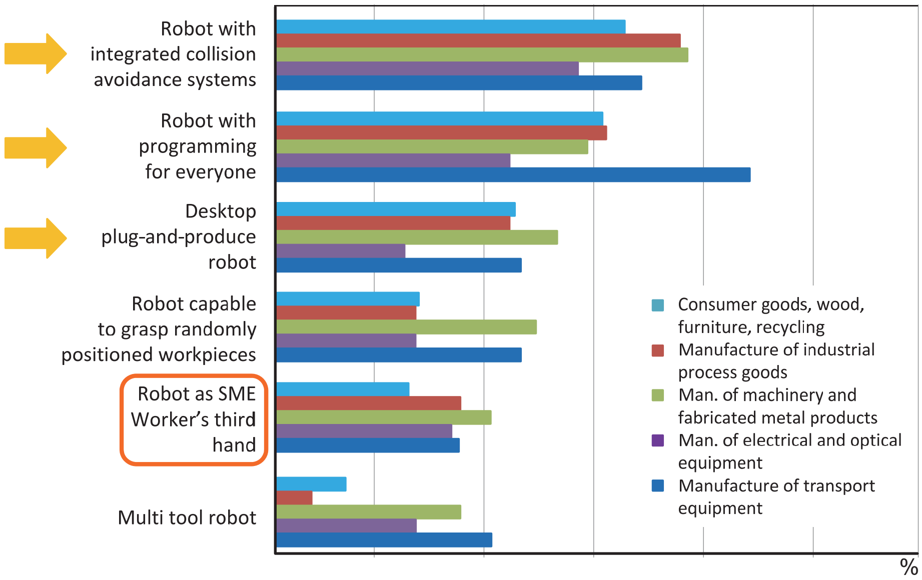
An Invited Talk on

Human-Robot Collaborative Assembly:
The State of the Art and Latest Advancement

Presentation Outline

- **Background** and **definition** of human-robot collaboration (HRC)
- **Safety** standards and **active collision avoidance** in HRC assembly
- **Dynamic** task **planning** and on-demand job **dispatching**
- **Adaptive** and **programming-free** robot control
- **In-situ** operator **support** in changing HRC assembly environment
- **Challenges** and future **research directions**

Why Human-Robot Collaboration

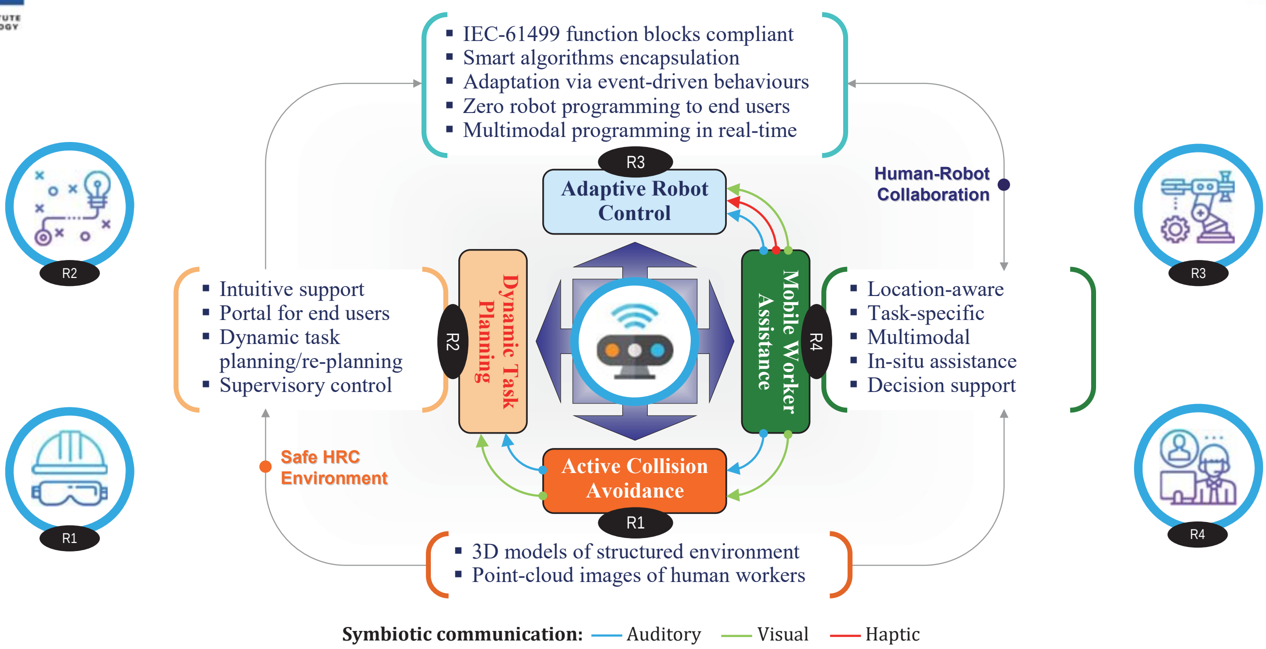


(Adapted from FP6 SME Robotics project's survey on 482 SMEs)

Key Requirements:

- Safe environment
- Programming-free
- Plug-and-produce
- User friendly

Scope of the Presentation

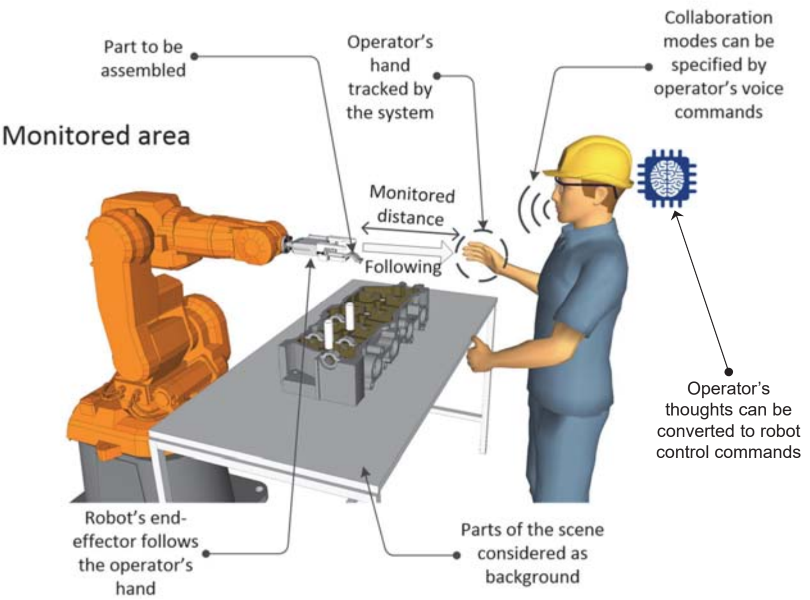


Classification of H-R Relationships

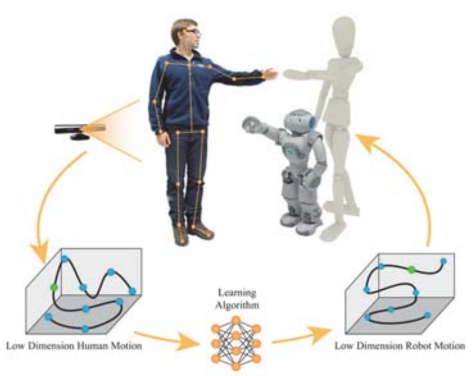
		Coexistence	Interaction	Cooperation	Collaboration
Shared	Workspace		✓	✓	✓
	Direct contact		✓		✓
	Working task		✓		✓
	Resource			✓	✓
	Simultaneous process	✓		✓	✓
	Sequential process		✓	✓	

Reference Wang XV, Seira A, Wang L (2018) Classification, personalised safety framework and strategy for human-robot collaboration. *Proceedings of CIE48*, Vol. 3, pp. 2302–2311.

