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Research paper

Development of A Novel Subsea Pipeline Inspection System Using Autonomous Underwater Vehicles

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Abstract

In inspection, the AUV travels the programmed pipeline path autonomously, capturing water column imagery with MBES, and monitors gas-filled bubbles to evaluate leak hazards. If detected, it surfaces to transmit a satellite alarm to the control center. The AUV is equipped with a variable buoyancy system (VBS) to navigate efficiently and uses online collision avoidance because of the complicated operating environment. Nevertheless, the traditional image segmentation method is inappropriate owing to high noise and bottom reverberation in the operating environment, thus the necessity for alternative methods. An enhanced Otsu algorithm is suggested to increase the denoise effect and operation speed based on the conventional technique. Consequently, an enhanced Otsu method is suggested to precisely detect impediments. To estimate dynamic obstacles, Kalman filtering is also introduced. Pipelines carrying natural gas underground are essential pieces of infrastructure for the delivery of energy. In addition to immediately endangering the ecosystems of lakes and coastal areas, any damage or leak in these pipelines could result in operational problems and financial losses for the energy supply chain. Due to their heavy reliance on divers, which is expensive and ineffective, existing techniques for identifying deterioration and conducting routine inspections of these submerged pipes are still limited. Because of these challenges, unmanned underwater vehicles (UUVs), which provide a more reliable and effective option for pipeline monitoring and repair, are becoming more and more significant in this industry.

Keywords: *Subsea; Pipeline Inspection; Autonomous Underwater Vehicles.*

1. Introduction

Deep-water oil and gas fields have an ever-increasing global exploitation capacity. Submarine pipelines carry natural gas and oil that is extracted from the water [1]. The integrity and dependability of subsea pipelines have long been at risk from a number of marine environmental uncertainties, including as sediment burial, seawater corrosion, and changes in geological structure [2]. These elements may cause leaks or damage to the pipeline [20]. Leakage points can be difficult to find and difficult to search for because of the marine environment's complexity [11]. Generally, the pipeline inspection is carried out by the working ship section by section [4]. Expanding subsea pipeline infrastructure has increased the cost and time required for underwater inspections [3].

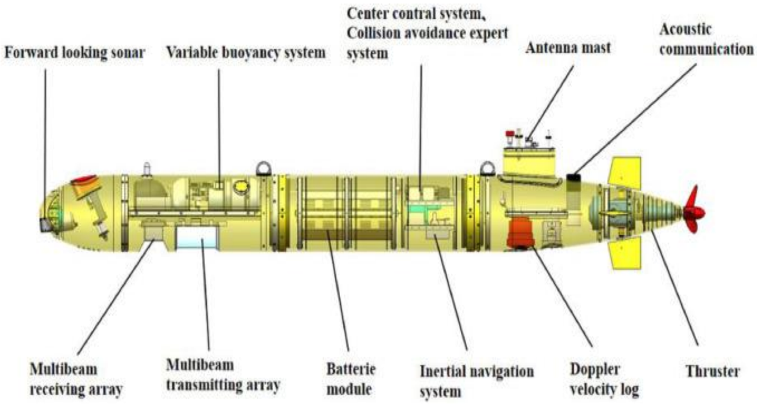

Fig. 1: Inspection of Submerged Pipeline Leaks Using an Autonomous Underwater Vehicle.

The Autonomous Underwater Vehicle, or AUV, has grown in popularity among remote underwater surveys because of the flexibility in the planning of a mission and decreasing dependence on an ongoing mother-ship monitoring effort [6]. Advances that have occurred most recently in the fields of sonar, navigation, control, and energy systems have made their widespread application within marine resource assessment, environmental investigations, and for military purposes, commonplace [12].

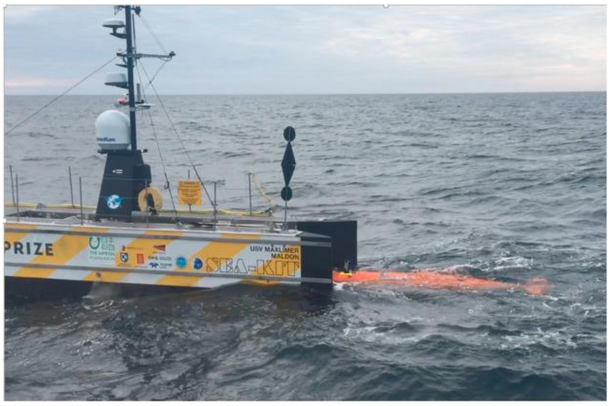

Fig. 2: The Application of Fully Unmanned Robotic Systems for Inspection of Subsea Pipelines.

