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Mechanical Design and Analysis of Six-Degree-of-Freedom (6-DOF) SCARA Robot for Industrial Applications

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***Abstract:** A six-degree-of-freedom (6-DOF) SCARA robot is an advanced robotic system capable of moving and manipulating objects in a three-dimensional space with a high degree of precision and flexibility. The term "SCARA" stands for "Selective Compliance Articulated Robot Arm," indicating its design that allows a combination of rigidity and compliance along specific axes. This unique combination of features makes 6-DOF SCARA robots highly versatile and suitable for a wide range of industrial applications. Unlike traditional SCARA robots that typically have four degrees of freedom, the addition of two extra degrees of freedom enhances the 6-DOF SCARA robot's spatial reach and manipulation capabilities. This enables the robot to perform tasks that require complex orientations, intricate movements, and precise positioning within a 3D workspace. The mechanical design, kinematics, and control strategies of these robots are carefully developed to ensure accurate and efficient performance, making them valuable tools in various industries. 6-DOF SCARA robots find applications in numerous industries where precise manipulation, efficient automation, and versatile positioning are crucial.*

The main objective of this project is mechanical design of six-degree-of-freedom (6-DOF) SCARA robot using CAD software, kinematic analysis for forward and inverse kinematics solutions, dynamic modeling to understand the robot's behavior under different loads.

I. INTRODUCTON

In today's rapidly evolving industrial landscape, automation plays a pivotal role in enhancing efficiency, productivity, and precision. Among the various types of robots employed in industrial settings, the Six-Degree-of-Freedom (6-DOF) SCARA (Selective Compliance Assembly Robot Arm) robot stands out as a versatile and reliable solution. This advanced robotic system offers a wide range of motion and dexterity, making it well-suited for intricate manufacturing processes across various industries.

The mechanical design of a 6-DOF SCARA robot involves careful consideration of several key components to ensure optimal performance and reliability. These components typically include the robot arm structure, joints, actuators, end-effectors, and control systems. The robot arm structure serves as the backbone of the SCARA robot, providing stability, rigidity, and flexibility in motion. It comprises multiple interconnected segments, allowing for multi-axis movement to navigate complex work spaces efficiently.

Joints are critical components that enable the rotational or linear movement along each axis of motion. Different types of joints, such as revolute, prismatic, or spherical, may be utilized based on the specific requirements of the application.

Actuators act as the driving force behind the motion of the robot arm. Electric motors, pneumatic cylinders, or hydraulic systems are commonly employed to provide the necessary torque or linear force for movement. End-effectors are attached to the robot arm and are responsible for interacting with the workpiece or performing specific tasks. Grippers, suction cups, welding torches, and sensors are examples of end-effectors used in industrial applications, enabling the robot to perform a wide range of tasks with precision. The control system of the SCARA robot coordinates the movement of each joint and ensures precise positioning and trajectory tracking. It comprises sensors, actuators, microcontrollers, and software algorithms for real-time feedback and control, enabling the robot to adapt to changing conditions and perform tasks accurately. Analysis of a 6-DOF SCARA robot involves various aspects to evaluate its performance, accuracy, and reliability in industrial applications. Kinematic analysis focuses on studying the motion of the robot arm without considering the forces involved. This analysis helps determine the workspace, reachability, and trajectory planning capabilities of the robot, ensuring optimal performance in navigating complex workspaces. Dynamic analysis considers the forces, torques, and accelerations experienced by the robot during operation. It helps assess factors such as payload capacity, stability, and energy efficiency, ensuring the robot can perform tasks accurately and efficiently while maintaining safety.

Structural analysis evaluates the mechanical integrity and durability of the robot arm under different loading conditions. Finite element analysis (FEA) techniques are commonly used to simulate stress, deformation, and fatigue life of critical components, ensuring the robot can withstand the rigors of industrial environments. Control system analysis verifies the performance of the robot's feedback control loop in maintaining accuracy and stability during operation. It involves testing the response to various commands, disturbances, and environmental conditions, ensuring the robot can adapt to changing conditions and perform tasks reliably.

