





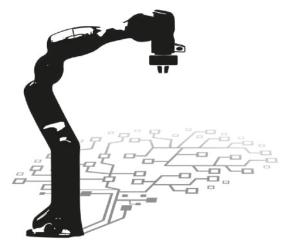
INCREASING THE CLOSED-LOOP DYNAMICS OF ROBOTICS RESEARCH

SAMI HADDADIN









Today





- Actual idea:
 - Defining what a robot should ideally be: standard Lagrangian dynamics (here)
 - Develop a reference platform: What do we want to have exactly?
 - Note:
 - I believe my argumentation holds for any robot type you want.
 - I am just taking the most basic form "robotics 1"



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- Use it to do research case study I: Learning dynamics
- Use it to do research case study II: Learning manipulation



Today

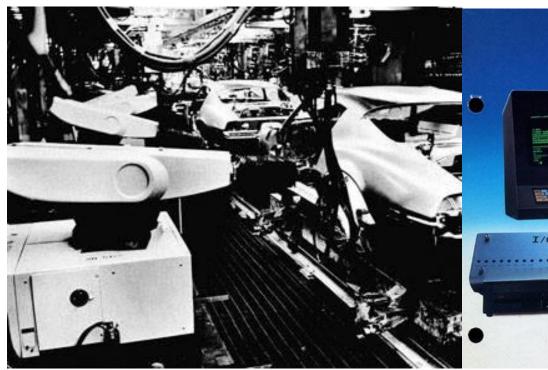
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The first robot generations

The first industrial robot George Devol & Joseph Engelberger in 50's

The first universally programmable robot Victor Scheinman at Unimation





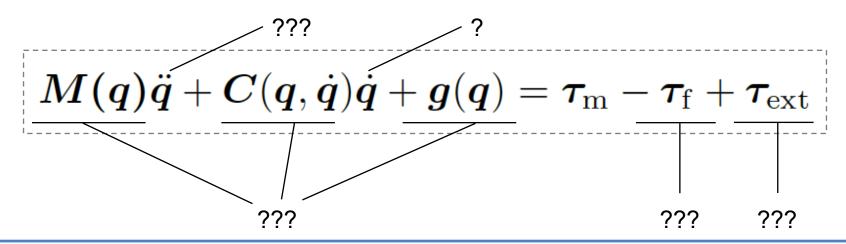


The ideal robot from "Robotics 1"

$$oldsymbol{M}(oldsymbol{q})\ddot{oldsymbol{q}} + oldsymbol{C}(oldsymbol{q},\dot{oldsymbol{q}})\dot{oldsymbol{q}} + oldsymbol{g}(oldsymbol{q}) = oldsymbol{ au}_{\mathrm{m}}$$



The robot from "Reality 1"



Fazit:

Let's do position control.

I hate friction identification anyways and no one needs models.

PID actually just works fine.



State of the art

www.electronicsb2b.com



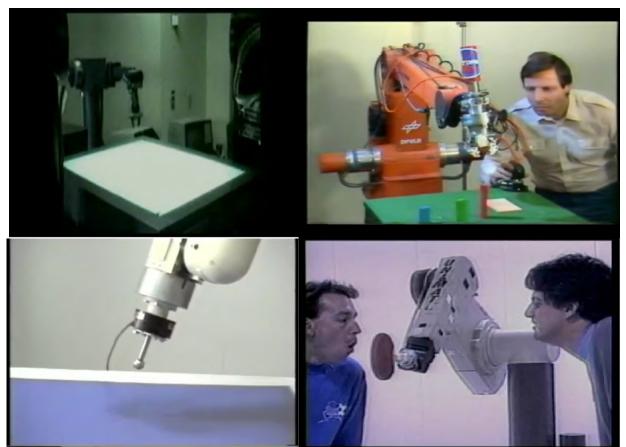
Spot welding and painting > 300k€ per robot installation Worldwide sales: 300k robots/ years

Chapter I

Develop a reference system

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The pioneers

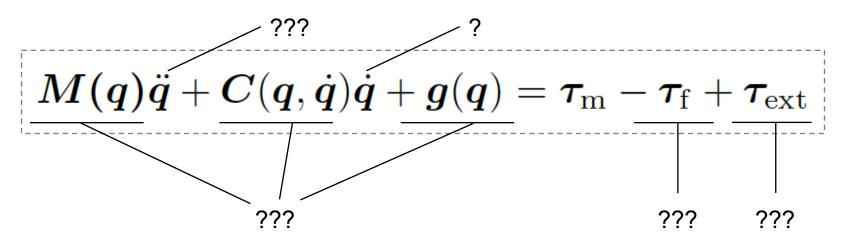






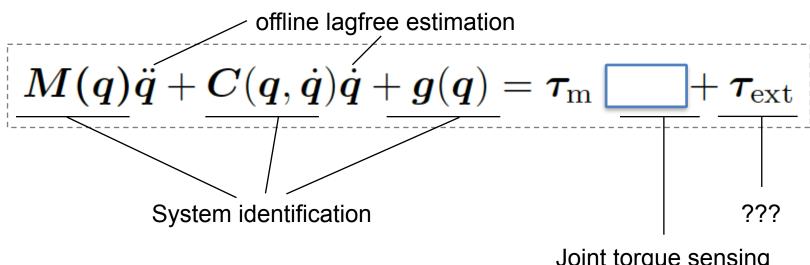


The robot from "Reality 1"





The robot from "Reality 1" to "Reality 2"



Joint torque sensing



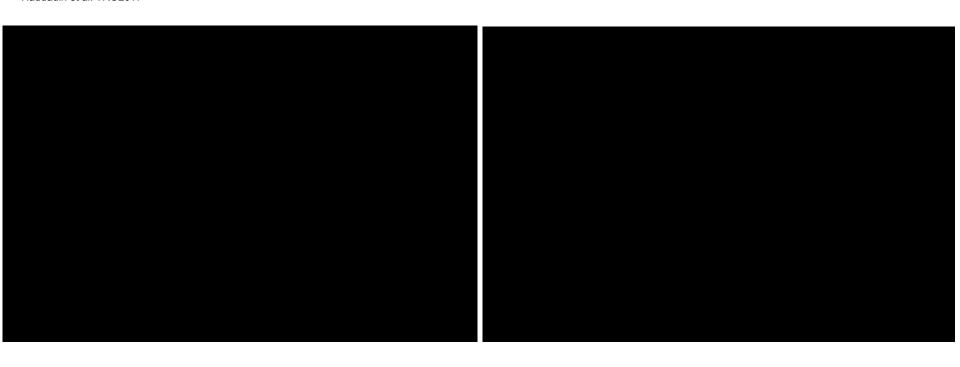
The robot from "Reality 1" to "Reality 2" to "Reality 3"



