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Intersubjective AI-driven multimodal interaction for advanced user-centric HRC applications - the JARVIS approach

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Abstract

The current EU manufacturing paradigm has shifted from mass production to highly customizable products, due to the green transition target of the community as well as the continuously varying needs of the population. To strengthen the competitiveness of the industry, there is an increasing need for flexible production, exploiting the capabilities of both the machinery and human workforce.
The JARVIS EU project aims to develop a reusable set of tools that enable AI driven multimodal means of interaction: i) involving interfaces for physical and remote information exchange, robot control and programming, ii) providing social skills to a variety of robots to achieve seamless user-centric interaction that extends human ability for complex tasks and iii) demonstrating scalability of application and ability to achieve economies at scale. The proposed technologies will be tested for flexibility, scalability, trustworthiness, and user acceptance in four use cases, aiming to demonstrate production line and cross sector applicability in Agile Manufacturing and Inspection and Maintenance (I&M). Each pilot has been carefully selected to challenge and thus highlight the capabilities of the proposed solutions, covering a range of needs for HRI, while keeping human in the loop.

Keywords: AI; Data; Advanced HRI; Robotics;

1. Introduction

Following the need of the industry for flexible and reconfigurable applications [1], which exploit both, machine and human capabilities, the growing market of robots has reacted, adapting to the changing situation by providing collaborative robotic solutions with a variety of characteristics in terms of payload (with solutions from 3kg to 170kg), type and mobility. Moreover, several technological solutions for perception and safety allow their coexistence with humans. While several research activities have been conducted over the past 5 years on this, wider industrial adoption is lagging due to the following restrictions: i) Limited cognition and intelligence: The proposed solutions can support coexistence, but not collaboration in the sense of a robotic coworker able to act as a human substitute. Robots lack cognition and intelligence to understand human actions, predict their intention and react proactively. ii) Low performance of collaborative operations: The performance of collaborative applications is restricted by low robot speeds due to outdated safety systems and fixed sequencing of robot actions. iii) Collaboration fluidity is rather low as the operators have to adapt to the particularities of the robots. iv) Complexity in robot programming, which requires the involvement of skilled engineers, does not provide flexibility in the execution phase, and does not benefit from the tacit knowledge of experienced operators.

Despite the fact the mechatronics are quite advanced, a perfect matching of mechanics and control is required to create robots that advance from repetitive and precision-oriented tasks to becoming intelligent and helpful coworkers. Proper human robot interaction (HRI) is the most important ground to be covered.

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Recent advancements in sensing, control algorithms, and hardware capabilities have significantly enhanced direct/physical robot control. Compliance control [2], model-based force control [3], impedance control [4], and tactile feedback [5] are advancements examples that allow robots to interact more naturally, On the other side, indirect HRI involves wearable devices such as AR glasses, smartwatches, tablets, projectors, and microphones [6] that allow information exchange among humans and robots. This form of interaction provides cognitive support for task execution, safety-related information [7] and indirect robot control and programming using hand gestures. Teleoperation and shared control of robots [8], allow operators to remotely control the robot's movements and actions, via an immersive control experience, improved situational awareness, and enhanced safety. VR egocentric (world perception from the robot's perspective) or robot-centric (observing the virtual environment freely) [9] interfaces enable remote control of robots, which is useful for hazardous or distant areas and maintains the operator's knowledge and expertise in the loop minimizing risks. Programming by demonstration uses statistical learning with approaches such as hidden Markov models, dynamic movement primitives, and Gaussian mixture modelling (GMM) [10]. Additional approaches include, cost learning, or reward learning [11], Markov decision process (MDP) and inverse reinforcement learning (IRL) methods [12].