Charicteristics of HRC Assembly

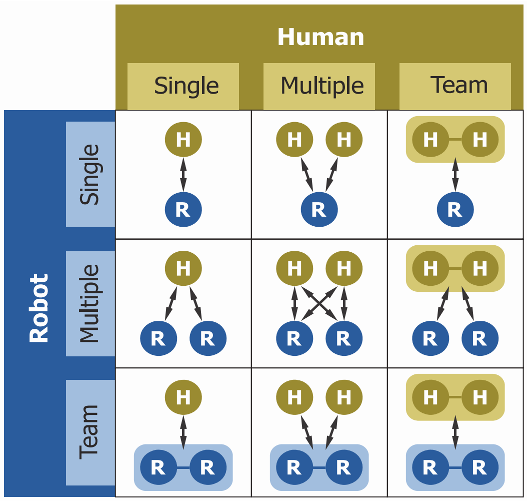


- The capability to track an operator's position allows controlling a robot to support the operator as needed

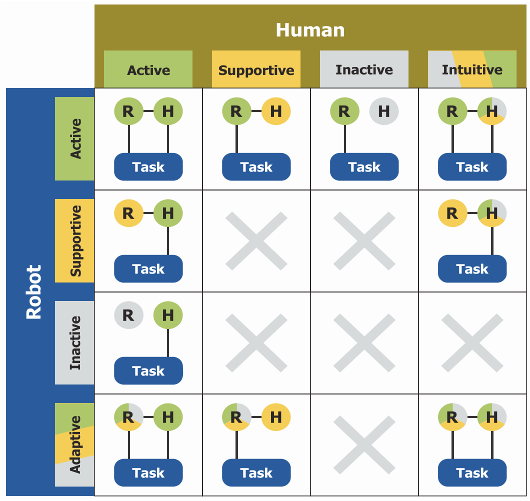


Key Properties of HRC Assembly

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.

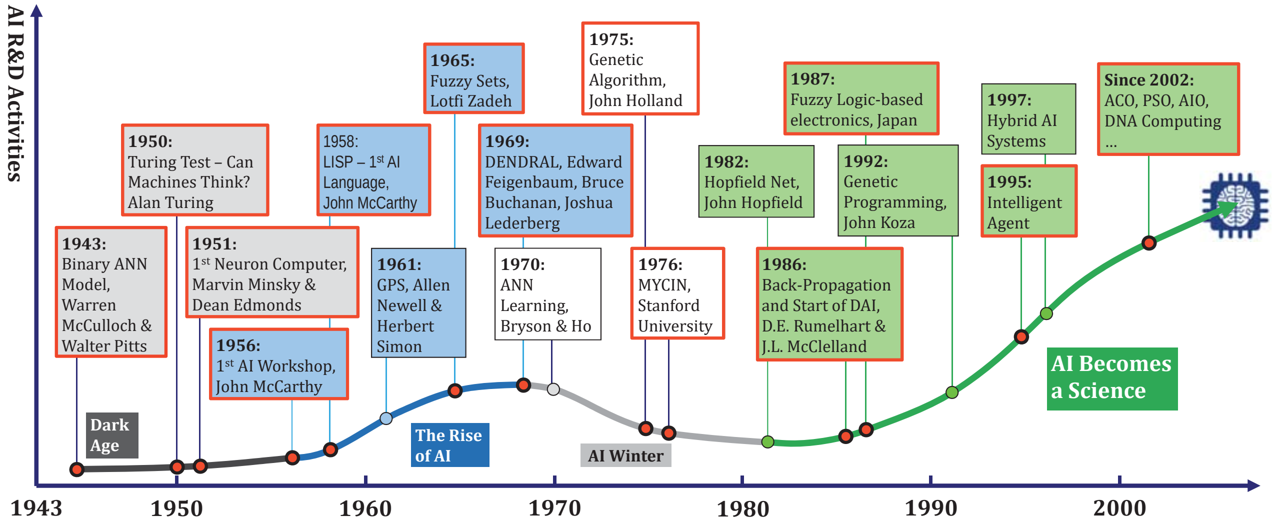
Definition of Symbiotic HRC

- **Symbiotic human-robot collaboration** places the interplay of human and robot into a cyber-physical environment where human and robot interact in a shared work environment to solve complex tasks which require the combination of their best, complementing competencies.

- **A symbiotic HRC system** possesses the skills and ability of perception, processing, reasoning, decision making, adaptive execution, mutual support and *self-learning* through real-time multimodal communication for context-aware human-robot collaboration.

Reference L. Wang, R.X. Gao, J. Váncza, J. Krüger, X.V. Wang, S. Makris and G. Chryssolouris, "Symbiotic Human-Robot Collaborative Assembly," *CIRP Annals – Manufacturing Technology*, Vol.68, No.2, pp.701-726, 2019.