Higher standards are thus proposed for the post-processing data's computation capacity and algorithm optimization. Comprehensive debugging of the MBES's core parameters is also necessary to avoid missing inspections [8]. However, the Blue View Company's sonar development kit (SDK) is used to implement the collision avoidance feature, allowing us to effectively obtain pings and gather sonar picture data [5].

2. Review of literature

A study by Harbin Engineering University on Autonomous Underwater Vehicles (AUVs) with optical vision sensors for pipeline inspection showed that AUVs are prone to light-water medium interactions, causing scattered and absorbed light, and hence decreased visibility (Liu, 2017).

Over long distances, the coustic sensor technique can demonstrate high sensitivity (Xavier, 2004). Because gas-filled bubbles in water have strong acoustic back scatter qualities, sonar is a good instrument for detecting gas leaks. Consequently, MBES is used in the majority of AUV-based techniques to detect gas-filled water bubbles. A study by Harbin Engineering University on Autonomous Underwater Vehicles (AUVs) with optical vision sensors used in pipeline inspection found that such vehicles are prone to light-water medium interactions, causing scattered and absorbed light, and thus, visibility is diminished (Liu, 2017). At the same time, research by Jilin University in China proved the applicative value of distributed fiber optic sensors in pipeline leak detection and location using a hybrid Sagnac and Mach-Zehnder interferometer-based pipeline leak detection system [13].

The Hugin AUV, which was outfitted with a synthetic aperture sonar (HIAS 1030) and a multibeam echo sounder (EM3002), examined thirty kilometers of undersea pipes to find particular damage [7]. During 2011 and 2012, significant research was conducted. A. Blomberg et al. performed sea tests in the North Sea using an Autonomous Underwater Vehicle (AUV) with HISAS 1030, and were able to identify gas-filled bubbles and two oil wells (Blomberg et al., 2017).

Fernandes et al. (2015) state that because the AUV has a set height of 15 to 30 meters and a distance of 30 to 50 meters from the pipeline, it can identify the precise pipeline damage [21]. Autonomous Underwater Vehicles (AUVs) need real-time obstacle avoidance to successfully maneuver through intricate underwater environments and avoid accidents [2]. AUV operations involve a range of tasks, including mine detection, seafloor topography mapping, pipeline and cable surveys, and underwater petroleum pipelines inspection (Desa et al., 2006). AUVs are also limited in sensing the aquatic environment, and thus integrating effective real-time obstacle avoidance systems is necessary to accomplish efficient inspection operations (Teo et al., 2009).

As a result, the car uses online collision avoidance with forward-looking sonar synchronization. Autonomous Underwater Vehicles (AUVs) need real-time obstacle avoidance features to traverse complicated environments and avoid collisions. AUV operations involve several tasks, such as mine detection, seabed topography mapping, pipeline and cable inspection, and underwater petroleum pipeline inspection (Desa et al., 2006). AUVs lack sufficient perception of the aquatic environment, so it is crucial to incorporate effective real-time obstacle avoidance systems to make inspection operations successful (Teo et al., 2009).

The PIAUV is intended to weigh 650 kg and have a diameter of 533 mm.

Wide-ranging financial and environmental repercussions may result from pipeline failure or damage. To ensure their integrity, these assets need to be assessed on a regular basis. A variety of approaches are used to check pipelines, including exterior inspection utilizing fiberoptic sensor (FOS), radiography, acoustics, and electromagnetic technologies, as well as internal inline examination by intelligent pigs and crawling robots [14].

In order to strengthen their green credentials, energy businesses are under increasing pressure to reduce costs while improving efficiency and safety. Accordingly, several companies are giving significant thought to replacing their existing dependence on traditional subsea inspection methods with unmanned inspection programs. Leading the charge in this movement is BP, which has set a goal of having all of its subsea asset inspections done by unmanned means by 2025.

