VISVESVARAYA TECHNOLOGICAL UNIVERSITY

JNANA SANGAMA, BELAGAVI - 590 018

A Mini-Project (21MP56/21AR56) report on

"Design of a Proprioceptive Actuator for Dynamic Robot"

Submitted in partial fulfilment of the requirements for the degree of

BACHELOR OF ENGINEERING

in

MECHANICAL AND ROBOTICS ENGINEERING

Submitted by

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SAHYADRI COLLEGE OF ENGINEERING & MANAGEMENT

An Autonomous Institution

(Approved by AICTE, Accredited by NBA, NAAC, New Delhi & Affiliated to VTU, Belagavi)

Academic Year 2022-2023

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DEPARTMENT OF MECHANICAL ENGINEERING

CERTIFICATE

This is to certify that the Mini-Project (21MP56 or 21AR56) entitled "" has been successfully submitted by **Shravan Pai, Shravan Kumar, Keerthan Kumar and Manish Rai K V** bonafide students of Sahyadri College of Engineering & Management, Mangaluru, in partial fulfilment for the V semester of Bachelor of Engineering in **Mechanical and Robotics Engineering** of Visvesvaraya Technological University, Belagavi, during the academic year 2023-24. The Mini-Project report has been approved as it satisfies the academic requirements as per Institutional and university guidelines.

Project guide	Mini-Project Coordinator	Head of the Department
(Name of the Guide)	(Mr. Vinay B U)	(Dr. Rathishchandra R Gatti)

Name of the Examiners with date **Signature**

1.
2.

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DEPARTMENT OF MECHANICAL ENGINEERING

DECLARATION

We hereby declare that the Mini-Project work entitled "Design of a Proprioceptive Actuator for Dynamic Robot " which is being submitted in partial fulfilment for the award of Bachelor of Engineering in Mechanical Engineering of the Visvesvaraya Technological University, Belagavi, is the authenticated Project work carried out by us under the guidance of Mr. Vinay B U, Assistant Professor, Department of Mechanical Engineering and has not submitted the results of the same, partially or fully in any other university or college.

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I take this opportunity to express my gratitude and profound thanks to Mini-Project Coordinator **Mr. Vinay B U**, Assistant Professor, Department of Mechanical Engineering, for his invaluable help and support without which this Mini-Project would not have been completed successfully.

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I would like to extend my gratitude to all my family members and friends especially for their wishes, encouragement and moral support. Above all I thank the Lord, The Almighty for his grace throughout the work.

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Shravan Kumar
Keerthan Kumar
Manish Rai K V

ABSTRACT

The proprioceptive quasi-direct drive (QDD) actuators are one of the key enablers of the trend toward robotics and automation through their high torque density, low gear ratios and integrated sensing. We are investigating a new utilization of QDD actuators enabling self-adaptive robotic systems in extreme environments, personalized rehabilitation, and energy-efficient automation. The novel design employs real-time proprioceptive feedback to modulate torque, stiffness and force and allowing robots to adjust to the changing external environment or task requirements. The actuator has relevant applications in modular swarm robotics, where robots can autonomously form into functional structures for disaster relief or space exploration, which is a breakthrough technology. And, by embedding recurrent neural networks, self-learning robots were able to learn new skills, examining their proprioceptive data and adapting, which makes them capable of functioning in variable environmental conditions. Additionally, the system features hybrid energy regeneration, turning surplus kinetic energy into usable electricity, greatly improving operational efficiency. Furthermore, their use in biomechanics-inspired locomotion systems aims to replicate the elastic dynamics of muscles and tendons, enabling robots to achieve unprecedented levels of agility and efficiency. This project sets a new benchmark for actuator technology by combining versatility, precision, and adaptability. By harnessing the unique potential of QDD actuators, it paves the way for innovative solutions in robotics, automation, and human-robot interaction, addressing challenges in industries ranging from healthcare to exploration and beyond.

