Lecture 02
Cobot Design

Song Chaoyang
Southern University of Science and Technology

A Review of Robot Design Towards Collaboration

A Historical Note on Collaborative Robots

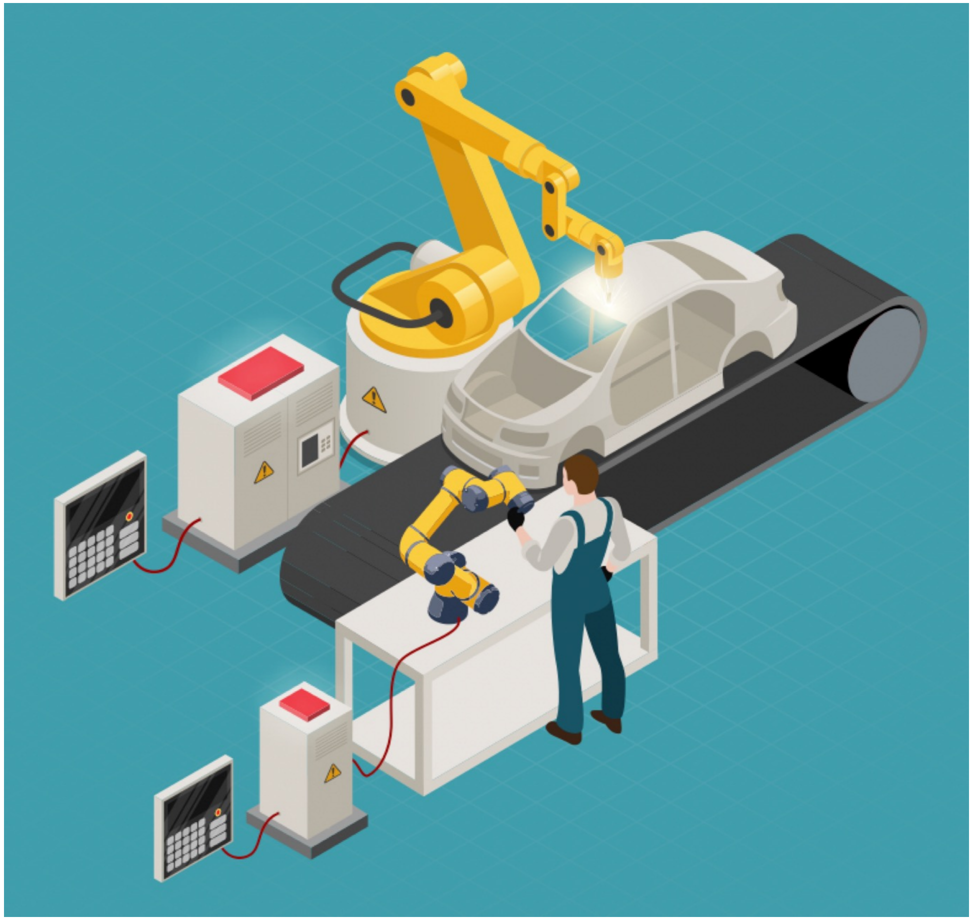
Examples of Engineering Specifications

Today's Agenda

Factory Robot
vs.
Collaborative Robot

Factory Robot vs. Collaborative Robot

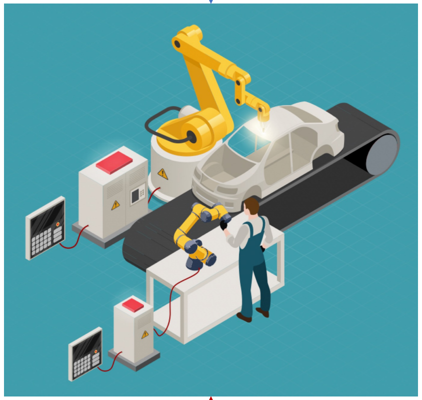
From engineering need to design specifications



Factory Robot vs. Collaborative Robot

From engineering need to design specifications

- Factory robots perform automated programmable movements in manufacturing.



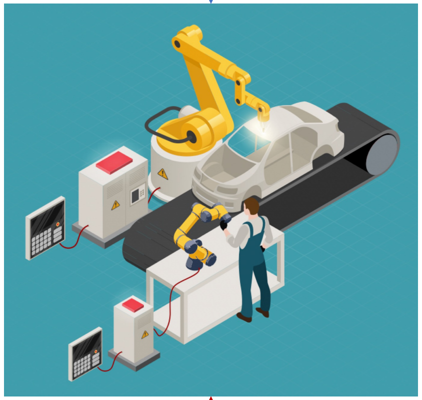
- Cobots work side by side with humans to improve work quality.

Factory Robot vs. Collaborative Robot

From engineering need to design specifications

- Factory robots perform automated programmable movements in manufacturing.

- Mechanical or sensor technologies can help keep factory robots from interfering with human activity.

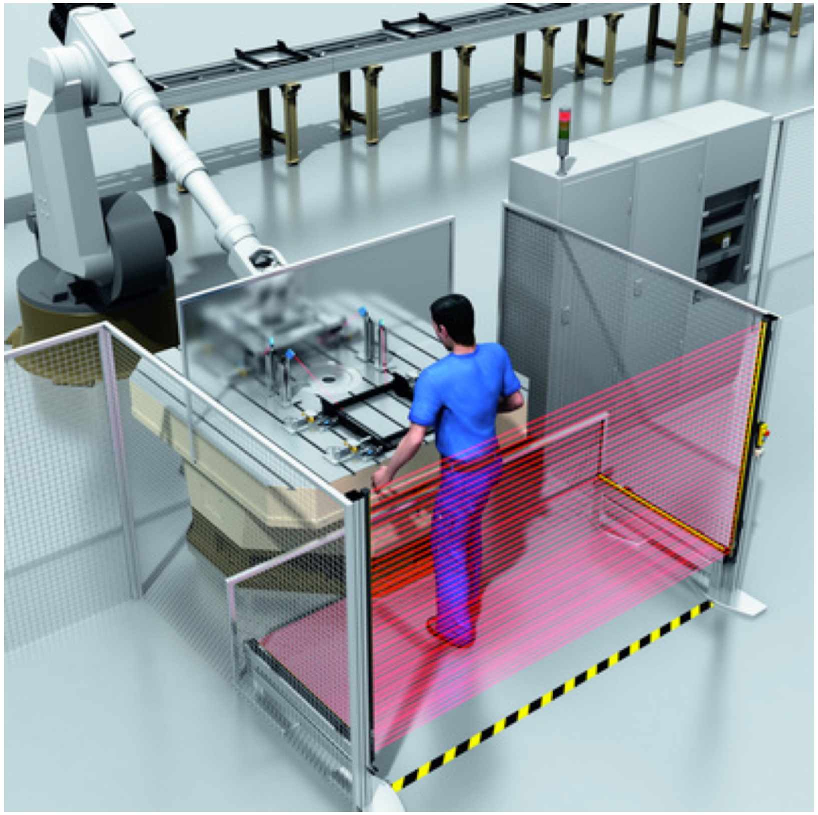


- Cobots work side by side with humans to improve work quality.

- A cobot can sense and stop movement, helping create a safer working environment.

Towards a Safer Working Environment

Mechanical or sensor technologies can help keep robots from interfering with human activity

