Real-Time Optimization Energy Management Strategy for Fuel Cell Hybrid Ships Considering Power Sources Degradation

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ABSTRACT In order to protect the marine environment, the fuel cell has become a good candidate for the main energy source of marine vehicles due to its remarkable performance of high efficiency, quietness, and cleanliness. However, the fuel cell of the hybrid power system has a critical drawback of short lifetime. For this reason, the development of the energy management strategy considering power sources degradation becomes significant and urgent. In addition, the power system configuration has a strong link with the control strategy. In this vein, a sizing method of the hybrid energy storage system for a fuel cell hybrid excursion ferry is proposed to prolong the fuel cell lifetime. Based on the configuration of the power system, a real-time optimization control strategy considering efficiency and durability is developed. To verify the control strategy, the mathematical model of the hybrid power system is established. Compared with the wavelet-based control strategy and rule-based control strategy, the proposed strategy has better performance in terms of the fuel economy, the system durability as well as the dynamic property.

INDEX TERMS Fuel cell hybrid ferry, energy management strategy, supercapacitors, battery, degradation.

I. INTRODUCTION
Nowadays, decreasing the negative environmental impact has been growing interest in the shipping industry. Shipping plays an important role in world trade, with 90% of the world trade being transported by ships [1]–[3]. In 2015, shipping emissions were responsible for 2.6% of global greenhouse gas emissions from fossil fuel use and industrial processes [4]. Also, 4 to 9% of global SOx and 15% of NOx emissions are produced by shipping [5]–[7]. Therefore, the development of green power systems of ships is considered as an efficient method to reduce pollutants.

The green ships are mainly of two types: battery electric ships, fuel cell hybrid ships. Battery electric ships only use the energy storage system (ESS). Fuel cell hybrid ship uses the fuel cell as a main energy source and battery/SC used as the auxiliary energy source to meet the load demand [8]–[11]. The advantage of battery-electric ships is that they have minimal auxiliary devices. Whilst, such a ship has a short cruising range as battery stores less energy compared with diesel and hydrogen. On the other hand, the fuel cell hybrid ship with zero emissions, low noise and high energy efficiency, has attracted the attention of the shipping [12]–[15]. However, the cost of fuel cell hybrid power systems has to be reduced and power sources degradation should be considered for fuel cell to compete with conventional power systems [4].

In the hybrid power system, the battery often suffers from frequent power fluctuation, leading to unexpected battery degradation [16]–[19]. To solve the issue, the supercapacitor (SC) as an auxiliary energy storage device with a combination of battery is adapted to become the hybrid energy storage system (HESS). The SC in the HESS deals with the power demand fluctuation for reducing the degradation of the battery, as the battery only needs to produce steady power. Due to its advantages shown in refs [20]–[23], the HESS consisting of batteries and SCs has been considered as an excellent ESS topology. Therefore, the HESS can be
used in the fuel cell hybrid power system, which not only reduces the degradation of the fuel cell but also avoids fast discharge/charge of the battery.

The FC-HESS hybrid power system has three power sources with different dynamic performance. It is of great importance to developing the energy management strategy controlling the power flow between different power sources and DC bus [9], [24]–[26]. The control strategy significantly affects the performance of the hybrid power system, and the power system configuration has a strong link with the control strategy.

**LIST OF ACRONYMS**

- B: Battery
- EMS: Energy management strategy
- ESS: energy storage system
- FBC: Filter-based control strategy
- FC: Fuel Cell
- HESS: Hybrid energy storage system
- SoC: State-of-charge
- PSO: Particle Swarm Optimization
- ECMS: Equivalent consumption minimization strategy
- SQP: Sequential Quadratic Programming
- SC: Supercapacitor
- \( \eta_{bat} \): Battery energy efficiency (%)
- \( \eta_{dcdc} \): DC-DC converter energy efficiency (%)
- \( \eta_{fc} \): Fuel cell energy efficiency (%)
- \( \eta_{sc} \): SC energy efficiency (%)
- \( C_{bat} \): Battery equivalent hydrogen consumption (g)
- \( C_{fc} \): Fuel cell equivalent hydrogen consumption (g)
- \( C_{sc} \): SC equivalent hydrogen consumption (g)
- \( C_{dfe} \): FC degradation equivalent hydrogen consumption (g)
- \( E_{fc} \): The maximum energy fluctuation of the SC
- \( E_{bat} \): The maximum energy fluctuation of the battery
- \( M_{fc} \): Fuel cell Price
- \( M_{bat} \): Battery Price
- \( P_{bat} \): Battery power output (kW)
- \( P_{fc} \): Fuel cell power output (kW)
- \( P_{sc} \): SC power output (kW)
- \( R_{bat} \): Battery resistance (Ω)
- \( R_{sc} \): SC resistance (Ω)
- \( s \): Laplace operator
- \( t \): time
- \( T \): Filter time constant
- \( v_{bat} \): Battery Voltage (V)
- \( v_{fc} \): Fuel cell Voltage (V)
- \( v_{sc} \): SC Voltage (V)
- \( k_{1} \): Battery penalty coefficient
- \( k_{2} \): SC penalty coefficient

This study aims to solve the complex task to design the hybrid power system and energy management strategy. The paper has the following configuration. Section 2 focuses on the literature review and contributions. Section 3 focuses on the sizing of the HESS for the hybrid power system. The models of the power system components are introduced in Section 4. In Section 5, the real-time optimization EMS based on the ECMS and FBC is proposed for the fuel cell hybrid ferry. The simulation results and analysis are presented in Section 6. The conclusions and future work are given in Section 7.

**II. LITERATURE REVIEW AND CONTRIBUTIONS**

In the literature, numerous researchers have proposed a variety of EMSs. According to optimization theory, EMSs can be classified as rule-based EMSs and optimization-based EMSs, as shown in Fig. 1. The rule-based EMSs include the deterministic rule-based EMSs and the fuzzy rule-based EMSs. Deterministic rule-based EMSs are usually designed through the methods, which include look-up tables, filter-based control (FBC), and wavelet transform. Han et al. [27] proposed a deterministic rule-based EMS designed through look-up tables to control the operating point of energy sources. The main feature of the strategy is to set the operating points of devices according to load demand and devices operating states. Filter-based EMSs are considered as one of the simplest control strategies due to its superior robustness and low computation complexity. Similar to filter-based control strategy (FBC), wavelet-based energy management strategies [28] control power allocation by frequency division. Li et al. [29] proposed a fuzzy-based EMS to improve the energy efficiency of hybrid cars. The rule-based EMSs have been widely used, however, the performance of the rule-based EMSs mostly depends on the researchers’ knowledge and engineering experience. In addition, EMSs are difficult to achieve the optimal performance of the power system.

