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Deep Learning-Assisted Triboelectric Smart Mats for Personnel Comprehensive Monitoring toward Maritime Safety

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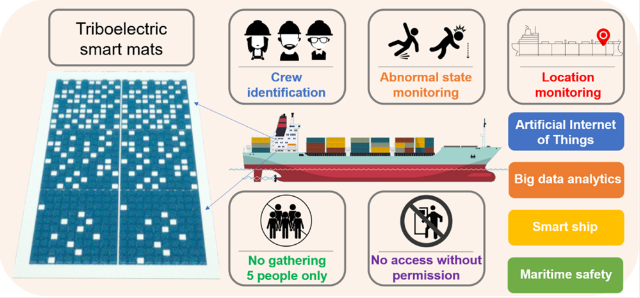
ABSTRACT: Monitoring the crew of a ship can be performed by combining sensors and artificial intelligence methods to process sensing data. In this study, we developed a deep learning (DL)-assisted minimalist structure triboelectric smart mat system for obtaining abundant crew information without the privacy concerns of taking video. The smart mat system is fabricated using a conductive sponge with different filling rates and a fluorinated ethylene propylene membrane. The proposed dual-channel measurement method improves the stability of the generated signal. Comprehensive crew and cargo monitoring, including personnel and status identification, as well as positioning and counting functions are realized by the DL-assisted triboelectric smart mat system according to the analysis of instant sensory data. Real-time monitoring of crews through fixed and mobile devices improves the ability and efficiency of handling emergencies. The smart mat system provides privacy concerns and an effective way to build ship Internet of Things and ensure personnel safety.



KEYWORDS: *smart mat, triboelectric nanogenerator, deep learning, crew monitoring, maritime safety*

■ INTRODUCTION

Shipping is an important and international industry. Workers on ships may encounter accidents and face dangerous situations. Thus, the foundation of maritime safety is personnel safety.[1,2] Seafarers often face many uncertain risk factors when working on board, such as asphyxiation in a confined cabin, sudden illness, and ship security issues. As the coronavirus epidemic is raging around the world, the issue of ship epidemic prevention and control has attracted increasing attention.[3] Improving the monitoring level of a ship can effectively improve the safety level of the ship and the safety sense of the crew. The Internet of Things (IoT), characterized by overall perception, reliable transmission, and intelligent processing, has been widely used in modern security systems.[4−6] Combining the IoT with ships to create a ship IoT composed of a large number of sensors can achieve comprehensive monitoring of crews to ensure the safety of the crew and ship in an epidemic environment.

Camera-based surveillance systems are the most common means of identifying personnel information and personnel status on board. However, high cost, complicated maintenance work, and personnel privacy concerns are the main reasons that restrict their application.[7,8] Optical equipment such as infrared and laser scanners provide solutions without infringing on personnel privacy.[9−11] However, the detection target is easily blocked by obstacles, resulting in the loss of information and discontinuous monitoring.[12] Each person has their own unique walking gait, and it is conceivable to obtain relevant information of a person from human stepping using tactile/contact sensors.

Triboelectric nanogenerators (TENGs) based on the conjunction of contact electrification and electrostatic induction have been proven to enable a broad range of sensing applications including tactile/contact sensing.[13−21] TENGs have been demonstrated to have a low cost, simple structure, easy fabrication, good scalability, and diversified material choices.[22−25] A mat, as a small piece of thick carpet or strong material that is used to cover part of a floor, can be placed at the door of almost all cabins on a ship, and the crew will step on it when entering the cabin. Thus, combining mats with TENG-based tactile sensors or designing a mat-type TENG tactile sensor to detect foot-stepping information is a solution to realize self-powered, low-cost, and large-scale crew monitoring. Furthermore, the relevant information can be obtained without privacy and obstructive issues, which can be further used to prevent the gathering of crew, an effective means to avoid the spread of the virus. It is also of great

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significance to count the number of crew and keep track of their identities in the cabin for safety records and issuing reminders.

Currently, most tactile/contact sensors can only recognize physical features such as location and pressure maps. However, for more complex personnel information recognition, this elementary perception function cannot be applied. To obtain personnel identification and status information from sensor data, advanced artificial intelligence (AI) technologies based on deep learning (DL)-assisted data analytics can be applied to a personnel monitoring system.[26−29] As the fusion of AI and IoT, an AI of things (AIoT) system can intelligently process data obtained by sensors.[30−32] By applying DL data analytics to the sensory information, personalized authentication and object status can be identified. A convolutional neural network (CNN) can learn to extract vital features from the original sensing signals, which provides a way to efficiently analyze audio, video, and image and provide a fast response. Introducing AI technology into a mat-based crew monitoring system is a way to realize personnel identification, personnel status monitoring, and locating. AIoT is a promising technology to promote intelligent levels of crew monitoring, ship security, epidemic prevention systems, and maritime safety.