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Collision Handling

De Luca et al. IROS 2006 Haddadin et al. IROS 2009 Haddadin et al. TRO2017



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The Paper





Towards the Robotic Co-Worker

Sami Haddadin, Michael Suppa, Stefan Fuchs, Tim Bodenmüller, Alin Albu-Schäffer, Gerd Hirzinger

sami.haddadin@dlr.de Institute of Robotics and Mechatronics DLR e.V. - German Aerospace Center P.O. Box 1116, D-82230 Wessling, Germany

Summary. Recently, robots have gained capabilities in both sensing and actuation, which enable operation in the proximity of humans. Even direct physical interaction has become possible without suffering the decrease in speed and payload. The DLR Lightweight Robot III (LWR-III), whose technology is currently being transferred to the robot manufacturer KUKA Roboter GmbH, is such a device capable of realizing various features crucial for direct interaction with humans. Impedance control and collision detection with adequate reaction are key components for enabling "soft and safe" robotics. The implementation of a sensor based robotic co-worker that brings robots closer to humans in industrial settings and achieve close cooperation is an important goal in robotics. Despite being a common vision in robotics it has not become reality yet, as there are various open questions still to be answered. In this paper a solid concept and a prototype realization of a co-worker scenario are developed in order to demonstrate that state-of-the-art technology is now mature enough to reach this aspiring aim. We support our ideas by addressing the industrially relevant bin-picking problem with the LWR-III, which is equipped with a Time-of-Flight camera for object recognition and the DLR 3D-Modeller for generating accurate environment models. The paper describes the sophisticated control schemes of the robot in combination with robust computer vision algorithms, which lead to a reliable solution for the chosen problem. Strategies are devised for safe interaction with the human during task execution, state depending robot behav-



What is the goal?

Ideal I

Reference platform that is as highly capable, affordable and accessible

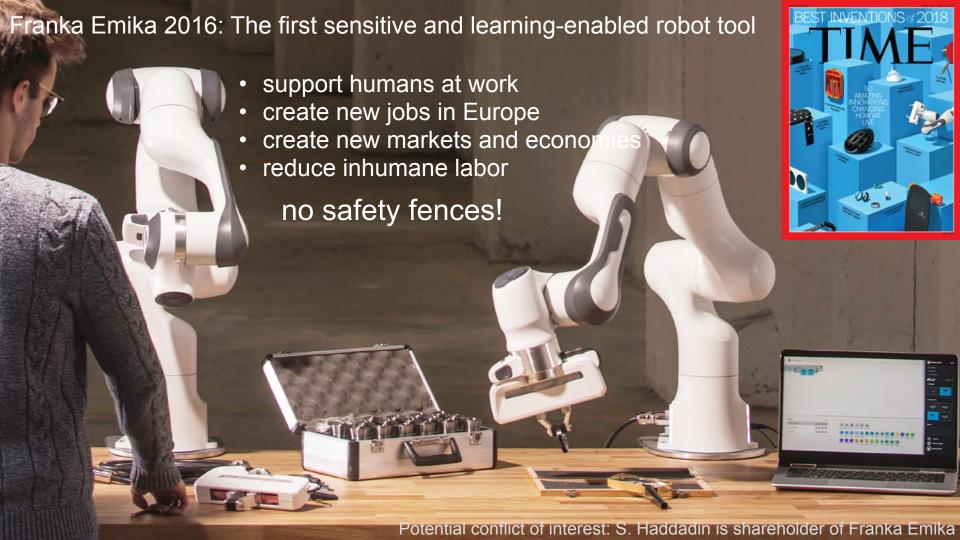
Ideal II

Behaves like Lagrangian dynamics and has the right interfaces

$$\boldsymbol{\tau}_{\rm in} = M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$$

Ideal III: HIGH PERFORMANCE

- Presumably is able to perform all reference skills (initially ambitious and grows along the lines or research ...)
- Joint torque (not current) interface
- Real-time control rate 1 kHz: joint torque / velocity, ...
- dexterity
- fast and accurate
- Precise torque, external torque and external wrench measurements << 1 N / Nm
- Dynamic models available < 2% error
- Precise position and velocity measurements < 0.1 mm



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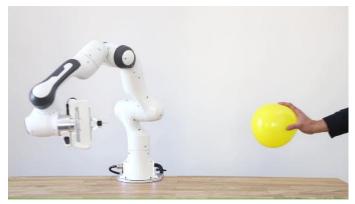
human like dexterity



sensitive assembly



safe reflexes



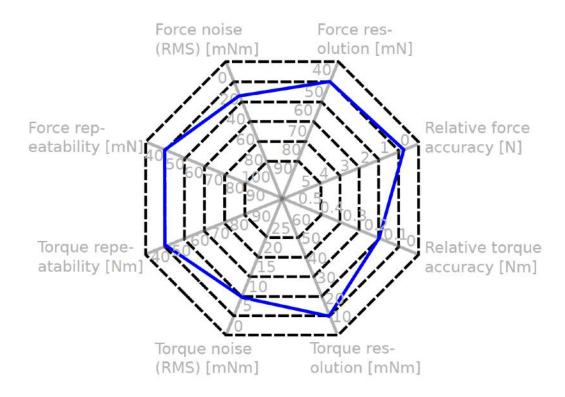
sensitive insertion







This is a new robot type. We need to redefine the robot data sheet





Redefining the robot data sheet

| HARDWARE | | | |
|----------------------------------|---|--|--|
| Arm | | | |
| Degrees of freedom | 7 | | |
| Payload | 3 kg | | |
| Workspace | see backside | | |
| Maximum reach | 855 mm | | |
| F/T Sensing | link-side torque sensors in all 7 axes | | |
| Expected nominal lifetim | e ^{3,4} 20,000 h | | |
| Joint position limits [°] | A1, A3, A5, A7: -166/166 A2: -101/101 A4: -176/-4 A6: -1/215 | | |
| Mounting flange | DIN ISO 9409-1-A50 | | |
| Installation position | upright | | |
| Weight | ~ 17.8 kg | | |
| Moving mass | ~ 12.8 kg | | |
| Protection rating | IP30 | | |
| Ambient temperature ² | 15 – 25 °C (typical) 5 – 45 °C (extended) | | |
| Air humidity | 20 – 80 % non-condensing | | |
| Power consumption | max. ~ 350 Wtypical application ~ 60 W | | |
| pro inpro inpro inpro co Co | nernet (TCP/IP) for visual intuitive ogramming with Desk out for external enabling device out for external activation device safeguard ontrol connector onnector for end-of-arm tooling | | |

Control

| Controller size (19") | 355 x 483 x 89 mm (D x W x H) |
|--------------------------------------|--|
| Supply voltage | 100 - 240 V _{AC} |
| Mains frequency | 47 - 63 Hz |
| Power consumption | ~ 80 W |
| Active power factor correction (PFC) | yes |
| Weight | ~ 7 kg |
| Protection rating | IP20 |
| Ambient temperature | 15 – 25 °C (typical) 5 – 45 °C (extended) |
| Air humidity | 20 - 80 % non-condensing |
| Interfaces | ethernet (TCP/IP) for internet and/or shop-floor connection power connector IEC 60320-C14 (V-Lock) Arm connector |
| | |



