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Sea Spider-Type Multifunctional High-Speed UAV-Boat Coupled System

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Abstract

The demand for waterborne patrol missions has intensified due to the growing need to safeguard maritime security and protect marine rights. In response to this challenge, an integrated unmanned aerial vehicle and vessel system is presented, capable of performing a wide range of tasks, including but not limited to coastal surveillance, precision military operations, and emergency maritime rescue. The sea spider-type vessel features a deformation mechanism driven by hydraulic transmission rods, enabling smooth and frequent transformations while maintaining operational stability and radar stealth. To address the hydrodynamic resistance encountered by the hull during movement, the Volume of Fluid (VOF) method and STAR-CCM+ software were employed for resistance analysis. Extensive physical model testing indicates that the system can achieve high-speed and stable navigation, significantly expanding reconnaissance coverage. Furthermore, its modular design supports mission-specific payload configurations, demonstrating strong potential for both military and civilian applications.

Keywords

Sea Spider-Type Unmanned Surface Vehicle, UAV-Boat Coupled System, Modular Design

1. Introduction

1.1. Development Background

With the continuous development of the marine economy and the rapid advancement of unmanned surface vessels (USVs), USVs have become an integral component of maritime unmanned systems. Shifts in waterborne transportation patterns and the redistribution of maritime risks have placed significant responsibilities on relevant authorities in areas such as water safety management, offshore patrols, and maritime search and rescue. The increasing demand for waterborne patrol missions—particularly the growing role of naval departments in safeguarding national sovereignty and protecting marine rights and interests—has become more pronounced.

Since 2012, escalating territorial disputes over the Diaoyu Islands and the South China Sea have prompted China to intensify patrol operations in these regions, substantially increasing the workload of patrol personnel. As a result, there is an urgent need to develop unmanned, autonomously navigable vessels capable of carrying out hazardous and repetitive tasks using various mission payloads to reduce reliance on human labor. Although domestic research on USVs in China began relatively late, it has progressed from initial conceptual design to practical implementation. Furthermore, in response to market demand and the growing need for smart ship technology development, the China Classification Society (CCS) launched a research initiative in May 2017 to compile inspection standards for USVs, culminating in the release of the first *Inspection Guidelines for Unmanned Surface Vehicles* at the end of that year.

Driven by the rapid development and widespread application of communication and artificial intelligence technologies, USVs have now entered a golden era of accelerated growth [1]. This development is primarily fueled by two major forces: expanding demand and continuous technological progress. The scope of USV applications has become increasingly extensive and in-depth, covering a broad range of fields, including environmental protection, hydrology, surveying and mapping, security patrols, military operations, and unmanned shipping [6]. In parallel, the core technologies enabling USV development—such as communication systems, control algorithms, object recognition, sensor integration, and deep learning—have matured and are being deployed across multiple industries [2]. As these technologies continue to advance, intelligent USVs are expected to play an increasingly vital role in both military and civilian domains.

1.2. Overall Design Scheme

The device adopts a modular design and comprises several functional modules, including the main hull module, deformation module, unmanned aerial vehicle (UAV) module, weapon module, and an ejection-based life-saving module. This modular architecture endows the system with characteristics such as high stability, rapid deployment capability, radar stealth, and strong payload capacity [6], as shown in **Figure 1**.

In military applications, the system can be equipped with mission-specific modules to conduct operations such as enemy reconnaissance and precision strikes. In civilian scenarios, it can rapidly respond to maritime emergencies to perform tasks such as rescuing drowning individuals and exploring high-risk sea areas.

