Deployment of UAS for Deep Water Pipeline Inspection

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Abstract- As equipment and technologies advance, it becomes necessary to evaluate the possibility of using tetherless unscrewed underwater vehicles (UUVs) as a replacement for deep-water pipeline inspection. The available methods for deep-water pipeline inspection, such as AUVs, ROVs, NDT, and ILI techniques, are expensive, provide limited access, and present risk to the environment and human life. The advantages of using Autonomous UUVs include their cost-effectiveness, safety, and reduced impact on the environment. The tetherless systems have the advantage of being more efficient and thorough in the assessment of the condition of a pipeline as they incorporate additional capabilities such as sonar, thermal vision, high-definition camera, and Artificial Intelligence Data analysis. Reviews and investigations of the use of UUVs in deep-sea environments and the social and legal issues that are associated with their use become more relevant. The integration of sensors, power sources, and regulatory requirements presents challenges to their adoption. However, the continuous improvement of tetherless subsea systems makes their use possible. This research concludes that UUVs are a feasible, future technology that has the capability of providing an improvement of pipeline integrity inspection and assurance at low operation cost and lower environmental impact than existing methods.

Indexed Terms- Tetherless subsea systems; Uncrewed underwater vehicles (UUVs); Deep-water pipeline inspection; Autonomous inspection; Sonar systems; Pipeline integrity; Subsea infrastructure; Maritime robotics; Non-destructive testing; Offshore operations.

I. INTRODUCTION

Underwater pipelines are a crucial component of the oil and gas sector that transport these commodities across large distances beneath the surface. As the pipelines age, they develop conditions such as corrosion, cracks, wear, and other damage that make it necessary to inspect them to prevent leakage and operational losses. Existing methods are using Autonomous Underwater Vehicle (AUV), Remote Operated Vehicle (ROV), and Non-Destructive Testing (NDT) equipment; but they are expensive, not easily portable, and a nightmare to mobilize because they are usually deployed offshore or deep-sea (Mishra et al., 2023). UUVs have recently been fitted to carry sonar devices, high-definition cameras, and thermal cameras, which enables effective assessment of deep-water pipelines. Tether-free subsea vehicles are more efficient and less costly than the normal method of pipeline inspection. The information gathered will seek to assess the possibility of using UUVs for pipeline inspection in place of conventional methods that are costly and time-consuming.

II. PROBLEM STATEMENT

Deep-water pipeline inspections via AUVs, ROVs, NDTs, and other technologies are costly and time-consuming, and can potentially pose a risk to pipeline integrity. Because of these limitations, uncrewed subsea systems (UUVs) can provide a more cost-effective, accessible, and environmentally friendly solution while maintaining or exceeding current standards for pipeline fault detection.

III. BACKGROUND

- Existing Methods of Deep-Water Pipeline Inspection

As stated by Guo et al. (2024), deep-sea pipelines are essential in the oil and gas industry and transport necessary resources from the seafloor fields to the processing plants. Pipelines undergo many environmental factors that cause their degradation, such as corrosion, leaks and ruptures, and structural deformations (due to seismic activity). Pipeline integrity checks involve general inspections for the structural conditions in areas that might be prone to causing more issues or mishaps in pipeline systems. Identifying various inspection technologies used for underwater pipeline inspection straightforward. Each method is distinguished by its respective advantages and disadvantages. Unmanned Underwater Vehicles (UUVs) are self-propelled but have a limited power supply and operating distance. ROVs offer the benefit of real-time observation, but they need expensive support ships and cables to control them. NDT is a reliable way to identify flaws inside an object but requires a professional approach to application and analysis. ILI systems can inspect the pipeline lengths endoscopically but fail to handle geometry changes and need elaborate modifications to the pipeline (Yang et al., 2020). Awareness of these conventional methods' disadvantages makes it important to look for better and cheaper ways of inspection.

- Autonomous Underwater Vehicles (AUV)

AUVs function autonomously without the presence of people in underwater conditions. As AUVs cruise down pipeline corridors, they gather information with the help of sonar, high-resolution cameras, and other equipment. AUVs efficiently give feedback concerning the condition of the pipelines based on precise corridor surveys (Rumson, 2021). Nonetheless, AUVs are costly to operate and maintain, making them unsuitable for routine large-area surveys. AUVs require a lot of maintenance and are appropriate only within a limited depth since there are battery limitations which reduce their operational range. The fact that AUVs are battery-operated and that there is a need for human intervention to maintain and repair them further restricts AUVs in deep-water, continuous, or large-scale operations (Yang et al., 2020). Some examples of these types of vehicles are presented in Figure 1 (Fun Sang Cepeda et al., 2023).