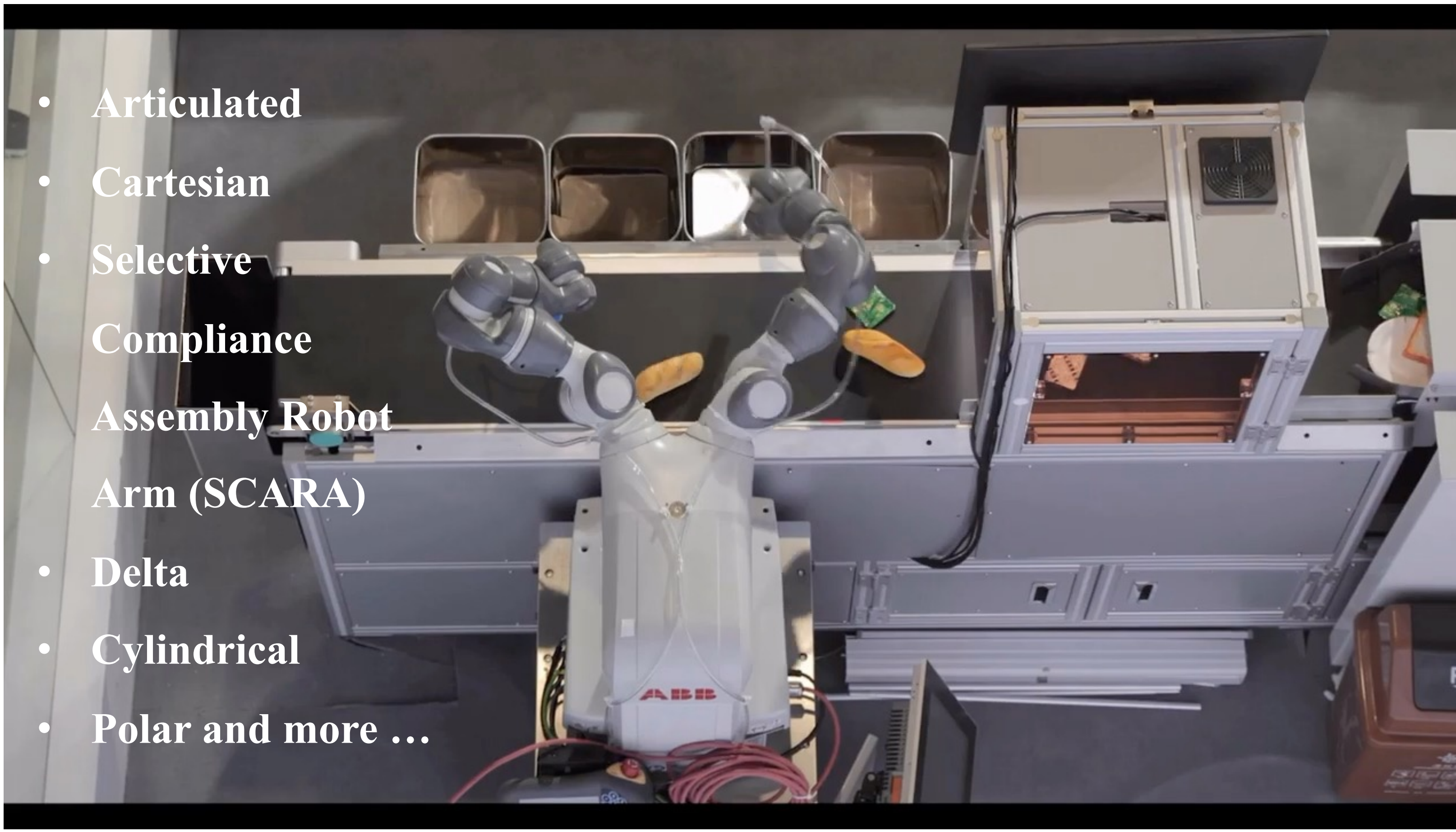


Common Designs of Robot @ Work

Task-specific Structure

Common Designs of Robot @ Work

Different robot types have different advantages depending on the application

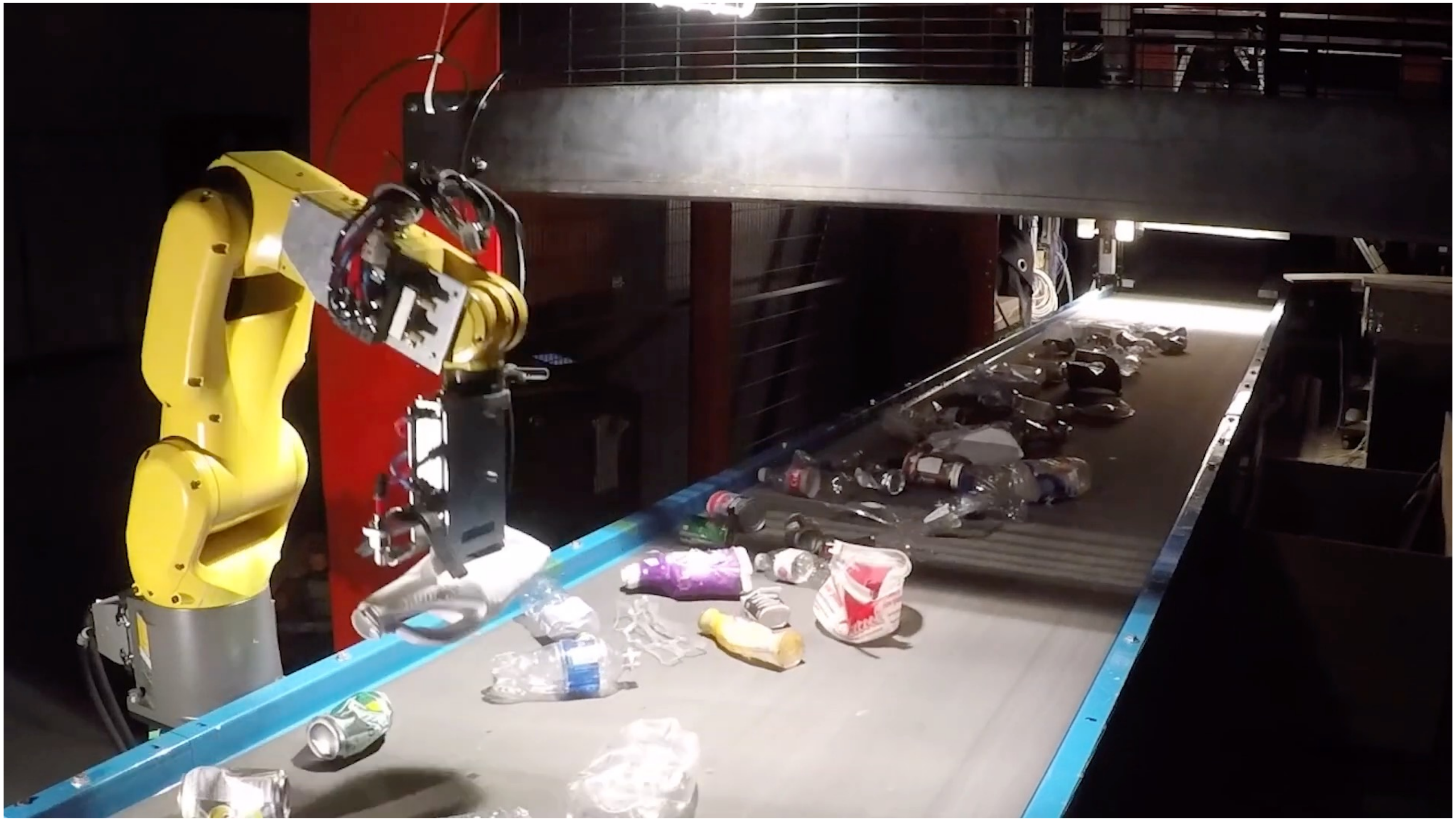


- **Articulated**
- **Cartesian**
- **Selective Compliance Assembly Robot Arm (SCARA)**
- **Delta**
- **Cylindrical**
- **Polar and more …**

Articulated Robot

- The manipulator connects to the base with a twisting joint.
- A rotary axis connects the links in the manipulator.
- Each axis provides an additional degree of freedom, or range of motion.

Features a rotary axis and can range from simple three-axis structures to 10 or more joints



Cartesian Robot

- Cartesian robots have three linear axes that use the Cartesian coordinate system (x, y and z).
- They may have an attached axis that enables rotational movement.
- Three prismatic joints facilitate linear motion along the axis.

Also called rectilinear or gantry robots

SCARA

- This selectively compliant manipulator for robotic assembly is primarily cylindrical in design.
- It features two parallel axes that provide compliance in one selected plane.

Selective Compliance Assembly Robot Arm

Delta Robot：

- 3 axes for the parallelograms; 1~3 axes for the end effector
- Delicate, precise movements in a dome-shaped work area
- Heavily used in food, pharmaceutical and electronic industries

Jointed parallelograms connected to a common base

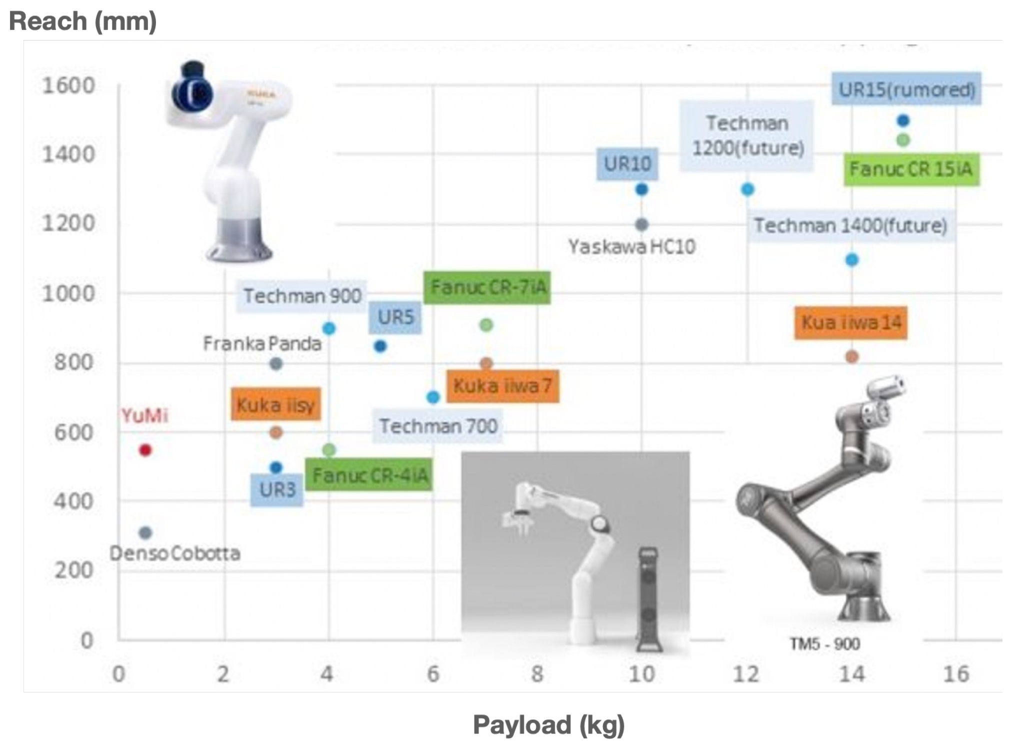
What are the Building Blocks of a Robotic System?

From the Industrial Perspective

Payload (weight) vs. Reach

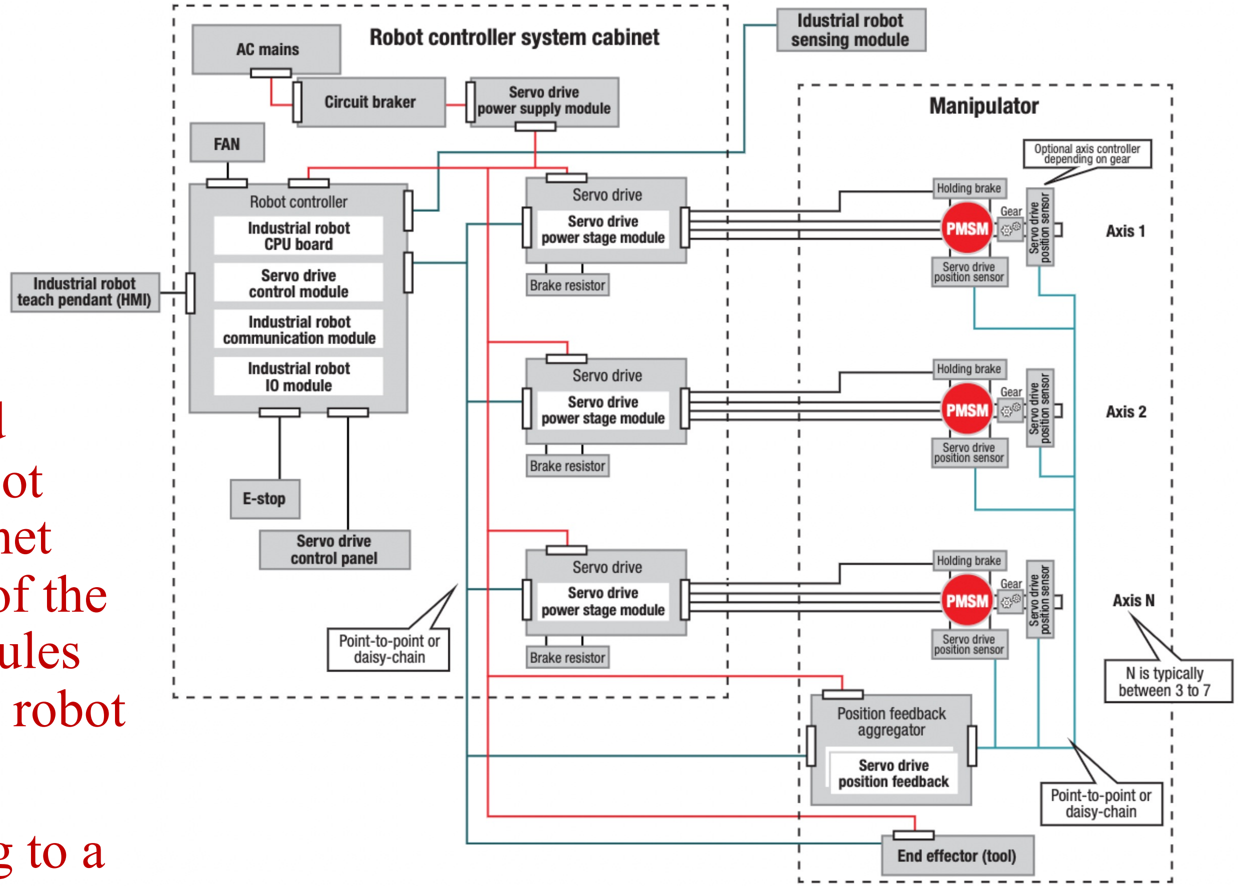
If heavier the object to move, then the motor needs to generate more force

- This force is generated with electric energy and is provided to the motor from the power stage.
- This power requirement is part of deciding whether the robot will be a high- or low-voltage system.
- A high-voltage robot system will require defined isolation architecture for safe operation.



Centralized Robotic System Example

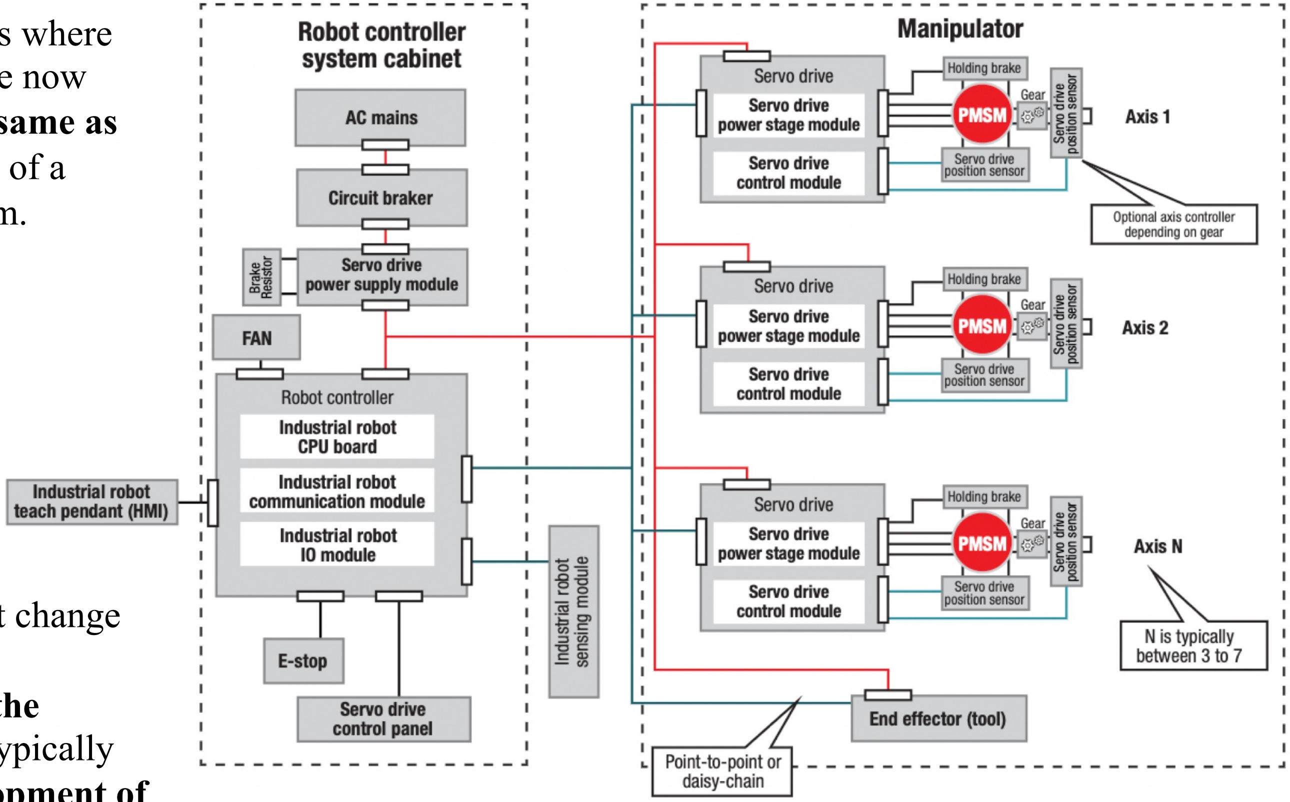
- In a centralized system, the robot controller cabinet includes most of the electronic modules that control the robot manipulator
- Usually leading to a larger size of the controller box



Decentralized Robotic System Example

Some modules move to the robot manipulator to support form factor of the cabinet, cabling and more

- The environments where the electronics are now used are **not the same as** the environments of a centralized system.