To resolve the issues, the optimization methods are introduced in the EMSs. Optimization-based EMSs include global optimization EMSs and real-time optimization EMSs. The strategies [30]–[36] are proposed to achieve the global optimization performance of the hybrid power system. However, the global optimization EMSs are difficult to apply for real-time control, as prior operation information generally cannot be achieved. Thus, the global optimization EMSs are usually used to verify a variety of control strategies. Therefore, the papers [37]–[40] proposed real-time optimal control strategies such as equivalent consumption minimization strategy (ECMS). Nevertheless, these strategies only focus on fuel consumption without considering the degradation of energy sources. When the fuel cell responds to the sharp fluctuation of load demand, the power system might achieve high energy efficiency, but the lifetime of the fuel cell will be rapidly shortened. Table 1 presents a summary of various energy management strategies.
Based on the analysis mentioned above, the optimization-based EMSs have excellent performance. However, the degradation of power sources is not considered. To solve the issues, a real-time optimization EMS taken into account the power sources degradation based on ECMS and FBC for a fuel cell hybrid ship is proposed in this paper. It includes the fuel cell degradation model, the high-pass filter, and the battery equivalent hydrogen consumption, etc. The main contributions of this work are summarized as:

1. A sizing method of the HESS is proposed for the fuel cell hybrid ferry, which considers not only the power, energy and voltage constraints but also the control strategy of the HESS;
2. A real-time optimization energy management strategy for fuel cell hybrid ships considering power sources degradation is proposed to improve energy efficiency and prolong devices lifetime;
3. A high-pass filter is used in the proposed control strategy for the HESS to prolong battery life and reduce the computation complexity.

III. THE ENERGY STORAGE SYSTEM DESIGN

Due to the particularity of the ship, first, the design of the energy storage system should analyze the general description and feature of the target ship, such as ship type, main particulars, and the general arrangement; then, the topology of the energy storage system is determined; finally, the size of the energy storage system is selected considering energy constraints, power constraints, etc.

A. THE TARGET SHIP

The zero-emission ferry “Alsterwasser” was developed as part of the ZEMSHIPS project. As Figure 2 shows, the ship hybrid power system has two PEMFCs with peak power of 48 kW and a battery of 360 Ah/560 V. The electrical loads mainly include auxiliary devices and propulsion motors. The load demand of the ferry has been measured [45], [46], as shown in Figure 3. The load profile of the ferry includes four main operation statuses:

1. Cruising: steady load demand to sail;
2. Docking: load demand fluctuations several times from 0 to 100kW.

TABLE 1. Summary of various energy management strategies.

| Type                  | Developed method                                      | Advantages/Disadvantages                                                                 | Ref  |
|-----------------------|-------------------------------------------------------|-----------------------------------------------------------------------------------------|------|
| Deterministic approach| Frequency split strategy / Wavelet Transform          | Simple & practical & can be optimized / Rely on human expertise & difficult to optimize | [41] |
| Fuzzy approach        | Fuzzy logic controller / fuzzy logic controller       | Easy to design & excellent performance/ difficulty reach the optimal & rely on human expertise | [28] |
|                       | using intelligent methods                             | Easy to design & excellent performance & can be optimized / highly dependent on the load profiles & may not applicable to other conditions. | [29] |
| Global optimization   | Dynamic programming / Pontryagin minimum principle    | Super performance & can be used as other strategies benchmark / need prior power demand information & high computation complexity Relatively light computation complexity & Closing to the global optimization/ Sensitive to initial values | [30-32] [33] |
| Real-time optimization | Equivalent consumption minimization strategy          | High real-time performance/ not consider devices degradation                           | [37-39] |
|                       | Model predictive control                              | High real-time performance/need to design dynamic models                               | [43] |
|                       | Artificial intelligence                               | High real-time performance, both improve fuel cell lifetime and fuel efficiency / need large data for training the model & low interpretability | [44] |
The data shows that the average load demand is 40.8 kW and the peak power is 108 kW. At docking, the load demand diagram shows the fastest dynamics. At standby, the ship docks at the port for passengers, without any load demand for propulsion. At the casting off, the ferry needs much power to accelerate ship speed from zero to the set speed, which results in huge peak power (110 kW).

**B. THE TOPOLOGY OF THE HESS**

Battery-SC hybrid energy storage systems have been proved to have excellent performance in terms of cost, efficiency, and durability. As figure 4 shows, the HESS has four common topologies:

- Passive topology. Its characteristics are the simplest construction and lowest cost, but it cannot control power distribution leading to fairly poor performance.
- Battery semi-active topology. The advantage is that it can control power flow and protect the battery. However, the structure cannot make the best use of the SC, due to the reason that the SC operates in a narrow range of voltage.
- SC semi-active topology. The advantage is that it can control power flow and make the most use of the SC. However, the topology requires a high-performance control algorithm to protect the battery.
- Active topology. The topology has more flexibility, in which both the battery and the SC can be controlled improving the accuracy of power allocation. Therefore, the topology is used in this study.

As Figure 5 shows, the proposed configuration of the hybrid power system includes a power generation subsystem (FC), an energy storage subsystem (battery-SC HESS) and a propulsion subsystem. The fuel cell is the main energy source and uses a unidirectional DC-DC converter to raise the fuel cell output voltage.

According to refs [17], [47]–[49], the main energy source should undertake the mean value of the power demand as the HESS suppresses the power fluctuations. As Fig. 5 shows, the power balance can be expressed as:

\[
P_{\text{load}}(t) = P_{\text{fc}}(t) + P_{\text{HESS}}(t) = P_{\text{fc}}(t) + P_{\text{bat}}(t) + P_{\text{sc}}(t)
\]

where \( P_{\text{fc}} \) is the output power of the fuel cell; \( P_{\text{HESS}} \) is the output power of the HESS, which consists of the battery output power \( P_{\text{bat}} \) and SC output power \( P_{\text{sc}} \).