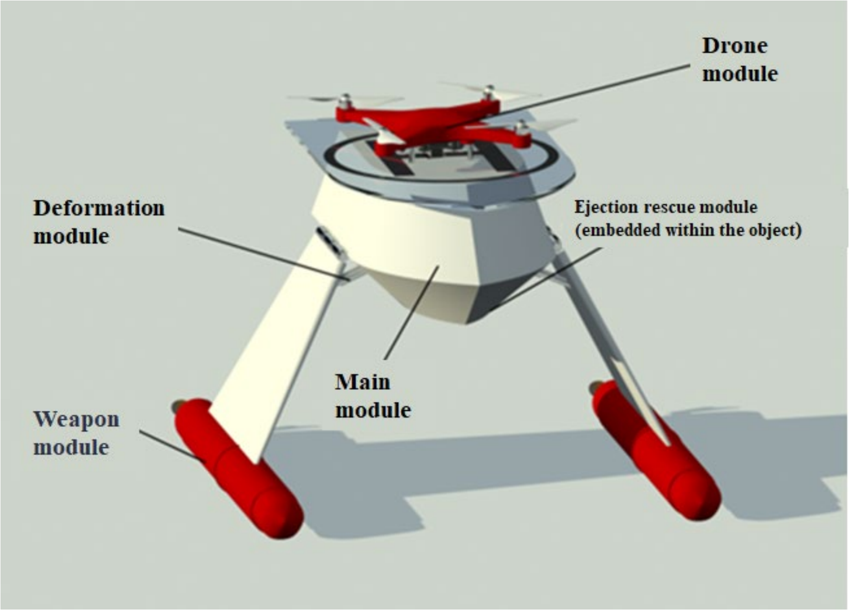

Figure 1. Schematic diagram of the sea spider-type multifunctional rapid unmanned aerial vehicle–boat coupling system.

2. Module Design

2.1. Main Hull Module Design

2.1.1. Hull Selection

With the continuous development of the shipbuilding industry, various novel high-speed hull forms, such as hydrofoils and catamarans, have been introduced. Upon comparison, catamarans generally offer superior stability compared to hydrofoils. The hull cross-sections of high-speed catamarans typically feature circular or pointed shapes, with square or semi-square sterns. The degree of stern contraction is closely related to the vessel’s design speed, increasing as the speed rises.

High-Speed Catamarans Offer Numerous Advantages:

1) Low wave resistance: At high speed, wave-making resistance constitutes the major portion of total resistance. The slender hulls of a catamaran effectively reduce wave-making resistance and form resistance on the water’s surface [3]. As a result, the performance of the catamaran is superior to that of a single-hull vessel under such conditions.

2) Enhanced stability: Catamarans have two hulls separated by a certain distance, which significantly increases the lateral moment of inertia in the waterline plane. This results in a large righting moment, thereby improving the initial stability of the vessel.

3) Improved maneuverability: Each hull is equipped with a propeller, enabling vessel steering by adjusting the motor speeds. Additionally, the spacing between the hulls creates a separation between the propeller axes, which enhances the catamaran’s turning performance.

By analyzing the drawbacks of existing vessels and the advantages of catamarans, a sea spider-type high-speed three-dimensional rescue unmanned boat was designed and fabricated, as shown in **Figure 2**.

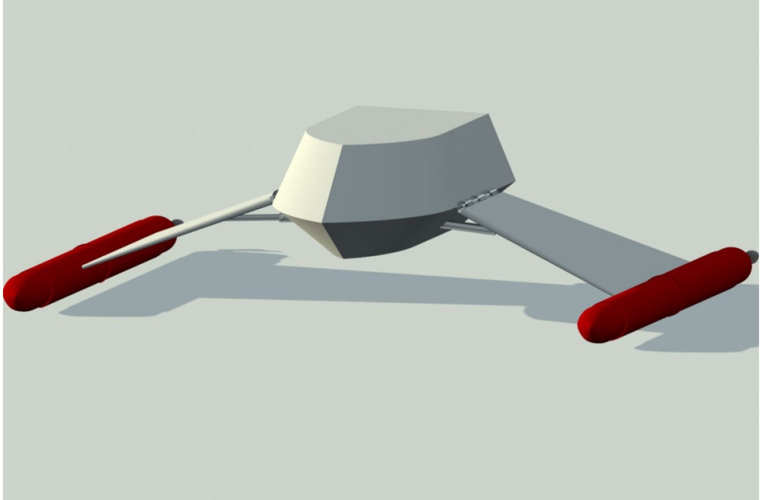

Figure 2. Sea spider-type high-speed three-dimensional rescue unmanned boat.

