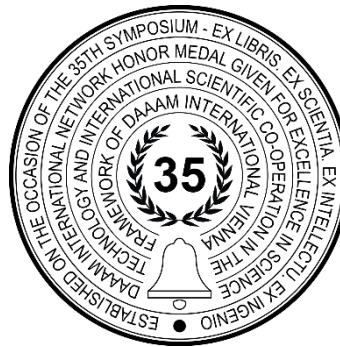


DESIGN AND IMPLEMENTATION OF AN ADDITIVELY MANUFACTURED, ALUMINIUM-REINFORCED 4-AXIS PICK-AND-PLACE ROBOT

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Abstract

This paper presents the design and implementation of a four-axis pick-and-place robot, manufactured using a combination of additive manufacturing techniques and aluminium reinforcements. The robot is intended for educational purposes and serves as a foundation for future research and development projects. Furthermore, it demonstrates the potential applicability of lightweight robotic manipulators in small and medium-sized enterprises (SMEs). The design process followed the VDI 2221 methodology and included conceptual design, simulation, and physical implementation. Structural simulations conducted in SolidWorks enabled the identification and resolution of mechanical weaknesses through iterative design optimization. The final prototype validated the simulation results and provided valuable insights for further refinement. The outcome is a cost-effective, lightweight robot with high precision and load-bearing capacity, suitable for a range of industrial and educational applications

Keywords: Additive Manufacturing; SCARA-Robot; SolidWorks-Simulation; Lightweight Design; Topology Optimization.

1. Introduction and Problem Statements

In recent years, industry has increasingly focused on sustainability and resource efficiency. This shift demands the reduction of emissions, minimization of waste, and greater reliance on renewable energy sources [1]. Additive manufacturing offers significant advantages in this context, enabling the rapid and cost-effective production of complex geometries [2]. As a result, development cycles are shortened, and time-to-market is reduced [3]. Expanding on earlier research and its findings [4], a four-degree-of-freedom robot [5] was created for pick-and-place tasks, including use cases like shelf handling. The robot was produced through additive manufacturing, supplemented with aluminium elements in areas requiring high dimensional accuracy. To maintain a methodical and consistent development process, the project adhered to the VDI 2221 design guidelines [6].

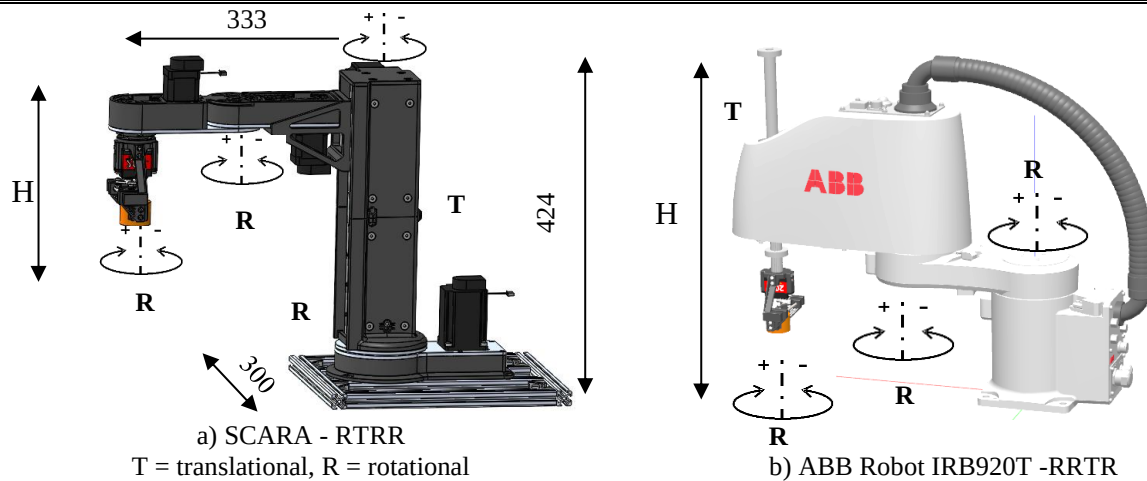


Fig. 1. SCARA Robot for Pick and Place applications with different structure a) RTRR and b) ABB Robot-RRTR.

