The lattice structure design enables topology optimization of a robotic arm

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Abstract -In the fast-paced consumer market, there has been an increasing demand for affordable and personalized products that cater to various needs. These products can be easily manufactured using additive manufacturing, also known as 3D printing, and optimized using the Creo design package and ANSYS software. To reduce weight, the robotic arm has been optimized using topology optimization strategies and lattice constructions. The ANSYS software is then used to conduct static structural analysis on the topologically optimized design, a generic design, and the lattice structure. The results of the finite element analysis (FEA) include equivalent stress, deformation, and safety factor. This analysis helps evaluate the impact of reduced mass density on the strength-to-weight ratio of the robotic arm. A comparative study is then conducted between the generic design and the topologically optimized design based on these parameters. Contour plots obtained from the FEA analysis are used to identify critical regions with high stresses and deformation. The percentage reduction in mass density is compared, and the effect of this reduction on the strength-to-weight ratio is evaluated..

***Key Words** - FEA, Hydraulic cylinder, Safety factor*

1. INTRODUCTION:

ANSYS: ANSYS is a widely used software suite for engineering simulation, including finite element analysis (FEA), computational fluid dynamics (CFD), and other multiphysics simulations. It provides tools for simulating and analyzing the behavior of structures, fluids, and electromagnetic systems.

FEA (Finite Element Analysis): FEA is a numerical method used to analyze the behavior of complex structures and systems under various loads and conditions. It divides the structure into smaller, finite elements to approximate the continuous behavior and solve the equations governing the system. FEA is commonly used to predict the stress, deformation, and performance of components or systems.

Structural Analysis: Structural analysis is a field of engineering that focuses on understanding the behavior and response of structures under different loads and conditions. It involves analyzing and predicting the stresses, strains, deformations, and stability of structures to ensure their safety, performance, and durability.

Additive Manufacturing: Additive Manufacturing, also known as 3D printing, is a manufacturing process that builds objects layer by layer using digital models. It allows for the creation of complex geometries and customized products by adding material rather than subtracting it. Additive manufacturing has revolutionized various industries by enabling rapid prototyping, cost-effective production, and design freedom.

Topological Optimization: Topological optimization is a computational design approach used to optimize the material distribution within a given design space. It aims to achieve the best structural performance while reducing weight or material usage. Topological optimization analyzes the material layout and removes unnecessary material or redistributes it to improve the performance of the structure, such as enhancing stiffness, reducing stress concentrations, or minimizing weight.

These concepts and techniques are often used together to optimize and analyze the behavior of structures, such as robotic arms, components, or products. By utilizing ANSYS software and conducting FEA, engineers can simulate and evaluate the performance of structures, including those manufactured through additive manufacturing methods, while also exploring the benefits of topological optimization to improve their design.

Topological optimization is a computational design method used to determine the optimal material distribution within a given design space. It aims to maximize the performance of a structure while minimizing its weight or material usage. By analyzing and optimizing the topology (i.e., the arrangement of material) within the design space, engineers can achieve designs that are more efficient, lighter, and exhibit improved mechanical properties.

The process of topological optimization typically involves the following steps:

1. Design Space Definition: The design space is the volume or region within which the optimized structure will be contained. It is typically defined based on the desired constraints and boundaries of the design problem.

2. Material Property and Load Conditions: The material properties of the structure, such as stiffness and density, are defined, along with the anticipated loads and boundary conditions that the structure will experience during its operation.

3. Density Mapping: The design space is discretized into a finite element mesh, and an initial density or material distribution is assigned to each element within the mesh. Commonly, a binary density mapping is used, where elements are assigned a value of 0 (void) or 1 (solid).

4. Optimization Algorithm: An optimization algorithm is employed to iteratively modify the density distribution within the design space. The algorithm adjusts the material density of elements based on specific criteria, such as minimizing compliance (maximizing stiffness) or maximizing structural performance subject to certain constraints.

5. Sensitivity Analysis: Sensitivity analysis is performed to evaluate the response of the structure to changes in the density distribution. It calculates the sensitivity of the objective function (e.g., structural performance) with respect to variations in the density distribution.

6. Iterative Process: The optimization algorithm iterates between steps 4 and 5, gradually refining the density distribution to converge towards an optimal design.

7. Post-Processing: Once the optimization process is complete, the resulting density distribution is converted into a geometric shape that represents the final optimized design. This shape can then be used as a basis for further detailed design and manufacturing.

Topological optimization has numerous applications across various industries, including aerospace, automotive, architecture, and consumer products. It allows engineers to explore innovative and efficient designs by optimizing material distribution and weight while maintaining or improving structural performance.

