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Conceptual Design of Inspection Robot Automatic Multimodal Sensor Based for Detection Oil and Gas Pipeline Damage

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Abstract— Oil and gas pipeline inspection need system accurate, adaptive, and secure detection for identify damage without stop flow fluid. Limitations single sensor approach in coverage and sensitivity detection has push development robot inspection system multimodal sensor- based research This designing architecture conceptual inspection robot automatic with integrate visual camera, ultrasonic, thermography infrared, and acoustic sensors in configuration crawler- equipped modular level data fusion feature for produce more detection comprehensive. Design results show that superiority performance system sourced from integration between subsystems, not just the number of sensors used. Multimodal integration is proven increase diagnostic accuracy through characteristics of interconnected sensors complement, although demand efficiency processing, temporal synchronization, and fault-tolerance in order to support performance real-time. This design give runway strategic for development prototype and implementation in industry oil and gas as solution inspection non-shutdown as well as supporters maintenance predictive with level greater safety and reliability tall.

Keywords— Oil and Gas Pipeline Inspection; Inspection Robot; Multimodal Sensor; Nondestructive; Data Fusion

I. Introduction

Infrastructure in industry oil and gas is vital components that ensure continuity of the transportation process fluid in a way safe and efficient, so that disturbance as small as anything against his integrity can impact directly on stability chain supply and sustainability production energy. Various incident like corrosion, cracks and leaks that occur in pipes indicate that damage structural No only potential hinder performance distribution, but can also trigger consequence economy, safety and environment in wide scale, including risk explosion, damage assets, pollution ecosystem, and termination operation in a way No planned. In the context of said, routine inspections are positioned as an integral part of system management asset for detect anomaly since early before develop become failure critical. However , the method inspection conventional Not yet capable answer need operational industry modern oil and gas because Still face challenge in the form of access difficult location, risk safety for workers, as well as limitations in detect damage small in a way consistent, especially in the closed area, it is below land, under pressure high, or own geometry complex (Korlapati et al., 2022; Ma et al., 2025).

One of evolving approach rapidly For overcome limitations inspection conventional is implementation of pipe inspection robots, which allows monitoring condition structure from part in without must stop operation main, so that activity inspection can done in a way sustainable without disrupt the distribution process fluid technology *in-line inspection* robot -based has implemented in a way extensive and proven effective in increase safety work , efficiency inspection , and accuracy detection because robots are capable reach difficult areas accessible man as well as minimize exposure worker to environment dangerous (Xu et al., 2025). Although thus, some big conventional robot systems Still relies on a single sensor, so performance detection limited to the type damage certain and less responsive to change condition field (Abubakar et al., 2025).

Multimodal sensor integration becomes opportunity strategic for increase effectiveness pipe inspection because approach This allows collection information from various mechanism sensing in a way simultaneously, so that condition structure can mapped in a way more comprehensive. Merger visual camera, *guided-wave* sensor ultrasonic, thermography infrared, as well as vibration sensors or acoustic give superiority diagnostic because each sensor has sensitivity to type different damages, starting from from disabled surface until internal damage and leaks micro. The multimodal approach does not only expand range inspection and improvement ability system in detect variation form damage, but also in a significant reduce risk occurrence *false negative* through utilization technique increasing data fusion ripe (Sui, 2025). In line with that, the studies latest confirm that system multisensor more reliable compared to single sensor approach, because capable produce representation more structural accurate and stable under conditions operation diverse fields, so that give base strong scientific for multimodal integration as direction development future industrial pipe inspections.

Ultrasonic guided-wave sensor is one of the the most effective method For detect corrosion and reduction material thickness of distance far, even in condition operation extreme (Lyu et al., 2024). On the other hand, thermography infrared

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Thermography infrared effective in identify anomaly thermal consequence leakage fluid, while the acoustic sensor or vibration play role important in catch pattern voice micro as indicator leakage early (Saleem et al., 2025). Although each technology own superiority specific, integration everything in one robotic platform Still seldom handled in study previously (Mahmoud & Hasan, 2025). Previous studies generally still focus on aspects partial, such as robot mechanism without integration multisensory, or study based one sensor without consider integration system mechanics and robot navigation (Kenzhekhan et al., 2023). Not many research that describes design conceptual in a way comprehensive that combines design mechanics, multimodal sensor configuration, architecture electronics and communications, as well as channel deep data fusion one model of inspection robot automatic.

