# Human-Centric Concept for a Reconfigurable Robotic System Enabling Low-Volume Assembly of Photonic and Quantum Modules

Andreas Wicht[1], Tobias Franke[1], Alina Hahn[1], Nils Håkansson[1], Christian Kürbis[1], Robert Smol[1],
Thomas Hulin[2,3], Thomas Eiband[2], Peter Lehner[2], Maximilian Mühlbauer[4,2], Korbinian Nottensteiner[2],
Richard Pietschmann[5], Bernhard Thaler[5,6], Diana Thaler[5,7], and Jürgen Bosse[5]

***Abstract*— This paper presents a novel concept for a reconfigurable robotic system specifically designed to meet the demands of hybrid integration for miniaturized photonic and quantum System-in-Packages (SiPs). The proposed solution introduces a distinctive approach to ultra-high-resolution, multi-telerobotic assembly and inspection. By integrating key Industry 5.0 principles, it establishes a human-centric control framework that minimizes both physical and cognitive stress while ensuring the human operator remains in full control at all times.**

**The robotic system features eight robots working simultaneously within a compact footprint of just $5{\times}10\,\mathrm{cm}^2$. A comprehensive digital twin framework constitutes a central element of the robotic system. It encompasses the robotic workcell, the SiP under assembly, and the components to be integrated, ensuring precise adherence to design specifications. Key functionalities include automated path planning in a multi-robotic environment, collision avoidance in a densely packed workcell, and virtual fixtures to guide teleoperation, enhancing the operator's control and interaction through advanced and intuitive human-machine interfaces (HMI). The proposed system meets the critical demands of ultra-high-resolution assembly for complex, high-value SiPs, providing high flexibility and ease of operation for small-batch manufacturing.**

## I. INTRODUCTION

The advent of Industry 5.0 represents a paradigm shift towards more intelligent and collaborative manufacturing processes. This new era aims to integrate human skills with advanced robotics to achieve unprecedented levels of flexibility, resilience, precision, and efficiency. As industries advance miniaturization and complexity in photonic and quantum System-in-Packages, traditional manufacturing techniques struggle to meet the stringent requirements on precision, to handle product complexity, and to automate production cost-efficiently for batch sizes as small as one.

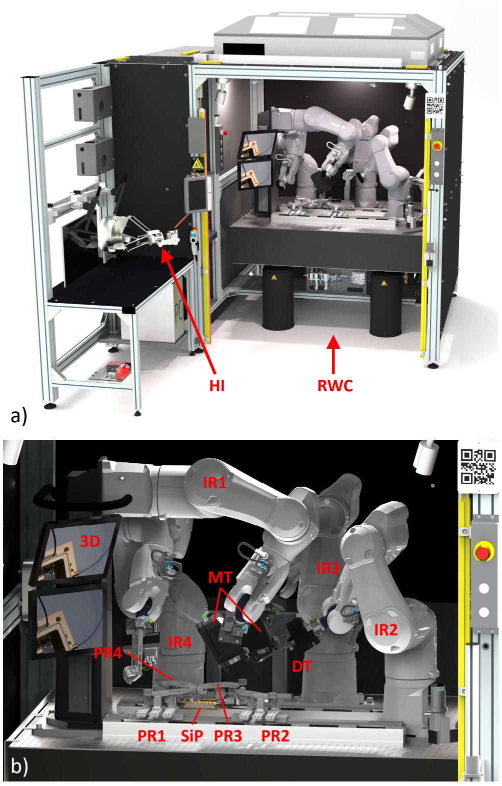

Fig. 1. (a) CAD drawing of the full workspace, and (b) corresponding zoomed-in view with the SiP at the center. The robotic workcell (RWC) features four single-arm, 6-axis industrial robots (IR1...4) and four ultra-high precision hexapod robots (PR1...4) on the optical table. The setup shows two industrial robots equipped with digital stereomicroscopes (MT), with images displayed on 3D monitors (3D), and another robot carrying a dispenser tool (DT). A haptic device (HI) on the left allows for teleoperation of both industrial and high-precision robots.

