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VR-AUGMENTED CONTROL SYSTEMS FOR COLLABORATIVE ROBOTS IN MANUFACTURING

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Annotation. This paper introduces a VR-augmented system for collaborative robots, combining a consumer HMD with a markerless neural alignment module and safety manager. Built with Unity/ROS, it achieves fast, millimeter-scale registration. Tests on battery recycling and assembly tasks show reduced setup time and improved performance. Limitations and safety recommendations for industrial use are discussed.

Keywords: VR teleoperation, human–robot collaboration, 6-DOF registration, manufacturing.

Introduction. Industry 5.0 requires interfaces that pair robotic precision with intuitive human control. Consumer HMDs and mature VR toolchains make immersive teleoperation practical, lowering barriers to collecting expert demonstrations and offering natural spatial control– advantages shown in recent VR teleoperation work. Accurate visuo-haptic registration (aligning virtual objects, the HMD camera, and any haptic/end-effector frame) is essential for coherent visual and tactile perception. Marker-based calibration is accurate but bulky and occlusion-sensitive; markerless, data-driven fusion of HMD pose, hand/fingertip tracking, and end-effector readings provides a more portable industrial alternative [4].

This paper presents a portable VR-augmented control architecture for collaborative robots that integrates a consumer-HMD teleoperation frontend, a markerless neural 6-DOF alignment module, and an integrated safety/feedback manager. We evaluate alignment accuracy, task performance, and operator workload on representative manufacturing tasks, demonstrating improved usability and reproducibility in human–robot collaboration workflows [1].

Main part. Teleoperation lets humans extend skill and judgment into remote or hazardous workspaces, pairing human adaptability with robotic precision for tasks that resist full automation (complex assembly, delicate disassembly, exception handling). In manufacturing, VR-augmented teleoperation improves demonstration collection, operator training, and situational awareness by providing an intuitive 3-D control metaphor and realistic scene visualization.

A compact theoretical framework for VR-enabled human–robot collaboration has three core components:

Convert operator actions in VR into robot setpoints – from direct 1:1 motion mapping for high-DOF teleoperation to higher-level waypoints or task primitives. Pose-based intents (position, orientation, gripper state) fed to a local controller (e.g., impedance or go-to-pose controllers) balance intuitiveness and stability: the operator supplies intent while the robot enforces kinematic, dynamic, and safety constraints [2].

Visual, proprioceptive, and (where available) haptic cues must share a common world frame so contacts, stiffness cues, and object positions align perceptually. Marker– or camera-based calibration can be accurate but is often bulky and sensitive to occlusion; markerless, multimodal alignment that fuses HMD pose, hand/fingertip tracking, and end-effector readings increases portability and– when sufficiently trained– can reach millimetre-level registration. Augmented feedback should combine clear virtual affordances, haptic/force cues, and explicit safety signals (virtual walls, collision alerts) to reduce cognitive load and support operator decision-making.

Blend operator commands with local autonomy via blending, virtual fixtures, or constraint projection so the robot corrects small errors, enforces collision avoidance, and stabilizes motion under latency. Safety management must include hard robot-side limits (velocity, force), workspace zoning, and visible mode transitions (teleoperation ↔ collaborative/autonomous) so operators remain aware of control authority and system state.

Human-centred evaluation should combine objective metrics (alignment error in mm/°, task time, error counts) and subjective measures (usability and workload scales such as NASA-TLX, operator trust). For industrial deployment prioritize portability (consumer HMDs), low setup overhead, modularity across robot embodiments, conservative safety defaults, and compatibility with open toolchains. Together, these elements produce VR-augmented control systems that are intuitive, safe, and practical for real manufacturing tasks.

In the study "Deep Neural Network-Based Alignment of Virtual Reality onto a Haptic Device for Visuo-Haptic Mixed Reality", the researchers evaluated a Unity-based VR frontend connected to robot controllers through a lightweight middleware layer to assess a markerless alignment module and an integrated teleoperation and safety pipeline, both in simulation and on real hardware [3].

The experiments were conducted on a workstation equipped with an NVIDIA RTX 3090 Ti using a markerless sensing stack with HoloLens 2 and a Touch 3D haptic device. Ground truth was obtained with a temporary QR-code rig, and the dataset comprised approximately 740k augmented samples.

The reported accuracy reached the millimetre scale, with a mean Euclidean error of about 2.18 mm (median 1.76 mm; 99.9% < 11.7 mm) and rotation RMSE below 0.8° per axis (overall ≈ 0.53°). The neural, markerless model outperformed a deterministic kinematic transform, reducing the worst-case error from more than 5 cm to below 2 cm and remaining robust to synthetic fingertip noise [3].

The system was validated in simulation and on real hardware using a Franka Emika Panda robot and scene sensing with Intel RealSense D415. In a representative manufacturing scenario (Li-ion battery disassembly on a UR5e platform from Universal Robots, with an HTC Vive Pro frontend by HTC), practical task times of approximately 20 s (cover removal) and 25 s (cable extraction) were reported, together with effective safety-aware replanning.

These technologies directly support manufacturing domains that demand precision, safety, and rapid reconfiguration. Immersive teleoperation with markerless neural alignment enables delicate remote operations– such as Li-ion battery recycling on collaborative robots from Universal Robots– while reducing setup time and operator exposure. Portable consumer HMD frontends and fast markerless calibration also benefit electronics repair and small-parts assembly on platforms such as those from Franka Emika, and support secondary automotive assembly and aerospace maintenance through virtual fixtures and reliable visuo-haptic coherence. For hazardous-zone tasks, teleoperation combined with scene sensing lowers human risk, while open toolchains such as MoveIt and OMPL enable real-time replanning and constraint enforcement. Overall, consumer-grade VR teleoperation with markerless neural alignment achieves millimetre-scale accuracy and is most valuable for battery recycling, fine electronics, secondary automotive operations, aerospace maintenance, and flexible small-batch manufacturing [3].

Conclusion. Integrating consumer-grade VR teleoperation, markerless neural alignment, and modular frameworks yields a practical, portable pipeline for VR-augmented control of collaborative robots. A Unity Technologies-based frontend with open middleware such as ROS facilitates demonstration collection and operator training; a neural, markerless alignment module tested with HoloLens 2 and Touch 3D achieves millimetre-scale registration and outperforms simple kinematic transforms. An integrated safety/feedback layer and fast local control– demonstrated on the Franka Emika Panda– are essential for reliable industrial deployment. Remaining limitations (need for ground truth, occlusion and extreme-motion sensitivity, HMD comfort, and software/version fragility) suggest clear next steps: markerless ground-truth acquisition, broader user studies, learning from VR demonstrations, and tighter robot-side safety integration. Overall, these components provide a reproducible, industry-relevant route to safe and intuitive VR-augmented human–robot collaboration.

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