II. LITRETURE RIVIEW

1) Design, construction and control of a SCARA manipulator with 6 degrees of freedom [Claudio Urrea, Juan Cortés, José Pascal] Journal of applied research and technology 2016.Over the past few decades, robotics has played a very important part in process automation, with robot manipulators assuming a leading role in the development of several productive areas. Nowadays, industrial robots are used for the automation of a variety of tasks such as assembling, transfer of materials, all kinds of welding, precision cutting of materials, palletizing, painting, remote surgical procedures, among many possible application .In general, industrial robots are employed to carry out repetitive jobs and/or those that require precision and speeds difficult to achieve by human beings. This has made it possible to improve the quality of products and the efficiency of their manufacturing.
2) Hexad robot: A 6-dof parallel PnP robot to accommodate antagonistic rotational capability and structural complexity,Guanglei Wu, Bin Niu,2024 .Mechanism and Machine Theory.Lightweight parallel robots are well adapted to high-speed pick-and-place (PnP) applications in material handling, of which the types are diverse, from 2 degrees of freedom (dof) planar robots to the general 6-dof robots. Amongst them, the most widely used ones, produce three independent translations and one rotation around an axis of fixed direction.Usually, most of the parallel robots with 2-/3-dof translational and SCARA motions are limited to "plane to plane" PnP operations. On the other hand, the robots with full mobilities, i.e., three translations and three rotations (3T3R), are needed and sometimes essential in some industrial applications,1 particularly in complicated electronic assembly
3) A novel error mapping of bi-directional angular positioning deviation of rotary axes in a SCARA-type robot by "open-loop" tracking interferometer measurement,Soichi Ibaraki, Ryota Usui,2022,Precision Engineering,In today's industry, industrial robots are mostly programmed by the teach method, where a human operates the robot manually by using a teach pendant, and the robot memorizes it. On the other hand, NC (numerically controlled) machine tools are typically programmed on a CAM (computer-aided manufacturing) software based on a 3D model of workpiece. This difference is partly due to a robot's significantly lower volumetric accuracy; a human operator's manual adjustment is often inevitable to successfully perform the given task. The volumetric accuracy, the term in Ref.
4) Design and Development ofa Low-Cost CNC Alternative SCARA Robotic Arm,Ashwin Misra, Ayush Sharma, Ghanvir Singh, Ashish Kumar, Vikas Rastogi,2020,Procedia Computer Science.the technology is aimed at increasing efficiency and accuracy by achieving optimization in the traditional manufacturing methods, its most major drawback is the high cost of maintenance and installation. The article discusses an affordable solution to this issue. As a viable alternative, a SCARA Robotic arm is used to execute the process. The initial computer aided design is analysed for feasibility in real conditions using rigorous finite element methods and experimental validation. The workspace of the SCARA is modelled on general usage approximations; a detailed kinematic and dynamic robotic analysis is also done to ensure better process conditions and the future possibility to achieve force feedback control.The workspace of the SCARA is modelled on general usage approximations; a detailed kinematic and dynamic robotic analysis is also done to ensure feedback control. This prototype can be operated using user-based systems and can be designed following the methodology proposed in this article.
5) An automated supermarket checkout system utilizing a SCARA robot: preliminary prototype development, Yesenia Aquilina, Michael A. Saliba, 2019 Procedia Manufacturing.A first prototype of an automated supermarket checkout system, exploiting the advantages of the SCARA robot and including machine vision, has been developed. The system is able to recognize various items placed by the customer on a conveyor, transfer the items to a container, pack them neatly, and total the bill. Evaluation of the prototype indicates that acceptable speed and reliability of the system can be attained..In recent years, a number of retail stores have introduced self-checkout systems at the cash point, however these normally require a high degree of participation by the customer, often leading to requests for help by store attendees. A review of the literature has shown that the use of robots at checkout points, with their potential to reduce customer effort, has not yet been addressed. A separate literature review has shown that the four-axis SCARA robot, used extensively in the manufacturing industry due to its advantages in cost, speed and rigidity, is rarely applied to service tasks. In this work these two research gaps are being addressed.

