The 20th International Conference on
Transport and Sedimentation of Solid Particles
26–29th September 2023, Wroclaw, Poland

ISSN 0867-7964 ISBN 978-83-7717-392-3

AN INTRODUCTION TO ROV BASED INTELLIGENT DEEP SEA MINING SYSTEM

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DOI: 10.30825/4.14-19.2023

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ABSTRACT: In view of difficulties existing in researches on deep-sea mining systems at home and abroad, including being stuck in seabed sediment for self-propelled deep-sea mining vehicles, uncontrollable movement of buffers, and the complications of pipeline transportation system, a remote-operated vehicle (ROV) is introduced in a new-type of intelligent deep-sea mining system, and structured the ROV-based intelligent deep-sea mining system. The components of the ROV-based intelligent deep-sea mining system, an overall concept design for it under a complex and dynamic ocean environment, are all presented in this paper.

KEY WORDS: ocean mineral resources; deep-sea mining; lift; ROV

1. INTRODUCTION

In recent years, growing attention has been paid to the idea that deep-sea mining may be more environmentally friendly and financially lucrative than terrestrial mining. This has sparked strong confidence and expectation in researching and exploiting marine mineral resources. The international community has also intensified efforts in the research and development of deep-sea mining technologies (Steve Rogers, Nautilus Minerals, 2012). This is a great step forward in the development of the mining system. Giving rise to the prevailing argument that the capacity for deep-sea mining may soon become a reality (Liu Shaojun and Yang Baohua, 2015). NORI and Allseas successfully concluded the integrated system test in the C-C Zone in the Pacific Ocean in October 2022 (Pita Ligaiula, 2022), further arousing people's deep-sea mining research interest.

2. EVOLUTION OF DEEP-SEA MINING SYSTEM

In the 1970s, consortia of Western developed countries saw the first surge in research on marine mineral exploitation. After abandoning the continuous line bucket (CLB) system known as the first-generation deep-sea mining system, three international consortia successively started research on underwater mining systems, which were mainly composed of seabed collectors and lift pipelines, and also carried out deep-sea mining experiments. Currently, collecting seabed minerals by seabed collectors and then lifting them to the ocean surface through pipelines and slurry pumps (following the principle of slurry pipeline transportation in terrestrial mines), as shown in Figure 1, is generally deemed to be the most commercially promising approach.

The mining system of OMI (Ocean Management Incorporated) is similar to that of Ocean Mining Associates (OMA). Both of them adopt towed seabed collectors, which adapt to the weak bearing capacity of seabed sediment. However, they are inefficient in mining, and unable to control seabed mining routes and avoid seabed obstacles. Such vehicles constitute the second-generation deep-sea mining system. The mining system of Ocean Minerals Company (OMCO) adopts Archimedes spiral self-propelled collectors, whose walking mechanisms are served by Archimedes spiral impellers. By pushing sediment backward, the vehicles gain forwards momentum, thus becoming controllable for the first time. This marks a big step forward in deep-sea mining technologies. However, this approach also has some weaknesses, such as the large turning radius of the seabed collector, the serious damage to the spiral impellers brought to the seabed environment by pushing sediment, and the uncontrolled height of the collecting mechanism away from the seabed. This kind of mining system is regarded as the third-generation deep-sea mining system (Jin S. Chung, 2013), which has been adopted and improved by many countries, consortia (Stuart Leach and Glen Smith, 2012), and international organizations that are developing deep-sea mining technologies. However, the movement of the mining system, which is mainly composed of mining vessels, buffers, and seabed ore collectors, is complicated. Under the action of steel pipes and hoses, the buffer is towed by the surface mining vessel and affected by the moving seabed collector, making its movement complicated and difficult to control. Consequently, the surface mining vessel, the buffer, and the seabed collector could hardly move in a harmonious way.

The deep-sea mining system has evolved from the first-generation one, known as the CLB system, that has no measurement and control units, to the second-generation one that adopts towed self-propelled collectors, and then to the third-generation one that adopts controllable self-propelled collectors (as shown in Figure 2). This fully reflects the fact the mining system is getting increasingly intelligent.

The movement of seabed collectors is closely related to the characteristics of seabed sediment. Ivo Dreiseitl studied the geotechnical properties of seabed nodules at 5,000m water depth in the contract area of the Interoceanmetal Joint Organization (IOM) in the Pacific CC Zone, and conducted in-situ sampling, testing, and analysis of sediments. It was found that 50% of the sediments had particle sizes finer than 0.074mm (Dreiseitl, 2013). Shinya Nishio's research on seabed sediments in the eastern part of Nankai Trough revealed that 95% of the sediment had particle sizes finer than 0.1mm (Shinya Nishio. 2013). Due to its fine grain size, seabed sediment is characterized by high water content, low cohesion, and weak bearing capacity. In consideration of that, collectors have evolved from the towed type to the self-propelled caterpillar one, overcoming the shortcomings of the former type. When moving on the surface of seabed sediment, however, the vehicle body is prone to sink into the sediment, and the movement mechanism may slip.