Hybrid integration of SiPs (see Fig. 2), particularly at the microscale for photonic and quantum applications [1], presents significant challenges. These include the need for ultra-precise active alignment (accuracy approximately 100 nm), complex and simultaneous multi-component assembly, and stringent quality control. Current solutions often fall short in terms of flexibility and scalability, especially in high-value, low-volume production scenarios typical of advanced technology sectors.

This work was supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy under grant number 50WP2104 (BECCAL) and 50WM2164 (CRONOS-Pathfinder), and project Factory of the Future Extended (FoF-X), by VDI Technologiezentrum GmbH with funds provided by the Federal Ministry of Education and Research under grant number 13N14906 (CaLas), and by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy – EXC2050/1 – Project ID 390696704 – Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) of Technische Universität Dresden.

[1] Ferdinand-Braun-Institut (FBH), 12489 Berlin, Germany

[2] Institute of Robotics and Mechatronics, German Aerospace Center (DLR), 82234 Wessling, Germany.

[3] Centre for Tactile Internet with Human-in-the-Loop (CeTI), Germany.

[4] Sensor Based Robotic Systems and Intelligent Assistance Systems, Technical University of Munich, 85748 Garching, Germany.

[5] Robo-Technology GmbH, 82178 Puchheim, Germany

[6] current address: Thaler Engineering GmbH, 82223 Eichenau, Germany

[7] current address: Coherent Munich GmbH & Co. KG, 82205 Gilching, Germany

Current robotic systems in advanced manufacturing face several limitations, specifically for the hybrid integration of photonic and quantum SiPs. Despite advancements, traditional systems encounter significant challenges in multi-robot coordination, path planning, and collision avoidance. These systems often depend on manual programming rather than reusable robot skills [2] and rely on offline planning, which proves inefficient in environments requiring frequent setup changes and high precision.

Moreover, integrating multiple robots using various tools within a confined workspace exacerbates these issues, leading to suboptimal placements of workcell components and tight motion constraints. Another critical concern is the lack of sophisticated human-machine interfaces. Existing systems typically offer limited and non-intuitive operator interaction capabilities, primarily through basic control panels, kinesthetic teaching, or rudimentary teleoperation setups, which are rarely integrated [3]. This limitation restricts the flexibility and adaptability of the manufacturing process, which are essential for producing low-quantity, high-value products. Additionally, the current implementation of virtual fixtures for guiding users during teleoperation is often inadequate, lacking the precision and intuitive control needed for sub-millimeter scale tasks.

This paper introduces a novel robotic concept tailored to the needs of low-volume hybrid integration, specifically for high-value photonic and quantum SiPs. Leveraging various aspects of Industry 5.0, this concept combines teleoperation and automation with intuitive human-machine interaction, implementing a human-centric operations approach crucial for flexibility in low-volume production and R&D applications.

Central to this concept is a multi-telerobotic setup comprising eight robots working in unison to perform ultra-precise assembly and inspection tasks. This system is supported by a detailed digital twin framework that digitally replicates the robotic workcell, the SiP under assembly, and the components to be integrated, based on a structured knowledge representation. The digital twin ensures strict adherence to design specifications, enhancing accuracy and reducing errors. Additionally, it facilitates a seamless transition between virtual planning and real-world execution through extended reality concepts.

Key innovations include automated path planning and collision avoidance algorithms designed for multi-robot environments, layout optimization of parts within the workspace [4], and adaptive virtual fixtures [5] that provide haptic feedback to guide operators during teleoperation. These features not only enhance the precision and reliability of the assembly process, but also reintegrate human expertise, creativity, and adaptability into the production environment, bridging the gap between automated precision and human intuition.

The following sections will first describe the existing robotic workcell and then propose an extended concept incorporating the digital twin framework, layout optimization, automated path planning and virtual fixtures.

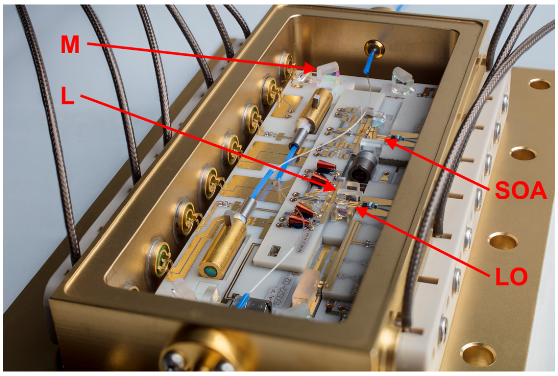

Fig. 2. Example of a photonic SiP for quantum technology application, featuring a diode laser module with a narrow linewidth local oscillator and a semiconductor optical amplifier (corresponding laser diodes LO and SOA). Micro-optical lenses (L) are positioned on the right, micro-mirrors (M) are visible in the foreground background; such a module was used in an iodine molecular optical clock onboard a sounding rocket [1].