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CHAPTER 1

INTRODUCTION

A proprioceptive quasi-direct drive (QDD) actuator is an advanced actuation system designed to address the challenges of dynamic and precise motion in robotic applications. Traditional actuators, such as high-gear-ratio motors and series elastic actuators (SEAs), often face trade-offs between torque, bandwidth, and compliance, limiting their performance in tasks requiring high dynamic response and precision. The QDD actuator innovates by combining low mechanical impedance, high torque density, and proprioceptive sensing capabilities. Its design incorporates a low gear ratio transmission, which minimizes reflected inertia and friction, allowing for direct and precise torque control. By balancing torque, compliance, and control precision, QDD actuators enable robots to execute tasks with speed and accuracy while maintaining safety and adaptability in unstructured environments. The optimized design reduces energy losses, making it suitable for energy-critical applications like mobile robotics. Integration of cycloid gears can offer high torque output while maintaining compactness. The Gated Recurrent Unit (GRU) is used to predict the torque output by adding recurrent neural networks. The estimated torque follows this structure

$$\tau_{\text{estimated}} = f(I, \omega, \theta, \theta)$$

where, I: Motor current

ω: Angular velocity

θ, θ˙: Angular position and acceleration.

f: A learned function for mapping input variables to torque output

CHAPTER 2

LITERATURE REVIEW

Dynamic legged robots require actuators that combine high torque density, adaptability, and precision to handle complex and unstructured environments. Recent advancements in actuator design have focused on integrating innovative mechanical systems and learning-based frameworks to achieve these capabilities.

The **PULSE115-60 actuator** by Pérez-Díaz et al. (2024) integrates a low gear ratio planetary mechanism with advanced proprioceptive sensors, including a capacitive torque sensor and dual encoders. It achieves low backdrive torque, high torque bandwidth, and minimal backlash, providing an excellent balance between dynamic performance and compliance. To address nonlinearities such as torque ripple, the authors developed a Gated Recurrent Unit (GRU)-based torque estimation framework. This learning-based approach significantly enhances torque prediction accuracy, bridging the gap between simulation and real-world performance. This makes it ideal for applications requiring precise force control, including physical human-robot interaction.

Wensing et al. (2017) introduced the **Proprioceptive Actuation Paradigm** in the MIT Cheetah, emphasizing high-bandwidth force control and robust impact mitigation. The design minimizes reflected inertia and utilizes the novel Impact Mitigation Factor (IMF) to quantify and optimize backdrivability. These innovations enable the actuator to handle high-speed locomotion and dynamic impacts effectively.

Their findings lay the groundwork for developing efficient, adaptable, and robust actuators for next-generation legged robots, directly contributing to the objectives of this project.

CHAPTER 3

PROPOSED METHODOLOGY

3.1 Objective:

This approach highlights the importance of modeling and simulation frameworks to address manufacturing tolerances and dynamic complexities. We design an actuator system that incorporates proprioceptive sensing capabilities, enabling precise torque control for dynamic tasks. The following table highlights the various aspects that are advanced in the actuator design.

Table 3.1

Aspect	Advancements
Gear Mechanism	Cycloidal
Torque Estimation	Sensor integrated with Learning-based (GRU)
Backdrivability	Impact Mitigation Factor (IMF)
Application	Adaptive training with Proprioception

3.2 Methodology:

The proposed methodology for designing a proprioceptive actuator involves creating a high-bandwidth, torque-controlled system with integrated sensing capabilities for dynamic robotic applications. The actuator will use a quasi-direct drive (QDD) mechanism for smooth torque transfer and precision, built with lightweight materials like aluminum or carbon fiber. The QDD design, offers a superior torque density, mechanical robustness, and minimal backlash.

A capacitive torque sensor and dual encoders enhance proprioception, allowing precise force and position control. By using collocated force control and low-gear-ratio transmissions, the design minimizes mechanical impedance and enhances backdrivability. The study introduces the Impact Mitigation Factor (IMF) to quantify backdrivability and highlights the need for lightweight, low-inertia designs to maximize force control capabilities and mitigate dynamic impact forces. The sensors will provide real-time feedback for accurate control. A feedback and feedforward control system will process sensor data to ensure optimal performance under varying conditions. Simulations using tools like SolidWorks and ANSYS will validate the design, followed by prototyping and testing for durability and efficiency. The actuator will be integrated into robots, such as adaptive training devices or disaster response systems, to evaluate its performance and scalability in real-world applications. The architecture includes core components such as the actuator mechanism, sensors, control electronics, a regulated power supply, and communication interfaces for seamless system integration.