Objectives of the Study

The system's suitability for underwater pipeline monitoring and maintenance in actual settings has been examined and verified.

While previous studies have demonstrated the potential of AUVs for subsea pipeline inspection, specific limitations persist, particularly regarding visibility in turbid environments and comprehensive inspection coverage. Liu (2017) highlighted the optical sensor challenges under such conditions, where scattered and absorbed light reduces visibility. The system proposed in this study addresses this by integrating acoustic sensing technologies that maintain inspection performance even in low-visibility environments. Existing platforms, such as the Hugin AUV, offer high-resolution imaging and deep-water capabilities but are often associated with significant operational costs and limited adaptability to complex pipeline geometries (Smith et al., 2024; Zhang et al., 2025). Table 1 presents a comparative overview of existing technologies and the proposed system, highlighting improvements in cost-efficiency and adaptability.

Feature/Technology	Optical Sensors	Acoustic Sensors	Hugin AUV (Kongsberg)	Proposed AUV System
Imaging in Turbid Water	Poor	Excellent	Excellent	Excellent (Acoustic + Optical)
Depth Capability	Limited	Suitable for deep sea	Up to 6000 meters	Tested up to 100 meters (pool) with deep-sea potential
360-Degree Inspection	Challenging	Possible with sonar array	Partial, depending on payload	Planned with additional sensor integration
Cost and Complexity	Low to moderate	Moderate	High	Low to moderate
Real-time Data Processing	Limited	Limited	Available but costly	Enhanced with Otsu algorithm

3. Materials and methods

The foremost aim of research and development in subsea pipeline monitoring and inspection technologies is to solve the above challenges. As maintaining the integrity of the main pipe body is essential for avoiding failures, numerous new technologies are first tried on plain pipes under controlled laboratory environments. Yet, technologies that work well on uncoated, thin pipes in the lab may not be implementable or effective for multilayered, thick-walled pipelines buried deep on the seafloor. Further engineering of the technology to address new problems is possible as it develops. The technology's economic benefits, such shorter inspection times and lower deployment costs, will also play a significant role in determining the direction of its development. The main goal of research and development in subsea pipeline inspection and monitoring technologies is to meet the above challenges. But technologies that are effective on uncoated thin pipelines in lab environments might not be viable or effective for multilayered thick-walled pipelines buried deep on the ocean floor [9].

During a pool test, an autonomous remotely operated unmanned underwater vehicle effectively followed a buried pipeline underwater and took pictures using its onboard camera. Even though pool testing showed that refraction, reflection, and glare of light affected image quality adversely, the CNN algorithm performed successful object detection but with reduced accuracy in the pool environment where there was interference by light. After the identification of pipeline damage by CNN within the pool setup, the site of the damage was matched to navigation data for the vehicle from its pressure sensor, gyroscope, and accelerometer. The difference between measured values for position and angle of deviation obtained during tracking of the pipeline was compared against actual pipeline geometry and found to have very accurate tracking. This research proves the viability of using unmanned underwater vehicles and deep learning algorithms for automatic, continuous, and safe detection and monitoring of underwater pipeline flaws.

The proposed AUV utilizes a Variable Buoyancy System (VBS) that facilitates precise depth control by adjusting internal air and water volumes through a pressure-regulated chamber. This design minimizes reliance on continuous thruster operation, enhancing energy efficiency and maneuverability near the pipeline.

Additionally, an Enhanced Otsu Algorithm has been implemented to optimize image thresholding for underwater conditions. The algorithm incorporates adaptive weighting based on underwater light attenuation models, improving segmentation accuracy for damaged pipeline sections in low-contrast environments.

Although the pool test provides a controlled environment for system validation, it does not fully replicate real-world subsea challenges such as ocean currents, biofouling, or varying pressure levels. Consequently, future work will involve open-water trials to assess system performance under realistic conditions.