From the operator side assessing acceptance and phycological impact is crucial in robotics. Different evaluation methods exist, such as physiological measurements, surveys, interviews, to identify acceptance and psychological impact and attitudes towards robots (Likert scale) [13]. Physiological measurements, such as heart rate and skin conductance, are used to measure stress and emotional response. EEG and fMRI provide insight into the neural processes of HRI [14]. UX design and user-centric interfaces for AI-enhanced HRI involve interfaces that are intuitive and friendly to operators. Usual techniques involve natural language processing, computer vision, and other AI techniques to enable robots to understand and respond to human inputs [15], always with ethical considerations, such as transparency and accountability for AI features. Robot behavior adjustment is performed in varying contexts, as for example ergonomics, human safety, and user preferences. Current state of the art includes sensorized systems to perceive human pose and position to adjust robot improving interaction's ergonomy, adjust robot dynamics (speed, forces, impedance, compliance etc.) preventing potential hazards, while also vision systems and wearables devices are also employed for gaze detection and human posture analysis for evaluating intents such as future motion or task execution thus commanding the robot to either prevent or encourage interaction according to the application specific requirements [16].

On runtime, open architectures can support security, safety, and trustworthy AI by incorporating different essential features, such as transparency (developers can identify potential security vulnerabilities), collaboration, flexibility (modification and adaptation of AI systems to meet specific requirements), interoperability (data sharing and collaboration), and accountability in AI systems (enabled transparent and auditable decision-making processes). Trustworthy AI is a well-studied topic that should always been considered during the design, development, and deployment phases of a system. The EU has provided extensive guidelines for this purpose where the overall approach for implementing trustworthy AI systems is described [17]. In addition, privacy and data governance should be guaranteed (data minimization and data protection impact assessments (DPIAs)) [18], while also trustworthy AI – based system should be also transparent via integrating explainable AI techniques [19] to let users understand how AI systems make decisions.

Hardware plays a crucial role in HRI systems. Environment and human awareness is achieved through 2D and 3D sensing elements. Collaboration safety is achieved using force-limiting joints and compliant end-effectors[20]. To ensure safety, safety barriers (physical or sensorial), and power/force-limiting technologies are also mandatory for enabling safe HRI [21]. Artificial intelligence applications include pedestrian avoidance for autonomous vehicles, identification of human tasks based on hand-object interactions [22], gesture-based recognition for commanding robot motion, EEG-based human intention recognition, human motion recognition, and synchronization of HRC tasks [23]. Planning systems for HRC in industrial settings should account for the technical capabilities of robots, including payload and reachability, as well as metrics such as process execution time, resource utilization, cost, and energy consumption [24]. Ergonomics and safety are also important considerations. Planning tools use decision-making logic and weighted criteria to generate and allocate tasks to operators and/or robots, with a focus on collaborative task completion [25]. Online replanning is used for changes in the environment (parts geometry), as well as changes in the operator behavior. Finally, Digital Twins (DT) show significant prospects for simulating, analyzing, and optimizing processes and products in various production scenarios, (low batch to series production elements), and can incorporate both articulated robots and Automated Guided Vehicles (AGVs) [26]. Though, DTs present challenges such as the difficulty of accurately collecting and processing data, as well as the lack of flexible models that can effectively enhance overall processes.

This paper discusses the concept of the EC project JARVIS (www.jarvis-project.eu) towards deploying intersubjective AI-driven multimodal interaction for advanced user-centric HRC applications, trying to address the aforementioned bottlenecks.

In Section 2 the proposed approach is detailed, while in Section 3 four reference use cases where the proposed approach will be applied are analyzed. In Section 4 the main Key Performance Indications (KPIs) that will allow the evaluation of the effectiveness of the proposed approach are presented. Finally, Section 5 concludes the work presented and includes information about future work.

2. Approach

JARVIS aims to address the bottlenecks in the wider industrial adoption of the HRC research of the past years, by introducing a reusable set of tools of interaction involving interfaces for physical and remote information exchange, robot control and programming, providing social skills to a variety of robots to achieve seamless user-centric interaction that extends human ability for complex tasks and demonstrating scalability of application. More details on the technologies introduced will be presented in the following sub-sections.