AI as the Foundation of HRC



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

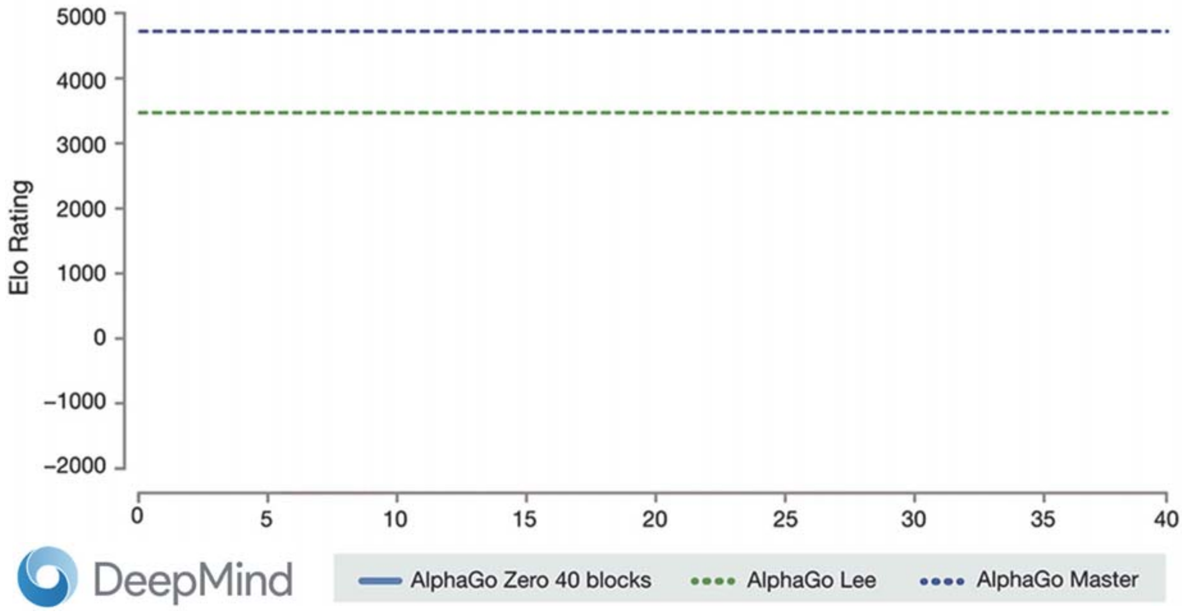
AlphaGo in 2016

AlphaGo vs. Lee Sedol

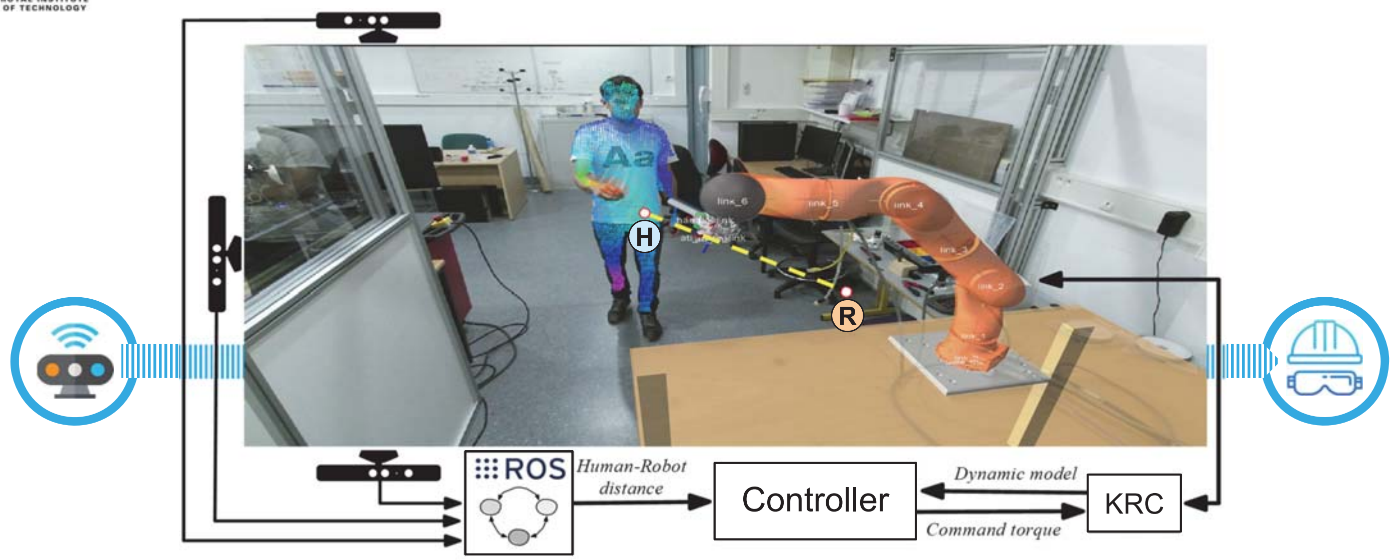
During the legendary matches:

- 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

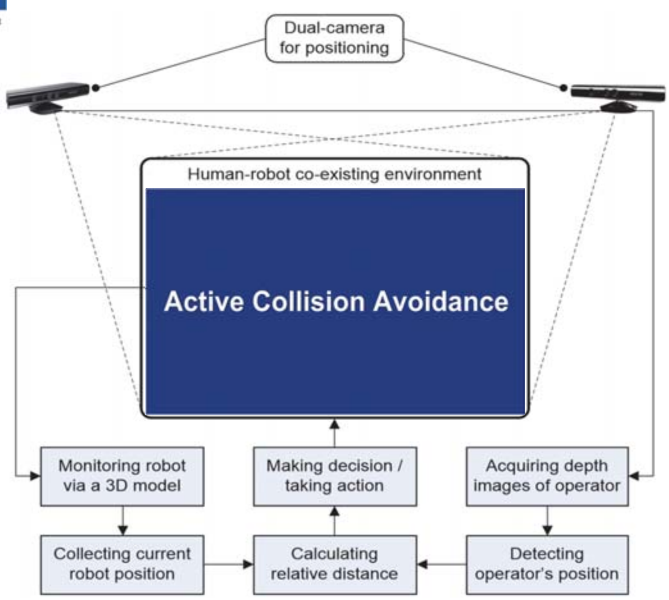


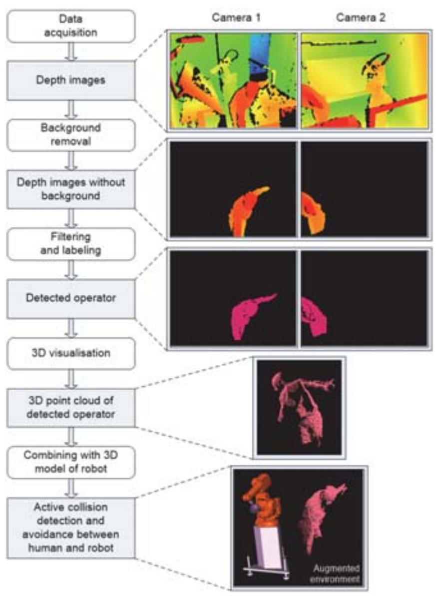
Human Tracking and Detection



Reference Meguenani A, et al. (2016) Energy based control for safe human-robot physical interaction. *Int. Symp. Exp. Robot*, pp 809–818.

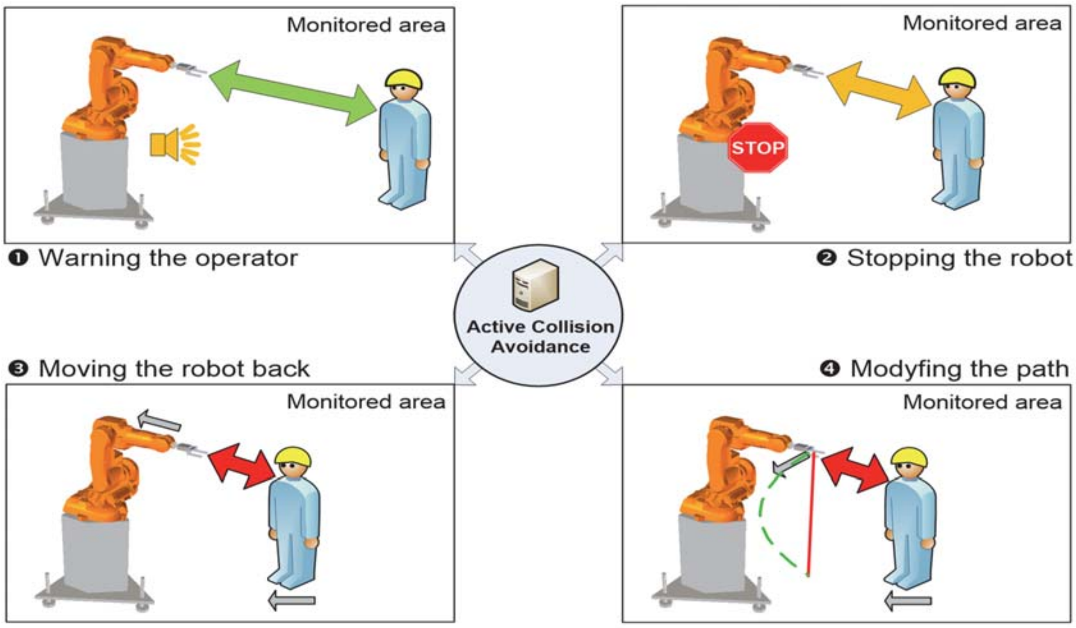
Active Collision Avoidance



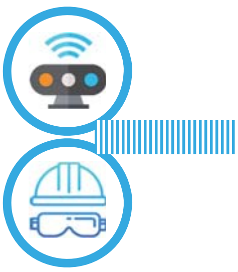


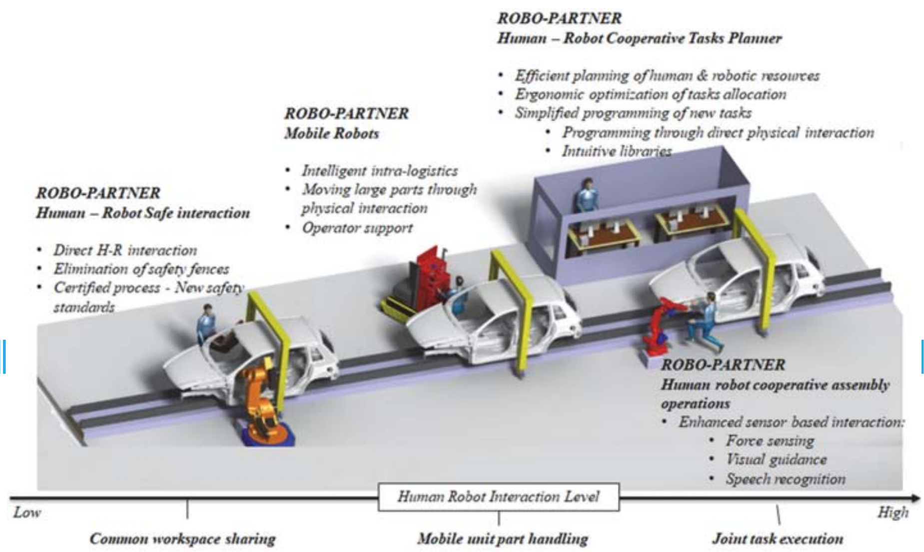
Reference Schmidt B, Wang L (2014) Depth camera based collision avoidance via active robot control. *J Manuf Syst* 33(4):711–7118.