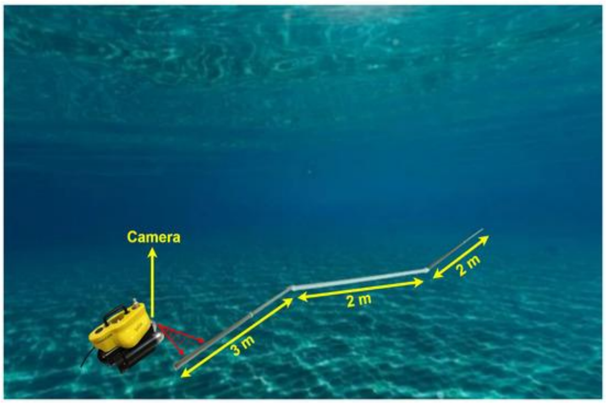

Figure 3. Schematic Representation of the Proposed AUV System

The Figure 3 illustrates key components, including the variable buoyancy module for depth regulation, onboard processing unit for real-time image analysis, integrated optical and acoustic sensor suite for robust inspection in turbid waters, thrusters for precise maneuvering, and the energy storage system.

While the research was successful, it was not without limitations. Therefore, damage to the bottom of the pipeline could go unnoticed, which is a major limitation, especially because the bottom surface is usually susceptible to corrosion or cracking. In order to surpass this limitation, subsequent developments may involve multi-angle camera systems that are able to capture the lower segment of the pipeline or other sensors that give a 360-degree perspective around the pipeline. Another constraint is the energy management required for extended underwater operations [15]. By processing just critical data, deactivating inactive sensors, or boosting battery capacity, the vehicle's operational lifespan could be increased.

Beyond the current limitations in bottom-surface inspection, the absence of a comprehensive 360-degree imaging capability remains a challenge. To overcome this, integration of multi-beam sonar or rotating camera systems is proposed, providing full circumferential pipeline inspection. Such technologies have demonstrated feasibility in similar subsea applications, though careful consideration is required to manage their power consumption and integration weight.

Real-world adoption of AUV-based pipeline inspection also faces regulatory and economic barriers. Compliance with maritime safety standards, acquisition costs of advanced sensors, and the need for skilled personnel to operate and maintain such systems can hinder widespread implementation. Future research will explore modular sensor designs, lightweight configurations, and cost-optimization strategies to promote practical deployment.

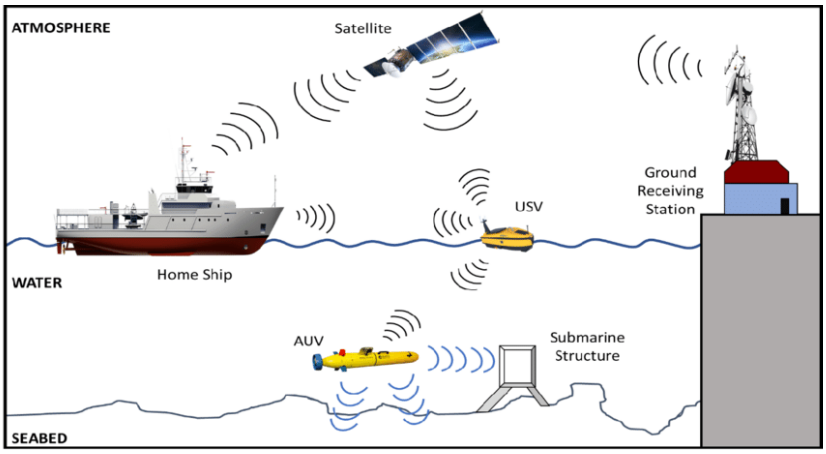

Fig. 4: System Framework.

The goal of developing subsea pipeline inspection and monitoring systems is to identify pipeline anomalies as thoroughly as possible while keeping costs as low as feasible. Further, the upfront capital investment in robotic inspection tools is small in comparison to the cost of repairing and cleaning up a failed pipeline that human inspectors might have missed. On the other hand, continuous data can be gathered by monitoring systems that are permanently installed along the pipeline [16].

The industry is paying more and more attention to fiber optic sensors in particular because of their potential for usage in subsea pipelines and other diverse applications. Fiber optic sensing allows for the rapid and accurate detection of a wide range of pipeline problems. In contrast to inspection, the requirement to permanently and reliably install lengthy fiber optic cables poses a distinct set of difficulties. In certain situations, the difficulties can be greater than the advantages. Additionally, the high cost of fiber optic interrogators at the moment can restrict their use to important pipelines or pipeline segments.