6) Design and development of an instructional mobile robot for effective learning of material handling in mechanical workshops in universities. Abdullahi I. Haruna a b, R. Sankar b, Abdullahi Samaila b.2023,Materials Today: ProceedingsRight now, the rate of scientific progress in the world as we know it is faster than it has ever been. As a direct result, the rate of change is also getting faster. In a world that is constantly changing, it is very important to be able to adapt to new situations and learn new skills and abilities . They also said that robotics is a result of the Industrial Revolution, human curiosity, hard work, and creative thought about how to make tools and machines that can solve problems and do unique tasks or activities on their own . They said that robotics is one of the results of revolution, curiosity, hard work, and creative thought. Robotics is one of the things that came about because people thought of ways to make tools and machines that could solve problems and do unique tasks or activities on their own. Robotics came about because people thought in this way. People are already getting help from robots in a variety of fields, including hard, dangerous, and repetitive jobs as well as service needs like helping experts and nurses in hospitals and schools.
7) Design of an adaptive fuzzy-neural inference system-based control approach for robotic manipulators, Mojtaba Hadi Barhaghtalab a, Mohammadreza Askari Sepestanaki a, Saleh Mobayen b, Abolfazl Jalilvand a, Afef Fekih c, Vahid Meigoli d, 2023 Applied Soft Computing,The topic of robot manipulation position control has attracted much research in recent years. Various control methods have been proposed to control the robotic manipulators, each of which has its merits and demerits. Among them, the following control methods can be mentioned: robust control,control with neural networks, etc. Proportional-derivative (PD) and PID controls are among the most common control methods for mechanical manipulators. However, it is very well known, that those controllers are ineffective in the presence of system uncertainties and disturbances. In recent years, intelligent control techniques (including neural networks and fuzzy control) have been considered as a suitable alternative to classical control techniques (including linear control, nonlinear control, sliding mode control, robust control, etc.).
8) Robots and its types for industrial applications. Gurjeet Singh a, V.K. Banga b. 2022.Materials Today: Proceedings Robots are playing a very important role in industries. The main task in the robotics, is to reach the end effector at desired position. Robots are used in every sector like hospitals, mining, domestic purpose, industries etc. The inverse kinematic robotics problem has proved to be of great significance because the solutions found provide control over the position and orientation of the robot hand. In this paper, a brief review of robots and its types has been discussed. The materials used in the robots is discussed in this paper.From daily life applications to military applications and from toys to satellites, robotics is extensive. In industrial applications and automation, robotic manipulators exhibit a significant role. Robots nowadays have become a part of human life. In the recent period, employing robots in industrial sectors is witnessed massively, and the trend is increasing day by day.
9) An expert system-based design of SCARA robot.Praveen Bhatia, Janarthanan,1998. Thirunarayanan, Nalin Dave Expert Systems with Applications,SCARA is an acronym for Selective Compliance Arm for Robotic Assembly. Robot designing is a complicated and iterative process, requiring highly skilled designers. Because of its iterative nature, robot design also proves to be a tedious task for the design experts. To solve this problem, an expert system has been designed which takes up the job of a designer in the iterative design of robots. The expert system, with the help of its knowledge base, carries out the static and dynamic analysis, and arrives at the dimensions of the individual parts of the robot. During the iterative design process, the expert system also ensures that any change in a component is also reflected on the components linked to it so the compatibility of the components is not lost.Expert systems can manipulate knowledge bases and take logical decisions by automated reasoning. These systems have proven to be effective in a number of problem domains which normally require the kind of intelligence possessed by a human expert.
10) Stochastic Analysis of a 6-DOF Fully Parallel Robot under Uncertain Parameters. F.A. Lara-Molina, E.H. Koroishi , D. Dumur , V. Steffen Jr.2015 IFAC-Papers On Line The uncertainties of the parameters are considered as small variations with respect to their nominal values modeled by means of random variables. The dynamics of the robot under uncertain structural and dynamic parameters including a computed torque position controller is analyzed. Additionally, a sensitivity analysis allows to determine the degree of influence of each uncertain parameter on the response of the robot. Numerical simulations illustrate the proposed methodology so that the effect of uncertain parameters on the dynamic performance of the robot is properly described.This paper aims at analyzing the effect of uncertain parameters on a 6-DOF fully parallel robot performance by using a stochastic approach.

III. METHODOLOGY

The methodology for the mechanical design and analysis of a Six-Degree-of-Freedom (6-DOF) SCARA robot for industrial applications involves a systematic approach aimed at ensuring optimal performance, reliability, and efficiency.

