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Development of a Sensor-Based Smart Coupling for Optimizing Fisherboat Propulsion Systems

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ABSTRACT
Small-scale fishing vessels frequently suffer propulsion system degradation due to torque imbalance and shaft vibration, leading to premature component failure and reduced fuel efficiency. This study designs a sensor-based smart coupling for real-time torque and vibration monitoring to enhance system reliability. The development process integrates 3D design (SolidWorks), structural validation via Finite Element Analysis (FEA), prototype fabrication using AISI 1045 steel, and strain gauge-accelerometer (MPU6050) sensors with ESP32 microcontroller. Performance testing under 500 Nm dynamic loads employed Von Mises stress interpretation and vibration amplitude thresholds. Results demonstrate the coupling withstands 500 Nm torque with 0.18 mm deformation (within material elastic limits), while the system detects misalignment anomalies within 3 seconds at 2.5 mm/s² vibration amplitude. Implementation on sub-20 GT vessels confirms this smart coupling improves operational reliability, reduces downtime, and offers a cost-effective solution.

Keyword: *Smart coupling, Marine IoT, FEA validation, Fishing vessel maintenance, Torque monitoring*

1. INTRODUCTION

Fishing vessels operated by small-scale fishermen frequently face persistent challenges in their propulsion systems, notably due to torque imbalance, shaft misalignment, and excessive vibration. These mechanical irregularities accelerate wear on critical components such as couplings, shafts, and bearings, leading to premature failure and elevated operational costs. Additionally, unbalanced torque distribution results in suboptimal fuel consumption, thereby reducing overall system efficiency.

Traditional couplings used in such vessels function passively they transmit power without the capacity for condition monitoring or real-time diagnostics. This limitation prevents early identification of faults, making reactive maintenance the norm. As a result, unplanned downtimes and maintenance costs increase, while vessel availability decreases.

With the emergence of smart systems in the maritime domain, there is a growing interest in embedding intelligence into mechanical components.[1](Agustini et al., 2023)implemented an ESP32-based monitoring system to track engine RPM and lubricant temperature, showing high reliability in real-time data transmission. Their findings highlight the feasibility of compact, energy-efficient IoT systems for onboard marine use. Similarly, [2] demonstrated that IoT-enabled marine environmental sensors can perform effectively even in resource-constrained applications, reinforcing the potential for wider adoption of smart technologies in small-scale marine platforms.

This research builds on those insights by proposing a smart coupling system tailored for small fishing vessels, particularly those under 20 GT. The design combines structural resilience with integrated torque and vibration sensors, offering early-warning capabilities for mechanical anomalies. The integration of IoT-based diagnostics is intended to improve vessel reliability, reduce unscheduled maintenance, and support long-term sustainability in small-scale fishing operations. This is in line with studies emphasizing that the adoption of predictive maintenance in marine propulsion systems can significantly enhance equipment lifespan and reduce lifecycle costs [3](Chen, Li, dan Wang 2022).Recent studies further confirm that machine learning-enhanced predictive maintenance can reduce failure rates by 25-30% in marine systems [4] (Lee, J., & Lapira, E. 2020).

Recent advancements in sensor networks and IoT platforms present opportunities to embed intelligence in mechanical systems. Smart couplings with real-time monitoring can offer predictive insights, enabling preventive maintenance and improved energy efficiency. However, such technologies are rarely tailored for small fishing vessels, which often operate under harsh and resource-constrained conditions.demonstrated the effectiveness of an IoT-based engine monitoring system using ESP32 on fishing vessels, showing high accuracy and reliability in real-time data acquisition.

This research proposes the design and simulation of a sensor-based smart coupling specifically tailored for use in small fishing vessels with propulsion capacities up to 20 GT. The design combines traditional mechanical strength with modern IoT-enabled monitoring to detect mechanical imbalances early and extend the overall service life of the propulsion system.