Design of Hull Connecting Wing Plates:

The trapezoidal connecting plates are attached to the main hull at their upper edges via a rotatable connection, while their lower edges are rigidly connected to the two side hulls, as shown in **Figure 3**. This design offers several advantages:

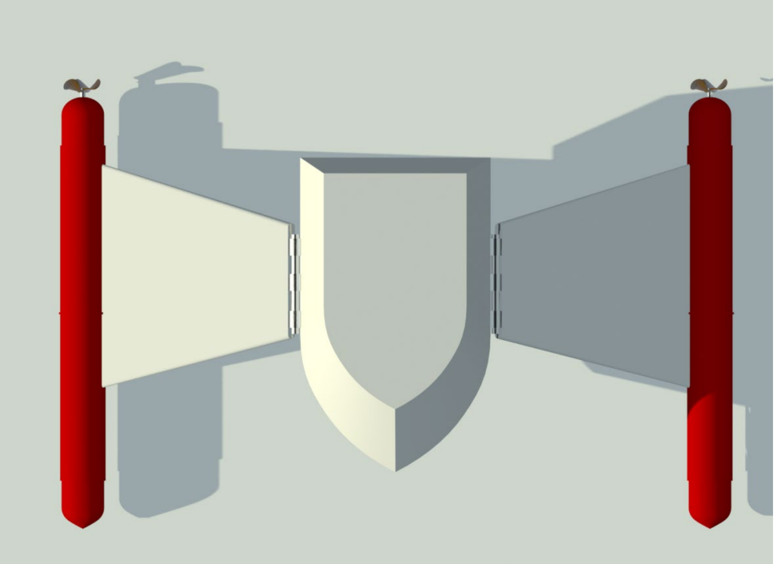

Figure 3. Side view of rotatable connecting plates.

1) Increased Structural Strength: Water pressure increases with depth, subjecting the lower parts of the vessel to greater forces. The trapezoidal design—narrow at the top and wider at the bottom—increases the contact area between the connecting plates and the hulls, thereby enhancing structural integrity and overall

vessel stability.

2) Improved Stability and Simplicity**:** The fixed lower edges contribute to greater structural stability and improved impact resistance. This configuration also simplifies hull construction and helps distribute forces more evenly during deformation, thereby preventing asymmetric deformation and structural imbalance.

2.1.2. Buoyancy Tank Design

During navigation, the buoyancy tanks remain submerged, and a significant portion of the vessel's hydrodynamic resistance arises from their movement through the water. To minimize resistance and improve overall performance, the design of the buoyancy tanks draws inspiration from torpedoes, which are known for their low resistance, low noise, and high maneuverability [12]. The resulting design is illustrated in **Figure 4**.

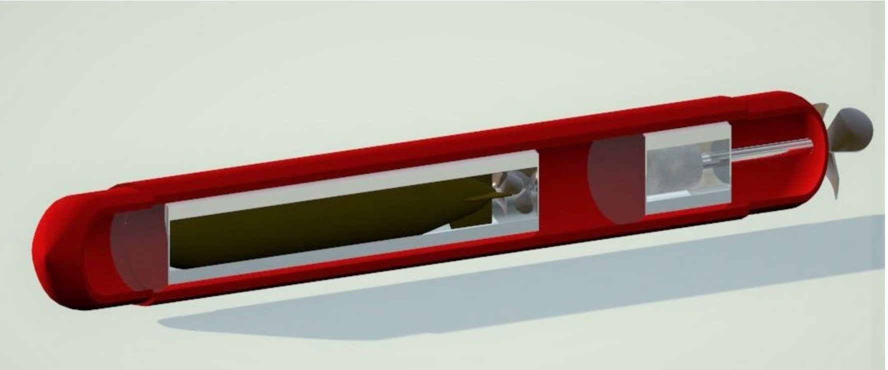

Figure 4. Design of the Buoyancy tank.

2.1.3. Design of the Unmanned Aerial Vehicle Landing Process

Considering the conditions of the operational water area and the capabilities of current unmanned aerial vehicles (UAVs), a guidance and landing procedure was developed to enable precise UAV landings on the charging platform atop the unmanned surface vessel (USV). The specific process is as follows: using custom-developed platform control software [5], the shore-based terminal guides the UAV toward the designated landing zone on the USV's platform. The UAV executes a precise landing using camera-based calibration. Once the piezoresistive sensor detects the UAV's weight, the wireless charging system is automatically activated to begin charging [4].