Based on need said, research this aim designing architecture conceptual inspection robot automatic multimodal sensor-based for support detection oil and gas pipeline damage in a way more comprehensive. New study this lies in the arrangement *blueprint* robot design that integrates ultrasonic guided-wave sensors, thermography infrared, visual cameras, and acoustic/vibration sensors on modular robotic platforms, as well as on the formulation channel data fusion according to characteristics oil and gas pipeline operations. Design This expected become base for development inspection robot prototype generation next more safe, adaptive, and effective in do monitoring pipe conditions in real time.

II. Method Research

Study this use conceptual engineering design approach to designing an inspection robot model automatic multimodal sensor -based as solution detection damage to oil and gas pipelines. This method chosen Because study Still is in phase development draft before manufacturing prototype and testing experimental. Modeled robot designed integrate a number of types of sensors such as camera resolution high, ultrasonic, gas, and acoustic for detect damage in real-time and non- invasively, in sync with findings that robotic platform multisensor capable increase reliability monitoring pipe conditions (Daniyan et al., 2021).

The research process involved four main stages. First, a system requirements analysis was conducted, covering the environmental characteristics of oil and gas pipelines, common types of damage, and inspection parameters required to improve detection accuracy. This stage also included determining technical requirements for mobility, environmental resilience, sensor resolution, and the form of interaction between subsystems.

Second, a technology selection analysis was conducted to determine candidate actuators, mechanical configurations, and nondestructive sensor types. This stage assessed the suitability of visual cameras, guided-wave ultrasonics, infrared thermography, and acoustic/vibration sensors to the internal and external damage profiles of the pipe. Third, the system design and architecture were formulated, including the mechanical-actuation structure, multimodal sensor integration, electronic and communication systems, and software for sensor signal processing and lightweight deep learning-based classification. The result of this stage was a comprehensive design that illustrates the relationships between robot modules.

Fourth, conceptual validation based on literature and operational scenarios was conducted, namely a rational evaluation of the design feasibility by comparing the design with the results of recent research and conducting thought-experimental scenarios. Four evaluation scenarios were used to assess the completeness of the design: surface corrosion, internal defects, microleakage, and acoustic disturbance. This method allows the research output to be a comprehensive system design, complete with technical specifications, sensor processing flow, advantages and limitations, and plans for the next development phase.

III. Result And Discussion

The automated inspection robot design in this study is built from four core subsystems: mechanical actuation, multimodal sensors, electronic and communication systems, and signal processing software for *lightweight deep learning- based classification*. A modular approach is used to ensure flexibility for technological upgrades and long-term compatibility with industrial applications. This modularity pattern aligns with global trends in pipe inspection robot design that emphasize adaptability to variations in pipe diameters and operational conditions in industrial environments (Lyu et al., 2024).

From a mechanical perspective, *a modular crawler design* equipped with adaptive wheels and elastomeric suspension was formulated to enable the robot to navigate pipes of varying diameters while simultaneously reducing vibration. Vibration reduction is necessary to maintain the stability of ultrasonic and acoustic signals, which are highly sensitive to mechanical disturbances. This stability aligns with research findings that indicate that nondestructive data quality is significantly influenced by the robot's motion characteristics (Kale et al., 2023). The inspection needs mapping results established the integration of four primary sensors: a visual camera, guided-wave ultrasonic, infrared thermography, and an acoustic/vibration sensor. This combination aims to detect surface damage, internal defects, material thinning, and micro-leaks due to thermal changes and sound patterns. This multimodal configuration aligns with international research findings that suggest a single sensor is incapable of comprehensively assessing pipe structural damage (Li et al., 2025).

In the data processing flow, the research design produces a *feature-level fusion scheme*, which combines features from heterogeneous sensors before classification. This approach was chosen because it provides a balance between accuracy and computational efficiency, so it can be run *on-board* without requiring industrial GPU capacity. This model has been validated by a recent study that confirmed the superiority *of feature fusion* over *decision fusion* for automated pipe inspection applications (Ma et al., 2025). Conceptual evaluation was also conducted through four scenarios: surface corrosion, internal defects, micro-leakage, and acoustic interference. Each sensor proved dominant under certain conditions, for example, visual cameras for open corrosion, guided-wave for internal defects, IR and acoustic for micro-leakage, so the effectiveness of the multimodal system is logically better than the single-sensor approach (Xu et al., 2025).