In this study, a DL-assisted smart mat system is developed and investigated to monitor crew, and unauthorized persons and to count the number of people in a cabin. This smart mat system is composed of several triboelectric-based smart mat units. Each smart mat unit is made of a conductive sponge and a fluorinated ethylene propylene (FEP) membrane. Conductive sponge electrodes with different filling rates are designed by referencing the quick response (QR) code system. When a person steps on the parallel connected smart mats, a distinguishable and stable signal can be generated. By judging the characteristics of the signal crest, the statistics of the number of people in the cabin can be realized. The signal generated from a smart mat corresponds to a certain cabin, enabling location mapping on board. More importantly, identity and status information associated with walking gait patterns can be extracted from the generated signals using the CNN model. Moreover, acquiring data from smart mats for analysis can save large amounts of computing resources compared to traditional camera-based identification processing systems, and fast data analytics for real-time monitoring on board can be achieved.

RESULTS AND DISCUSSION

Structure and Working Mechanism of the Smart Mat.

Whether a crew member is in a living cabin of the accommodation deck (Figure 1b) or an enclosed cabin (Figure 1c) of the engine room, the personnel state needs to be monitored for safety reasons. Figure 1a shows the application scenario of the smart mat system. The proposed smart mats for crew comprehensive monitoring are shown in Figure 1d, where the enlarged views show a schematic of the conductive sponge and the triboelectric layer of the smart mat, which is composed of a conductive sponge and FEP membrane. The dimensions of the mat unit with different filling rates are shown in Figure S1. The mat is encapsulated in a polyvinyl chloride membrane for waterproofing and cleaning. A flexible and elastic conductive sponge is used as the substrate and electrode. This makes the smart mat have the same cushioning capacity as an ordinary door mat. Meanwhile, the conductive sponge has a long conductive validity period, and the conductive performance is not affected by temperature and humidity. Since the conductive sponge can be compressed, the deformation produced by different people is different. This results in a smart mat with a larger dynamic response range and higher sensitivity.[33] Every smart mat unit is a contact sensor. The distinguished signals can be generated when a person steps on the three pairs of mats with different filling rates. From a practical point of view, the filling rates of the three pairs of mats are 50, 70, and 90%. The filling rates of the conductive sponge are changed by punching holes (2.5 × 2.5 mm^2) in it. A photograph of the smart mats is shown in Figure S2a, and the surface morphology images of the conductive sponge and FEP membrane are shown in Figure S2b.

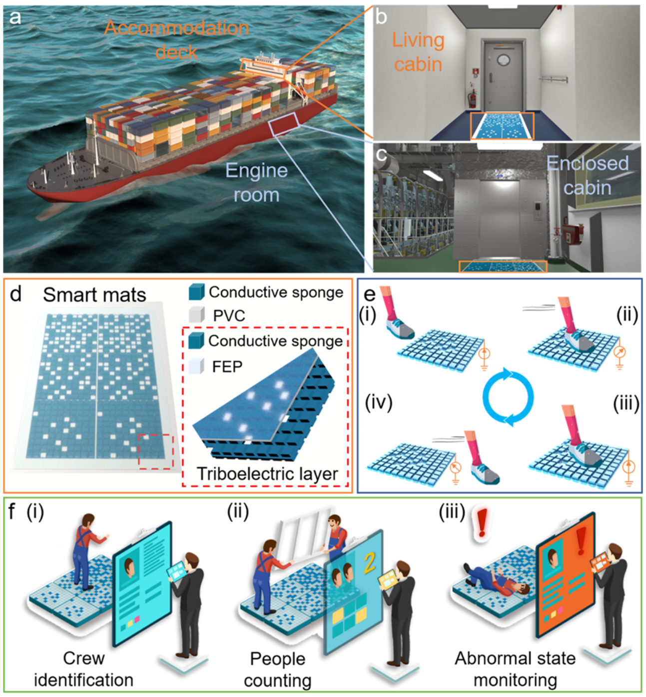

Figure 1. DL-assisted triboelectric smart mat systems for seafarer monitoring and its applications. (a) Potential conceptual application of smart mats in the maritime industry. Enlarged views of (b) living cabin and (c) enclosed cabin where crews should be monitored for epidemic prevention and personal safety. (d) Assembled triboelectric smart mats with a 3 × 2 arrangement, where the enlarged views show the triboelectric layer fabricated by conductive sponge and FEP. (e) Working mechanism of the triboelectric smart mat unit. (f) Applications based on the AIoT sensing system.