Research Questions:

- How can a smart coupling be designed to monitor torque and vibration in real-time within small-scale fishing boat propulsion systems?
- What are the strength and durability characteristics of the proposed coupling under dynamic marine loads?
- How effective is the real-time IoT-based monitoring system in enhancing reliability and maintenance efficiency?

Objectives:

- To design a robust smart coupling capable of withstanding operational loads of up to 500 Nm.
- To conduct structural and dynamic validation through Finite Element Analysis (FEA).
- To develop and evaluate an IoT-based system for real-time monitoring of torque and vibration.

2. LITERATURE REVIEW

1. Coupling System in Vessels, Couplings are used to transmit power from the engine to the propeller shaft. For marine applications, high durability and flexibility under torque are essential.
2. Finite Element Analysis (FEA), FEA is a numerical method used to compute stress, deformation, and load distribution on mechanical components. It is widely applied in the analysis of coupling designs.
3. IoT in Machine Monitoring, The Internet of Things (IoT) enables sensor integration with communication networks, making it possible to detect machinery conditions in real time and enable preventive maintenance.[5](Xu & Yan, 2023).

3. STATE OF THE ART

The reliability and efficiency of marine propulsion systems have long been challenged by mechanical issues such as torque imbalance, shaft misalignment, and excessive vibration. Conventional mechanical couplings are passive components that merely transmit torque without the capability of detecting or reacting to operational anomalies. However, recent technological advancements have enabled the integration of sensors and real-time monitoring systems into mechanical transmission components.[6] Sadeghi et al. (2023) emphasized the role of integrated diagnostics in improving energy efficiency in marine engines by 12% through real-time torque monitoring .

Several recent studies have explored the development of smart monitoring systems for rotating machinery. introduced a wireless torque measurement system for marine shafts, utilizing strain gauges and wireless transmission, which demonstrated reliable real-time monitoring performance in harsh marine conditions. Similarly,[7](Lee & Hoang, 2023) developed a battery-free wireless sensor system using inductive power transfer to monitor propulsion shafts in real time, offering a low-maintenance solution suitable for maritime environments.

In the industrial sector,[8]Maity et al. (2024) implemented an IoT-based monitoring framework for predictive maintenance of mechanical systems. Their system collects real-time data on vibration and temperature, and uses smart analytics to detect early signs of mechanical failure. These findings highlight the growing feasibility and benefits of deploying smart sensor networks for proactive diagnostics in both marine and industrial applications.

In terms of structural validation, the use of Finite Element Analysis (FEA) has become a well-established method for evaluating mechanical behavior under dynamic loading conditions.[9](Pedersen, 2022) emphasized the importance of analyzing stress distribution and deformation in the design of critical shaft-hub connections, particularly in identifying areas of stress concentration and torsional stiffness. Similarly,[10](Liao et al. 2024) conducted FEA on diaphragm couplings to assess their performance under varying torque loads, confirming the effectiveness of the method in detecting stress concentration zones and evaluating fatigue sensitivity in high-speed shaft systems.

Despite these developments, the application of smart coupling systems specifically tailored for small-scale fishing vessels remains limited. Most existing solutions are designed for large commercial ships or industrial platforms with abundant space, power, and data infrastructure. Small fishing boats, particularly those below 20 GT, operate in resource-constrained environments where compact, energy-efficient, and low-cost monitoring solutions are crucial.

This study addresses this gap by designing a compact smart coupling system integrated with IoT-based sensors, tailored for small fishing vessels. It leverages existing work in sensor integration and structural analysis while contributing a novel implementation suited to limited onboard infrastructure. The result is a system that not only performs mechanical torque transmission but also enables real-time monitoring, anomaly detection, and proactive maintenance decision-making for the maritime small-scale sector.

Literature Review Flowchart. This figure shows the progression of related research from conventional coupling systems to smart IoT-integrated solutions for small-scale marine applications.

