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Factories of the Future

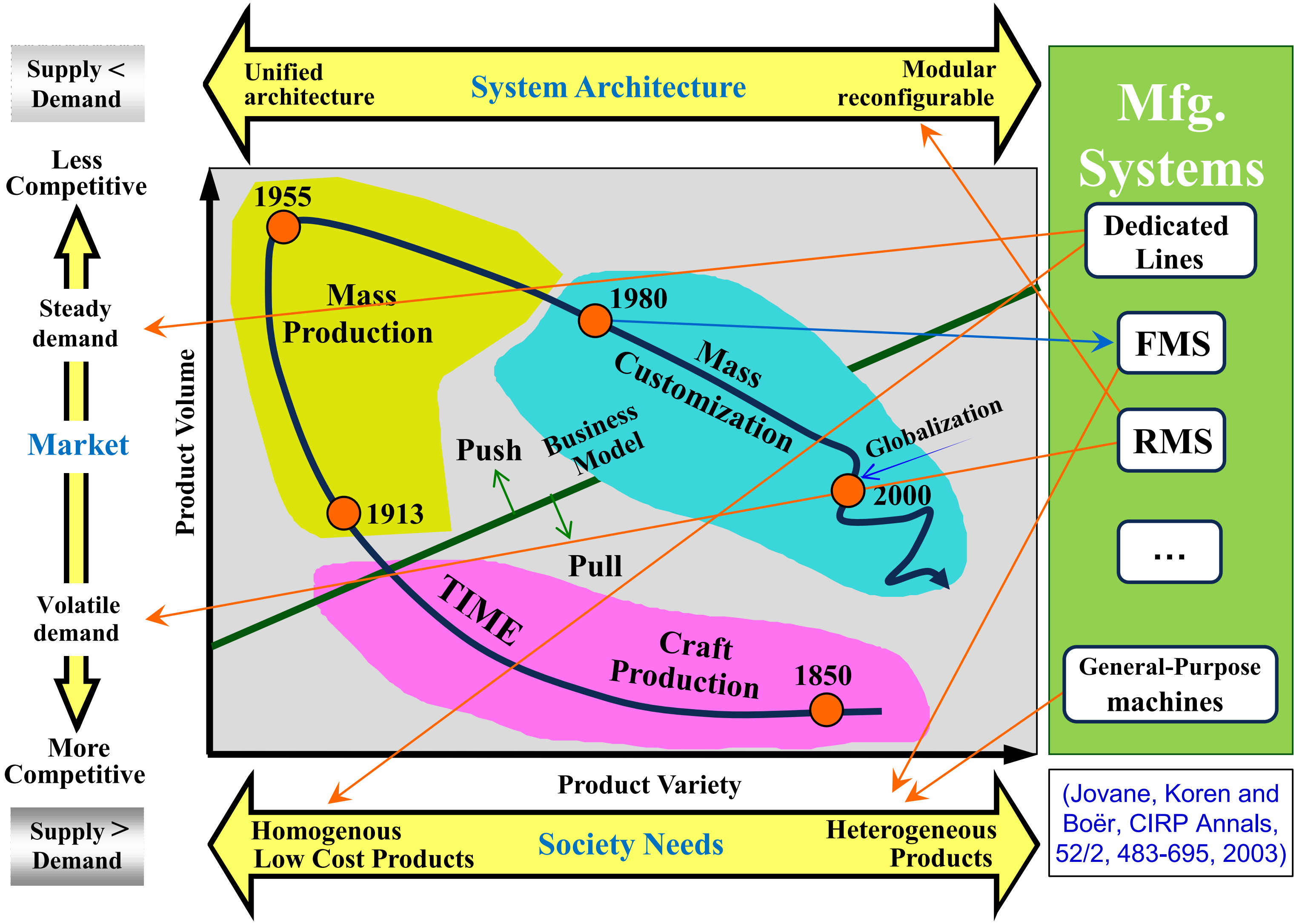
through AI-Driven Smart Manufacturing

Presentation Outline

- **Past**: Manufacturing and AI Background
- **Present**: Smart Manufacturing Research
  - Remote Monitoring and Control
  - Human-Robot Collaboration
- **Future**: Research Directions

Past

Manufacturing in a Nutshell

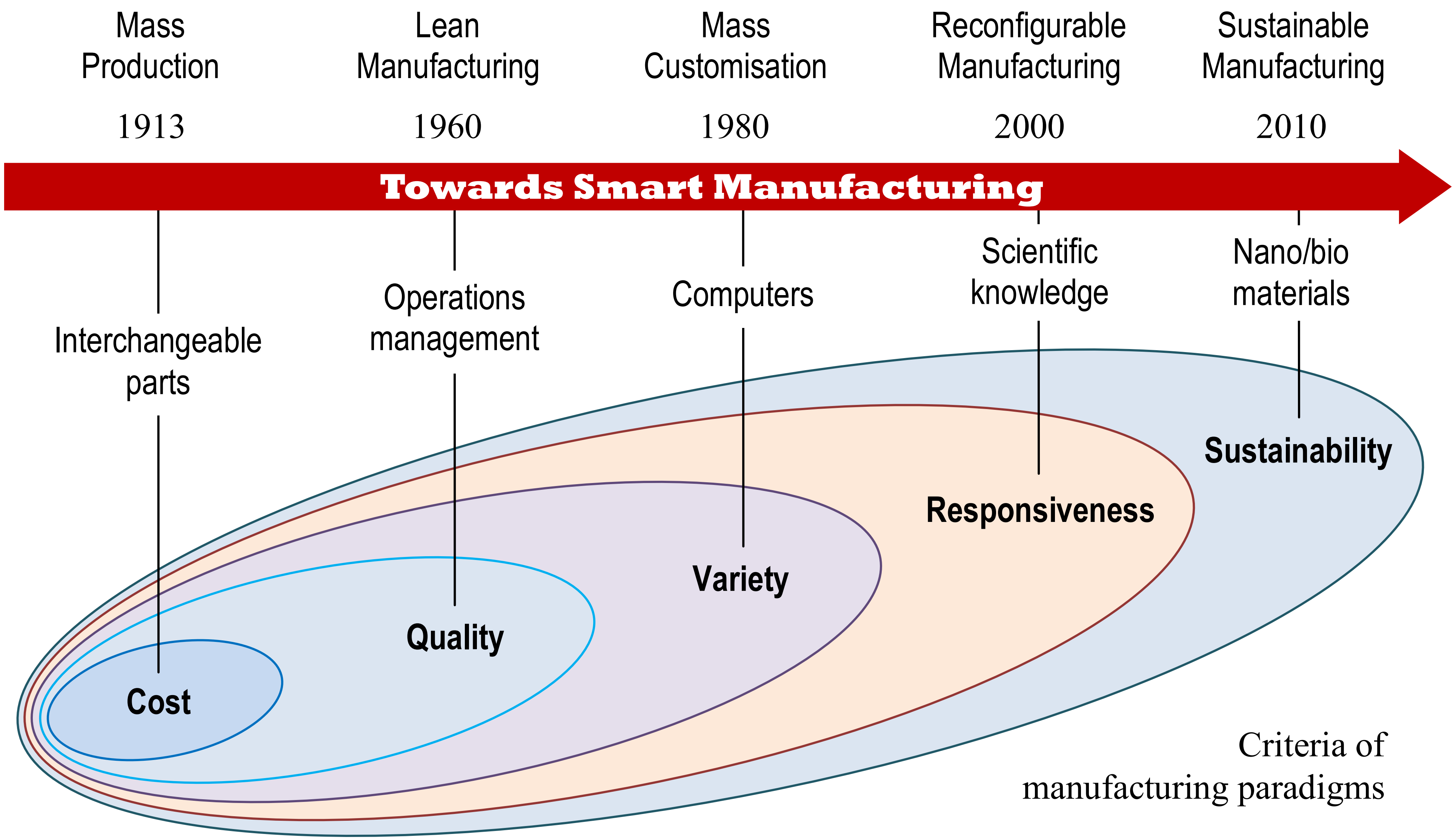


(Jovane, Koren and Boër, CIRP Annals, 52/2, 483-695, 2003)

Current Focus:

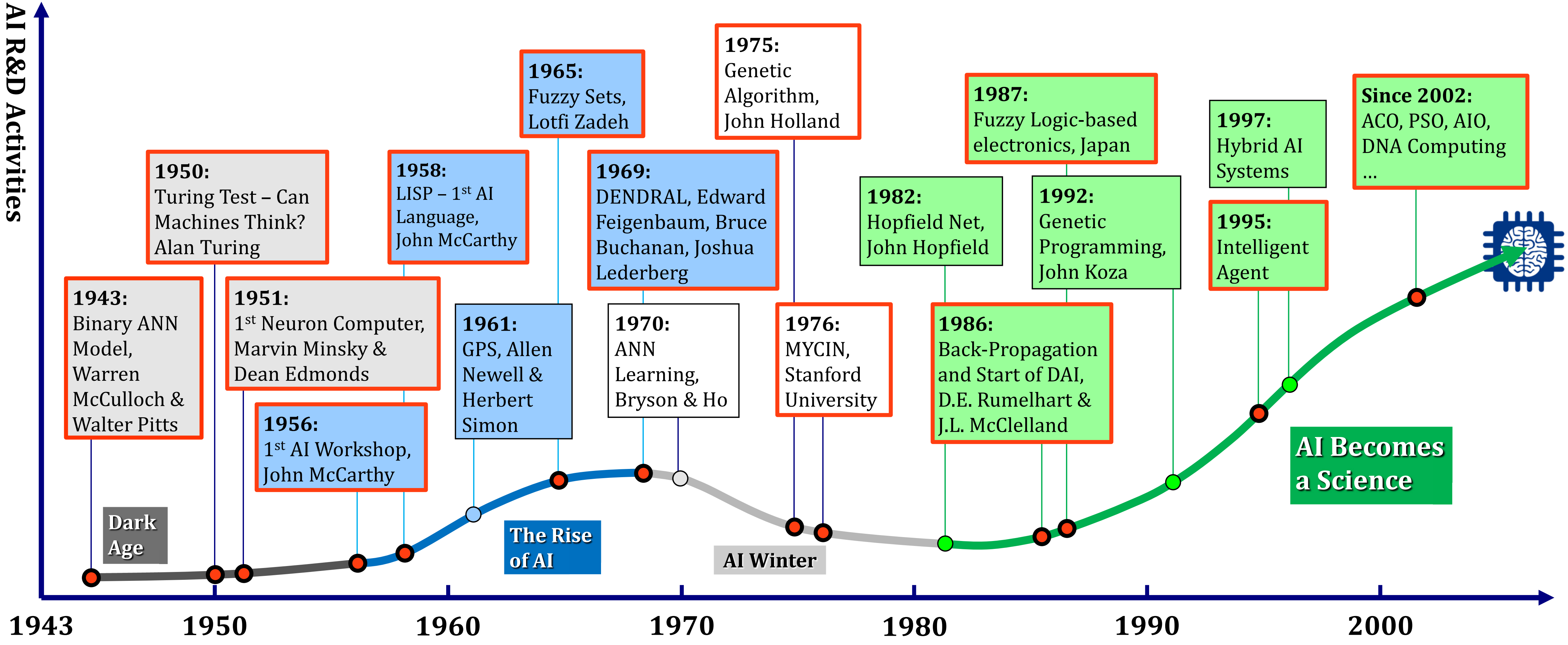
- Sustainable manufacturing
- Cloud manufacturing
- Human-robot collaboration
- Programming-free machine control
- Additive manufacturing
- CPS in manufacturing

Manufacturing Paradigms



(Adapted from Koren and Ulsoy, "Reconfigurable manufacturing systems," ERC/RMS, University of Michigan, 1997)

A Brief History of AI



Reference L. Wang, "From Intelligence Science to Intelligent Manufacturing," *Engineering*, Vol.5, No.4, pp.615-618, 2019.

Earlier AI Applications

Garry Kasparov playing Deep Blue in 1997

Honda ASIMO walking downstairs in 2005

AlphaGo in 2016

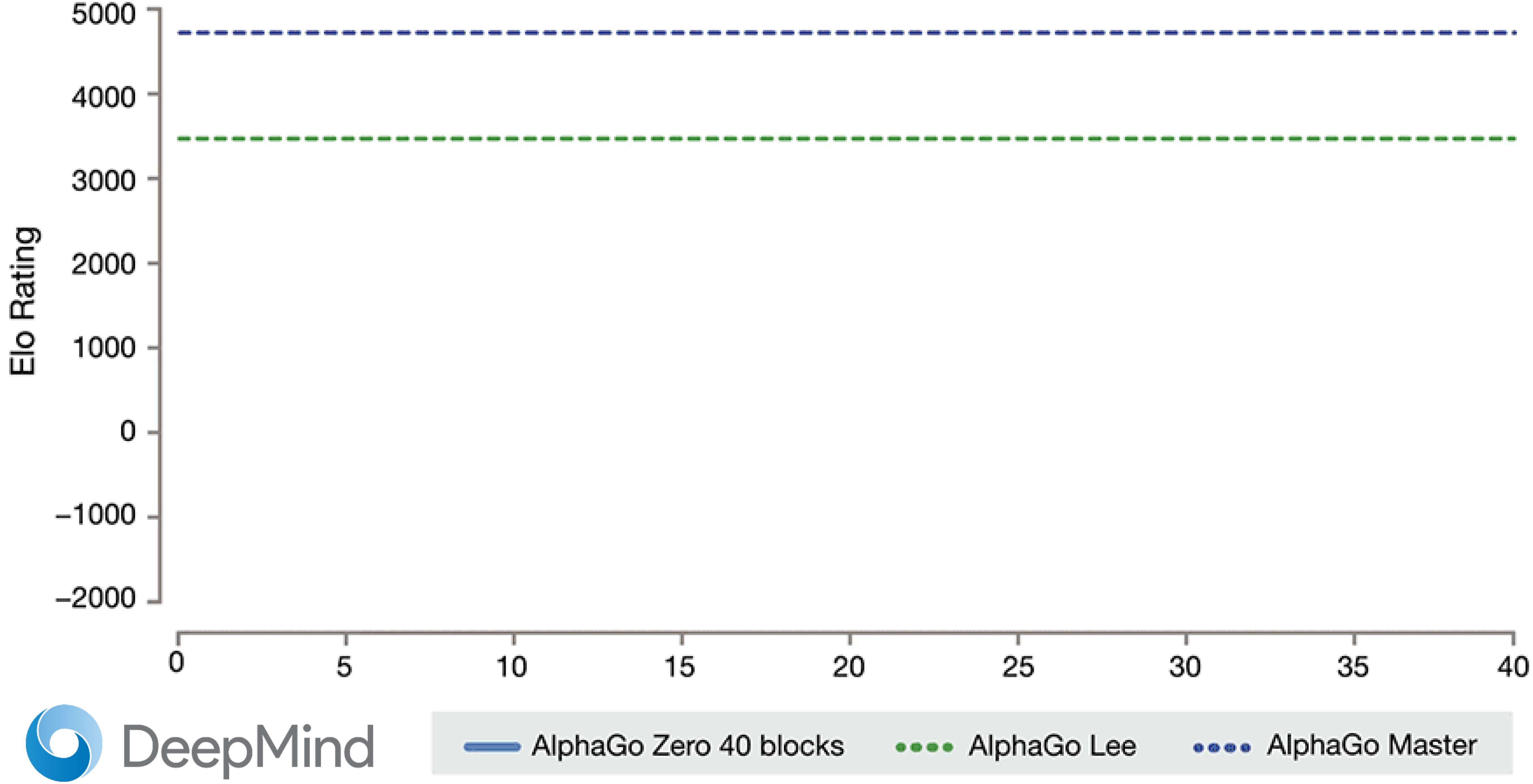
DeepMind
Servers in USA

AlphaGo vs. Lee Sedol

During the legendary matches:

- Google cloud servers in the USA using 1920 CPUs, 280 GPUs and 64 search threads.
- Big data: 30 million moves.
- Reinforcement leaning, Monte Carlo search combined with deep neural network for decision making.