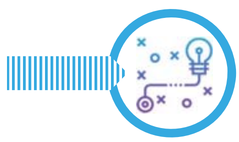
Four Safety Policies



Dynamic Planning and Dispatching



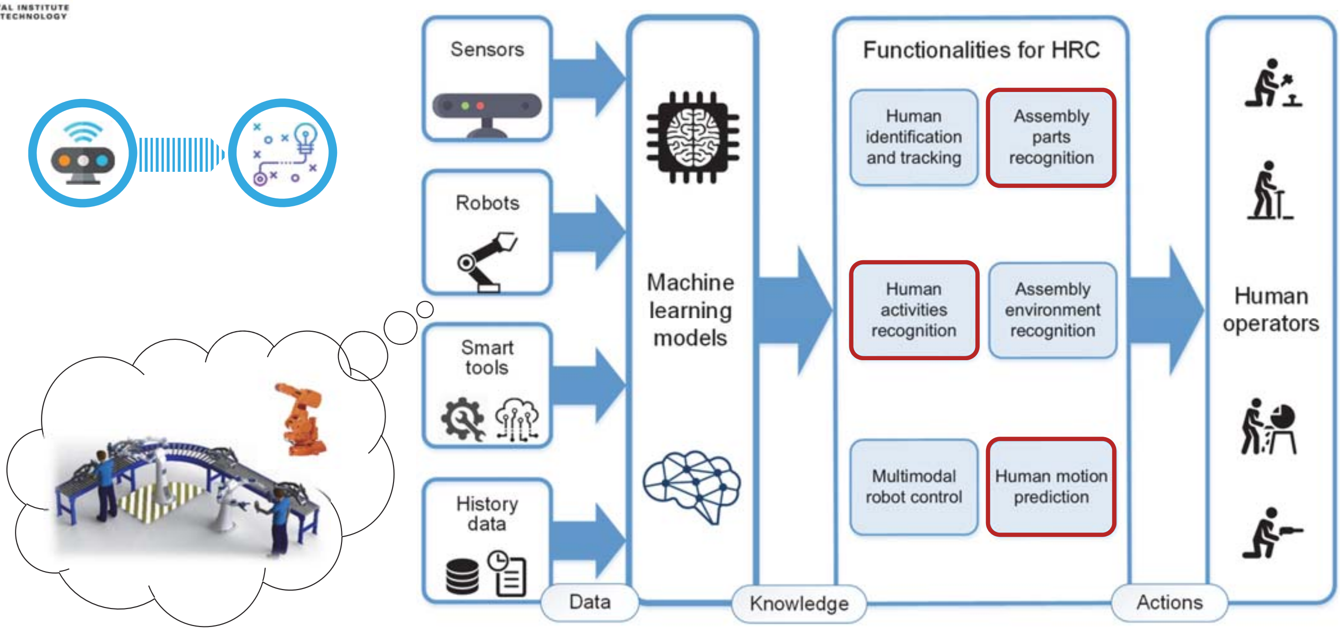




Reference

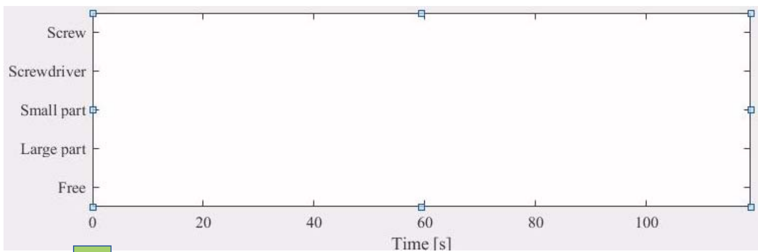
Michalos G, et al. (2014) ROBO-PARTNER: Seamless human-robot cooperation for intelligent, flexible and safe operations in the assembly factories of the future. *Procedia CIRP* 23:71–76.

ML in HRC Assembly Planning

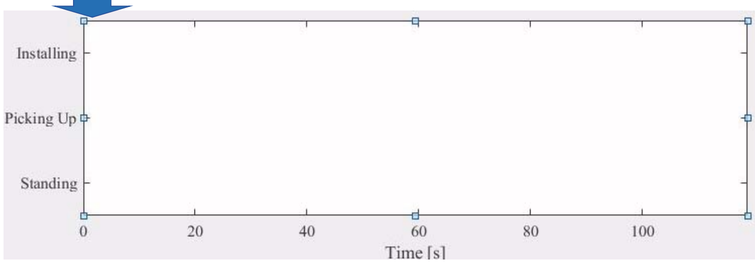


Deep Learning of Assembly Context

Part/tool identification



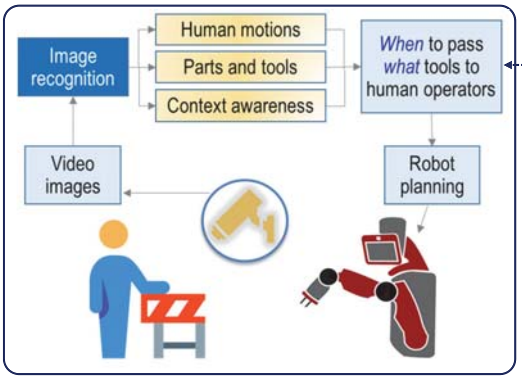
- Part/tool identification: recognize what the human operator picks up
- Identified part/tool: valid for a "picking up" + "installing" combination



Human action recognition

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.

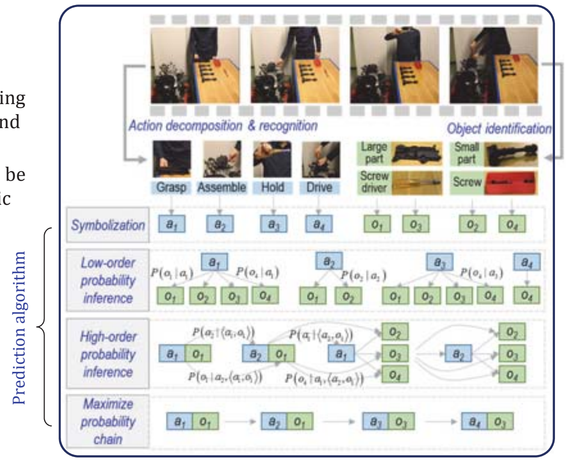
Prediction for Robotic Assistance



Prediction

$$\begin{cases} P(\sigma|s) = \dfrac{P(\sigma s)}{P(s)} = \dfrac{\sum_{i,j} X^{i,j}_{\sigma s} / \sum_i (l_i - |\sigma s| + 1)}{\sum_{i,j} X^{i,j}_{s} / \sum_i (l_i - |s| + 1)} \ge P_{\min}, \forall \sigma \in \Sigma \\ \dfrac{P(\sigma|s)}{P(\sigma|\mathrm{suf}(s))} \ge \beta, \quad \beta: \text{positive constant} \end{cases}$$