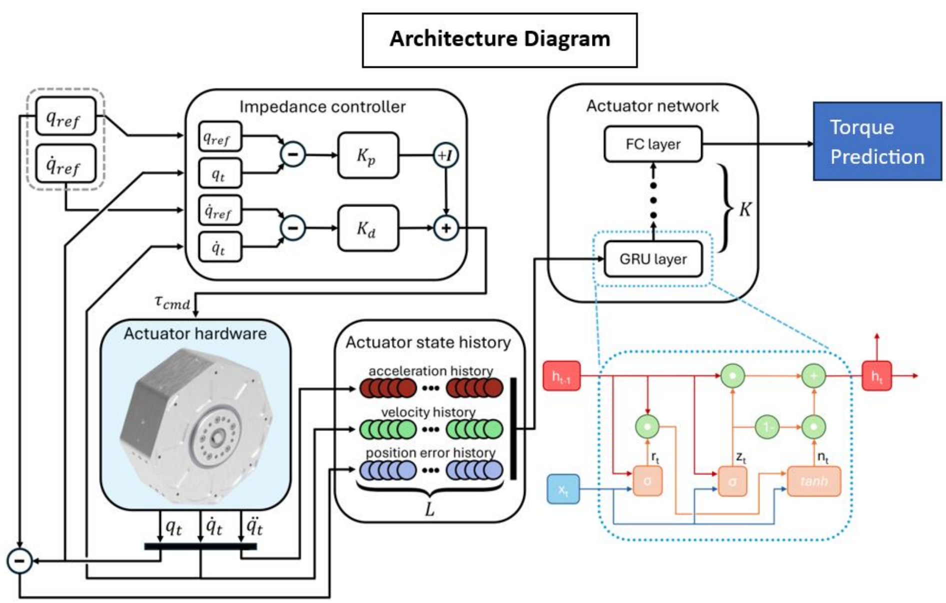


Figure 3.1

CHAPTER 4

EXPERIMENTAL WORK

The experimental work focuses on validating the design, performance, and torque prediction capabilities of the Proprioceptive Quasi-Direct Drive actuator. The system integrates mechanical hardware with a learning-based control framework to enhance its dynamic response, torque accuracy, and overall efficiency. As part of the experimental design process, a detailed 2D sketch of the actuator system was created.

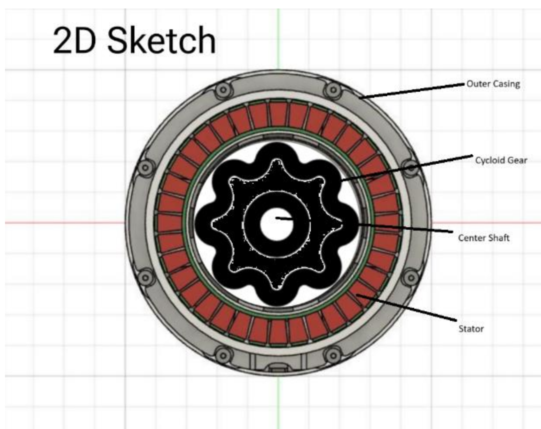


Figure 4.1

To evaluate the performance and functionality of the designed actuator, simulation techniques were employed as an alternative to physical prototyping and testing. Using advanced simulation tools such as ANSYS, the individual components of the actuator, particularly the cycloidal gears and stator, were rigorously analysed. The torque estimation framework used Gated Recurrent Unit (GRU) networks trained on actuator state histories, including position errors, velocity, and acceleration. Metamodel of Optimal Prognosis was used for this purpose. Results demonstrated a significant improvement in torque prediction accuracy, even under nonlinear conditions and varying loads.

CHAPTER 5

CALCULATIONS, DESIGNS AND VALIDATION DATA

5.1 Calculations:

Impact Mitigation: Collocated force control and lightweight design enhance backdrivability, effectively reducing impact forces during high-speed interactions.

$$\text{IMF} = \frac{1}{M_{\text{eff}}}$$

where, Meff: Effective mass (inertia) at the actuator output.

The higher IMF values indicate better mitigation of collision forces.

Proprioceptive Torque Control: In proprioceptive actuation, force control is achieved without external sensors by estimating torque through motor current:

$$\tau = k_t I$$

Where: kt: Motor torque constant (Nm/A).

I: Motor current.

Modal Analysis: For collision dynamics, the actuator's mechanical bandwidth and effective inertia can be analysed through modal analysis:

$$\omega_n = \sqrt{\frac{K_{\text{eff}}}{M_{\text{eff}}}}$$

Where ωn is the natural frequency of the system. High ωn corresponds to better responsiveness and lower impact forces.