In such a case, the collector is unable to completely follow the planned route and may even get deeply stuck in the sediment. In a collection experiment conducted by Chinese researchers at a depth of 134m in Fuxian Lake, Yunnan Province (COMRA, 200), the collector sank at the bottom of the lake, skidded into the sediment, and had a large turning radius. Therefore, one of the key technologies is to ensure collecting mechanisms to extract ores from seabed sediment in a friendly way.

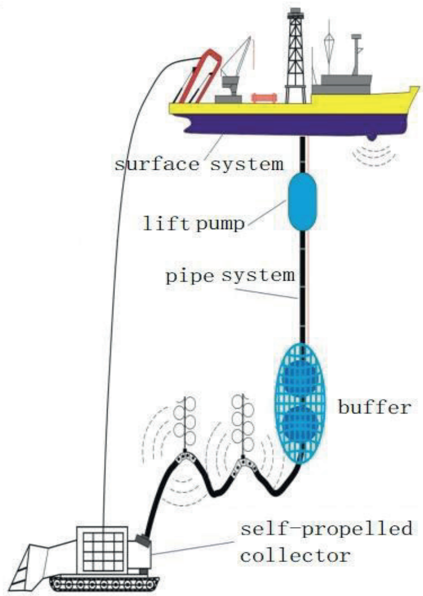

Fig. 1 Schematic diagram of a deep-sea mining system

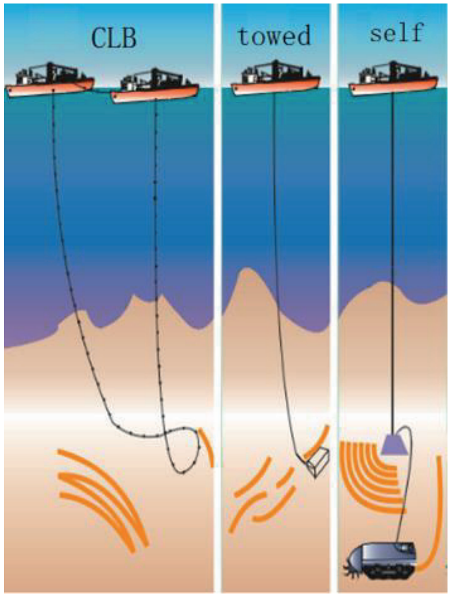

Fig. 2 Evolution of deep-sea mining system

Before the third-generation mining system is used for commercial mining, the following technical difficulties need to be further addressed:

(1) The self-propelled collector is prone to skidding and has difficulty moving on seabed sediment. Although it has overcome the shortcomings of the towed ore collector, including blindness, low efficiency, and inability to control the seabed mining route and avoid obstacles, the collector is still prone to sink into the sediment, and the travelling mechanism may slip when moving on the surface of seabed sediment. In such case, the ore collector is unable to completely follow the planned route, and may even get deeply stuck in the sediment.

(2) During the operation of a mining system, the surface mining vessel, buffer, and seabed collector need to run in a coordinated and integrated way, which makes it extremely complicated to control the system. The movement of the buffer is influenced not only by the offshore mining vessel through hard lifting pipes, but also by the seabed collector through hoses. It is therefore very complicated, even uncontrollable and unpredictable. A mining system needs to get more intelligent to realize harmonious linkage among a mining vessel, a buffer, and a collector.

(3) The series connection between conveying hoses and hard lifting pipes in the buffer is open-loop. The seabed ore is transported by a transport pump from a collector to the feed bin of a buffer through hoses, then fed into hard pipes by the feeder under the

feed bin, and then lifted to a surface vessel by an electric lift pump connected in series with hard pipes. Therefore, the transport and lifting system of a mining system, formed by the open-loop connection between two independent pipeline transport systems in a buffer, has a complex overall structure and entails the matching of the operation parameters of two independent pipeline systems. This makes the mining system less reliable and efficient.

Based on the potential technical difficulties of the above-mentioned third-generation mining system, the author thoroughly incorporates the advantages of the second- and third-generation deep-sea mining systems and proposes a novel ROV-based intelligent deep-sea mining system.