To have high energy efficiency, the fuel cell should operate in a high-efficiency range. Meanwhile, the HESS responds to the fluctuations of the load demand. The sizing method of the HESS (detailed in the paper [45]) is used in this study, however, the method does not consider the EMS. Based on the papers [42, 46], we propose the sizing method considering the control strategy of the HESS. As Figure 6 shows, the load demand fluctuation is decomposed of the low-frequency component and the high-frequency component (detailed in Section 4.2).

The energy requirement of SC can be achieved by integrating the output power of the SC, as shown in Fig. 6. Under the...
energy constraint, the energy capacity of the SC is calculated as:

\[ E_{sc} = E_{fsc}/\eta_{sc}\eta_{dcdc}(v_{scmax}^2 - v_{scmin}^2)/v_{scmax}\]  (2)

where: \(E_{fsc}\) is the energy fluctuation of the SC, \(E_{fsc} = 0.30\ \text{kWh}\); \(\eta_{sc}\) is the energy efficiency of the SC, \(\eta_{sc} = 0.9\); \(\eta_{dcdc}\) is DC-DC energy efficiency, \(\eta_{dcdc} = 0.9\); \(v_{scmax}\) and \(v_{scmin}\) are the upper and lower limits of SC voltage, respectively; \(E_{sc}\) is the energy capacity of the SC, \(E_{sc} = 0.49\ \text{kWh}\).

As shown in Figure 6, the power fluctuation of SC is obtained by using the filter to decompose load demand fluctuation. To meet power constraint, the SC power capacity is calculated as:

\[ P_{csc} = P_{fsc}/(\eta_{dcdc} \cdot \eta_{sc}) \]  (3)

where: \(P_{fsc}\) is the maximum power fluctuation of the SC, \(P_{fsc} = 86.64\ \text{kW}\); \(\eta_{sc}\) is SC energy efficiency, \(\eta_{sc} = 0.9\); \(P_{csc}\) is the power capacity of the SC, \(P_{csc} = 106.96\ \text{kW}\).

Similar to the SC, the battery energy capacity is calculated as:

\[ E_{bat} = E_{fbat}/(\varepsilon_{bat}\eta_{bat}\eta_{dcdc}(B_{socmax} - B_{socmin})) \]  (4)

where: \(E_{fbat}\) is the maximum energy fluctuation of the battery, \(E_{fbat} = 0.39\ \text{kWh}\); \(\varepsilon_{bat}\) is battery safety factor, \(\varepsilon_{bat} = 0.6\); \(\eta_{bat}\) is battery energy efficiency, \(\eta_{bat} = 0.8\); \(B_{socmax}\) is the upper limit, \(B_{socmax} = 0.8\); \(B_{socmin}\) is the lower limits, \(B_{socmin} = 0.4\); \(E_{bat}\) is the energy capacity requirement of the battery, \(E_{bat} = 2.26\ \text{kWh}\).

Similar to the SC, the battery power capacity is calculated as:

\[ P_{cbat} = P_{fbat}/(\eta_{dcdc} \cdot \eta_{bat}) \]  (5)

where: \(P_{fbat}\) is the maximum power fluctuation of the battery, \(P_{fbat} = 34.43\ \text{kW}\); \(\eta_{bat}\) is battery energy efficiency, \(\eta_{bat} = 0.8\); \(P_{cbat}\) is the power capacity of the battery, \(P_{cbat} = 48.81\ \text{kW}\).

Considering energy, power and voltage constraints (shown in Table 2), the design of a suitable battery pack for the fuel cell hybrid ferry is based on 7 modules (112 Ah, 76.8 V) in series; the design of the SC for the fuel cell hybrid ferry can be based on 12 modules (165 F, 48 V, Maxwell) in series.

### IV. THE HYBRID POWER SYSTEM MODEL

As can be seen in Figure 7, the hybrid power system model includes fuel cell, battery, SC, DC-DC, load, and EMS. The fuel cell as the main energy source is connected to DC bus via a unidirectional DC/DC converter. The HESS as the subsidiary energy source is directly connected to DC bus.

#### A. FUEL CELL

In this study, we use a simplified fuel cell model (detailed in the paper [50]). In many papers, the model has been adopted to design many energy management strategies. The fuel cell voltage \(v_{fc}\) is calculated as:

\[ v_{fc} = E - (v_{ohm} + v_{act} + v_{conc}) \]  (6)

where \(v_{fc}\) is the fuel cell voltage, \(E\) is the open-circuit voltage of the fuel cell, \(v_{ohm}\) is the ohm voltage loss, \(v_{act}\) is the fuel cell activation voltage loss, \(v_{conc}\) is the concentration voltage loss.

#### B. BATTERY

Battery as energy storage devices of vehicles (bus, car, ferry, boat, and tramways) has different types, such as NiMH, Pb-Acid, NiCd and Li-ion. Compared with other battery, Li-ion battery has better response, durability, and security. Therefore, a Li-ion battery is used in this study.
The battery model performance has been presented in SimPowerSystems of MATLAB/Simulink [51]. In this study, the battery is modeled by a circuit equivalent model, which includes a controlled voltage source and a resistor. For the lithium-ion battery type, the model uses the equation:

$$v_{bat} = \begin{cases} 
  v_0 - k \cdot \frac{Q}{\int i_{bat} \, dt} - 0.1Q \cdot i_{bat}^k - k \cdot \frac{Q}{\int i_{bat} \, dt} \cdot \int i_{bat} \, dt \\
  + A \cdot \exp(-B \cdot \int i_{bat} \, dt) \quad i_{bat}^k > 0 \\
  v_0 - k \cdot \frac{Q}{\int i_{bat} \, dt} - k \cdot \frac{Q}{\int i_{bat} \, dt} \cdot \int i_{bat} \, dt \\
  + A \cdot \exp(-B \cdot \int i_{bat} \, dt) \quad i_{bat}^k < 0
\end{cases}$$

(7)

where $v_{bat}$ is the battery open-circuit voltage, $k$ is the polarization constant, $v_0$ is the battery constant voltage, $Q$ is the battery capacity, $i_{bat}$ is the battery current.

