Article	Title	Use case Description	Use Case Activity	Robotic Collaboration Type	Physical Twin Perception capacity	Embedded/ none embedded	Communication Protocol	Digital concept	DT application level	Geometry	Physics	Behavior	Rule	XR	Interaction number
Burghardt et al., 2020	Programming of Industrial Robots Using Virtual Reality and Digital Twins	Programming of industrial robot based on gesture capture of operators in virtual reality.	Robot programming	Fully programmed	None	No sensors	Home made	DG	Control	Robot, Drying chamber, compressor, suction device, heating ultrathermostat, loading and receiving station, safety elements	Robot Studio force module/Six axis robot, load capacity pf 80 kg, Human Arm	Robot Studio/program genrated by RobotStudio software	Industrial robot controller: cleaning	VR	5,6
Aschenbrenner et al. 2020	Mirrorlabs-creating accessible Digital Twins of robotic production environment with Mixed Reality	Inspection use case: Teaching use case Direct interaction use case Factory planning use case	Monitoring Monitoring Monitoring Monitoring	Fully autonomous Fully autonomous Fully autonomous Fully programmed	Sensors(type not precise) Any kind of sensor (data) in ROS	Embedded Embedded Embedded Embedded	ROSbridge ROSbridge ROSbridge ROSbridge	DS DM DS DS	Identify Identify Visualize Visualize	- Robot - Robot, Shop floor, end effector - Robot - Robot -Object	- Robot's articulations - Joint state, Robot dual arm, human hand - Robot joints - Robot Arm -None Unity	- Operation mouvement - Planning - None - None -None ROS	- None - Execution condition - None - None -None	VR VR AR AR	5,9
Stavropoulos, P. 2021	An AR based Digital Twin for Laser based manufacturing process monitoring	Implementation of a digital twin dedicated to simulation. The specific case is a remote welding process integrating a laser, a mirror, a thermal camera and the part to be welded. The digital twin is considered here as a means of digital prototyping and decision support for engineers in order to choose and correctly configure the elements. All parameters (temperature, absorption, radiation transmission, etc.) have been modeled. The digital twin also provides a visualization.	Monitoring	No robot	IR Camera + Microsoft Hololens detecting QR codes	Embedded+None embedded	Home made	DS	Predict	workpiece, source, dichroic mirror tool: vuforia	Radiation, wavelength of radiation, the amplitude of a radiation in distance z, initial amplitude of radiation tool: vuforia	None	None	MR	No
Choi et al. 2022	An integrated mixed reality system for safety-aware human-robot collaboration using deep learning and digital twin generation	The proposed approach can accurately measure the minimum safe distance in real-time and provide MR-based task assistance to the human operator	Monitoring	Collaboration	2 RGBD Sensors MR Tracking Azure kinect sensor	Embedded+None embedded	TCP/IP	DT	Predict	Robot, assembly component tool: Unity	robot joints +IK tool: Unity	Procedure of pick & place tool: Unity	safety status from MR tracking Tech: Deep Learning tool: Open 3D library	MR	7,9
Li et al. 2022	AR-assisted digital twin-enabled robot collaborative manufacturing system with human-in-the-loop	We have 2 use cases: - single-robot teleoperation, which was designed to present the functionality and performance. Peg-in-hole - multi-robot collaborative disassembly	Monitoring Monitoring	Fully programmed Fully autonomous	wrist camera force torque sensor	None embedded None embedded	TCP/IP TCP/IP	DT DT	Control Control	- Robot, bear - Robot, AGV, box, cable Tool: unity	- bear form, robot joint - Box form, robot joints Tool: unity	-Insert bear into the base - push the box, cut cable, drag, pickplace Tool: Unity	Tech: Reinforcement learning, teleoperation task command (user command)	AR AR	None
Williams et al. 2020	Augmented reality assisted calibration of digital twins of mobile robots in maintenance environments	This article presents an augmented reality assisted digital twin solution that can be used to calibrate mobile robots in maintenance environments. Providing the user the ability to predict the battery charge of the mobile robot.	Monitoring	Co-existence	None	No sensors	Home made	DT	Identify	None	None	None	Maintenance data & predicted results Tool: RapidMiner Tech: Machine Learning	AR	None