3. ROV-BASED INTELLIGENT DEEP-SEA MINING SYSTEM

The remotely operated vehicle (ROV) has been widely used in underwater engineering, becoming the most effective equipment for underwater observation and operations. It has been widely used in deep-sea research, offshore oil exploitation, salvage, submarine pipeline laying and inspection, cable laying and maintenance, reservoir and dam maintenance, and military fields. It can be applied in almost all in all marine areas of the earth. At present, there are more than 250 types of ROV across the world, ranging from small observation-oriented ROV weighing several kilograms to large operational ROVs with a mass of more than 20t (Zhu Xinke and Jin Xianglong, 2013). In China, there are more than 400 manufacturers providing all kinds of ROVs machines, parts, and services. ROVs have become mature products, forming a new and comprehensive industrial field — the ROV industry. In view of technical difficulties in the existing mining system, which consists of a seabed collector, pipeline, and hydraulic lifting system, Zou Weisheng, the author of this paper, proposed a new method and equipment for marine mineral resources mining, which were patented in China in 2018 (Zou Weisheng and Lu Yong, 2013). As shown in Figure 3, the seabed mineral resources mining system consists of a ROV-based seabed collector, a pipeline, and a lift pump station. The ROV-based submersible collector, which is composed of a submersible ROV and a towed seabed collector, runs at a certain height from the seabed with the help of buoyancy and the thrust of seawater. By making full use of the basic conditions of buoyancy in the deep-sea operational environment, it mitigates the impact of complex topography and geological conditions on its driving performance, thus greatly improving the controllability, reliability, and efficiency of seabed mineral collection. The ROV-based collector, being designed to have certain positive buoyancy, is connected with the seabed collector through an articulated flexible steel frame. It is pushed by a thruster on the working surface at a certain height from the seabed, and tows the seabed collector to mine on the surface of the seabed. Combining the advantages of the seabed towed collector and the self-propelled collector, the ROV-based collector is no longer subject to the restrictions imposed by the complex topography and slope of seabed, and can prevent its own chassis from skidding and sinking on the sedimentary layer and the uncontrollability of the mining route. This greatly mitigates the disturbance of seabed sediment by ore collection, thus greatly reducing the impact of ore collection on the seabed environment, and the height of the collecting mechanism from the ground also becomes controllable.

In the deep-sea mining system composed of a ROV-based collector, lifting pipeline, and an electric lift pump, the electric lift pump is installed at a depth of about 150 meters from the seabed to form the lifting pump station, and it plays the role of counterweight to the vertical hard lifting pipe. Replacing the buffer, the lifting pump station combines two sets of independent pipeline transportation systems connected in an open-loop way in the buffer into a closed-loop lifting transportation system. Therefore, compared with the pipeline lifting system with a buffer currently under research, this novel system reduces many intermediate links of the mining system, lowers the load on the lifting pipeline, and improves the strength of the lifting pipeline, making the mining system more efficient and reliable.