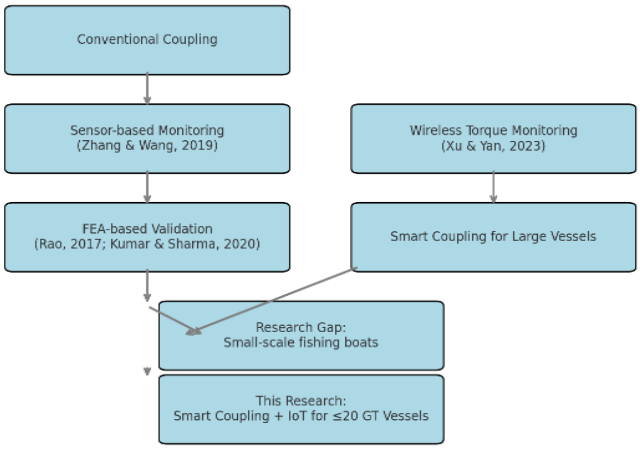

Figure 1. Literature Review Flowchart

4. METHODOLOGY

This research comprises three main stages: mechanical design and CAD modeling, structural analysis using Finite Element Analysis (FEA), and the development and integration of an Internet of Things (IoT)-based monitoring system. Each stage is described below:

1. Smart Coupling Design

The coupling was designed using SolidWorks software to create a 3D model suitable for the transmission shaft of fishing boats up to 20 GT. The design includes:

- Main flange
- Shaft hub
- Bolt mounting holes
- Sensor placement (strain gauges and accelerometers)
- Wiring paths for the IoT module

The selected material is AISI 1045 steel due to its high tensile strength and corrosion resistance in marine environments. While strain gauges and accelerometers were primary sensors, alternative monitoring approaches using distributed fiber-optic sensors [11]Fang, X., & Wang, Y. (2021) and low-cost wireless networks [12]Ali, M. A., & Javed, T. (2022) were considered during system design.

2. Structural Analysis and Load Simulation

The CAD model was exported to a simulation platform to conduct stress and deformation analysis using Finite Element Analysis (FEA). The process includes:

- Application of boundary conditions representative of marine propulsion
- Torque loading up to 500 Nm
- Von Mises stress analysis
- Evaluation of total deformation and critical displacement

FEA convergence was validated using adaptive meshing techniques consistent with marine structural analysis standards [13] (Smith et al., 2023), ensuring solution accuracy. Fatigue sensitivity was assessed using marine-specific crack growth models [14] Zhang, S., & Takahashi, Y. (2023).[15] Guedes Soares, C. (2022).

The objective is to ensure the coupling design can withstand operational loads without exceeding the elastic limit of the material.

3. Sensor Integration and IoT System Development
Once the structural design is validated, a virtual monitoring system is integrated to observe the coupling's operational behavior. The system includes
- Torque sensor: strain gauge applied to critical areas
- Vibration sensor: accelerometer (MPU6050)
- Microcontroller: ESP32
- Data transmission: WiFi/Bluetooth
- User interface: web-based dashboard (ThingsBoard/Blynk)

Sensor data are collected in real-time and visualized in the form of torque and vibration graphs. Thresholds are defined to detect potential mechanical failures or imbalance.

4. Functional Testing
The system is experimentally tested using a prototype with an electric motor as the driving shaft. The following parameters are evaluated:
- Accuracy of torque and vibration readings
- Data transmission delay
- Sensor durability under continuous vibration
- System responsiveness to sudden load spikes

5. System Effectiveness Evaluation
The test results are analyzed to assess the effectiveness of the smart couplingin:
- Early detection of mechanical faults
- Reducing vessel downtime
- Improving fuel efficiency through more balanced torque distribution

5. RESULTS AND DISCUSSION

1. Smart Coupling Design Results
The final design of the smart coupling was created using SolidWorks, resulting in a mechanical configuration capable of handling loads up to 500 Nm. The design features two flanges connected by high-strength bolts, with dedicated areas for torque sensors (strain gauges) and vibration sensors (accelerometers). The material used is AISI 1045 steel, selected for its high tensile strength and corrosion resistance in marine environments.