Lacomblez et al. 2018	Co-Simulation Architecture Between a Digital Twin and a Virtual Reality Environment in an Industrial Context	propose an architecture of communication, based on Functional Mockup Interface to standardize communication processes and development between simulation software and virtual reality software Use case based on a robotic arm	Layout design	Collaboration	None	No sensors	ZMQ	DM	Control	3D models / Unity 3D for VR and 3D Experience for robotics	Mechanical, Physicals constraints, kinematic / Unity 3D for VR and 3D Experience for robotics	Task sequences / Unity 3D for VR interaction and 3D Experience for task sequences Tech: Functional Mock-up Interface.	Order from human in VR	VR	7,9
Qiu et al. 2019	Digital assembly technology based on augmented reality and digital twins: a review	Reviw in AR&DT	Training	No robot	Camera (any type)/Sensor tracking	None embedded	Home made	DG	Identify	3D Models	None	None	Assembly guide	AR	None
Pérez et al. 2020	Digital Twin and Virtual Reality Based Methodology for Multi-Robot Manufacturing Cell Commissioning	Creating a digital twin of the manufacturing process with an immersive virtual reality interface to be used as a virtual testbed before the physical implementation. The aim of this process is to classify the different manufactured parts, to assemble the parts and the covers, and to put them on a tray for inspection and delivery.	Layout design Layout design	Co-operation Fully autonomous	Sick microScan 3 Core (laser) Vision system (for inspection) scanner laser 3D: FARO Focus3D X130 HDR	None embedded Embedded	Home made Home made	DM DM	Predict Predict	3D models: Robot, Convoyor, belt, tables, parts Tool: Unity 3D	robot joints, belt speed and validity Tool: Unity 3D	Assembly, delivery Grab part, pick and place Tool: Unity 3D	Inspection Safety (operator near the robot => reduce robot speed) tool: Control system (no specification)	VR VR	5,6
Havard et al. 2019	Digital twin and virtual reality: a co-simulation environment for design and assessment of industrial workstations	co-simulation and communication architecture between digital twin and virtual reality software. use case on a human-robot collaborative workplace design and assessment.	Workstation design Robot programming	Co-existence Assistance	sensor suit Sensors	Embedded None embedded	ZMQ ZMQ	DS DM	Predict Predict	3D models tool: Unity 3D	Mechanics & Physical constraints Tool: unity 3D	Assembly Tool: unity 3D	Ergonomics assesment Collision detection	VR VR	5

Kuts et al. 2019	Digital twin based synchronised control and simulation of the industrial robotic cell using virtual reality	Simulation of an industrial robot and collision prediction	Robot control	Co-existence	Sensors Proximity sensor	Embedded+None embedded	Home made	DT	Control	Robot 3D model Tool: Autodesk Maya	robot joints, rotation angles Tool: 3DS	Asked task (fig 8): Move joint, wait for, gripper open Tool: Unity	collision prediction	VR	5
Garg et al. 2021	Digital Twin for FANUC Robots: Industrial Robot Programming and Simulation Using Virtual Reality	-Trajectory planning for complex Edges - Program Creation for programming an engine component	Robot programming Robot programming	Fully programmed Fully programmed	- Not precise - Not Precise	Embedded No sensors	TCP/IP TCP/IP	DT DT	Predict Identify	Ground plane, Robot & component 3D models. Unity	Robot axis & articulations BioIK for inverse kinematics	-Grasp -Welding	Avoid any collision	VR VR	5,7
Kuts, Vladimir; Otto, Tauno et al. 2020	Digital Twin: Collaborative Virtual Reality Environment for Multi-Purpose Industrial Applications	- Make a digital replica of a laboratory - Warehouse digital replica	Robot programming Robot programming	Co-existence Collaboration	None	No sensors No sensors	Home made Home made	DM DM	Control Visualize	3D models: Human, robot, robot's desk. Tool: Unity	Position, rotation, Human articulation, robot's arm. Tool: Unity	- None - Transporting Tool: Unity	- None - Presence of the pallet	VR VR	5,6
KUTS, Vladimir; CHEREZOVA, Natalia et al. 2020	Digital Twin: industrial robot kinematic model integration to the virtual reality environment	Authors propose an real time inverse kinematics algorithm that allows to simulate the robot while writing the robot program (RAPID language). The study shows the precision of the IK algorithm compared to the real obtained position of the robot. Therefore they can use the algorithm to show case and demonstration of it and to program the robot.	Robot control	Fully programmed	Nothing	No sensors	Home made	DT	Control	Robot 3D Model Tool: Unity	kinematic, joint values, velocity Tool: Unity	Move to point sequences Tool: Unity	None	VR	5