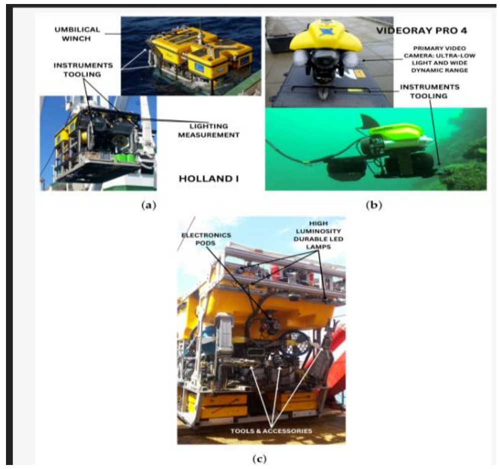

Figure 1
Three models of ROVs for offshore structure inspection: (a) Holland I ROV; (b) VideoRay Pro 4; (c) Work class ROV

- Remotely operated vehicles (ROVs)

ROVs are remotely operated, surface-controlled vehicles that are mounted with cameras, sonar equipment, and robot arms to enable different kinds of inspections (Fun Sang Cepeda et al., 2023). ROVs are widely utilized in inspections of offshore pipelines and are more maneuverable than AUVs. ROVs can carry out both external and internal pipeline inspections with real-time visual feedback and ultrasonic scanning to detect defects. However, ROVs are expensive to operate and require highly advanced support vessels and highly skilled operators. Owing to their tethered characteristics, ROVs are limited to cable length, meaning that only pipelines at moderate distances away are within their operational area. ROV operations are also dangerous to humans, especially where operations are in hostile conditions demanding long-term intervention by humans (Singh et al., 2022).

- Non-Destructive Testing (NDT)

NDT technologies such as ultrasonic, acoustic emission, and magnetic particle tests are widely applied to identify internal pipeline defects in subsea pipelines. Ultrasonic testing, acoustic emission tests, and magnetic particle tests make use of acoustic waves, electric current, or a magnetic field to detect cracks, corrosion, or weaknesses without damaging the structure. NDT is beneficial to the integrity assessment of pipelines since internal defects not visible to the naked eye can be detected (Ma et al., 2021). The applications are time-demanding and call for experts to analyze the data obtained. Environmental conditions restrict NDT efficiency since some areas of the pipeline can be inaccessible. The extensive human involvement in operations increases costs and exposes workers to significant risks, potentially including life-threatening situations or hazardous conditions.

- In-Line Inspection (ILI)

In-Line Inspection, or more popularly 'smart pigging', utilizes self-guided equipment (smart pigs) that travel within pipelines to gather information on internal conditions. The equipment is outfitted with a wide range of sensors, such as magnetic flux leak and ultrasonic, to identify corrosion, cracks, or structural deformities. ILI is advantageous for full length inspection of a pipeline without anyone needing to enter the pipeline. The disadvantage is that ILI systems use sophisticated equipment and high maintenance instrumentation which require costly support infrastructure (Zhu et al., 2024). The smart pig is limited by some pipeline configurations, especially with confined bends or valves. This can leave gaps in data that have the potential to overlook severe pipeline faults.

IV. CHALLENGES OF CURRENT INSPECTION METHODS

Although very effective, standard deep-water pipe inspection methods have several disadvantages that hinder their use. These limitations can be broken down into four general categories: operational expenses, limitations in coverage, safety issues, and environmental effects.

- High Operational Costs

The cost of operating today's pipeline inspection technologies is prohibitively expensive. The deployment of AUVs, ROVs, and smart pigs involves a lot of initial equipment, personnel, and mother vessel investments (Beckman, 2025). In some cases, operations with ROVs or AUVs utilize large surface vessels which are expensive to operate and require trained personnel to operate the systems and analyze the data, adding to operational costs. Continuous inspections, particularly in remote or offshore locations, can be prohibitively expensive, highlighting the need for more cost-effective solutions.