## II. DESCRIPTION OF ROBOTIC WORKCELL

The robotic workcell, as illustrated in Fig. 1, is a multi-telerobotic assembly and inspection facility designed for the ultra-precise hybrid integration of photonic and quantum SiPs, exemplified by the module shown in Fig. 2. The workcell features eight strategically deployed robots that manage various tasks critical to SiP integration. The configuration combines industrial and ultra-high-precision robots.

The assembly process involves manipulating optical components, such as micro-optical lenses, with a resolution of 10 nm / 10 µrad and adhesive bonding with an accuracy better than 100 nm / 100 µrad. Up to four components must be handled simultaneously while, for example, the laser under assembly is operated and its performance is optimized through active alignment of these components. Ultra-precise manipulation is achieved using four independent hexapod robots (Smaract Smartpods), which employ piezo-based actuators to allow for nanometer precision. At present, tasks beyond high-precision manipulation are carried out manually by a human operator, but in future they will be executed by industrial robots. These include: (i) positioning components within the reach of the ultra-high-precision robots, (ii) applying adhesives (typically 100 nanoliters in volume) using dispensers after alignment, (iii) positioning UV-curing tools at appropriate locations and orientations, (iv) positioning a stereomicroscope to guide the operator during component manipulation and adhesive application, (v) collecting radiation from the SiP during alignment to direct it to various analysis tools for performance evaluation, and (vi) performing high-resolution stereoscopic imaging of the SiP post-assembly as part of quality assurance.

Four industrial six-arm robots (Stäubli TX2-60) handle tasks (i) through (vi), utilizing tools retrieved from a tool exchange station. Available tools include a tweezer, a dispenser, a UV-curing tool, and two stereoscopic microscope tools with adjustable resolution down to approximately 5 µm. A beam picker tool directs radiation from inside the SiP to a designated position around the workcell's perimeter, from where it is automatically coupled to radiation analysis tools. During manufacturing, the system needs to be reconfigured multiple times to equip the arms with the appropriate combination of tools for the given tasks. Furthermore, depending on the type of SiP, different sets of tools and different process flows are required.

The micro-optical benches of SiPs typically possess a footprint of $5\,\mathrm{cm} \times 10\,\mathrm{cm}$, with distances between micro-components in the millimeter to sub-millimeter range. Hence, reliable operation of multiple robots and of their corresponding tools in a strongly confined workspace poses a serious challenge for the HMI, the telerobotic control concept and for any operator assistance like path planning or utilization of virtual fixtures.

Industry-grade control panels are available for controlling the industrial robots. Additionally, advanced human-machine interface (HMI) tools have been selected to facilitate intuitive human-system interaction: a haptic interface (Force Dimension Sigma-7) provides input and force feedback across seven degrees of freedom (DoF), augmented reality (AR) goggles (Microsoft HoloLens 2) support acoustic feedback and voice control, and eye-tracking 3D monitors (3D Global) offer real-time spatial perception of stereoscopic images.

The existing system faces several challenges. A significant issue is the coordination and synchronization of the eight robots within the confined workspace. The current setup relies heavily on manual programming and offline planning, which are time-consuming and prone to errors. This approach also limits the system's adaptability to changes in the assembly process and the introduction of new components into the workspace. Furthermore, path planning and collision avoidance are managed through heuristic methods and expert intervention, which are not scalable for complex, multi-robot environments in a flexible production setting. The lack of automated, real-time planning tools results in inefficiencies and potential collision risks, particularly when robots operate in close proximity.

Additionally, the HMI of the current system is relatively basic, offering limited interaction capabilities for the operator, and is not yet intuitive. This limits the flexibility and adaptability required for low-quantity manufacturing and R&D applications. Finally, the implementation of virtual fixtures is rudimentary, lacking the precision and intuitive control necessary for the execution of tasks requiring sub-millimeter accuracy. Telerobotic operation at this scale places both the robotic tools and high-value SiPs at risk.