Redefining the robot data sheet

Motion Joint velocity limits [°/s] A1, A2, A3, A4: 150 A5, A6, A7: 180 Cartesian velocity limits up to 2 m/s end effector speed Pose repeatabillity <+/- 0.1 mm (ISO 9283) Path deviation 3 <+/- 1.25 mm Force

Sensing ³

| Force resolution | <0.05 N |
|--------------------------|-----------|
| Relative force accuracy | 0.8 N |
| Force repeatability | <0.15 N |
| Force noise (RMS) | <0.035 N |
| Torque resolution | <0.02 Nm |
| Relative torque accuracy | 0.15 Nm |
| Torque repeatability | <0.05 Nm |
| Torque noise (RMS) | <0.005 Nm |

1 kHz Control ³

| Minimum controllable force (Fz) | | 0.05 N |
|------------------------------------|--------------|------------|
| Force controller bandwidth (-3 dB) | | 10 Hz |
| Force range [N] | Nominal case | Best case |
| Fx | -125 – 95 | -150 – 115 |
| Fy | -100 - 100 | -275 – 275 |
| Fz | -50 – 150 | -115 – 155 |
| Torque range [Nm] | Nominal case | Best case |
| Mx | -10 - 10 | -70 – 70 |
| My | -10 - 10 | -16 - 12 |
| Mz | -10 - 10 | -12 - 12 |

| Interaction | | |
|---|---|----------------|
| Guiding force | | ~ 2 N |
| Collision detection time | | <2 ms |
| Nominal collision reaction time ^{3,4} | | <50 ms |
| Worst case collision reaction time ³ | | <100 ms |
| Adjustable translational stiffness | | 0 - 3000 N/m |
| Adjustable rotational stiffness | | 0 - 300 Nm/rad |
| Monitored signals | Joint position, velocity, torque Cartesian position, velocity, force | |

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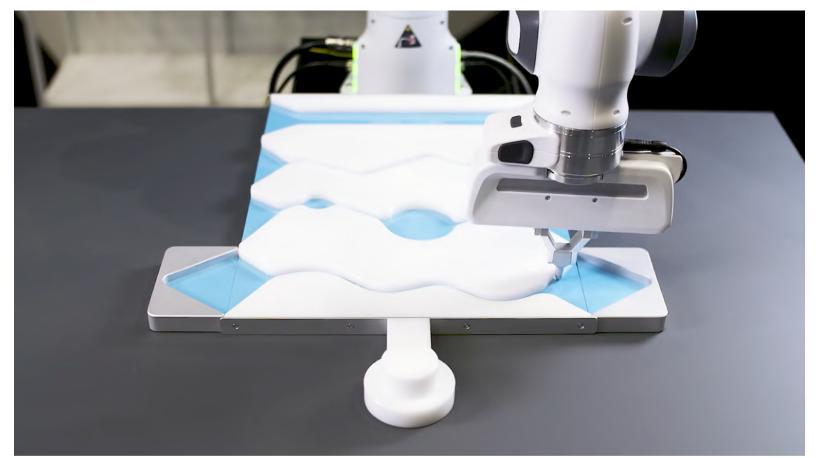
Force measurement without force sensor





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Impedance Control





ПШ

Force Control F_d = 7.8 N





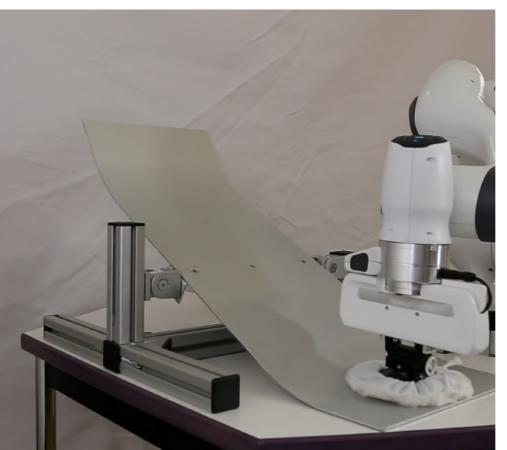
Munich School of Robotics and Machine Intelligence Technische Universität München

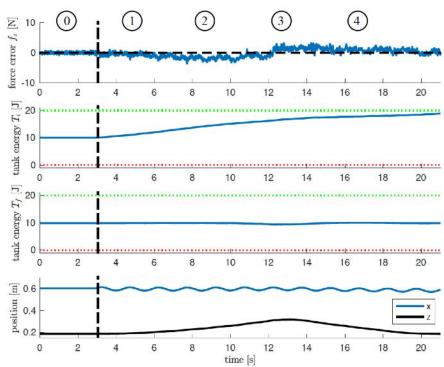
Wrench control with contact loss stabilization



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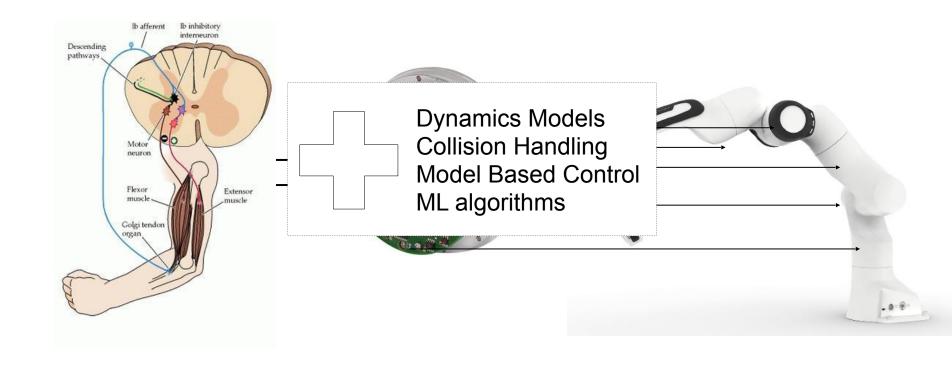
Force tracking





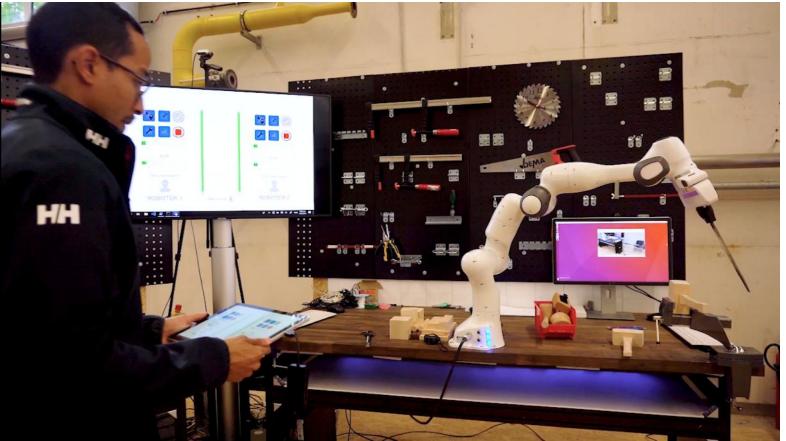


The key to sensitivity + manipulation



Human-Robot Collaboration 10 years after







Chapter II

Increasing Research Closed-Loop Dynamics



Why a reference platform?

