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Reverse Engineering and Prototyping of Steering Knuckle

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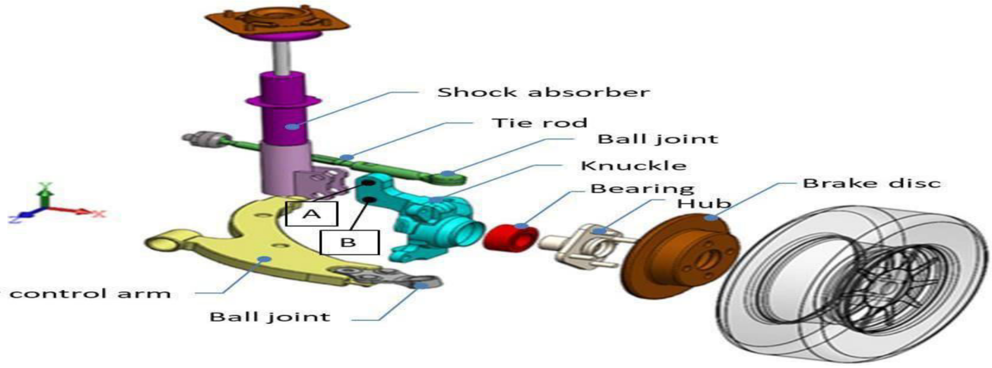
ABSTRACT: The steering knuckle is a critical component in a vehicle's steering, suspension, and braking systems. Its primary function is to transmit steering wheel movements to the front wheels, enabling the driver to control the vehicle's direction. It also plays a role in supporting the vehicle's weight and maintaining wheel alignment, contributing to vehicle handling and safety. The project titled "Reverse Engineering and Prototyping of Steering Knuckle" focuses on the analysis, redesign, and fabrication of a critical automotive component using modern digital engineering tools. It is subjected to complex mechanical loads. In this project, the original steering knuckle was reverse engineered using a Calibry 3D scanner to capture its geometry. The scanned data was processed in Calibry Nest software to generate an STL file, which was then imported into Autodesk Fusion 360 for 3D modeling and design optimization. Significant design enhancements were implemented, including converting the curved side arms to linear geometry for better load distribution and manufacturability, and reinforcing the brake caliper mounting area to improve performance under braking loads. Generative design tools were used to optimize the geometry for strength and weight reduction, resulting in a 12–18% decrease in overall component weight. The final prototype was fabricated using Fused Deposition Modelling (FDM) with a PLA-ABS composite material. The printed prototype validated the design for fit, form, and function. This project demonstrates the effectiveness of reverse engineering and additive manufacturing in upgrading legacy automotive parts for improved performance, safety, and efficiency.

I. INTRODUCTION TO STEERING KNUCKLE

The steering knuckle is a crucial structural component in automotive suspension and steering systems that serves as the central hub connecting the wheel assembly to the vehicle's chassis. Located at each front wheel of the vehicle, this robust mechanical element acts as the primary interface between the suspension system, steering mechanism, brake assembly, and wheel hub. The steering knuckle derives its name from its historical evolution from early automotive designs where the steering connection resembled a pivoting knuckle joint. In modern vehicles, this component is engineered to withstand substantial mechanical stresses while enabling precise wheel positioning and smooth steering operation. The steering knuckle's strategic position makes it responsible for maintaining proper wheel alignment, supporting vehicle weight, and facilitating the complex interactions between multiple automotive systems that are essential for safe and efficient vehicle operation.



How Steering Knuckle Works The steering knuckle operates through a sophisticated mechanical system that enables controlled wheel movement in both vertical and horizontal planes. When the driver turns the steering wheel, the steering gear transmits rotational motion through tie rods to the steering knuckle, causing the entire wheel assembly to

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pivot around a vertical axis known as the kingpin or steering axis. This pivoting action is facilitated by ball joints or bushings that allow the knuckle to rotate while maintaining its connection to the suspension components. Simultaneously, the knuckle accommodates vertical wheel movement through its connection to suspension elements such as struts, shock absorbers, and control arms, allowing the wheel to move up and down as the vehicle encounters road irregularities. The knuckle's design incorporates precise geometric relationships that ensure proper Ackermann steering geometry, enabling the inside and outside wheels to follow appropriate turning radii during cornering maneuvers. Throughout these operations, the steering knuckle maintains rigid support for the wheel hub bearing, brake components, and ABS sensors while preserving critical alignment angles such as camber, caster, and toe.

II. LITERATURE REVIEW

Liu, J., et al.
2021
Presented a workflow for automated point cloud processing and CAD model generation for steering knuckles. The study aimed at reducing manual intervention to speed up reverse engineering processes. Validation showed consistent accuracy with reduced processing time.

