IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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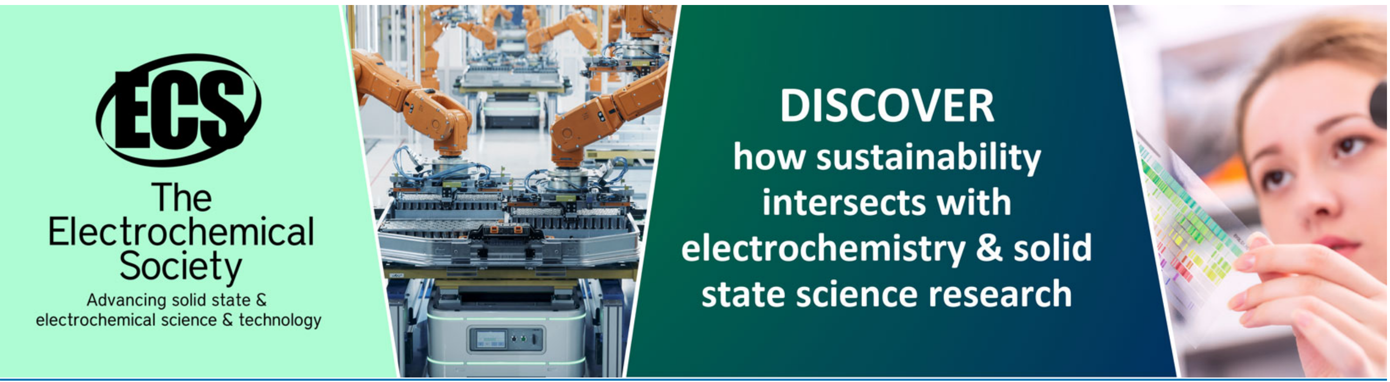
To cite this article: Y Q Ge *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **861** 072008



Development and Sea Trial of the Terrain Monitoring Device Based on MEMS Sensing Array

Y Q Ge[1], J W Chen[1,*], C Cao[1], J M He[1], P Zhou[1], F Gao[1], C Y Xu[2]
[1] Ocean college, Zhejiang University, Zhoushan, China
[2] College of Engineering, Shantou University, Shantou, China
* corresponding author's e-mail address: arwang@zju.edu.cn

Abstract: Seabed terrain monitoring is an important and essential part of the environmental monitoring and early warning system in the process of trial production of natural gas hydrate. Since the first exploitation of natural gas hydrates in the South China Sea in 2017, China has once again succeeded in trial production of combustible ice in the sea area using horizontal well drilling technology in March 2020, which has achieved another major achievement in the process of industrialization. Therefore, for the purposes of ensuring green and safe development of natural gas hydrate, it is necessary to carry out research on the monitoring technology and equipment of seabed topography changes. This paper proposed a submarine terrain monitoring system based on MEMS (Micro-Electro-Mechanical System) sensor array. In November 2020, the developed device was successfully deployed in the Shenhu area of the South China Sea to perform in-situ monitoring mission for 6 months. Sea trial results proved that the terrain monitoring device can successfully monitor the subsidence and uplift of the seabed and provide a guarantee for the safe exploitation of natural gas hydrates.

1. Introduction

Natural gas hydrate is an important green (low-carbon) energy source, which is an ice-like substance comprised of water and low-molecular-weight gases, usually methane, that forms within sediment under conditions of low temperature, high pressure and adequate gas concentration [1-2]. Gas hydrate will decompose and generate a large amount of methane gas and water if phase equilibrium condition changes (temperature rise or pressure decrease), leading to gas accumulation and liquefaction formation, reducing the strength of the sediments, and inducing large-scale seabed instability, collapses and other engineering accidents and geological disasters [3]. The monitoring and evaluation of the environmental effects in the development process of natural gas hydrates is an important work that all countries in the world must carry out before, during and after mining. It is currently the main development direction to conduct in-situ and long-term monitoring of the seafloor environment, especially the deformation of the seafloor formation, analyzing and studying the monitoring data to realize the natural gas environmental assessment.