Example: probabilistic modeling of human action and intention



Prediction

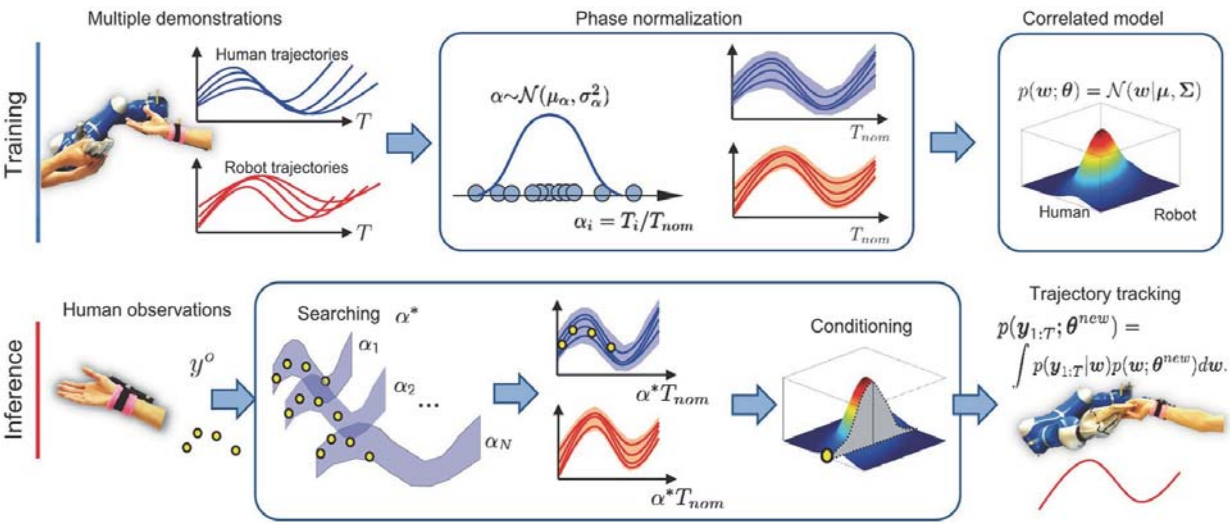
- Based on cognition and modeling of human *behavioral pattern* and preference
- Human *heterogeneity* needs to be accounted for, in a probabilistic manner

Action

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

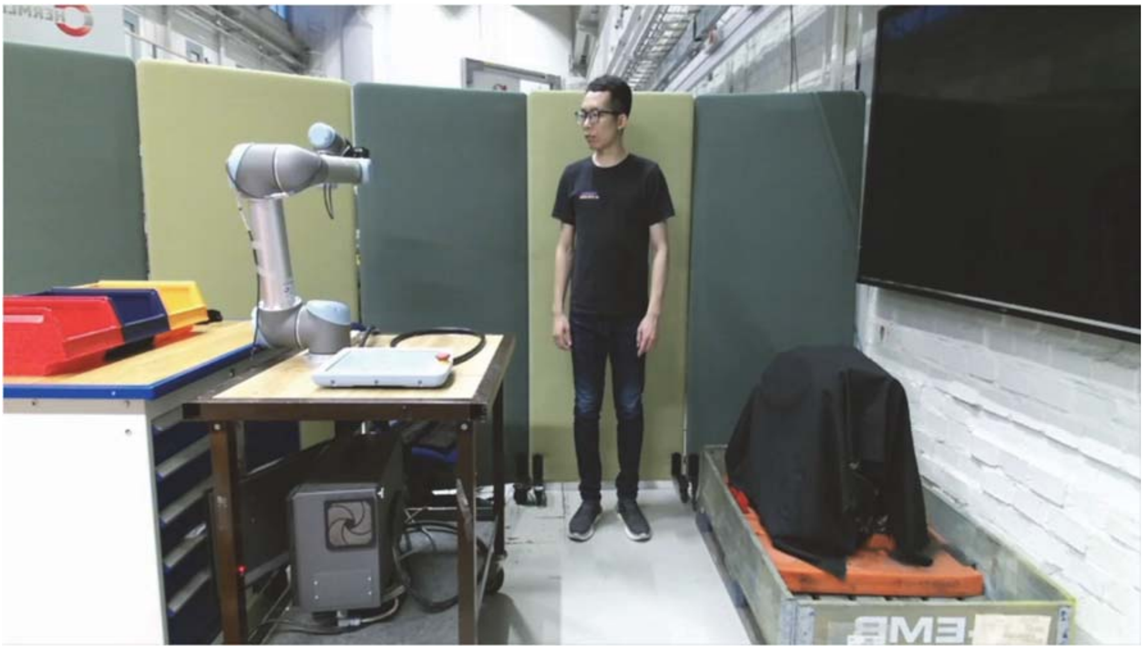
Reference Wang P, Liu H, Wang L, Gao RX (2018) Deep learning-based human motion recognition for predictive context-aware human-robot collaboration. *CIRP Ann - Manuf Technol* 67(1):17–20.

Context-Aware Trajectory Planning



Reference Maeda G, et al. (2017) Phase estimation for fast action recognition and trajectory generation in human–robot collaboration. *Int J Rob Res* 1–16.

Robot Assisting Human in Assembly



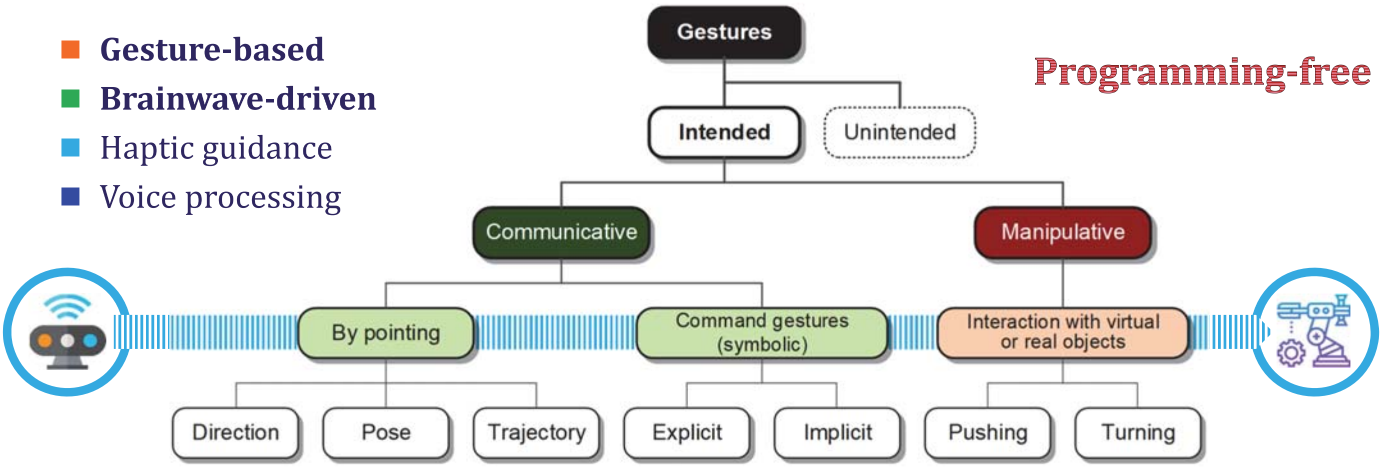
Typical Machine Learning Models

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

Multimodal H-R Communication

- **Gesture-based**
- **Brainwave-driven**
- Haptic guidance
- Voice processing

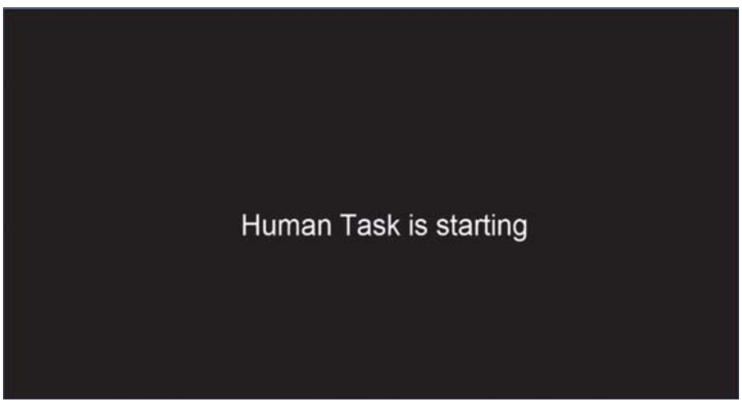
Programming-free



Reference Pavlovic VI, Sharma R, Huang TS (1997) Visual interpretation of hand gestures for human-computer interaction: A review. *IEEE Trans Pattern Anal Mach Intell* 19(7):677–695.