Hence, while the existing multi-telerobotic workcell holds considerable technological potential, it requires significant improvements in coordination, planning, and human interaction to become Industry 5.0-ready for intuitive, flexible, and ultra-precise assembly of photonic and quantum SiPs.

## III. ADVANCED SYSTEM CONCEPT

This section details the proposed advancements for the multi-telerobotic system, highlighting its key components and innovations. The proposed concept integrates Industry 5.0 principles to ensure the operator remains in control at all times. It leverages human intuition and creativity, particularly for low-volume production and R&D activities, where established assembly processes are often unavailable and frequent system reconfiguration is necessary. At the same time, it alleviates stress on the human operator by taking over tedious tasks and delivering real-time data analysis and process evaluation throughout the process chain.

Alongside the eight robots, the system features an advanced and intuitive HMI, as well as a comprehensive digital twin framework. This digital twin encompasses the robotic workcell, the SiP under assembly, and the individual components. It provides automated path planning, collision avoidance, and precise setup of tools and SiP positions. Additionally, the concept introduces advanced virtual fixtures within the digital twin, which guide the operator through visual AR indications and force feedback, ensuring precise teleoperation. Detailed descriptions of these technologies are provided in the following subsections.

### *A. Digital Twin Framework*

The digital twin framework is central to the robotic control system depicted in Fig. 1. It consists of three parts: (i) the digital twin with all robots and their tools, ensuring precise modeling of the physical environment, (ii) the digital twin of the SiP under assembly, (iii) the digital twin of the components to be integrated into the SiP.

The human operator interacts with the digital twin through various HMI tools, as described earlier. These tools allow the operator to intuitively configure a specific workcell, such as positioning robotic tools, and locating, orienting, and configuring virtual fixtures. This configuration process is carried out entirely within the digital twin environment using extended reality (AR/VR goggles, gestures), a haptic interface, and voice control.

Utilizing the data held by the digital twin, automated planning methods (see section III-B) analyze the operator's configuration request for feasibility and determine the assignment of requested tools to the industrial robots. Based on the information available from the digital twin, the planning tools also establish suitable trajectories for the industrial robots. Given the confined workspace, effective path planning relies heavily on advanced collision avoidance tools, which are also informed by data from the digital twin of the robotic workcell, the SiP, and the components to be integrated.

Once path planning is successfully completed, the planned activity can be intuitively evaluated and validated by the operator. This can be done either in the fully digital twin environment using VR or by overlaying the planned action onto the real hardware using an AR approach.

With the latter, the operator can account for any discrepancies between the digital twin data and the real world, ensuring flexible and safe use of the robotic system.

Conducting detailed planning and configuration within the digital twin enhances the availability of the robotic hardware for production and mitigates the risks associated with planning activities, such as those arising from trial-and-error methods.

Automated execution of motions along the planned path then positions the robotic tools in an optimal start position and orientation, from which the human operator takes over through telerobotic operation. This operation heavily relies on the digital twin: teleoperation is supported by virtual fixtures defined within the digital twin (see section III-C). To facilitate intuitive operation, the haptic interface provides force feedback, signaling the operator about the proper (nominal) motion of the tool "on the last millimeter" along the path set by the virtual fixtures. Real-time comparison between the actual hardware, as imaged by the stereomicroscope, and its virtual counterpart within the digital twin enables real-time updates to the digital twin.

The digital twin not only provides access to essential functionality for planning, validating, and executing robotic activities but also plays a crucial role in operator training. Training using the digital twin, rather than the actual robotic hardware, enhances hardware availability for production and significantly reduces the risk of damaging delicate robotic tools and/or SiPs.

Finally, the digital twin serves as a valuable tool for R&D on the robotic system. This use case not only offers the previously mentioned advantages but also allows for much faster and more extensive testing as compared to physical hardware, as no real motions are required. In particular, actions associated with high or uncertain risk of damage can be tested and evaluated safely.