When a person steps on the smart mat unit, as shown in Figure 1e, a triboelectric signal is generated by the contact of the FEP and the conductive sponge according to the triboelectric contact-separation mechanism. The detailed charge generation process is shown in Figure S3. In the initial state, the sponge is fluffy. The conductive sponge is compressed when a person steps on the smart mat unit. The contact area between the FEP and conductive sponge is increased; thus, an electric signal is generated. The triboelectric contact sensor (smart mat unit) can be treated as a variable capacitor model, in which the open-circuit voltage can be expressed as $V_{oc} = Q/C$, where Q is the charge generated by contact electrification, and C is the equivalent capacitance of the smart mat unit. The parallel-connected smart mat units share the same equivalent capacitance in the output generation.

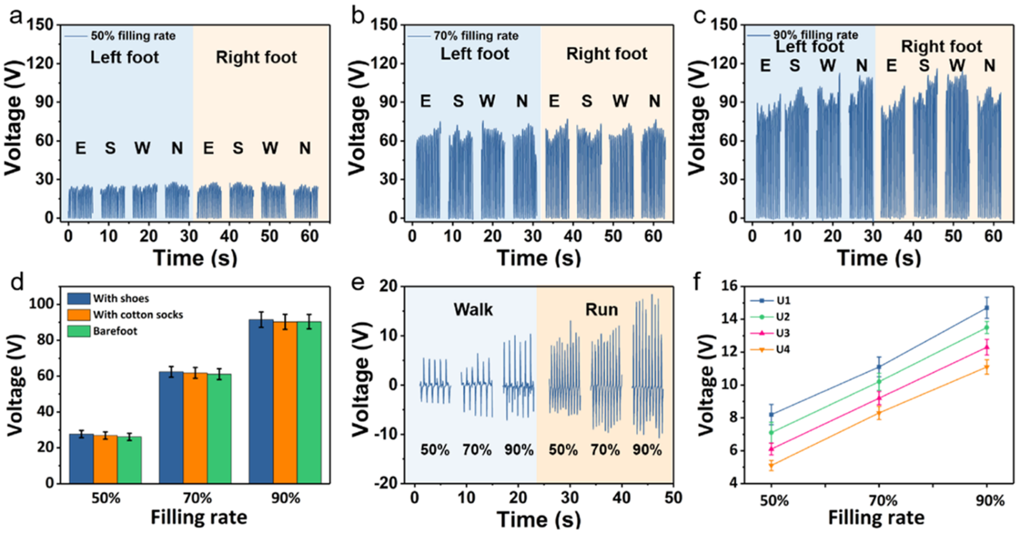

Figure 2. Characteristics of the smart mat unit. The voltage signals generated by repeatedly stepping on the smart mat unit (from four directions with left and right foot) with electrode filling rates of (a) 50, (b) 70, and (c) 90%. (d) Effect of different step materials worn by the same user on the average output voltage. (e) Effect of a user walking and running on the output of the voltage of the smart mat unit with different filling rates. (f) Effect of different users on the output voltage of a smart mat unit.