- This environment change necessitates a **re-specification of the electronics** and typically requires **redevelopment of part of the system**.

How will the different subsystems of the robot communicate with each other?

What are the interface requirements?

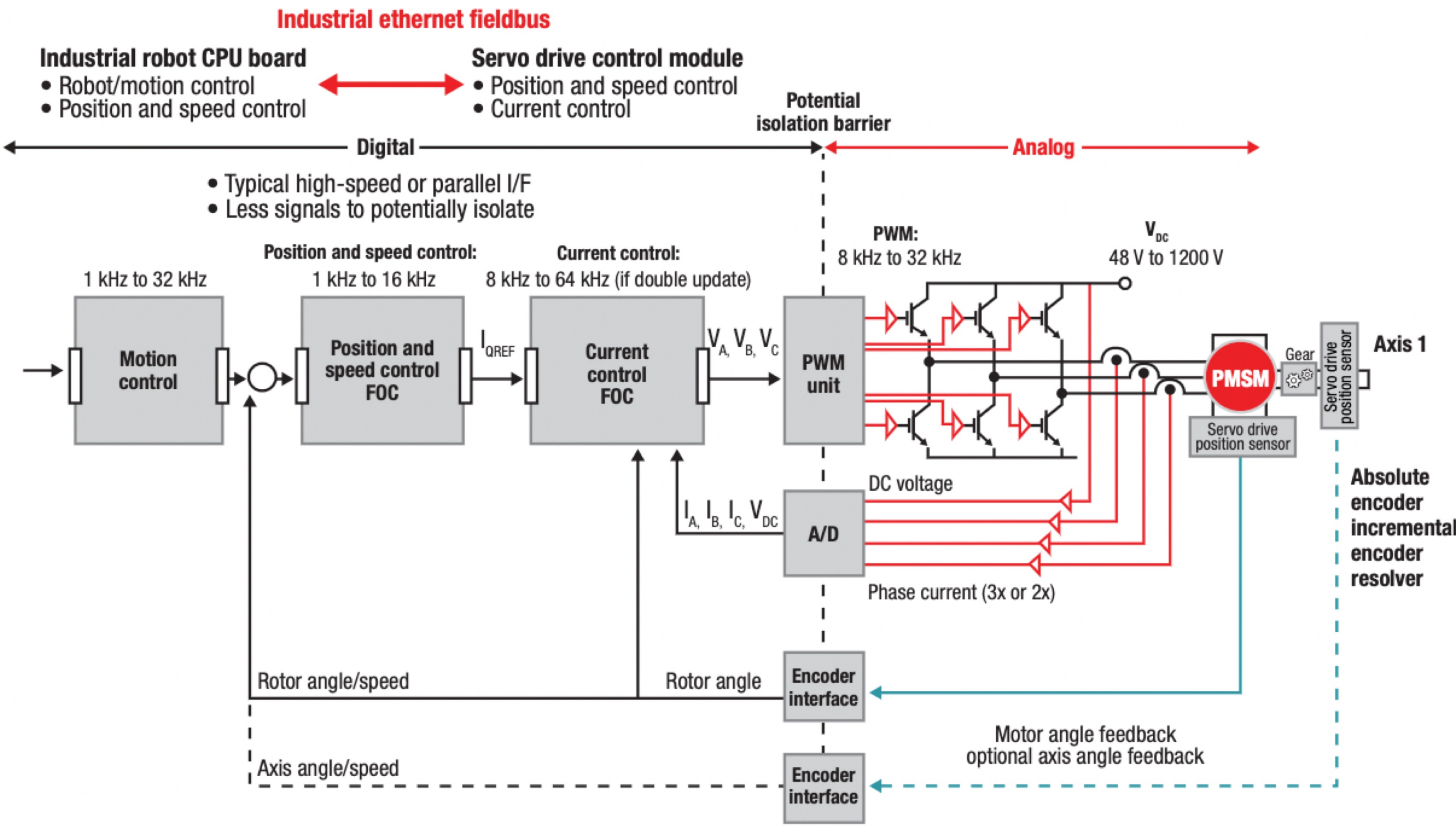
How does the programming interface work?

Will the robot operate from the user interface or through task programming?

Will you need an extra interface to connect the teaching pendant or joystick in order to enable operator functionality?

Other design questions …

Real-time Communication Timing Needs for Robot Control



Is the Robot Nonadaptive or Adaptive?

Design question …

Nonadaptive or Adaptive

Any feedback received from the environment, or ways to react

- A **nonadaptive robot** does not receive feedback from the environment and will execute its task as programmed.

- **Adaptive robots** use input and output data to generate environment data. With this data, the robot can react to environmental changes and stop its task if necessary.
  - It is important to define the environment data to which the robot is reacting. The data might be pre-defined parameters, like material amounts or sizes or shapes for quality definitions.
  - Or it might be uncontrolled parameters, like having people move around the robot or malfunctions that when detected put the robot in a safe state.

Collaborative Robots

A Historical Note

Early Concept of CoBot

From 1994 to 2003

General Motors FOUNDATION

US005952796A

United States Patent [19]

Colgate et al.

[11] **Patent Number: 5,952,796**

[45] **Date of Patent: Sep. 14, 1999**

[54] **COBOTS**

[76] Inventors: **James E. Colgate**, 2210 Ashbury, Evanston, Ill. 60201; **Michael A. Peshkin**, 4843 Fargo, Skokie, Ill. 60077

[21] Appl. No.: **08/959,357**

[22] Filed: **Oct. 28, 1997**

Related U.S. Application Data

[63] Continuation-in-part of application No. 08/605,997, Feb. 23, 1996.

[51] **Int. Cl.**^{6} **H02K 7/00**

[52] **U.S. Cl.** **318/1**; 318/568.11; 901/19

[58] **Field of Search** 318/1, 2, 580, 318/587, 568.11, 568.12, 568.14, 625, 560; 901/1, 2, 4, 19, 20, 50; 180/6.44, 6.54–6.62

pp. 633–638.

Peshkin et al., Passive Robots and Haptic Displays Based on Nonholonomic Elements, Proceedings of the 1996 IEEE International Conference on Robotics and Automation, Minneapolis, Minnesota, Apr. 1996, pp. 551–556.

Colgate et al., Nonholonomic Haptic Display, Proceedings of the 1996 IEEE International Conference on Robotics and Automation, Minneapolis, Minnesota, Apr. 1996, pp. 539–544.

Colgate et al., Cobots: Robots for Collaboration With Human Operators, Proceedings of the ASME Dynamic Systems and Control Division, DSC–vol. 58, Nov. 1996, Atlanta, GA, pp. 633–638.

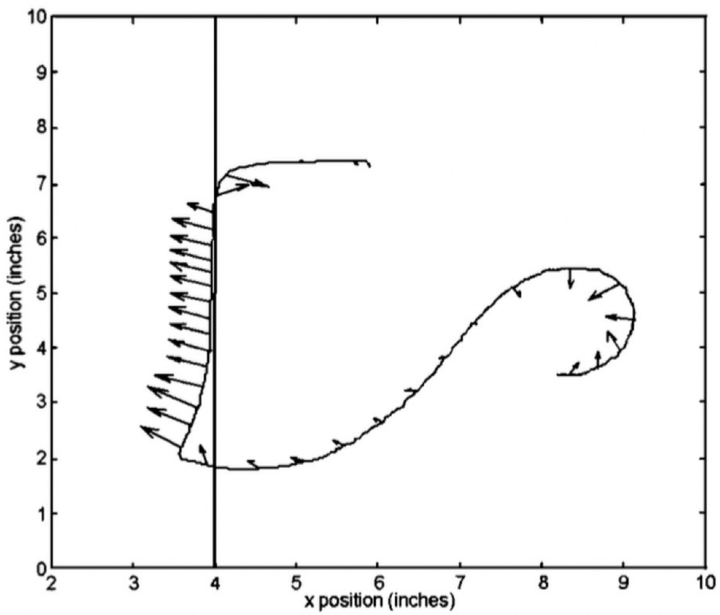
Kelley et al., On The Development Of a Force–Feedback Mouse and Its Integration Into a Graphical User Interface, DSC–vol. 55–1, Proceedings of the ASME Dynamics and Control Division, 1994, pp. 287–294.

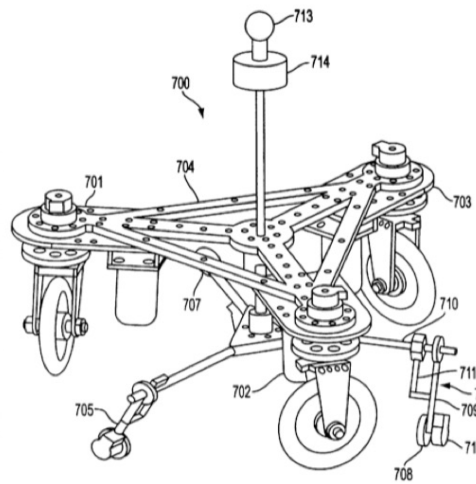
(List continued on next page.)

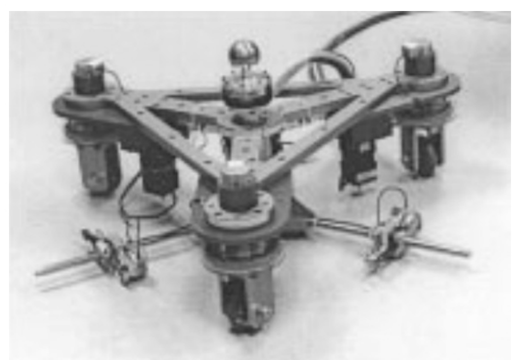
Early Concept of CoBot

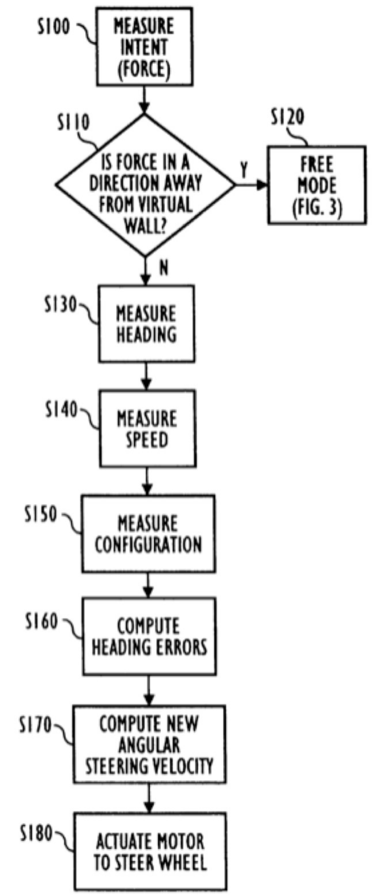
From 1994 to 2003

General Motors FOUNDATION









Early Concept of CoBot

From 1994 to 2003

General Motors FOUNDATION

IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, VOL. 17, NO. 4, AUGUST 2001 377