The implementation of the digital twin is envisioned as follows. Information is organized in a knowledge base that maintains the state of the robotic workcell, the SiP under assembly, and all individual components within the workcell. These components are represented by their geometric meshes, textures, and their pose relative to various reference frames. Further properties describe the state about locked resources and semantic relationships between components. Additionally, properties like non-rigidity or articulated mechanisms, such as cables or foldable parts, can be modeled. System capabilities can be expressed through an ontological knowledge base, which assists users and automated planning algorithms in fully exploiting the functionality of the multi-arm robotic workcell [3], [6].

The state of the digital twin can be examined by querying information about objects within the workcell and their interrelationships (Fig. 3). The operator can interact with selected objects by moving them within the workspace, while potential placements are evaluated in real-time. This evaluation takes into account constraints such as kinematic reachability and manipulability by the robots, as well as permissible assembly patterns.

### B. Automated Workcell Layout and Path Planning

In the proposed advanced system, the interactive process can be further supported by automated planning methods accessible to the operator through the digital twin. This reduces the manual effort required to introduce and modify tasks, as the system autonomously handles necessary preparation steps. These steps include defining the layout of a reconfigurable workcell and transferring the system into a starting configuration before the actual manufacturing process begins with teleoperation.

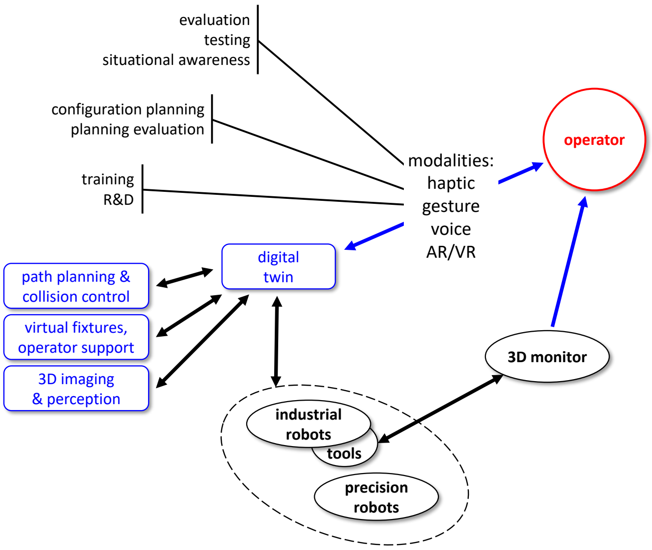

Fig. 3. Communication diagram of the robotic system; hardware (black), software (blue) and operator (red). The schematic emphasizes the role of the digital twin and its relation to the HMI, planning tools, planning tasks, and to the robotic hardware.

Determining the layout of a workcell is a high-dimensional problem and presents a practical challenge due to the complexity of assessing reachability and other kinematic constraints from the robotic system and the manufacturing process. Feasible poses for all relevant parts located in the workcell, such as robotic manipulators, tool placements, the SiP under assembly, and component feeders, need to be defined. Typically, this is addressed by experts using heuristics and trial-and-error methods during offline planning or setup at the real system. This process is inefficient in rapidly changing setups and for small batch sizes, where a system needs to be reconfigured frequently. The challenge is further exacerbated by the presence of multiple robots in a confined workcell, which limits the available space for movements and tool placements.

In our previous work, we demonstrated how task-specific workspace maps can be generated in a flexible multi-robot setup [7], including tasks for single-arm robots as well as for cooperative execution with multiple arms. These maps can be used to (visually) analyze the placement of workcell parts in the digital twin and provide feedback to the user. Additionally, the object-centric specification of task frames can be applied for automated planning of workcell layouts, as shown for a dual-arm setup and specific task sequences in [8] using a genetic algorithm for optimizing placements. Furthermore, task and object information can be provided through the knowledge base populated with annotated CAD data, allowing for autonomous reconfiguration of the workcell [4].