Lattice structure design refers to the creation of structures with a repeating pattern of interconnected struts or beams, resulting in a porous or cellular structure. These structures often exhibit a high strength-to-weight ratio and have unique mechanical properties that make them suitable for various applications, such as lightweight components, load-bearing structures, and energy absorption systems.

The lattice structure design process typically involves the following steps:

1. Design Considerations: The first step is to define the design requirements and constraints. This includes considering factors such as load requirements, desired mechanical properties, material selection, manufacturing constraints, and geometric constraints.

2. Unit Cell Selection: A unit cell is a basic repeating pattern that defines the geometry of the lattice structure. Various unit cell designs are available, such as cubic, diamond, gyroid, and octet truss, each with different mechanical characteristics. The selection of the unit cell depends on the specific application and desired properties.

3. Topology Optimization: Topological optimization techniques, as mentioned earlier, can be employed to optimize the lattice structure design. This involves determining the optimal material distribution within the design space, ensuring that the lattice structure meets the desired performance criteria while minimizing weight or material usage.

4. Structural Analysis: Once the lattice structure design is optimized, it is important to perform structural analysis using methods like finite element analysis (FEA). This analysis evaluates the mechanical behavior of the lattice structure under various loads and conditions, ensuring that it meets the required strength, stiffness, and stability requirements.

5. Manufacturing Considerations: Lattice structures can be manufactured using additive manufacturing techniques, such as 3D printing. Manufacturing considerations include selecting appropriate printing parameters, material choices, and optimization of the manufacturing process to achieve the desired lattice structure design accurately.

6. Post-Processing and Finishing: After manufacturing, post-processing steps may be necessary to remove support structures, refine the surface finish, or apply additional treatments to enhance the mechanical properties or aesthetics of the lattice structure.

Lattice structures offer several advantages, including lightweight design, improved mechanical performance, and efficient material usage. They find applications in industries like aerospace, automotive, biomedical, and architecture, where weight reduction, structural integrity, and customized design are crucial considerations.

Robotics is a multidisciplinary field that involves the design, construction, programming, and operation of robots. Robots are machines or mechanical systems that are capable of carrying out tasks autonomously or under human control. They are designed to perform a wide range of functions, from simple repetitive tasks to complex operations that require high levels of precision and intelligence.

Key components and aspects of robotics include:

1. Robot Hardware: This encompasses the physical structure, mechanical systems, and electronic components that make up a robot. It includes components like sensors (e.g., cameras, proximity sensors), actuators (e.g., motors, pneumatic systems), and the overall mechanical design, which can vary widely depending on the robot's intended function.

2. Robot Software: Software plays a critical role in robotics as it provides the instructions and algorithms that control the robot's behavior. Robot software can range from low-level firmware and drivers to higher-level programming languages and frameworks that enable functions such as perception, decision-making, and control.

3. Sensing and Perception: Robots rely on sensors to gather information about their environment. These sensors can include cameras, lidar, radar, infrared sensors, force sensors, and more. Perception algorithms process the sensor data to understand the robot's surroundings, detect objects, navigate obstacles, and interact with the environment.

4. Control and Actuation: Control systems enable robots to execute desired actions based on the information gathered from sensors and processed by perception algorithms. Control algorithms determine how the robot moves and interacts with its environment, ensuring precise and accurate execution of tasks. Actuators, such as motors and robotic arms, are responsible for converting control signals into physical movements.

5. Robot Programming: Programming robots involves developing software and algorithms to enable various functionalities, such as motion planning, path following, object manipulation, and decision-making. Programming languages and frameworks specific to robotics, as well as general-purpose languages, are used for this purpose.

6. Applications of Robotics: Robotics finds applications in numerous industries and domains, including manufacturing, healthcare, agriculture, logistics, space exploration, defense, and entertainment. Industrial robots automate production processes, while surgical robots assist in performing delicate surgeries. Autonomous drones, self-driving cars, and exploration rovers are examples of robots used in transportation and exploration.

7. Human-Robot Interaction: Human-robot interaction focuses on enabling seamless and intuitive communication between humans and robots. This includes interfaces, such as touch screens, voice commands, and gestures, as well as safety measures and collaborative robotics, where humans and robots work together in shared workspaces.

Robotics continues to advance rapidly, with ongoing research and development in areas like artificial intelligence, machine learning, computer vision, and autonomous navigation. The field holds great potential for enhancing efficiency, safety, and convenience across a wide range of industries and improving the quality of life for humans.