Manipulation learning and control approaches are difficult to compare and validate.







Amazon picking challenge

So far: Benchmark tasks instead of skills



Why a reference platform?

Manipulation learning and control approaches are difficult to compare and validate.







Amazon picking challenge

Enable *objective comparisons* and reproducible results with a *reference platform This is not a one-time effort. This is a community mission!*



The reference system-skill loop

Community:
Set of reference
skills (What?)

Community:
Comparison metrics
(time, energy, force,...)

New technologies
Disruptive ideas

This is what I probably need.

Community:
Reference platforms

This is my new algorithm

- comparable to existing works
- papers at

Control and learning algorithms

This is what I can currently get:

New robots

- available
- capable
- affordable

International Conference on **Robotics and Automation**



ICRA Workshop: Bringing perception-based manipulation to the real world: standardizing robot manipulation learning















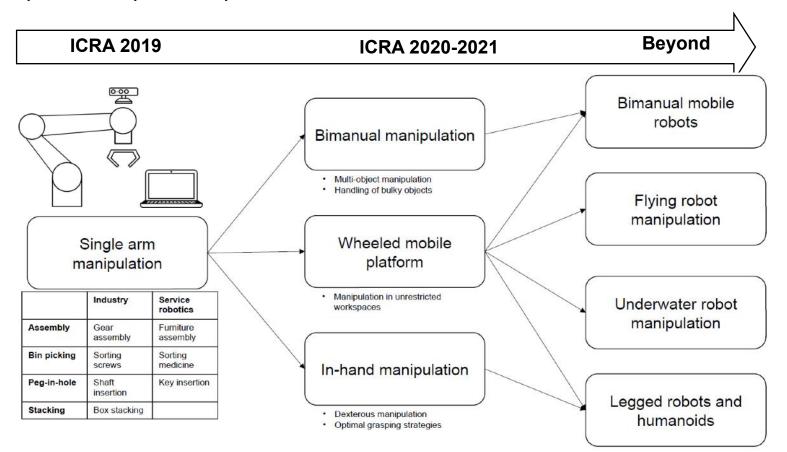








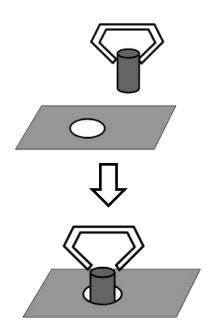
Roadmap for manipulation platforms and reference skills



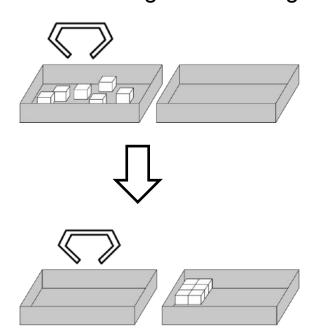


Industrial reference skills I

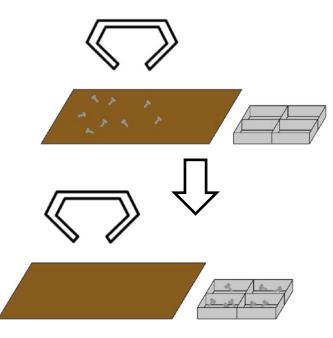
Shaft insertion



Sorting and stacking



Sorting screws





Industrial reference skills II

Gear assembly







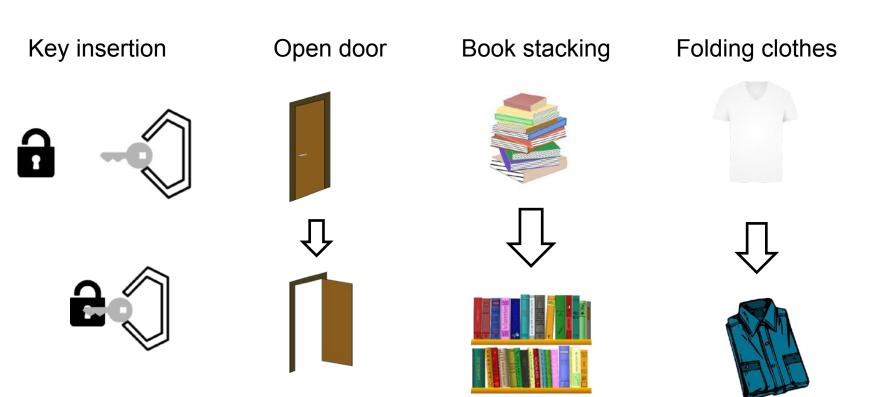
Cabling





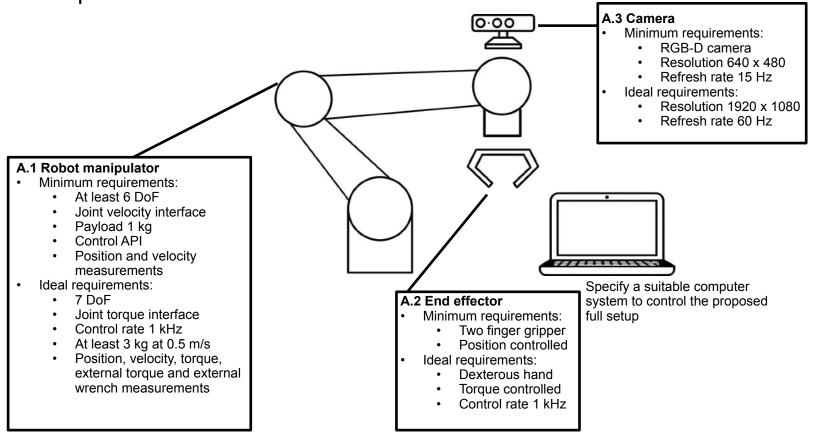


Household reference skills I





Platform requirements



Reference system submissions

on, juilet relocity (from position sensor casa) is, multi-famparature

P FRANKA EMIKA

Point cloud, depth image, RGB:

C++, Python (ROS)

| | | JRS + Wodular Grasper + Kinect | UR19 + Dexterous Hand Plus + Kiner |
|------------|--|--|---|
| | Price of every component from quantity 1 | Mobiler (I)major CICK URS for exademic E21.44. Kneet 6240. Ohms G078. | Cesterous Rand 1169 UR10 for academia £25.99k Minet 12761 Others: COTS |
| | Where avalable on g. US. EU. China, etc.) | Occuriy | Chibally |
| Hordware : | erfiguration | | |
| | How many parts in total | | 3 |
| | Power requirements (Average / Maximum) in Wotts | Man #50VK | Max 458W |
| | Cable corrections for any external devices | | |
| Semon | | | |
| | in rebot arm | Jeint position | Joint postion |
| | is robot gripper | dealt position, part velocity (from position sensor data), part longus, maillar femperature. | Joint position, just relocity (from point tendor force, restor temperature. |
| | in correct | Point cloud, depth image, PCB image | Point cleud, depth image, RGB image |
| | Additional sensors | Tactile sensor options | Tautte sensor optore |
| Low-level | | | |
| Team or | Bolt command of values at every interface cycle) | | |
| | API language(s) (s.g. C++, Python, Java) | G+1, Python (ROB) | C++: Python (ROE) |
| | Interface thecuency (read and write) in His | Modular Grouper Hinto UR-6: 12546 | Frank Place 1995 UR-00: 12540 |
| | Command level (s.g. Position/Volacity/Torque, John space / Carleson space) | Modular Graquer Joint troque (§ 144) from host (§ 1504) resemble long on sQL, Joint position (§ 1414 1916 5 Joint produce velocity (§ 1558) Movemberg stop or product activates path presenting and recording for and effective. | Frank Plan: Joint prostlers @ 1492. Fand from trast (@SkPiz internation) on util UR-37. Jeef postlers/valuely @ 12946 Movet integration provides (arterian pa securities for and official). |
| | Rebot state: What data is available via the interface, e.g. q set do? | Arms Joint position, Joint velocity | Arms Joint position, Joint |
| | | | Fixed URDF model is use MHQ.Elso. |
| | Gr Jearning | A 2019 Workshop on Bringing perception-based manipulation to the real world: standardizing robot manipulation in a second | |
| | | No many | |
| | UEARNING PLATFORN: URSe + rc Visard + End effector (Sc | LEASMING PLATFORM: URSe + rc Visard + End effector (Schmaiz Cobot - Robotic gripper - Schunk gripper) | |
| | The DATASHE | DATASHEET | |
| | P) | •• | DirecCAT (Hand Floo), 7 |
| | M . | | Z awaitabne restwork pertis |

KINOVA* Gen3 Ultra lightweight robot Fact Sheet

Franka Emika Al Platform Main Specifications Proposal for standard manipulation learning platform by Franka Emika and NVIDIA



COMPONENTS AND AVAILABILITY:

| Robot manipulator: URSe (Universal Robots) | Worldwide | |
|---|---------------|--|
| Vision: rc_visard 160 (Roboception) | EU / Americas | |
| End effector – option 1: Vacuum generator ECBPI (Schmult) | Worldwide | |
| End effector – option 2: Robotiq 2F-85 (Robotiq) | Worldwide | |
| End effector—option 3: Schunk Co-Act gripper | Worldwide | |

Price final price of each component is provided by the corresponding manufacturer. Final prince depends on the options chosen for each product and the geographical location (local currency/exchange rate/customs)

All hardware has a BRGaps package for communication with the robot manipulator.

| Price of every component | Panda Robot (including Arm, Hand and controller with FCI interface, without taxes) | € 15.500 |
|--------------------------------------|--|---------------|
| | Carriera, e.g. Intel RealSense D435i | €2004 |
| bore see see see | Computer, e.g. Neidia Jesson Xavier | €1.342 |
| Where is it available? | All hardware components are available globally. | |
| Hardware configuration | | |
| How many parts are there in tota? | (Arm, Hand, Mount, Camera) + Controller + Computer | - 3 |
| Power requirements | (Average / Maximum) | (140 / 430) W |
| Cable connections | Controller power cable + controller-robot cable + controller-computer cable + computer power cable | |
| Sensors | and the second s | |
| In robot arm | Dedicated position, current and torque (link-side) ser- sors in all 7 joints | |
| In robot gripper | Position and force (via current) sensing | |
| In carriera | The Intel Real Sense offers complete depth cameras in- tegrating vision processor, stereo depth module, RGB sensor with color image signal processing and Inertial Measurement Unit (IMU) | |
| Additional sensors | | |
| Low-level interface | | |
| API baguage(s) | Oper Source C++ library with official integration into MATLAB Simplink, RCS, Movelt1 and NVIDIA Issac | |
| Interface frequency (read and write) | | 1000 Hz |
| Commano level | Joint position, joint velocity, cartesian pose, cartesian velocity and torque control | |
| Robot state | Joint level signals: motor and estimated joint angles and their derivatives, joint torque and derivatives, estimated external torque, joint collision/contacts | |
| | Cartesian level signals: cartesian pose, configured end effector and load parameters, external wrench acting on the end effector, cartesian contains | |
| Model | Numerical values of M. C. G. J are available at 1 kHz | |
| Gripper commands | Gripper width, velocity and grasping force | |
| Gripper state | Gripper width and force | |
| Gripper access | Gripper is accessed via TCP/IP-based commands, not in real-time. | |
| Hareware connection | Ethernet cable, using the Franka Control Interface | |
| Protecol | UDF-based | |
| Minimum PC requirements | Linux with PREEMPTLRT patched kernel, 100BASE-TX network card | |

1. ICRA 2019 promotional price (Europe), valid until June 30th, 2019.

2. Reference price from the manufacturer's web store.

Call for platforms Standardizing robot manipulation learning http://www.nismi.tum.de/en/rsi/cra19_workshop

Fact Sheet

SCHUNK platform for Robot manipulation learning



ecotion-based manipulation to the real world: standardizing robot manipulation learning

TIAGo

versatile and scalable mobile manipulator with integrated perception and Al capabilities

FACT SHEET

PAL Reportion S.L.



r@de.schunk.com



ntrolland ROSidevers

ar howith 1 en sobot and groose: or currently controlled gripper

also with KD down abowth FDS diver 2 adapters





Starting at 48,000 €

Europe, Asia, Japan, US, Latin America.

- 2x 20 Ah 36 V battery packs (8-10h autonomy) Charging at 100-240 VAC with external charger (40.8 V 8 A) connected to:
 - Manual plug on the robot Dock Station (automatic charging)
- Expansion ports:
- a 2x USB

KINDVA

Low-level interface

- · 2x GigE
- o 1x 12 V 5 A power supply CAN Service port
- . Laser rangefinder 5.6 / 10 / 25 m range
- . 6 DoF IMU in the base . Sensor currents at each arm and gripper joints.
- . ATI mini45 6-axis Force/Torque sensor on the wrist Endoscopic camera on oripper
- . Orbbec Astra / Astra S / Astra Pro in head
- . API language(s): ROS API (C++, Python) Interface frequency: 100 Hz
- Command level: Position / Velocity / Torque
- Joint space / Cartesian space · Robot state: q, dq, effort (current consumption), temperature Model available at 100 Hz (computed by RBDL from URDF)
- · Gripper commands: position, max current
- . Gripper state: aperture, current consumption, temperature · Gripper access frequency: 100 Hz
- Hardware connectivity:
 - Ethernet o Wi-Fi
- Protocol: TCP/IP
- · Minimum requirements external computer:
 - Any computer ready to run Ubuntu 16.04 + ROS Kinetic
 - NVIDIA GPU recommended for graphical visualization purposes



What is the (first!) GPU in Robotics?