Self-Learning of AlphaGo Zero

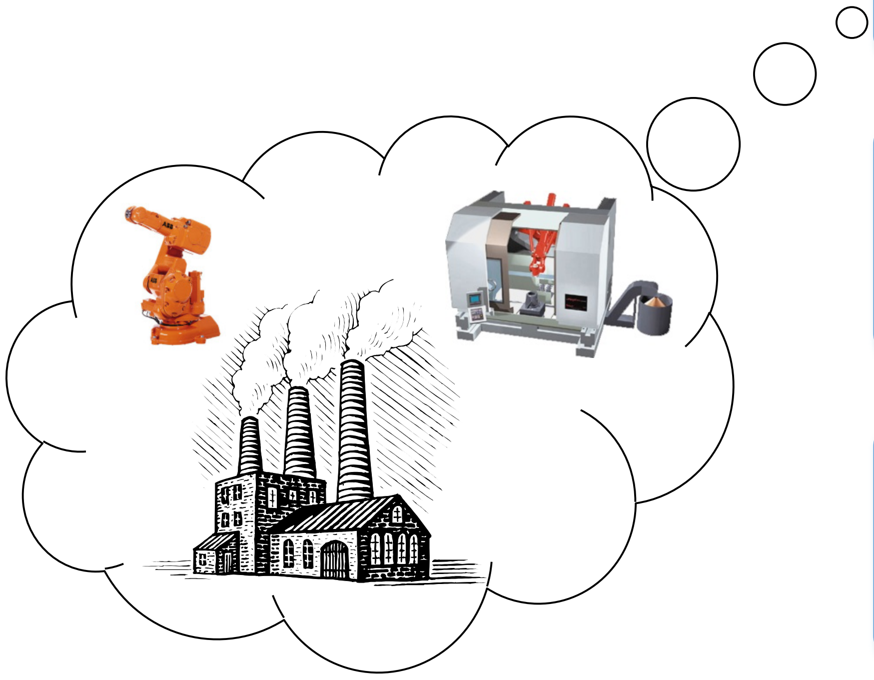


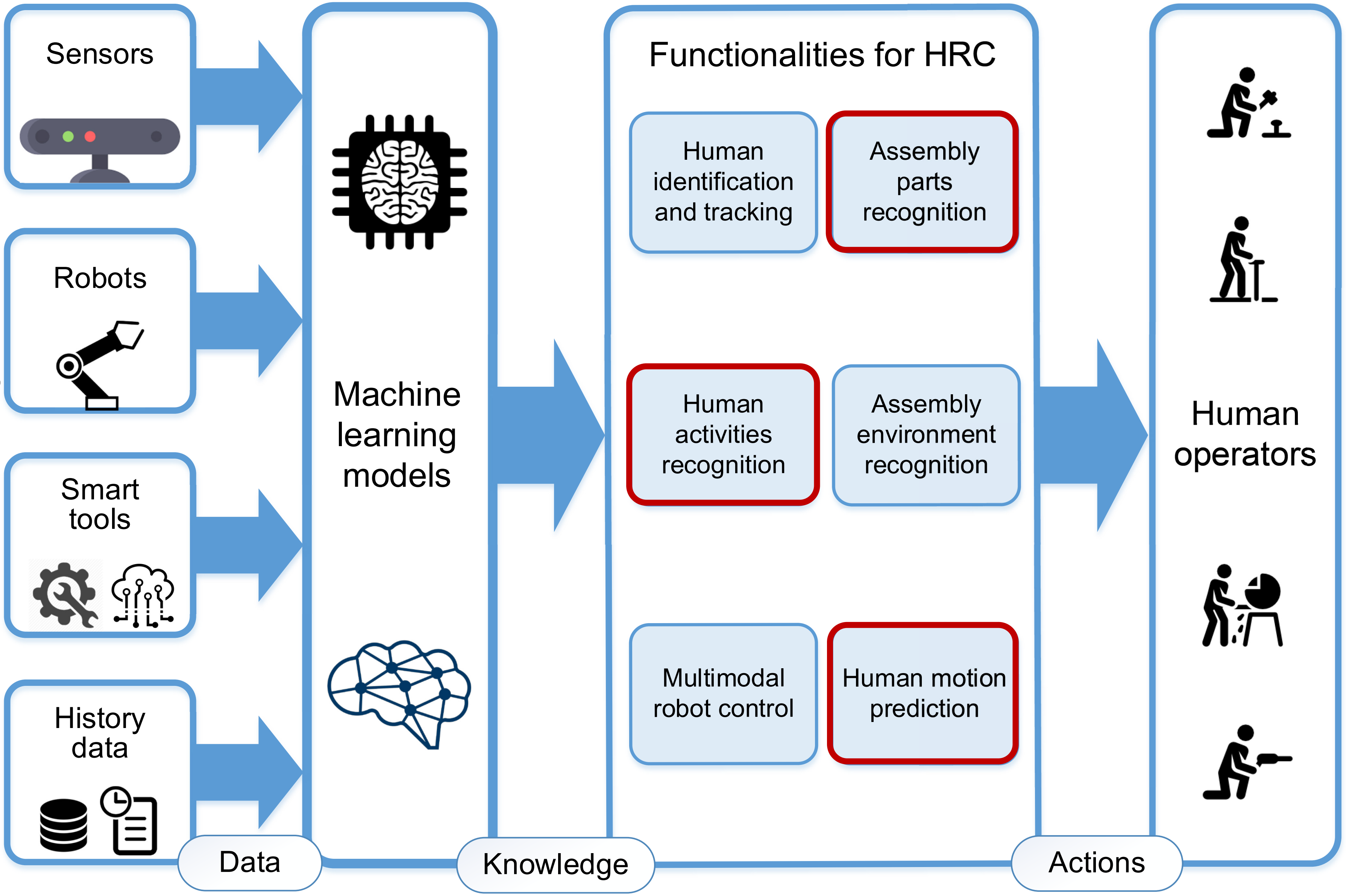
DeepMind

AI for Smart Manufacturing

Reference

L. Wang, "From Intelligence Science to Intelligent Manufacturing," *Engineering*, Vol.5, No.4, pp.615-618, 2019.





Typical Machine Learning Models

Machine learning models	Supervised/ Unsupervised/ Semi-supervised	Discriminative/ Generative	Deep learning/ Not deep learning
K-Means Clustering	Unsupervised	Generative	Not deep learning
K-Nearest Neighbours	Supervised	Discriminative	Not deep learning
Support Vector Machine	Supervised	Discriminative	Not deep learning
Hidden Markov Model	Supervised	Discriminative	Not deep learning
Random Forest	Supervised	Discriminative	Not deep learning
XGBoost	Supervised	Discriminative	Not deep learning
Ensemble Methods	Supervised	Discriminative	Not deep learning
Convolutional Neural Network	Supervised	Discriminative	Deep learning
Recurrent Neural Network	Supervised	Discriminative	Deep learning
Long Short-Term Memory	Supervised	Discriminative	Deep learning
Naive Bayes	Supervised	Generative	Not deep learning
Gaussian Mixture Model	Supervised	Generative	Not deep learning
Generative Adversarial Nets	Semi-supervised	Generative	Deep learning

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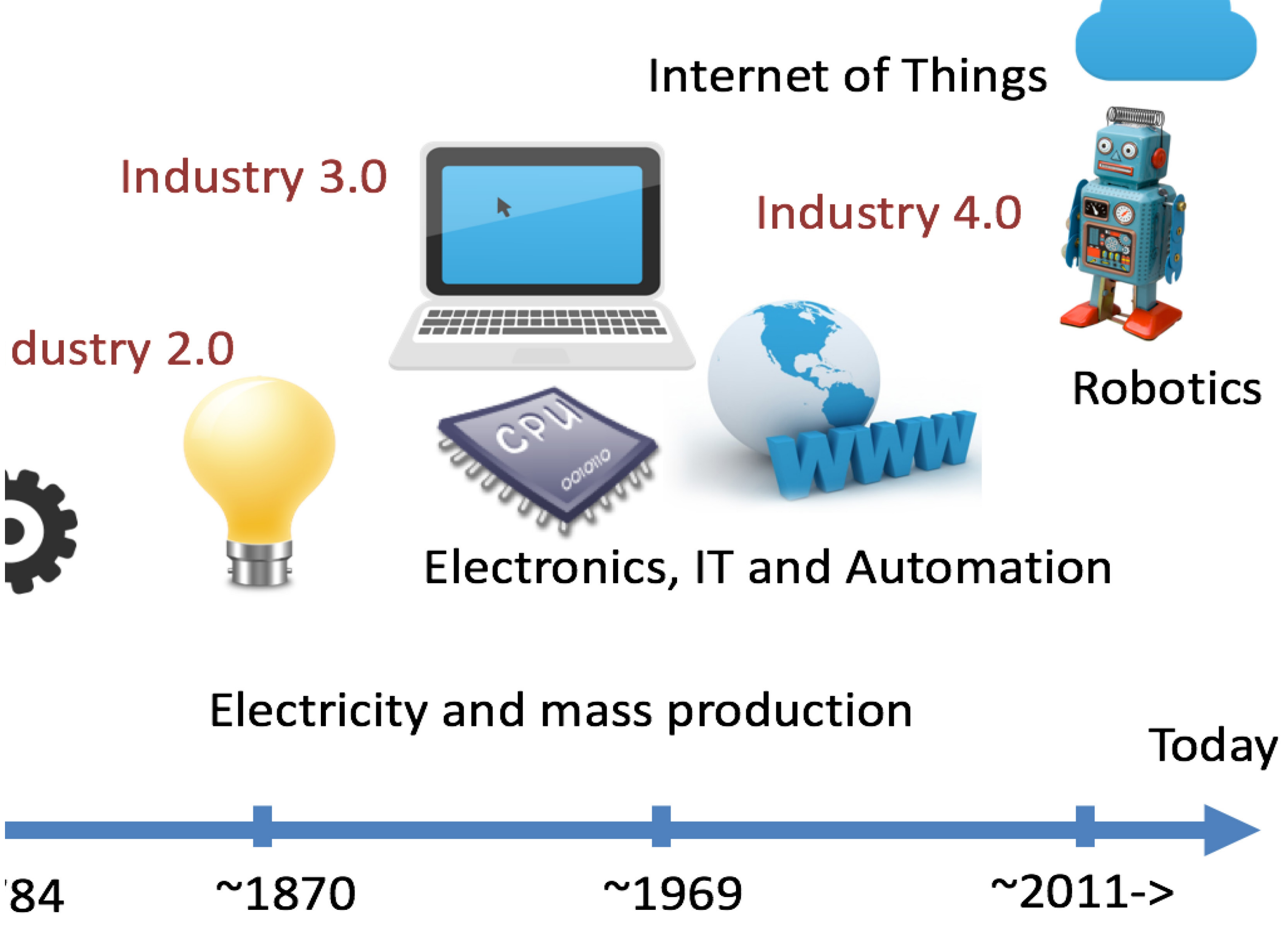
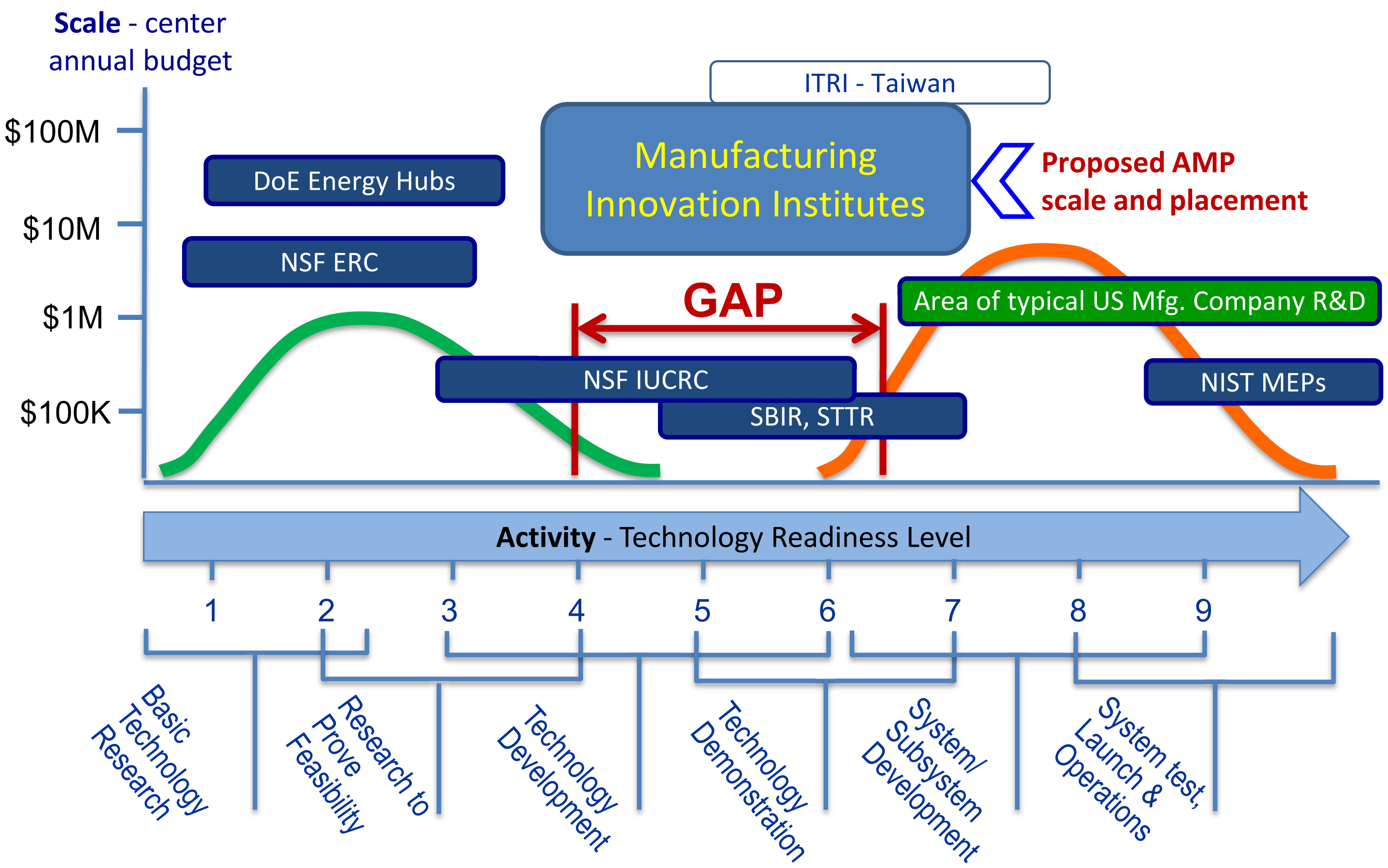
Present

Industry 4.0 and Opportunities

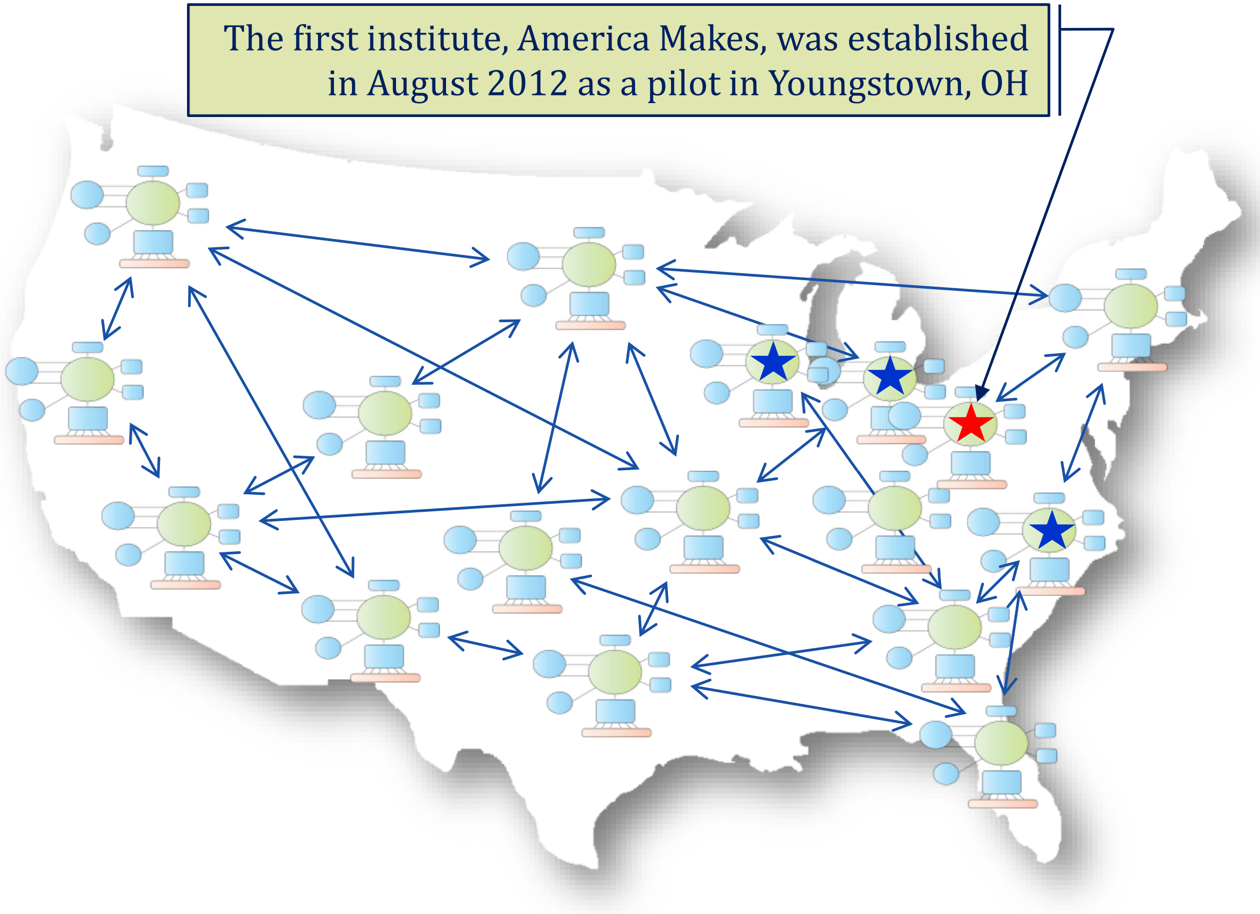
(Adapted from Baur C., Wee D.: Manufacturing's Next Act. MacKinsey & Company Digital, June 2015, https://www.mckinsey.com/business-functions/operations/our-insights/manufacturings-next-act)