C. SC

SC is modeled as an equivalent circuit model, which consists of a capacitor and a resistance. A capacitor is used to simulate supercapacitor dynamic performance and resistance is used to simulate the energy losses. The energy of the SC is directly related to its terminal voltage, so its SoE can be calculated through Eqs (30)-(32):

$$v_{sc} = \frac{N_c Q_T d}{N_p N_c e \varepsilon_0 A_1} + 2 \frac{N_c N_e R_T}{F} \ar sinh \left( \frac{Q_T}{N_p N_c^2 A_1 \sqrt{8RT e \varepsilon_0 c}} \right) - R_{sc} \cdot i_{sc}$$

(8)

$$E_{sc} = \frac{1}{2} c_{sc} \cdot v_{sc}^2$$

(9)

$$SoE = \frac{E_{sc}}{E_{sc, max}} \cdot 100\% = \frac{v_{sc}^2}{v_{sc, min}^2} \cdot 100\%$$

(10)

where $c_{sc}$ is the SC capacity; $E_{sc}$ is the SC energy capacity.

D. DC-DC

The power system has two types of DC-DC converter. The one is a unidirectional DC-DC, which can only control power flow via one direction. It is generally used to fuel cell, electric machine or solar photovoltaic. In this study, the DC-DC is used to control the output power of the fuel cell system as shown in Fig. 8(a). The other one is a bidirectional DC-DC, which can control bi-direction power flow and is generally applied to battery or SC and other energy storage devices. Fig. 8(b) shows this kind of DC-DC, which is used to control the power of the battery and SC.

E. LOAD DEMAND

We use a controlled DC current source to simulate the ferry load demand, which includes the propulsion motors...
and auxiliary services. The block consists of a DC current source, mathematical operation, time-clock and look-table (load demand profiles).

V. THE PROPOSED OPTIMIZATION EMS

The proposed EMS is based on optimizing the hydrogen consumption while considering the degradation of the fuel cell and battery. To achieve this objective, the ECMS and the filter-based control (high-pass filter) are used in this study.

A. THE EQUIVALENT HYDROGEN CONSUMPTION MODEL

The strategy focuses on calculating the optimal power allocation that minimizes the hydrogen consumption of the hybrid power system. Therefore, it is difficult to design a cost function for the real-time optimization that minimizes the hydrogen consumption of the hybrid power system. The proposed EMS is based on optimizing the hydrogen consumption (load demand profiles).

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1. Fuel cell hydrogen consumption model

   The relationship between \( P_{fc} \) and \( P_{fc} \) can be expressed as:
   \[
   C_{fc} = a \cdot P_{fc}^2 + b \cdot P_{fc} + c
   \]  
   (12)

   where \( a, b, \) and \( c \) are the fit parameters.

2. Fuel cell degradation model

   An empirical fuel cell model is found to be acceptable when used in the proposed EMS. The main factor of fuel cell degradation is the variation degree of operating conditions. The paper uses the fuel cell degradation model (detailed in [52], [53]), shown as follows:
   \[
   \frac{\partial \delta_{v, decay}}{\partial t} = \frac{1}{3600} \left[ k_{fuel} \sigma \left( P_{f, f}^3 - 4, P_{f, f}^2 - 3, P_{f, f}^2 - 2, P_{f, f}^2 - 1, P_{f, f}^2 \right) + 10 \right]
   \]  
   (13)

   where \( \delta_{v, decay}/\delta_{t} \) is fuel cell voltage degradation rate; \( \sigma \) is standard deviation function; \( P_{f, f} \) is the output power of the fuel cell at time \( t \).

   As \( \delta_{v, decay} \) is different from hydrogen consumption, it is difficult to design a cost function for the real-time optimization EMS. Therefore, \( \delta_{v, decay} \) is transformed into hydrogen consumption according to the price of fuel cells and hydrogen fuel as:
   \[
   C_{Dfc} = \frac{\partial \delta_{v, decay} M_{FC}}{10\% C_{H_2}}
   \]  
   (14)

   where \( C \) is the hydrogen fuel price, \( M_{FC} \) is the fuel cell device price and the 10% performance degradation of the fuel cell system is the maximum allowable value.

3. Battery equivalent hydrogen consumption

   In general, it is hard to identify the work conditions of the fuel cell, battery, and SC. Thus, the average work conditions are used in this paper. The battery equivalent hydrogen consumption \( C_{bat} \) can be calculated as:
   \[
   C_{bat} = \sigma \cdot \frac{P_{bat} \cdot C_{FC, avg}}{P_{FC, avg}}
   \]  
   (15)

   where \( C_{FC, avg} \) is the average consumption of the fuel cell, \( P_{FC, avg} \) is the average power of the fuel cell, \( \sigma \) can be calculated as:
   \[
   \sigma = \begin{cases} 
   \frac{1}{\eta_{bat, chgavg} \cdot \eta_{bat, dis}} & P_{bat} \geq 0 \\
   \eta_{bat, chg} \cdot \eta_{bat, dis} & P_{bat} < 0
   \end{cases}
   \]  
   (16)

   where \( \eta_{bat, chgavg} \) is average charge efficiency of the battery; \( \eta_{bat, dis} \) is average discharge efficiency of the battery; \( \eta_{bat, chg} \) and \( \eta_{bat, dis} \) are the battery discharging resistance and charging resistance, respectively. In this study, we assume that \( R_{bat, dis} \) and \( R_{bat, chg} \) are equal to the internal resistance, \( R_{bat} \).

   According to the paper [51], the parameters of \( k_{bat} \) can be calculated as:
   \[
   k_{bat} = 1 - 2 \mu \cdot \frac{B_{soc} - 0.5(B_{soc} + B_{socL})}{B_{soc} + B_{socL}}
   \]  
   (19)

   where \( \mu \) constant parameters; \( B_{soc} \) is battery SoC; \( B_{socL} \) is the upper limit of SoC; \( B_{socL} \) is the lower limit of SoC.

4. Battery degradation model

   The main factors of battery degradation are the variation degree of current and high current. According to the paper [54], the battery degradation model is used in this study to avoid high current, expressed as:
   \[
   C_{Dbat} = \frac{i_{bat} t_{EMS} M_{Bat}}{Q_{bat} B_{cycle} C_{H_2}}
   \]  
   (20)

   where \( t_{EMS} \) is the sample time of the EMS, \( M_{bat} \) is the battery device price, \( B_{cycle} \) is the cycle time of the battery.