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Initially, a comprehensive analysis of the specific requirements of the industrial task is conducted, including factors such as payload capacity, reach, precision, and environmental constraints. This analysis guides the conceptual design phase, where considerations such as workspace optimization, kinematics, and joint configurations are addressed to meet the defined requirements. Subsequently, rigorous kinematic analysis is performed to understand the robot's motion capabilities, ensuring smooth and accurate movement within the desired workspace while minimizing singularities. Dynamic analysis follows, evaluating the forces, torques, and accelerations experienced by the robot's components during operation, aiding in the optimization of structural design for stability and performance. Structural design and optimization entail selecting suitable materials, dimensions, and geometries through Finite Element Analysis (FEA), ensuring mechanical robustness and minimizing weight without compromising strength. Component selection and integration involve careful consideration of actuators, motors, gears, bearings, and sensors, ensuring compatibility and reliability within the overall design. Sensing and control systems are then integrated, enabling precise positioning, trajectory tracking, and interaction with the environment. Prototyping and testing phases validate the design's functionality, performance, and safety under simulated operating conditions, allowing for iterative refinements. Ultimately, upon successful testing, deployment and maintenance ensure the SCARA robot's continued optimal performance throughout its operational lifespan in the industrial setting. This structured methodology ensures that the 6-DOF SCARA robot meets the demanding requirements of industrial applications, offering a reliable and efficient solution for automation tasks.

IV. DESIGN AND ANALYSIS

Fig-1 Front View of SCARA ROBOT

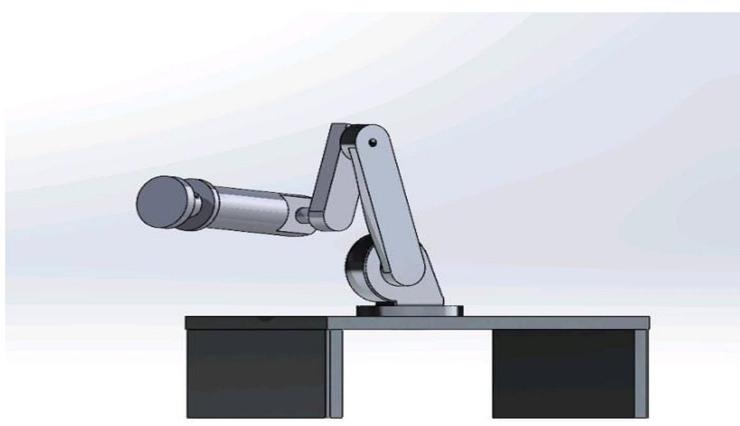

Fig-2 Side View of SCARA ROBOT

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Fig-3 3D View

Designing a Six-Degree-of-Freedom (6-DOF) SCARA (Selective Compliance Articulated Robot Arm) robot for industrial applications involves several key steps to ensure optimal performance, reliability, and efficiency.

A. Conceptual Design
1) Define the specific requirements of the industrial application, including payload capacity, reach, precision, and environmental constraints.
2) Determine the overall configuration of the SCARA robot, considering factors such as workspace optimization, kinematics, and joint configurations.
3) Select an appropriate size and scale for the robot to meet the defined requirements.

B. Kinematic Design
1) Develop the kinematic structure of the robot, including the arrangement of joints and links to achieve the desired range of motion.
2) Analyze the kinematics of the robot to ensure smooth and accurate movement within the workspace while minimizing singularities.
3) Use software tools such as MATLAB or SolidWorks Motion to simulate and validate the kinematic behavior of the robot.

C. Dynamic Design
1) Conduct dynamic analysis to evaluate the forces, torques, and accelerations experienced by the robot's components during operation.
2) Optimize the design to minimize vibrations and resonance effects, ensuring stability and performance.
3) Consider factors such as inertia forces, gravitational forces, and external loads to ensure structural integrity.

D. Structural Desig
1) Select appropriate materials for the robot's structure, considering factors such as strength, stiffness, and weight.
2) Use Finite Element Analysis (FEA) techniques to evaluate the structural integrity and stress distribution under various loading conditions.
3) Optimize the design to minimize weight while maintaining strength and rigidity.