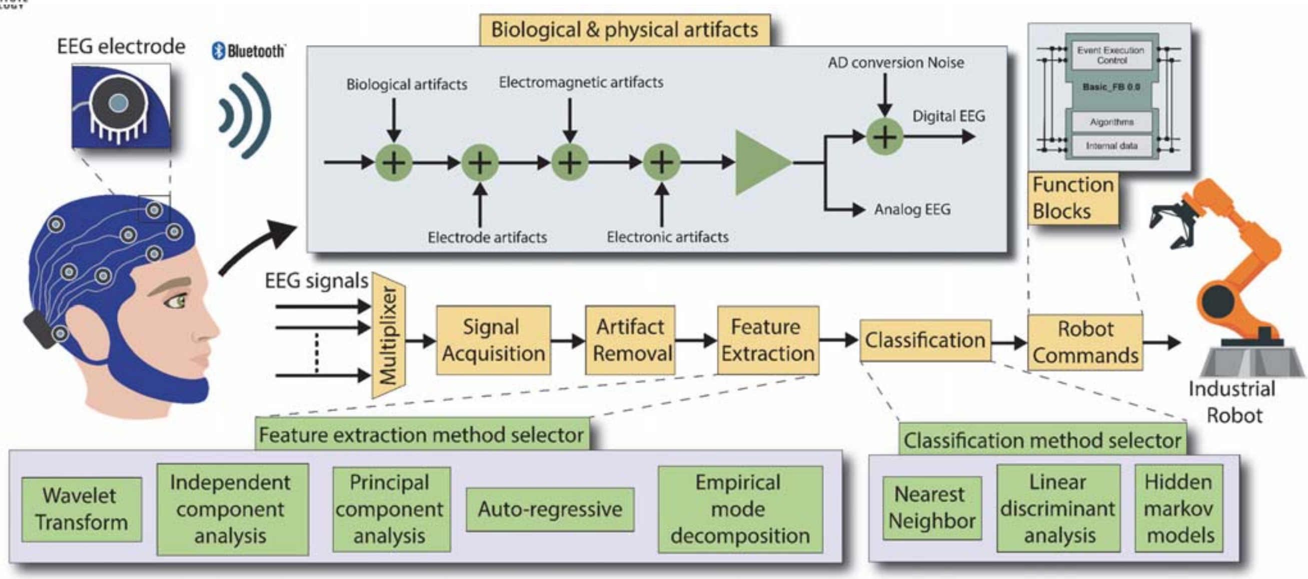
Gesture-Based Robot Control

Reference Lambrecht J, Krüger J (2012) Spatial programming for industrial robots based on gestures and augmented reality. *IEEE/RSJ Int. Conf. IROS*, pp 466–472.



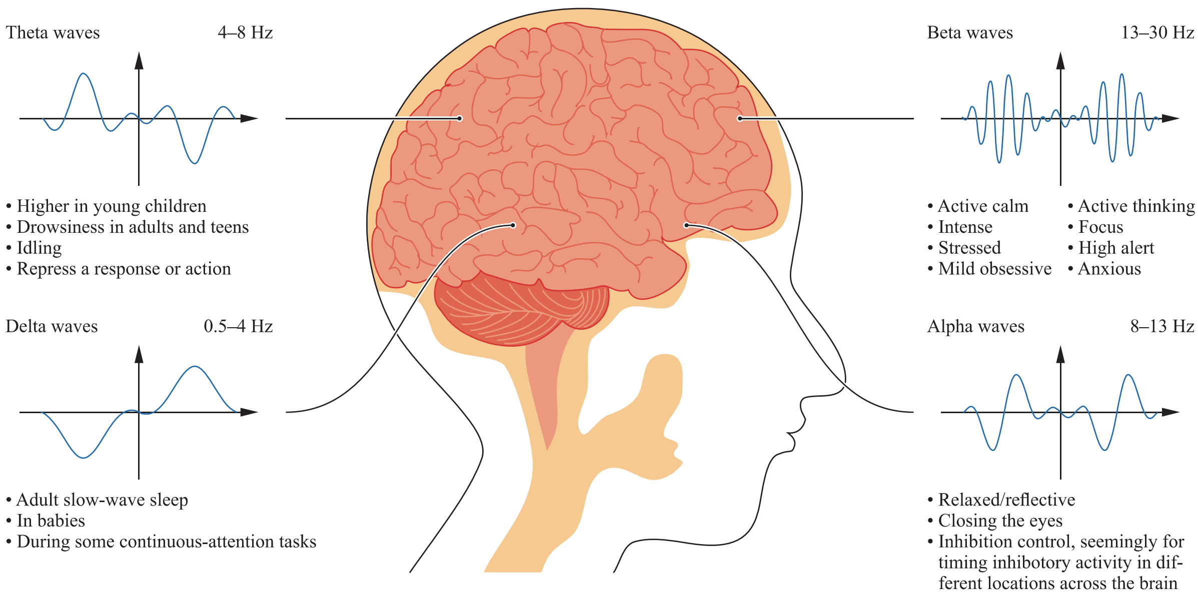
Reference Makris S, Tsarouchi P, Surdilovic D, Krüger J (2014) Intuitive dual arm robot programming for assembly operations. *CIRP Ann - Manuf Technol* 63(1):13–16.