5. SC equivalent hydrogen consumption

   Similar to battery equivalent hydrogen consumption model, instantaneous hydrogen consumption of the SC is calculated as:
   \[
   C_{sc} = \sigma \cdot \frac{P_{sc} \cdot C_{FC, avg}}{P_{FC, avg}}
   \]  
   (21)

   With
   \[
   \sigma = \begin{cases} 
   \frac{1}{\eta_{sc, chgavg} \cdot \eta_{sc, dis}} & P_{bat} \geq 0 \\
   \eta_{sc, chg} \cdot \eta_{sc, dis} & P_{bat} < 0
   \end{cases}
   \]  
   (22)
where $P_{sc}$ is the SC power; $\eta_{sc\_chg\_avg}$ is the SC average charge efficiency and $\eta_{sc\_chg}$ the SC charge efficiency, $\eta_{sc\_dis\_avg}$ is the SC average discharge efficiency and $\eta_{sc\_dis}$ the SC discharge efficiency.

In this study, the first-order RC model is used to model the SC, which is similar to the battery model. Based on the battery model, the charging and discharging efficiencies of SC can be calculated as:

$$\eta_{sc\_dis} = \frac{1}{2} \left( 1 + \sqrt{1 + \frac{4R_{sc\_dis} P_{sc}}{v_{sc}^2}} \right)$$

$$\eta_{sc\_chg} = \frac{1}{2} \left( 1 + \sqrt{1 + \frac{4R_{sc\_chg} P_{sc}}{v_{sc}^2}} \right)$$

where $v_{sc}$ is the SC voltage. As the SC has a small resistance, we can reasonably assume that $R_{sc\_dis}$ and $R_{sc\_chg}$ are equal to the internal resistance of the SC, $R_{sc}$.

**B. FILTRATION BASED CONTROL FOR HESS**

In order to reduce computation complexity, the filtration based controller (FBC) is used in the HESS. The FBC utilizes a filter to split the load demand fluctuation into different frequency components. This control method is very simple and has excellent performance [15]. In the paper, the filter-based control strategy with a supercapacitor energy controller (SCEC) for the HESS has excellent performance. According to Fig. 9, the SC power output can be calculated (given in Appendix A).

$$P_{sc} = f_{\text{highpassfilter}}(P_{\text{HESS}}) = f_{\text{highpassfilter}}(P_{load} - P_{load\_avg})$$

$$P_{bat} = P_{\text{HESS}} - P_{sc} \quad (25)$$

**C. SEQUENTIAL QUADRATIC PROGRAMMING (SQP)**

The multi-objective energy management strategy, in essence, is a nonlinear problem of optimization, which can be solved by the Sequential Quadratic Programming (SQP). The SQP algorithm based on optimization theoretical achieves optimal results for a large-scale engineering problem. SQP is an iterative procedure that models the nonlinear programming problem at a given approximate solution $x^k$, by a Quadratic Programming (QP) subproblem [55]. We consider the application of the SQP method to the proposed real-time optimization EMS of the form:

$$\text{Minimize : } f(x) = C_{fc} + C_{D_{fc}} + k_1 \cdot C_{bat} + C_{D_{bat}} + k_2 \cdot C_{sc}$$

Subject to:

$$0 \leq P_{fc} \leq P_{fc\_max}$$

$$|P_{sc}| \leq P_{sc\_max}$$

$$v_{sc} \leq v_{sc\_max}$$

$$v_{sc} \geq \frac{1}{2} v_{sc\_max}$$

Initial value:

$$x(1) = P_{fc}(t - 1)$$

$$x(2) = P_{fc}(t - 2)$$

$$x(3) = P_{fc}(t - 3)$$

$$x(4) = P_{fc}(t - 4)$$

$$x(5) = P_{\text{HESS}}(t - 1)$$

$$x(6) = B_{SOC}(t - 1)$$

In this study, the $x$ includes the variables: the fuel cell power $P_{fc}$, the power of the HESS $P_{\text{HESS}}$ and the SoC of the battery $B_{SOC}$. The optimum values of all the above parameters are determined from this SQP algorithm.

**D. THE DC-DC CONTROL**

The proposed method outputs the control signals and sends them to the low-level control system, which is used to control the converters. The DC-DC converters of the fuel cell and battery operate on control-current mode, and the DC-DC of the SC operates on control-voltage mode. Fig. 10 shows the control system of the fuel cell hybrid power system. Fig. 10(a) shows the proposed energy management strategy and Fig. 10(b) shows the low-level control loops to generate control signals of the converters.

A limit block is used to restrict the power output of the fuel cell and battery for protecting the safe operation of devices. In addition, the fuel cell has a time-delay response as the electrochemical reaction needs execution time, which could result in a reaction breakdown and a large voltage fluctuation. In this study, we limit the slope of the $P_{fc\_opt}$ set by the proposed EMS. According to data in the literatures [52, 57, 58], the fuel cell system could change the power output, $\Delta P_{fc}$, from 10% to 90% of the rate power in 2 s. And, a low-pass filter is used to solve the starvation problem of the fuel cell system due to the power demand fluctuations. The reference current of the fuel cell DC-DC converter is calculated by the fuel cell reference power, $P_{fc\_ref}$, dividing the voltage of the DC bus. A PI controller is used to generate the duty cycle of the DC-DC converter by the difference of output current.
of the converter and the reference current. Regarding the battery, the control loop is similar to the control loop of the fuel cell. The control loop of the SC supports the DC bus voltage, which is maintained at 560 V by using a PI controller. In addition, we also use the SCEC method to control the energy of SC.

VI. SIMULATION RESULTS

The hybrid power system for the ferry with the proposed real-time optimization EMS based on the ECMS and FBC have been evaluated in MATLAB/Simulink environment, as shown in Figure 10. The power demand of the fuel cell ferry is shown in Figure 3. The main parameters of the power system model are presented in Table 3.

A. SENSITIVITY ANALYSIS

Many papers [58] show that the initial battery SoC may affect the performance of the EMSs. Therefore, we use different initial battery SoC to test the impact of the hybrid power system under the same typical voyage.

Figure 11 shows the fuel cell power curves at different initial battery SoC (30%, 60%, 90%). It can be noticed that increasing the initial battery SoC can reduce the power fluctuation of the fuel cell. The fuel cell power with initial SoC

![FIGURE 10. The proposed control system of the hybrid power system.](image-url)

![FIGURE 11. The fuel cell power curves at different initial battery SoC (30%, 60%, 90%).](image-url)

| Parameters                  | Variable | Values    |
|-----------------------------|----------|-----------|
| DC bus voltage              | $v_{dc}$ | 560 V     |
| SC module voltage           | $v_{sc}$ | (48*12*0.8)V |
| Battery module voltage      | $v_{bat}$ | 537.6 V   |
| The high-pass filter        | $T_{filter}$ | 1/15 s    |
| The Battery SoC upper limit | $B_{soc_{hi}}$ | 80%       |
| The Battery SoC lower limit | $B_{soc_{lo}}$ | 40%       |
| The parameter (in Eq.(14))  | $\mu$    | 0.6       |
of 90% is lower than the average value of power demand as the battery is lower than the operation range. The output power of the fuel cell with initial SoC of 30% is higher than the average value of power demand to charge the battery, which is lower than the operation range.