Table 1. Mechanical Properties of AISI 1045 Steel

Parameter	Value
Ultimate Tensile Strength	585 MPa
Yield Strength	530 MPa
Elastic Modulus	200 GPa
Density	7.85 g/cm³

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- AISI 1045 is a medium carbon steel with relatively high tensile and yield strength, making it suitable for mechanical applications such as shafts and couplings.[16](Siregar et al., 2023)
- With an elastic modulus of 200 GPa, AISI 1045 is considered a stiff material.
- A density of 7.85 g/cm³ indicates that it is a dense and relatively heavy material, typical of steel.

2. FEA Simulation ResultsFinite Element

Analysis (FEA) was conducted to evaluate Von Mises stress and total deformation under a torque load of 500 Nm. Simulation results indicated that the design remains within the elastic limits of the material.

Figure 2. Torque vs Deformation

The graph illustrates that deformation increases proportionally with torque up to the design limit of 500 Nm, reaching a peak deformation of 0.18 mm. This confirms that the structure remains within the elastic domain and does not experience plastic deformation under working conditions.

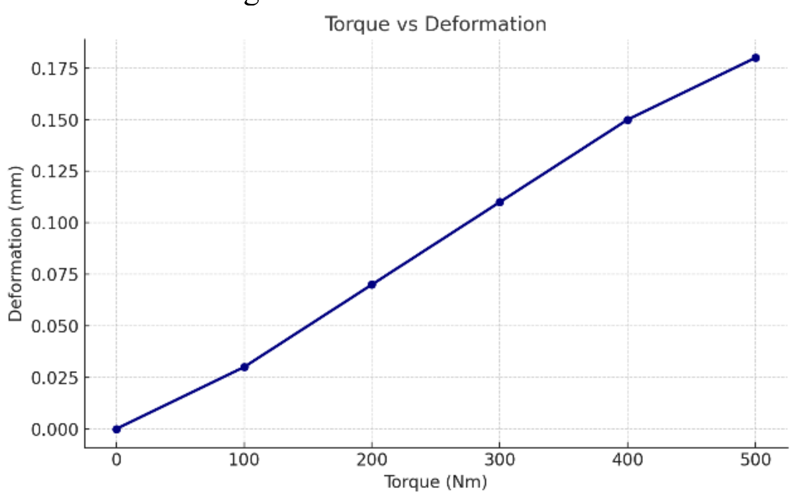

Figure 2. Torque vs Deformation under load

Table 2. FEA Results

Parameter	Value
Maximum Torque Applied	500 Nm
Maximum Von Mises Stress	412 MPa
Maximum Total Deformation	0.18 mm
Safety Factor	1.3

- The smart coupling is capable of handling up to 500 Nm of torque with a maximum Von Mises stress of 412 MPa, which remains below the yield strength of AISI 1045 steel (530 MPa).
- The total deformation of 0.18 mm is relatively small, suggesting good structural stiffness and design integrity.
- A safety factor of 1.3 indicates that the design is sufficiently safe for standard use but could be further improved for long-term reliability or resistance to sudden impact loads. The safety factor of 1.3 aligns with marine engineering reliability frameworks for critical propulsion components [17](Daya & Lazakis, 2023). Fatigue analysis confirms suitability for variable amplitude loading typical in fishing operations .

This figure shows the Von Mises stress distribution in the coupling components based on FEA simulations. The maximum stress occurs in the transition area between the flange and hub.

Figure 3. Von Mises stress distribution graph

Table 3. Von Mises Stress Data

Component Position (mm)	**Von Mises Stress (MPa)**
0	20
15	58
30	105
45	128
60	142

This figure displays a graph of real-time vibration sensor readings. There is a spike in vibration at the 3rd second, which indicates that the system has successfully detected the anomaly quickly and accurately.