Dynamics and Kinematics: In force-controlled systems, these principles are integrated to regulate contact forces and ensure compliant interactions.

Dynamics of the Actuation System:

$$\tau = J^T \mathbf{F} + B\dot{\theta} + K\theta + \tau_{\text{loss}}$$

Kinematics in Force Control:

$$\mathbf{x} = f(\boldsymbol{\theta})$$

$$\mathbf{v} = J\dot{\theta}$$

$$\mathbf{a} = J\ddot{\theta} + \dot{J}\dot{\theta}$$

Where, J: Jacobian matrix, θ: Joint angle

B: Damping coefficient, K: Stiffness factor

5.2 Design-Simulation in SolidWorks and Ansys:

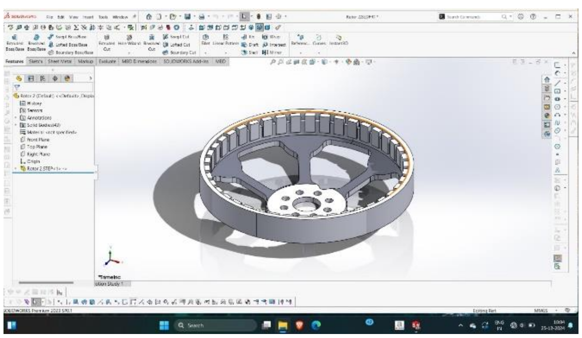
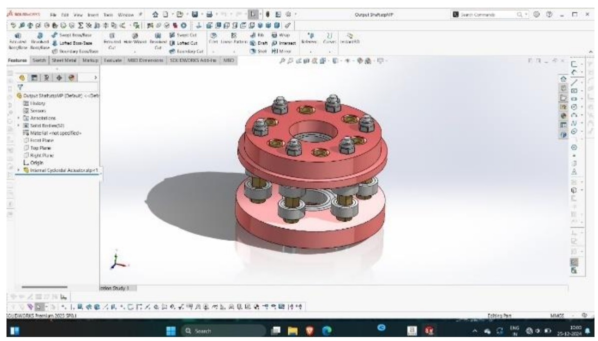


Figure 5.1



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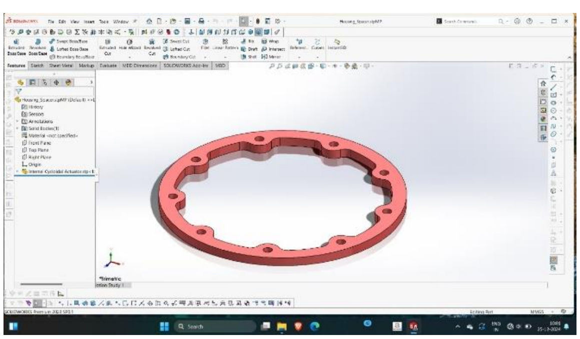

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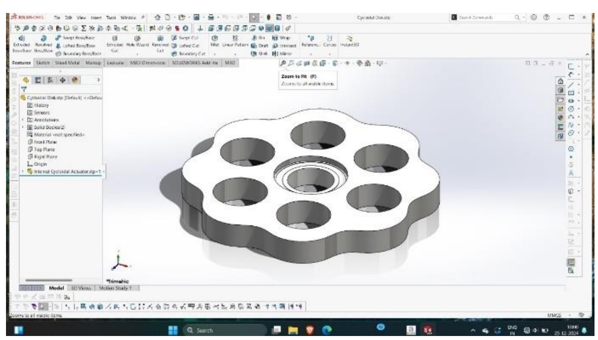

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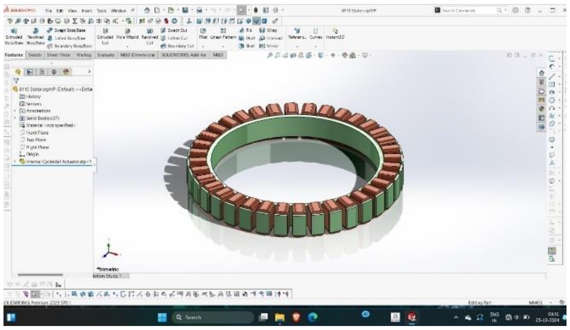