AMP 2.0 on Manufacturing Innovation



National Network of Mfg Innovation



Source: M Molnar, Advanced Manufacturing National Program Office, with modifications

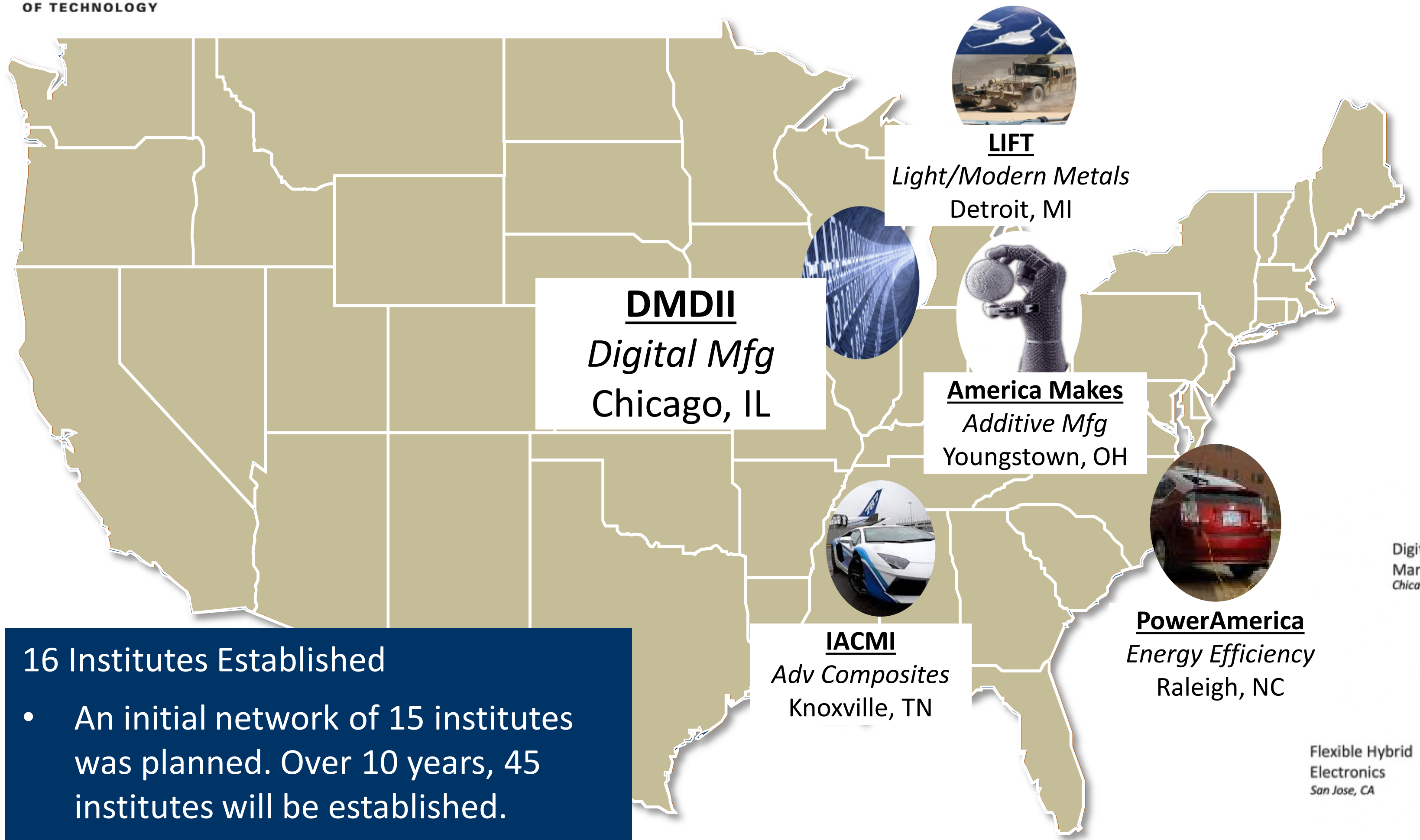
- Regional hubs for manufacturing innovation
- Promote collaboration between institutes
- Establish common policies when appropriate
- Provide a forum for sharing best practices
- Link activities through the Manufacturing Portal

3 More Institutes founded in 2014

President Obama announced the Power Electronics Manufacturing Institute in North Carolina on ***January 15, 2014***

President Obama announced the Manufacturing Institutes in Light Weight Metals Manufacturing (Detroit) and Digital Manufacturing and Design Innovation (Chicago) on ***February 25, 2014***

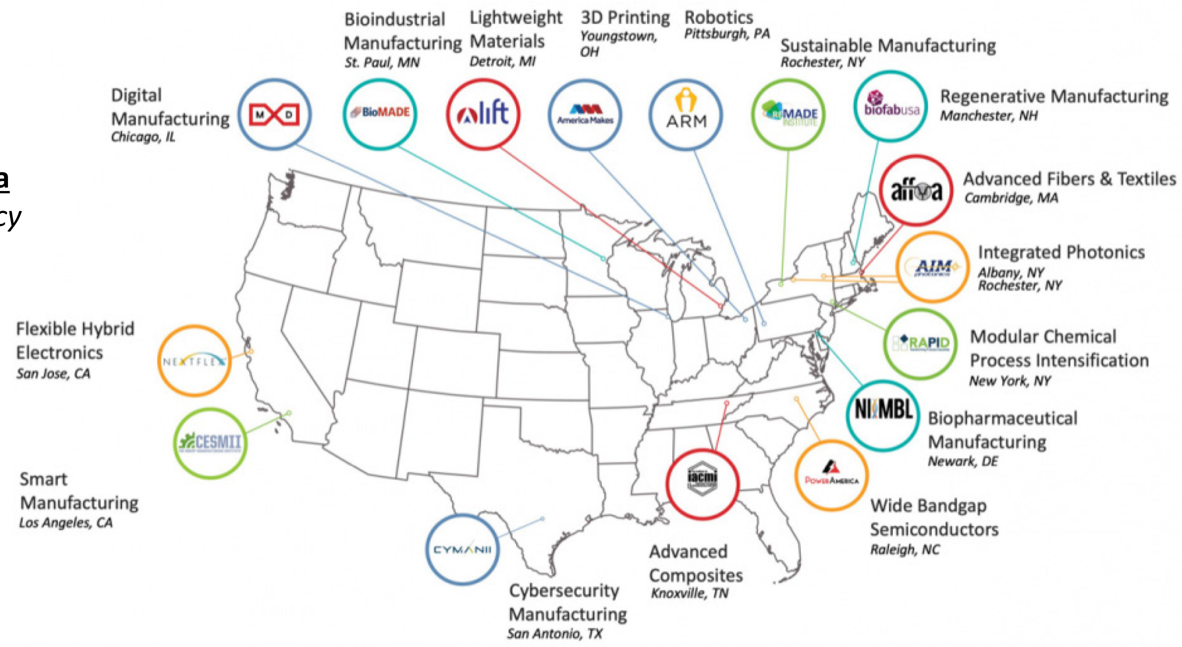
16 Institutes as Part of NNMI



16 Institutes Established

- An initial network of 15 institutes was planned. Over 10 years, 45 institutes will be established.
- At launch, 349 companies and universities active partners from all across the country

Manufacturing USA



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Other Innitiatives

FoF

Factories of the Future

Public Private Partnership

PRODUKTION2030

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Smart Manufacturing: CPS in Mfg

Cyber-Physical Systems

Industrial Internet

Smart

Big Data

Internet of Things

Cloud Manufacturing

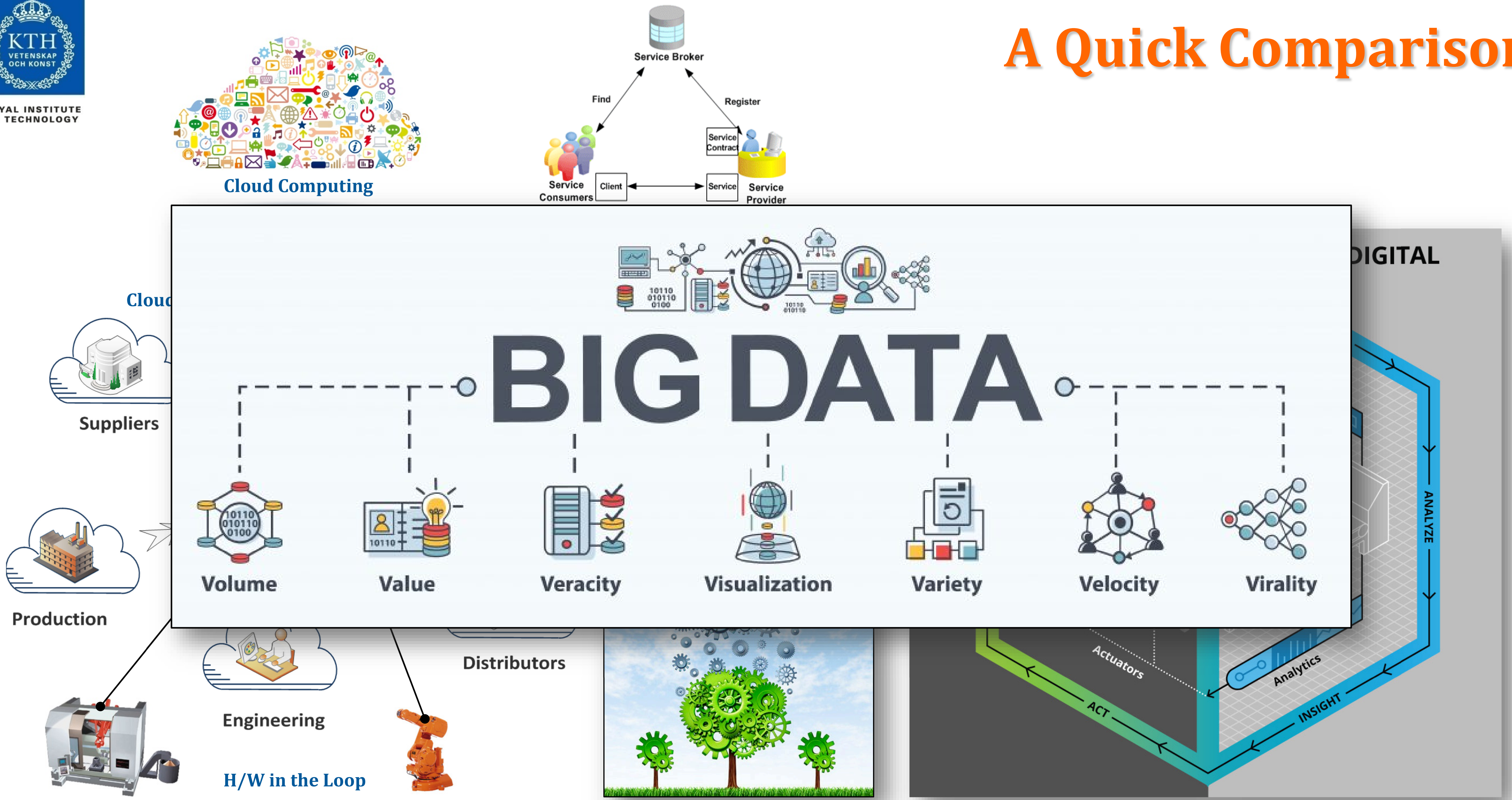
Manufacturing

Digital Twin

Embedded Systems

System of CPS

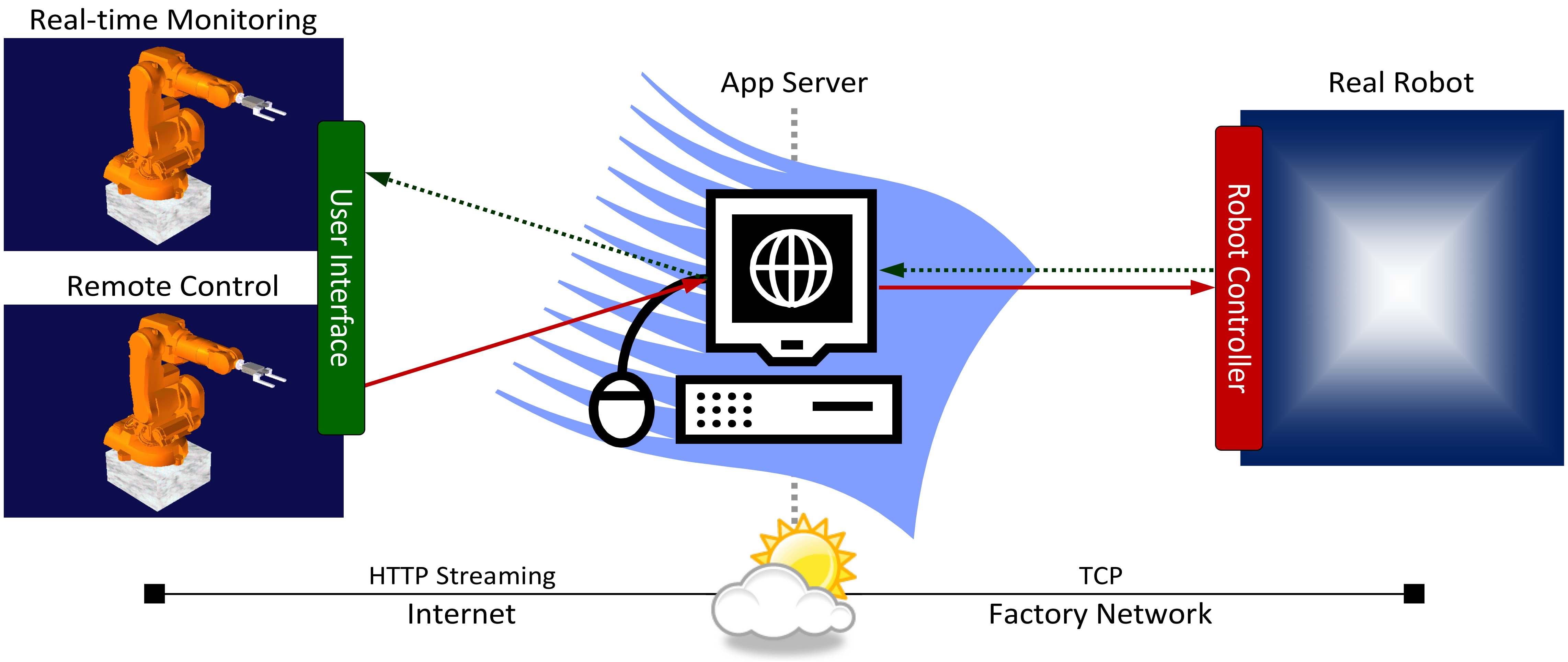
A Quick Comparison



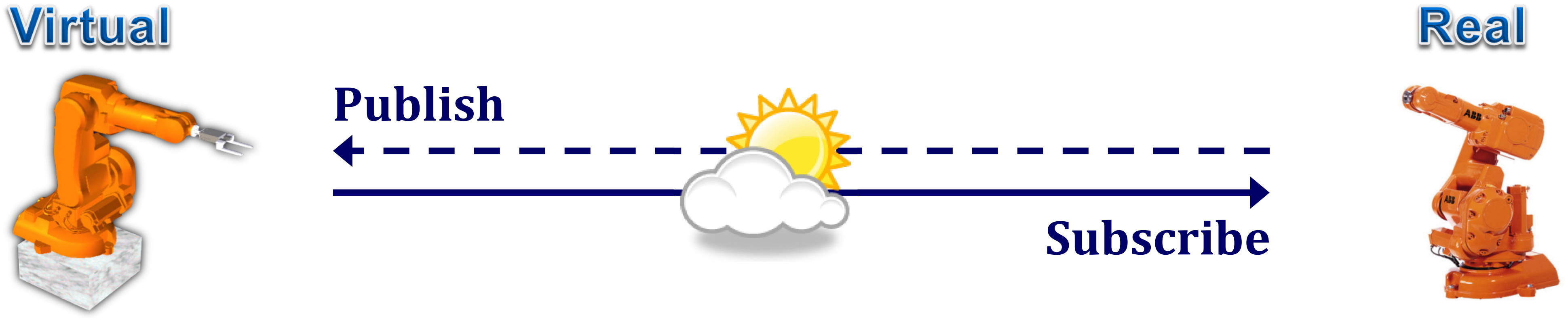
Topic 1:

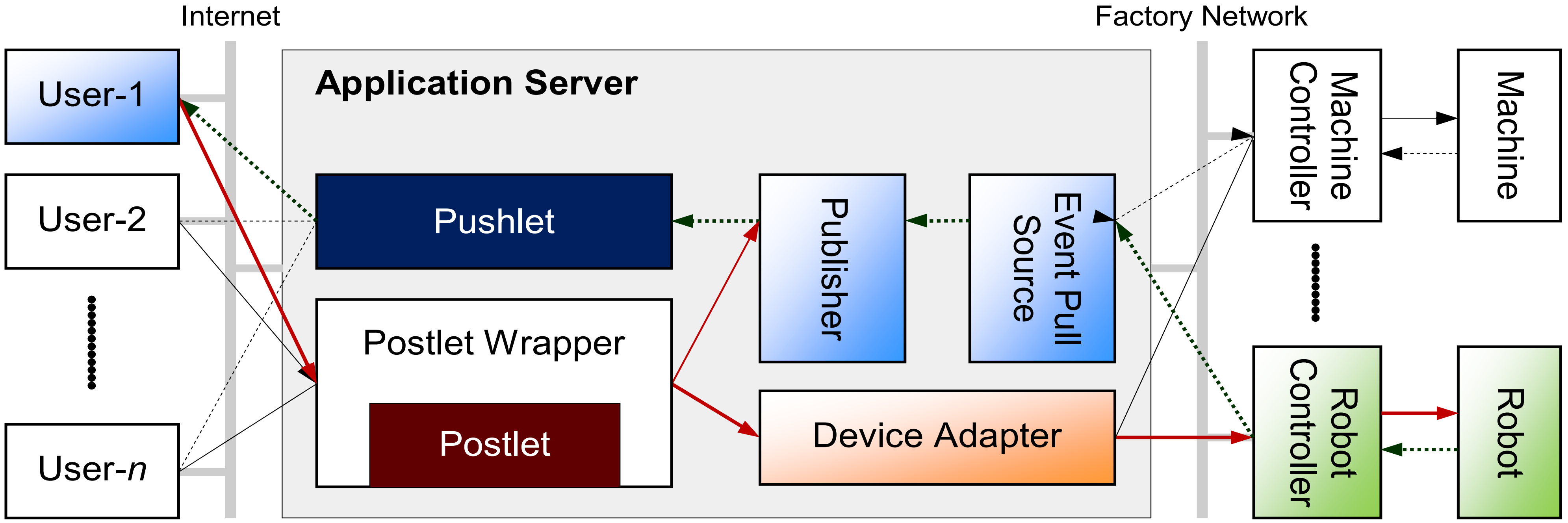
Remote Monitoring and Control

A CPS in the Cloud

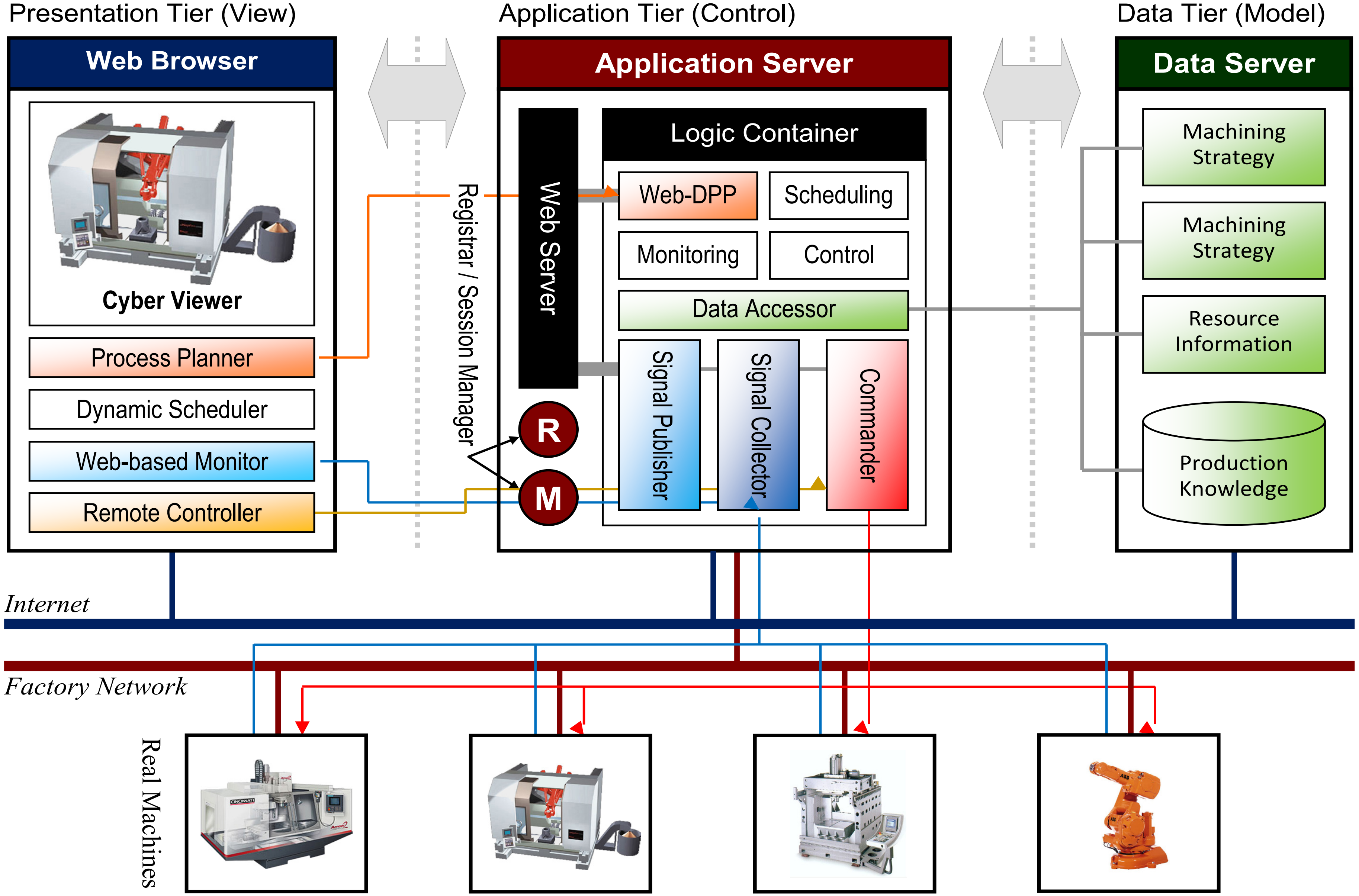


Virtual to Real via Cloud





System Architecture

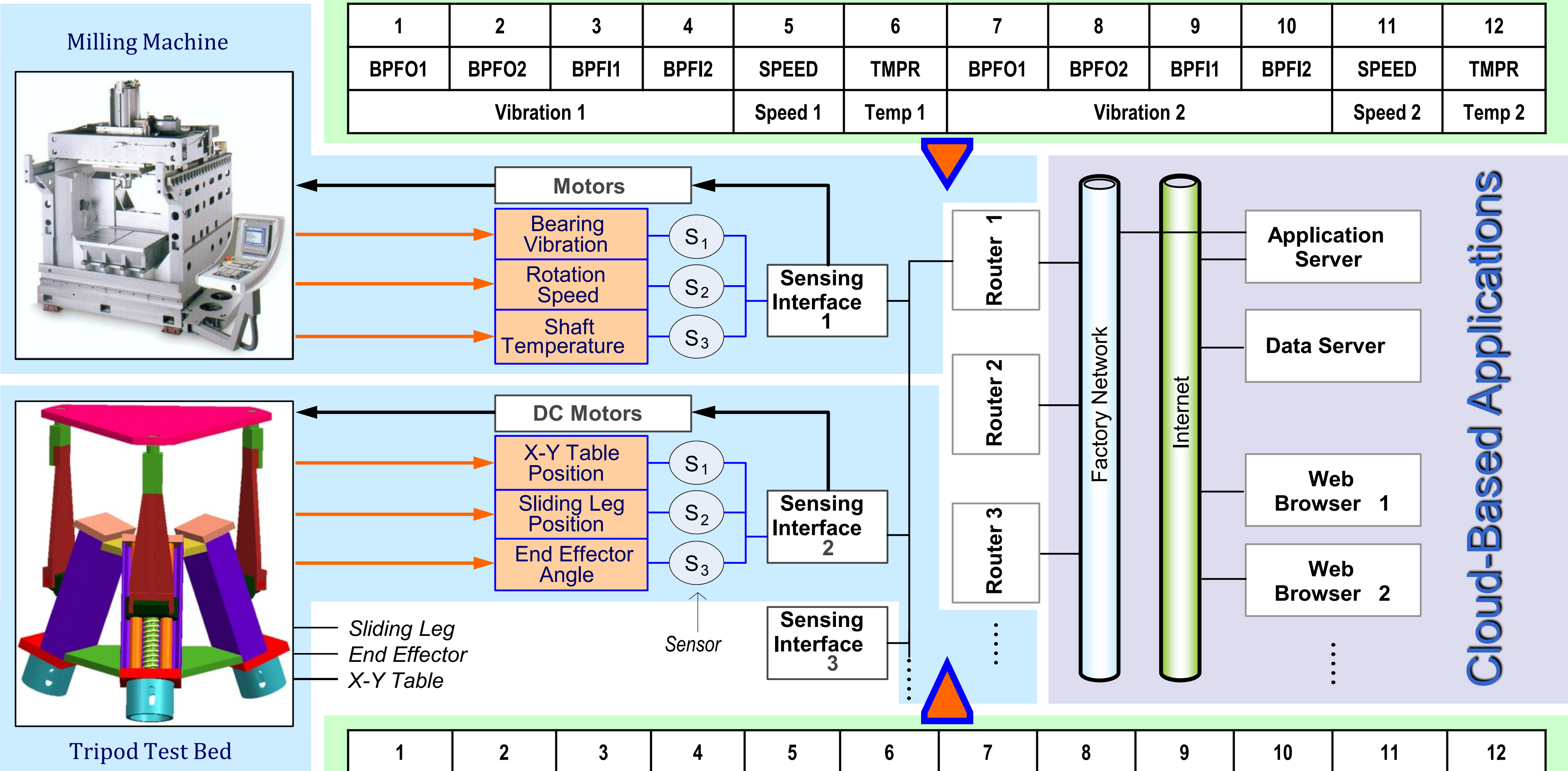


Sensor Data Collection

In collaboration with Professor Robert Gao, CWRU

Health Monitoring Data Format

1	2	3	4	5	6	7	8	9	10	11	12
BPFO1	BPFO2	BPFI1	BPFI2	SPEED	TMPR	BPFO1	BPFO2	BPFI1	BPFI2	SPEED	TMPR
Vibration 1				Speed 1	Temp 1	Vibration 2				Speed 2	Temp 2



1	2	3	4	5	6	7	8	9	10	11	12
Axis1	Axis2	Axis3	Axis4	Axis5	Axis1	Axis2	Axis3	Axis4	Axis5	Feed Rate	SPEED
Relative Position					Absolute Position						

Motion Monitoring Data Format

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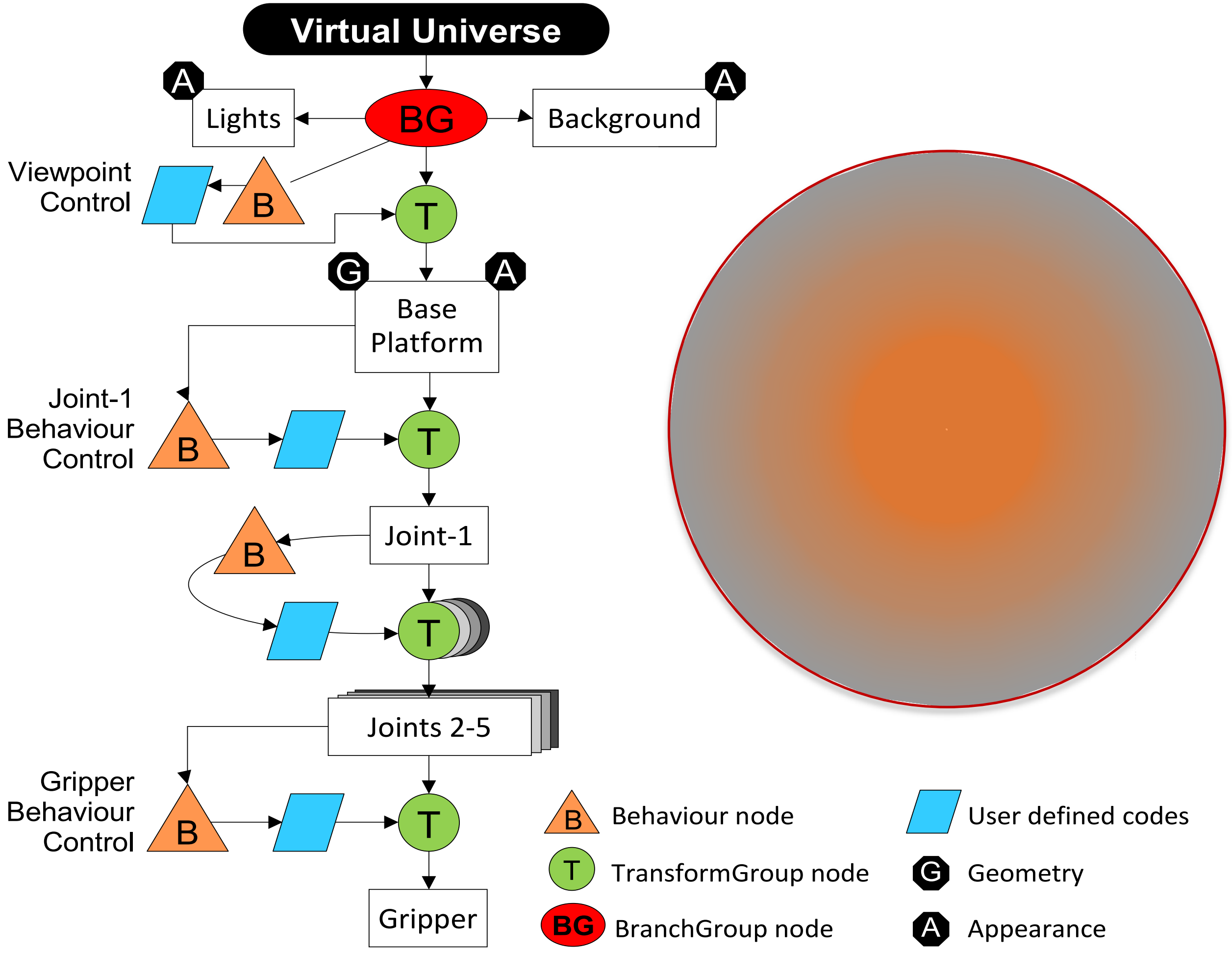
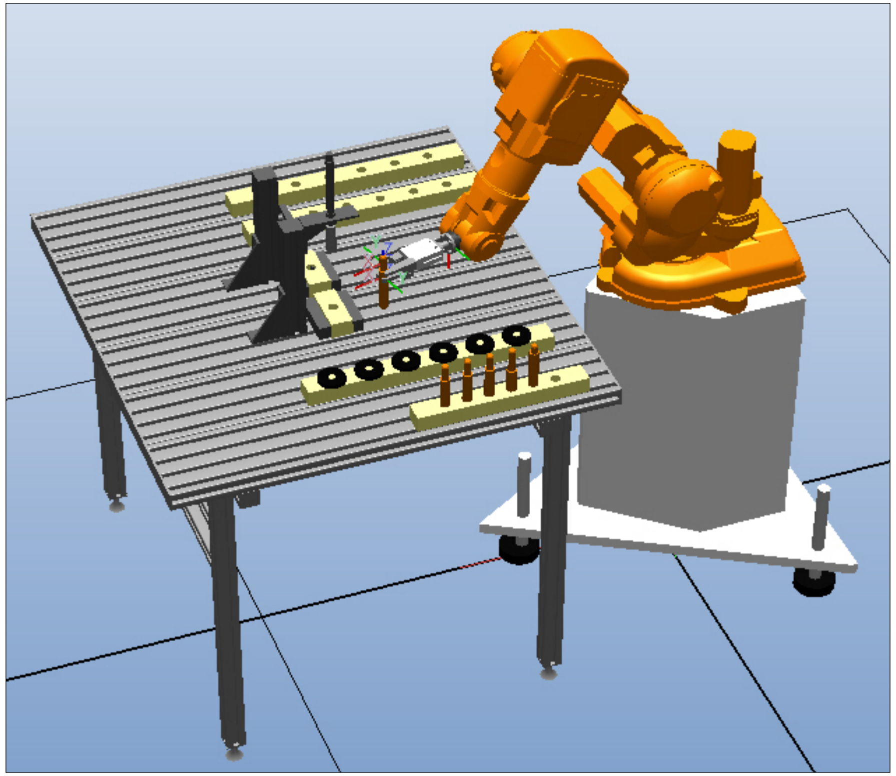
A Mini Robotic Assembly Cell