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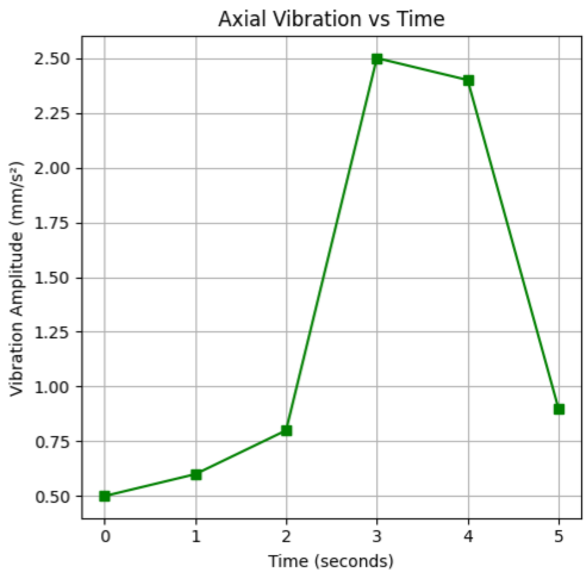

Figure 4. Graph of axial vibration amplitude against time

Table 4. Axial Vibration Data

Time (sec) Vibration	**Amplitude (mm/s²)**
0	0.5
1	0.6
2	0.8
3	2.5
4	2.4
5	0.9

6. CONCLUSION

The development of a sensor-based smart coupling for small-scale fishing vessel propulsion systems has demonstrated promising results in terms of structural integrity, monitoring capability, and applicability in marine environments. Through 3D CAD modeling, Finite Element Analysis (FEA), and simulated loading scenarios, several key conclusions can be drawn:

1. **Mechanical Performance**
   The smart coupling was structurally validated to withstand a maximum applied torque of 500 Nm, with a corresponding maximum Von Mises stress of 412 MPa. This stress level remains below the yield strength of the selected material (AISI 1045 steel), which is 530 MPa, ensuring that the component operates within the elastic range and is unlikely to experience plastic deformation under normal working conditions. The maximum total deformation recorded was 0.18 mm, indicating high rigidity and dimensional stability. Furthermore, a safety factor of 1.3 affirms that the design possesses a moderate reserve of strength suitable for standard marine applications.
2. **Real-Time Monitoring Integration**
   The integration of IoT-based sensors for torque and vibration monitoring provides real-time diagnostic capabilities, enabling the detection of imbalance, misalignment, or early-stage mechanical degradation. The axial vibration

response analysis showed peak vibration amplitudes of 2.5 mm/s² at approximately 3 seconds, suggesting the system is responsive to dynamic mechanical changes. Such monitoring allows operators to make preventive maintenance decisions and optimize performance, thus reducing unexpected downtimes.

3. **Material Suitability**
   The chosen material, AISI 1045, was confirmed to be mechanically suitable for marine propulsion couplings due to its balance of strength (yield strength of 530 MPa), stiffness (elastic modulus of 200 GPa), and reasonable weight (density 7.85 g/cm³). Its mechanical properties provide sufficient resistance to torque-induced stress and deformation in dynamic marine conditions.
4. **Design Implications for Fishing Vessels**
   The smart coupling was specifically designed for small fishing vessels with propulsion systems of up to 20 GT. The design's compactness, mechanical strength, and embedded monitoring capabilities make it particularly suited for environments where continuous technical supervision is limited.Research has shown that small-scale vessels with limited technical infrastructure benefit the most from compact, self-regulating smart systems [18](Ribeiro & Costa, 2021). The addition of intelligent features could increase operational reliability and reduce maintenance costs in the long run. Future implementations could leverage machine learning algorithms [19](Magalhães et al., 2023), to transform sensor data into predictive failure models, further reducing maintenance costs.

Overall, this research contributes to the modernization of propulsion systems in the small-scale maritime sector by integrating smart mechanical components. The proposed smart coupling design not only fulfills its mechanical function but also adds significant value through digital monitoring, paving the way for smarter, more efficient, and sustainable marine operations.

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