- Limited Inspection Reach

AUVs and ROVs have limited capability to routinely inspect wide pipeline stretches. AUVs are limited by their battery-operated function, which limits the time of inspection and distance. Additionally, ROVs are hindered by umbilical cables which require inspection and become a challenge in deep waters or inaccessible locations (Singh et al., 2022). Both AUVs and ROVs' time-consuming launching, recovering, and surveying processes limit their operational efficiency in conducting continuous, large-area inspections, so inspecting long pipeline systems or more than one pipeline with conventional methods becomes extremely time-consuming.

- Safety Risks

Conventional inspection techniques present a safety risk to humans involved with their operation. Most ROV operations and NDT procedures involve human divers or surface personnel exposed to risks of deep-sea pressure, limited visibility, and marine hazards. Human involvement in ROV control involves extra risk factors (Yang et al., 2020). Operating complex tethers and mechanized inspection equipment increases the risk of accidents, which could lead to personnel injuries or environmental contamination.

- Environmental Impact

Conventional pipeline inspection methods are harmful to marine ecosystems. Support vessels and diving operations disrupt the seafloor and marine life. ROVs and AUVs can be dangerous to marine life by causing noise and physical contact (Shams et al., 2023). The release of chemicals during the servicing of ROVs, AUVs, and smart pigs can pollute the marine environment, underscoring the need for less intrusive inspection methods.

V. STRATEGY/RECOMMENDATION SOLUTION

- Comparison of Tethered Subsea Systems with AUVs and ROVs

Although aerial unmanned systems have been useful for surface surveillance, their use in inspecting deep-water pipelines is inherently restricted by their susceptibility to high pressures in the water. Tetherless subsea systems (UUVs) optimized to operate in undersea conditions are a more suitable technology for this purpose. Nauticus Robotics and VideoRay are two companies that are in the process of developing autonomous deep-sea pipeline inspection tools using advanced UUVs. The comparison below highlights the merits of these tetherless subsea systems over typical AUVs and ROVs (Beckman, 2025).

- Cost-Effectiveness

The use of UUVs is more economical than the use of AUVs and ROVs in deep-sea operations (Singh et al., 2022). Traditional approaches are expensive in terms of the equipment required, the deployment vessels, operating crews, and training. In contrast, UUVs require less preparation, personnel, and maintenance, contributing to lower operational costs. This is because they are self-operated and require less equipment than the scan trail method, especially when several pipelines require assessment. The table below shows comparative costs of the three major types of uncrewed vehicles mentioned (Singh et al., 2022).

System Type	Equipment Cost	Operational Cost	Notes
Autonomous Underwater Vehicles (AUV)	Varies widely, from $5,000 to $100,000+ depending on capabilities	Maintenance, battery replacement, and mission-specific software can add significant costs	Used for mapping, surveillance, and oceanographic research
Remotely Operated Vehicles (ROV)	Can range from $3,000 to $140,000, with high-end models exceeding $500,000	Operational costs depend on tethering, control systems, and maintenance	Commonly used for underwater inspections, search and rescue, and industrial applications
Uncrewed Underwater Vehicles (UUV)	Some models, like the Sea Dart, start at $150,000, while military-grade systems can exceed $1 million	Costs vary based on mission complexity, autonomy level, and payload requirements	Includes military and commercial applications, such as mine detection

Table 1
Comparative costs of the three uncrewed vehicles

- Operational Flexibility

As mentioned earlier, the tetherless subsea systems are more flexible than the conventional AUVs and ROVs. Sophisticated UUVs like the ones developed by Nauticus Robotics can operate autonomously and learn the state of the pipelines in terms of cracks, corrosion, and leakage on the seafloor (Sandifer et al., 2023). In the absence of cable tethers, these systems can inspect inaccessible pipelines in deep seas. Moreover, AI-assisted tetherless UUVs have a longer runtime and are suited to long-term pipeline monitoring and intricate inspection missions where adaptability is paramount.

- Safety

Traditional methods of inspection present an elevated level of risk to diving or ROV personnel. Uncrewed undersea systems eliminate much of this risk by allowing independent, AI-based inspections without divers or ROV personnel in danger areas (Singh et al., 2022). By keeping onsite personnel to a minimum, UUVs eliminate both safety risks and the potential for human error. The autonomous mode of operation addresses the risks of tethered vehicles with their cables exposed to mechanical failure by the connection cables to the surface vessel.