2.1. AI Enhanced Interaction for seamless human-robot communication, control, and programming

Physical interaction will be enhanced by adapting the robot behavior (i.e., robot impedance) to higher-level multimodal perception control, enabling the robot to change force sensitivity in response to task contact state, human intent, human fatigue, or task certainty, to optimize task-, human or risk-centered objectives. The development of a cognitive interaction framework based on mixed reality interface, gesture and natural voice interactions and multi-channel fusion is proposed. The mixed reality interface will share digital twin's information to the operator though interactable holograms. Via AI, recognized gestures, facial and body expressions will enable communication of feedback, requests, and feelings. A sophisticated vision system will perform a calibration process in real-time allowing a both seamless and accurate remote robot control, reducing exposure to harmful environments. Virtual mechanisms enabling dynamic robot adaptation will be developed including digital twin technology for collision detection and trajectory optimization with the aim to eliminate mental exhaustion during teleoperation. AI based robot programming for robot control, environment perception and decision making will also be under the supervision of the programmer, keeping the programmer and the user always in the loop. Anomaly detection and uncertainty aware perception will allow the robot to identify novel or risky situations and ask for new demonstrations, enabling an interactive teaching for lifelong manipulation. JARVIS will develop an interaction pipeline (Figure 1) where modalities will be filtered or blended for supporting bilateral human robot understanding.

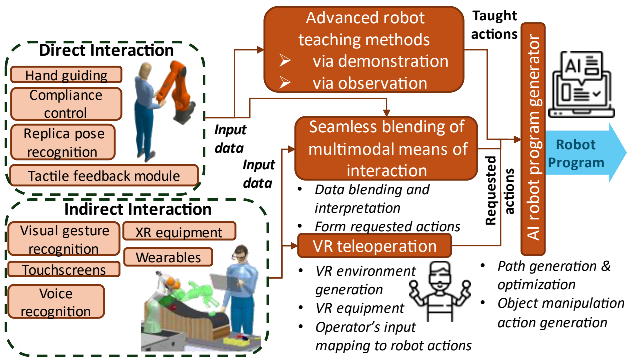

Figure 1: Interaction, teleoperation, and programming approach

2.2. User-centric social interaction

The proposed framework will focus on assessing operator acceptance and phycological impact of the technologies developed. This will lead to the evaluation of the added value provided by the technologies and highlighting of future improvements. Based on traditional HMI principles (e.g., conformity with user expectation, self-descriptiveness, controllability, error tolerance) robot actions will be clearly explicated either through visualizations or through interaction using other modalities (e.g., audio, touch) to construct a shared understanding of the tasks to be done, their goals, and steps to achieve them. Such a shared understanding will improve user acceptance and trust. Robot interactive behaviors will be designed to improve trust and acceptance, operationalizing SSH-principles in methods for the planning of robot trajectories and interactive behaviors. This includes methods which allow the human to understand the robot's current goal, and the task advancement, as well as to improve the short-term predictability of its behavior, and easily control the robot. Finally, JARVIS initiative seeks to develop robots with advanced learning capabilities, including the ability to learn social skills through observation during HRI. By integrating machine learning techniques and machine vision, JARVIS seeks to enable robots to develop learning capabilities including the ability to learn social skills through observation during HRI. The described architecture is presented in Figure 2.