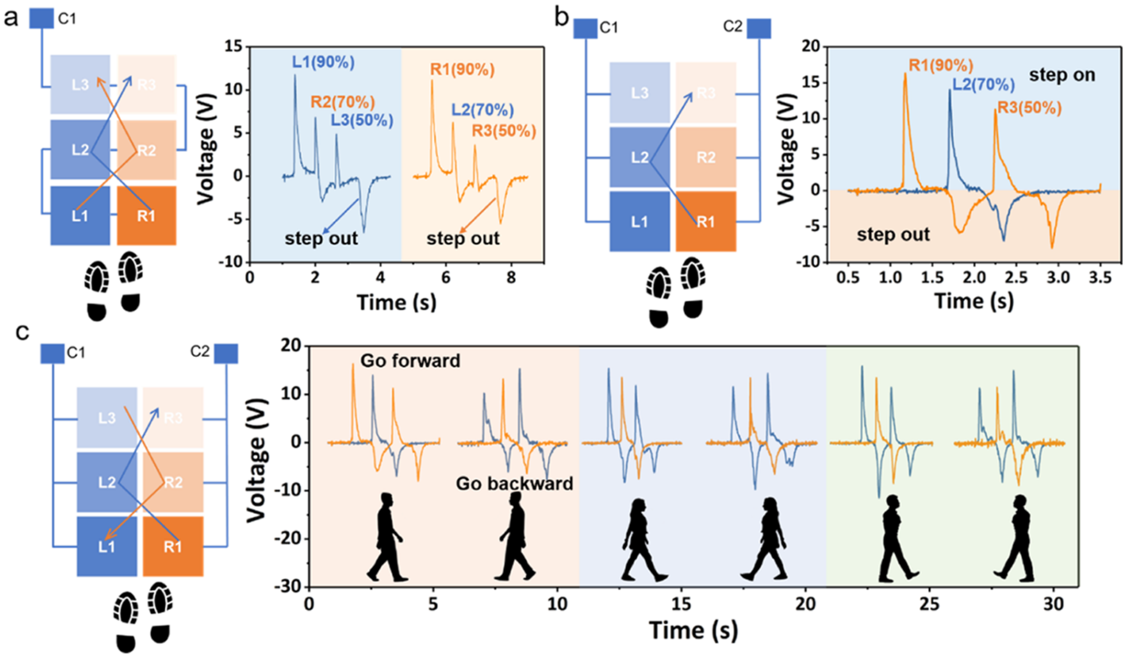

Figure 3. Output characteristics of the mat unit series and parallel. (a) Schematic diagram of six smart mat units connected in series and their output characteristics. (b) Schematic diagram of six smart mat units connected in parallel and their output characteristics. (c) Characteristics of the generated signals by different users walking forward and backward.

In this regard, different magnitude signals can be generated by different filling rate mat units. The higher filling rates of the conductive sponge correspond to a larger contact area when a person is stepping on the smart mat, which results in more charge being generated. By integrating a CNN, counting module, location module, and communicating module, the smart mat system can be applied on board for personnel comprehensive monitoring and epidemic prevention functions, as shown in Figure 1f.

Characteristics of the Smart Mat Output and Connection Method. The stability of the output signal is an important parameter of the smart mat. Theoretically, the output of the smart mat will not be affected by external environmental factors. The output voltage signal from different filling rates of the smart mat unit is measured by stepping on the mat repeatedly by both the right and left feet in four directions. The output voltage signals are shown in Figure 2a–c, which represent that higher filling rates result in higher outputs. Experiments on a user with different stepping materials are conducted. As shown in Figure 2d, the output voltage shows a similar increment trend and average magnitude. This indicates that if a person steps on the mat, the mat sends out a signal without being affected and restricted by the stepping material. People walking or running across the mat apply different accelerations to the mat. According to the results of Pang et al.[34] and Chen et al.,[35] there is a linearly