Pick-and-place operations involving workpieces are among the most common applications in industrial automation [7]. These tasks are typically characterized by high-speed execution and high positional repeatability. Among the most established kinematic architectures for such applications are the SCARA (Selective Compliance Assembly Robot Arm) and Delta robots. Both are specifically optimized to meet the demands of precision and energy efficiency in high-speed environments. However, certain application scenarios require alternative kinematic solutions.

One such case is shelf handling, where the spatial dimensions of the robot arm — particularly its vertical reach — are more critical than maximum operating speed. As illustrated in Figure 1, the height (H) and overall form factor of the robot arm differ significantly between robot (a) — a customized unit developed at UAS Technikum Wien (SICHA robot) and robot (b) — a conventional SCARA robot (ABB IRB 920T) [8]. To address the specific spatial constraints of the shelf-handling task, the translational joint typically located at the third axis in the traditional SCARA configuration was repositioned to the second joint in the customized design. Consequently, the conventional RRTR axis sequence (R = rotational, T = translational) was modified to RTRR. While the modified robot architecture offers improved adaptability for the specific application scenario, it exhibits limitations in terms of dynamic performance. As a result, it is inherently less suitable for high-speed pick-and-place operations. Another relevant constraint concerns the arrangement of objects: if this arrangement is predefined by the customer, a 4-axis robot can be more energy-efficient than a conventional 6-axis robot, due to its simpler kinematics and reduced degrees of freedom.

This observation leads to the central research question addressed in this work: What are the implications of this kinematic configuration on the robot's design process? How can the robot poses be efficiently computed within this framework and control strategy?

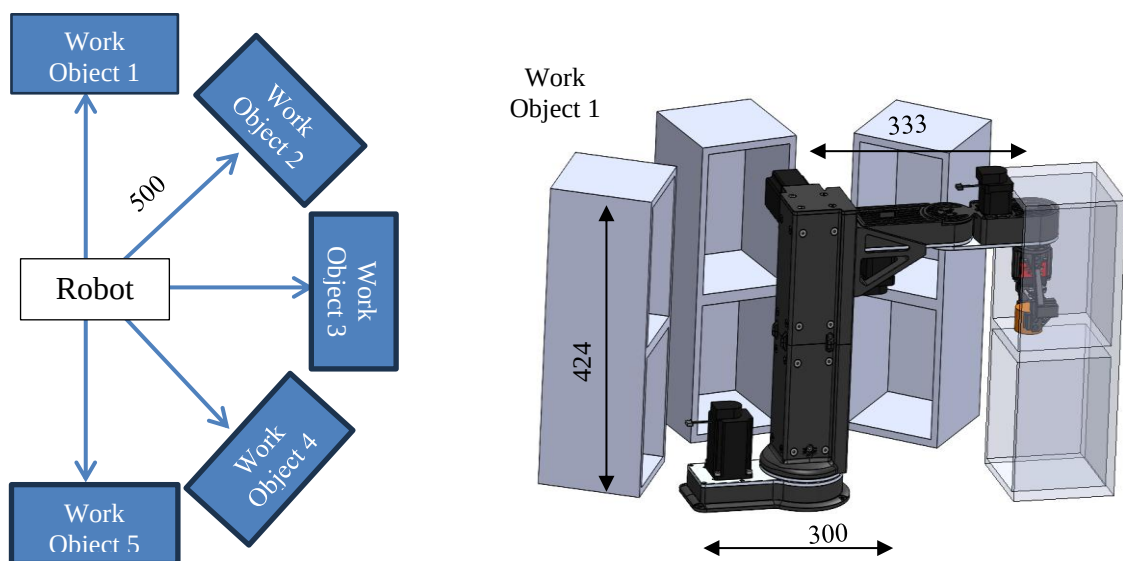


Fig. 2. Customer applications using SICHA-Robot.