SVM chooses the best decision boundary by maximizing the distance between two classes and hence reducing errors [10]. In such a scenario, SVM takes the output of CNN as input, determines important features, and then classifies the classes. Classification is done through this process. A database of images depicting pipeline damage was formed using deep learning and image augmentation to train the Convolutional Neural Network (CNN) framework. Data augmentation was utilized to form the underwater pipeline damage dataset for the diagnosis of damage inquiry without changing the unique characteristics of the images.

4. Results and analysis

Despite its modest size, the damaged part of the underwater pipeline was located using the CNN algorithm. Lighting factors, light refraction, reflections, and glare can all affect how accurate a detection is in a pool area. Usually, artificial lighting is used in the pool to create a more consistent illumination. The underwater damage detection test has given the autonomous underwater vehicle the capability to detect items, as shown in Figure 5.

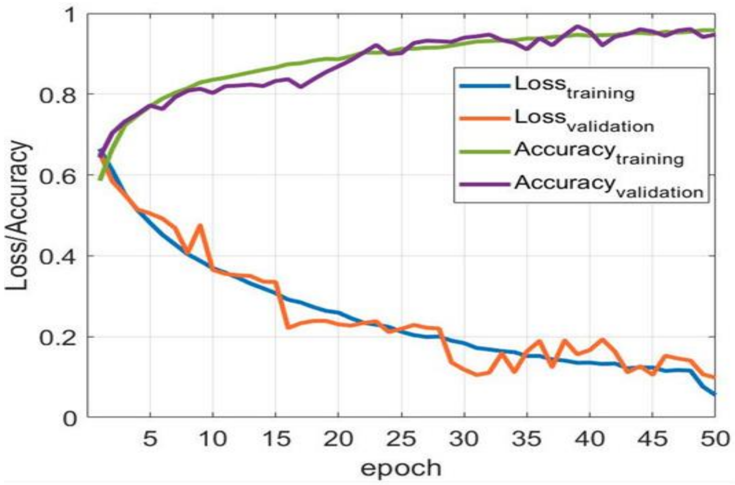

Fig. 5: CNN Training Consistency and Loss Curves.

Underwater pipeline tracking was done in a pool environment using a remotely driven underwater vehicle that had autonomous features. This made it possible to identify and pinpoint the area of pipe damage. Data augmentation techniques employed were zooming, dark, light, and color changes, horizontal and vertical rotation, rotation at precise angles, and shifting in the horizontal and vertical directions. Every image gathered by CNN via the Labelling software was provided with a specific label, creating .xml files during labeling. After labeling was complete, images were separated into two different files for the training algorithm: training and test folders.

