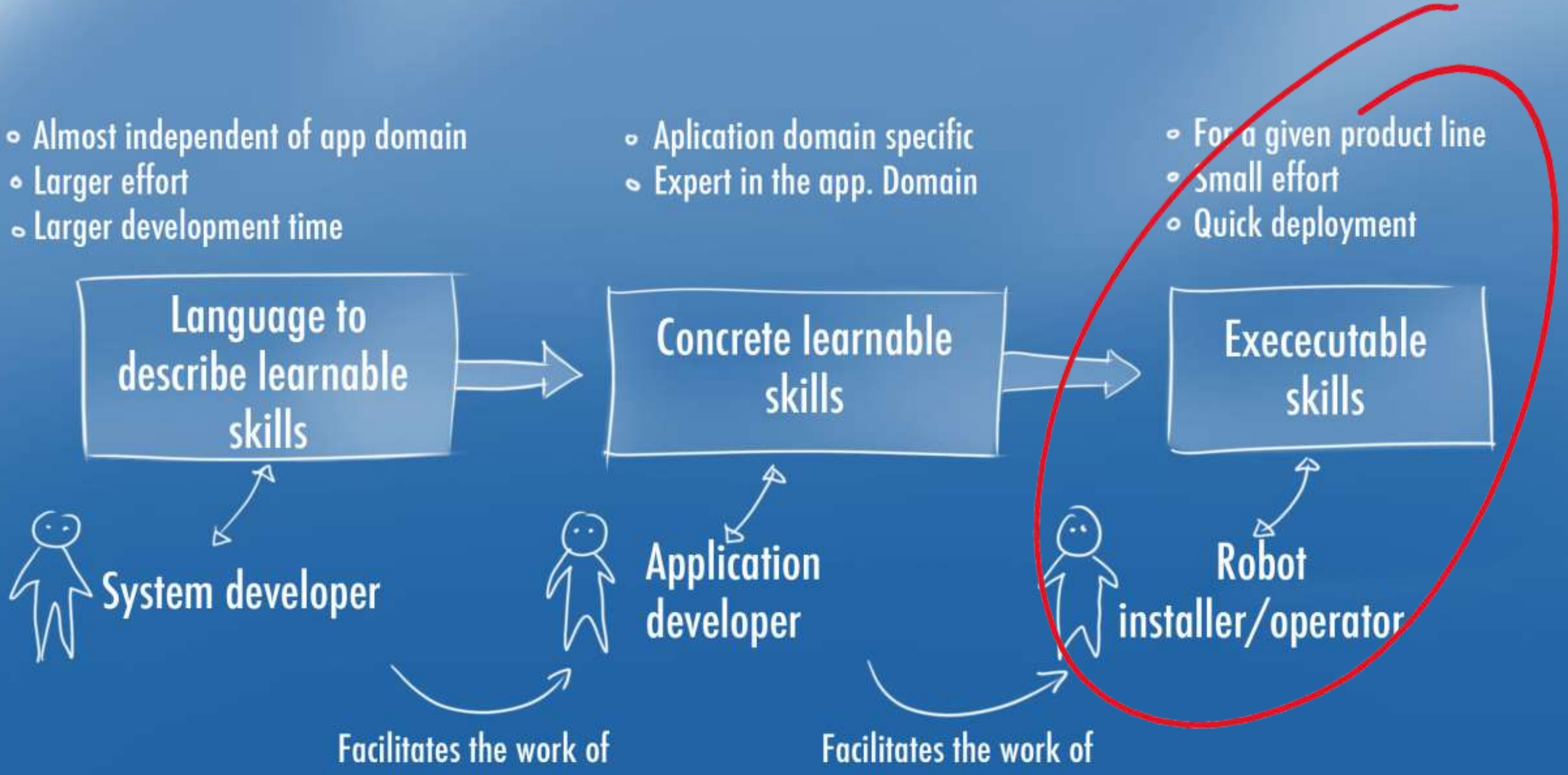
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