- Environmental Benefits

Uncrewed undersea systems have some environmental benefits over AUVs and ROVs when inspecting pipelines (Rumson, 2021; Singh et al., 2022). No large, fuel-guzzling supporting vessels with associated carbon emissions are needed. The small size and sophisticated self-navigating capability reduce the amount of environmental disruption and habitat intrusion. This is an environmental advantage compared to conventional AUVs or ROVs, where a lot of underwater operations and manned boats that are potentially harmful to marine ecosystems are involved.

VI. TECHNOLOGICAL CONSIDERATIONS FOR UUV DEPLOYMENT

For optimal deep-sea pipeline inspection, unmanned undersea systems should be equipped with onboard technologies that can operate in hostile underwater environments (Mishra et al., 2023). There are several critical technologies necessary for UUV pipeline monitoring.

- Sonar Technologies

Advanced UUVs would include advanced sonar technologies to conduct extensive pipeline inspections. Multibeam Echo Sounders (MBES) and Forward-Looking Sonars (FLS) efficiently detect external and internal pipeline features like corrosion, cracks, or leaks (Zhang et al., 2024). The technologies make it possible to have tetherless subsea equipment to accurately analyze pipeline conditions. Sonar technologies enable UUVs to detect defects that are not visible to the naked eye, and continuous innovations in sonar technologies will make autonomous inspections more powerful.

- Thermal Cameras

Thermal imaging plays a key role in successful tetherless subsea inspection. Thermal cameras identify temperature differences within pipelines, indicating problems of leaks, clogging, and corrosion (Adesina et al., 2019). Thermal technology allows subtle defects to be detected that would be undetectable under other circumstances. In the case of subsea infrastructure, thermal imaging offers a non-invasive technique to inspect structural health without physically inspecting, especially useful when combined with autonomous UUV systems.

- High-Resolution Cameras

High-resolution cameras and optical equipment are necessary to conduct detailed inspections of pipes, collecting precise visual information (Cable-Locators Survey, 2023). HD cameras mounted on UUVs take visually excellent photographs and footage needed for detecting damage, corrosion, or structural faults. Operations personnel use this precise visual data to identify surface deformities or cracks, allowing real-time, evidence-based decision-making. AI-driven advanced UUVs with sophisticated image processing capabilities can detect potential faults by themselves from visual information, a development that surpasses conventional practice.

- Data Processing and Transmission

Bidirectional real-time data transmission aids in achieving effective integration of UUVs. Communication systems that are efficient allow untethered seafloor systems to send continuous inspection data to surface control centers. Improved data transmission technologies enable UUVs to operate effectively at distant sites and send data under harsh conditions (Cable-Locators Survey, 2023). Advanced data-processing systems that are based on artificial intelligence enable quick analysis of the collected data to support swift decision-making and timely pipeline maintenance interventions without permanent human monitoring.

VII. SOCIAL, ENVIRONMENTAL, AND LEGAL CONSIDERATIONS

Implementing uncrewed subsea systems for offshore pipeline inspections requires addressing various social, environmental, and legal considerations.

- Social Implications

Employment in industries involved in diving and ROV operations could be affected by the adoption of autonomous UUVs to inspect pipelines. Though untethered subsea systems decrease the level of personnel needed to conduct inspections, they provide the potential to retrain workers in UUV programming, maintenance, and data interpretation. Public perception of autonomous technology in the marine operating environment can create issues with reliability, ethics, and environmental concerns.

Mitigating the concerns involves proactive public affairs and communications that ensure the public sees the safety and environmental advantages of UUVs.

- Environmental Factors

Even with a less invasive environmental impact compared to traditional methods of inspection, operations of uncrewed subsea systems pose some environmental concerns that demand attention. Special notice should be taken of those species that use sound to navigate and communicate because noise generated by UUV operations will have a negative effect. Another environmental issue with battery management is that incorrect disposal will result in pollution (Waste, 2024). Energy efficiency, reduction of noise levels, and use of biodegradable material will all be vital in reducing the environmental impact of tetherless subsea operations.