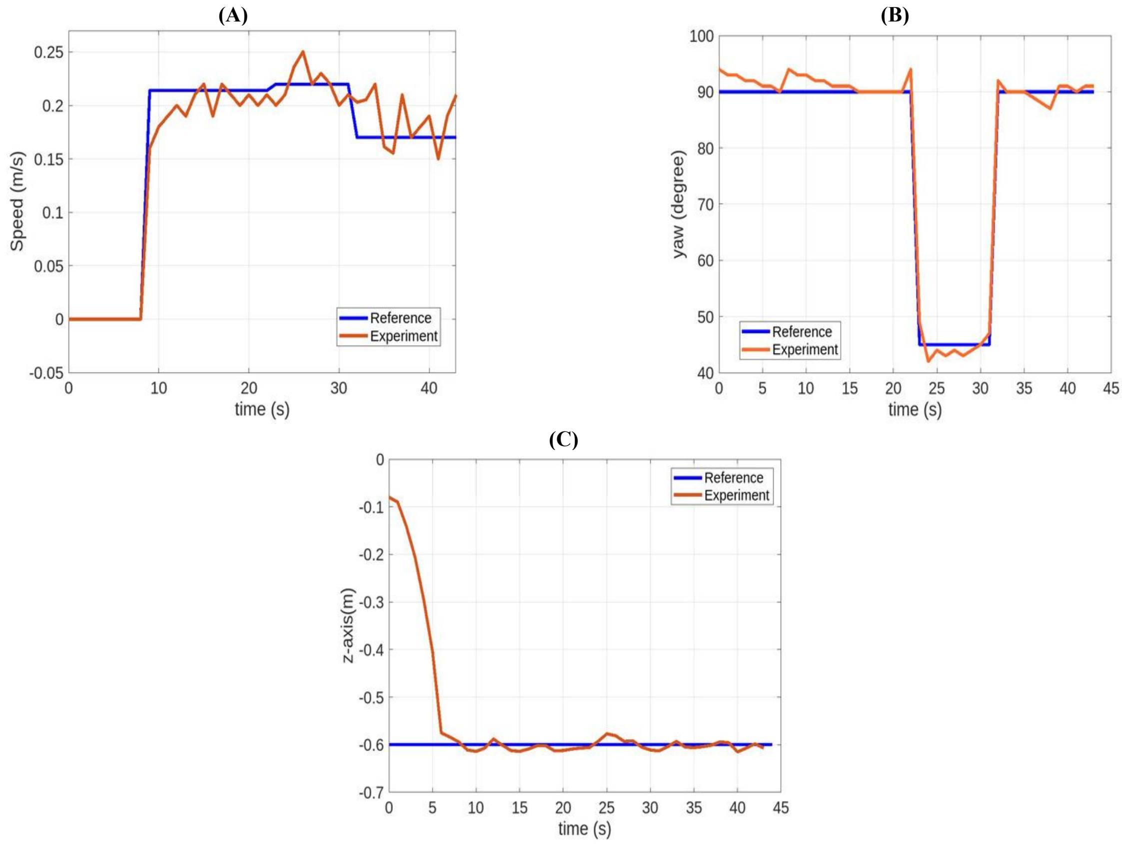

Fig. 6: (A) Reference Surge Speed (B) Reference Yaw Angle (C) Reference Depth Value.

An underwater pipeline scenario was schematically depicted throughout the experiment. Using the information from these initial experiments, an object tracking algorithm was created to allow the car to follow the target item on its own. As the car followed the pipeline, the damage was found using the CNN technique previously mentioned. The testing folder held 20% of the images of the object to be recognized, and the training folder had 80% since the CNN began its training process. Out of the 2000 data that were gathered, 1500 were used for training, and 500 were used for testing. There is at least one damage label on every image in the training set.

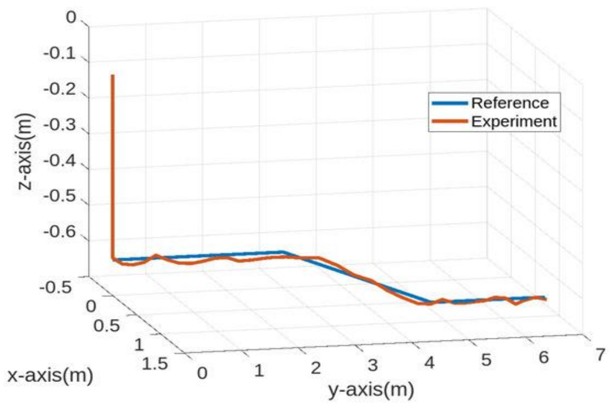

Fig. 7: Reference Path.

The CNN algorithm has trouble accurately recognizing objects when there are shadows or glare in the image due to reflections from artificial lights or direct light entry into the water. When objects appear different from their true form due to light refraction, it can be difficult for the algorithm to distinguish them effectively.

5. Conclusions

An operator console, a user computer, and a cable section make up the autonomously outfitted remotely operated underwater vehicle (ROV) used in this investigation. Over long distances, the coustic sensor technique can demonstrate high sensitivity (Xavier, 2004). Because gas-filled bubbles in water have strong acoustic back scatter qualities, sonar is a good instrument for detecting gas leaks. Autonomous Underwater Vehicles (AUVs) need real-time obstacle avoidance to successfully maneuver through intricate underwater environments and avoid accidents. AUV operations involve a range of tasks, including mine detection, seafloor topography mapping, pipeline and cable surveys, and underwater petroleum pipelines inspection (Desa et al., 2006). AUVs are also limited in sensing the aquatic environment, and thus integrating effective real-time obstacle avoidance systems is necessary to accomplish efficient inspection operations. As a result, the car uses online collision avoidance with forward-looking sonar synchronization. Autonomous Underwater Vehicles (AUVs) need real-time obstacle avoidance features to traverse complicated environments and avoid collisions. AUV operations involve several tasks, such as mine detection, seabed topography mapping, pipeline and cable inspection, and underwater petroleum pipeline inspection

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