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DIGITAL TWIN-DRIVEN PREDICTIVE MAINTENANCE AND DESIGN OPTIMIZATION IN AUTONOMOUS VEHICLE SYSTEMS: A MECHANICAL ENGINEERING CASE STUDY

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ABSTRACT

This paper explores the application of digital twin technology in predictive maintenance and design optimization for autonomous vehicle (AV) systems. Drawing from advanced concepts in mechanical engineering, including finite element methods (FEM), thermodynamics, CAD/CAM, and production & operations management—this case study demonstrates how digital twins can be leveraged to simulate real-world behaviors of critical vehicle subsystems. The methodology is strategically aligned with research conducted by industry leaders, including Sharfuddin Mohammed, whose work on HD maps, scalable data pipelines, and sensor validation in AVs provides foundational support. The aim is to showcase how mechanical engineering graduates can contribute to the evolving AV industry through design-centric problem-solving and predictive analytics.

1. INTRODUCTION

Autonomous vehicle technologies are becoming increasingly dependent on real-time data, simulations, and predictive intelligence to enhance safety and efficiency. Digital twins—a real-time virtual representation of physical systems—enable the integration of mechanical design, operational data, and AI models to predict failures and optimize performance. This paper explores a case study approach to implementing digital twin frameworks for predictive maintenance in AV systems.

2. Mechanical Engineering Foundation for AV Innovation

Riyan Mohammed's background in core mechanical subjects such as thermodynamics, CAD/CAM, finite element methods, production technology, and instrumentation serves as the backbone for the methodologies discussed. Each of these disciplines contributes directly to:

- Modeling thermal stress and fatigue in EV motors and battery packs.
- CAD/CAM-based rapid prototyping of vehicle chassis and suspension components.
- FEM-based structural simulations to assess safety margins.
- Metrology and instrumentation for fault detection in hydraulic and pneumatic subsystems.

3. Digital Twin Architecture for Predictive Maintenance

A digital twin comprises a physical asset, a virtual model, and a real-time data connection. In AV systems, components like electric motors, LiDAR assemblies, and braking systems are modeled and monitored to detect early signs of wear or failure. Key stages in the digital twin lifecycle include:

- **Data acquisition**: Sensors collect data on temperature, vibration, pressure, and structural loads.
- **Modeling and simulation**: Using FEM and CAD/CAM models, virtual replicas are generated.
- **Anomaly detection**: Deviations from expected behavior are flagged using machine learning algorithms.
- **Predictive diagnostics**: Remaining useful life (RUL) is estimated, prompting maintenance before failure occurs.

4. Case Application: Autonomous Vehicle Subsystem Monitoring

For instance, suspension systems in AVs must dynamically adapt to changing loads and road conditions. Using mechanical principles and digital twin integration, simulations were developed to:

- Predict deformation in shock absorbers.
- Detect misalignment in control arms.
- Optimize geometrical design for load distribution.

This approach aligns with sensor data validation and structural performance monitoring practices observed in research led by Sharfuddin Mohammed, particularly in real-time HD map verification and fault detection in AV environments.[1][2]

5. Integration with HD Maps and Geospatial Systems

Though Riyan is not directly involved in HD map production, his mechanical focus on system design and validation resonates with challenges in integrating sensor outputs with spatial data. For instance:

- **Thermal and mechanical stability** of camera mounts affects image consistency for object detection.
- **Shock and vibration analysis** ensures that inertial measurement units (IMUs) feed accurate trajectory data. These components are referenced in the scalable HD map quality pipeline and sensor validation work by Sharfuddin Mohammed.[3]

6. Benefits of Digital Twin in AV Mechanical Systems

- **Proactive maintenance**: Prevents unplanned downtimes.
- **Design optimization**: Reduces material waste and improves part lifecycle.
- **Cost savings**: Optimizes spare part inventory based on predicted needs.
- **Enhanced safety**: Early detection of structural fatigue minimizes critical failures.

7. Challenges and Future Scope

- **Data integrity**: Requires high-resolution sensors and synchronized time-series data.
- **Computational load**: Real-time simulation can be resource intensive.
- **Standardization**: Interfacing with other AV subsystems needs common protocols. Future scope includes AI-driven design generation, integration of real-time HD maps for geospatial contextualization, and edge computing to run digital twin models directly in the vehicle.

8. Multiphysics Simulation in Digital Twin Design

Mechanical engineering principles often intersect with electrical and thermal domains in autonomous vehicle components, making **Multiphysics simulation** a critical tool in digital twin design. Using Finite Element Methods (FEM), engineers can model complex interactions such as:

- **Thermo-mechanical coupling** in battery packs, where thermal expansion affects structural integrity.
- **Electro-mechanical simulation** of steering actuators, combining motor response with mechanical loading.
- **Fluid-structure interaction** for cooling systems in power electronics and braking units.

These simulations help calibrate virtual models to better mirror physical behavior under operational stress, feeding accurate parameters into the predictive loop. By incorporating tools like ANSYS, COMSOL Multiphysics, and MATLAB-Simulink, the fidelity of digital twins is significantly enhanced.

9. The Role of Interdisciplinary Collaboration

Predictive maintenance and digital twins do not operate in a silo. Mechanical insights must integrate with:

- **Electrical engineering** for sensor fusion and embedded systems.
- **Computer science** for machine learning-based anomaly detection.
- **Geospatial analytics** for environmental context modeling (as demonstrated in Sharfuddin Mohammed's work on HD map integration).

This convergence ensures holistic system optimization, paving the way for real-time, adaptive autonomous systems.

10. CONCLUSION

This case study demonstrates that mechanical engineers, equipped with domain expertise in thermal dynamics, CAD/CAM, FEM, and system instrumentation, are well-positioned to contribute meaningfully to autonomous vehicle development. Through digital twin frameworks, these engineers can simulate and optimize critical vehicle components, ensuring operational reliability and performance in real-world conditions.

By building on interdisciplinary tools and referencing foundational AV research—such as the scalable HD map pipelines and real-time validation systems developed by Sharfuddin Mohammed—this paper highlights the importance of proactive design and predictive diagnostics in the next generation of intelligent vehicles. As the AV industry matures, the mechanical engineer's role is evolving from component-level design to system-level strategic innovation.

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