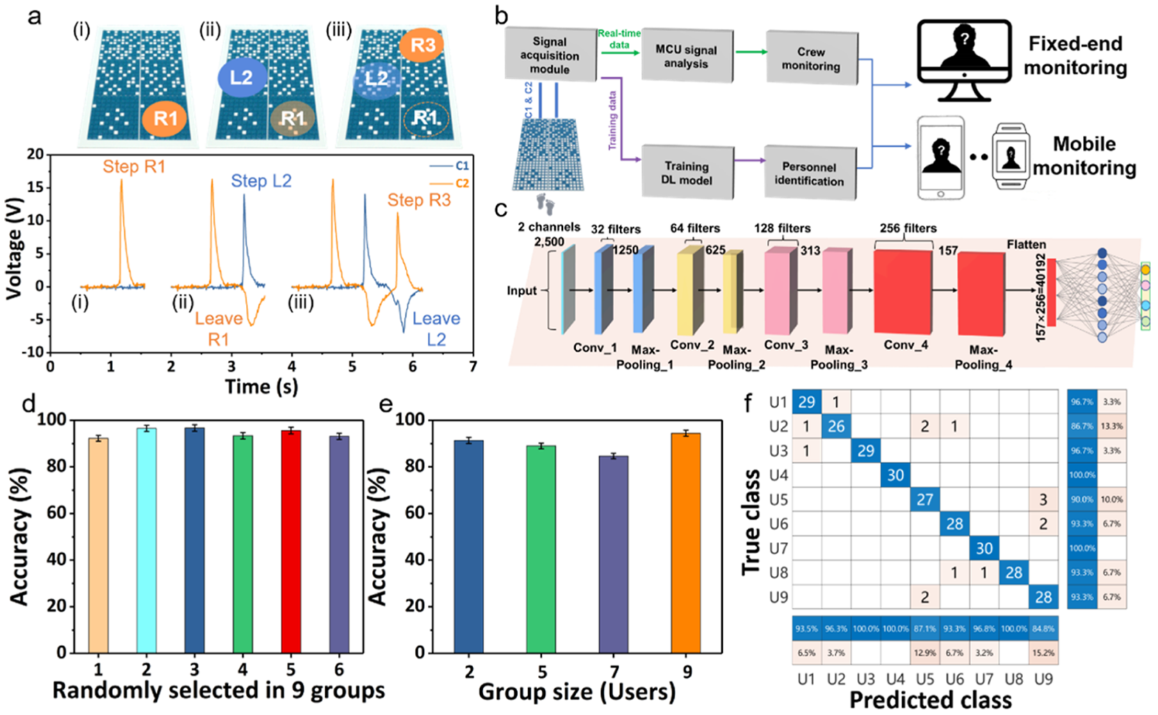

Figure 4. Smart mats integrated with a DL module for data analytics. (a) Real-time trajectory tracing and position sensing. (b) Schematic diagram of the smart mat monitoring system for personnel identification. (c) Detailed structure of the CNN training model. (d) Classification accuracy of six groups with five randomly selected users. (e) Classification accuracy of four data sets with group size increasing from 2 to 5, 7, and 9 users. (f) Confusion matrix for personnel identification of nine users.

proportional relationship between the acceleration and the output voltage. As shown in Figure 2e, running on the smart mat unit shows a higher output and frequency than walking on it. Smart mats can also be adopted to monitor the activity of a person as different activities have distinguishable output signals on the overall magnitude and frequency. Due to the unstable output of the smart mat, a regulating circuit is applied to stabilize the output voltage of the mat. A stable and clear electrical signal is more conducive to subsequent processing and DL module training. Detailed information on the regulating circuit is shown in Figure S4. Four persons of different weights and genders are selected as test subjects. Their weights are 50, 65, 70, and 75 kg. When each user steps on mat units with different filling rates, the mat outputs a signal with obvious discrimination, as depicted in Figure 2f. A distinguishable and stable signal can be generated by different users stepping on the mat.

Six smart mat units with three filling rates are used to make up a smart mat array. As shown in Figure 3a, the six mat units are numbered, and the shade of the color is used to indicate the filling rate. With the series connection of the six fabricated smart mats (50, 70, and 90%) to form a minimalist output channel, the output from the smart mat array is first tested by walking across the smart mats with two cases, that is, right foot first and left foot first. Since stepping on two mats with two feet at the same time may cancel out the charges generated by the mats and overlap the voltage signal, the signal becomes unstable, as shown in Figure 3a. It is not reasonable to use a series connection method here. However, it can be seen from the signal graph that the signals generated by the mats with the same filling rate are roughly the same.

To promote the output signal of the smart mats, the parallel dual-channel measurement is utilized and investigated, as shown in Figure 3b. A positive pulse is generated from stepping on smart mat unit R1, while a negative pulse is generated when stepping out of R1, as depicted in Figure 3b. Similarly, the same signal waveform can be produced in the stepping motion on L2 and R3. A more stable voltage signal can be generated by utilizing the parallel dual channel measurement method, which is conducive to subsequent signal analysis and processing. This measurement method is used in subsequent experiments. Each person's walking gait is different, and the signal generated by each person stepping on the mat is also different. As shown in Figure 3c, the output signals from three persons walking forward and backward on the smart mats are obviously different. Identity information associated with walking gait patterns can be extracted from the output signals using the CNN. Simultaneously, according to the increment–decrement trend of the waveform, people entering or leaving a cabin can be identified to realize the function of counting the number of people in the cabin. The dimension of the smart mat unit is small, making it impossible for two people to step on it simultaneously. Even if two people step on the smart mats at the same time, as long as they walk through one by one, they can be counted by the smart mat by analyzing the characteristics of the generated signal.