-

Chapter III

Robot Learning: Dynamics



Standard Problem: Learning Dynamics (never worked)

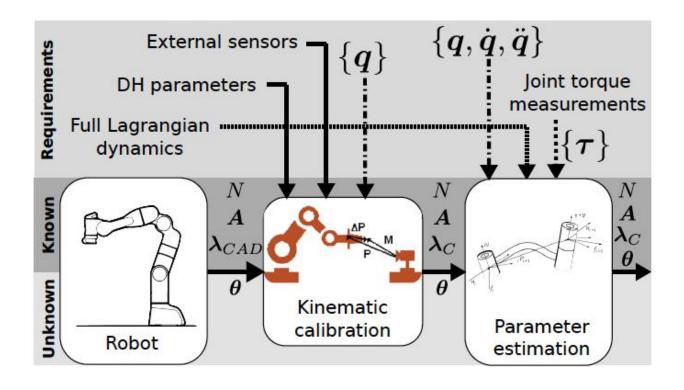
CAN WE LEARN ROBOT DYNAMICS?

$$oldsymbol{M(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)= au_{\mathrm{m}}}$$



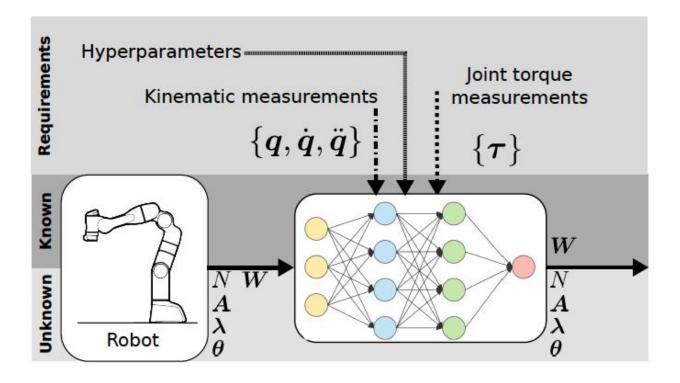


System identification





Neural Networks based





Typical challenges in neural networks

- Approaches rely on approximation capabilities of the specific network
- Weights usually no physical meaning
- Only little leveraging of available system knowledge
- Architecture choice depends on skilled human architect
- Generalization requires training sets to cover vast regions of input-output space

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ROBOT DYNAMICS: LINEAR REGRESSION FORM

Overall energies: $T = \sum$

$$T = \sum_{j=1}^{n} T_j$$
 & $U = \sum_{j=1}^{n} U_j$

Lagrangian function:

$$L = T - U$$

Euler-Lagrange equation:

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\boldsymbol{a}}} \right) - \frac{\partial L}{\partial \boldsymbol{a}} = \boldsymbol{\tau}$$



$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = au_{
m m}$$







ROBOT DYNAMICS: LINEAR REGRESSION FORM

Overall energies:

$$T = \sum_{j=1}^{n} T_{j}$$
 & $U = \sum_{j=1}^{n} U_{j}$

Lagrangian function:

$$L = T - U$$

Euler-Lagrange equation:

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{a}} \right) - \frac{\partial L}{\partial a} = \tau$$



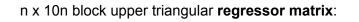
n-D input joint torque vector

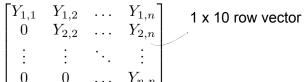


10n-D inertial parameters vector:

$$X^T = [X_1^T, \dots, X_n^T]$$

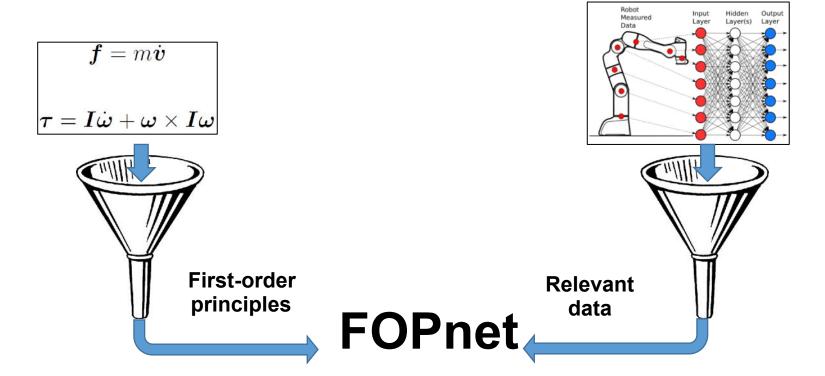
 $\boldsymbol{\tau} = Y(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})X$





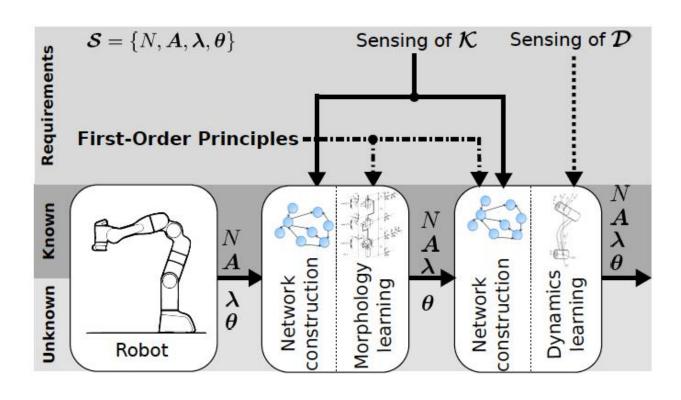
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IDEA FOPnet