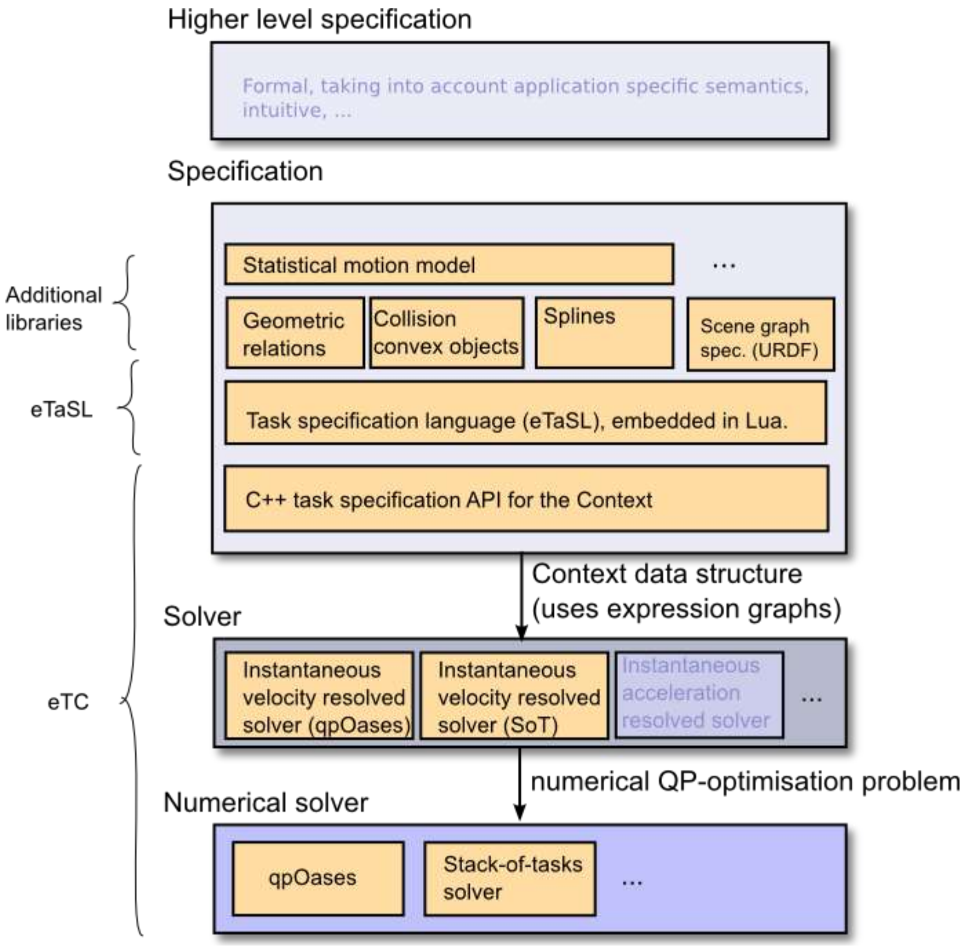
Available software