A mini robotic assembly cell

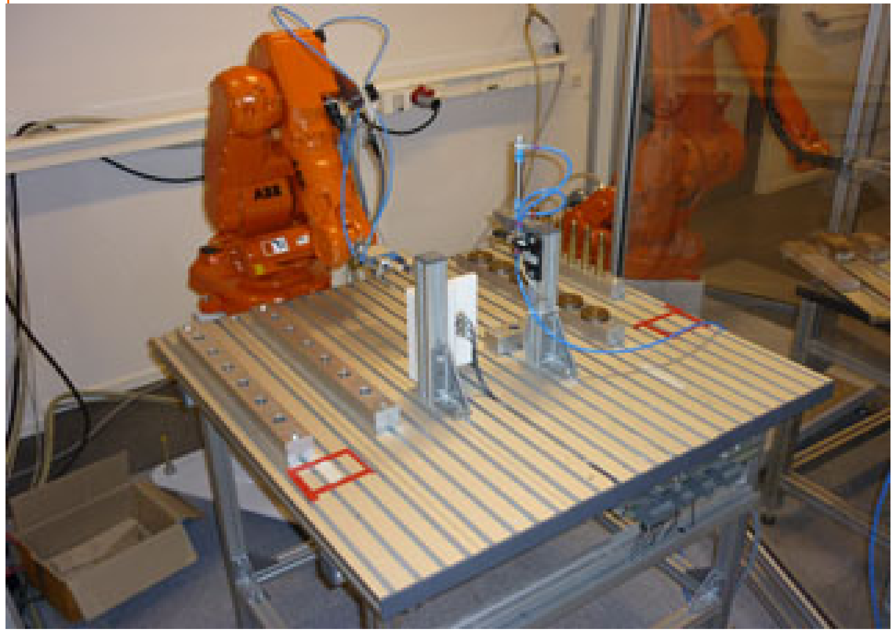
Demo

Data Size Comparison

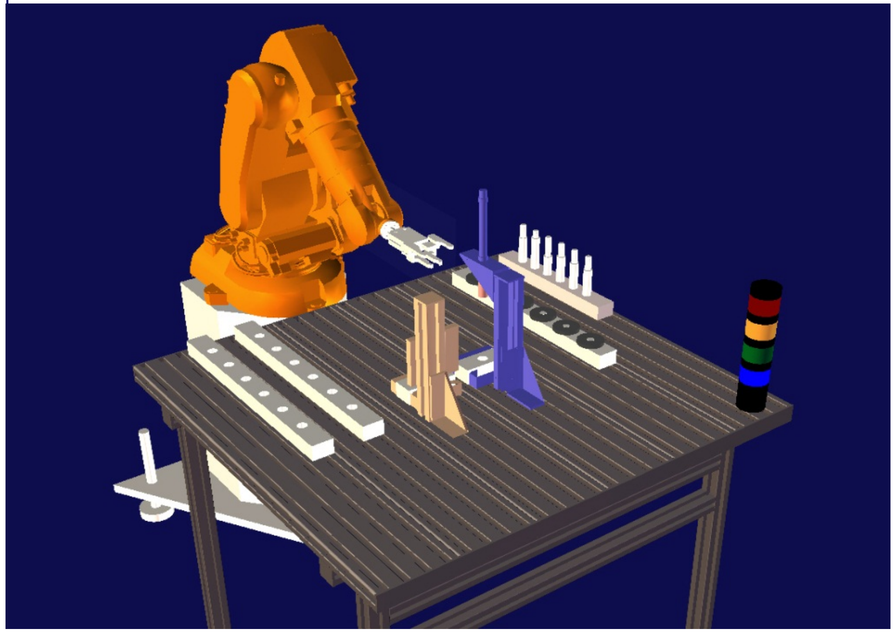
1	2	3	4	5	6	7	8	9	10	11	12	13
Relative position of 6 joints						Absolute position of 6 joints						CW

0.017%

100%



An 8-bit VGA Camera Image
640×480 (307,200 bytes)



One Scene in Java 3D
Any size (52 bytes)

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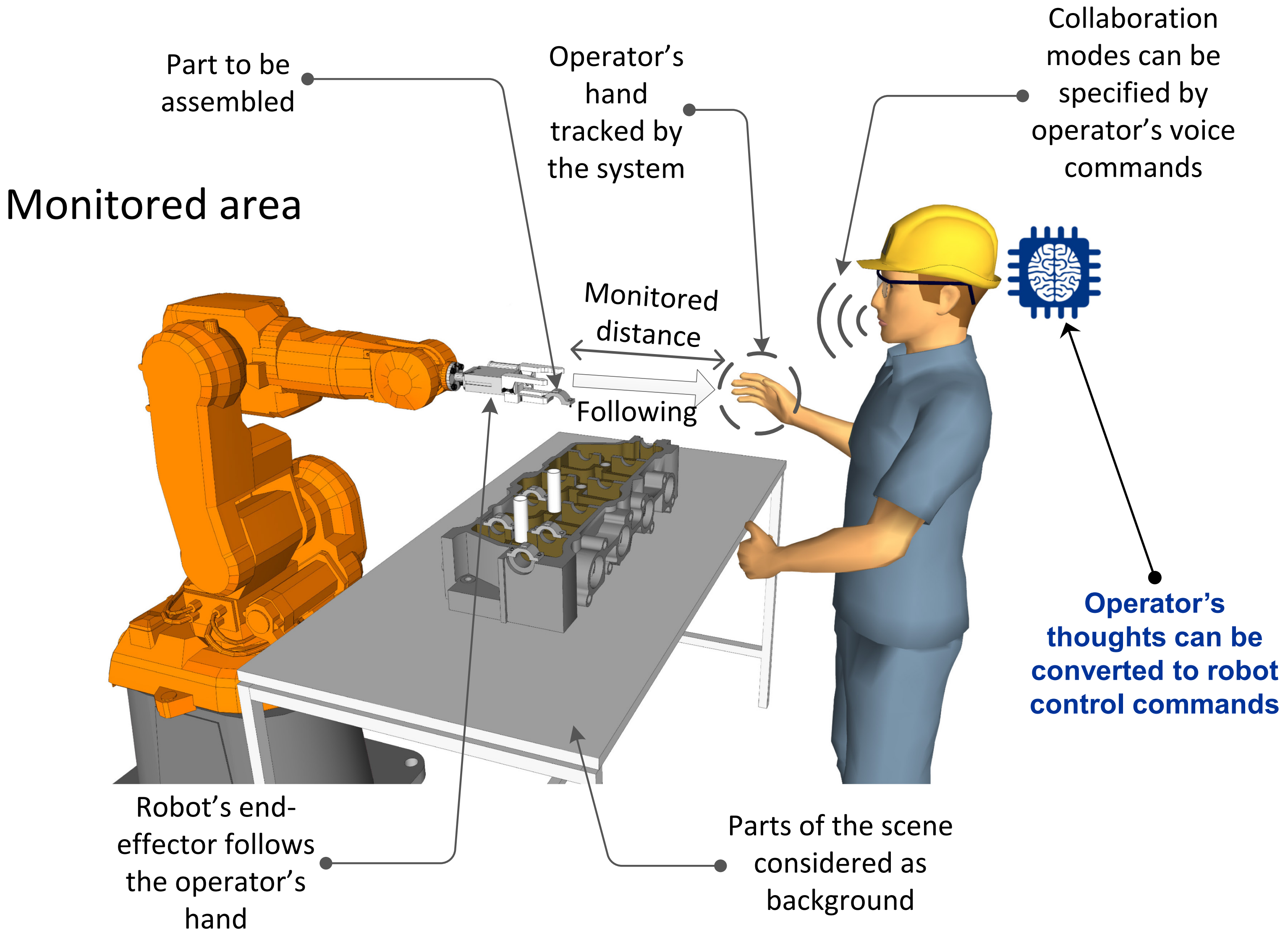
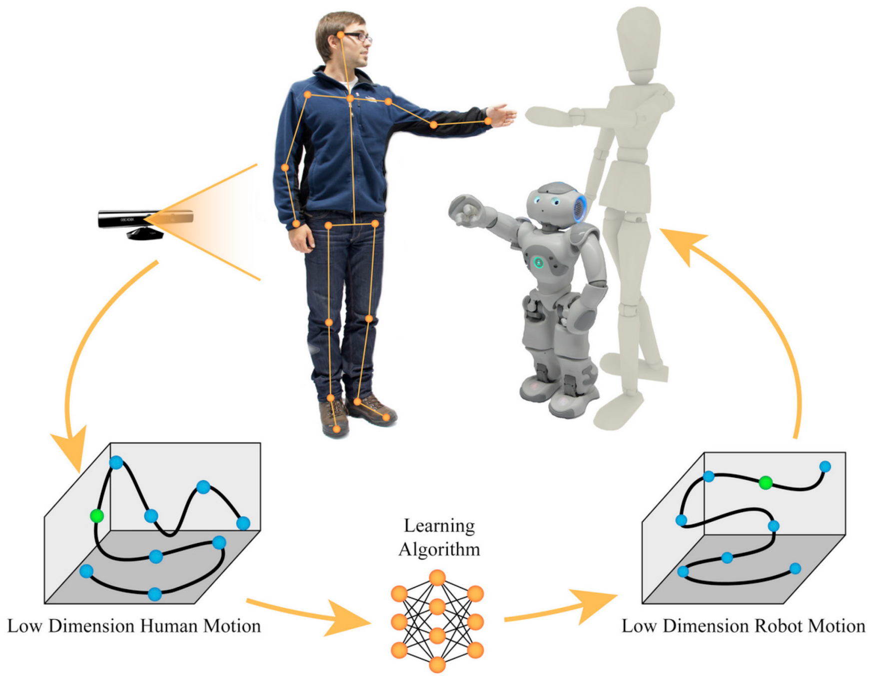
Topic 2:

Human-Robot Collaboration

Human-Robot Collaboration

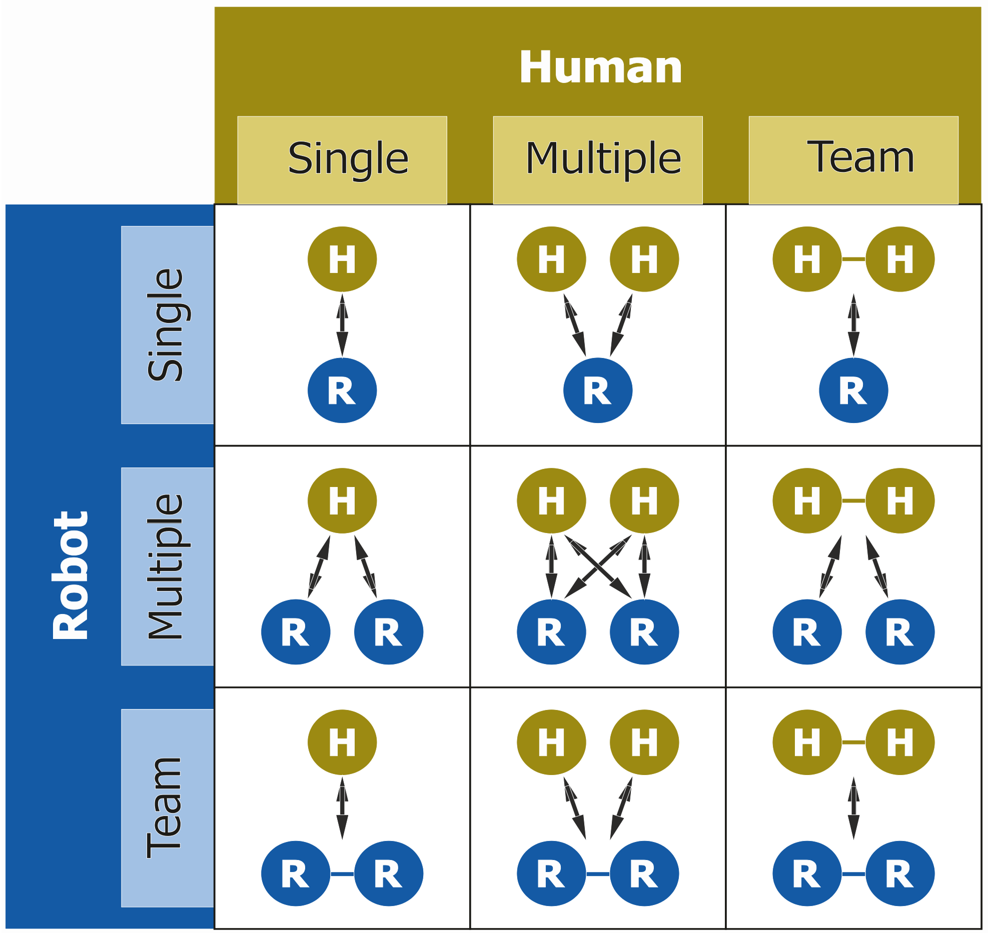


- The capability to track an operator's position allows controlling a robot to follow the operator