2 Literature Review

The current chapter examines the research conducted by various authors in the field of robotics and its practical applications. Goldenberg et al. [1] developed an explosives disposal robot designed specifically for hazardous environments. This robot features a wheeled platform and a winder mechanism that keeps the remote control cable and attachments clear. The robot incorporates a bulkhead for quick and easy attachment of various end effectors. These end effectors are mounted on a turret mechanism, allowing unlimited rotation, and are coaxial with the winder mechanism. The manipulator arm section consists of a first arm pivoting approximately 110° and a second arm pivoting approximately 120°. The end effectors include connections of different lengths, extension links, a wrist and gripper mechanism, an aiming and disruptor mechanism, and a mobile surveillance camera. The robot's precision and strength are enhanced by robust, zero-backlash joints, enabling delicate or less delicate actions. The wrist and gripper mechanism, along with the extension links, allow even novice operators to perform dexterous tasks easily. The compact, highly maneuverable, and cost-effective design of this robot meets the specific requirements of law enforcement, military, and environmental agencies.

Lee et al. [2] possess expertise in the design and construction of mobile welding robots. Their robot consisted of servo and stepper motors, an ECU, and a microcontroller. With six degrees of freedom, the robot underwent an optimization process comprising coarse and fine searching steps. The coarse searching process established a feasible parameter region (FPR) that satisfied the geometric design requirements without considering the objective functions. The fine searching stage employed the optimization strategy of the conjugate gradient method to locate the design parameters within the overall FPRs. This proposed technique for calculating task-oriented workspace and achieving optimal design is anticipated to find applications in typical industrial robots.

Volpe et al. [3] developed a robot named Rocky 7, equipped with all-wheel drive capabilities akin to the Mars Rover Prototype. Their research delves into various aspects such as methods, electrical design layout, algorithms, and data science. It provides an overview of the recently created Rocky Mars rover prototype, encompassing its mechanical, electrical, software, algorithmic, scientific instrument, and preliminary testing components. This approach showcases advancements over previous iterations and offers a viable pathway forward

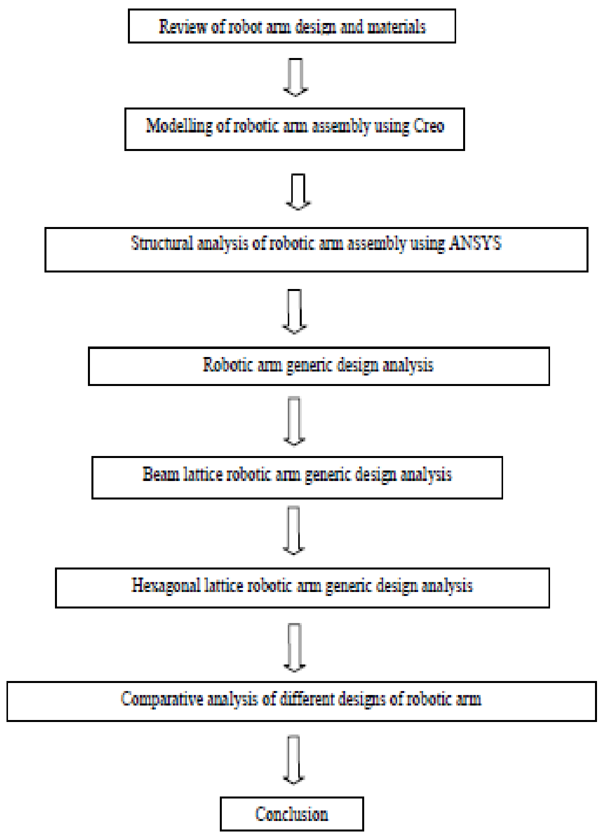
RedZone Robotics Inc. developed the Pioneer robot [4] specifically designed for operating in radiation-exposed environments. This robot's primary purpose is to handle radiation leaks within reactors while retrieving data from the reactor zone. The Pioneer robot is a unique, tethered, bulldozer-like robot that enables remote research. It is equipped with stereo vision for real-time 3D mapping, a core-drilling and sample device, and a range of radiation and other sensor equipment. The team has set November 1998 as the anticipated arrival date of the Pioneer robot at Chernobyl.

Xu et al. [5] focused on designing and constructing a movable detachable manipulator for lunar stations. The robot comprises a wheeled mobile base and a detachable manipulator arm with grippers on each end. The robot can transform into a mobile splitter and perform exploratory tasks such as gathering soil samples, studying the lunar surface, and transporting equipment and supplies. When the arm links to the mobile base by grabbing a handle with one of its grippers, the manipulator arm can detach from the base and move hand-over-hand along a lunar center structure, enabling tasks such as structure inspection, part delivery, and simple assembly tasks. The paper covers the concept, benefits, system development, and software architecture of this robot.