Ideally, the operator can concentrate fully on the assembly process without having to deal with the simultaneous con-

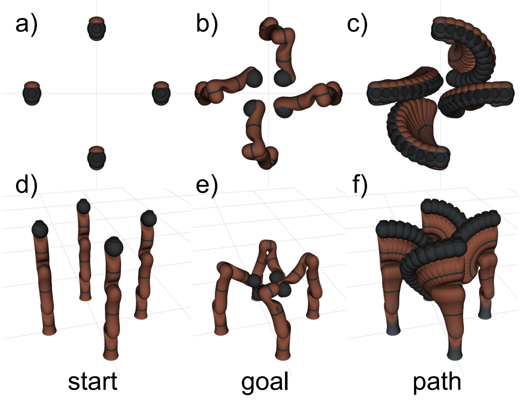

Fig. 4. Case study of motion planning for multiple manipulators in a simulated environment, visualized in a top down (a-c) and orthographic (d-f) perspective. The start configuration is shown in (a, d), the goal configuration in (b, e) and one example path is shown in (c, f).

figuration of several arms in joint space. The system should autonomously establish an optimal start configuration for the operator, who would then perform the fine manipulation tasks. The system might also autonomously pick up required tools and components. In addition to achieving a feasible layout, the automation methods can plan the necessary robot trajectories and ensure collision-free execution in the multi-arm setup.

While single-arm motion planning has seen significant advancements, state-of-the-art solutions for multi-robot environments are still limited due to the increasing complexity of planning problems in high-dimensional configuration spaces. Existing solutions include dual-arm motion planning or heuristic methods for multi-arm setups, but there is a notable lack of approaches for collision-free, synchronized motions of multi-arm systems in confined spaces [9], [10]. Therefore, we propose extending advanced probabilistic path planning methods [11], [12], which have been demonstrated with various robotic manipulators and for planning constrained motions; see Fig. 4 for a preliminary case study in a simulated environment. Future work will need to address the efficient online planning of constrained trajectories in confined workspaces for multiple manipulators, adapting to the perceived changes in the semi-unstructured laboratory environment.

### C. Adaptive Virtual Fixtures for Teleoperation

While many preparation and process steps can be automated, certain tasks still require human intervention or can benefit from human problem-solving capabilities. To harness these human strengths, we propose a teleoperation system enhanced by motion scaling [13], [14], [15] and force feedback provided by Virtual Fixtures (VFs) [16]. VFs are virtual force fields that guide the human operator during teleoperation.

VFs provide support during teleoperation to ensure precision and accuracy for complex tasks that require fine manipulation. They are particularly valuable in collaborative or shared control environments where high accuracy is essential, such as in the assembly of delicate apparatuses [17], [18]. VFs can be classified into two main types: forbidden region VFs and guiding VFs. Forbidden region VFs prevent the robot from entering specific areas to avoid damage to sensitive components or tissues. While commonly used in surgical robotics [19], they have also shown potential in industrial applications [20]. Guiding VFs, on the other hand, direct the robot along predefined trajectories, facilitating precise movements (see Fig. 5).

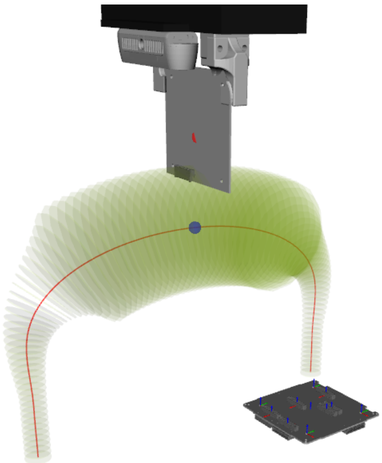

Fig. 5. The position-based VFs along a trajectory are illustrated, with the red line marking the trajectory center and green circles showing varying translational stiffness [21]. The fixture force pulls the robot (red dot) orthogonally towards the trajectory (blue dot), with dots displayed at an offset for visualization.

Recent advancements enable the integration of static guiding fixtures with dynamic, vision-based fixtures, offering adaptable and precise guidance based on real-time environmental perception through a probabilistic formulation. The combination of vision-based and position-based fixtures using a Product of Experts (PoE) [22] approach allows for the merging of the strengths of both fixture types, providing comprehensive guidance across the entire workspace [21], [5]. By weighting each fixture according to its covariance, optimal guidance for each degree of freedom can be achieved.

To make these VFs economically viable and effective in real production environments, especially for non-robotics experts, intuitive programming and adaptation methods are essential. This can be facilitated through hands-on demonstrations as well as modifications of fixture properties via a graphical user interface (GUI). Future research needs to bridge the gap between data-driven fixture definitions and human-tunable parameters for fixture adaptation.