2. Materials and Methods

The methodological framework of this study is based on the VDI 2221 guideline [6], which outlines a systematic approach to the development of technical products. The objective is to design a functional, stable, and lightweight 4-axis robotic system that can be manufactured using a combination of additive and subtractive production methods. The development process is divided into four sequential phases: requirements analysis, concept development, design and detailing, and validation.

2.1 Requirements Analysis

The first phase involves identifying and clearly defining the customer's requirements as well as the technical constraints. The main criteria include:

- the use of a 4-axis kinematic configuration,
- high structural stability and stiffness,
- low production costs,
- compatibility with FDM 3D printing and CNC machining,

2.2 Concept Development

Based on the defined requirements, three alternative design concepts for the 4-axis robot were developed. Each concept adopts a hybrid manufacturing approach that combines Fused Deposition Modelling (FDM) for the primary structural components with aluminium reinforcements to increase mechanical rigidity and durability. To identify the most promising solution, a structured evaluation was conducted using a weighted scoring method. The assessment considered key factors such as overall weight, structural stability, manufacturability, cost, and energy efficiency. This systematic approach ensures an objective comparison and supports a rational decision-making process. The evaluation results indicate that the concept featuring an RTRR kinematic structure best meets the customer requirements and the defined criteria. Additionally, it allows a high degree of modularity and simplifies future design modifications or scaling. Therefore, this concept was selected for further detailed development and subsequent simulation studies.

2.3 Design and Detailing

The chosen concept was further developed in the CAD software SolidWorks, following the iterative design process defined in the VDI 2221 guideline. Throughout this phase, particular attention was given to mechanical integrity, manufacturability, and functionality. The design was optimized for additive manufacturing by minimizing material usage and printing time while ensuring sufficient structural strength. In addition, tolerances were explicitly defined within the CAD model to guarantee precise fitting and reliable functionality of the components after production. In Figure 3, the iterative development process of the last robot chain according to VDI 2221 is illustrated using simulation and finite element analysis (FEA). The left side of the figure represents the initial design simulation, while the right side shows the final design simulation. In both cases, the assembly was fixed at the screw connections to the preceding arm, while the contact surfaces of the bearing seats were constrained using a *Sliding Fixture*. The loads were applied at the locations where the respective components are supported—namely at the interfaces of the stepper motor, the end effector, the workpiece, and the remaining attachments. As shown in Figure 3a, the maximum displacement in the initial design amounts to 2.211×10^{-1} mm, whereas in the final design (highlighted in red) it was successfully reduced to 4.113×10^{-2} mm. This corresponds to an improvement by a factor of five compared to the original design and confirms that the resulting displacement is negligible for the intended application.

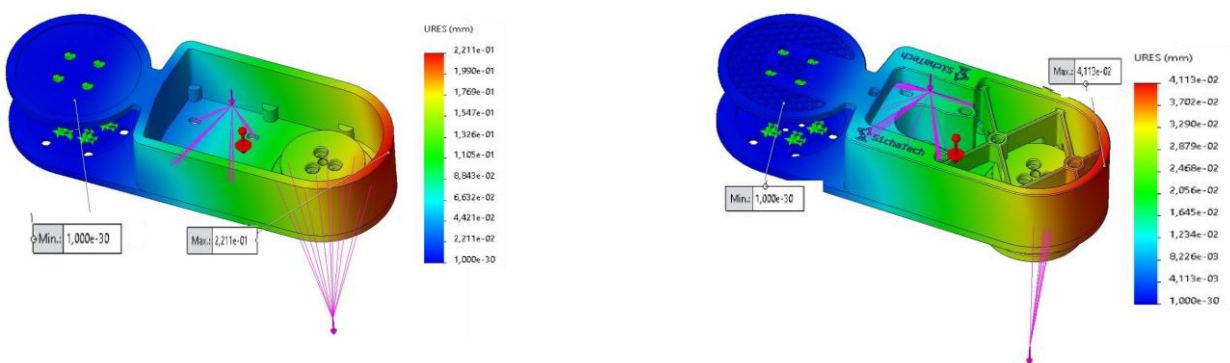


Fig. 3. Iterative design of the SICHA-Robot using the FMEA tool in SolidWorks.