The design results show that the multimodal sensor-based automatic inspection robot is built from four core subsystems mechanical, sensor, electronics & communication, and *feature-level fusion- based signal processing which are designed to improve the accuracy of oil and gas pipeline* damage detection. clarify contribution each sub systems and relationships between component design, core research findings summarized in the table following.

TABLE 1. SUMMARY OF CONCEPTUAL DESIGN RESULTS OF MULTIMODAL SENSOR-BASED AUTOMATIC INSPECTION ROBOT

No	Component Focus	Key Findings	Implications Practical
1	Architecture System	Four sub system technical integrated	Convenience upgrades and modularity
2	Mechanics & Navigation	Crawler-modular, adaptive wheels, and suspension	Stable navigation → more accurate sensor data
3	Multimodal Sensor	Visual, ultrasonic, IR, acoustic-vibration	Wide detection coverage & low *false negative*
4	Data Processing & Fusion	*Feature-level fusion* and classification light	Efficient For *on-board inference*
5	Evaluation Scenario	4 scenarios inspection conceptual	System adaptive to various damage
6	Performance Prediction	Accuracy increased, load computing increase	Need compression features & sensor synchronization
7	Aspect Operational	Inspection without *shutdown*	Efficient & safe but needs *fault-tolerance*
8	Plan Advanced	Stage conceptual to be continued to prototype	Prototype development, dataset & field testing

Table 1 shows that the design advantage lies not only in the presence of multiple sensors, but also in the level of integration between subsystems that ensures mechanical stability, nondestructive signal acquisition accuracy, and processing efficiency within a single inspection robot platform. Mechanical stability is crucial because excessive vibration can degrade the sensitivity of ultrasonic and acoustic sensor readings during the robot's movement within the pipeline, thus significantly impacting the quality of detection by navigation stability. Multimodal integration contributes to increased accuracy because each sensor complements the other in detecting various types of damage. However, this increased accuracy comes at the cost of greater computational and synchronization demands, making processing efficiency strategies a prerequisite for the system's *real-time functionality* on the robot. Based on this interpretation, the discussion focuses on two main dimensions: (1) the technical advantages of multimodal designs compared to single-sensor-based approaches, and (2) the challenges of implementing inspection robots in the oil and gas industry, which demands multisensor synchronization, data management, and *fault tolerance* to ensure safety and reliability.

Multimodal integration in sensor systems offers significant technical advantages because it combines the strengths of each sensor, resulting in more comprehensive and accurate data. Visual cameras excel at detecting surface damage, ultrasonic sensors effectively analyze internal defects, infrared thermography detects thermal anomalies, and acoustic sensors are sensitive to micro-leaks. This combination reduces the risk of *false negatives* and increases diagnostic reliability, in line with the trend of utilizing artificial intelligence (AI) to support multimodal sensor fusion in data processing and automated decision-making, making systems more intelligent and adaptive (Wang et al., 2025).

Furthermore, multimodal integration enables more *robust anomaly detection* by combining cross-domain information, such as time and frequency domains, that cannot be achieved by a single sensor (Chen et al., 2025). In robotics and inspection applications, multimodal fusion has been shown to improve pattern recognition accuracy and system resilience to environmental disturbances, as well as resulting in more precise damage mapping and tracking (Zeng et al., 2025). Thus, multimodal integration is not simply about increasing the number of sensor types, but placing each sensor as part of a complementary diagnostic system.

On the other hand, research this also found challenge necessary implementation considered at the stage development prototype. Challenge main covers temporal synchronization between operating sensors with acquisition frequency and interval different; improvement burden computing Because large number of sensors; and need data compression and efficiency processing for guard consumption energy still low. Resilience operational (*fault-tolerance*) also becomes crucial remember closed pipe environment potential cause disturbance navigation and obstacles communication. Challenges the reinforced by the findings study about constraint implementation of inspection robots in infrastructure industry critical (Gjerde, 2024; Silveira et al., 2024).