DL-Based Data Analytics. AI has made great progress thus far. The AIoT broadens the concept of the IoT at the application level. It also gives the IoT the ability to make intelligent decisions and automatic control at the same time.[36] As a pillar industry of global trade, the shipping industry combined with AI will inevitably bring leap-forward progress to this traditional industry. A smart mat system integrated with a CNN can achieve the goal of personnel identification. As mentioned above, each person has a unique walking gait pattern. A signal with a unique feature can be generated by

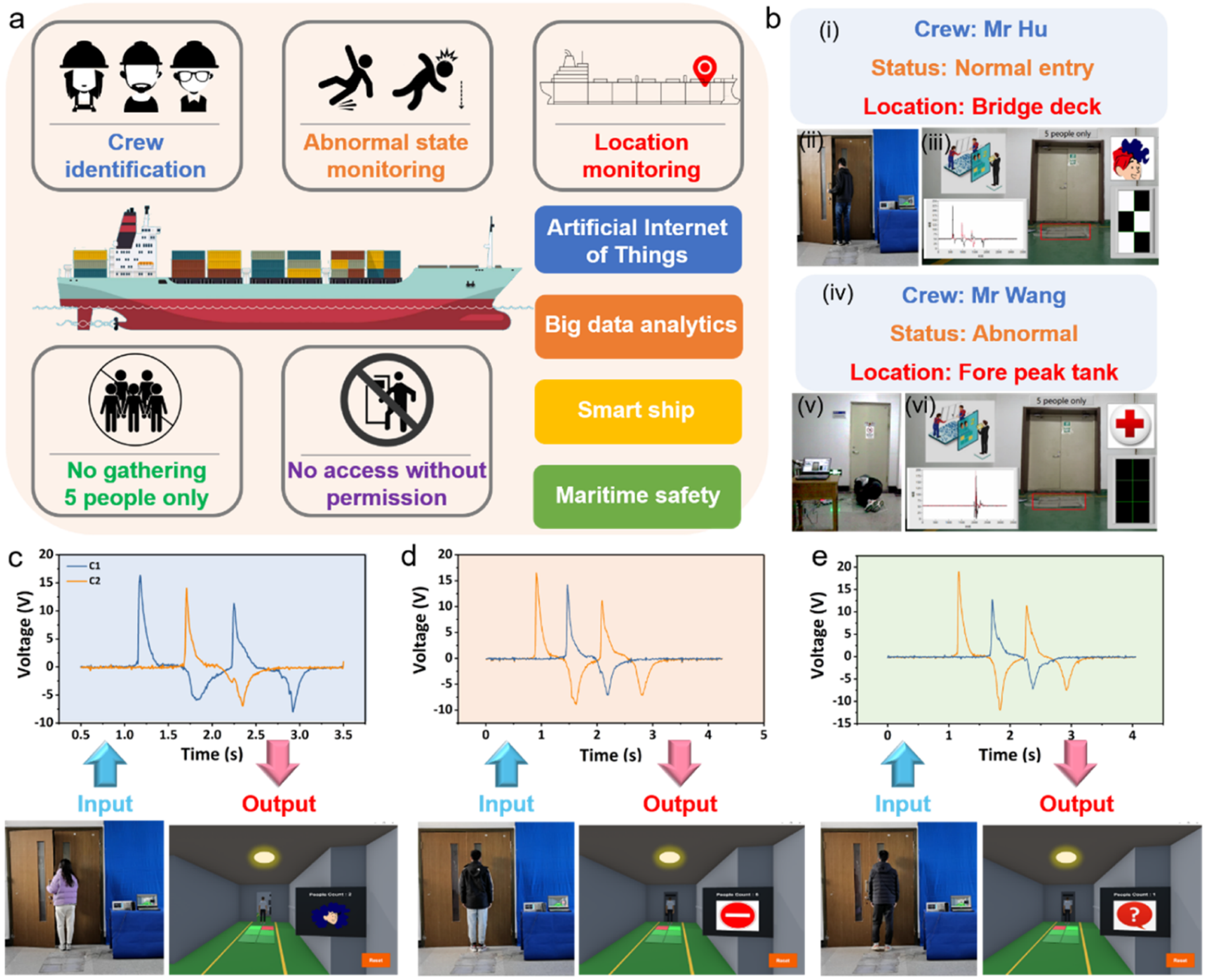

Figure 5. Application of the smart mat system on board. (a) Schematic of the functions of the smart mat system on board. (b) Demonstrations of different users in real-time positioning, personnel identification, and state monitoring. (c−e) Demonstration of the trajectory tracking, people counting, and personnel identification of the smart mat system in a virtual display.

stepping on the mat for individual recognition. As shown in Figure 4a, when a person steps on smart mat unit R1, a positive waveform is generated. When they step on L2 and leave R1, there is a second positive waveform and a negative waveform generated. There is a third positive waveform and a negative waveform generated when they step on R3 and leave L2. As mentioned above, according to the signal characteristics, the personnel identification and people counting as well as the trajectory tracing of the person is collected and analyzed by the smart mat system, as shown in Figure 4b.