Cobot Architecture

Michael A. Peshkin, *Member, IEEE*, J. Edward Colgate, *Member, IEEE*, Witaya Wannasuphoprasit, Carl A. Moore, R. Brent Gillespie, *Member, IEEE*, and Prasad Akella, *Member, IEEE*

***Abstract*—We describe a new robot architecture: the collaborative robot, or cobot. Cobots are intended for direct physical interaction with a human operator. The cobot can create smooth, strong virtual surfaces and other haptic effects within a shared human/cobot workspace. The kinematic properties of cobots differ markedly from those of robots. Most significantly, cobots have only one mechanical degree of freedom, regardless of their taskspace dimensionality. The instantaneous direction of motion associated with this single degree of freedom is actively servo-controlled, or steered, within the higher dimensional taskspace. This paper explains the kinematics of cobots and the continuously variable transmissions (CVTs) that are essential to them. Powered cobots are introduced, made possible by a parallel interconnection of the CVTs. We discuss the relation of cobots to conventionally actuated robots and to nonholonomic robots. Several cobots in design, prototype, or industrial testbed settings illustrate the concepts discussed.**

***Index Terms*—Cobot, ergonomics, haptics, human/machine interaction, intelligent assist device (IAD), nonholonomic, passive.**

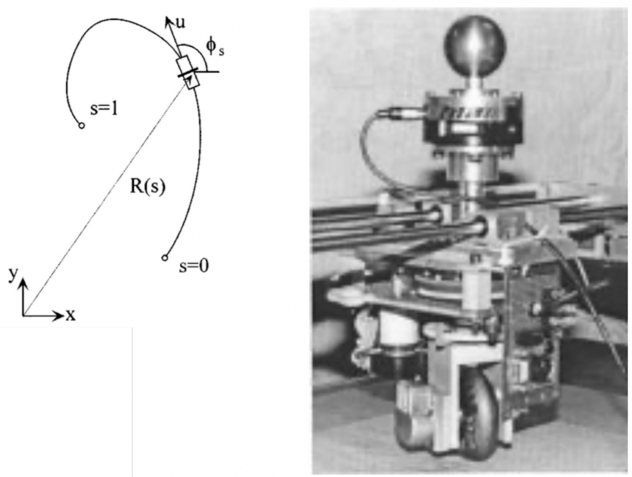
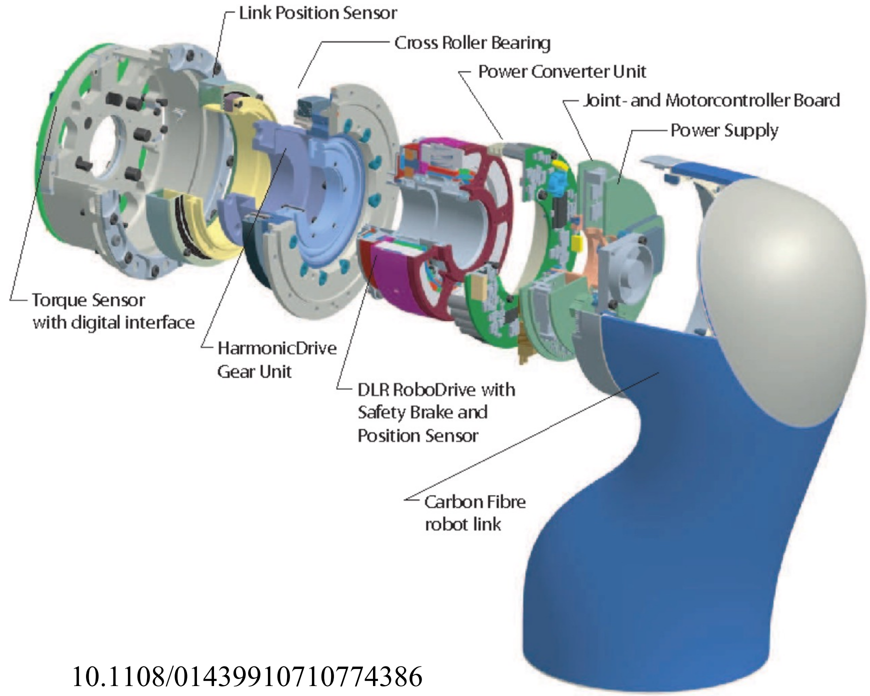


Fig. 1. A single wheel in contact with a planar rolling surface is the simplest cobot, having a 2-D taskspace. From top to bottom are the user's handle, a force sensor to measure the user's applied (xy) force, a rail system which holds the assembly upright and incorporates xy position sensors, a steering motor which can reorient the rolling direction of the wheel, and the "steerable transmission" which is central to all cobots—in this case a single free-rolling Rollerblade™ wheel. An encoder monitors the rolling speed of the wheel.

DLR/KUKA

From 2003 to 2013

- Integrated force/torque sensing at joint level



10.1109/ARSO.2011.6301962

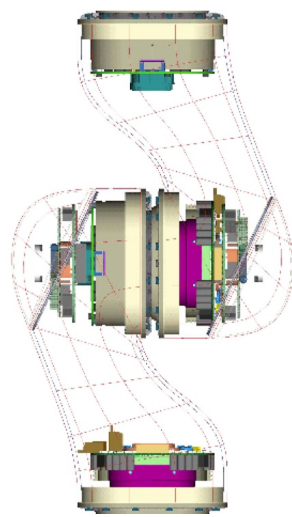
LWR-I

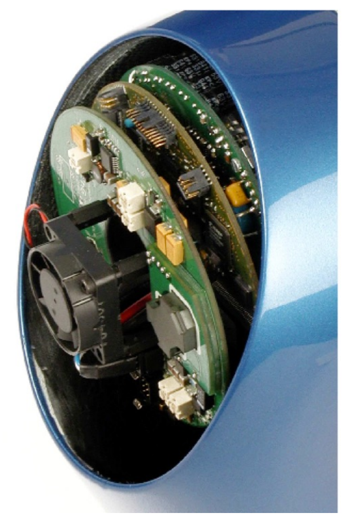
LWR-II

LWR-III

KUKA LWR

10.1108/01439910710774386



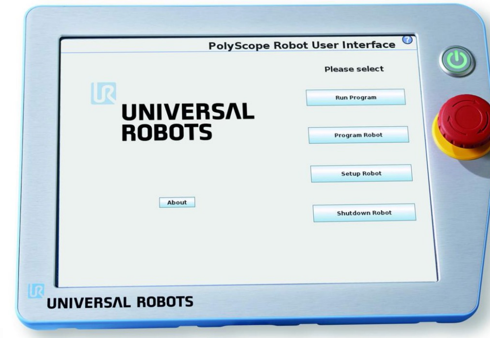


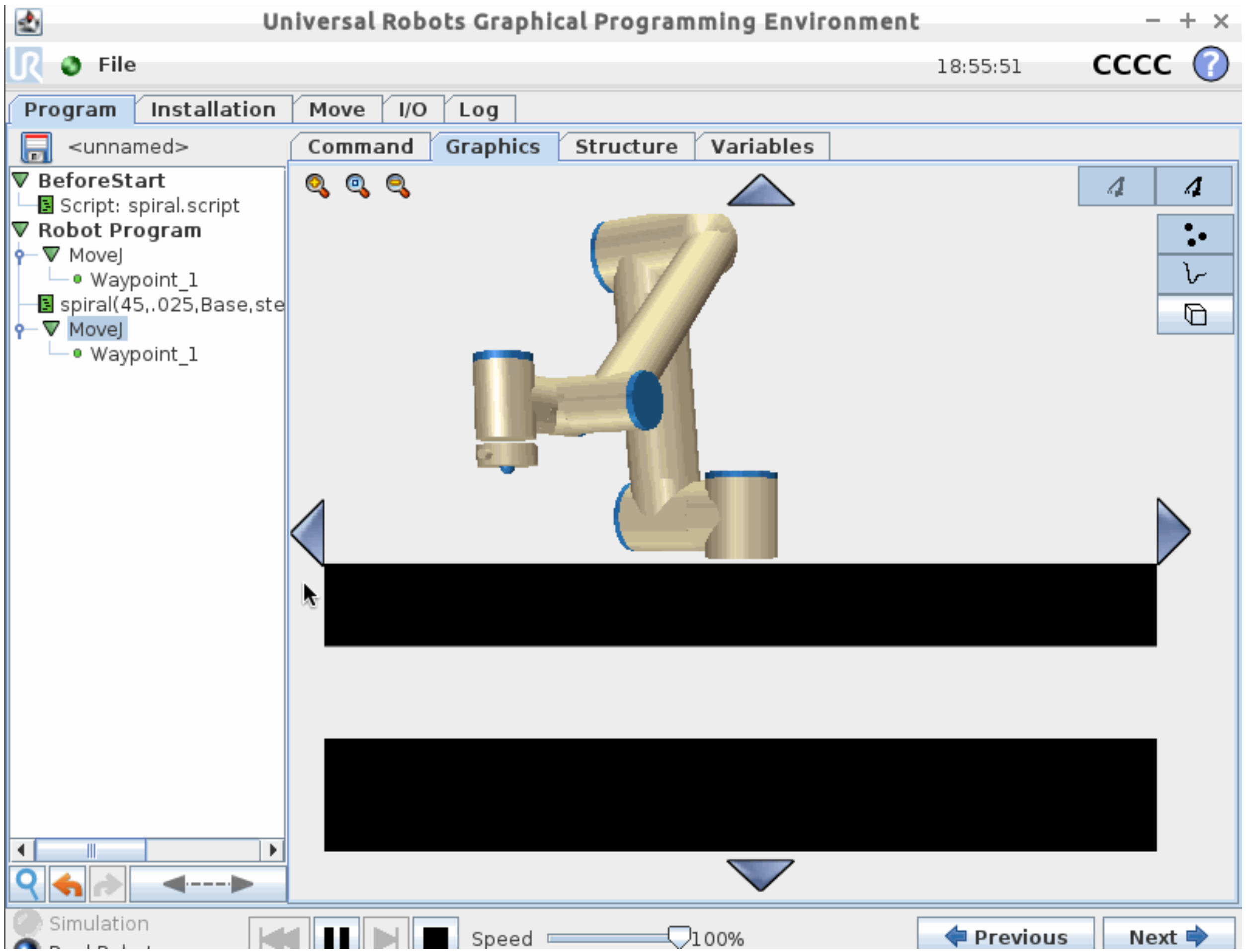
Soft-tissue injury in robotics

10.1109/ROBOT.2010.5509854

Universal Robots

From 2003 to 2013





- Cheaper to buy, and
- Easier to use

(12) **United States Patent**
Kassow et al.

(10) **Patent No.: US 8,614,559 B2**
(45) **Date of Patent: Dec. 24, 2013**

(54) **PROGRAMMABLE ROBOT AND USER INTERFACE**

(71) Applicant: **Universal Robots ApS**, Odense C. (DK)

(72) Inventors: **Kristian Kassow**, København S. (DK); **Esben Hallundbæk Østergaard**, Odense C. (DK); **Kasper Støy**, Odense C. (DK)

(73) Assignee: **Universal Robots ApS**, Odense S. (DK)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **13/827,824**

(22) Filed: **Mar. 14, 2013**

(65) **Prior Publication Data**

US 2013/0255426 A1 Oct. 3, 2013

(52) **U.S. Cl.**
USPC **318/568.11**; 318/568.12; 318/568.16; 318/568.2; 318/568.21; 700/245; 700/261; 901/8; 901/15; 901/28; 901/30; 901/38

(58) **Field of Classification Search**
USPC 318/568.11, 568.12, 568.13, 568.2, 318/568.21, 568.23, 560, 362, 372, 375, 318/376; 901/8, 9, 15, 24, 27, 28, 30, 38; 700/245, 261
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,155,423 A * 10/1992 Karlen et al. 318/568.11
5,293,107 A * 3/1994 Akeel 318/568.11

* cited by examiner

Primary Examiner — Anthony M Paul
(74) *Attorney, Agent, or Firm* — Stites & Harbison PLLC; Douglas E. Jackson

(57) **ABSTRACT**

A programmable robot system includes a robot provided with

(12) **United States Patent**
Kassow et al.