The existing marine geophysical instrument (multi-beam sounder, side scan sonar and et al.) can achieve seabed terrain monitoring [4], but, these kind of equipment have long observation period and low spatial resolution, and generally need to be carried by a scientific research ship or ROV and AUV, making it difficult to achieve long-term in-situ monitoring. A servo-accelerometer system and pressure sensors have been applied to measure the seabed stability and seabed subsidence or uplift during the methane hydrate production in Nankai Trough of Japan [5-6]. Regardless of the servo-accelerometer system or pressure sensors, the measurement area is limited, only a single point measurement can be achieved. Recently, submarine cabled observatory have developed rapidly, many countries have established cabled observatory to in-situ long-term monitoring of the environment in the hydrate trial production area [7]. However, the submarine cabled observatory is commonly fixed on the seabed, with poor mobility, high cost, and difficult deployment. In summary, there is still a lack of a system that can achieve in-situ, long-term surface shape monitoring, which can well monitor the terrain deformation of the seabed.

Compared with traditional sensors, MEMS (Micro-Electro-Mechanical System) sensors have the advantages of small size, light weight, low power consumption, low cost, high reality, easy intelligence and digitization [8], and the deformation monitoring technology composed of it has also been gradually introduced in the field of geological engineering measurement [8-9]. The Canadian company MEASURAND uses a MEMS accelerometer array to monitor the spatial shape of the object to be measured [8]. The company's SAA (Shape Accel Array) monitoring system has been widely employed on land, including monitoring applications such as tunneling process deformation, dam deformation, landslides and seabed deformation in the shallow water area. Prior et al. [10] Used a three-axis MEMS acceleration sensor to monitor the deformation of the Yellow River Delta due to storm-induced submarine landslides. Uchimura et al. [11] apply MEMS tilt sensors and volumetric water content sensors for landslide monitoring (on land). These sets of equipment have been deployed at several slope sites in Japan and China, and its feasibility and reliability in monitoring landslides have been proved in field application.

This paper for the first time verifies the feasibility of applying MEMS sensor arrays to deep-sea terrain subsidence monitoring, deploying the developed underwater device in the Shenhu area of the South China Sea to perform in-situ monitoring mission for 6 months, not only ensure the safe exploitation of hydrates in the sea, but also provide new methods and related technologies for the monitoring of the seafloor terrain.

2. Design of Terrain Monitoring System Based on MEMS Sensor Array

The terrain monitoring system based on the MEMS sensor array is composed of multiple MEMS 6-axis sensors which arranged on the seafloor surface. There are a total of four arrays arranged vertically, where 21 sensors with a pitch of 1 meter are arranged as a diagonal, so that a square area of 30×30 square meters can be monitored (see figure 1). Each sensing node consists of a signal conversion module and a MEMS sensor. Because the signal transmission distance is more than 20 meters, the RS485 bus is used to increase the communication reliability. Based on the RS485 bus, we adopt an inquiry-type acquisition method by setting different RS485 physical addresses for the sensor nodes of the network to inquire the sensor data of each node in turn (see figure 2).

Due to the time drift caused by the difference in the physical properties of the acquisition system, it is difficult to ensure that the synchronous acquisition can be maintained after working for six months, even if all of them start working at the same time. Therefore, the control system is set in the centre of the entire system, which is responsible for time synchronization. The control system sends a time synchronization command through the RS485 bus, sending the time in the chip to the acquisition board, so that the acquisition board maintains synchronous acquisition and record the time (see figure 2).

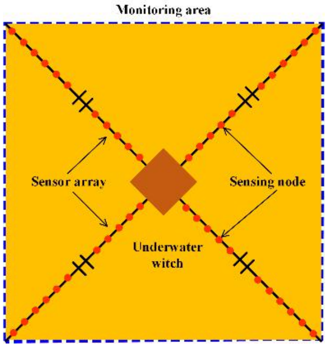


Figure 1. The solution of array deployment plan and monitoring area.

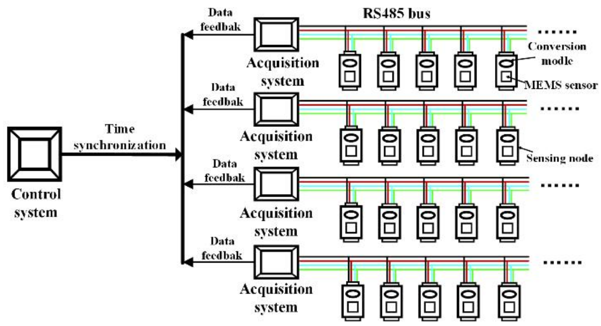


Figure 2. The acquisition and control system.