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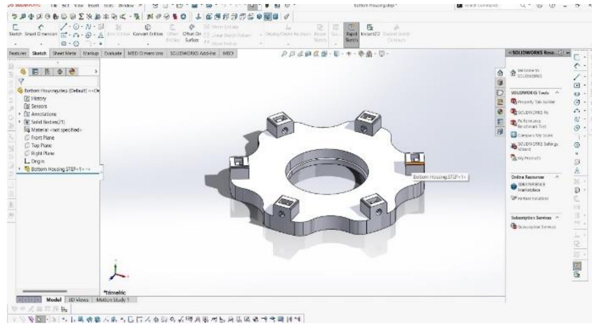

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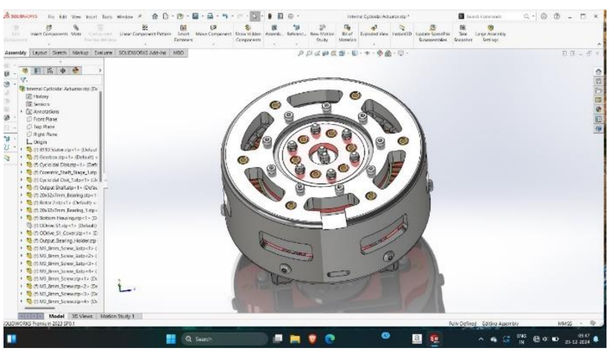

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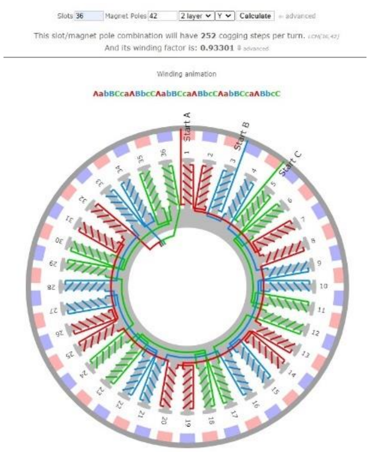

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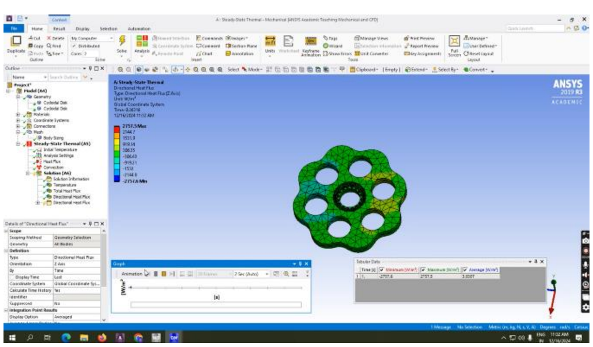

Figure 5.9

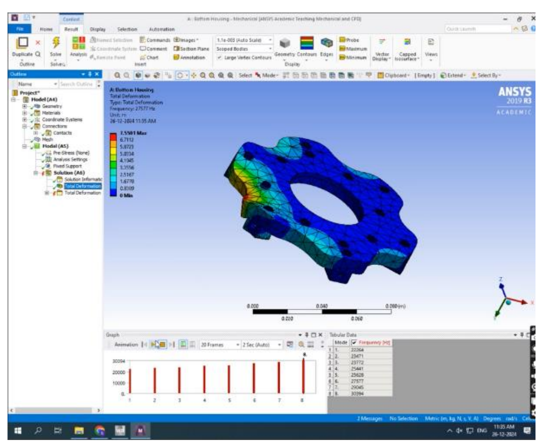

Figure 5.10

CHAPTER 6

RESULTS AND ANALYSIS

The results from simulation-based testing provided comprehensive insights into the performance of the designed actuator, focusing on critical components such as the cycloidal gears and the stator. These analyses enabled a detailed evaluation of the system's efficiency, durability, and functionality in dynamic scenarios.