Study This confirm that transition from single sensor system to multimodal architecture that integrates subsystem mechanical, electrical, and devices soft is step strategic for developing inspection robots generation next. Fusion process optimization features and data management become key to increasing burden computing still allows *real-time inference* within the robot (Lu et al., 2023). The need to develop multimodal datasets that reflect variations in real-world operational conditions such as pipe diameter, fluid pressure, and temperature is also an important factor in training adaptive damage classification models (Dai et al., 2025).

From the perspective industry, direction development technology tend towards the inspection robot *non-shutdown* that allows monitoring pipe condition without need stop flow fluid, so that support continuity production and safety operational. Implementation This requires integration with system management digital assets and mechanisms maintenance predictive (Wei & Rey, 2024). Success adoption depends on synergy between academics, practitioners, and industry for speed up innovation and strengthening efficiency operations in the sector oil and gas. Therefore that, research This give runway scientific at a time strategic in development of more multimodal inspection robots sophisticated, reliable, and applicable in the field (Halder & Afsari, 2023).

IV. CONCLUSION

Study This designing design A conceptual multimodal sensor-based automated inspection robot for comprehensive oil and gas pipeline damage detection. The analysis shows that the design's superiority lies not in the number of sensors, but rather in the integration between subsystems that ensures mechanical stability, accurate nondestructive signal acquisition, and efficient data processing in a single platform. The integration of visual cameras, ultrasonic, thermographic, and acoustic sensors provides complementary diagnostic capabilities that can reduce the risk of false negatives and increase the reliability of damage identification.

In addition to these technical advantages, this research also identifies implementation challenges such as multisensor synchronization, computational load, fault-tolerance requirements, and communication stability in a closed pipeline environment. Therefore, innovation in sensor architecture must be accompanied by processing efficiency and operational reliability strategies. This research contributes as an initial blueprint for prototype development, field testing, and expansion of multimodal datasets to facilitate predictive maintenance and non-shutdown inspections in the oil and gas industry. Future system development will focus on testing robot performance under real-world operational conditions, optimizing AI-based feature fusion, and integrating with industrial digital asset management systems.

Overall, the findings of this study indicate that the success of an inspection robot design is not solely determined by the performance of each individual sensor, but by the system's ability to orchestrate all subsystems in an integrated manner so that accuracy, mechanical stability, and processing efficiency can be achieved simultaneously. In other words, multimodal integration is not simply about adding more sensors, but rather a journey towards a more intelligent, comprehensive, and resilient diagnostic approach to oil and gas pipeline operational variability. This implication emphasizes that improving inspection effectiveness is no longer centered on individual sensor innovation, but rather on the alignment of mechanical, electrical, software design, and data fusion strategies within a single system architecture. In addition to providing guidance for prototype development, this study also broadens the research horizon towards the establishment of an inspection ecosystem based on automation and predictive analytics, which in the future will play a crucial role in improving process safety, maintenance efficiency, and the resilience of oil and gas infrastructure to the risk of structural failure.

REFERENCES

[1] A. Abubakar, O. A. Abisoye, I. O. Alabi, A. Solomon, and I. O. Oyefolahan, “Systematic literature review and bibliometric analysis of pipeline monitoring and leakage detection techniques,” *Discover Mechanical Engineering*, vol. 4, no. 1, p. 17, 2025, doi: 10.1007/s44245-025-00102-w.

[2] L. Chen, X. Zhou, P. Zhou, X. Sun, and S. Zheng, “Anomaly detection method for power system information based on multimodal data,” *PeerJ Computer Science*, vol. 11, 2025, doi: 10.7717/peerj-cs.2976.

[3] R. Dai, R. Wang, C. Shu, J. Li, and Z. Wei, “Crack detection in civil infrastructure using autonomous robotic systems: A synergistic review of platforms, cognition, and autonomous action,” *Sensors*, vol. 25, 2025, doi: 10.3390/s25154631.

[4] I. Daniyan, V. Balogun, B. Oladapo, O. K. Ererughurie, and O. Daniyan, “Development of an inline pipe inspection robot for the oil and gas industry,” *International Journal of Automation and Smart Technology*, 2021, doi: 10.5875/ausmtv12i1.2251.

[5] K. Gjerde, “Scaling autonomous inspection robots for industrial facilities: Challenges and opportunities,” in *Proc. Society of Petroleum Engineers ADIPEC 2024*, 2024, doi: 10.2118/222004-MS.