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(73) Assignee: **Universal Robots ApS**, Odense S. (DK)

(*)

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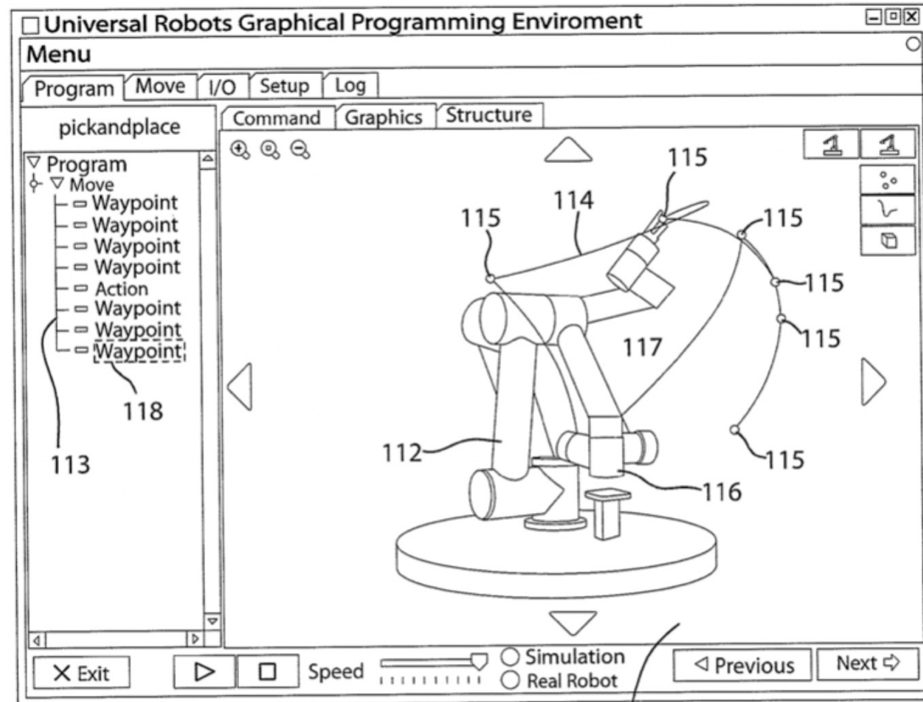


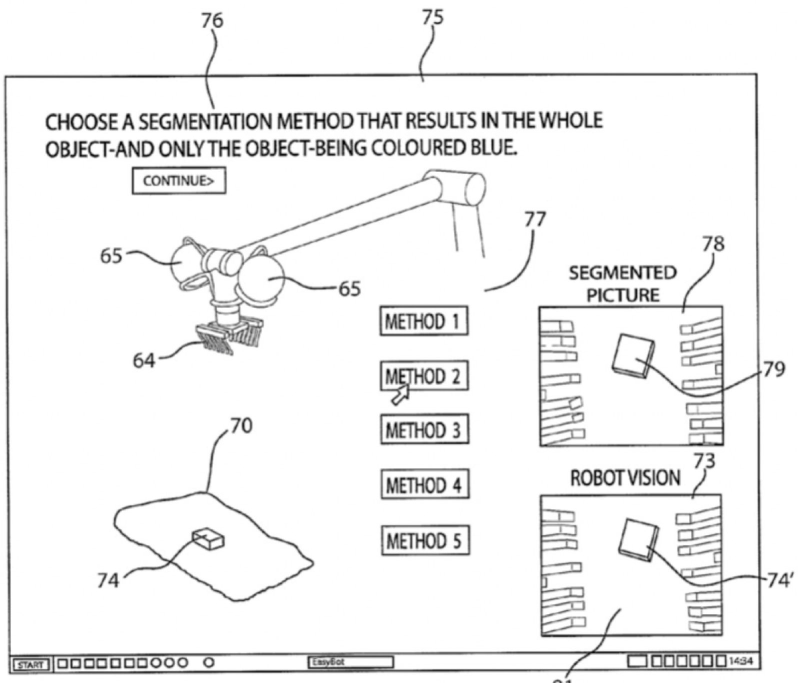
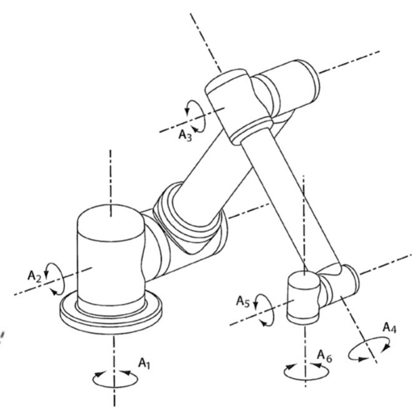
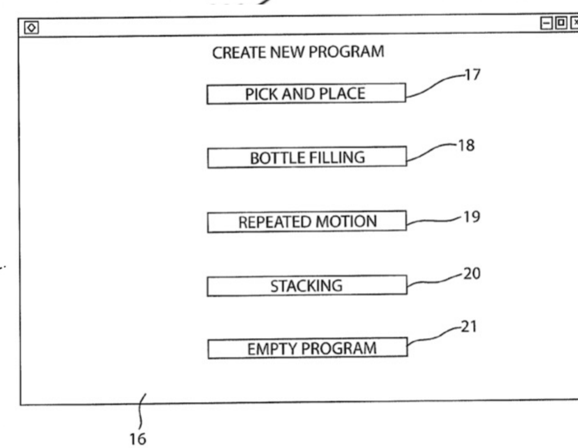
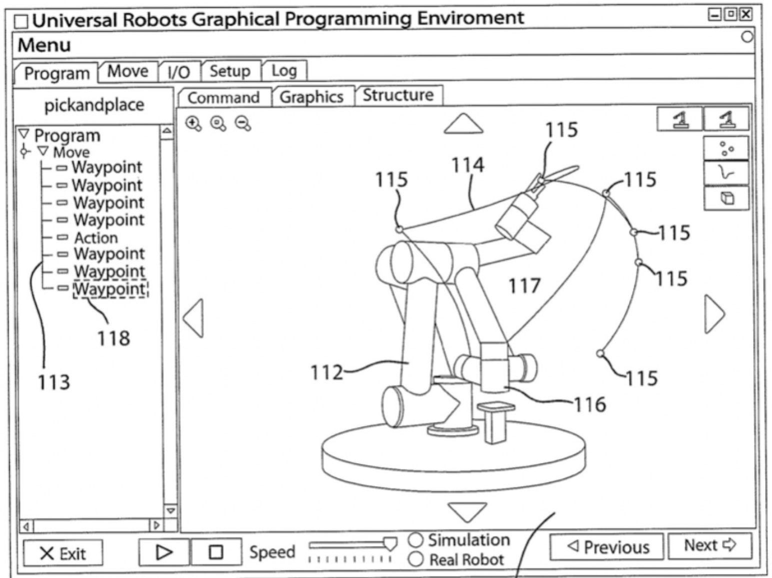


Fig. 19






Universal Robots Graphical Programming Enviroment
Menu
Program
Move
I/O
Setup
Log
pickandplace
Command
Graphics
Structure
Program
Move
Waypoint
Waypoint
Waypoint
Waypoint
Action
Waypoint
Waypoint
Waypoint
115
114
115
115
115
115
115
117
118
113
112
116
X Exit
Speed
Simulation
Real Robot
Previous
Next

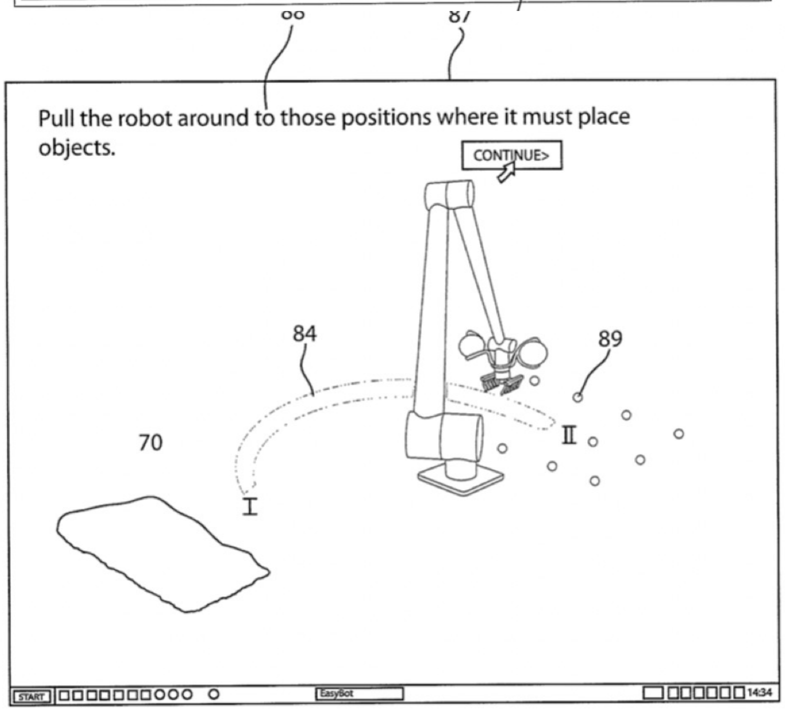
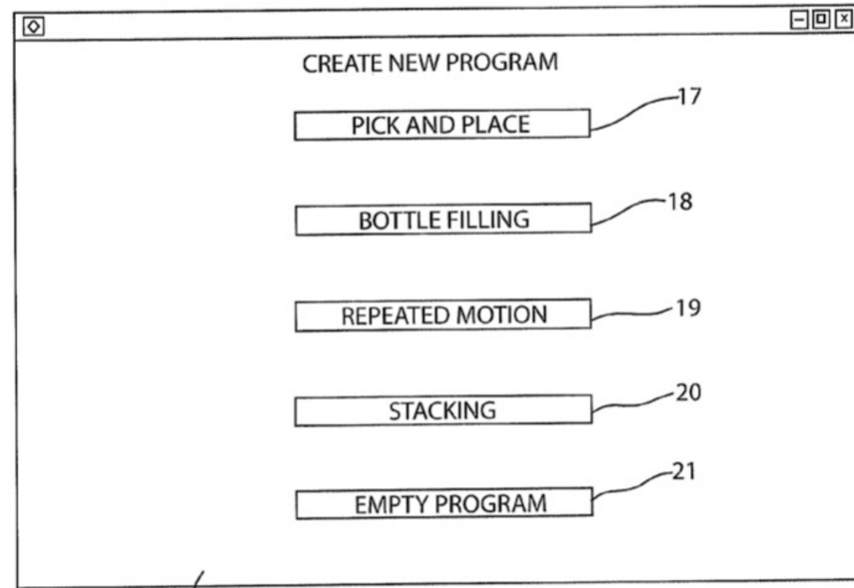

88
87
Pull the robot around to those positions where it must place objects.
CONTINUE>
84
89
70
I
II
START
EasyBot
14:34

Fig. 22


CREATE NEW PROGRAM
PICK AND PLACE
17
BOTTLE FILLING
18
REPEATED MOTION
19
STACKING
20
EMPTY PROGRAM
21
16

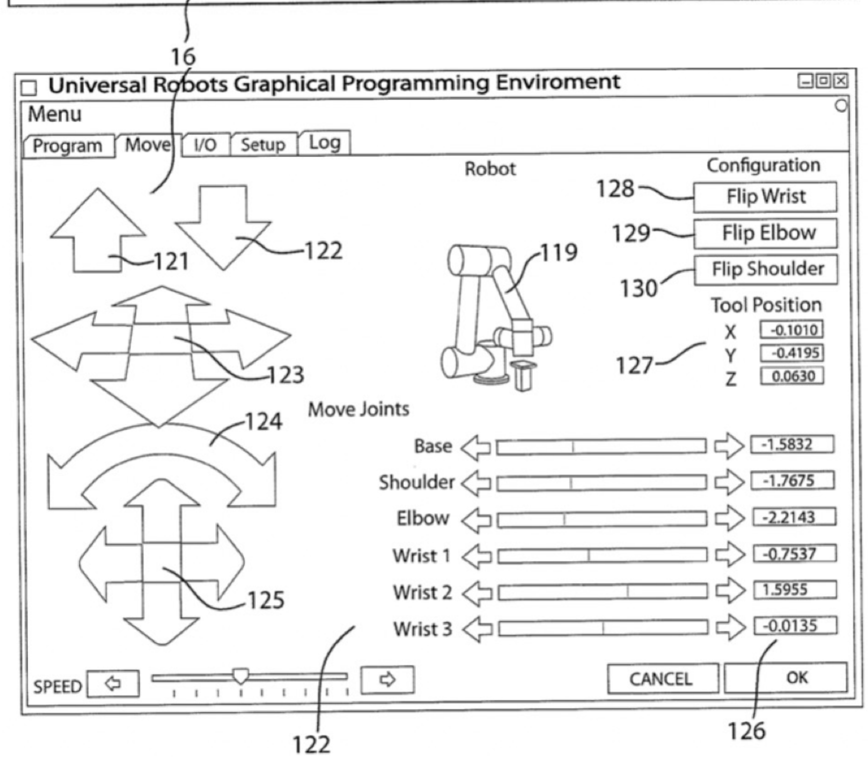

Universal Robots Graphical Programming Enviroment
Menu
Program
Move
I/O
Setup
Log
Robot
Configuration
128
Flip Wrist
129
Flip Elbow
130
Flip Shoulder
Tool Position
121
122
119
123
127
X -0.1010
Y -0.4195
Z 0.0630
124
Move Joints
Base -1.5832
Shoulder -1.7675
Elbow -2.2143
Wrist 1 -0.7537
Wrist 2 1.5955
Wrist 3 -0.0135
125
SPEED
CANCEL
OK
122
126

Fig. 25

Modular Design of Robotic Joint

What's so special about the Universal Robots?