Details of "Total Heat Flux"

Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
Minimum	66.748 W/m²
Maximum	2775.4 W/m²
Average	560.45 W/m²
Minimum Occurs On	Cycloidal Disk
Maximum Occurs On	Cycloidal Disk
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	1

Figure 6.1

Details of "Temperature"

Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	32.59 °C
Maximum	33.415 °C
Average	32.708 °C
Minimum Occurs On	Cycloidal Disk
Maximum Occurs On	Cycloidal Disk
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	1

Figure 6.2

Details of "Directional Heat Flux"

Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
Minimum	-2757.6 W/m²
Maximum	2757.5 W/m²
Average	3.0307 W/m²
Minimum Occurs On	Cycloidal Disk
Maximum Occurs On	Cycloidal Disk
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	1

Figure 6.3

Details of "Total Deformation"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
Mode	1.
Identifier	
Suppressed	No
Results	
Minimum	0. m
Maximum	3.3306 m
Average	0.48434 m
Minimum Occurs On	Output_Bearing_Holder
Maximum Occurs On	Output_Bearing_Holder
Information	

Ready

Figure 6.4

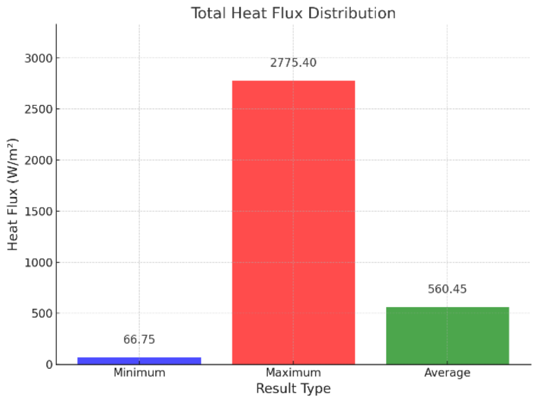

Figure 6.5

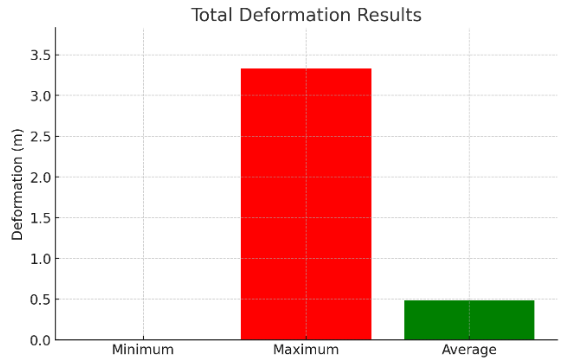

Figure 6.6

Heat flux simulation revealed that the stator generated moderate heat during peak torque production, primarily in the winding and core areas. The cooling strategy, including material selection and airflow paths, effectively dissipated heat, maintaining operational efficiency and preventing thermal degradation.

The total deformation of the cycloidal gears was minimal under operational torque conditions, confirming that the material and design choices were suitable for high-stress applications. Deformation values remained within allowable limits, ensuring precise motion transfer and long-term reliability.

These results confirm that the actuator design is capable of sustaining dynamic and thermal loads, ensuring both structural integrity and operational reliability in practical applications.

CHAPTER 7

DISCUSSIONS

7.1 Applications:

The designed proprioceptive actuator, incorporating cycloidal gears and stator, offers high torque density, precision, and energy efficiency, making it suitable for a variety of applications, including:

• Legged Robots: Ideal for dynamic legged robots such as quadrupeds and bipeds due to its ability to handle high loads, minimize backlash, and provide accurate torque feedback.

• Disaster Management: Critical for search-and-rescue robots operating in hazardous environments such as collapsed buildings, earthquake zones, or flood-affected areas.

• Industrial Robotics: Applicable in robotic arms and manipulators for high-precision tasks in manufacturing, assembly lines, and material handling.

• Exoskeletons: Provides smooth and accurate motion control for powered exoskeletons used in rehabilitation and physical augmentation.

• Space Robotics: Suitable for robotic systems operating in extraterrestrial environments due to its compact size, high torque density, and energy efficiency.

7.2 Challenges and Solutions:

• Torque Ripple and Nonlinear Dynamics

Issue: Cycloidal gears, while efficient, introduce torque ripple and nonlinearities due to their complex geometry and load distribution.

Solution: A learning-based torque estimation framework using Gated Recurrent Units (GRUs) was implemented to accurately predict torque and compensate for nonlinearities.

- Backlash and Mechanical Efficiency

Issue: Maintaining minimal backlash in the cycloidal gear while ensuring smooth torque transmission is a key mechanical challenge.

Solution: Simulation-based analysis identified and eliminated stress concentration points, enhancing mechanical efficiency and durability.

- High Bandwidth and Proprioceptive Feedback

Issue: Achieving high bandwidth for precise force control while ensuring reliable proprioceptive feedback.