eTaSL Software

https://etasl.pages.gitlab.kuleuven.be/



The **separation of specification and controller implementation**

Specifications can be manipulated and assembled (even on-the fly if needed)

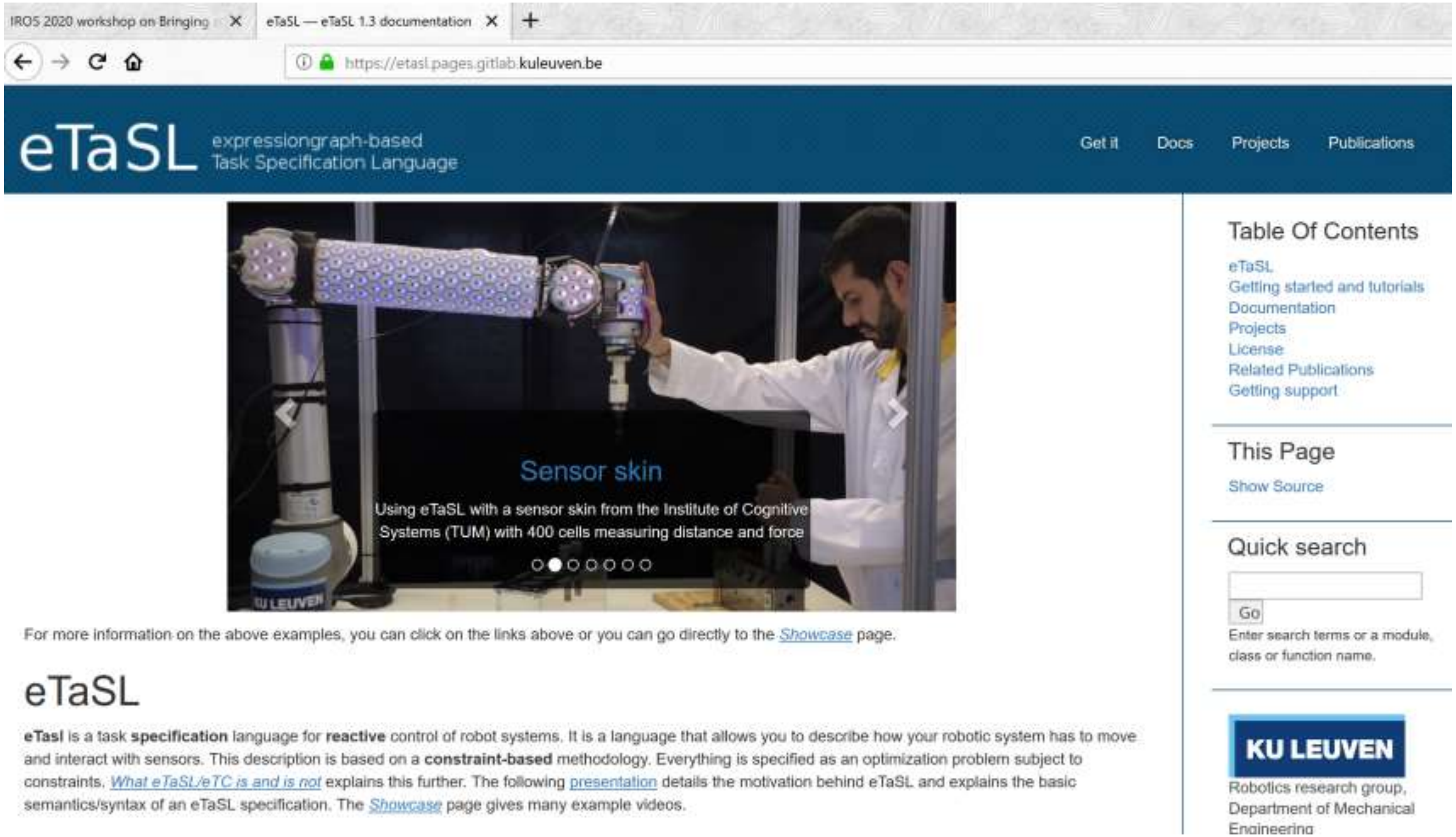
Layered approach:

- eTaSL is a library.
- a Python driver for quick prototyping
- ROS/OROCOS-RTT/eTaSL for more complete robot applications.

Libraries for all different types of constraints

eTaSL Software

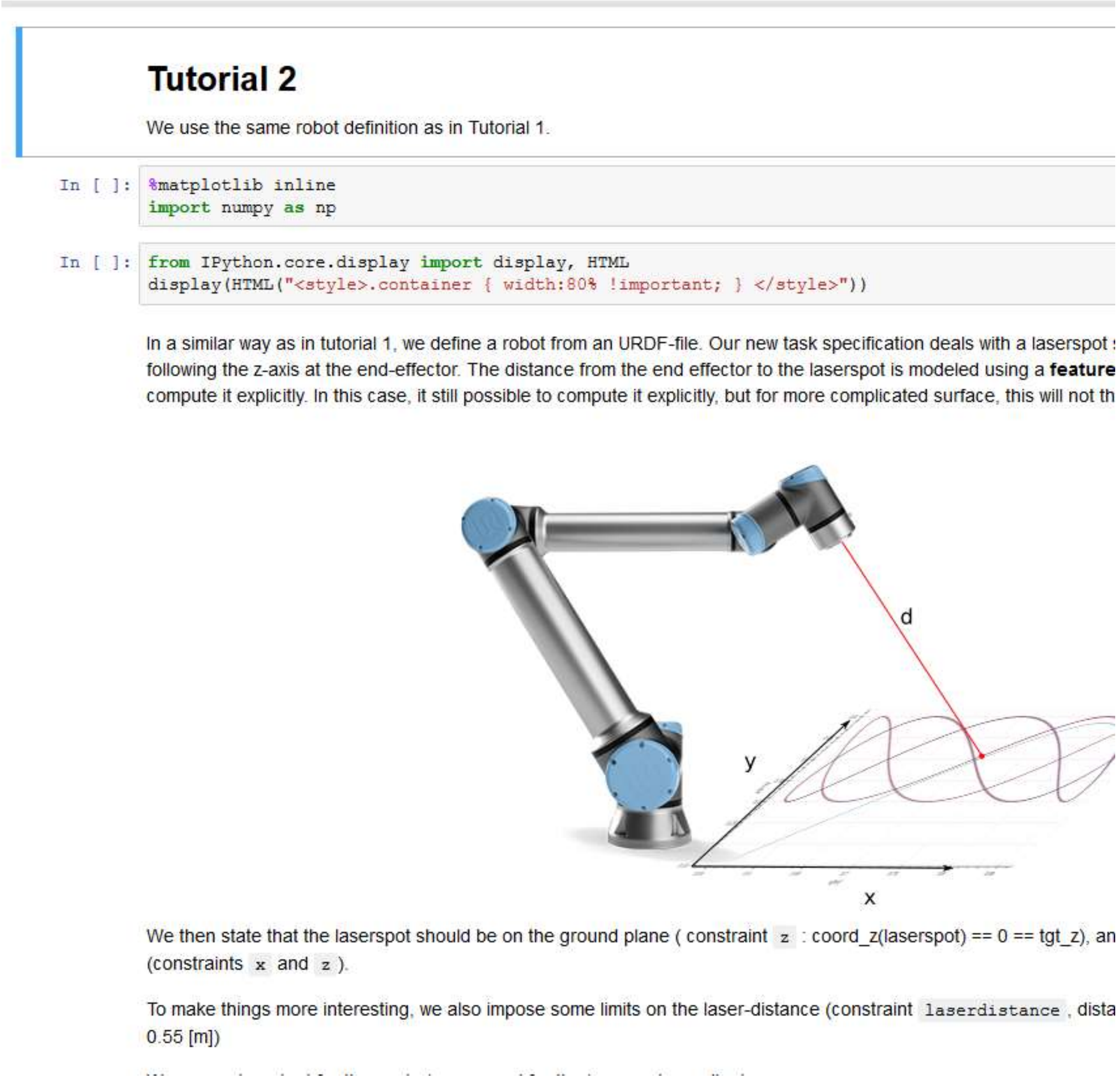
- https://etasl.pages.gitlab.kuleuven.be/