In the context of multi-arm systems with multiple collaborative robots operating simultaneously, VFs play a crucial role in ensuring precise and collision-free operations. VFs can guide each robot to avoid forbidden regions, prevent collisions with other moving robots, and follow accurate motion trajectories. The use of VFs in a multi-arm setup not only enhances overall system performance but also increases flexibility and ease of operation, making it possible to efficiently handle small quantities of custom SiPs.

Key to this performance improvement is the parameterization of fixtures using data from the digital twin. This has been previously explored [23], [24], [25] but needs to be adapted to the proposed multi-robot setup.

The implementation of VFs in a multi-arm workcell, as proposed in this paper, further highlights their potential. Integrating VFs with digital twin models and advanced sensor technologies will facilitate real-time adjustments and enhance the system's adaptability and flexibility. To achieve this, future research must address the interaction among multiple VFs to enable multi-robot manipulation and to dynamically arbitrate and update VFs based on the state of other fixtures and robots. Additionally, new tools are necessary for learning such fixtures from small datasets and for configuring them intuitively.

## IV. CONCLUSION

The proposed concept for a reconfigurable robotic system promises significant advancement in the field of hybrid integration of photonic and quantum SiPs. By integrating a multi-telerobotic setup with a comprehensive digital twin framework and intuitive operation, the system addresses critical challenges related to the high level of task complexity, the requirement for sub-micrometer precision, and for flexibility and efficiency in low-quantity, high-value manufacturing.

Key technologies such as automated layout and motion planning, collision avoidance, and virtual fixtures enhance the assembly process, ensuring strict adherence to design specifications while leveraging human adaptability. However, the realization of such an advanced robotic workcell depends on further advancements in technologies including digital twinning, multi-robot coordination, and virtual fixtures, each with its own set of unresolved issues.

Seamless digital integration across subsystems involved in the alignment or assembly task will allow for data-driven automation. Data collected from the robotic control system, HMI tools, and measurement equipment during alignment and assembly will be stored in a database to identify patterns in the operation of hardware operation, human activity and measurement results that are critical to successful task performance. This process could automate tasks typically requiring specialist expertise, combining precision with flexibility. Achieving these goals will pave the way for a new era of ultra-precise, flexible, and efficient manufacturing in Industry 5.0, empowering humans to intuitively and effortlessly operate complex and highly functional robotic systems.

## REFERENCES

[1] C. Kürbis, R. Smol, A. Peters, A. Wicht, and G. Tränkle, "Extended cavity diode laser master-oscillator-power-amplifier for operation of an iodine frequency reference on a sounding rocket," *Applied Optics*, vol. 59, no. 2, pp. 253–262, 2020.

[2] M. Pantano, T. Eiband, and D. Lee, "Capability-based frameworks for industrial robot skills: a survey," in *IEEE Int. Conf. on Automation Science and Engineering (CASE)*, 2022, pp. 2355–2362.

[3] T. Eiband, F. Lay, K. Nottensteiner, and D. Lee, "Unifying skill-based programming and programming by demonstration through ontologies," *Procedia Computer Science*, vol. 232, pp. 595–605, 2024.

[4] T. Bachmann, O. Eiberger, T. Eiband, F. Lay, P. Angsuratanawech, I. Rodriguez *et al.*, "Task-specific reconfiguration of variable workstations using automated planning of workcell layouts," in *Int. Symp. on Robotics (ISR)*, 2023, pp. 250–257.

[5] M. Mühlbauer, T. Hulin, B. Weber, S. Calinon, F. Stulp, A. Albu-Schäffer *et al.*, "A probabilistic approach to multi-modal adaptive virtual fixtures," *IEEE Robotics and Automation Letters*, vol. 9, no. 6, pp. 5298–5305, 2024.

[6] P. M. Schäfer, F. Steinmetz, S. Schneyer, T. Bachmann, T. Eiband, F. S. Lay *et al.*, "Flexible robotic assembly based on ontological representation of tasks, skills, and resources," in *Int. Conf. on Principles of Knowledge Representation and Reasoning (KR)*, vol. 18, 2021, pp. 702–706.