Figure 12 shows the battery power curves at different initial battery SoC (30%, 60%, 90%). It can be observed that increasing the initial battery SoC can improve battery power. The battery with an initial battery SoC of 30% has the lowest battery power because the battery cannot supply sufficient energy to load devices. Also, the battery still produces power with initial battery SoC of 90% at 240∼360 s.

Figure 13 shows the SC power curves at different initial battery SoC (30%, 60%, 90%). As can be seen from Fig. 13, the SC power is weakly dependent on the battery SoC, as the SC absorbs the high-frequency component of the load demand, which is determined by load demand and the high-pass filter of the proposed EMS.

The energy consumption results of different SoC are presented in Figure 14 and Table 4. The total energy consumption includes the energy consumption of fuel cell, battery and SC (calculation process is given in Appendix B). It can be found that increasing the initial battery SoC can reduce energy efficiency, as the battery energy comes from the fuel cell.

According to the above analysis, it can conclude that the proposed control strategy has excellent robustness with different initial battery SoC.
### TABLE 4. The Energy consumption results with different initial SoC.

| EMS Parameters | ECMS-Filter (SoC=30%) | ECMS-Filter (SoC=60%) | ECMS-Filter (SoC=90%) |
|----------------|-----------------------|-----------------------|-----------------------|
|                | $E_{fc}$              | SoC                   | $E_{fc}$              | SoC                   | $E_{fc}$ | SoC                   | $E_{fc}$ | SoC                   |
| Initial state  | 0                     | 30%                   | 460.81V               | 0                     | 60%      | 460.81V               | 0         | 90%                   | 460.81V   |
| Final state    | 26.75(10^3kJ)         | 30.59%                | 466.38V               | 21.98(10^3kJ)         | 59.53%   | 465.36V               | 19.24(10^3kJ) | 88.86%                | 463.07V   |
| $E_{total}$    | 23.72(10^3kJ)         |                       |                      | 24.28(10^3kJ)         |          |                      | 24.95(10^3kJ) |                      |          |

## B. PERFORMANCE ANALYSIS

Then the proposed strategy ECMS-Filter is compared with the rule-based control strategy [27] and wavelet-based control strategy [28]. The rule-based control strategy is implemented in the original configuration of the ferry (detailed in Section 2.1). The ECMS-Filter control strategy and wavelet-based control strategy are implemented in the proposed configuration of the ferry (detailed in Section 2.2). Fig. 15∼14 shows monitoring results during the typical navigation cycle for different strategies. The curves of the ECMS-Filter, rule-based EMS, and wavelet-based EMS are shown in green, red and blue color, respectively.

Figure 15 shows the fuel cell output power with different strategies. It can be noticed that the ECMS-Filter controls the fuel cell to produce steady power, during casting off and docking. Compared with the wavelet-based control strategy and rule-based control strategy, the maximum power fluctuation of the fuel cell system reduces 68.37%. The peak power of the fuel cell is about 43.80% lower than the rule-base EMS and wavelet-based EMS. That means the proposed ECMS-Filter EMS can prolong the fuel cell lifetime and reduce the cost.

The battery power and SC power variations are shown in Fig. 16 and 17. As previously mentioned, battery and SC produce the low-frequency component and high-frequency component of the HESS power, respectively. Compared with rule-based EMS and wavelet-based EMS, the ECMS-Filter controls the battery to produce steady power during casting off and docking, due to the high-pass-filter used in the HESS. Besides that, the maximum battery power fluctuation of the EMS-Filter reduces 38.98% compared with the rule-based control strategy. The wavelet-based control strategy has the lowest peak power of the battery, however, its fuel cell is not well protected compared with the ECMS-Filter. In addition, the utilization of the SC under the ECMS-Filter is higher than the wavelet-based EMS, as shown in Fig. 17 and Fig. 19 (c).

The energy consumption results of different EMSs studies are presented in Figure 18 and Table 5. The total energy consumption includes the energy consumption of fuel cell, battery, and SC. Clearly, the energy efficiency of the ECMS-Filter control strategy improves 6.47%, 5.60% compared with the rule-based control strategy and wavelet-based
TABLE 5. The Energy consumption results with different EMSs.

| EMS       | ECMS-Filter EMS | Rule-based EMS | Wavelet Filter-based EMS |
|-----------|-----------------|----------------|--------------------------|
| Parameters | $E_{fe}$ | SoC | $v_{sc}$ | $E_{fe}$ | SoC | $v_{sc}$ | $E_{fe}$ | SoC | $v_{sc}$ |
| Initial state | 0 | 60% | 460.81 V | 0 | 60% | --- | 0 | 60% | 460.81 V |
| Final state | 21.98($10^3$ kJ) | 59.53% | 465.36 V | 24.21($10^3$ kJ) | 59.90% | --- | 25.29($10^3$ kJ) | 59.93% | 461.52 V |
| $E_{total}$ | 24.28($10^3$ kJ) | 25.85($10^3$ kJ) | 25.64($10^3$ kJ) |

VII. CONCLUSION

The development of real-time optimization EMSs is seen to have a better potential for improving the dynamic performance of the hybrid ship. In this paper, the sizing of the HESS for a fuel cell hybrid excursion ship is proposed based on the active topology of the HESS. The fuel cell as the main power source undertakes the steady power demand (nearly average power demand), and the battery-SC hybrid energy storage system undertakes the fluctuation of power demand. Based on the configuration of the hybrid power system, we develop the ECMS-Filter control strategy, which considers not only energy efficiency but also power sources degeneration. The experiment results indicate that the proposed control strategy has excellent robustness, and can minimize the fuel cost by keeping the fuel cell working in the high-efficiency range and prolong the lifetime of the fuel cell and battery.