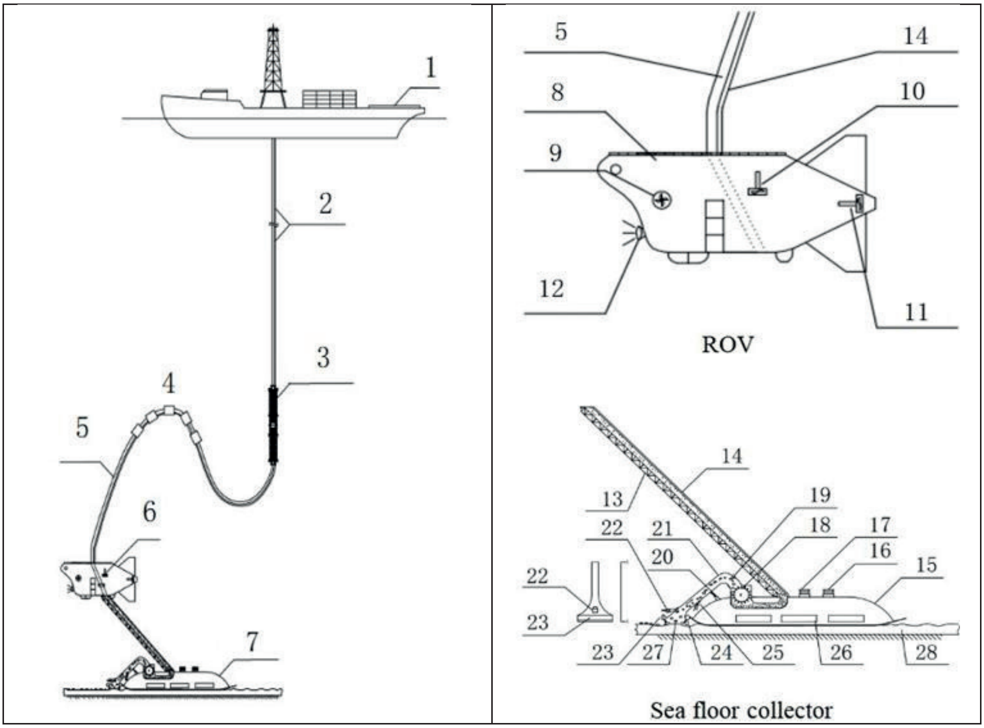

Fig. 3 Schematic diagram of the ROV-based deep-sea mining system

1. surface mining vessel; 2. steel lifting pipe; 3. multi-stage electric lift pump set; 4. buoyant; 5. lifting hose; 6. submersible ROV; 7. the seabed collector; 8. ROV body; 9. lateral thruster; 10. vertical thruster; 11. tail thruster; 12. ROV-based measurement and control system; 13. articulated flexible rigid frame; 14. underwater cable; 15. submarine sliding body; 16. hydraulic station; 17. jet water pump; 18. toothed roller crushing mechanism; 19. hinge shaft; 20. telescopic rod; 21. draft tube; 22. front-row ascending jet nozzle; 23. front-row disturbing jet nozzle; 24. rear-row disturbing jet nozzle; 25. rear-front-row ascending jet nozzle; 26. Buoyant 2; 27. seabed minerals; 28. seabed sediment.

According to the seabed mining mode, the ROV tows the seabed collector on the working surface at a certain height from the seabed through the articulated flexible steel frame, making it slide orderly on the seabed. The seabed mineral ore collected by the collecting mechanism of the collector is crushed by the crushing mechanism, sucked by the lift pump from Fig. 1 Schematic diagram of a deep-sea mining system Fig. 2 Evolution of deep-sea mining system the inlet of the lifting conveying hose, and lifted to the surface mining vessel by the hard lifting pipe through the lift pump after passing through the lifting hose.

The ROV-based collector consists of a submersible ROV and a towed seabed collector, which are connected with each other through an articulated flexible steel frame. The seabed collector is towed by an ROV and slides along the surface of the seabed, following the seabed mining mode. Its ground pressure is controlled to be lower than the bearing capacity of seabed sediment. It is suggested that ground pressure should be controlled under 2 kPa between the seabed collector and the surface of seabed sediment by the preliminary numerical calculations. This could ensure that the seabed collector slides on the seabed surface without sinking, thus keeping the height of the mining mechanism from the seafloor constant and improving the efficiency of the mining mechanism. Ascending the submersible ROV and increasing the angle of the articulated flexible rigid frame can ensure sufficient turning ability for the collector towed by the submersible ROV.

As for the difficulties existing in the research of a deep-sea mining system that adopts a self-propelled seabed collector, this paper introduces a significantly innovative ROV-based intelligent deep-sea mining system. The author is studying such key technologies as the dynamic modeling of an overall coupling system of the mining system, an optimal design of the overall linkage dynamic characteristics and matching parameters in a complex marine environment, the characteristics of an integrated pipeline system in transporting coarse slurry, and the requirements of a mining system for ROV working characteristics. With the purpose of forming novel deep-sea mining technology systems and theories, these efforts are aimed at promoting the existing deep-sea mining technologies to evolve into a new generation of intelligent deep-sea mining systems.

4. CONCLUSIONS

Compared with other deep-sea mining systems currently under research, this ROV-based deep-sea mining system has the following advantages:

(1) The ROV-based deep-sea mining system replaces the buffer in the deep-sea mining system developed at home and abroad with a lift pump station. The conveying hose and the hard lifting pipe are directly connected to the lift pump station, forming a closed pipeline system extending from the seabed collector to the surface mining vessel, which improves the efficiency of the electric lift pump. The parameters of the hose and the hard pipe could be simply matched by selecting hose and hard pipe of reasonable diameters. The elimination of the hose transfer pump, feed bin, and feeder makes the ROV-based deep-sea mining system simple, reasonable, highly reliable, and efficient in lifting and transportation.

(2) Comprehensively combining the advantages of the self-propelled seabed collector and the towed collector, the submersible ROV-based collector is no longer subject to the restrictions imposed by the complex topography and slope of the seabed, and prevents its own chassis from skidding on and sinking into the sedimentary layer. This greatly mitigates the disturbance of seabed sediment by ore collection, enables the seabed collecting mechanism to intelligently adapt to the seabed topography, and intelligently addresses the problem that the height of the collecting mechanism from the seafloor is difficult to control, thus improving the collection efficiency.

(3) By controlling ROV, the relative positions of a surface mining vessel, a lift pump station, and a ROV-towed seabed collector in the mining system become controllable, thus a seabed collector can follow a predetermined mining route within the area allowed by a mining vessel. This enables the whole system to become more intelligent, operating in a coordinated, harmonious, and adjustable way.

ACKNOWLEDGEMENT

This research work was supported by the National Natural Science Foundation of China (Grant No. 52071138). The authors express appreciation to the National Natural Science Foundation of China.

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