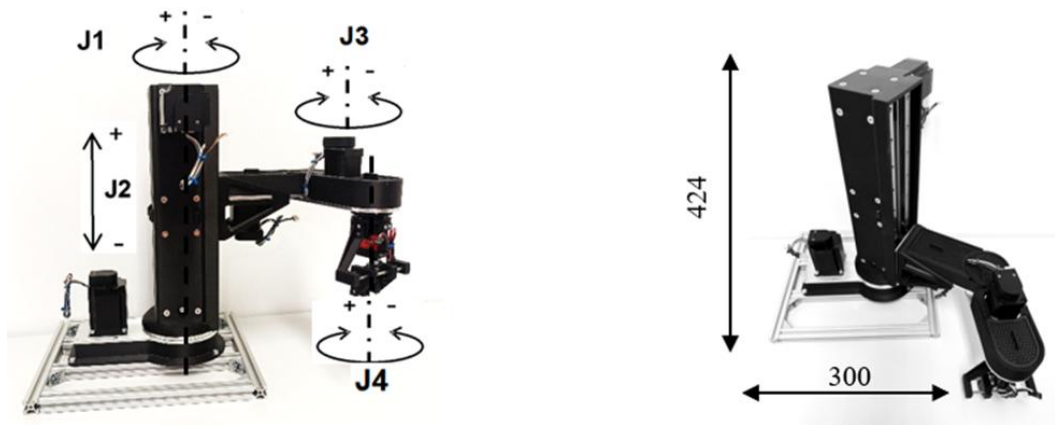


Fig. 4. Manufacturing and assembly of SCARA robot.

2.4 Manufacturing and Assembly

The robotic components are fabricated using a combination of FDM 3D printing and CNC machining. Prior to production, the 3D printer is calibrated, and tolerance tests are performed to ensure dimensional accuracy. PA6-CF - Polyamide 6 (CF = Carbon Fiber) filament is used for the printed parts, while aluminium elements are manufactured using CNC technology. Following fabrication, all components are assembled into a functional prototype. Special attention is paid to joint precision, alignment, and overall structural stability during assembly. To verify mechanical behaviour under load, the manipulator is statically loaded with a payload of 0.5 kg for a duration of 30 seconds. The resulting deflection is measured using a dial gauge. These measurements are then compared with simulation results to identify and analyse deviations between the virtual model and real-world behaviour.

2.5 Simulation and Validation

Prior to any physical experimentation, the unconventional 4-axis robot with an RTRR kinematic arrangement is subjected to a comprehensive analysis in a virtual simulation environment. This digital evaluation serves to examine the kinematic workspace, positioning precision, and the system's ability to sustain operational loads. The numerical results obtained from these simulations are subsequently compared with experimental measurements carried out on the prototype. Differences between the predicted and the observed behaviour are carefully documented and interpreted in order to detect possible inaccuracies in design, modelling assumptions, or control strategy. A key step in this process involves topology optimization, which helps to adjust the mass distribution within the structure according to the expected load paths. Material is selectively reduced in regions where the mechanical stresses are minimal, thereby lowering the overall mass without compromising structural strength. The resulting geometry leads to a more efficient structure with reduced inertia and enhanced dynamic properties. For the load-bearing components, the high-performance composite PA6-CF is employed. This material offers an advantageous balance of stiffness and weight, enabling the design of a slim and lightweight robotic structure. The reduced mass contributes directly to improved responsiveness, lower energy consumption, and increased dynamic performance during operation. This combination of virtual validation, material selection, and structural optimization allows critical aspects of the robot's performance to be fine-tuned before physical testing begins. As a result, development time can be reduced, while the likelihood of major design modifications at later stages is significantly reduced.