The UAV Landing and Charging Procedure Can Be Summarized as Follows:

1) After the high-speed three-dimensional rescue unmanned surface vessel (USV) deploys the unmanned aerial vehicle (UAV), the UAV performs cruising and monitoring operations in the designated maritime area. During this process, the shore-based terminal continuously evaluates whether the UAV requires recharging to maintain operational continuity.

2) The operator reviews relevant information displayed on the terminal—including the USV's position, environmental data, and system status—and remotely selects a safe area where the USV can stop and support the UAV's landing proce-

dure.

3) Utilizing the BeiDou Navigation Satellite System (BDS), the shore-based terminal commands the UAV to approach the marked location of a navigation reference point indicated on the electronic nautical chart.

4) Due to possible variations in the USV's position and inherent positioning system errors, a hybrid landing strategy is employed. This combines onboard landing guidance software on the USV with shore-based control [2] to ensure the UAV lands precisely on the wireless charging pad located at the navigation reference point.

5) Upon successful landing, a piezoresistive sensor detects the UAV's weight, automatically triggering the wireless charging system to initiate the charging process.

2.1.4. Design of the Video Transmission of the Unmanned Aerial Vehicle-Boat Coupling System

To enhance situational awareness for operators of the unmanned surface vessel (USV) and to support the efficient execution of on-site rescue operations or precision strikes, a dedicated video transmission system has been developed for the UAV–USV coupling platform. This system enables real-time monitoring of both the platform itself and its surrounding maritime environment, thereby improving operational effectiveness and safety [4].

The camera captures video signals, which include information on the operational status of the unmanned surface vessel (USV), environmental conditions, and any individuals falling into the water. These video signals are transmitted by a video signal transmitter via an antenna to a remote receiver. The receiver processes the incoming analog signals by sampling, quantizing, and encoding them into digital signals using a video capture card. This enables the monitor at the receiving end to accurately display the video captured by the camera. The system's structural diagram is shown in **Figure 5**.

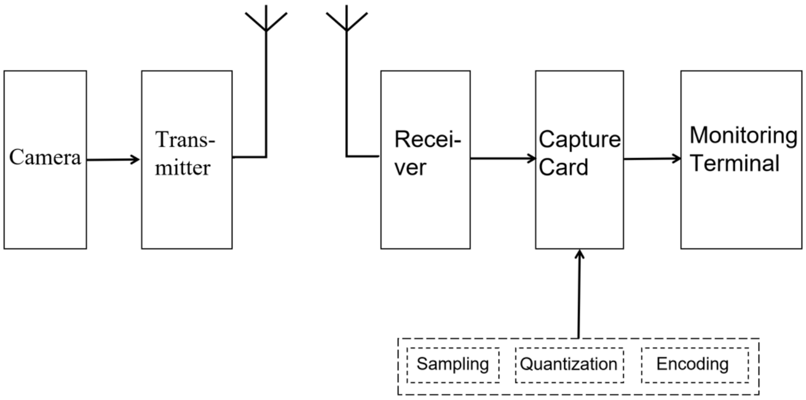

Figure 5. Structural diagram of the UAV–USV coupling video transmission system.

In this system, the wireless image transmission module employs the TS832 transmitter and the RC832 receiver [8], enabling the transmission of analog video signals over distances exceeding 3 km in an open environment. The receiver's frequency modulation controls allow the selection of the appropriate transmitting and receiving frequency points, which are displayed on an LED digital display. With up to 40 selectable frequency points, the system offers excellent anti-interference performance. The physical components are shown in **Figure 6**.

Figure 6. Physical components of the transmitter and receiver.

3. Analysis of Ship-Type Resistance

The Volume of Fluid (VOF) method is a numerical technique originally developed to track and locate the free surface of a single fluid, but it is now widely applied to simulate multiphase fluid flows. As an Eulerian method, it features a stationary or prescribed-moving computational grid that adapts to the evolving interface shape. In the VOF method, the interface is captured using a marker function, represented by the volume fraction of the reference-phase fluid within each computational cell.

Computational fluid dynamics (CFD) has been widely adopted in fluid flow analysis. When performing numerical simulations using CFD, an effective mesh discretization method is essential for generating the computational domain. The speed and quality of mesh generation significantly influence the overall computational efficiency, accuracy, and numerical stability. According to relevant studies, mesh generation can account for approximately 60% of the total computational time in CFD simulations [3].