3. The Terrain Reconstruction Method

3.1 The Arc Model

Firstly, we focus on the morphological reconstruction of the sensor array. Since the device is mainly used for the subsidence monitoring of the seafloor terrain, as for the sensor array, the two-dimensional modelling can reflect its overall shape. The MEMS sensor local reference system is $\{G_s\}$ $|O_s, X_s, Y_s, Z_s|$. The calculation of the tilt angle θ is based on the gravitational, *g*. The change of seabed terrain is considered slow. When the MEMS accelerometer is in the constant motion or a static state, the line acceleration $a \cong 0$. The acceleration vector modulus of the MEMS sensor, $A^T = [a_x, a_y, a_z]$ can be expressed as equation (1), and the pitch angle θ can be expressed as equation (2) [12].

$$g^2 = a_x^2 + a_y^2 + a_z^2 \tag{1}$$

$$\theta = sin^{-1}(-a_y/g) = sin^{-1}\left(-a_x\Big/\sqrt{a_x^2+a_y^2+a_z^2}\right) \tag{2}$$

where a_x, a_y and a_z are the three component of acceleration of the MEMS sensor.

Due to the sensor array is flexible, it is most appropriate to approximate the shape between the two sensors with an arc, where the sensors are arranged at equal intervals. The starting point of the array (the position of the first sensor) is known. We can define the coordinates of the end point (the position of the next sensor) by calculating the arc radius with centre coordinates, and so on [12-13]. The modelling is shown in the figure 3.

$$\alpha_i = \theta_{i+1} - \theta_i \tag{3}$$

Where θ_i is the pitch angle of the sensor *i* around Y axis, which is set as a positive sign in accordance with the right-hand principle. α_i is the central angle of the arc between P_i and

P_{i+1}. If the distance between the sensors is l, then the radius of the arc is:

$$R_i = l/\alpha_i \tag{4}$$

The centre C_i in the coordinate system where P_i is the origin is:

$$C_i = [0,0,R_i]^T \tag{5}$$

When $\alpha \neq 0$, P_{i+1} in the coordinate system where P_i is the origin is:

$$P_{i+1}^i = [dx,0,dz]^T = [R_i sin\alpha_i,0,R_i - R_i cos\alpha_i]^T \tag{6}$$

When $\alpha = 0$, P_{i+1} is:

$$P_{i+1}^i = [l,0,0]^T \tag{7}$$

P_{i+1}^0 in the system coordinate $\{G\}$ (O is the origin) is:

$$P_{i+1}^0 = Q_i^0 P_{i+1}^i + P_i^0 \tag{8}$$

Where P_i^0 is the coordinate of the sensor i in the system coordinate, Q_i^0 is the bending matrix from the system coordinate to the sensor coordinate, which satisfies:

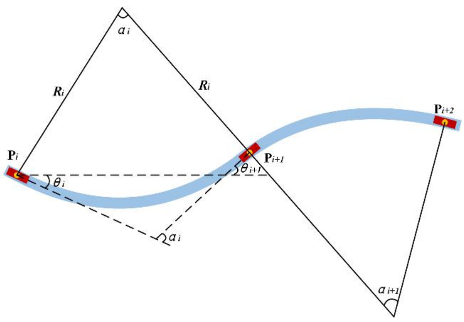
$$Q_1^0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$Q_{i+1}^0 = Q_i^0 Q_{i+1}^i (i \geq 1) \tag{10}$$

$$Q_{i+1}^i = \begin{bmatrix} C\theta_{i+1}^i C\varphi_{i+1}^i & C\theta_{i+1}^i S\varphi_{i+1}^i & -S\theta_{i+1}^i \\ -S\varphi_{i+1}^i C\phi_{i+1}^i + C\varphi_{i+1}^i S\phi_{i+1}^i S\theta_{i+1}^i & C\varphi_{i+1}^i C\theta_{i+1}^i + S\theta_{i+1}^i S\phi_{i+1}^i S\varphi_{i+1}^i & C\theta_{i+1}^i S\phi_{i+1}^i \\ C\varphi_{i+1}^i S\theta_{i+1}^i C\phi_{i+1}^i + S\varphi_{i+1}^i S\theta_{i+1}^i & -S\theta_{i+1}^i C\varphi_{i+1}^i + S\theta_{i+1}^i C\phi_{i+1}^i S\varphi_{i+1}^i & C\phi_{i+1}^i C\theta_{i+1}^i \end{bmatrix} \tag{11}$$

Where $C(*)$ and $S(*)$ are shortened for $\sin(*)$ and $\cos(*)$, θ_{i+1}^i, φ_{i+1}^i and ϕ_{i+1}^i are:

$$\begin{cases} \theta_{i+1}^i = \theta_{i+1} - \theta_i \\ \varphi_{i+1}^i = \varphi_{i+1} - \varphi_i \\ \phi_{i+1}^i = \phi_{i+1} - \phi_i \end{cases} \tag{12}$$