[7] T. Bachmann, K. Nottensteiner, I. R. Brena, A. Stemmer, and M. A. Roa, "Using task-specific workspace maps to plan and execute complex robotic tasks in a flexible multi-robot setup," in *Int. Symp. on Robotics (ISR)*. VDE, 2020, pp. 1–8.

[8] T. Bachmann, K. Nottensteiner, and M. A. Roa, "Automated planning of workcell layouts considering task sequences," in *IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2021, pp. 12 662–12 668.

[9] J. Motes, T. Chen, T. Bretl, M. M. Aguirre, and N. M. Amato, "Hypergraph-based multi-robot task and motion planning," *IEEE Trans. on Robotics*, vol. 39, no. 5, pp. 4166–4186, 2023.

[10] A. Orthey, C. Chamzas, and L. E. Kavraki, "Sampling-based motion planning: A comparative review," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 7, 2023.

[11] P. Lehner and A. Albu-Schäffer, "The repetition roadmap for repetitive constrained motion planning," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 3884–3891, 2018.

[12] P. Lehner, M. A. Roa, and A. Albu-Schäffer, "Kinematic transfer learning of sampling distributions for manipulator motion planning," in *IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2022, pp. 7211–7217.

[13] F. Conti and O. Khatib, "Spanning large workspaces using small haptic devices," in *IEEE World Haptics Conf. (WHC)*, 2005, pp. 183–188.

[14] F. Richter, R. K. Orosco, and M. C. Yip, "Motion scaling solutions for improved performance in high delay surgical teleoperation," in *IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2019, pp. 1590–1595.

[15] M. Panzirsch and R. Balachandran, "Time domain control for passive variable motion and force scaling in delayed teleoperation," *IFAC-PapersOnLine*, vol. 52, no. 18, pp. 31–36, 2019.

[16] L. B. Rosenberg, "The use of virtual fixtures as perceptual overlays to enhance operator performance in remote environments," Wright-Patterson AFB OH: USAF Armstrong Laboratory, Tech. Rep., 1992.

[17] J. J. Abbott, P. Marayong, and A. M. Okamura, "Haptic virtual fixtures for robot-assisted manipulation," in *Int. Symp. on Robotics Research (ISRR)*. Springer, 2007, pp. 49–64.

[18] S. A. Bowyer, B. L. Davies, and F. R. y Baena, "Active constraints/virtual fixtures: A survey," *IEEE Trans. on Robotics*, vol. 30, no. 1, pp. 138–157, 2013.

[19] F. Ryden and H. J. Chizeck, "Forbidden-region virtual fixtures from streaming point clouds: Remotely touching and protecting a beating heart," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*. IEEE, 2012, pp. 3308–3313.

[20] B. Bischof, T. Glück, M. Böck, and A. Kugi, "A path/surface following control approach to generate virtual fixtures," *IEEE Trans. on Robotics*, vol. 34, no. 6, pp. 1577–1592, 2018.

[21] M. Mühlbauer, F. Steinmetz, F. Stulp, T. Hulin, and A. Albu-Schäffer, "Multi-phase multi-modal haptic teleoperation," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*. IEEE, 2022.

[22] G. E. Hinton, "Products of experts," in *Int. Conf. on Artificial Neural Networks (ICANN)*, vol. 9. IET, 1999, pp. 1–6.

[23] K. Hagmann, A. Hellings-Kuß, J. Klodmann, R. Richter, F. Stulp, and D. Leidner, "A digital twin approach for contextual assistance for surgeons during surgical robotics training," *Frontiers in Robotics and AI*, vol. 8, 2021.

[24] F. Kempf, M. S. Mühlbauer, T. Dasbach, F. Leutert, T. Hulin, R. Radhakrishna Balachandran *et al.*, "AI-In-Orbit-Factory - AI approaches for adaptive robotic in-orbit manufacturing of modular satellites," in *Int. Astronautical Congress (IAC)*, 2021.

[25] F. Leutert, D. Bohlig, F. Kempf, K. Schilling, M. Mühlbauer, B. Ayan *et al.*, "AI-enabled cyber–physical in-orbit factory - AI approaches based on digital twin technology for robotic small satellite production," *Acta Astronautica*, vol. 217, pp. 1–17, 2024.