- Legal Aspects

Deployment of UUVs in pipeline inspections must meet current maritime law and upcoming regulations concerning autonomous seafaring vessels. Maritime operations are overseen by maritime authorities, yet detailed regulatory frameworks for seafloor operations by autonomous means are still in development within various jurisdictions. Standardized and transparent regulations are necessary to establish the use of tetherless seafloor systems in seafloor environments in the interest of safety, efficiency, and compliance. Furthermore, data collection by UUVs raises privacy and security issues. Data should be protected in transit, storage, and analysis to avoid unauthorized disclosure and possible abuse.

VIII. RECOMMENDATIONS FOR FUTURE RESEARCH

To improve the use of tetherless subsea systems in deep-water pipeline inspection, the following research areas should be investigated. First, high-frequency sonar, better cameras, and high-resolution thermal imaging cameras would enhance the UUV's ability to identify hairline cracks that may be invisible to the naked eye or other regular methods. The existing sonar technology has drawbacks in resolution and sensitivity, especially when detecting microcracks in pipelines that are underwater in murky waters (Sandifer et al., 2023). Investment in multi-frequency acoustic imaging and enhanced signal processing could, therefore, enhance the detection systems. In the same way, the improvement of photogrammetry in the underwater environment and 3D modeling would be useful for structural analysis to monitor progressive degradation of the pipeline integrity.

Second, the development of more powerful and longer-lasting energy sources and AI-driven energy control would enable UUVs to stay at sea for longer periods for deep-sea inspection, where recharging is not feasible. Current battery technologies allow continuous operation for only about 12-24 hours, which is not enough for the survey of large pipeline networks. Some future research opportunities are as follows: lithium-polymer batteries of greater energy density, submersible hydrogen-oxygen fuel cells, and smaller nuclear batteries for long endurance (Yang et al., 2020). In parallel with these power developments, efficient and intelligent energy management systems based on AI could also distribute power according to the mission requirements, environmental conditions, and sensor feedback.

Thirdly, the formulation of comprehensive legal framework specific to UUVs would guarantee safe, legal, and efficient use of UUVs in navigation, protection of the environment, and data protection. Modern maritime laws have been developed for manned ships and are not adapted to many problems facing unmanned underwater vehicles. Cooperation with other nations is required to set up guidelines for the use of UUVs, especially in territorial waters, the economic exclusion zone, and the ecologically sensitive zones (Adesina et al., 2019). This framework must promote technological advancement as well as environmental conservation to overcome new challenges of cybersecurity in remotely operated systems.

Lastly, the incorporation of AI-enhanced UUV data with the currently existing pipeline monitoring system would bring a comprehensive change in the inspection process by providing intelligent real-time analysis, which would enable predictive maintenance and early fault detection before the occurrence of major breakdowns (Guo et al., 2024). When used in advanced machine learning algorithms, it would be possible to predict pipeline deterioration before it leads to failure, thus shifting from reactor mode to preventative mode. It could also be possible to have integrated cloud data systems that compile data from many different inspection sources to develop full structural and operational models of pipeline systems. This would change the approach from a structure with a pipeline integrity check every few years to a continuous monitoring system that greatly minimizes the chances of major pipeline failure and environmental disasters.

CONCLUSION

Tethered uncrewed subsea vehicles (UUVs) are a reasonable substitute for AUVs and ROVs in monitoring deep-water pipelines. Tetherless UUVs are cheaper, safer, easier to operate, and environmentally friendly as compared to tethered UUVs. With the help of advanced technologies such as AI, sonar, thermal vision, and high-definition cameras with autonomous features, UUVs can effectively and comprehensively inspect pipelines without the constraints of tethers. However, designing such advanced subsea vehicles that can be used on a large scale requires overcoming the challenges, such as the integration of sensors, power supply, as well as compliance with legal requirements (Mishra et al., 2023). More future work will be dedicated to the enhancement of the tethered subsea systems for deep-sea pipelines and to making the subsea pipelines more reliable and safer with a lower chance of being affected by environmental factors.