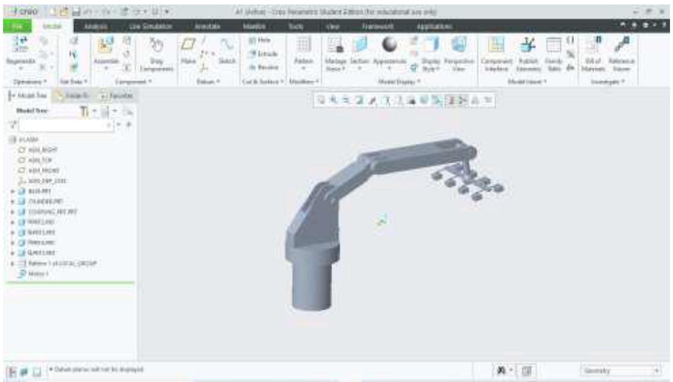
Ben-Tzvi et al. [6] present an example of a mechanical hybrid portable robot with an innovative design perspective that combines parallel and sequential connections. This hybrid mechanism comprises a mobile robot platform for movement and a manipulator arm for manipulation, utilizing both parallel and serially connected linkages. The improved capability of the robot is complemented by an adjustable track tension and suspension mechanism integrated into part of the mobile robot connections, which creates the robot's locomotion subsystem. The mechanical design was evaluated using a virtual prototype created with MSC ADAMS software, assessing the robot's enhanced mobility features through animations of various potential activities requiring diverse locomotion and manipulation abilities. The design was optimized by selecting appropriate operational factors and components, including weight optimization and defining motor torque needs for different robot configurations. The performance of the mobile robot was determined by visualizing it on simulated terrains such as level highways, barriers, stairs, ditches, and ramps, aiding in the final creation of requirements for producing a full-scale prototype.

3. Research Methodology

4.1 Research Flow Chart



4. Result: Robotic arm modelling using CADUsing the design software Creo, a model of the robotic arm assembly is created. The robotic arm assembly's dimensions were obtained from published works [4].



The robotic arm 1's dimensions are listed below."Part length (L) = 0.45 metres"

Part thickness (t) equals 0.08 metres

The part's width (b) is 0.153 metres.

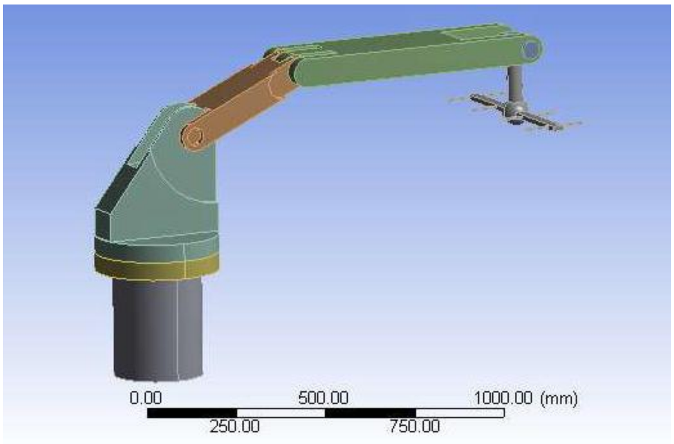


Figure 4.1 Imported CAD model of a robotic arm assembly.

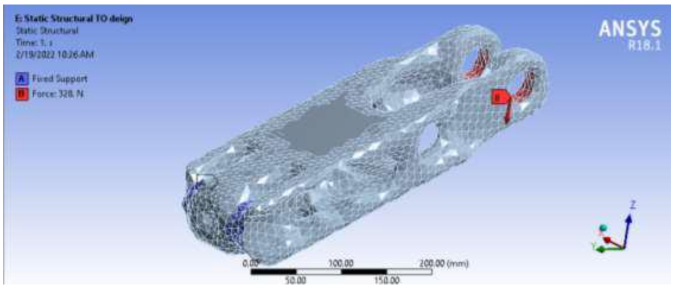
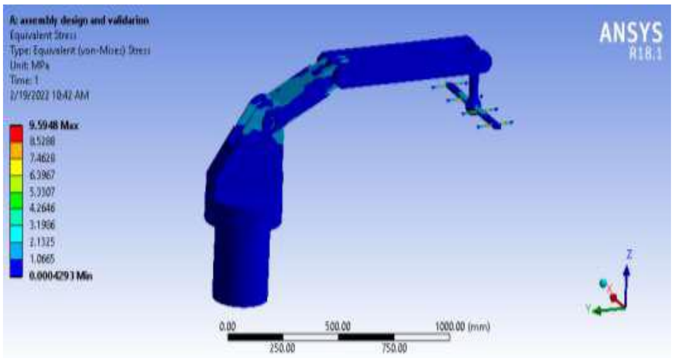