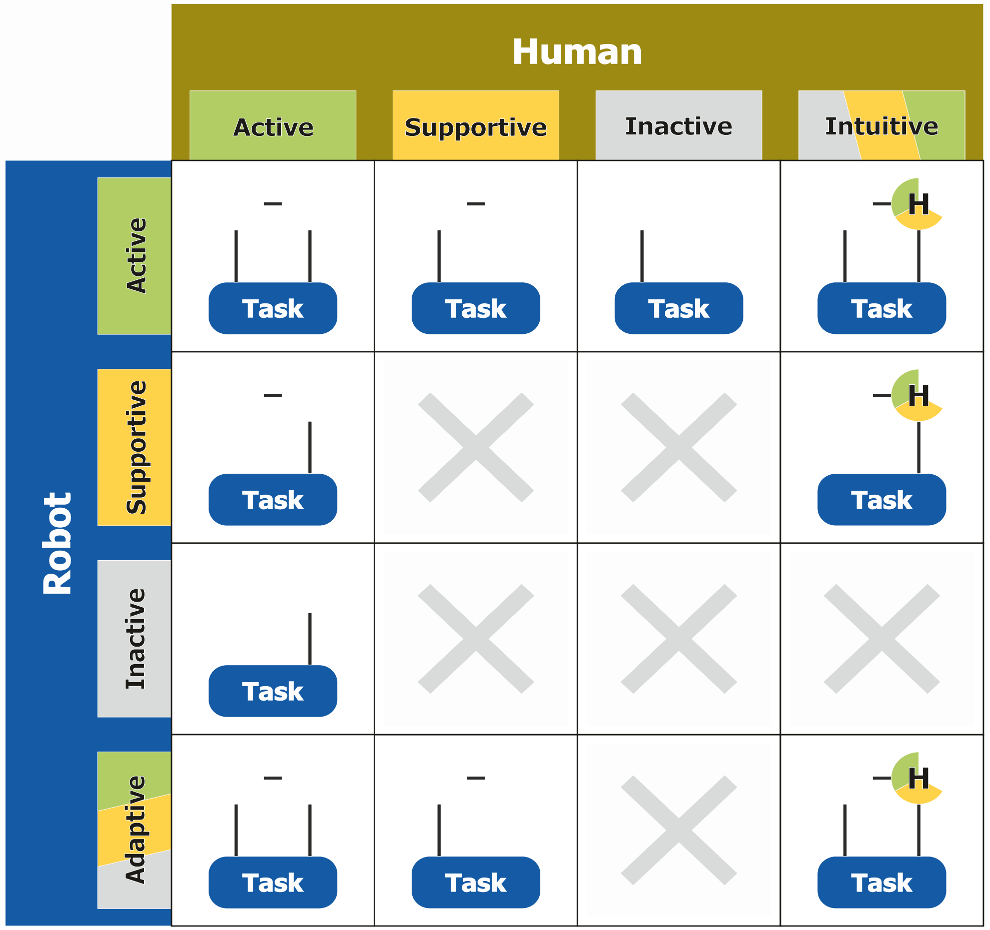


Key Properties of HRC Assembly

Multiplicity

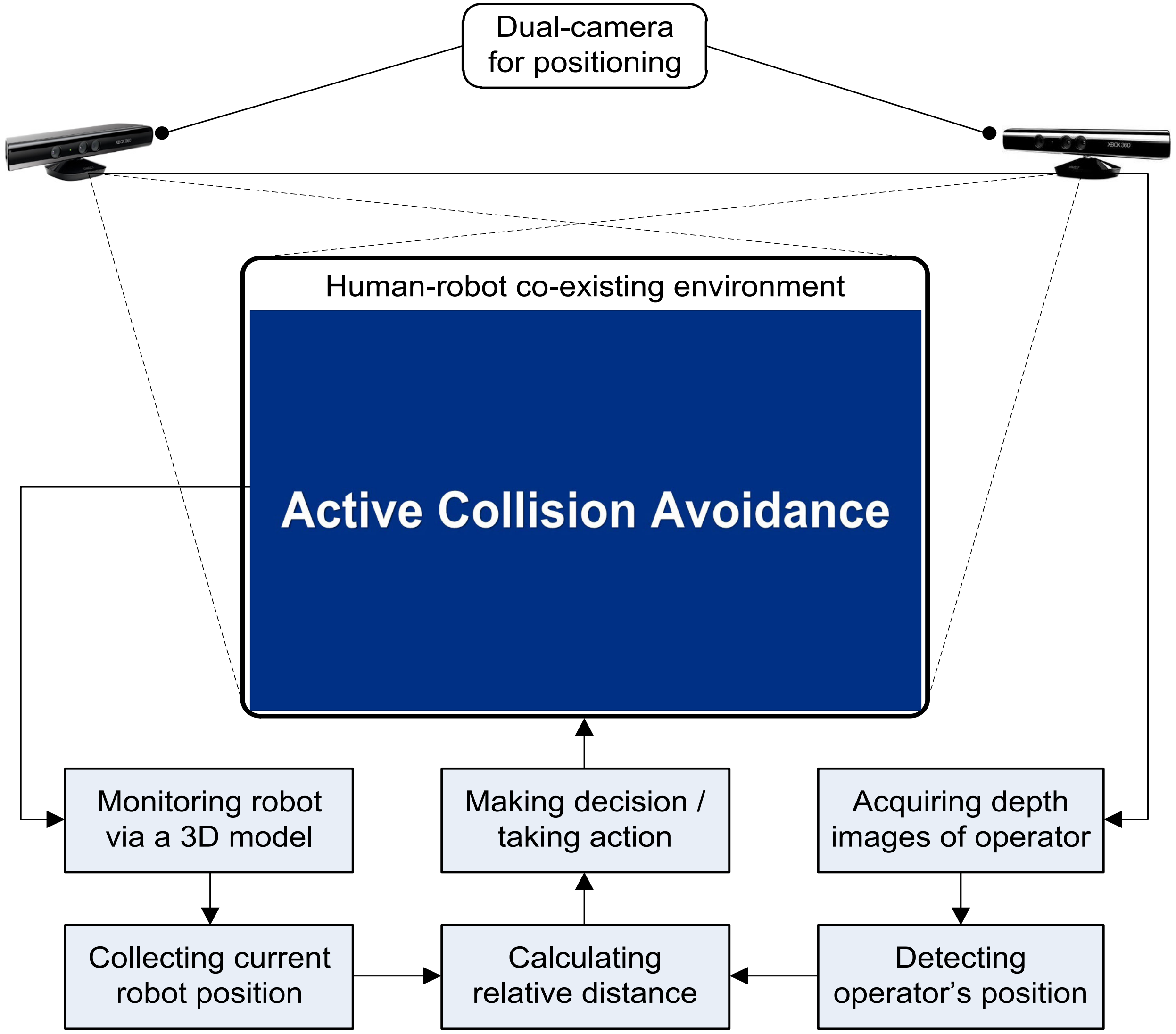


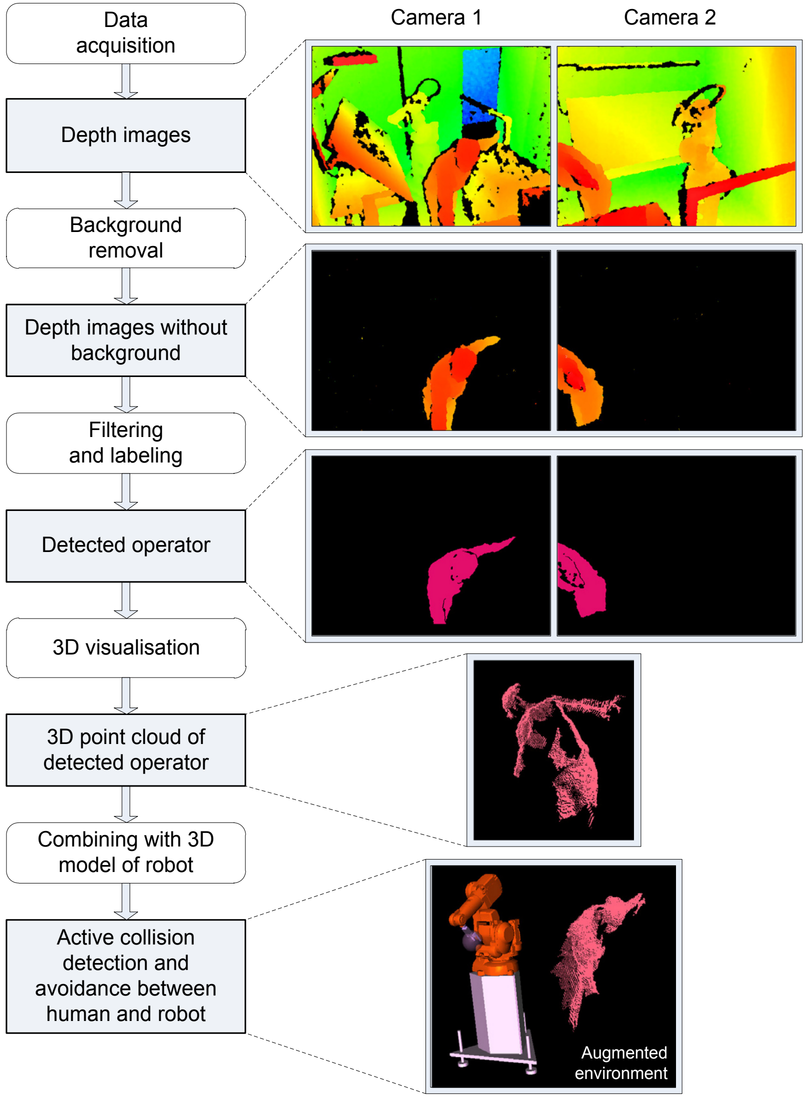
Initiative



Reference Wang XV, Kemény Z, Váncza J, Wang L (2017) Human–Robot Collaborative Assembly in Cyber-Physical Production: Classification Framework and Implementation. *CIRP Ann - Manuf Technol* 66(1):5–8.

Active Collision Avoidance

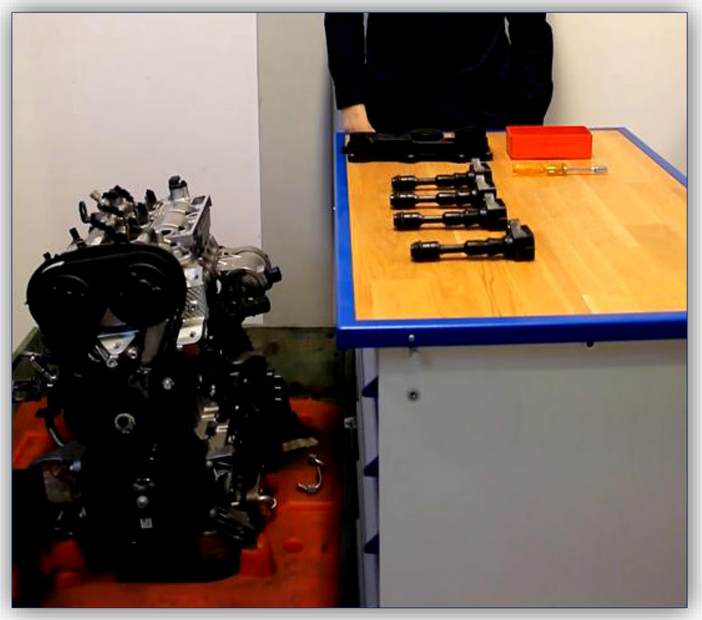




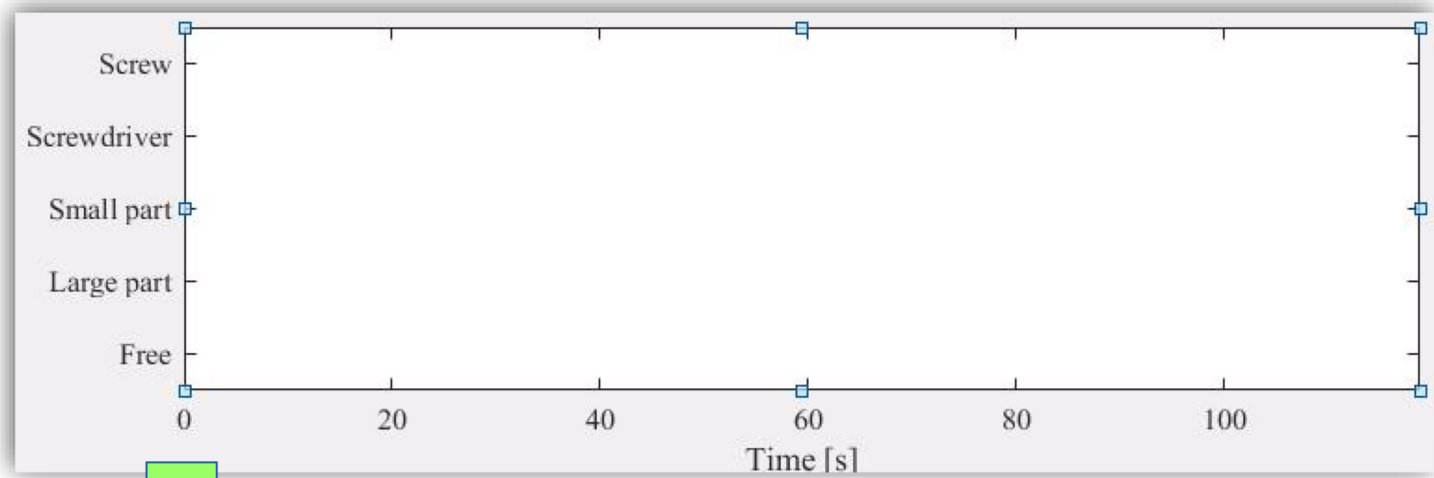
Reference Schmidt B, Wang L (2014) Depth camera based collision avoidance via active robot control. *J Manuf Syst* 33(4):711–7118.

Deep Learning of Assembly Context

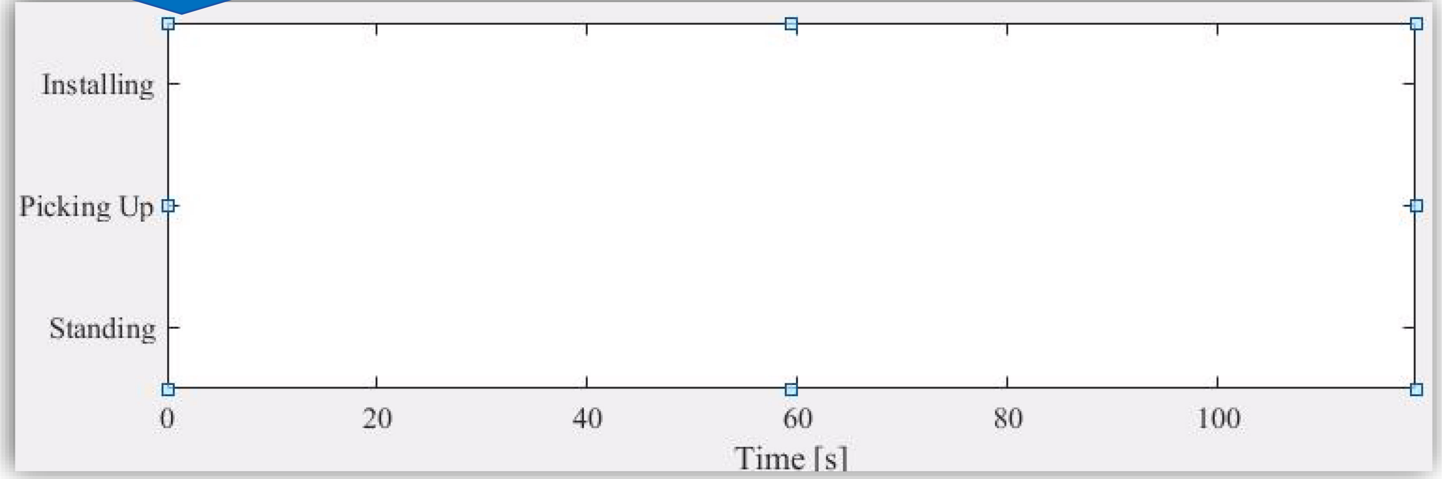
Part/tool identification



Human action recognition

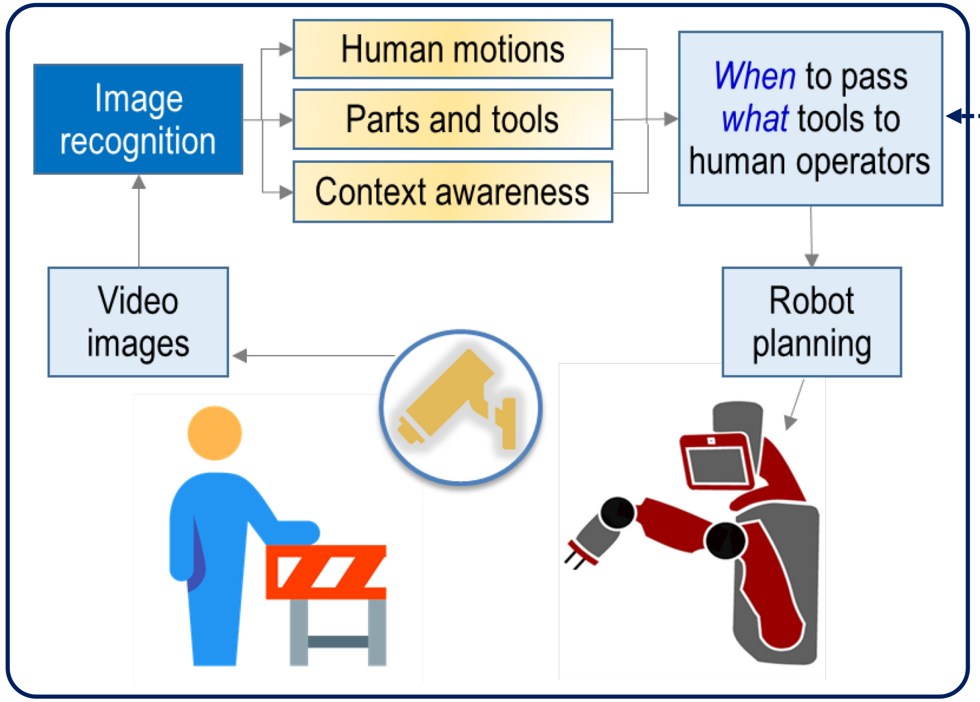


- Part/tool identification: recognize what the human operator picks up
- Identified part/tool: valid for a "picking up" + "installing" combination



Reference Wang P, Liu H, Wang L, Gao RX (2018) Deep learning-based human motion recognition for predictive context-aware human-robot collaboration. *CIRP Ann - Manuf Technol* 67(1):17–20.

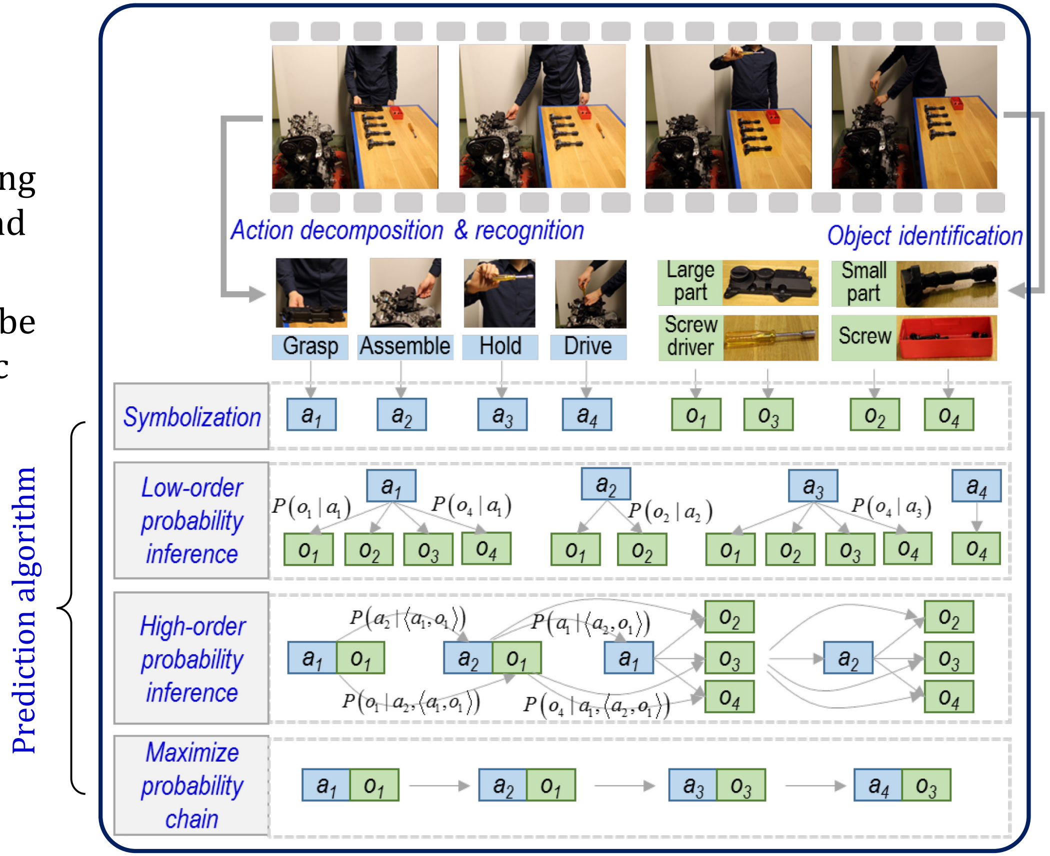
Prediction for Robotic Assistance



Prediction

$$\begin{cases} P(\sigma \mid s)=\dfrac{P(\sigma s)}{P(s)}=\dfrac{\sum_{i,j} X_{\sigma s}^{i,j} / \sum_i \left(l_i-|\sigma s|+1\right)}{\sum_{i,j} X_{s}^{i,j} / \sum_i \left(l_i-|s|+1\right)} \geq P_{\min}, \forall \sigma \in \Sigma \\ \dfrac{P(\sigma \mid s)}{P(\sigma \mid \operatorname{suf}(s))} \geq \beta, \quad \beta: \textit{positive constant} \end{cases}$$

Example: probabilistic modeling of human action and intention



Prediction

- Based on cognition and modeling of human *behavioral pattern* and preference
- Human *heterogeneity* needs to be accounted for, in a probabilistic manner

Action

- Safely *adapt to* human worker's planned and unplanned interactions

Reference

Wang P, Liu H, Wang L, Gao RX (2018) Deep learning-based human motion recognition for predictive context-aware human-robot collaboration. *CIRP Ann - Manuf Technol* 67(1):17–20.