E. Component Selection and Integration
1) Select high-quality actuators, motors, gears, bearings, and sensors that meet the performance requirements of the application.
2) Integrate these components into the robot's structure, ensuring compatibility and reliability.
3) Consider factors such as power consumption, heat dissipation, and ease of maintenance during component selection.

F. Sensing and Control Systems

1) Integrate sensors for feedback control, such as encoders, accelerometers, and force/torque sensors, to enable precise positioning and interaction with the environment.
2) Develop control algorithms for trajectory planning, obstacle avoidance, and safety to ensure efficient and safe operation.
3) Implement a robust control system to monitor and adjust the robot's behavior in real-time.

G. Prototyping and Testing

1) Build a prototype of the SCARA robot based on the finalized design.
2) Conduct rigorous testing under simulated operating conditions to validate the functionality, performance, and safety of the robot.
3) Iterate on the design based on test results, making adjustments as necessary to meet specifications and standards.

H. Deployment and Maintenance

1) Deploy the SCARA robot in the industrial environment, where it undergoes further validation and fine-tuning for specific tasks.
2) Establish a regular maintenance schedule to ensure optimal performance and longevity.
3) Provide training for operators and maintenance personnel to ensure proper operation and upkeep of the robot.

By following this structured approach to design and analysis, engineers can develop a 6-DOF SCARA robot that meets the demanding requirements of industrial applications, offering a reliable and efficient solution for automation tasks.

V. MATERIAL SELECTION MECHANICAL DESIGN AND ANALYSIS OF SIX-DEGREE-OF-FREEDOM (6-DOF) SCARA ROBOT FOR INDUSTRIAL APPLICATIONS.

When selecting materials for a 6-DOF SCARA robot for industrial applications, several factors should be considered, including strength, stiffness, weight, durability, cost, and compatibility with manufacturing processes. Common materials used for such applications include:

1) *Aluminum Alloys:* Lightweight, easy to machine, and relatively inexpensive. Aluminum alloys offer good strength-to-weight ratio and corrosion resistance, making them suitable for many robotic components such as the frame, arms, and brackets.
2) *Steel:* Provides high strength and stiffness, making it suitable for components subjected to heavy loads or high stress, such as the base or structural elements. Various types of steel, including carbon steel and stainless steel, may be chosen based on specific requirements for strength, corrosion resistance, and machinability.
3) *Titanium Alloys:* Known for their high strength-to-weight ratio, corrosion resistance, and biocompatibility, titanium alloys are ideal for applications where weight reduction is critical or where components will be exposed to harsh environments.
4) *Composite Materials:* Fiber-reinforced composites, such as carbon fiber or fiberglass, offer excellent strength-to-weight ratio and stiffness. These materials are often used for robotic arms and links to reduce weight while maintaining structural integrity.
5) *Engineering Plastics:* High-performance plastics like polyether ether ketone (PEEK), acetal (Delrin), or nylon are chosen for their low friction, chemical resistance, and ease of machining. They are commonly used for components such as gears, bearings, and bushings in robotic mechanisms.
6) *Cast Iron:* Provides excellent damping properties and thermal stability, making it suitable for components requiring vibration Absorption or thermal management, such as the base or frame.

The material selection should be based on a thorough analysis of the robot's design requirements, including load-bearing capacity, precision, environmental conditions, and cost considerations. Additionally, material compatibility with manufacturing processes such as machining, welding, casting, or additive manufacturing should also be evaluated.

VI. RESULT

The mechanical design and analysis of a six-degree-of-freedom (6-DOF) SCARA (Selective Compliance Assembly Robot Arm) robot involves several key considerations to ensure optimal performance and reliability. SCARA robots are renowned for their ability to manipulate objects within a specific workspace with high precision and speed, making them ideal for assembly and pick-and-place applications in manufacturing industries. The design of a 6-DOF SCARA robot begins with determining the required workspace, payload capacity, and precision. These factors influence the selection of materials, actuators, and overall dimensions of the robot. Typically, SCARA robots feature rigid aluminum or steel frames to ensure stability and minimize deflection during operation. The design must also account for the robot's reach, ensuring it can access all desired points within its workspace.