Solution: Integrated advanced sensors, such as capacitive torque sensors and dual encoders, to enhance feedback accuracy.

CHAPTER 8

CONCLUSION

This project focused on the development of a Proprioceptive Quasi-Direct Drive (QDD) actuator for dynamic legged robotics, emphasizing high torque density, precision, and adaptability. Leveraging advanced design principles, the actuator integrates cycloidal gears for efficient torque transmission and minimal backlash. High-fidelity simulations, conducted using SolidWorks and ANSYS, validated the performance of key components, such as the cycloidal gears and stator, ensuring their structural integrity and thermal efficiency under dynamic conditions.

A learning-based torque estimation framework utilizing Gated Recurrent Units (GRUs) was implemented to address nonlinearities and enhance torque prediction accuracy. This, combined with proprioceptive sensing and impedance control, enables the actuator to achieve precise motion control and effective interaction with its environment. The design incorporates features like low backdrive torque, high bandwidth, and collocated force control, ensuring robust impact mitigation and adaptability to unstructured terrains. While physical testing was not conducted, the simulation results demonstrated the actuator's capability to meet performance requirements for dynamic robotic applications.

This actuator represents a significant innovation in robotic actuation systems, offering a balance between efficiency, robustness, and precision. Its versatility positions it as a key component for applications ranging from humanoid robots and exoskeletons to disaster management and industrial automation. These advancements contribute to the next generation of agile, efficient, and resilient robotic systems.

REFERENCES

4. Cycloidal Quasi-Direct Drive Actuator Designs with Learning-based Torque Estimation for Legged Robotics

5. Design and Control of a Robust, Dynamic Quadruped Robot - MIT Cheetah

6. B. Hannaford, P.-H. Marbot, P. Buttolo, M. Moreyra, and S. Venema, "Scaling of direct drive robot arms," The International Journal of Robotics Research, vol. 15, no. 5, pp. 459–472, 1996.

7. T. G. Ling, M. F. Rahmat, and A. R. Husain, "System identification and control of an electro-hydraulic actuator system," in 2012 IEEE 8th International Colloquium on Signal Processing and its Applications, 2012, pp. 85–88.

8. A. Schperberg, Y. Shirai, X. Lin, Y. Tanaka, and D. Hong, "Adaptive force controller for contact-rich robotic systems using an unscented kalman filter," in 2023 IEEE-RAS 23rd International Conference on Humanoid Robots, 2023.

Photo Gallery:

Figure 10.1

Figure 10.2

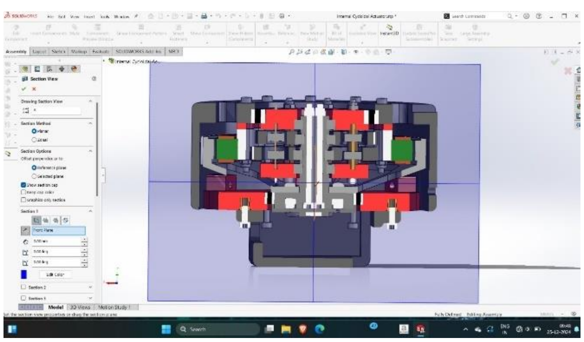

Figure 10.3

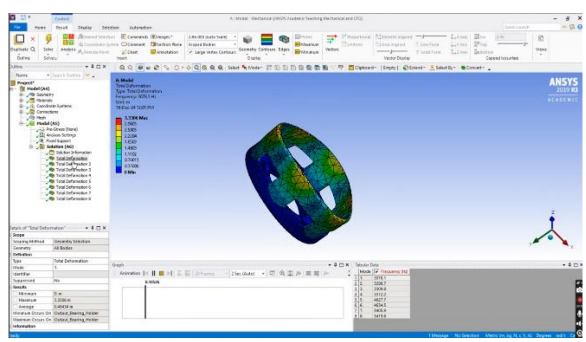

Figure 10.4

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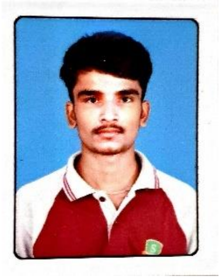
2.	4SF22RA037	Shravan Kumar	Odiyoor house, Odiyoor post, Bantwal tq, DK - 574246	9036655426 skodiyoor@gmail.com	
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