Figure 4.2 Applied loads and boundary conditions on arm 1's topologically optimised design are shown in

Generic Robotic Arm Design Results

The robotic arm assembly is subjected to FEA analysis, and structural output parameters are established. The robotic arm 1 is where the largest equivalent stress is found according to the FEA analysis. According to figure 6.1, the highest equivalent stress obtained is 9.594 MPa.



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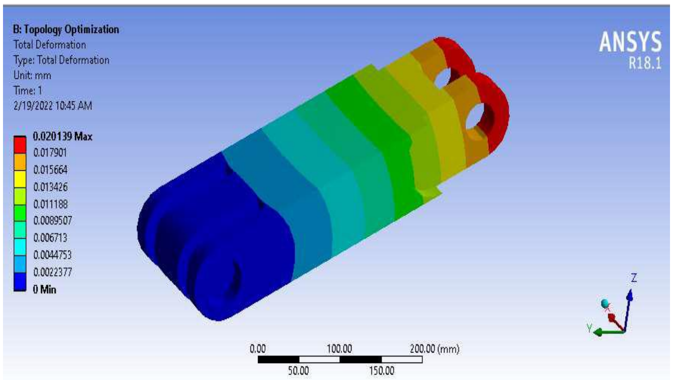
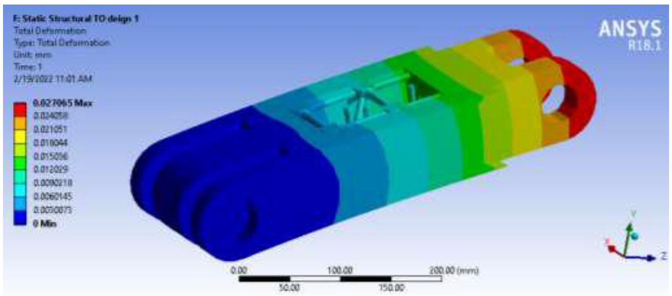


Deformation graph for a basic robotic arm programme, Figure 6.2

Results of the Beam Lattice Robotic Arm

Figure 6.5 below analyses the robotic arm 1 using a beam lattice structure design. At the surface of the load application, a maximum deformation of.027mm is seen. Robotic arm 1's cylindrical support region has low distortion.



Comparative Research

Based on the output parameters, equivalent stress, deformation, and mass, comparison analysis is done for various robotic arm designs.

Table 6.1: Comparison of the outcomes for various designs

Table 6.1: Result comparison for different designs

Design Type	Generic Design	Beam Type Lattice Design	Hexagonal Type Lattice Design	Topologically Optimized Design
Equivalent Stress (Mpa)	2.3182	2.949	13.145	2.4065
Total Deformation (mm)	0.0201	0.027	0.0146	0.00928
Mass (Kg)	11.363	9.0772	9.283	6.649

Through the utilization of lattice structure and topological optimization techniques, significant weight reduction of the robotic arm components can be achieved. The detailed findings are as follows:

5. Conclusion

1. The topology optimized design and lattice structure design of the robotic arm result in an increase in equivalent stress and deformation compared to the generic design.
2. Among the optimized designs of the robotic arm, the hexagonal lattice design exhibits the highest equivalent stress, while the topologically optimized design demonstrates the lowest equivalent stress.
3. Among the optimized designs of the robotic arm, the beam-type lattice design exhibits the highest deformation, whereas the topologically optimized design shows the lowest equivalent stress.
4. The beam lattice structure design of the robotic arm achieves a mass reduction of 20.11% when compared to the standard design of the robotic arm.
5. The hexagonal lattice structure design of the robotic arm demonstrates a mass reduction of 18.305% when compared to the generic design of the robotic arm.
6. The topologically optimized design of the robotic arm achieves a significant mass reduction of 41.48% when compared to the generic design of the robotic arm.

These findings highlight the effectiveness of utilizing lattice structures and topological optimization techniques in achieving weight reduction in the robotic arm design, leading to improved efficiency and performance.

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