The output signals from walking through the smart mat array are acquired by the digital oscilloscope TBS 1072B-EDU. The length of the measured data is 2500 data points with two channels, and 100 samples are collected for each user (70% for training and 30% for testing). A whole data set is built from nine users, with a total number of 900 samples. The CNN is created to efficiently extract the features and identify them with high accuracy, as shown in Figure 4c and Table S1. The classification accuracy of six groups randomly selected in nine users is shown in Figure 4d, with average accuracies of 92.26, 96.56, 96.68, 93.34, 95.56, and 93.12%. Meanwhile, the detailed classification results of the selected users for each group are shown in Figure S5. Data sets with different numbers of users (i.e., 2, 5, 7, and 9) are explored as the training inputs for the 1D CNN model. The resultant classification accuracy for each data set size is summarized in Figure 4e, with average accuracies of 91.33, 89.00, 84.67, and 94.44% for increasing the number of users. After the CNN training process with 50 training epochs, the average recognition accuracy can reach 94.44% (Figure 4f), which ensures the high accuracy requirements of the recognition system based on DL in the application process.

Demonstration of the Smart Mat System. With the assistance of the CNN, the identification, status, and location of the seafarer can be monitored in real time, as shown in Figure 5a. To demonstrate the functions of the smart mat system, Movie S1 and Figure 5b show the working process of the smart mat system in two simulated scenarios with fixed-end and mobile monitoring devices. A user first walks across the smart mats, and the corresponding signal waveform is shown in Figure 5b(iii). Simultaneously, the signal is processed and analyzed by the CNN model, and his name (Mr. Hu), state, and photograph are shown on the monitor screen. When a crew member enters a closed cabin (such as the fore peak tank), they may encounter an accident; for example, they may suffocate and fall due to the low oxygen content. Therefore, the identification, state, and location of the crew are also necessary for the implementation of rescue work after the accident. In such a scenario, if a crew member (Mr. Wang) falls on the smart mats, an emergency alert is issued by the smart mat system, as shown in Figure 5b(vi), to alert the watchman that Mr. Wang needs timely physical aid. The demonstration experiment shows that the smart mat system has a potential application value in ship security and safe operation.

Avoiding gatherings of people and prohibiting unvaccinated people from participating in social activities are effective ways to prevent the spread of the virus. If the epidemic prevention measures of a ship are that one cabin cannot accommodate more than five people, unauthorized personnel are prohibited from entering, as depicted in Figure 5a. Hence, personnel identification and counting are of great significance to ship epidemic prevention. The principle of counting is shown in Figure S6. While realizing the counting function, it can also track the movement trajectory of the personnel, which is also of great significance for realizing more precise positioning of the personnel in the future. To demonstrate practical usage scenarios, a virtual corridor environment mimicking the real corridor is built to reflect the real-time state of a person stepping on smart mats, including position sensing, counting, and personnel identification through DL prediction. As shown in Figure 5c and Movie S2, when a person walks across the mats, the smart mat system shows the person's identity according to the generated signal, allows them to enter, and records the real-time number of people in the cabin. Once the number of people in the cabin reaches the upper limit, when someone intends to enter the room, the system will issue an alarm to remind the person, as shown in Figure 5d. However, if the person's information is not included in the CNN model, when they intend to enter the room, the smart mat system will issue a security alert for the security watchman, as shown in Figure 5e. Overall, the demonstration experiments show the feasibility of the smart mat system in the field of ship epidemic prevention.

It is also necessary to monitor the condition of the cargo because the falling of the cargo will threaten the safe navigation of the ship. When the smart mat is arranged in the cargo hold, it can be used to monitor the falling of the cargo, as depicted in Figure S7a. Different signals can be generated by different falling shape items. Spherical, cylindrical, square, cylindrical, and hemispherical cargo generate corresponding signals when they fall on the mat, as shown in Figure S7b. The generated output signals from the two channels in the time domain are presented, which are used to identify the shape. The average recognition accuracy reached 95.7% (Figure S7c). According to the characteristics of the generated signal, it can also be judged which cargo hold has a cargo falling accident as different forms of cargo are stored in different cargo holds.