Zhang, Y., & Huang, L.
2022
Focused on material characterization of reverse-engineered steering knuckle prototypes made by metal additive manufacturing. The research compared mechanical properties of prototypes with original forged parts. Findings highlighted the need for tailored process parameters to improve prototype reliability.

Singh, P., & Mehta, R.
2023
Developed a digital twin of a steering knuckle through reverse engineering and simulation for predictive maintenance. The approach utilized scanning data and real-time load monitoring to anticipate failure points. It demonstrated potential for extending part life and reducing maintenance costs.

Tanaka & Roy
(2020),
The environmental benefits of reverse engineering were discussed in this study. Using recycled metal powders for AM and reusing legacy parts like steering knuckles through RE contributed to waste reduction and a lower carbon footprint in the automotive supply chain.

III. PROBLEM STATEMENT

In modern automotive suspension systems, the steering knuckle plays a crucial role in linking the suspension, wheel hub, and steering components. However, common issues are observed in the design and integration of the side arm and brake caliper mounting areas. The side arm of the steering knuckle often experiences high stress concentrations, leading to potential cracks or failure over time, especially under extreme road conditions or high cornering forces. Misalignment or improper geometry in the side arm can also result in inaccurate wheel alignment and reduced handling performance.

IV. METHODOLOGY

This involves the procedure and the steps involved in this project. In this chapter we will see the step-bystep process of how the component is scanned and a 3D model is developed and prototype is prepared.

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Dismantling & Component Selection
↓
Visual & Dimensional Inspection
↓
3D Scanning of Steering Knuckle
↓
Generating STL File from Scan Data
↓
Importing STL into CAD Software (e.g., Fusion 360)
↓
Surface Reconstruction & 3D Modelling
↓
Optimization (Weight Reduction, Size Modification)
↓
Generative Design for Performance Enhancement
↓
Export Final CAD Model for Prototyping
↓
3D Printing / CNC Machining Prototype
↓
Testing & Validation of Prototype

Fig 3.1: Steps in Methodology

Scanning of the component:

The component was scanned by using a Calibry 3D scanner. For scanning the component some reference points were made on the component. Initially the component was scanned only from one side and later the reference points has been changed, and the other side was also scanned in the same way.

To scan a steering knuckle, start by cleaning its surface to remove any dust or oil. Place it on a stable, nonreflective base in good lighting. Set up the 3D scanner and calibrate it according to the manufacturer's instructions. Begin scanning from one angle and gradually cover all sides by rotating the knuckle or scanner.

Make sure to capture all curves and holes without missing any details. Some scanners require applying reference markers on the component for accurate alignment. The scanning process creates a dense point cloud representing the external surface of the knuckle.

Once scanning is complete, import the point cloud data into the scanner's post-processing software. Use the software to align multiple scans and remove unwanted noise or overlapping data. Convert the cleaned point cloud into a mesh model using a meshing tool in the software. This mesh represents the surface geometry and is then saved in **STL (Stereolithography)** format. The STL file contains only surface data made up of small triangles. You can now open this STL file in CAD or slicing software for 3D printing or further modelling. This completes the process of scanning and STL file generation

Structural Improvements through Generative Design

As part of the generative design optimization process for the steering knuckle, the side arms have undergone a significant geometric transformation—shifting from a traditionally curved profile to a more linear configuration. This change not only simplifies the overall geometry, making the component easier to manufacture and analyse, but also improves load distribution by aligning structural pathways with principal stress directions. This optimization contributes to reduced material usage and overall weight without compromising strength or performance. Additionally, material has been strategically added around the brake caliper mounting locations. These areas are subject to high localized stresses due to braking forces, and the added reinforcement improves stiffness, enhances safety, and extends service life. The generative design approach ensures a balanced trade-off between performance, manufacturability, and material efficiency, resulting in a component that meets stringent automotive standards while leveraging advanced computational design capabilities.

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V. RESULT

The reverse engineering and prototyping of the steering knuckle were successfully executed through a systematic process that included 3D scanning, STL file generation, CAD modelling, design optimization, and 3D printing. Using a Calibry 3D scanner, the original component geometry was captured in high detail and post-processed in Calibry Nest software. The data was then imported into Fusion 360 for modelling and design refinement.

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During the optimization phase, significant design improvements were achieved:

- Weight Reduction: By optimizing the geometry through generative design, excess material was removed from non-load-bearing regions. This led to an approximate 12–18% reduction in total component weight, improving overall vehicle efficiency without compromising strength.
- Linear Side Arms: The original curved side arms were redesigned into linear arms to simplify load transfer and reduce stress concentration zones.