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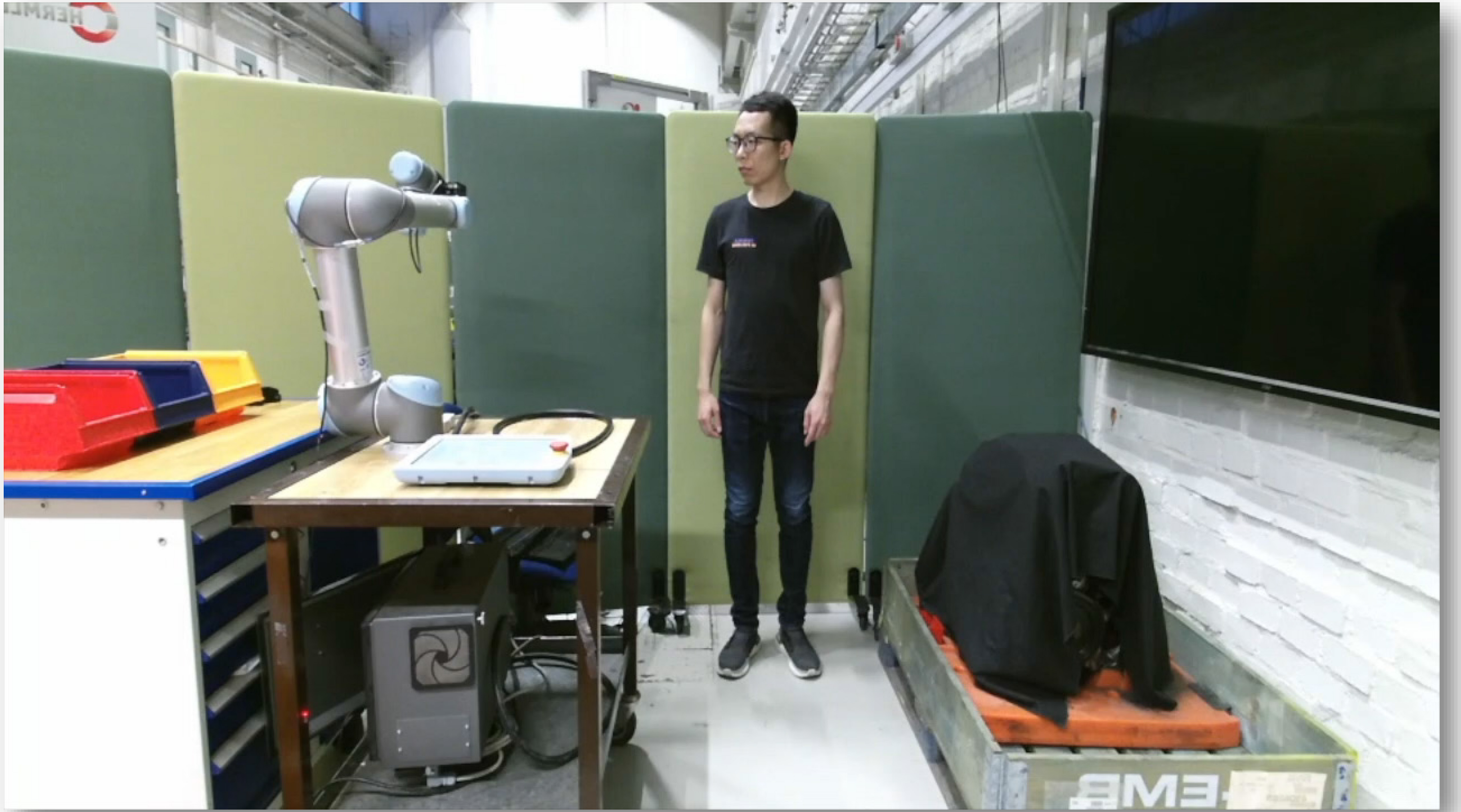
Robot Assisting Human in Assembly

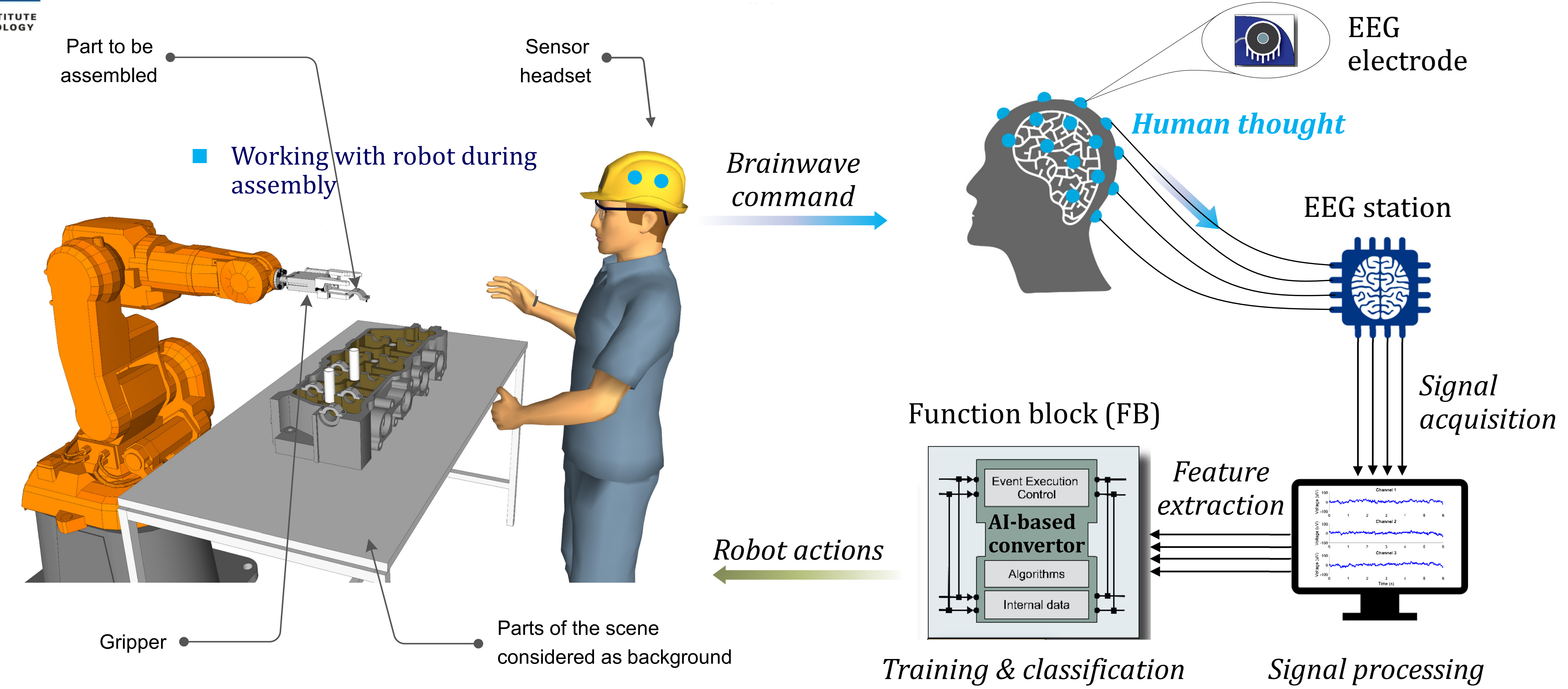
Reference

J. Zhang, H. Liu, Q. Chang, L. Wang and R. X. Gao, "Recurrent Neural Network for Motion Trajectory Prediction in Human-Robot Collaborative Assembly," *CIRP Ann - Manuf Technol*, 69(1), 9-12, 2020.



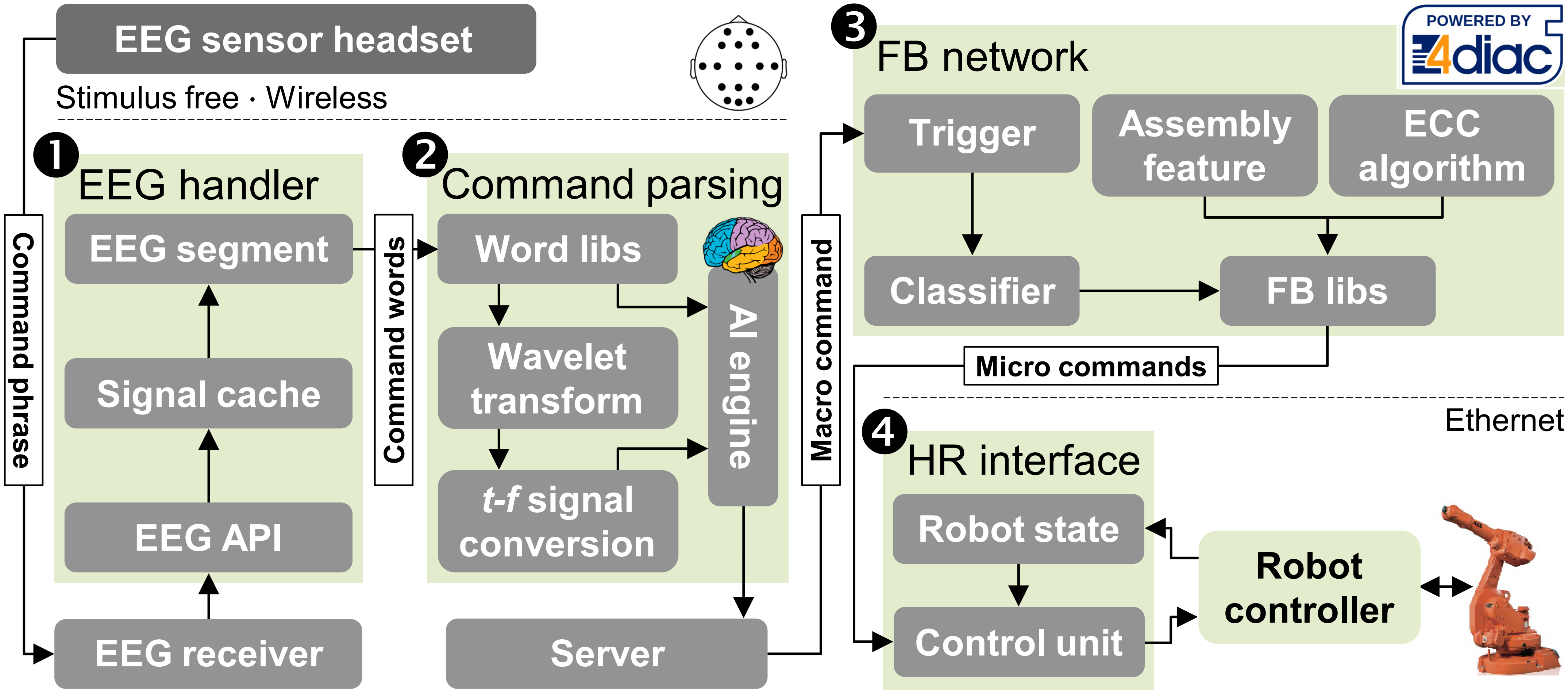
Future

Concept of Brain Robotics



Reference L. Wang, S. Liu, C. Cooper, X. V. Wang and R. X. Gao, "Function Block-Based Human-Robot Collaborative Assembly Driven by Brainwaves," *CIRP Annals – Manufacturing Technology*, Vol.70, No.1, pp.5-8, 2021.

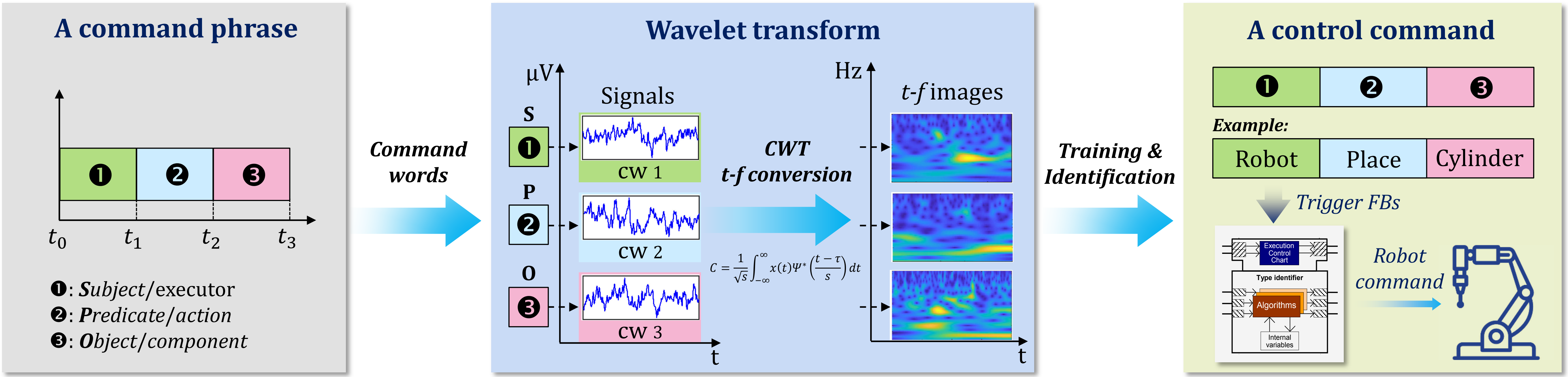
System Architecture and Configuration



Reference

L. Wang, S. Liu, C. Cooper, X.V. Wang and R.X. Gao, "Function Block-Based Human-Robot Collaborative Assembly Driven by Brainwaves," *CIRP Annals – Manufacturing Technology*, Vol.70, No.1, pp.5-8, 2021.

From Brainwaves to Control Commands

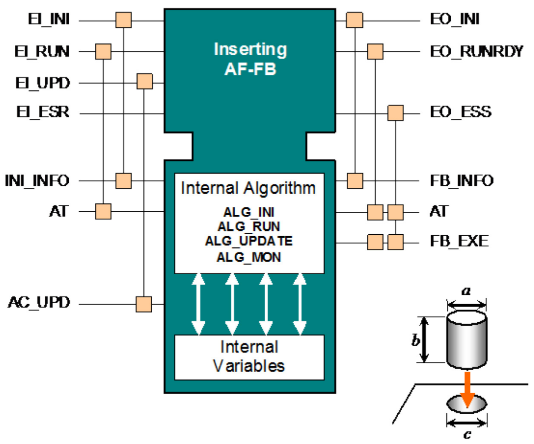


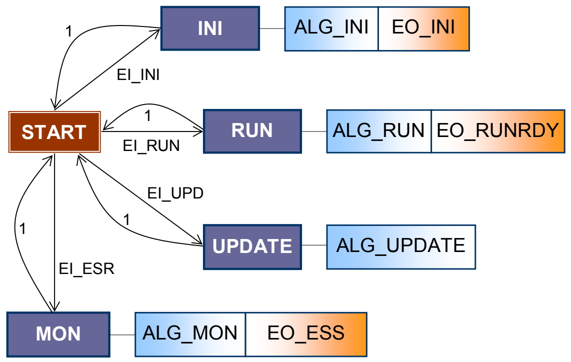
cw: command word

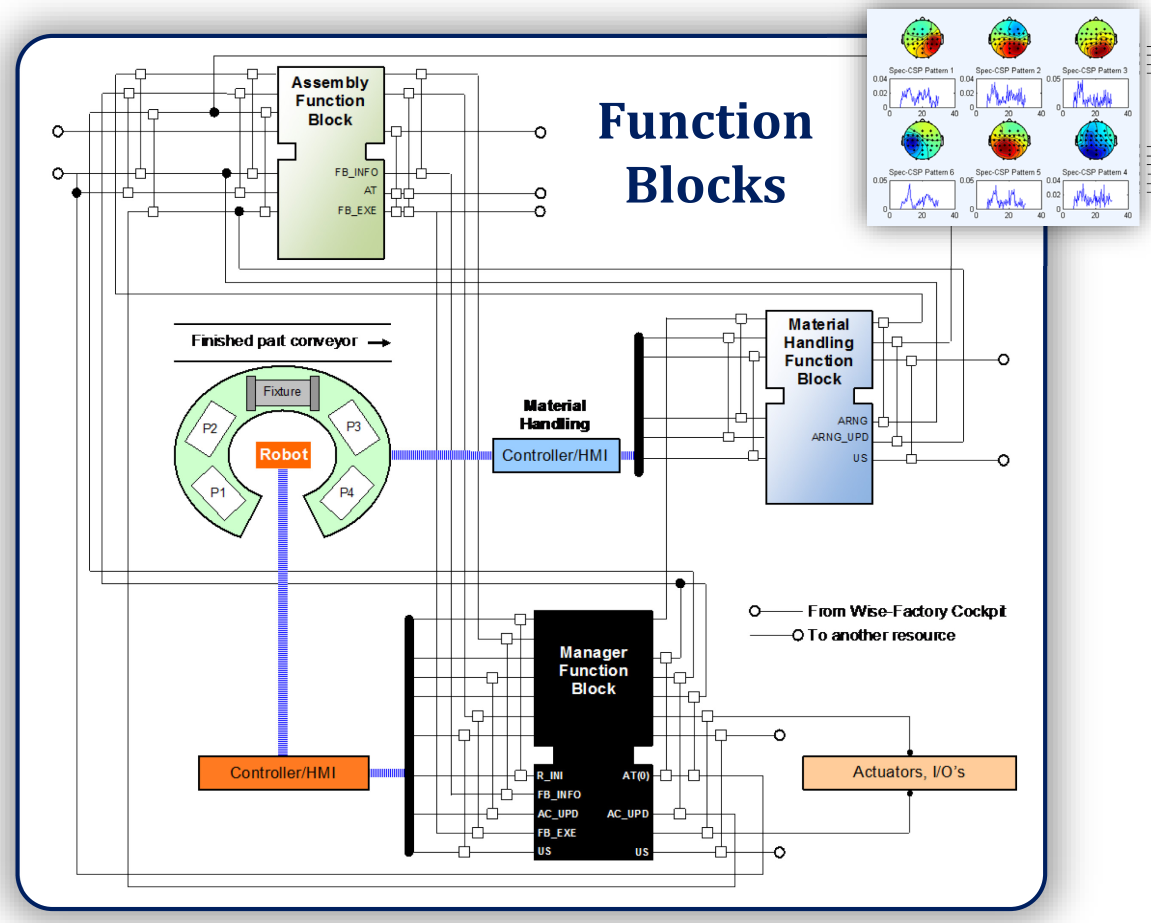
- **Base wavelet selection:** according to the mean values of energy-to-entropy ratio of B-Spline (80), Bump (66), Morlet (172), Morse (130) and Shannon (149), Morlet is chosen in this research.