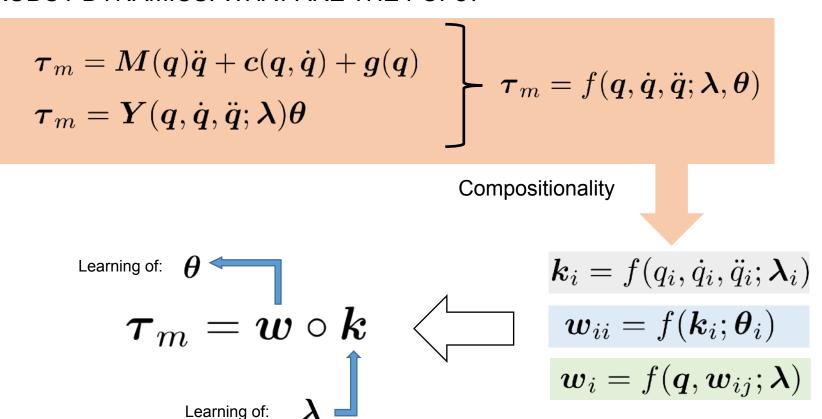


First-Oder Principles Network



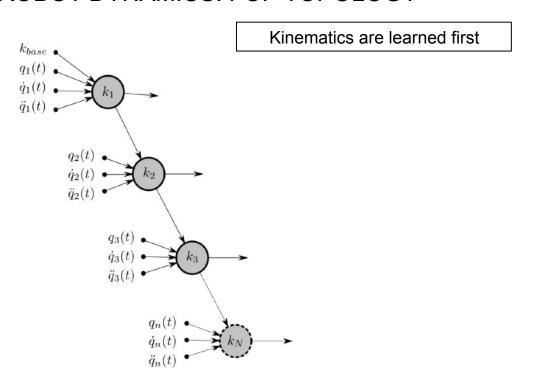


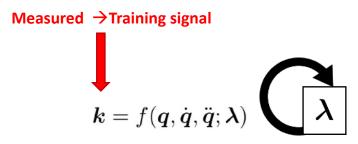
ROBOT DYNAMICS: WHAT ARE THE FOPs?





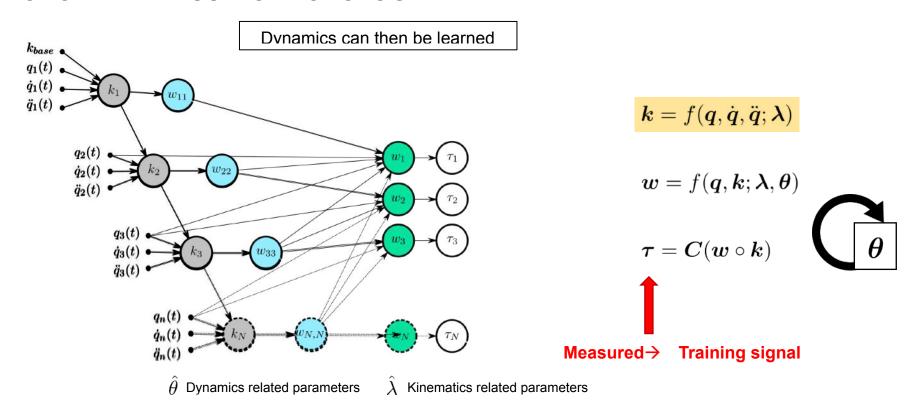
ROBOT DYNAMICS: FOP TOPOLOGY







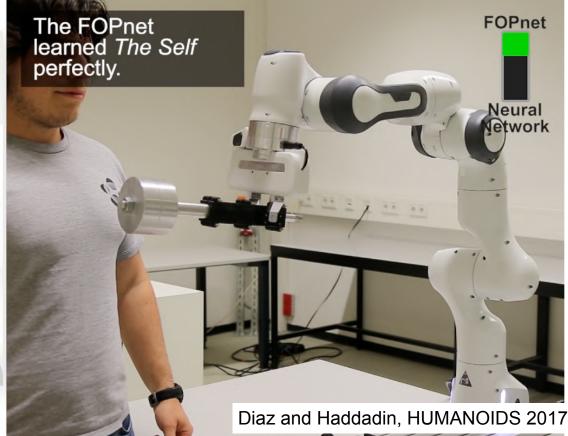
ROBOT DYNAMICS: FOP TOPOLOGY





LEARNING THE SELF (i.e., Kinematics and Dynamics)





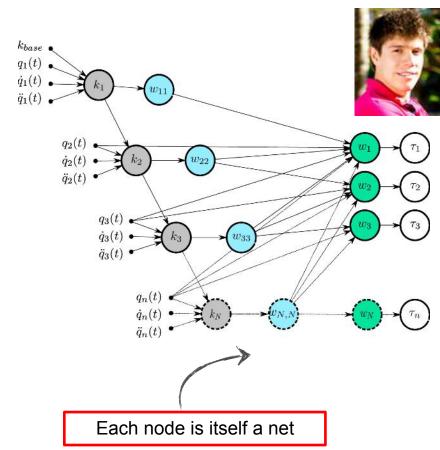


ТΙΠ

Constructive architecture

- NE-formulation used for network structure
- Three subnetworks:
 - Kinematics network (gray): links rigid body velocities and accelerations
 - Self-dynamics network (blue): wrench due to link inertial parameters
 - 3. Inter-dynamics network (green): includes wrenches from succeeding links