To further improve the performance of the hybrid power system, our future work will focus on the real-time hardware implementation, the fuel cell degradation model, the battery degradation model and the integrated optimization problem considering the configuration and sizing of the power system and the design of the control strategies.

APPENDIX A

According to Fig. 9, the SC power output can be calculated as:

$$P_{sc}(s) = \frac{a s^2}{a s^2 + (1 + a K_p)s + K_p} P_{HESS}(s)$$

$$- \frac{K_p s}{s + K_p} (E_{sc,ref}(s) - E_{sc}(s)) \quad (A.1)$$

Assuming,

$$E_{sc,ref}(s) = E_{sc}(s) \text{ or } E_{sc,ref}(s) \approx E_{sc}(s) \quad (A.2)$$

The transfer function $P_{sc}(s)$ can be calculated from as,

$$P_{sc}(s) = \frac{a s^2}{a s^2 + (1 + a K_p)s + K_p} P_{HESS}(s) \quad (A.3)$$

Similarly, the transfer function $P_{bat}(s)$ can be calculated as,

$$P_{bat}(s) = \frac{(1 + a K_p) s + K_p}{a s^2 + (1 + a K_p)s + K_p} P_{HESS}(s) \quad (A.4)$$
APPENDIX B

In section V, the calculation process of the energy consumption is presented. Total energy consumption is calculated as:

\[ E_{\text{total}} = E_{\text{fuelcell}} + \Delta E_{\text{battery}} + \Delta E_{\text{sc}} \]  

(B.1)

\[ \Delta E_{\text{battery}} = (\Delta SoC \cdot E_{\text{battery\_normal}})/(\eta_{\text{fc}} \cdot \eta_{\text{bat}}) \]  

(B.2)

\[ \Delta E_{\text{sc}} = (\Delta SoV \cdot E_{\text{sc\_normal}})/(\eta_{\text{fc}} \cdot \eta_{\text{sc}}) \]  

(B.3)

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REFERENCES

[1] K. Kim, K. Park, J. Lee, K. Chun, and S. Lee, “Analysis of battery/generator hybrid container ship for CO₂ reduction,” IEEE Access, vol. 6, pp. 15437–15446, 2018.
[2] V. Eyring, I. S. A. Isaksen, T. Berntsen, W. J. Collins, K. J. Reddy and S. Natarajan, “Energy sources and multi-input DC-DC converter used in hybrid electric vehicle applications–A review,” Int. J. Hydrogen Energy, vol. 43, no. 28, pp. 15392–15397, Jul. 2018.
[3] Y. Gonzalez, S. Rodriguez, J. C. Guerra Garcia, J. L. Trujillo, and R. Garcia, “Ultrafine particles pollution in urban coastal air due to ship emissions,” Atmos. Environ., vol. 45, no. 28, pp. 4907–4914, Sep. 2011, doi: 10.1016/j.atmosenv.2011.06.003.
[4] E. Marmer and B. Langmann, “Impact of ship emissions on the Mediterranean summertime pollution and climate: A regional model study,” Atmos. Environ., vol. 49, no. 26, pp. 4659–4669, Aug. 2005, doi: 10.1016/j.atmosenv.2005.04.014.
[5] K. Ettihir, L. Boulon, and K. Agbossou, “Optimization-based energy management strategy for a fuel cell/battery hybrid power system,” Appl. Energy, vol. 156, pp. 26–34, Nov. 2015, doi: 10.1016/j.apenergy.2015.08.031.
[6] E. Marmer and B. Langmann, “Impact of ship emissions on the Mediterranean summertime pollution and climate: A regional model study,” Atmos. Environ., vol. 49, no. 26, pp. 4659–4669, Aug. 2005, doi: 10.1016/j.atmosenv.2005.04.014.
[7] F. Wang, X. Wang, Y. Qiu, Z. Zhang, and T. Li, “Adaptive management strategy for fuel cell/battery hybrid electric system,” Int. J. Hydrogen Energy, vol. 44, no. 16, pp. 9511–9523, Apr. 2019, doi: 10.1016/j.ijhydene.2018.11.046.
[8] J. Hou, J. Sun, and H. Hofmann, “Control development and performance evaluation for battery/fuel cell hybrid energy storage solutions to mitigate load fluctuations in all-electric ship propulsion systems,” Appl. Energy, vol. 212, pp. 919–930, Feb. 2018, doi: 10.1016/j.apenergy.2017.12.098.
[9] D. Shiu, Y. Kim, J. Seo, N. Chang, Y. Wang and M. Pedram, “Battery-supercapacitor hybrid system for high-rate pulsed load applications,” in Proc. Design, Automat. Test Eur., IEEE, Mar. 2011, pp. 1–4.
[10] D. Shiu, Y. Kim, Y. Wang, N. Chang, and M. Pedram, “Constant-current regulation-based battery-supercapacitor hybrid architecture for high-rate pulsed load applications,” J. Power Sources, vol. 205, pp. 516–524, May 2012, doi: 10.1016/j.jpowsour.2011.12.043.
[11] Y. Zhang and Y. Wei Li, “Energy management strategy for supercapacitor in droop-controlled DC microgrid using virtual impedance,” IEEE Trans. Power Electron., vol. 32, no. 4, pp. 2704–2716, Apr. 2017.
[12] S. Zhang, R. Xiong, and F. Sun, “Model predictive control for power management in a plug-in hybrid electric vehicle with a battery energy storage system,” Appl. Energy, vol. 185, pp. 1654–1662, Jan. 2017, doi: 10.1016/j.apenergy.2015.12.035.
[13] R. Hemmati and H. Saboori, “Emergence of hybrid energy storage systems in renewable energy and transport applications–A review,” Renew. Sustain. Energy Rev., vol. 65, pp. 11–23, Nov. 2016, doi: 10.1016/j.rser.2016.06.029.
[14] L. Zhang, X. Hu, Z. Wang, F. Sun, J. Deng, and D. G. Dorrell, “Multiojective optimal sizing of hybrid energy storage system for electric vehicles,” IEEE Trans. Veh. Technol., vol. 67, no. 2, pp. 1027–1035, Feb. 2018, doi: 10.1109/TVT.2017.2762368.
[15] H. C. Chen, Y. Qin, H. Cao, X. Song, C. Huang, H. Feng, and X. S. Zhao, “Synthesis of amorphous nickel-cobalt-manganese hydroxides for supercapacitor-battery hybrid energy storage system,” Energy Storage Mater., vol. 17, pp. 194–203, Feb. 2019, doi: 10.1016/j.ensm.2018.07.018.
[16] K. J. Reddy and S. Natarajan, “Energy sources and multi-input DC-DC converters used in hybrid electric vehicle applications–A review,” Int. J. Hydrogen Energy, vol. 43, no. 36, pp. 17387–17408, 2018.
[17] A. Djerouil, A. Houari, S. Zeghlache, A. Saim, M. F. Benkhoris, T. Mesbahi, and M. Machmoum, “Energy management strategy of Super-capacitor/Fuel cell energy storage devices for vehicle applications,” Int. J. Hydrogen Energy, vol. 44, no. 41, pp. 23416–23428, Aug. 2019.
[18] B. S. Sami, N. Sihem, and Z. Bassam, “Design and implementation of an intelligent home energy management system: A realistic autonomous hybrid system using energy storage,” Int. J. Hydrogen Energy, vol. 43, no. 12, pp. 19352–19365, Jun. 2018.
[19] J. Han, J.-F. Charpentier, and T. Tang, “An energy management system of a fuel Cell/Battery hybrid boat,” Energies, vol. 7, no. 5, pp. 2799–2820, 2014.
[20] X. Zhang, C. C. Mi, A. Masur, and D. Daniszewski, “Wavelet-transform based power management of hybrid vehicles with multiple on-board energy sources including fuel cell, battery and ultracapacitor,” J. Power Sources, vol. 185, no. 2, pp. 1533–1543, Dec. 2008.
[21] Q. Li, W. Chen, Y. Li, S. Liu, and J. Huang, “Energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle based on fuzzy logic,” Int. J. Electr. Power Energy Syst., vol. 43, no. 1, pp. 514–525, Dec. 2012, doi: 10.1016/j.ijepes.2012.06.026.
[22] Y. Wu, A. Ravey, D. Chenko, and A. Miraoui, “Demand side energy management of EV charging stations by approximate dynamic programming,” Energy Convers. Manage., vol. 196, pp. 878–890, Apr. 2019.
[23] S. Zhang and R. Xiong, “Adaptive energy management of a plug-in hybrid electric vehicle based on driving pattern recognition and dynamic programming,” Appl. Energy, vol. 155, pp. 68–78, Oct. 2015, doi: 10.1016/j.apenergy.2015.06.003.
[24] Z. Chen, C. C. Mi, B. Xia, and C. You, “Energy management of power-split plug-in hybrid electric vehicles based on simulated annealing and Pontryagin’s minimum principle,” J. Power Sources, vol. 272, pp. 160–168, Dec. 2014.
[25] B. S. Sami, “An intelligent power management investigation for stand-alone hybrid systems using short-time energy management strategy,” Int. J. Power Electron. Drive Syst. (IJPEDS), vol. 8, no. 1, p. 367, 2017.
L. X. L. H. LIN Xin-you, “Performance study and efficiency improvement of hybrid system dedicated to transport application,” Int. J. Hydrogen Energy, vol. 42, no. 17, pp. 12777–12789, Apr. 2017.