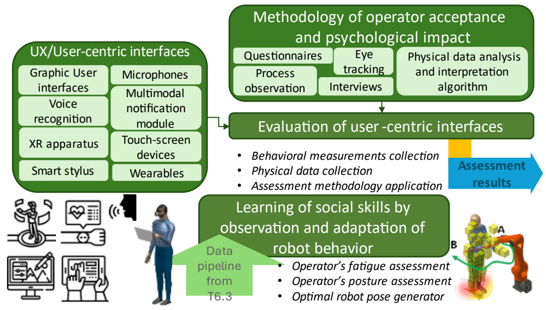

Figure 2: User-centric social interaction methodology

2.3. Security, privacy, and safety towards trustworthy AI

A crucial goal is to develop a flexible and secure software architecture for AI-driven HRI, based on open standards to ensure compatibility across various hardware and software components. This architecture will prioritize security and privacy, safeguarding sensitive data exchanged during interactions. By adhering to ISO directives, the proposed framework will focus on safety standards and guidelines to ensure risk-free HRI operations, covering areas like risk assessment, hazard analysis, and emergency response, to ensure physical safety. Additionally, attention will be given to psychological well-being, addressing ethical implications such as data usage, privacy, and fairness in line with regulations like GDPR and AI guidelines from the EU. These guidelines will also address concerns of bias, discrimination, and informed consent, which are not only ethically and legally essential, but are also critical to gaining the trust and acceptance of AI-driven HRI systems.

2.4. Cognitive and intelligent mechatronics for advanced HRI

JARVIS will prioritize HRI with mechatronic solutions adhering to safe design principles and ISO directives. Intelligent grippers will enhance operator safety in unforeseen circumstances. These solutions will facilitate both physical and remote interaction for improved operator acceptance, trust, accuracy, and safety during collaboration. By utilizing a multimodal perception system, depth sensing with IMUs, gyroscopes, and F/T sensors for environment awareness will be combined, enabling autonomous navigation and obstacle avoidance while ensuring human presence detection for safe HRI. Robots will perceive human actions via a sensor network sharing real-time data, employing embedded cognition to assess ongoing actions. Machine vision and statistical modeling will infer interaction configurations in real-time, optimizing HRI through an awareness system evaluating future human intents and motions. Towards flexible manufacturing, a sophisticated production orchestrator will be developed that will be based on an agile software architecture for increased system reconfigurability, making the solution suitable for different scenarios. Heuristics for human safety, process optimization and adaptation to operator needs will be evaluated in the AI based planner. Digital twins will enable sensor data collection and exploitation from the shop floor, deploying pre-trained perception systems and enhancing reconfigurability. The state-of-the-art sensory network along with beyond state-of-the-art AI techniques will constitute a smart DT with increased cognition enabling robot autonomy. The information flow for cognition and intelligence in mechatronics, as well as the perception systems is presented in Figure 3.

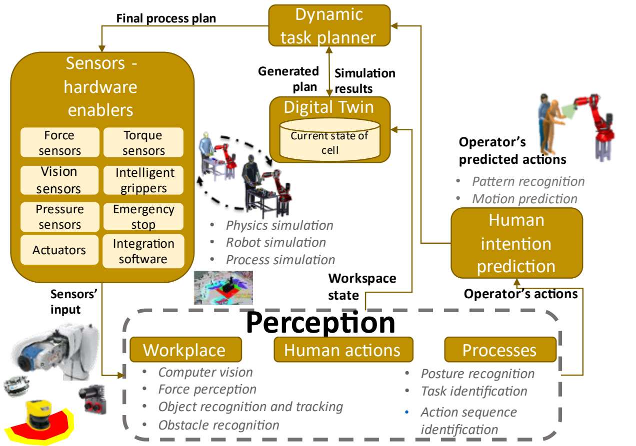

Figure 3: Perception and planning data flow

3. Use cases

3.1. Passenger aircraft seats production

Current state: The use case is part of composite shell manufacturing, specifically, the use case concerns the layup and manufacturing of polymer matrix composites for aircraft interior shells. Currently, the process comprises the following steps. First, the operator lays up the fabric, next, the unidirectional reinforcement of the of the fabric is performed followed by the stiffener lay-up, both performed automatically. Finally, the assembly is bagged up and cured to form the final molded panel. The process involves human operators who either actively lay-up plies of material or continuously monitor each step and are responsible for the right execution, inspecting in between each task the correct lay-up position, orientation, and thickness. Lay up of UD tape has been successfully automated, however lay-up of fabric is still a manual process with attendant labor costs and repeatable part quality issues.