From Brain Signals to Robot Actions

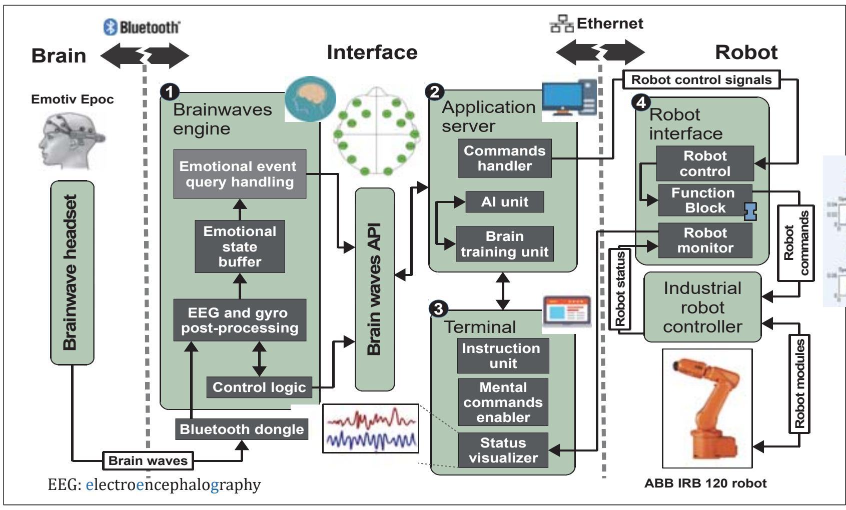


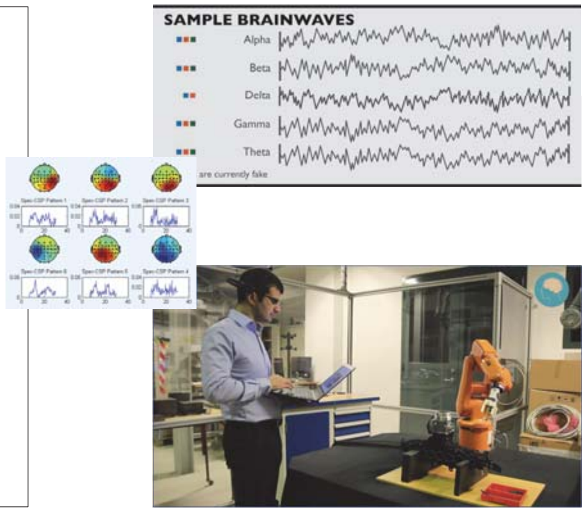
EEG: electroencephalography

Types of Brainwaves



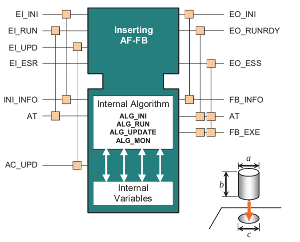
Brainwave-Driven Robot Control

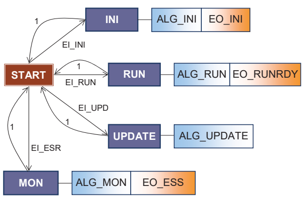


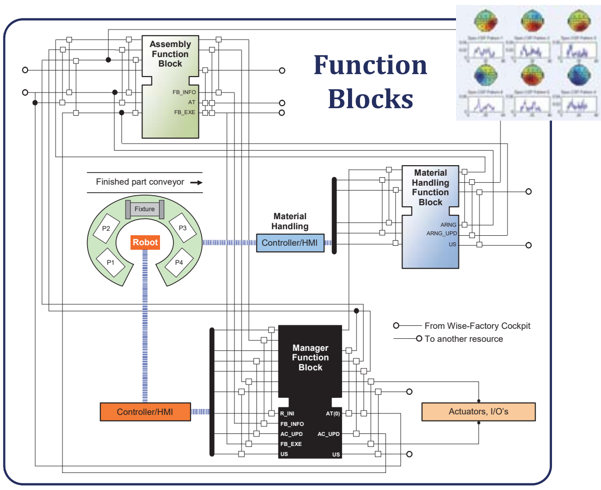


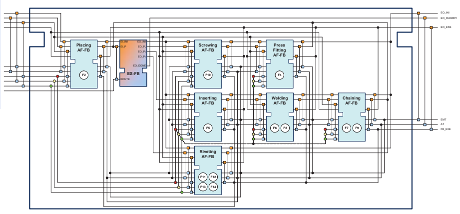
Reference Mohammed A, Wang L (2018) Brainwaves driven human-robot collaborative assembly. *CIRP Ann - Manuf Technol* 67(1):13–16.

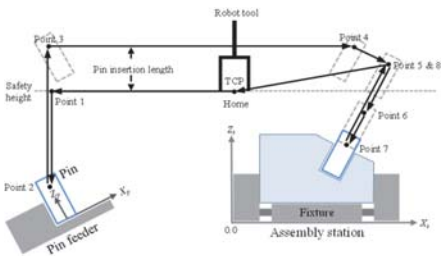
Macro-Micro Robot Control by FBs





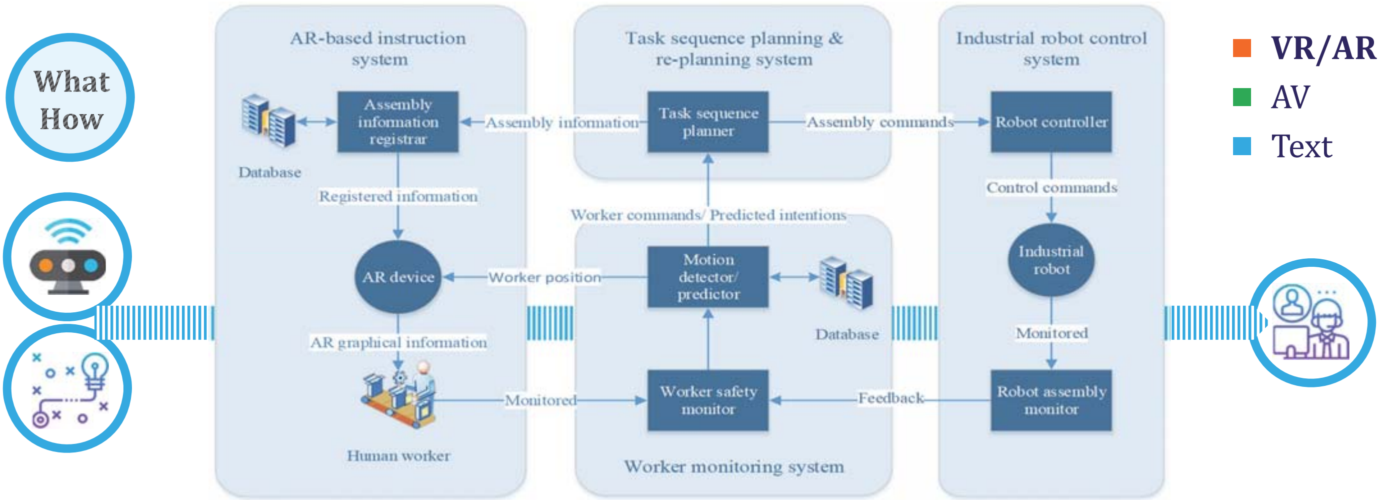






Reference Wang L, Schmidt B, Givehchi M, Adamson G (2015) Robotic assembly planning and control with enhanced adaptability through function blocks. *Int J Adv Manuf Technol* 77(1–4):705–715.

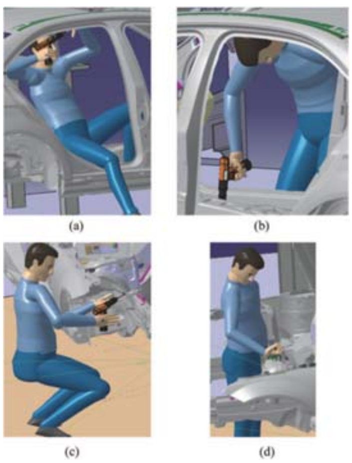
In-Situ Support to Mobile Workers



- VR/AR
- AV
- Text

Reference Liu H, Wang L (2017) An AR-based Worker Support System for Human-Robot Collaboration. *Procedia Manuf.*, pp 1–9.

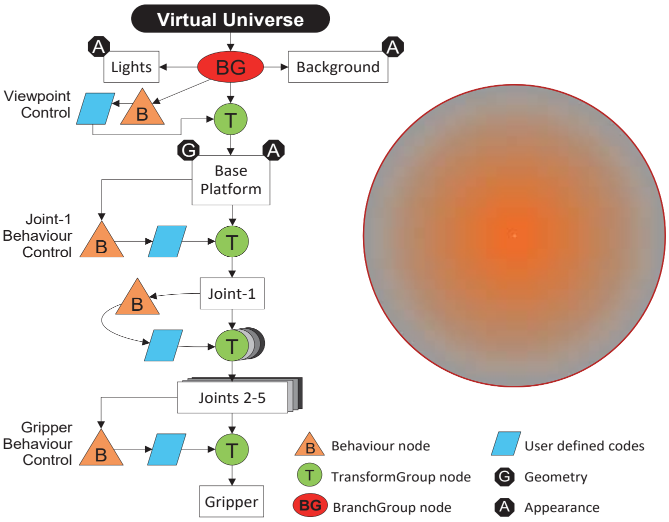
VR/AR Assisted HRC Assembly

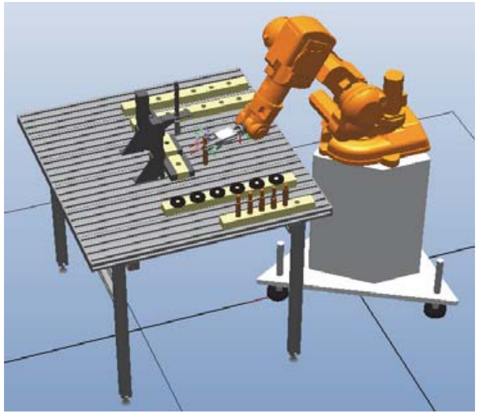


Reference Alexopoulos K, et al. (2013) ErgoToolkit: an ergonomic analysis tool in a virtual manufacturing environment. *Int J Comput Integr Manuf* 26(5):440–452.

Reference Makris S, et al. (2013) Assembly support using AR technology based on automatic sequence generation. *CIRP Ann - Manuf Technol* 62(1):9–12.