CONCLUSIONS

In this study, a DL-assisted triboelectric smart mat system was developed and investigated for comprehensive personnel monitoring on board. The smart mat units with different filling rates composed of FEP and conductive sponge exhibit stable output performance and distinguishable output signals. A smart mat system is constructed by integrating the 3 × 2 array of mats with DL-based data analytics, which has the functions of personnel identification, state monitoring, and people counting. A CNN model is used to accurately extract the identity information related to walking gait patterns from the output signal, which shows an accuracy of 94.44% by analyzing 900 data samples from nine users. Analyzing the complete walking signal through the CNN model can predict the identification of the person and walking status, as well as counting the people in the cabin. Moreover, when the smart mat is arranged in the cargo hold, accidents involving falling cargo can also be monitored. Compared with camera-based surveillance systems, smart mat systems provide a video-privacy-protected minimalist structure and a high-accuracy recognition approach. The smart mat system shows major advantages in cost, structure, scalability, and privacy protection. It has a promising application on ensuring maritime and manufacturing safety, as well as constructing ship and smart building IoT in the future.

METHODS

Fabrication of the Smart Mat Monitoring System. The proposed smart mats consist of six parallel connected smart mat units. Each smart mat unit is made of a conductive sponge inside and an FEP membrane (100 μm thickness) outside. The QR code-like conductive sponge is used as the electrode of the smart mat unit, whose dimension is 305 × 305 × 4 mm. The conductive sponge electrodes are evenly divided into 100 pieces and numbered by a 3D printing mold. By generating random numbers, the conductive sponge electrodes are cut out of 10, 30, and 50 pieces. All material surface morphology images were taken using LEXT OLS4000 3D. The electrodes with different filling rates can ensure that a distinguished electrical signal can be generated when a person steps on the mats. The distinguished signals can be used to identify people entering and leaving the cabin and to identify personnel information in the CNN.

Electrical Output Measurements. The voltage signals from different directions are measured using a Keithley 6514 electrometer. The voltage signals processed by the regulating circuit are measured using a digital oscilloscope TBS 1072B-EDU to illustrate the change in the waveform.

Data Processing and CNN Model. The signals acquired by an Arduino Mega 2560 microcontroller are used for CNN training. The structure of the CNN model is as follows. The form of the loss function is the categorical cross-entropy function. Adaptive moment estimation (Adam) is used as the update rule, and prediction accuracy is used to evaluate the model training. The CNN model is developed in MATLAB. The feature-based model is trained on a standard consumer-grade computer. Each time the specified 20 epochs pass, the learning rate will be reduced by 10 times.

Application of DL-Based Smart Mats. The two-channel triboelectric generated signals by people stepping are transmitted to a voltage-regulating circuit to deliver a stable signal for subsequent processing. The output signals are transmitted to the analog input of the Arduino MEGA 2560 microcontroller. The received signals are processed in MATLAB for peak detection and identification. When the first wave peak is generated, the signal is sent to MATLAB through a unique communication protocol. Unity 3D and LabVIEW obtain the signal to determine the first triggered smart mat unit and control the door access ("granted"/"denied"). Meanwhile, the detailed information of the person, number of people indoors, or alarm signals is sent to the mobile monitoring applications. The signal of the smart mats is transmitted to the computer through the wireless module (XBee), and then, host computer software (MATLAB) transmits the result to the mobile phone through the network.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.2c05734.

> Mat unit with different filling rates; photograph of the smart mat array and morphology images of the conductive sponge and FEP membrane; detailed working mechanism of the smart mat unit; signal regulating and acquisition circuit; confusion matrix for six randomly selected nine users; process flow of the counting; smart mat system for cargo monitoring; and parameters for constructing the CNN model (PDF)
>
> Smart mat system for crew identification, counting, and abnormal state monitoring (MP4)
>
> Smart mats system for monitoring authorized crew and unauthorized persons (MP4)

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Author Contributions

Yan Wang, Z.H., and J.W. contributed equally to this work. Yan Wang and Q.S. conceived the idea. Z.H., J.W., and H.Y. wrote the algorithms for DL and demonstration. Yan Wang and X.L. contributed to the data analysis and drafted the manuscript. Yawei Wang and L.Q. designed some diagrams. J.L. and L.Z. performed the demonstration experiments and donated personal information. Y.L., Z.Y., C.L., and M.X. edited the manuscript.

Notes

The authors declare no competing financial interest.

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