Future vision: The overall objective of this use case is to reduce the exposure of operators in tasks involving unhealthy materials (CFRP, resins) while increasing the efficiency and the reliability of composite ply placement and mechanical assemblies through the introduction of Advanced Smart Manufacturing Human-machine Collaborative Systems It is expected that the robot, in cooperation with the human operator, will lay up the fabric. Additionally, in-situ inspection will be performed, and the human operator will intervene when corrective actions are required. The interactions will involve cooperative human-robot execution of tasks and visual-based systems for the inspection and information presentation to the operator based on camera sensors and AR interfaces. Recording of data from the process will be used to develop a digital data platform for monitoring and recording the state of the process to create a digital twin that can be used for further decision making such as re-learning/adjusting the process for improving performance. Automated quality inspection will focus on the use of robotics to analyze defects of complex operations and support the integration of in-line quality.

3.2. Assembly of hybrid cars battery packs

Current state: The hybrid battery assembly line consists of five stations where all the operations are performed manually. The manipulation of heavy loads is performed with supportive loading equipment. The hybrid battery consists of six (6) main parts: the metal case, the cable group, the battery, the inventor, the subgroup, and the brackets. In addition to the assembly of these parts there is also a final diagnostic test to be performed before the hybrid battery leaves the line. Wheeled assembly fixtures are used to transport the assembly around the different stations. The tasks are performed manually, involving loading of the metal base of the hybrid battery on the assembly fixture, cable assembly, assembly of metal base, scanning of barcodes, diagnostic testing. The final step is to marry the battery pack to the chassis of the car.

Future vision: Mobile collaborative robots are going to be integrated to the assembly line to execute several high ergonomic risk tasks in terms of load and repetitiveness. Operators will contribute to the assembly by performing several high dexterity tasks as well as inspecting the whole process. The mobile cobots will also act as assembly fixtures to carry around the assemblies and eliminate the need to transfer the hybrid battery assembly from one line to the other. The various tasks will be undertaken either by humans or robots, working simultaneously on the same piece. The robot will understand the needs and intention of the operator and adapt accordingly, using advanced perception and cognition, integrated with digital twins. Also, new skills will be learnt automatically by observation. In-time knowledge/ information

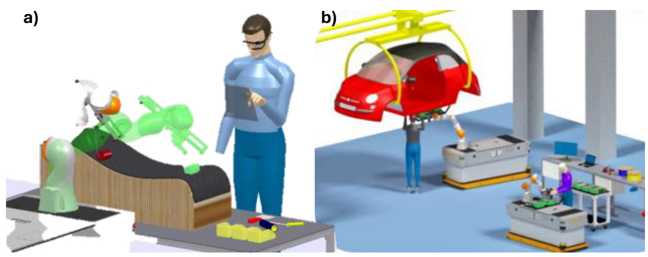

Figure 4: JARVIS vision for a) aircraft seat production b) battery assembly

will be provided to the operator, through user-centric AR interfaces, which will further enable indirect communication.

3.3. Nuclear plants decommissioning

Current state: The nuclear plant decommissioning requires several stages. First electromechanical dismantling takes place, consisting of the removal and cutting up of all the present equipment. Depending on the component it is segmented either on site or in an off-site facility. After the building is emptied the decontamination takes place which involves sampling to define the radiological condition of the plant and tasks perform decontamination by surface removal at the required positions. Most of the operations involved are performed manually. Thus, operators are exposed to a radioactive and hazardous environment, working on non-ergonomic postures, which affect their health despite the PPE used. Remotely performed handling or cutting tasks could intrinsically optimize workers' exposure to radiation as well as other hazards.