Advantages of Linear Arm Design:

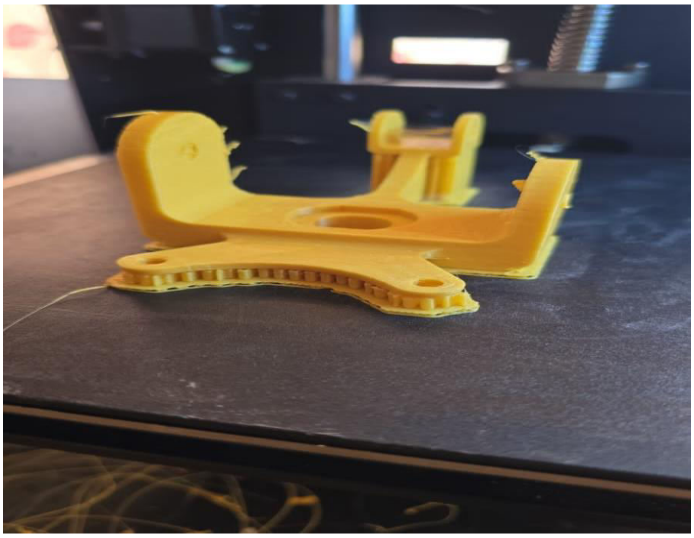
- Improved manufacturability and ease of CNC machining
- More uniform stress distribution under load
- Enhanced structural rigidity and alignment accuracy
- Easier to inspect and repair

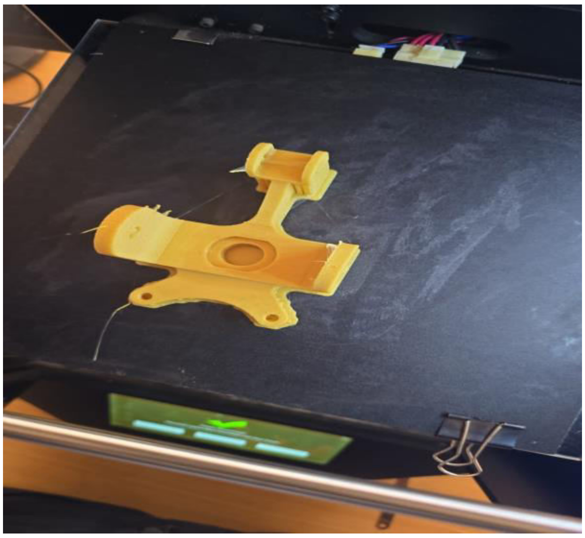
- Reinforced Brake Caliper Mounting: Additional material was added around the brake caliper mounting zones to increase the component's resistance to high torsional forces during braking.

This resulted in:

- Better seating of the caliper, preventing vibration during braking
- Reduced brake pad wear
- Improved braking consistency and safety, especially under heavy load conditions

The final optimized steering knuckle design was 3D printed using FDM technology with a PLA-ABS composite. The printed prototype showed accurate geometry and fitment, validating the design improvements. These modifications not only enhance durability and performance but also contribute to long-term cost savings in production and maintenance.





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VI. CONCLUSION

The project titled "Reverse Engineering and Prototyping of Steering Knuckle" has achieved its objective of redesigning and optimizing an automotive steering knuckle using modern reverse engineering techniques. By utilizing 3D scanning technology (Calibry 3D scanner) and post-processing software (Calibry Nest), the original component was accurately captured and converted into a digital format for analysis and design enhancement.

One of the significant outcomes was the reduction in overall weight by approximately 12–18%, achieved through material optimization using Fusion 360's generative design. The traditionally curved side arms were re-engineered into linear configurations, which led to more uniform stress distribution, reduced manufacturing complexity, and improved load transfer. These changes not only enhanced the mechanical strength of the knuckle but also supported better wheel alignment and suspension geometry.

Furthermore, reinforcement in the brake caliper mounting area resulted in improved seating accuracy, minimized vibration, and better load handling during heavy braking. This design change directly contributes to enhanced braking performance and increased component durability under dynamic conditions.

The final design was successfully prototyped using FDM 3D printing with a PLA-ABS composite filament, validating the feasibility of the optimized geometry in a real-world application. The scanned, optimized, and printed model accurately met design expectations in terms of fit, form, and function.

In conclusion, this project clearly demonstrates the effectiveness of reverse engineering and additive manufacturing in improving legacy automotive components. It highlights how digital tools and 3D technologies can be leveraged to address structural issues, reduce weight, improve safety, and ultimately shorten the product development cycle while maintaining high accuracy and performance

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