[6] S. Halder and K. Afsari, “Robots in inspection and monitoring of buildings and infrastructure: A systematic review,” *Applied Sciences*, 2023, doi: 10.3390/app13042304.

[7] N. Kale, N. Joshi, S. Karanje, and H. Sarode, “Design and development of pipe inspection robot,” *International Journal of Advanced Research in Science, Communication and Technology*, vol. 3, no. 7, pp. 362–370, 2023, doi: 10.48175/IJARSCT-10231.

[8] A. Kenzhekhan *et al.*, “Design and development of an in-pipe mobile robot for pipeline inspection with AI defect detection system,” in *Proc. Int. Conf. Control, Automation and Systems (ICCAS)*, 2023, pp. 579–584, doi: 10.23919/ICCAS59377.2023.10316817.

[9] N. V. S. Korlapati, F. Khan, Q. Noor, S. Mirza, and S. Vaddiraju, “Review and analysis of pipeline leak detection methods,” *Journal of Pipeline Science and Engineering*, vol. 2, no. 4, p. 100074, 2022, doi: 10.1016/j.jpse.2022.100074.

[10] D. Li *et al.*, “A review of technical advances and applications of intelligent inspection robots in structural health monitoring,” *SmartBot*, vol. 1, no. 3, pp. 1–30, 2025, doi: 10.1002/smb2.70000.

[11] S. Lu, H. Sun, and T. Feng, “Review of intelligent sensing technology research for power inspection robots,” in *IET Conference Proceedings*, vol. 2023, no. 15, pp. 1185–1191, 2023, doi: 10.1049/icp.2023.2460.

[12] F. Lyu, X. Zhou, Z. Ding, X. Qiao, and D. Song, “Application research of ultrasonic-guided wave technology in pipeline corrosion defect detection: A review,” *Coatings*, vol. 14, no. 3, p. 358, 2024, doi: 10.3390/coatings14030358.

[13] Q. Ma, W. Liang, and P. Zhou, “A review on pipeline in-line inspection technologies,” *Sensors*, vol. 25, no. 15, p. 4873, 2025, doi: 10.3390/s25154873.

[14] A. A. K. L. Mahmoud and R. Hasan, “A comprehensive survey on pipeline monitoring technologies: Advancements, challenges, market opportunities and future directions,” *Journal of Pipeline Science and Engineering*, p. 100353, 2025, doi: 10.1016/j.jpse.2025.100353.

[15] F. Saleem, Z. Ahmad, M. F. Siddique, M. Umar, and J. M. Kim, “Acoustic emission-based pipeline leak detection and size identification using a customized one-dimensional DenseNet,” *Sensors*, vol. 25, no. 4, 2025, doi: 10.3390/s25041112.

[16] F. Silveira, R. M. Gago, R. L. De Moura, and G. M. Freitas, “A framework for selecting and implementing ground mobile inspection robots in industrial applications,” in *Proc. Latin American Robotics Symposium (LARS)*, 2024, pp. 1–6, doi: 10.1109/LARS64411.2024.10786440.

[17] X. Sui, “Structural health monitoring technology: Advances in multi-modal sensing and data fusion,” in *Proc. 2nd Int. Conf. Electrical Engineering and Intelligent Control (EEIC)*, 2025, pp. 924–941, doi: 10.2991/978-94-6463-864-6_80.

[18] H. Wang *et al.*, “Recent progress on artificial intelligence-enhanced multimodal sensors integrated devices and systems,” *Journal of Semiconductors*, vol. 46, 2025, doi: 10.1088/1674-4926/24090041.

[19] X. Wei and W. Rey, “Advancements in substation inspection robots: A review of research and development,” *E3S Web of Conferences*, 2024, doi: 10.1051/e3sconf/202452802017.

[20] C. Xu *et al.*, “A review: Research and application of pipeline robots in the oil and gas industry,” *Journal of Pipeline Science and Engineering*, p. 100356, 2025, doi: 10.1016/j.jpse.2025.100356.

[21] R. Zeng, Z. Zheng, Z. Pan, and L. Yu, “Multimodal sensors fusion SLAM based on local control and multiscale distance analysis,” *IEEE Sensors Journal*, vol. 25, pp. 5361–5369, 2025, doi: 10.1109/JSEN.2024.3515137.