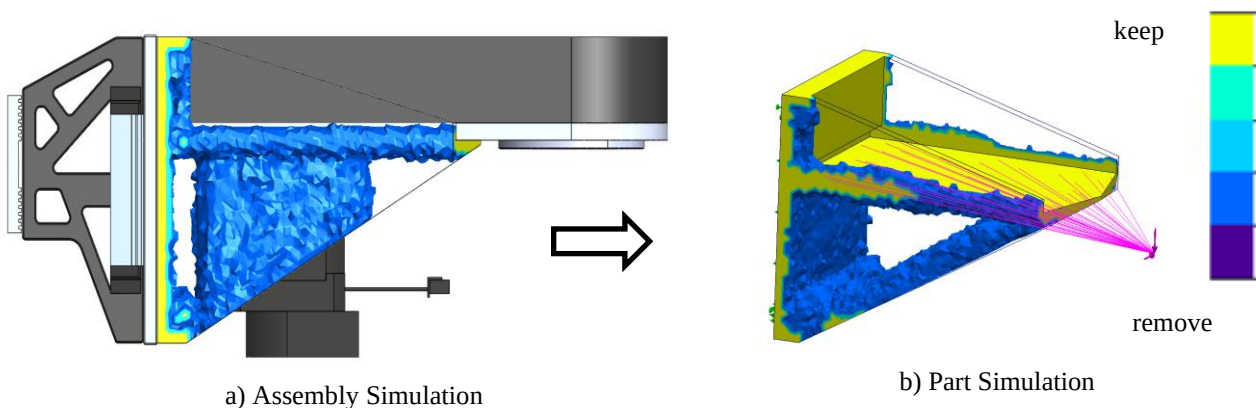


Fig. 5. Topology optimization of robot components.

3. Results and Discussion

The simulation results demonstrate that the robot meets the required load-bearing capacity and precision through the combination of additive manufacturing and aluminium reinforcements. Under a maximum acceleration of 2 m/s^2 and the specified payload of 0.5 kg, the simulation yielded a maximum displacement of the TCP (Tool Centre Point) of 0.16 mm. These results highlight the critical role of aluminium reinforcements in ensuring the mechanical stability of the structure. During the static load tests with a 0.5 kg payload, a displacement of 0.43 mm was measured at the TCP, with the robot's tower (vertical axis module) mechanically locked. The tower was fixed to obtain more accurate results, as the bearing between the base and the tower was identified as a minor but noticeable structural weak point. This measure was taken to isolate the influence of this specific weakness and analyse the robotic arm independently. The resulting deviation between simulation and real-world measurements was 0.27 mm. After removing the mechanical lock, the displacement increased to 0.53 mm, underscoring the relevance of the tower bearing as a critical factor in the overall structural stability. Furthermore, the experimental measurements indicate that external influences—such as manufacturing tolerances, material inconsistencies, and the variable properties of the 3D printed components—play a significant role. These factors were not fully captured in the simulation model, which explains the observed discrepancy between simulated and actual behaviour. For the calculation of Robot Target and Inverse kinematics Law of Cosines can be used.

4. Summary and outlook

This study demonstrates the feasibility of developing a lightweight, energy-efficient 4-axis robotic system through a systematic design approach based on the VDI 2221 guideline. By combining additive manufacturing with aluminium reinforcements, a structurally stable prototype was realized that meets the defined functional and mechanical requirements. Simulation results showed that the robot maintained high precision under dynamic loading conditions, with a maximum TCP displacement of 0.16 mm. The subsequent experimental validation confirmed the general accuracy of the simulation, though minor deviations were observed. In particular, the static tests revealed a displacement of 0.43 mm with the tower locked, and 0.53 mm when unlocked. These findings emphasize the relevance of the tower bearing as a critical structural component and highlight the impact of real-world factors such as material inconsistencies, manufacturing tolerances, and 3D printing variability—none of which were fully accounted for in the simulation model. The methodology applied—combining conceptual design, CAD modelling, hybrid manufacturing, and physical testing—proved effective in bridging the gap between digital simulation and physical implementation. It also revealed the limitations of simplified simulation models in predicting mechanical behaviour with full accuracy. Overall, the results confirm that the proposed robotic concept is viable for applications requiring moderate payloads and precision. Further optimization—particularly in the bearing design and selection of printing materials—could enhance system stability and performance. Future work may include dynamic testing under varying load conditions, long-term durability assessments, and integration of advanced materials or sensor-based feedback systems.

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