eTaSL Software

https://etasl.pages.gitlab.kuleuven.be/

- Two types of tutorials available:
  - 1. Python notebooks (via Binder)

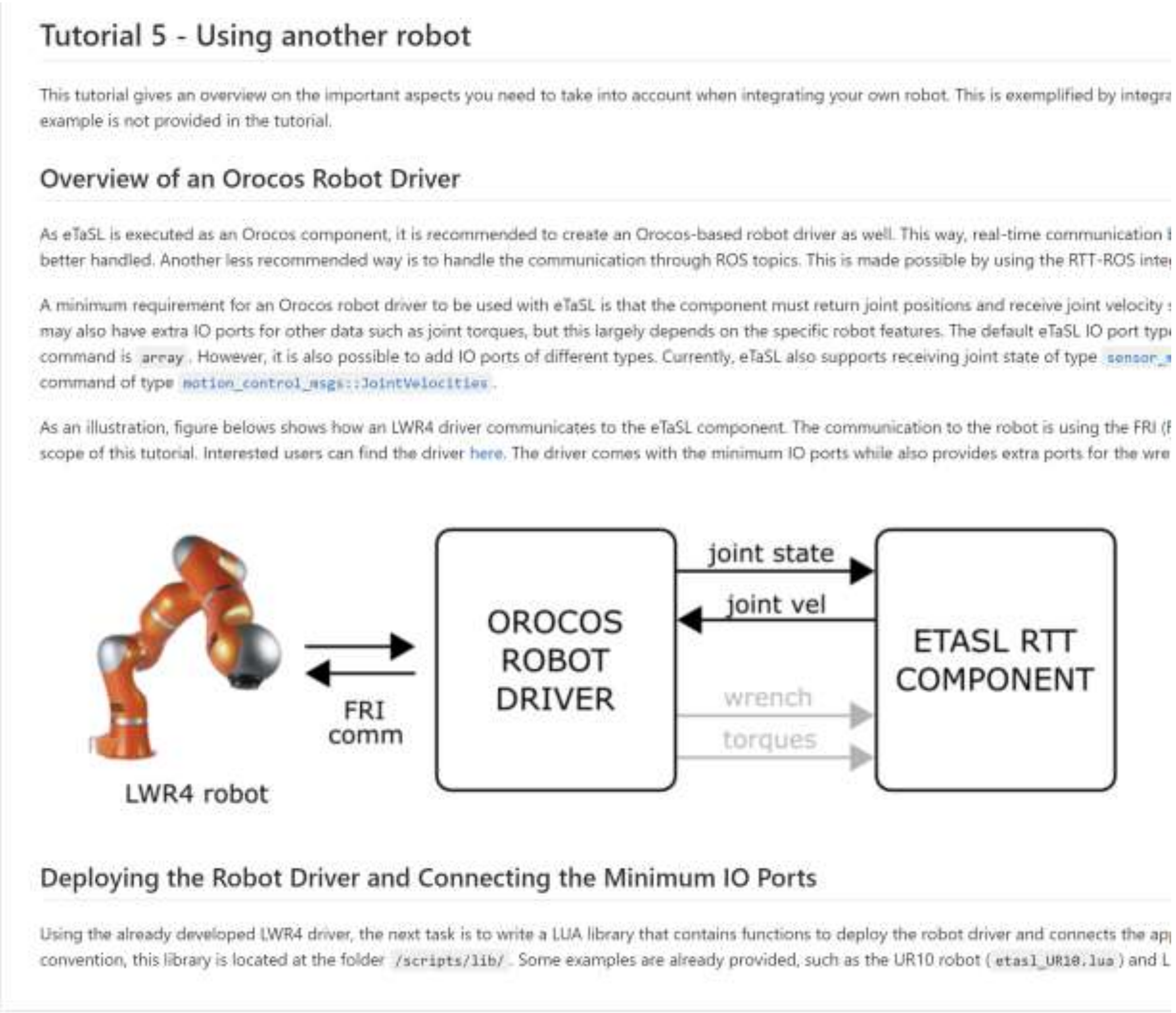


eTaSL Software

https://etasl.pages.gitlab.kuleuven.be/

- Two types of tutorials available:
  - 2. Full robot application example and template using ROS/Orocos/eTaSL

(Directly supporting: simulation, UR10, Kinova Gen 3, Franka Emika-Panda, KUKA-iiwa)


Tutorial 5 - Using another robot

This tutorial gives an overview on the important aspects you need to take into account when integrating your own robot. This is exemplified by integra
example is not provided in the tutorial.

Overview of an Orocos Robot Driver

As eTaSL is executed as an Orocos component, it is recommended to create an Orocos-based robot driver as well. This way, real-time communication i
better handled. Another less recommended way is to handle the communication through ROS topics. This is made possible by using the RTT-ROS inte

A minimum requirement for an Orocos robot driver to be used with eTaSL is that the component must return joint positions and receive joint velocity
may also have extra IO ports for other data such as joint torques, but this largely depends on the specific robot features. The default eTaSL IO port typ
command is `array`. However, it is also possible to add IO ports of different types. Currently, eTaSL also supports receiving joint state of type `sensor_`
command of type `motion_control_msgs::JointVelocities`.

As an illustration, figure belows shows how an LWR4 driver communicates to the eTaSL component. The communication to the robot is using the FRI (
scope of this tutorial. Interested users can find the driver here. The driver comes with the minimum IO ports while also provides extra ports for the wre