Y. Wang, Z. Sun, and Z. Chen, “Energy management strategy for battery-supercapacitor/fuel cell hybrid source vehicles based on finite state machine,” Appl. Energy, vol. 254, Nov. 2019, Art. no. 113707.

W. Shi, N. Li, C. Chu, and R. Gadh, “Real-time energy management in microgrids,” IEEE Trans. Smart Grid, vol. 8, no. 1, pp. 228–238, Jan. 2017.

P. García, J. P. Torreglosa, L. M. Fernández, and F. Jurado, “Viability assessment of demand response, islanding, and control of both fueling flows of the fuel cell hybrid power system under a variable load demand and an unknown renewable power profile,” Energy Convers. Manage., vol. 184, pp. 1–14, Mar. 2019, doi: 10.1016/j.enconman.2019.01.024.

N. Bizon, “Sensitivity analysis of the fuel economy strategy based on load-following control of the fuel cell hybrid power system,” Energy Convers. Manage., vol. 199, Nov. 2019, Art. no. 111946, doi: 10.1016/j.enconman.2019.111946.

K. Long, X. Wang, and X. Gu, “Multi-material topology optimization for the transient heat conduction problem using a sequential quadratic programming algorithm,” Eng. Optim., vol. 50, no. 12, pp. 2091–2107, Dec. 2018.

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---

[35] B. S. Sami, N. Sihem, B. Zafar, and C. Adnane, “Performance study and efficiency improvement of hybrid system dedicated to transport application,” Int. J. Hydrogen Energy, vol. 42, no. 17, pp. 12777–12789, Apr. 2017.

[36] Y. Wang, Z. Sun, and Z. Chen, “Energy management strategy for battery-supercapacitor/fuel cell hybrid source vehicles based on finite state machine,” Appl. Energy, vol. 254, Nov. 2019, Art. no. 113707.

[37] W. Shi, N. Li, C. Chu, and R. Gadh, “Real-time energy management in microgrids,” IEEE Trans. Smart Grid, vol. 8, no. 1, pp. 228–238, Jan. 2017.

[38] P. García, J. P. Torreglosa, L. M. Fernández, and F. Jurado, “Viability assessment of demand response, islanding, and control of both fueling flows of the fuel cell hybrid power system under a variable load demand and an unknown renewable power profile,” Energy Convers. Manage., vol. 184, pp. 1–14, Mar. 2019, doi: 10.1016/j.enconman.2019.01.024.

[39] N. Bizon, “Sensitivity analysis of the fuel economy strategy based on load-following control of the fuel cell hybrid power system,” Energy Convers. Manage., vol. 199, Nov. 2019, Art. no. 111946, doi: 10.1016/j.enconman.2019.111946.

[40] K. Long, X. Wang, and X. Gu, “Multi-material topology optimization for the transient heat conduction problem using a sequential quadratic programming algorithm,” Eng. Optim., vol. 50, no. 12, pp. 2091–2107, Dec. 2018.

[41] Z. Zhang was born in Shandong, China, in September 1994. He received the B.Sc. degree in marine engineering from Shanghai Maritime University, Shanghai, China, in 2016, and the M.S. degree from the Wuhan University of Technology, Wuhan, China, in 2019. He is currently pursuing the Ph.D. degree with the College of Software, Nankai University, Tianjin, China. His current research interests include computer vision and intelligent control.

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