Kuts et al. 2018	Enabling the teaching factory leveraging a virtual reality system based on the Digital Twin	The system consists on an interactive and explorative virtual reality environment which faithfully reproduce the physical factory and is fully sychronized with the latter, thus allowing to support a learning by doing approach set in a realistic context	Training	Fully programmed	Camera 3D Laser IoT devices	Embedded	Home made	DT	Visualize	Festo module Robot (see columns PT Industrial Robot) Avatar's arm	Robotic Arm joints Avatar's arm skeleton	AGV movement Robotic arm movement Avatar inverse kinematic	None	VR	5,6
Alfrink et al. 2019	Enhanced Interaction with Industrial Robots Through Extended Reality Relying on Simulation-Based Digital Twins	Approach to interact with heterogenous robot types. Record a trajectory virtualy, then communicate it to the real robot.	Robot control	Fully programmed	camera AR Tracker - HoloLens	Embedded+None embedded	TCP/IP	DT	Control	Robot 3D model, 3D Cursor Tool: VEROSIM	Robot axis & joints Tool: VEROSIM	Follow trajectory predefined Tool: VEROSIM	None	AR	9
Pizzagalli et al. 2021	Evaluation of Virtual Reality Interface Interaction Methods for Digital Twin Industrial Robot Programming and Control, A Pilot Study	Controlling a DT robot arm in a simple pick and place task. comparison between 3 different Human - system interaction techniques	Robot programming	Fully programmed	None	No sensors	Home made	DM	Visualize	Robot 3D model Tool: Unity	Robot joints tool: unity	Rotate, pick, place tool: unity	Object picked tool: unity	VR	None
Eyre et al. 2018	Immersive Applications of Industrial Digital Twins	- Data Overlay of Engineering Information of Hosokawa's air classifier - Immersive Visualisation for training and monitoring - Closed loop process digital twin: Discrete Event simulation application by having a realtime simulation and visualisation of contexutal information	Monitoring Monitoring Prediction	No robot No robot Fully programmed	- No information - No information - No information	No sensors No sensors No sensors	Home made Home made Home made	DS DS DS	Identify Identify Identify	- 3D models: human, air classifier mill(tool: visionary render) - 3D models: conveyor, cutter head (visionary render) - robot (tool: unity)	- speed, pressure, vibration,... (tool: visionary render) - current, speed, temperature, torque, angle,... (visionary render) -robot joints (unity)	- Air classifier (tool: visionary render) - Cutting (tool: visionary render) - Pick and place (tool: siemnes plant simulation)	None	VR VR VR	- None - None - None
Müller et al. 2021	Real-time combination of material flow simulation, digital twins of manufacturing cells, an AGV and a mixed-reality application	Simulation model of the production logistics scenario, robots in the manufacturing part and an AGV for the logistic part, with a major focus on communication protocol.	Prediction Prediction	Fully autonomous Fully autonomous	2D laser scanner LIDAR (odométrie)	Embedded Embedded	MQTT MQTT	DS DS	Predict Predict	AGV 3D model, workshop equipment tool: Unity	None	Follow trajectory sequences of tasks tool: VINCENT	None	VR MR	None
Rabah et al. 2018	Towards improving the future of manufacturing through digital twin and augmented reality technologies	Propose a POC about the integration of DT with AR in predective maintenance field. Develop a DT and AR industrial solution as a part of a predictive maintenance. Detection of forces and failures in rolling bearings.	Monitoring	No robot	sensors	Embedded	Home made	DT	Identify	Banc EREM digital model tool: NX-MCD Siemens	None	None	evaluates states and establish maintenance intervention scenario tool: TIA Portal	AR	None
Cai, Yi; Wang, Yi; Burnett, Morice 2020	Using augmented reality to build digital twin for reconfigurable additive manufacturing system	Use of augmented reality to communicate the layout information between a reconfigurable additive manufacturing robotic arm and its digital twin for toolpath planning and simulation	Layout design	Fully autonomous	1080 P Full HD webcam AR Markers	None embedded	Home made	DG	Predict	Robot tool: solidworks	Robot joints tool: solidworks	Rotate, translate solidworks	Position detection tool: NyAR-Toolkit	AR	None