Deploying the Robot Driver and Connecting the Minimum IO Ports

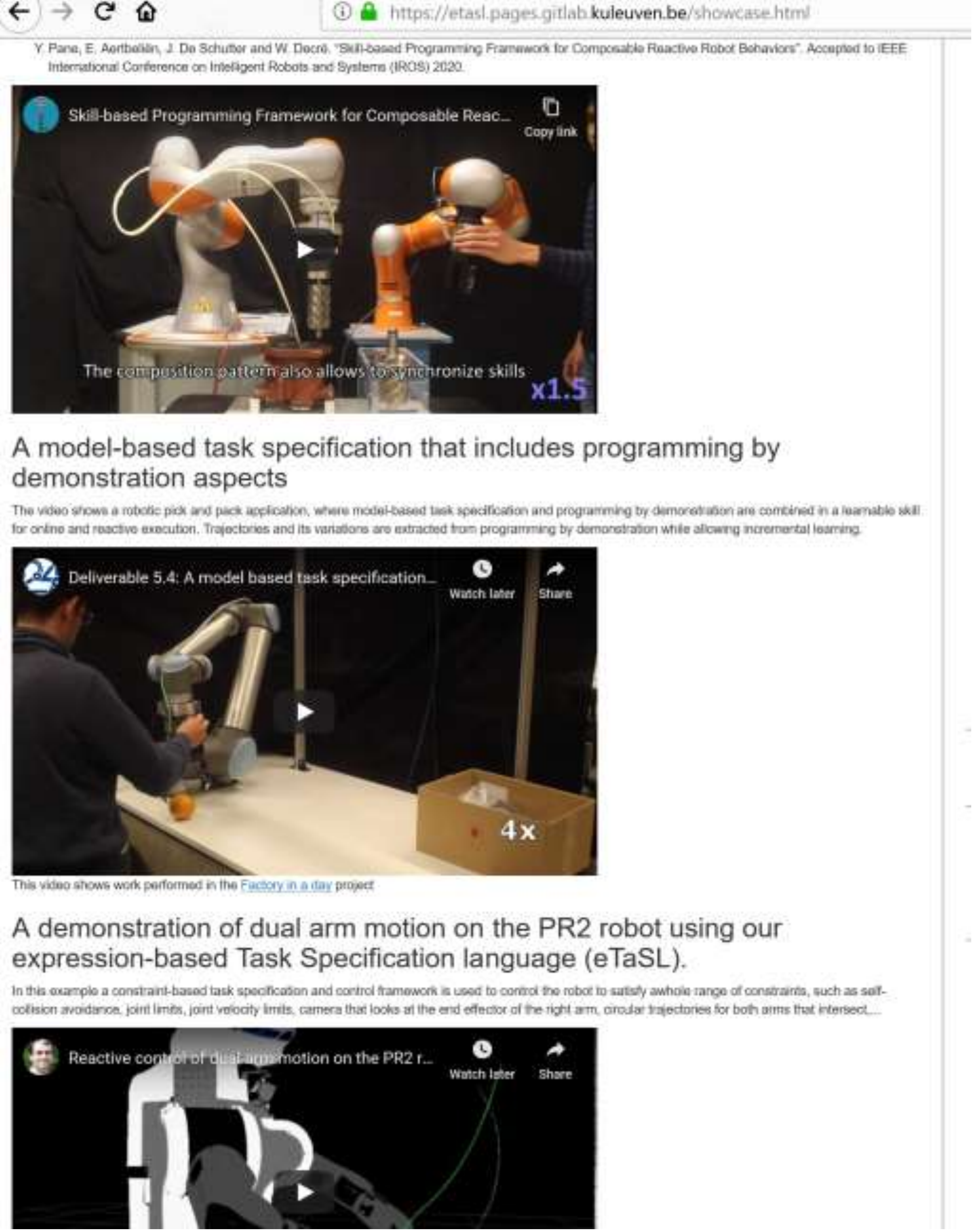
Using the already developed LWR4 driver, the next task is to write a LUA library that contains functions to deploy the robot driver and connects the ap
convention, this library is located at the folder `/scripts/lib/`. Some examples are already provided, such as the UR10 robot (`etasl_UR10.lua`) and L

eTaSL Software

https://etasl.pages.gitlab.kuleuven.be/

- Show-case of examples:

  https://etasl.pages.gitlab.kuleuven.be/showcase.html



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Acknowledgements

Erwin Aertbeliën

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Cristian Vergara

Santiago Iregui

Yudha Pane

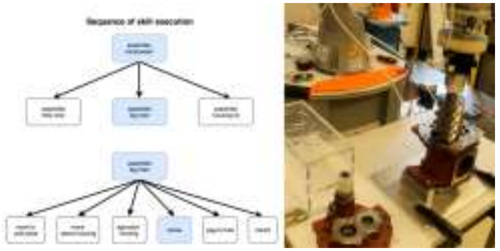
A list of publications related to this presentation:

https://etasl.pages.gitlab.kuleuven.be/pub.html

KU LEUVEN

Acknowledgements

EU-FP7 Robohow.cog

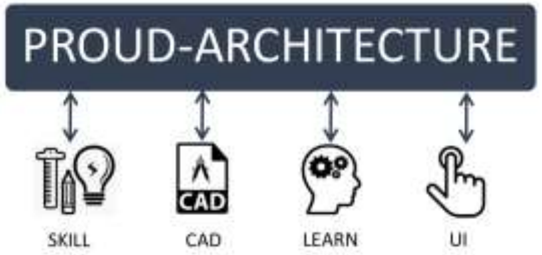


Flanders Make project
FINROP

EU-FP7 Factory-in-a-day

Flanders Make project
MULTI-ROB

EU-FP7 Echord++ - 3D Smart Sense and Control



Flanders Make project
PROUD

The Robotics research group of KU Leuven is a core lab of Flanders Make