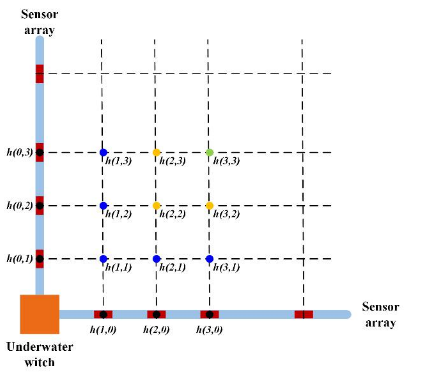


Figure 3. The arc model (The blue one is the sensor array, while the red one is the MEMS sensor).

Figure 4. Interpolation schematic.

3.2 Terrain Reconstruction

To achieve surface monitoring of the seafloor terrain, we have to deploy multiple arrays.

We adopt the method of radial placement. As shown in figure 1, four arrays are placed perpendicular to each other, which form four diagonal lines to monitor a square area. The position of the underwater winch is the reference point.

h is defined as the displacement of the point in the monitoring area in the Z direction, where $h > 0$ means terrain uplift, $h < 0$ means terrain subsidence. The terrain of the sensing node on the sensor array can be accurately monitored and obtained (see section 3.1), for the other points in the monitoring area, we adopt the following interpolation. As shown in figure 4, $h(0,:)$ and $h(:,0)$ have been obtained, then the blue, yellow and green points can be solved as:

$$\begin{cases} h(0,0) = 0 \\ 1 \leq i \leq m \\ 1 \leq j \leq m \\ h(i,j) = \frac{1}{2}(h(i-1,j) + h(i,j-1)) \end{cases} \tag{13}$$

Where m is the number of points divided by sensor array, the larger the m, the smoother the reconstructed surface. A “triangle” area can be reconstructed through two adjacent arrays, while a “square” area can be reconstructed by four mutually perpendicular arrays to realize the three-dimensional reconstruction of the terrain of the monitoring area.

4. Experiment and results

4.1 35Mpa pressure environment test

To verify the feasibility of the underwater winch and sensor array in the 3000-meter seafloor application and the stability of the communication between the acquisition system and control system, a pressure test was conducted in the Ocean College of Zhejiang University on September 14, 2020. The overall process of the pressure test was to put the underwater winch into the pressure cylinder, raise the pressure to 35Mpa, and hold the pressure for 18 hours. The pressure test process is shown in the figure 5 and figure 6.

The sensor array collected data under normal pressure can be compared with the data under high pressure (35Mpa), where the error between the two was analysed to verify the influence of the pressure environment on the accuracy of the sensor. The error of sensor array position between 0Mpa and 35Mpa is shown in table 1.

Table 1. Error of sensor array position between 0Mpa and 35Mpa.

Sensor array	Mean absolute error (mm)	Root mean square error (mm)	Maximum absolute error (mm)
1#	0.475	0.713	1.89
2#	0.122	0.186	0.429
3#	1.10	1.49	2.31
4#	0.884	1.19	2.47
overall	0.645	1.02	2.47

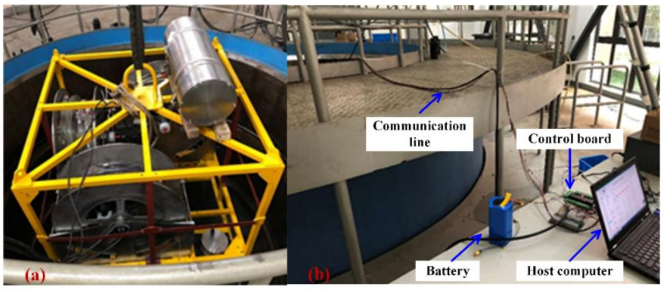


Figure 5. (a) Underwater winch hoisting; (b) connection between host computer and control board.

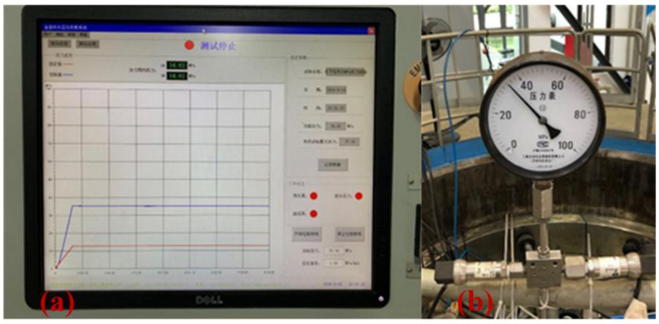


Figure 6. (a) Pressure curve; (b) Pressure indicator.