REFERENCES

[1] Adesina, M., Adegboye, Mutiu Adesina, Fung, W.-K., & Karnik, A. (2019). Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches. Sensors, 19(11), 2548. https://doi.org/10.3390/s19112548

[2] Beckman, J. (2025, March 12). Shore-based control is gaining traction for inspection AUVs, survey USVs. Offshore. https://www.offshore-mag.com/subsea/article/55273501/oceaneering-shore-based-control-gaining-traction-for-inspection-auvs-survey-usvs

[3] Cable-Locators Survey. (2023, October 19). Pipe inspection cameras: pipeline assessment tools. Cablelocatorsandsurvey.com; Cable Locators and Survey. https://cablelocatorsandsurvey.com/blog/post/pipe-inspection-cameras-for-pipeline-assessments

[4] Fun Sang Cepeda, M., Freitas Machado, M. de S., Sousa Barbosa, F. H., Santana Souza Moreira, D., Legaz Almansa, M. J., Lourenço de Souza, M. I., & Caprace, J.-D. (2023). Exploring autonomous and remotely operated vehicles in offshore structure inspections. Journal of Marine Science and Engineering, 11(11), 2172. https://doi.org/10.3390/jmse11112172

[5] Guo, X., Fan, N., Zheng, D., Fu, C., Wu, H., Zhang, Y., Song, X., & Nian, T. (2024). Predicting impact forces on pipelines from deep-sea fluidized slides: A comprehensive review of key factors. International Journal of Mining Science and Technology, 34(2), 211–225. https://doi.org/10.1016/j.ijmst.2024.02.001

[6] Ma, Q., Tian, G., Zeng, Y., Li, R., Song, H., Wang, Z., Gao, B., & Zeng, K. (2021). Pipeline in-line inspection method, instrumentation and data management. Sensors, 21(11), 3862. https://doi.org/10.3390/s21113862

[7] Mishra, V., Avtar, R., Prathiba, A. P., Mishra, P. K., Tiwari, A., Sharma, S. K., Singh, C. H., Chandra Yadav, B., & Jain, K. (2023). Uncrewed aerial systems in water resource management and monitoring: A review of sensors, applications, software, and issues. Advances in Civil Engineering, 2023, 1–28. https://doi.org/10.1155/2023/3544724

[8] Rumson, A. G. (2021). The application of fully unmanned robotic systems for inspection of subsea pipelines. Ocean Engineering, 235, 109214. https://doi.org/10.1016/j.oceaneng.2021.109214

[9] Sandifer, P. A., Brooks, B. W., Canonico, G., Chassignet, E. P., Kirkpatrick, B., Porter, D. E., Schwacke, L. H., Scott, G. I., & Kelsey, R. H. (2023). Observing and monitoring the ocean.

Elsevier EBooks, 549–596. https://doi.org/10.1016/b978-0-323-95227-9.00026-9

[10] Shams, S., Prasad, D. M. R., Imteaz, M. A., Khan, M. M. H., Ahsan, A., & Karim, M. R. (2023). An assessment of environmental impact on offshore decommissioning of oil and gas pipelines. Environments, 10(6), 104. https://doi.org/10.3390/environments10060104

[11] Singh, R., Sarkar, P., Goswami, V., & Yadav, R. (2022). Review of a low-cost micro remotely operated underwater vehicle. Ocean Engineering, 266, 112796. https://doi.org/10.1016/j.oceaneng.2022.112796

[12] Waste, D. (2024). The impact of batteries in skips: An environmental and safety perspective. Dunmowgroup.com. https://www.dunmowgroup.com/blog/the-impact-of-batteries-in-skips-an-environmental-and-safety-perspective

[13] Yang, X., Utne, I. B., Sandøy, S. S., Ramos, M. A., & Rokseth, B. (2020). A systems-theoretic approach to hazard identification of marine systems with dynamic autonomy. Ocean Engineering, 217, 107930. https://doi.org/10.1016/j.oceaneng.2020.107930

[14] Zhang, F., Tan, T., Hou, X., Zhao, L., Cao, C., & Wang, Z. (2024). Underwater mapping and optimization based on multibeam echo sounders. Journal of Marine Science and Engineering, 12(7), 1222. https://doi.org/10.3390/jmse12071222

[15] Zhu, H., Chen, J., Lin, Y., Guo, J., Gao, X., Chen, Y., Ge, Y., & Wang, W. (2024). In-Line Inspection (ILI) Techniques for subsea pipelines: State-of-the-art. Journal of Marine Science and Engineering, 12(3), 417. https://doi.org/10.3390/jmse12030417