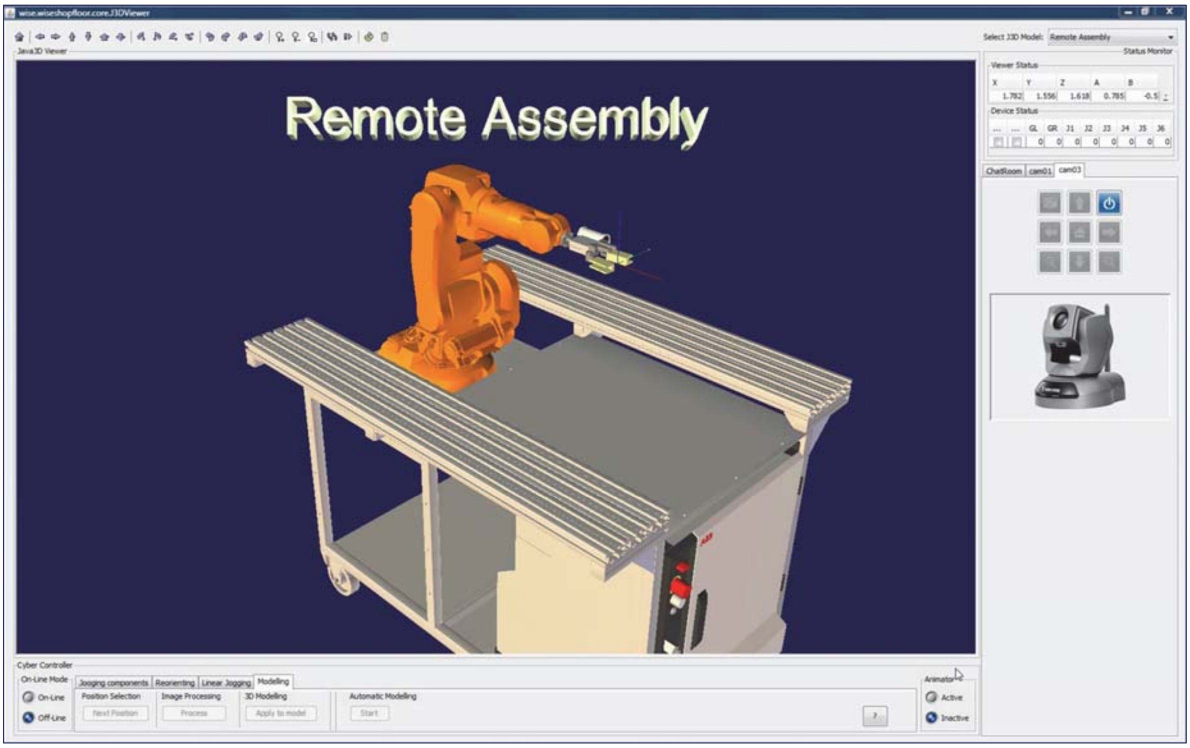
Remote HRC: Monitoring and Assembly





A mini robotic assembly cell

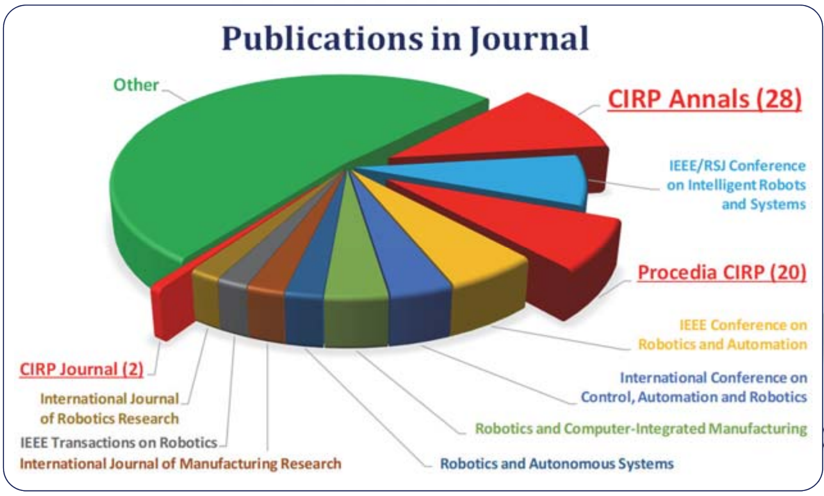
Reference L. Wang, M. Givehchi, G. Adamson and M. Holm, "A Sensor-Driven 3D Model-Based Approach to Remote Real-Time Monitoring," *CIRP Annals – Manufacturing Technology*, Vol.60, No.1, pp.493-496, 2011.



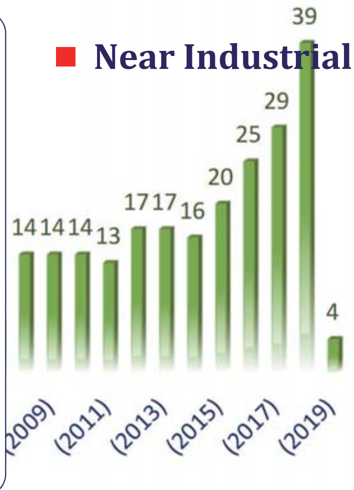
Future Research Directions

- Current standards do not yet address many key issues of mixed teams of humans and robots. More *realistic* standards are needed.
- Digital twin shall combine and align all aspects of modelling the function, structure and behaviour of the robotic cell including the worker, representing the *multimodal* and *bidirectional* channels of communication and control when effectively tuned to the real environment.
- Emergency cases require fast and guaranteed mitigation to bring the situation back to normal without interruption if the situation does not endanger the integrity or safety of human.
- AR-based support to workers in dynamic HRC assembly deserves more attention to be both *intuitive* and *mental stress-free*. Work instructions need to be adaptive to not only the changing competence level of individual workers but also the declining focus and concentration during the day or within the week.
- When adding humans to shared robotic environments, the trust of the humans on the robotic environments is unavoidably important and deserves attention.
- In HRC assembly, mental stress and psychological discomfort leading to any potential accident can be monitored and diagnosed via the *brainwaves* of workers, collected by sensors embedded in a *safety helmet*.

Statistics of Cited References



- Near Industrial Applications

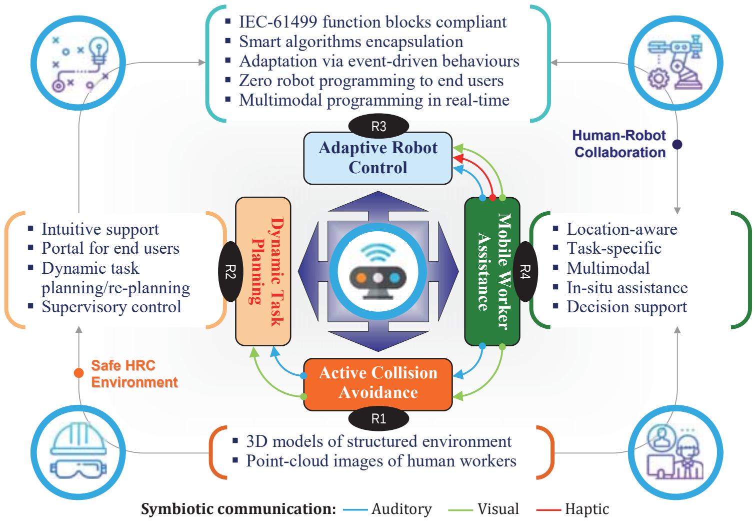


Symbiotic HRC Assembly in Action

Acknowledgement

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

Summary



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- **Dynamic** assembly **planning** and on-demand job **dispatching**
- **Adaptive** and **programming-free** robot control
- **In-situ** operator **support** in changing HRC assembly environment
- **Challenges** and future **research directions**

Thank You for Listening

Lihui Wang

Professor of Sustainable Manufacturing

KTH Royal Institute of Technology • Stockholm • Sweden

Reference

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