First, the overall structural model of the unmanned surface vessel is created using SolidWorks and imported into the computational mechanics software STAR-CCM+. A CFD model is then established by applying appropriate wave and current boundary conditions. The Volume of Fluid (VOF) method is employed to simulate and analyze free-surface flow phenomena, thereby evaluating the structural stability of the unmanned surface vessel. The mesh refinement used for the simulation is illustrated in **Figure 7**.

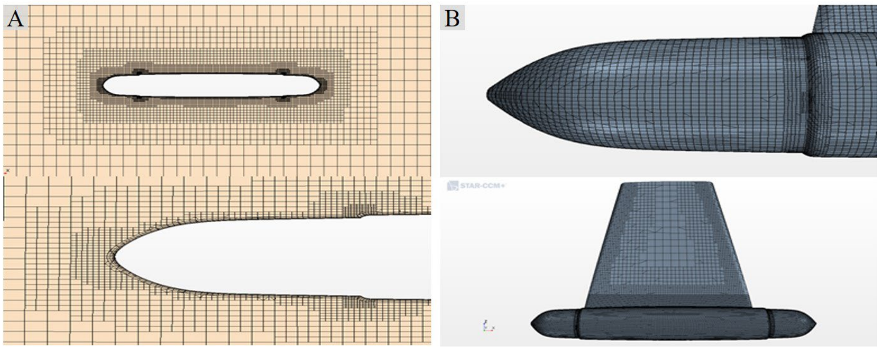

Figure 7. Computational mesh distribution from different perspectives. (A) Mesh distribution on the elliptical cylinder cross-section; (B) Volume mesh distribution of the overall unmanned surface vessel structural model.

During a ship's navigation, the total resistance encountered is typically divided into two components: above-water resistance and underwater resistance. The above-water resistance is primarily air resistance, while the underwater resistance consists of frictional resistance, wave-making resistance, and viscous pressure resistance. A common approach to calculating total ship resistance, R_t, is to decompose it into frictional resistance R_f, viscous pressure resistance R_{pv}, and wave-making resistance R_w, such that: $R_t = R_{pv} + R_f + R_w$.

Among these components, the frictional resistance R_f is typically estimated using an equivalent flat plate model. The viscous pressure resistance R_{pv} and the wave-making resistance R_w are collectively referred to as the residual resistance and are commonly derived using similarity laws.

For low-speed vessels, frictional resistance accounts for approximately 70%–80% of the total resistance, viscous pressure resistance exceeds 10%, and wave-making resistance contributes only a small portion. In contrast, for medium- and high-speed vessels, wave-making resistance increases significantly, constituting 40% - 50% of the total resistance. Therefore, effectively reducing both frictional and wave-making resistances is essential for enhancing vessel speed and overall propulsion efficiency.

The distribution of wave-making resistance is closely related to the geometry and position of the ship's hull. Unlike frictional resistance, wave-making resistance is highly sensitive to the hull form, and appropriate modifications to the hull design can lead to a significant reduction in wave-making resistance. Based on simulation results, the distribution of wave-making resistance during the operation of this unmanned surface vessel is illustrated in **Figure 8**. The wave-making resistance is most pronounced at the bow and stern, while it becomes considerably less evident toward the midsection of the vessel.

The analysis results of the total resistance and viscous pressure resistance are shown in **Figure 9**. Simulation results indicate that the total resistance of the vessel is approximately 13.4492 N, while the viscous pressure resistance is about 6.1870