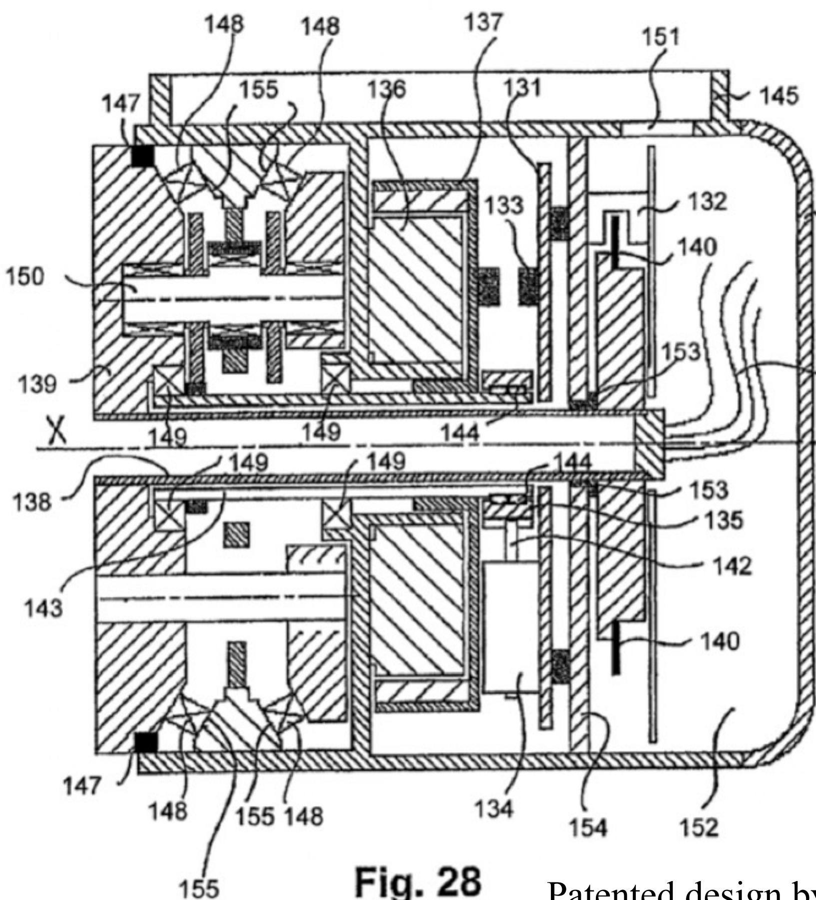
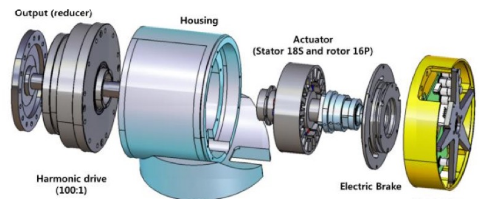
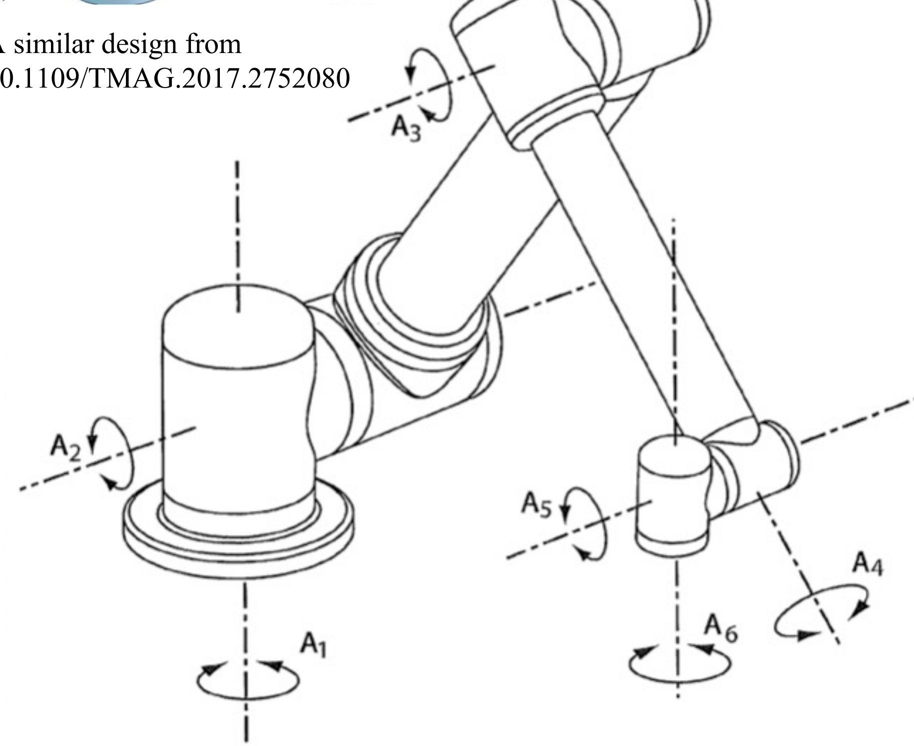