Future vision: The scenario focuses on large components teleoperated complex segmentation activities. JARVIS will introduce technology which will operate in hazardous environments and assist the human operators with the task execution without removing them from the loop. Human-centric smart interfaces will be employed to minimize the cognitive load of the operators while maximizing the interaction capabilities allowing them to monitor the process and tele operate the robot, without entering radioactive and hazardous areas. Perception systems will enable autonomic navigation, reducing the need for manual on site deployment of robotic equipment. Object identification capabilities introduced to the robot will enable components recognition identifying characteristics such as material, size, and type. The robot will be equipped with various end effectors to perform cutting and handling operations. XR equipment will be used to increase the immersion of the human in the operating environment, maximizing teleoperations efficiency. Finally, safety features will be integrated to minimize accidents during teleoperation.

3.4. Inspection and maintenance of offshore energy installations

Current state: Today, inspection and maintenance operations, as well as emergency handling, on topside offshore energy production installations are to the most degree carried out by onsite personnel. The variety of tasks to be carried out is large. e.g., visual close-up inspection, general inspection, detecting deviations and faults from change in sound from production equipment, intervention operations such as open lid and turn valve, etc. Moreover, to get to equipment access can pose challenges as there are stairs and sometime a need to reach over equipment.

Future vision: Using teleoperated robots with AI-based capabilities represents in many cases a safer, more cost efficient and faster (more production) operational standard compared to today's approach. The developed technologies will increase efficiency and reliability in inspection and intervention operations with mobile manipulators at offshore energy production plants. The operations will be performed as human-in-the-loop control with a combination of teleoperation, virtual reality (VR), automated planning, and/or autonomous navigation. The exact operations to target in the project will be determined during JARVIS and priorities changes with time, but an initial estimate includes the following main type of operations where human operators are interacting with the robot through a remote connection: a) human-robot/AI collaboration for teleoperation of operations with mobile manipulators, e.g., open lid to access equipment in the field, or operate valve, b) rapid situational awareness through teleoperation and collaborative control (between operator and robot) with mobile manipulators in emergency scenarios (e.g. a gas leak at a processing plant), c) efficient monitoring and control of inspection and intervention rounds with mobile manipulators.

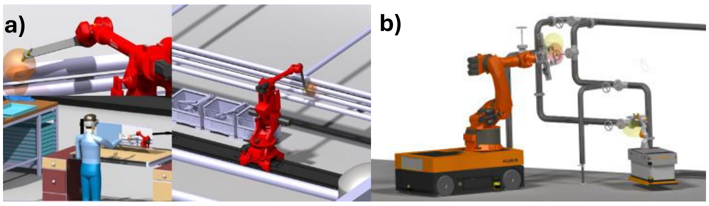

Figure 5: JARVIS vision for a) nuclear decommissioning b) offshore I&M

4. Results & Discussion

Although the use cases presented in Section 3 seem to diverse a lot, a common Key Performance Indicators (KPIs) can be extracted that will allow to evaluate the benefits of the proposed approach. The main KPIs are presented below:

- Decrease of cycle time
- Decrease of reconfiguration and programming time
- Reduction of time spent by the operators in hazardous environments, posing health issues.
- Improvement of ergonomic conditions for collaborative applications
- Quality assurance - reduction of assembly and/or process errors
- Improvement of training efficiency and knowledge transfer
- Reduction of operational costs related to manual operations.
- Increase in the operator acceptance in new technologies

5. Conclusions & Future work

This paper presented a high-level presentation of a framework that will deliver AI enhanced means of interaction for seamless and safe human-robot collaboration. The enabling technologies are parts of a reusable set of tools which will be thoroughly tested in the four indicative use cases, along with the main KPIs which will enable the evaluation of the proposed approach. The proposed approach is currently being implemented under the JARVIS EC funded project and will be integrated in the mentioned pilots, demonstrating production line and cross sector applicability.

Future work will focus on the development of the technologies suggested in Section 2, their optimization, and their integration under a common production station.

Moreover, future work will focus on the deployment of the developed production station in an industrial environment. This will allow to accurately measure the performance of the system as a whole and highlight any bottlenecks as well as demonstrate the importance of AI towards achieving advanced HRI.

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