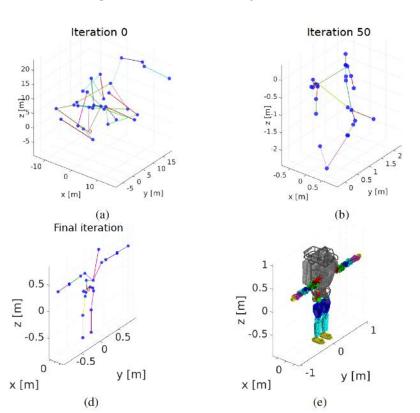


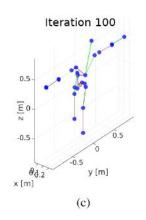


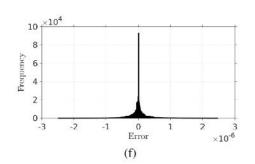
Diaz & Haddadin, Humanoids 2017

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Learning Humanoid Dynamics



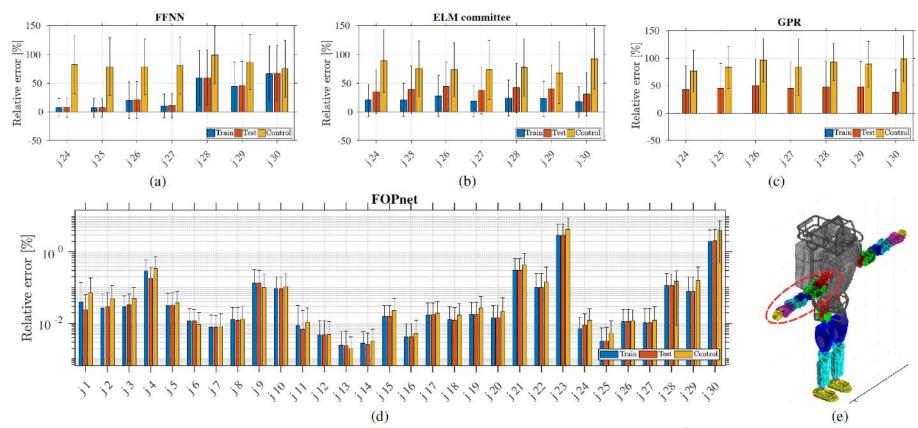








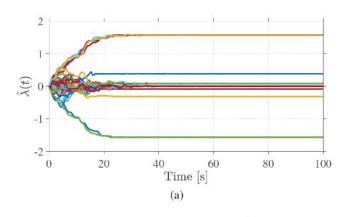
Learning Humanoid Dynamics

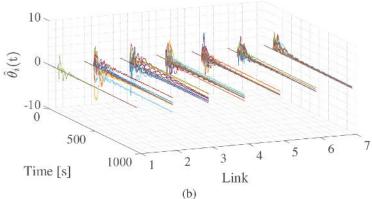


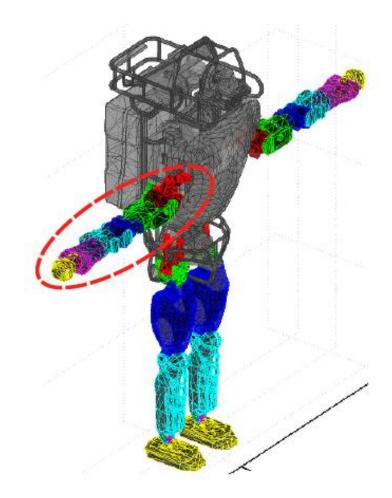
Diaz & Haddadin, Humanoids 2018

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Learning Humanoid Dynamics







Diaz & Haddadin, Humanoids 2018

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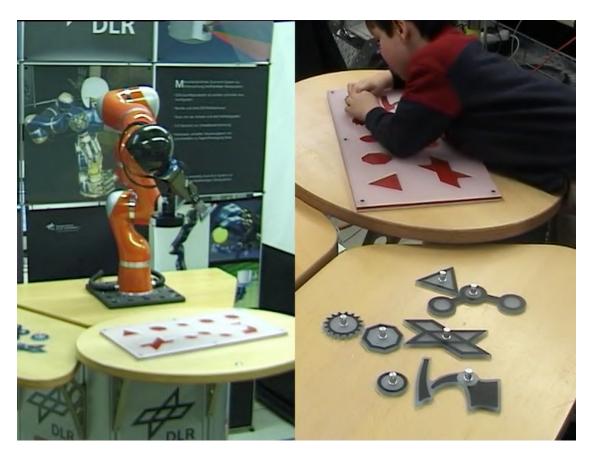
Chapter III

Robot Learning: Manipulation



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The DLR Papas experiment





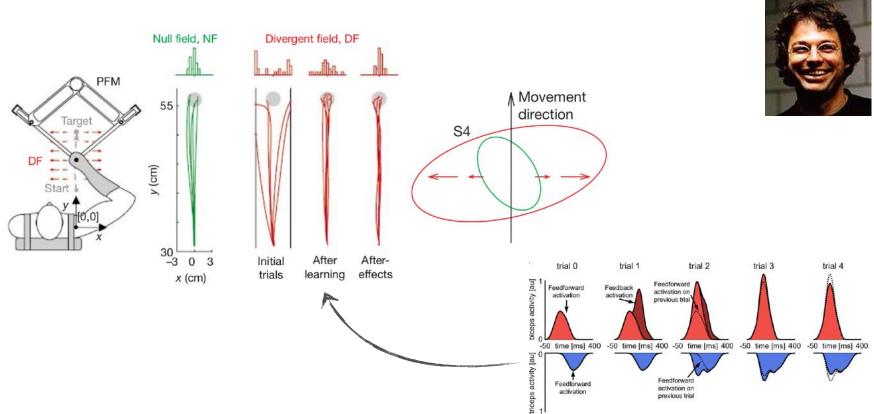


Andreas Stemmer & Paolo Robuffo Giordano, DLR

Burdet, E., Franklin, D. W., motor control. MIT press.

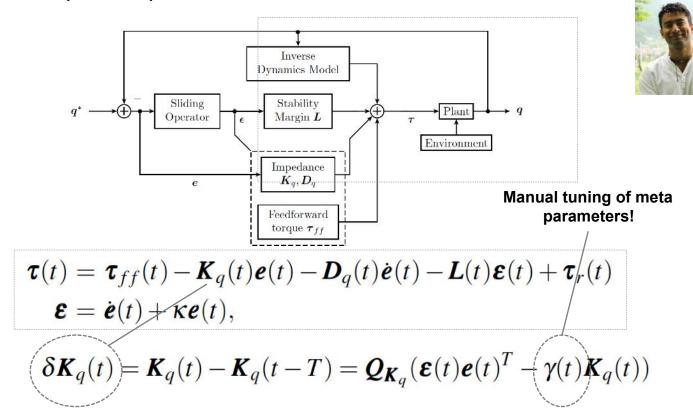
T. E. (2013). Human robotics: neuromechanics and







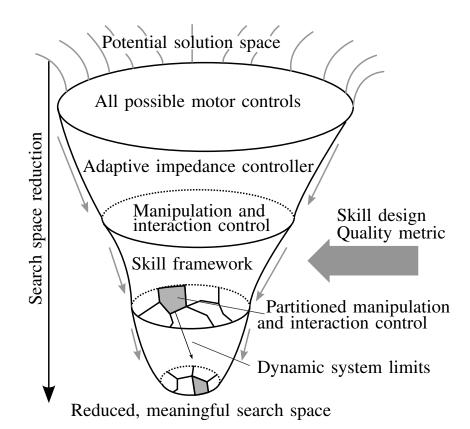
Bio-inspired adaptive impedance control







Skill framework I









Learning peg in hole

The system including adaptive control and meta learning runs on a micro-PC.





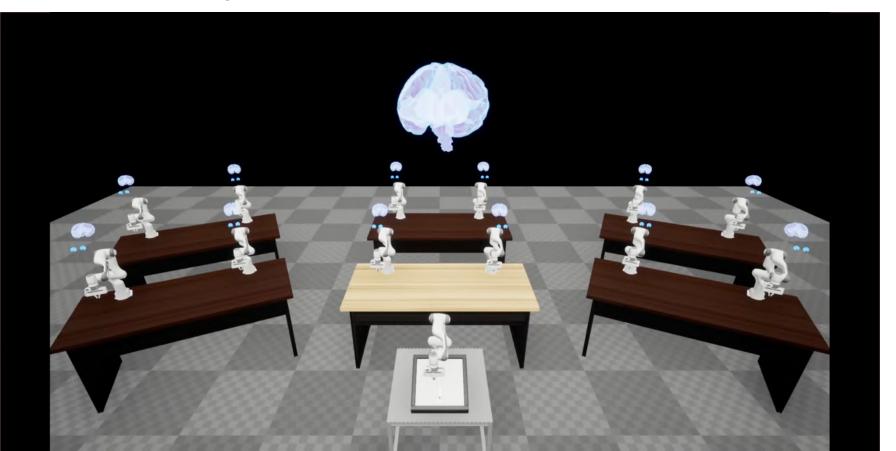


Collective Learning: "n robots learn m keys"



ТШП

Collective Learning









































































THANK YOU VERY MUCH!

GEFÖRDERT VOM







Deutsche Forschungsgemeinschaft

Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie















Die Stimme der Hochschulen