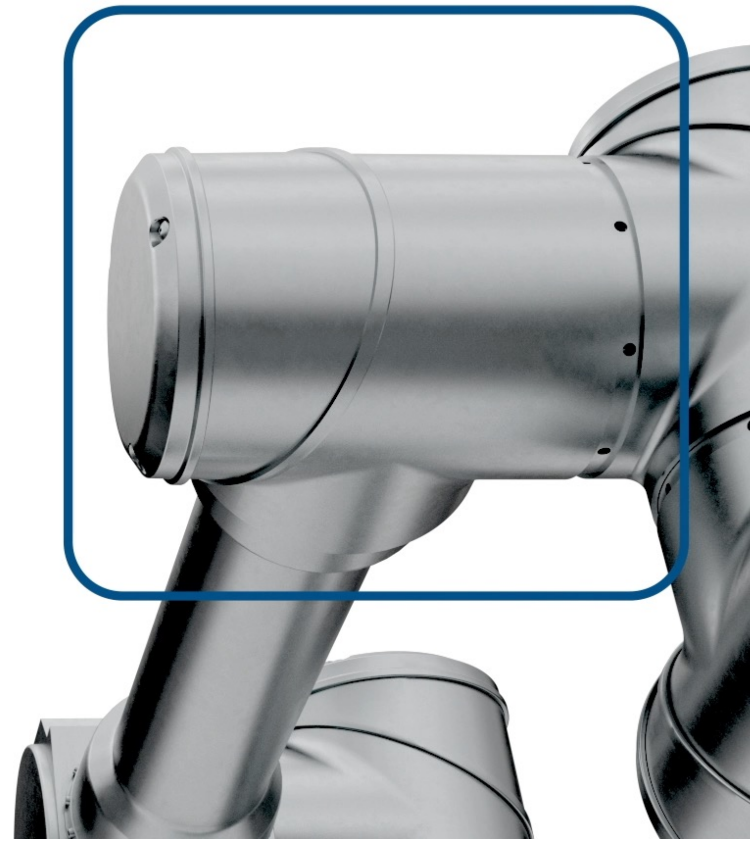
Fig. 28



A similar design from 10.1109/TMAG.2017.2752080



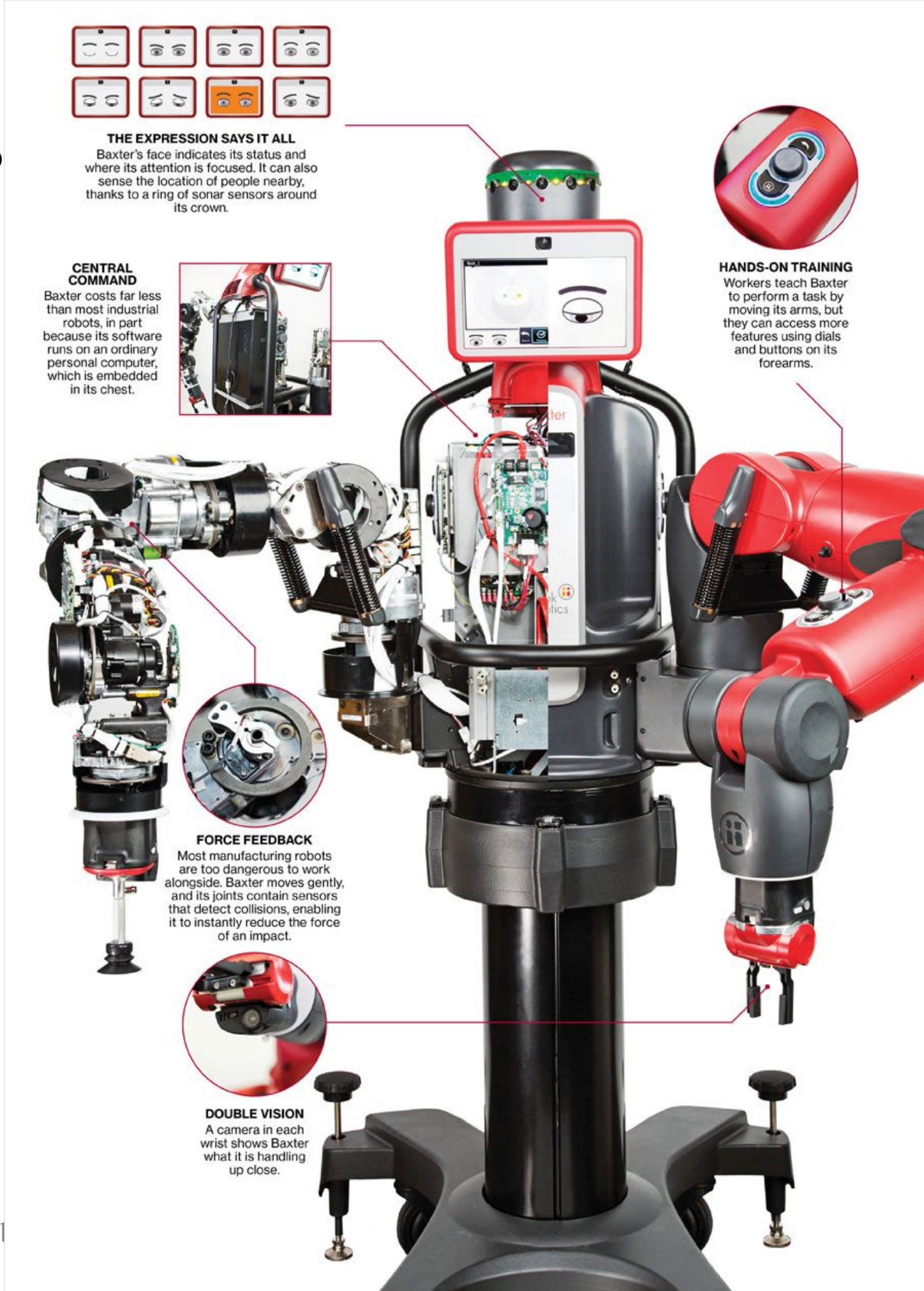
Patented design by UR

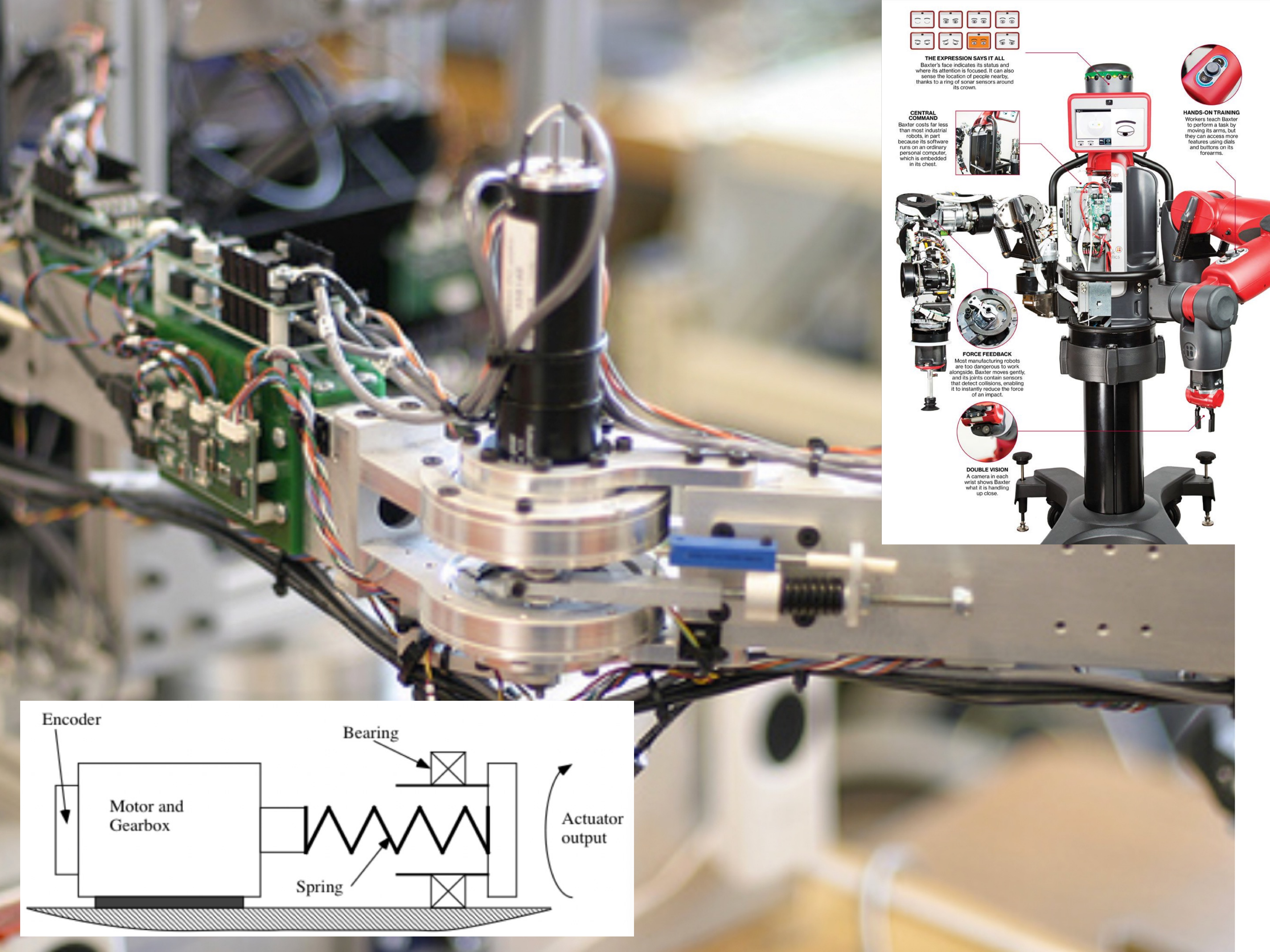


Rethink Robotics

From 2003 to 2013

- Video, dual arm, UX with a cute face
- Series Elastic Actuator with Integrated sensing
    - Patented by MIT in 1993
    - Inexpensive way to get good force control
        - Make robots that are compliant, good at tasks, safer around humans, good in unstructured environments etc.
    - Spring in series with gearbox
    - Turn force control problem into position control
    - Spring filters gearbox nonlinearities, gives smooth output torque
    - Gain in compliance, sacrifice bandwidth



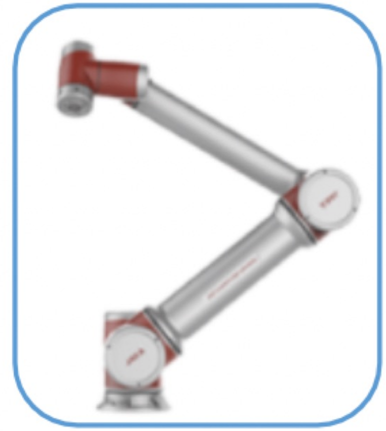

THE EXPRESSION SAYS IT ALL
Baxter's face indicates its status and where its attention is focused. It can also sense the location of people nearby, thanks to a ring of sonar sensors around its crown.
CENTRAL COMMAND
Baxter costs far less than most industrial robots, in part because its software runs on an ordinary personal computer, which is embedded in its chest.
HANDS-ON TRAINING
Workers teach Baxter to perform a task by moving its arms, but they can access more features using dials and buttons on its forearms.
FORCE FEEDBACK
Most manufacturing robots are too dangerous to work alongside. Baxter moves gently, and its joints contain sensors that detect collisions, enabling it to instantly reduce the force of an impact.
DOUBLE VISION
A camera in each wrist shows Baxter what it is handling up close.
Encoder
Bearing
Motor and Gearbox
Actuator output
Spring

More and more designs …

Since 2013 …







Source: Rokae

Examples of Engineering Specifications

Reading the Technical Data Sheet

TDS

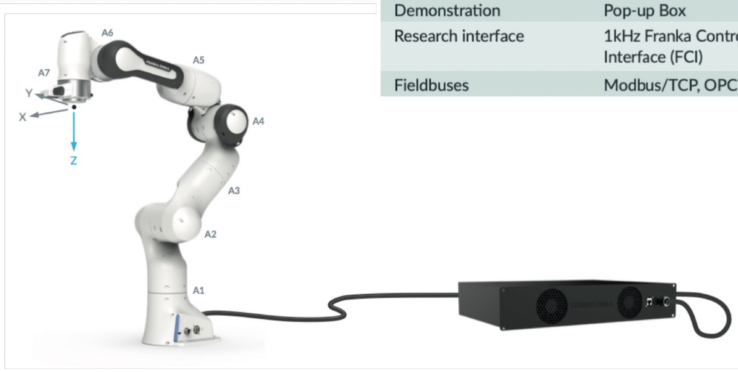
HARDWARE

Arm

Degrees of freedom	7
Payload	3 kg
Workspace	see backside
Maximum reach	855 mm
Force/ Torque sensing	link-side torque sensors in all 7 axes
Expected nominal lifetime [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 W • typical application ~ 60 W
Interfaces	• ethernet (TCP/IP) for visual intuitive programming with Desk • input for external enabling device • input for external activation device or safeguard • Control connector • Connector for end effector

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



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

ADD-ONS

Safety retrofit option with safety-rated PLC	PLd Cat. 3 • Safe torque off (STO) • Safe OSSD inputs
Fully integrated end effectors	• 2-finger gripper • Vacuum gripper
Fast mounting	Clamping Adapter
Demonstration	Pop-up Box
Research interface	1kHz Franka Control Interface (FCI)
Fieldbuses	Modbus/TCP, OPC UA

SOFT-ROBOT PERFORMANCE

Motion

Joint velocity limits	A1, A2, A3, A4: 150°/s A5, A6, A7: 180°/s
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]

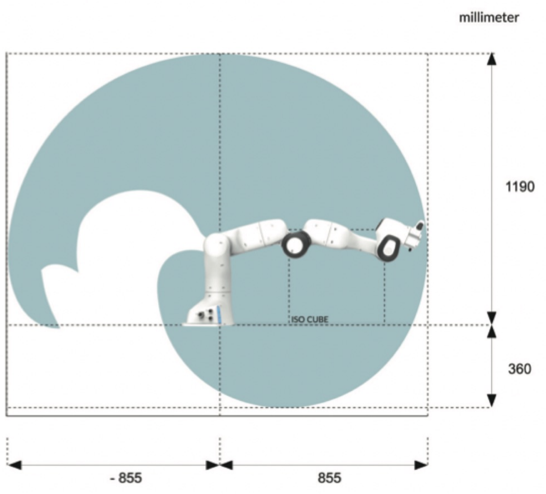
Force resolution	<0.05 N
Relative force accuracy	0.8 N
Force repeatability	0.15 N
Force noise (RMS)	0.035 N
Torque resolution	0.02 Nm
Relative torque accuracy	0.15 Nm
Torque repeatability	0.05 Nm
Torque noise (RMS)	0.005 Nm

1 kHz Control [3]

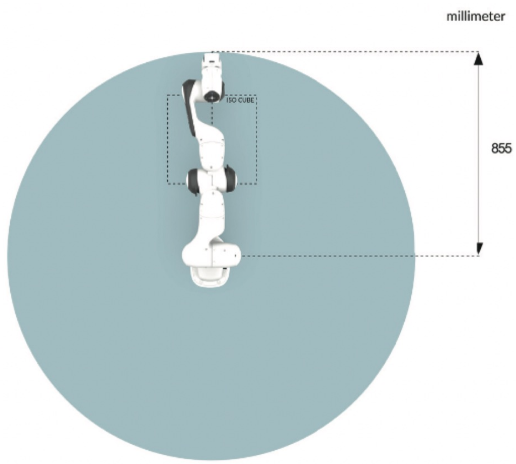
Minimum controllable force (Fz)	0.05 N	
Force controller bandwidth (-3 dB)	10 Hz	
Force range [N]	Nominal case	Local best case
Fx	-125 – 95	-150 – 115
Fy	-100 – 100	-275 – 275
Fz	-50 – 150	-115 – 155
Torque range [Nm]	Nominal case	Local best case
Mx	-10 – 10	-70 – 70
My	-10 – 10	-16 – 12
Mz	-10 – 10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

