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

Key Requirements:
- Safe environment
- Programming-free
- Plug-and-produce
- User friendly

Scope of the Presentation

- IEC-61499 function blocks compliant
- Smart algorithms encapsulation
- Adaptation via event-driven behaviours
- Zero robot programming to end users
- Multimodal programming in real-time

Symbiotic communication:  
- Auditory  
- Visual  
- Haptic
Classification of H-R Relationships

<table>
<thead>
<tr>
<th>Shared</th>
<th>Coexistence</th>
<th>Interaction</th>
<th>Cooperation</th>
<th>Collaboration</th>
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</thead>
<tbody>
<tr>
<td>Workspace</td>
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<td>✓</td>
<td>✓</td>
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<td>Direct contact</td>
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<td>Working task</td>
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<tr>
<td>Resource</td>
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<td>Simultaneous process</td>
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<tr>
<td>Sequential process</td>
<td>✓</td>
<td>✓</td>
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</tbody>
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Characteristics of HRC Assembly

- The capability to track an operator’s position allows controlling a robot to support the operator as needed.
- Operator’s thoughts can be converted to robot control commands.
**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.

AI as the Foundation of HRC

1943: Binary ANN Model, Warren McCullough & Walter Pitts
1950: Turing Test – Can Machines Think? Alan Turing
1951: 1st Neuron Computer, Marvin Minsky & Dean Edmonds
1956: 1st AI Workshop, John McCarthy
1965: Genetic Algorithm, John Holland
1966: DENDRAL, Edward Feigenbaum, Bruce Buchanan, Joshua Lederberg
1969: ANN Learning, Bryson & Ho
1970: MYCIN, Stanford University
1975: Fuzzy Sets, Lotfi Zadeh
1987: Fuzzy Logic-based electronics, Japan
1997: Hybrid AI Systems

Earlier AI Applications

Garry Kasparov playing Deep Blue in 1997
Honda ASIMO walking downstairs in 2005

AlphaGo in 2016

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 learning, Monte Carlo search combined with deep neural network for decision making.

Self-Learning of AlphaGo Zero
Human Tracking and Detection

Reference

Active Collision Avoidance

Reference
Four Safety Policies

1. Warning the operator
2. Stopping the robot
3. Moving the robot back
4. Modifying the path

Dynamic Planning and Dispatching

ML in HRC Assembly Planning

Machine learning models

Data → Knowledge → Actions

Human action recognition

Part/tool identification

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

Deep Learning of Assembly Context

Reference

**Prediction for Robotic Assistance**

**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


Reference


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**Context-Aware Trajectory Planning**

Reference


Reference

## Robot Assisting Human in Assembly

![Image of robot assisting human in assembly](image)

## Typical Machine Learning Models

<table>
<thead>
<tr>
<th>Machine learning models</th>
<th>Supervised/Unsupervised / Semi-supervised</th>
<th>Discriminative/Generative</th>
<th>Deep learning/Not deep learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-Means Clustering</td>
<td>Unsupervised</td>
<td>Generative</td>
<td>Not deep learning</td>
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<tr>
<td>K-Nearest Neighbours</td>
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<td>Discriminative</td>
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</tr>
<tr>
<td>Support Vector Machine</td>
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<tr>
<td>Hidden Markov Model</td>
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<tr>
<td>Random Forest</td>
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</tr>
<tr>
<td>XGBoost</td>
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<td>Not deep learning</td>
</tr>
<tr>
<td>Ensemble Methods</td>
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<td>Discriminative</td>
<td>Not deep learning</td>
</tr>
<tr>
<td><strong>Convolutional Neural Network</strong></td>
<td>Supervised</td>
<td>Discriminative</td>
<td>Deep learning</td>
</tr>
<tr>
<td>Recurrent Neural Network</td>
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<td>Deep learning</td>
</tr>
<tr>
<td>Long Short-Term Memory</td>
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<td>Discriminative</td>
<td>Deep learning</td>
</tr>
<tr>
<td>Naive Bayes</td>
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<td>Gaussian Mixture Model</td>
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<tr>
<td>Generative Adversarial Nets</td>
<td>Semi-supervised</td>
<td>Generative</td>
<td>Deep learning</td>
</tr>
</tbody>
</table>
**Multimodal H-R Communication**

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

**Programming-free**


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**Gesture-Based Robot Control**


From Brain Signals to Robot Actions

Types of Brainwaves

- **Theta waves**: 4–8 Hz
  - Higher in young children
  - Dreaming in adults and teens
  - Idling
  - Represents a response or motion

- **Delta waves**: 0.5–4 Hz
  - Adult slow-wave sleep
  - In babies
  - During some continuous-attention tasks

- **Beta waves**: 13–30 Hz
  - Active calm
  - Focused
  - Relaxed/reflexive
  - Closing the eyes
  - Inhibition control, seemingly for timing inhibitory activity in different locations across the brain

- **Alpha waves**: 8–13 Hz
  - Active thinking
  - High alert
  - Stressed
  - Mild obsessive
  - Anxious
Brainwave-Driven Robot Control


Macro-Micro Robot Control by FBs

In-Situ Support to Mobile Workers

VR/AR Assisted HRC Assembly

Reference

Reference

Reference
Remote HRC: Monitoring and Assembly

Reference
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
Summary

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Symbiotic communication: Auditory, Visual, Haptic

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