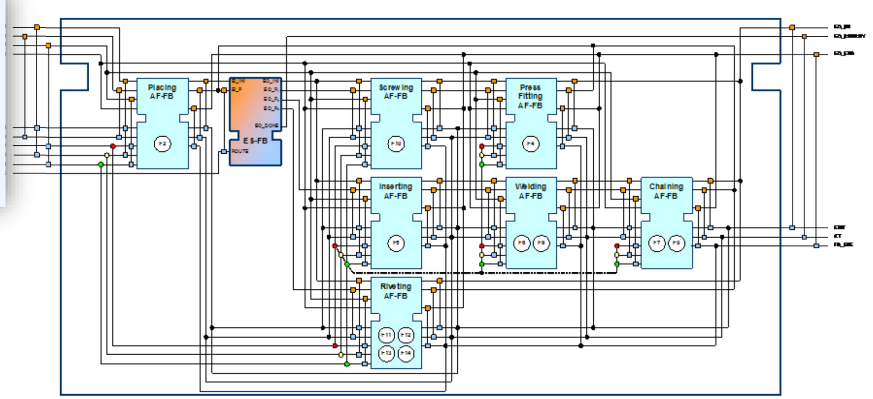
Reference L. Wang, S. Liu, C. Cooper, X. V. Wang and R. X. Gao, "Function Block-Based Human-Robot Collaborative Assembly Driven by Brainwaves," *CIRP Annals – Manufacturing Technology*, Vol.70, No.1, pp.5-8, 2021.

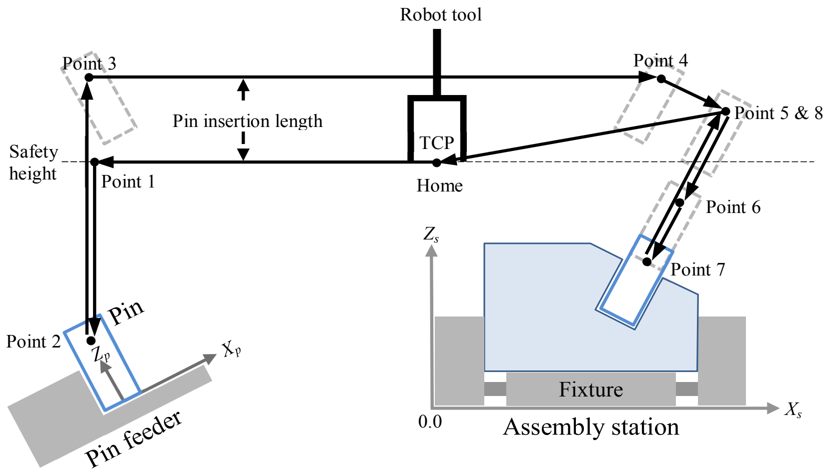
Macro-Micro Robot Control by FBs





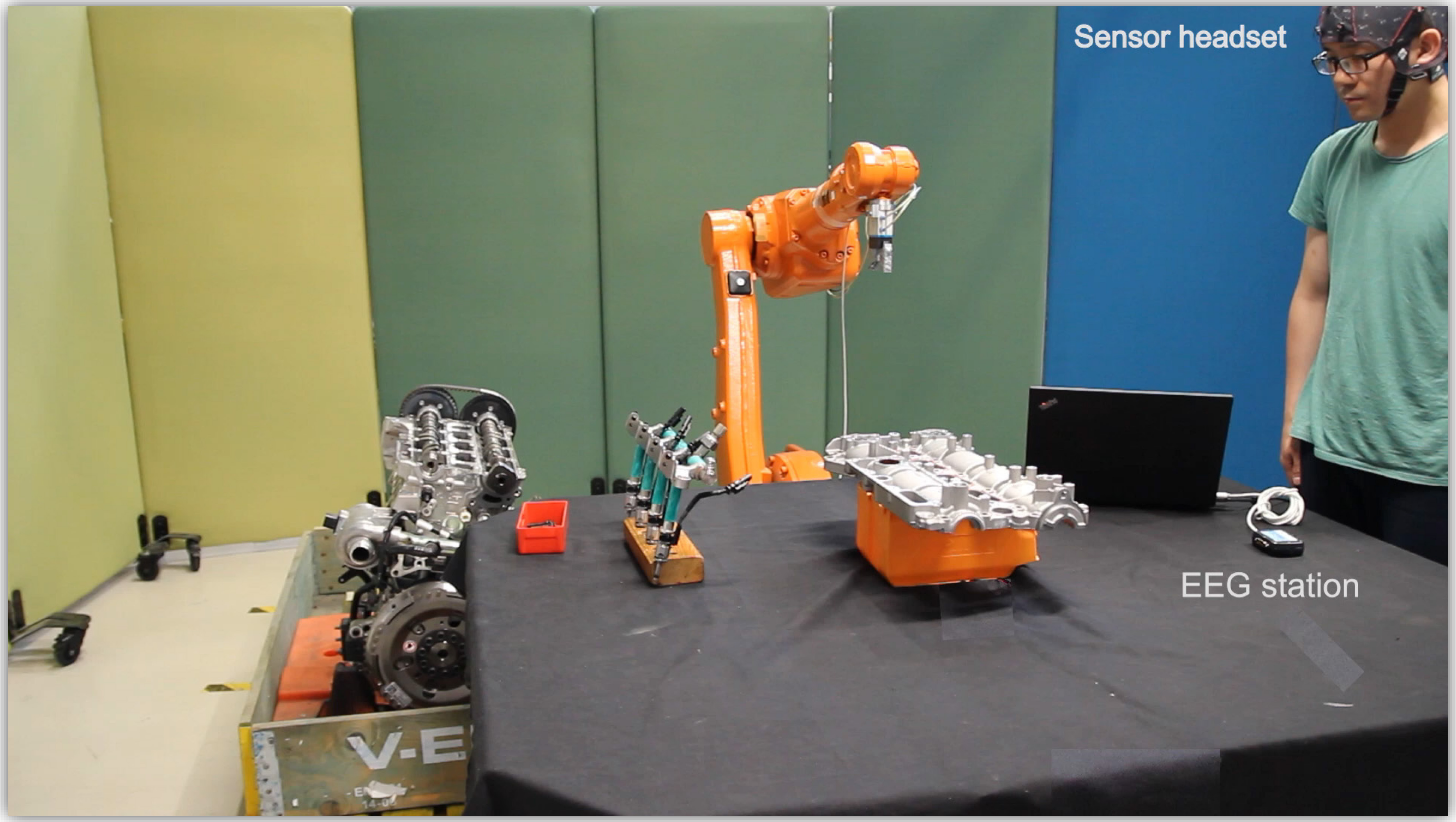






Reference Wang L, Schmidt B, Givehchi M, Adamson G (2015) Robotic assembly planning and control with enhanced adaptability through function blocks. *Int J Adv Manuf Technol* 77(1–4):705–715.

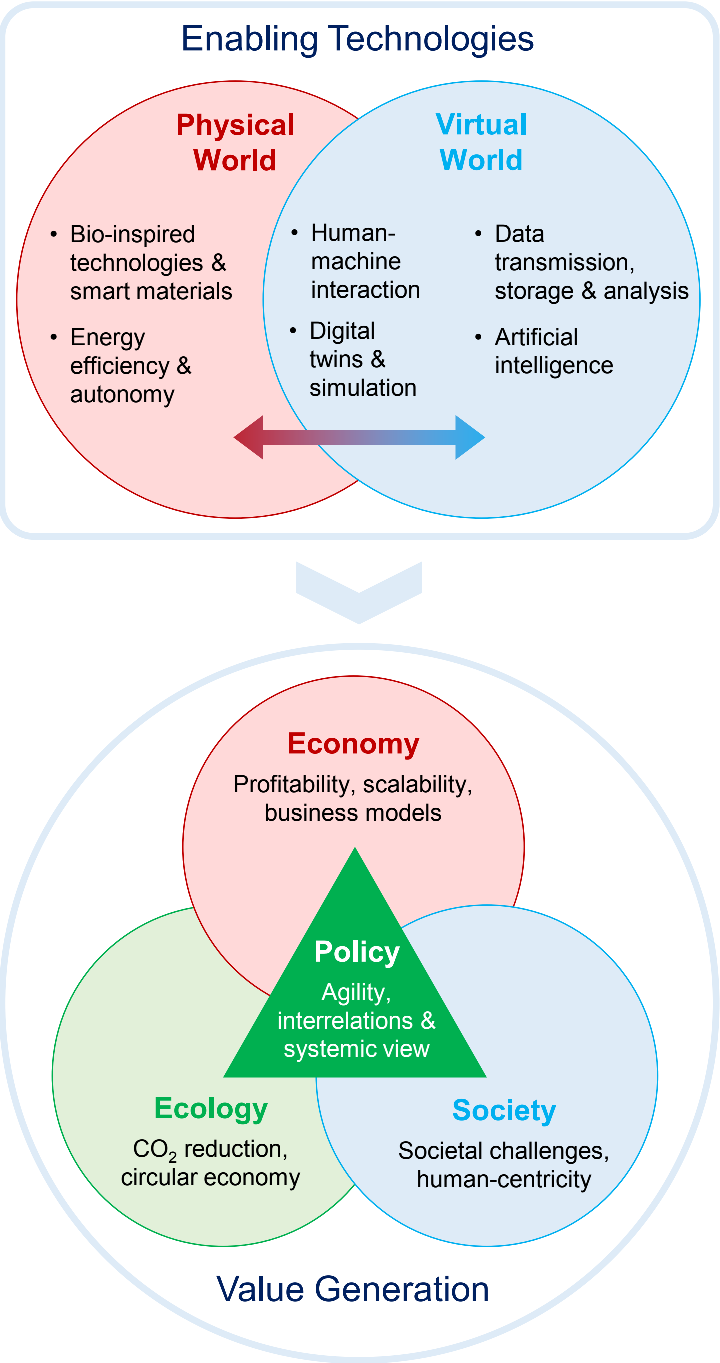
Stimulus-free Brainwave-driven HRC Assembly



Reference

L. Wang, S. Liu, C. Cooper, X. V. Wang and R. X. Gao, "Function Block-Based Human-Robot Collaborative Assembly Driven by Brainwaves," *CIRP Ann - Manuf Technol*, 70(1):5-8, 2021.

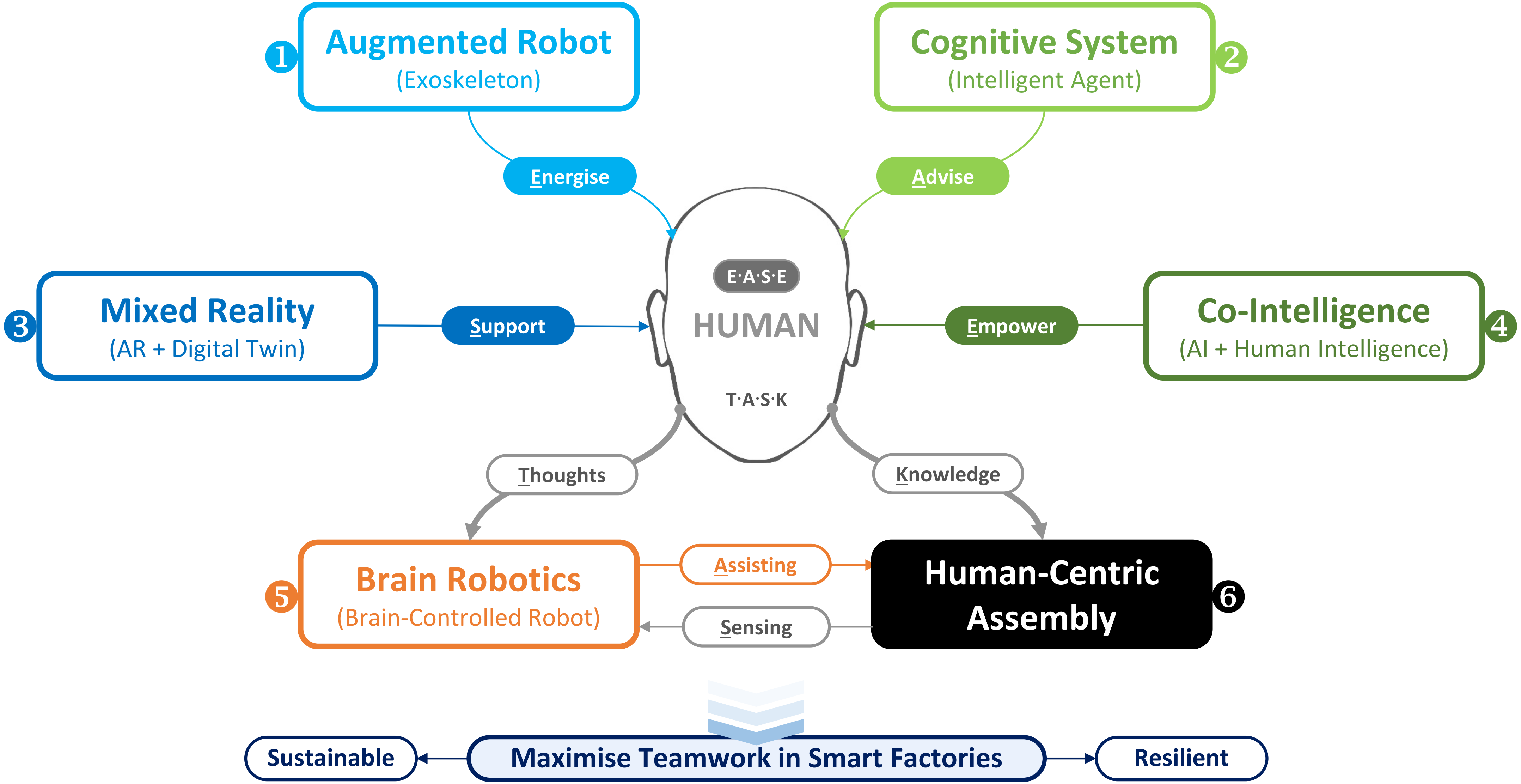
From Technologies to Values



Reference

X. Xu, Y. Lu, B. Vogel-Heuser and L. Wang, "Industry 4.0 and Industry 5.0—Inception, Conception and Perception," *Journal of Manufacturing Systems*, Vol.61, pp.530-535, 2021.

Human-Centric Assembly in the Future



Reference L. Wang, "A Futuristic Perspective on Human-Centric Assembly," *Journal of Manufacturing Systems*, Vol.62, pp.199-201, 2022.

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Symbiotic HRC Assembly in Action

Acknowledgement

SYMBIO-TIC project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 637107.

https://youtu.be/_0lPxs0rYls (complete version)

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Thank You for Listening

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Chair Professor of Sustainable Manufacturing

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