Reading the Technical Data Sheet

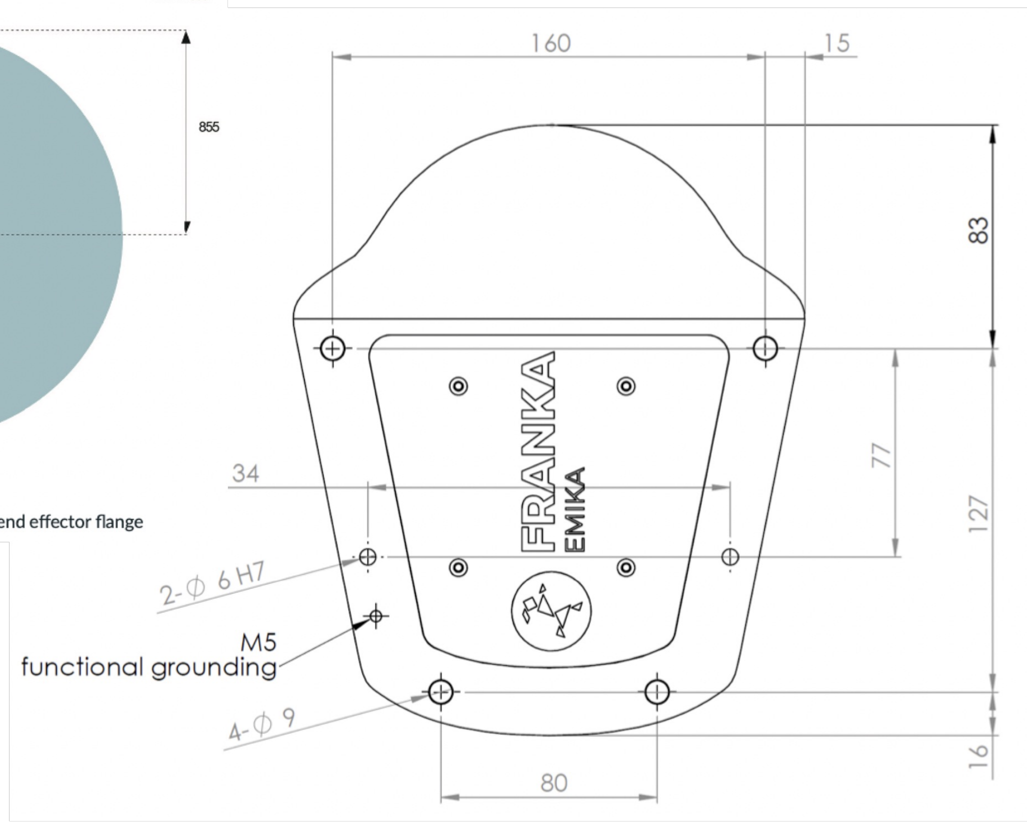
TDS



Side-view: reachable space for the end effector flange



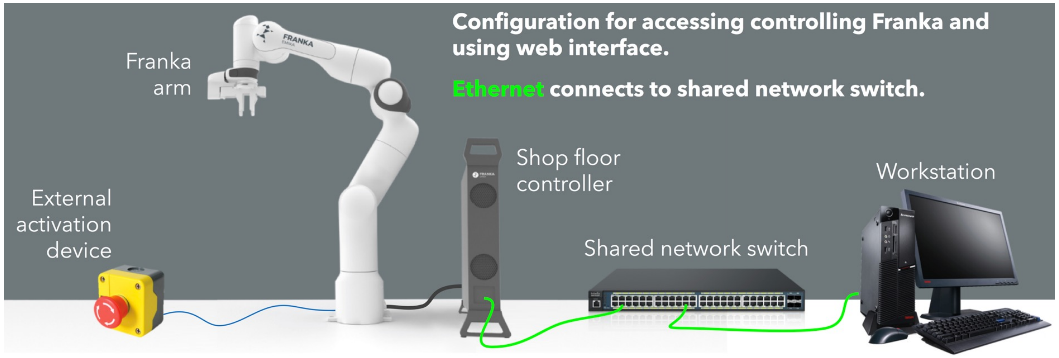
Top-view: reachable space for the end effector flange

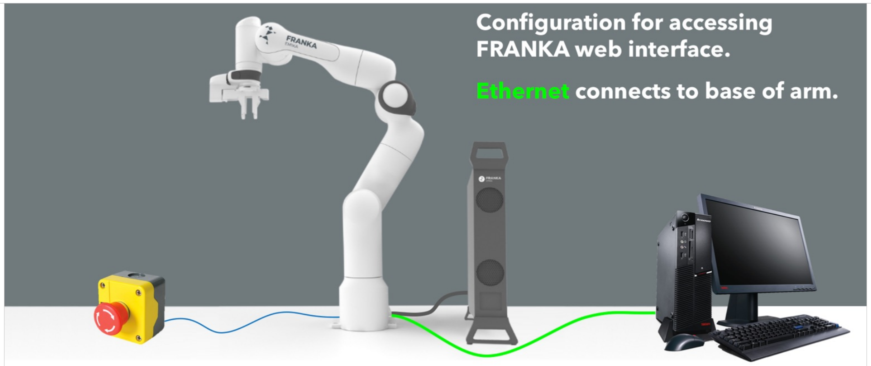


Reading the Technical Data Sheet

TDS

- https://support.franka.de/
- https://github.com/bionicdl-sustech/DeepClaw
- https://de3-rob1-chess.readthedocs.io/en/latest/franka.html
- https://visp-doc.inria.fr/doxygen/visp-daily/tutorial-franka-pbvs.html
- https://github.com/ARISE-Initiative/robosuite
- https://github.com/stepjam/RLBench





Reading the Technical Data Sheet

Another robot …

TECHNICAL SPECIFICATIONS:

Robot Type	AUBO-i5 Articulated Type / Modular
Controlled Axes DoF	6 axes (J1, J2, J3, J4, J5, J6) J7max
Reach	924 mm, 880 mm (working range)
Payload	5Kg
Weight	24 Kg
Footprint	172 mm diameter
Collaborative Operation	Safety monitored stop, speed and separation monitoring, hand guide operation, power and force limiting design
Certifications	ISO 10218-1:2011, EN 60204-1:2006 + A1:2009, ISO 12100: 2010, ISO 13849-1:2008, CE
Repeatability	(+/- 0.05 mm)
Linear Velocity	2.8 m/s adjustable
Power Consumption	200 watts typical application
Materials	Aluminum, Steel, Plastic
Ambient Humidity	Normal 75% RH or less without frost or dew, 85% RH short term
Ambient Temperature	0 to 45 degrees Celsius
IP Classification of Robot	IP54
Programing	Teach pendant with user interface, guide to teach, ROS compatibility through an API, Lua or Python
Communication	CAN bus
Motor Type	Harmonic drive 48 Volt
Installation Orientation	Any Ceiling, Floor, Wall

AXIS MOVEMENT

AXIS MOVEMENT	WORKING RANGE	MAXIMUM SPEED	MAX. JOINT MOMENTS
J1 axis rotation base	(+/-) 175°	150°/sec	207 Nm
J2 axis rotation shoulder	(+/-) 175°	150°/sec	207 Nm
J3 axis rotation elbow	(+/-) 175°	150°/sec	207 Nm
J4 axis wrist rotation	(+/-) 175°	180°/sec	34 Nm
J5 axis wrist swing	(+/-) 175°	180°/sec	34 Nm
J6 axis wrist rotation	(+/-) 175°	180°/sec	34 Nm

I/O PORT ON WRIST

Voltage	Current	Digital In	Digital out	Analog In	Analog Out
0/12/24 V	800 mA	4	4	2	0

CONTROL BOX

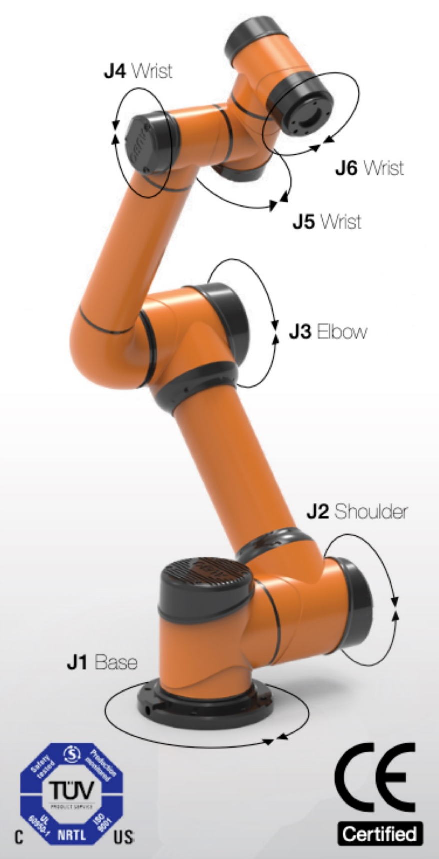
Dimensions (LxWxH)	683x220x622 mm
Weight	20Kg
Cabling	5mm
Color	Black
Communication	TCP/IP, Modbus RTU/TCP
Power supply	100 - 240 VAC, 50 - 60 Hz
IP Classification	IP54

I/O PORTS

I/O PORTS	User I/O	Safety I/O
Digital in	16	16
Digital out	16	16
Analog In	4	-
Analog out	4	-
Power input	24 Volts	
Power output	3A	

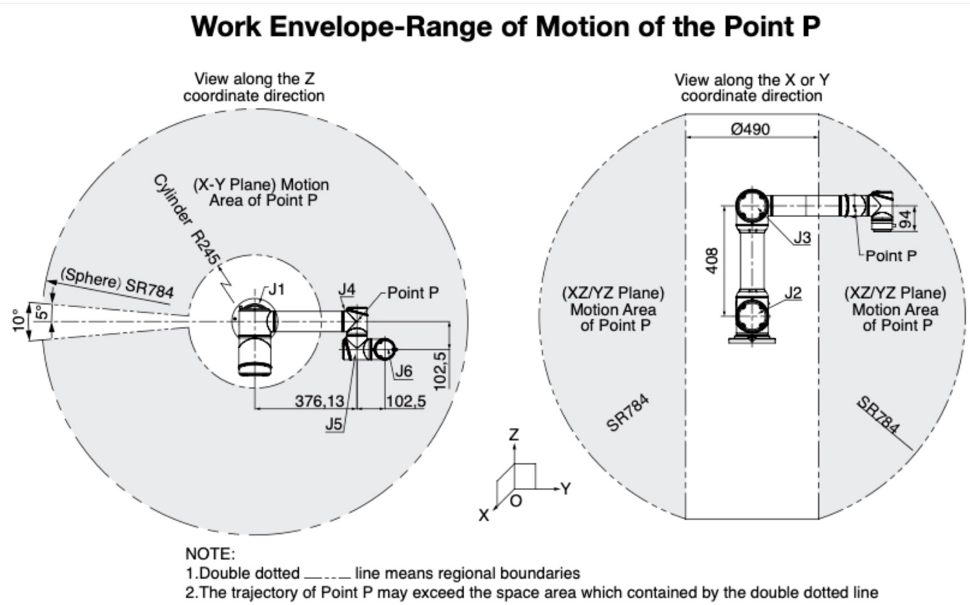
TEACH PENDANT

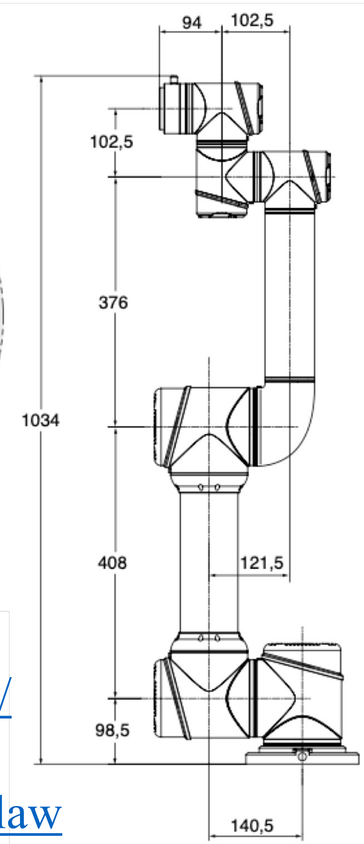
Dimensions (LxWxH)	355x235x54 mm
Weight	1.8 Kg
Display Screen	30 cm Touch LCD Screen
Cabling	4.5 mm
IP Classification	IP54
Color	Orange

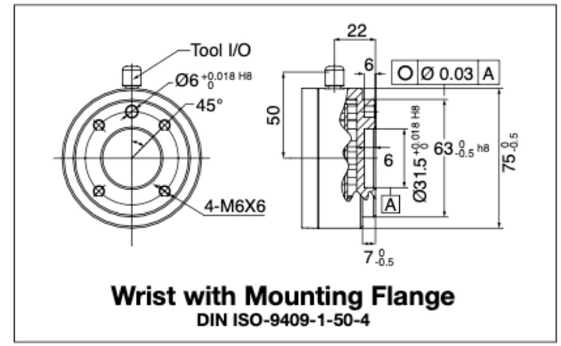


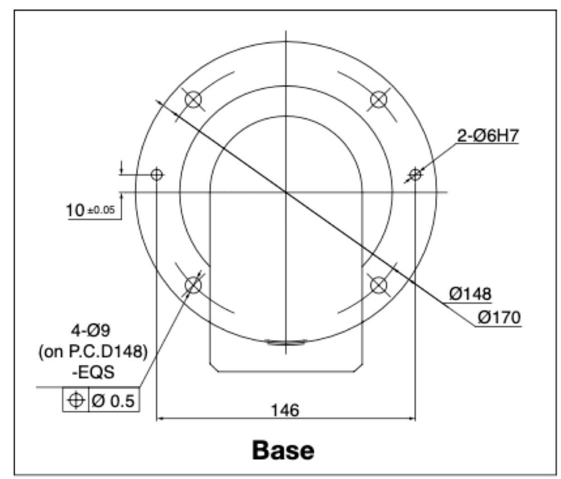
Reading the Technical Data Sheet

Another robot …









- https://aubo-robotics.com/products/aubo-i5/
- https://github.com/lg609/aubo_robot
- https://github.com/bionicdl-sustech/DeepClaw

Tell us about yourself

Have you worked with a Collaborative Robot before?

What do you expect to take away from the class?

Do you perfer to work alone or as a team?

Tell us about your coding experience …

Thank you ~

Song Chaoyang
Southern University of Science and Technology