Each joint of the SCARA robot requires careful analysis to achieve the desired range of motion and accuracy. This involves selecting appropriate actuators, such as electric motors or pneumatic cylinders, and designing efficient transmission systems to convert rotational motion into linear motion. Additionally, kinematic analysis is performed to optimize the robot's joint configurations and ensure smooth trajectories during operation.

Furthermore, structural analysis is conducted to evaluate the robot's mechanical integrity and identify areas of potential weakness or excessive stress. Finite element analysis (FEA) techniques are commonly employed to simulate various loading conditions and assess the structural performance of critical components. This analysis helps optimize the design to withstand the forces and torques encountered during operation while minimizing weight and material usage.

In addition to mechanical considerations, the design of a 6-DOF SCARA robot includes integration of sensors and feedback mechanisms to enable precise control and monitoring. Encoders, proximity sensors, and force/torque sensors are often incorporated to provide real-time feedback on the robot's position, orientation, and interactions with the environment. This feedback loop allows for adaptive control strategies, enhancing the robot's accuracy and responsiveness.

Once the mechanical design is finalized, prototype testing and validation are essential steps to verify the performance and reliability of the 6-DOF SCARA robot. This involves rigorous testing under various operating conditions to assess factors such as repeatability, accuracy, speed, and payload capacity. Any necessary refinements or adjustments are made based on the test results to ensure the final product meets or exceeds the specified requirements.

In conclusion, the mechanical design and analysis of a 6-DOF SCARA robot require a multidisciplinary approach, incorporating principles of mechanical engineering, robotics, and control theory. By carefully considering factors such as workspace requirements, kinematics, structural integrity, and sensor integration, engineers can develop a robust and efficient robot capable of performing complex tasks with precision and reliability in industrial automation settings.

VII. CONCLUSION

The design and analysis of a six-degree-of-freedom (6-DOF) SCARA robot represent a significant endeavor in the field of robotics, offering advancements in precision, flexibility, and efficiency in industrial automation. Through meticulous mechanical design and comprehensive analysis, this project aimed to optimize the performance and capabilities of the SCARA robot, ensuring its suitability for various industrial applications. The mechanical design phase involved meticulous consideration of factors such as kinematics, dynamics, structural integrity, and manufacturability. By leveraging advanced CAD software and simulation tools, the team meticulously crafted the robot's components, ensuring seamless integration and optimal functionality. The design process prioritized precision and reliability, essential qualities for tasks requiring intricate manipulation and high-speed operation.

Key aspects of the mechanical design included the selection of materials, motor specifications, actuator mechanisms, and joint configurations. Attention to detail was paramount to ensure smooth motion, minimal backlash, and robustness in diverse operating conditions. Additionally, the design incorporated safety features and ergonomic considerations to enhance usability and mitigate potential hazards in industrial environments. Following the design phase, rigorous analysis was conducted to validate the performance and functionality of the SCARA robot. Finite element analysis (FEA) was employed to assess structural integrity, identify potential points of failure, and optimize component dimensions for optimal strength-to-weight ratio. Kinematic analysis facilitated the evaluation of motion trajectories, workspace limitations, and velocity profiles, ensuring precise and efficient operation. Moreover, dynamic simulations enabled the assessment of dynamic response, vibration characteristics, and stability under varying loads and operating conditions. These analyses provided valuable insights into the robot's behavior and performance, guiding iterative improvements and refinements in the design. The culmination of the design and analysis efforts resulted in a highly capable and versatile 6-DOF SCARA robot, poised to revolutionize industrial automation. With its enhanced precision, agility, and reliability, the robot offers unprecedented efficiency in tasks such as pick-and-place operations, assembly, machining, and inspection.

Furthermore, the modular design facilitates ease of maintenance, upgrades, and customization, ensuring adaptability to evolving industry requirements. The integration of advanced sensors, actuators, and control algorithms further enhances the robot's capabilities, enabling seamless interaction with its environment and human operators.

In conclusion, the mechanical design and analysis of the 6-DOF SCARA robot represent a testament to the interdisciplinary collaboration and innovation driving the advancement of robotics. Through meticulous design optimization and rigorous analysis, the project has yielded a cutting-edge solution poised to redefine automation in various industrial sectors. As technology continues to evolve, the SCARA robot stands as a testament to the transformative potential of engineering ingenuity in shaping the future of manufacturing and beyond.

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