N. Therefore, the wave-making resistance accounts for approximately 46% of the total resistance [9].

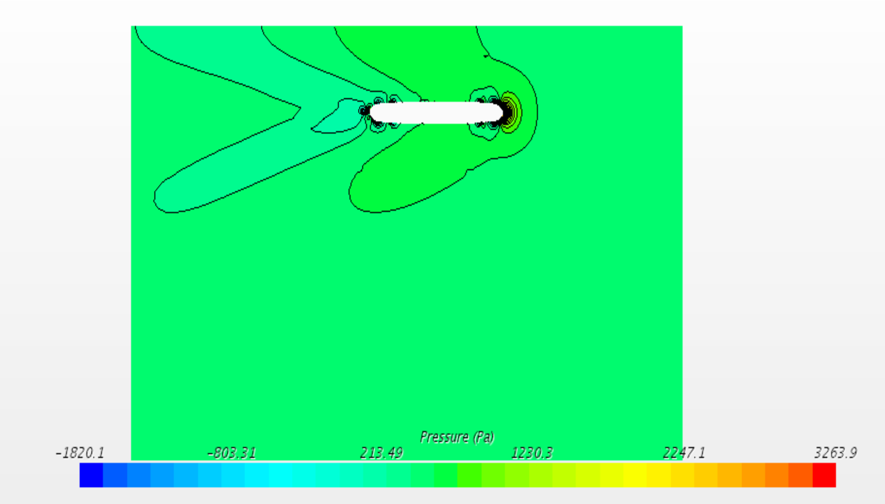

Figure 8. Schematic diagram showing the distribution of wave-making resistance during vessel operation.

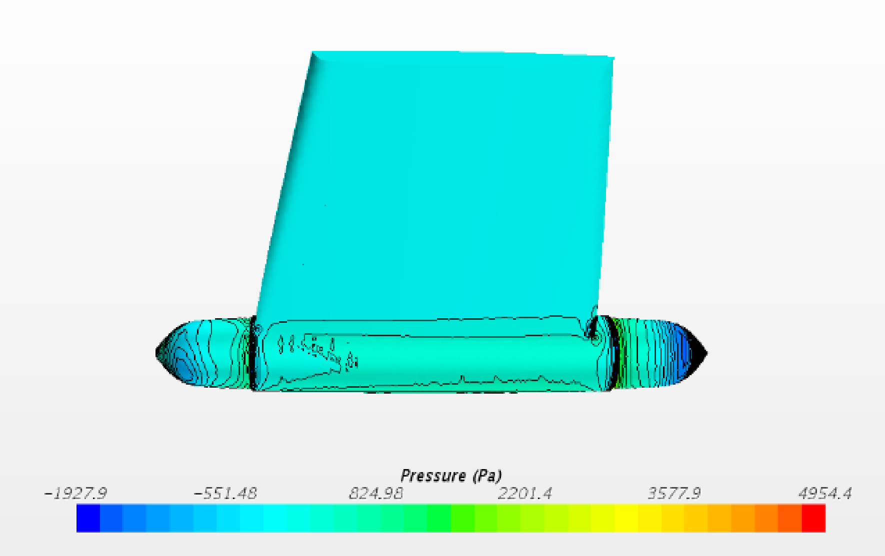

Figure 9. Schematic diagram of the analysis results for total resistance and viscous pressure resistance.

4. Conclusions

This study presents an innovative unmanned surface vessel (USV) design featuring a deformable structure capable of switching between high-speed mode and stealth mode. The ability to transition between these two operational states significantly enhances the vessel's versatility and performance across diverse mission scenarios.

In high-speed mode, the side plates are retracted, which minimizes drag and optimizes hydrodynamic efficiency, enabling the vessel to achieve significantly higher speeds during deep-sea navigation. This configuration allows the USV to effectively avoid ocean waves, thereby improving stability and fuel efficiency, while also ensuring rapid response times in mission-critical situations such as maritime patrols and search-and-rescue operations.

Conversely, in stealth mode, the side plates are deployed, and the hull is designed to sail closer to the water surface. This design minimizes the radar cross-section (RCS) by reducing the radar reflection area on the water, making the vessel less detectable by enemy radar systems. Additionally, the hull is coated with radar-absorbing materials, further enhancing its radar stealth capabilities [5]. This dual-mode functionality ensures that the USV can effectively operate in both high-speed, high-performance environments and covert, low-detectability missions, making it ideal for both military and civilian applications.

The successful integration of these adaptive design features demonstrates the potential for this USV to address modern maritime challenges, ranging from reconnaissance and surveillance to emergency response and military operations. The system's ability to seamlessly transition between different operational modes enhances its effectiveness and survivability in complex and dynamic maritime environments, providing a significant strategic advantage in both defense and rescue operations. Future developments could focus on further optimizing the vessel's performance in extreme conditions [11], as well as exploring advanced autonomy algorithms, such as adaptive path planning under dynamic maritime challenges [7], for enhanced operational efficiency and decision-making capabilities [10].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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