4.2 Sea trial

The seabed terrain monitoring system was carried on the 202007 voyage of the China Geological Survey "HYDZ6" scientific research vessel on November 18, 2020 to conduct equipment deployment and function verification sea trials. On the night of the 19th, we arrived at the Shenhu trial mining area in South China Sea, where the water depth was about 1200 meters. As shown in figure 7, the vessel-borne steel cable hoist the underwater winch to the seabed at a speed of about 50 meters per minute. After the device reached the seafloor, the acoustic communicator was used to connect the system and confirm the working status of the underwater winch.

The Haima-2 ROV dived to the seafloor to find the underwater winch according to the position information recorded by the research ship with front sonar. The high-definition camera was used to confirm whether the appearance and the state of the underwater winch is normal. Finally, ROV's manipulator pull four sensing arrays out sequentially, making them placed vertically against the seabed surface, as shown in figure 8.

After the ROV completed the operation, the acoustic communicator was used to read the sensor data of four arrays. Taking the position of the underwater winch as a reference and combining with the initial status information measured in the laboratory, the position changes of the sensors on the four arrays were calculated, which are shown in Table 2.

It was not difficult to find from the table that the terrain here was relatively flat, which was consistent with the scene observed by ROV's high-definition camera.

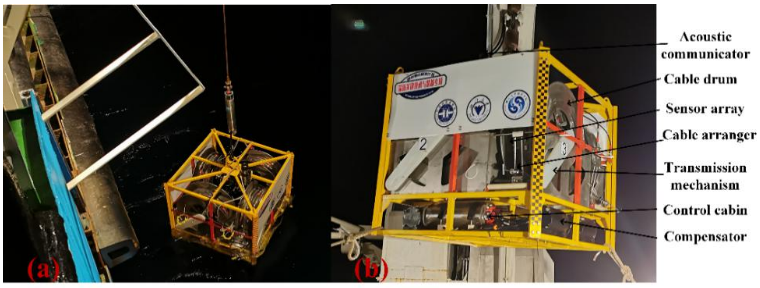


Figure 7. (a) Underwater winch hoisting; (b) Underwater winch.

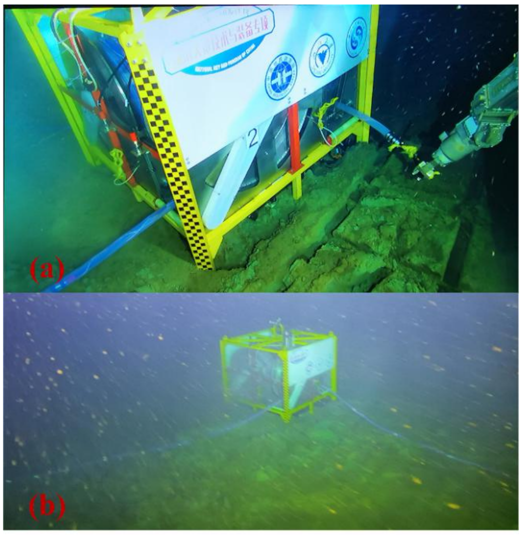


Figure 8. (a) ROV's Manipulator pull out the sensor array; (b) Sensor array deployment.

Table 2. Subsidence of each point on the sensor array (absolute value)

Sensor array	Mean displacement (cm)	Maximum displacement (cm)
1#	0.6	1.45
2#	1.72	3.04
3#	0.58	1.39
4#	0.29	1.12
overall	0.80	3.04

5. Conclusion

Aiming at the problem of in-situ long term monitoring of terrain changes of natural gas hydrate mining area, this paper designs a submarine terrain monitoring system based on MEMS sensor array. In the meantime, the way for terrain reconstruction was proposed. Finally, the terrain monitoring device was deployed in the Shenhu area of the South China Sea, and the collected data successfully reconstructed the initial state of the monitoring area. Future research will be focus on analysing the impact of hydrate trial mining on the changes of the seafloor terrain.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (41976055), National Key Research and Development Program of China (2017YFC0307703), Finance Science and Technology Project of Hainan Province (ZDKJ202019), and Key Research and Development Project of Zhejiang Province (2018C03SAA01010).

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