Weistroffer et al. 2022	Using Physics-based Digital Twins and Extended Reality for the Safety and Ergonomics Evaluation of Cobotic workstations	Simulation of safety and ergonomics evaluation of robotic workstation in several use cases multi user* - A robot and an operator working on a motor together - UR10 and an operator on an assembly line - UR5 robot working with an operator on an assembly line - *Picking of industrial parts from a sliding ramp to the conveyor - simulation of a factory line - Assembly line*	Workstation design Workstation design Workstation design Workstation design Workstation design Workstation design	Collaboration Co-operation Collaboration Fully autonomous Co-operation Co-operation	- Zed camera, HTC Vive Trackers - Kinect Azure, Zed Camera - Zed mini camera - Zed camera - Kinect camera - kinect camera	Embedded+None embedded Embedded+None embedded None embedded None embedded None embedded None embedded	OPC/OPC UA OPC/OPC UA OPC/OPC UA OPC/OPC UA OPC/OPC UA OPC/OPC UA	DS DS DS DS DM DM	Identify Identify Identify Identify Identify Identify	Digital Human Model Robot Digital Model tool: Unity 3D	joints positions, velocities and torques bones and degrees of freedom tool: XDE Physics Engine	Task procedure (see robotic usage) tool: extended dynamics engine, RTDE.	Ergonomics and security Assessment tool: The Rapid Upper Limb Assessment RULA.	MR MR MR MR VR VR	- None - None - 9,13 - None - 6 - 6
Deac et al. 2020	Virtual Reality Digital Twin for a Smart Factory	The papers presents engine 8agora allows creating a DT of a warehouse It presents the feature of the 8agora engine: compression data, event for animation, WebRTC for video, Webscoket for communication The animation are preprogrammed and run based on data events. There is no interaction in VR, only visualization	Monitoring	Fully programmed	Camera	None embedded	OPC/OPC UA	DS	Visualize	3D models of factory equipment tool: PBR	robot joints tool: PBR	factory manufacturing flow event based tool: PBR	None	VR	None
Zhu et al. 2019	Visualisation of the Digital Twin data in manufacturing by using Augmented Reality	AR application to visualise the DT data of a CNC milling machine	Monitoring	No robot	Data acquisition devices	None embedded	TCP/IP	DT	Identify	Milling machine 3D model, cutting tools, workpiece tool: Unity 3D	Milling speed tool: unity	milling (rotation of the cutting tool) tool: unity	None	AR	13
Calandra et al. 2022.	Digital twin-and extended reality-based telepresence for collaborative robot programming in the 6G perspective	A local user wearing a MR hololens in the real workspace consisting of the collaborative robot and a workpiece, work with a remote user equipped with VR HMD, and they two control the robot through a user interface	Robot control	Fully programmed	camera intel D435i	None embedded	ZMQ	DT	Control	3D models: robot, workpiece, human Tool: unity 3D	robot joints tool: unity 3D	Give control, Go to production, open/close grip, teach gripper status, teach point tool: unity	User UI predefined task tool: unity	MR	5,7
Vidal-Balea et al. 2022.	A Collaborative Industrial Augmented Reality Digital Twin: Developing the Future of Shipyard 4.0	digital twin system that provides a dynamic way for industrial companies to perform operator training with a full-size model of the real equipment	Training	No robot	IIoT Sensors	None embedded	MQTT	DT	Identify	valve 3D model tool: unity	Temperature in/out tool: unity	None	None	AR	None
Begout et al. 2022	Augmented Reality Authoring of Digital Twins: Design, Implementation and Evaluation in an Industry 4.0 Context	Helping re-organizing a workstation by knowing if pieces are in the right position.	Workstation design	No robot	Markers + hololens sensors	Embedded	Webservice	DS	Identify	electrical screwdriver 3D model tool: untiy 3D	None	None	Placement checking	AR	13
Shaaban et al. 2022	Integrating Digital Twin And Mixed Reality In Human-Robot Collaboration	This article propose a software architechture with a simple implementation of a pick & place task	Monitoring	Co-operation	Zed2 (stereo + IMU + barometer + magnetometer) + MOCAP + robot perception modules	Embedded+None embedded	ROSbridge	DT	Predict	Geometry: Room, Thiago, Human, Bottle Tool: Unity	Physic: Robot Arm, Human Arm (Zed2 camera) Tool: Unity	Behaviour: Robot High-Level Task Controller, Navigation module, Arms Motion Planner Tool: Unreal engine	Rule: Robot: Perception module (detect that human gives bottle) Tool: ROS	MR	None
Caiza et al. 2022	Digital Twin for Monitoring an Industrial Process Using Augmented Reality	Monitoring the state of the process and the product development using augmented reality	Monitoring	No robot	industrial sensors	None embedded	MQTT	DS	Visualize	Classification Station 3D model Tool: Blender	None	Station normal working Tool: Unity	None	AR	None
Geng et al. 2022	Digital Twin in smart manufacturing: remote control and virtual machining using VR and AR technologies	Case study on CNC milling machine, they had simulated a milling process, and positionning of product before milling.	Monitoring	No robot	Camera of a mobile device	Embedded+None embedded	TCP/IP	DT	Control	piece 3D model, milling machine 3D model Tool: Unity 3D	Machine axis Tool: Unity 3D	Milling Process Tool: Unity	Product right positionned	AR	None