Research on Teaching Reform of Cruise Emergency Drill Based on Virtual Simulation — Against the Background of Safety Supervision Requirements for Cruises in Hainan Free Trade Port

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Abstract: *Cruise emergency drill teaching faces cognitive load challenges arising from multi-system coordination, compressed time windows, and dense personnel distribution. The special shipping environment of Hainan Free Trade Port further introduces systematic compression effects on navigational area accessibility restrictions and the baseline of emergency response time. The traditional scripted drill mode exhibits adaptability limitations in dynamic scenario simulation, such as insufficient branch coverage and prolonged feedback delays. This study, supported by virtual simulation technology, constructs a teaching model for cruise emergency drills, which includes hierarchical modeling and interaction mechanisms for immersive emergency scenarios, a logically parametric design method for teaching-oriented emergency event chains, and a distributed virtual environment architecture for multi-role collaborative drills. On this basis, this study proposes a teaching process reconfiguration scheme oriented to regulatory requirements. Through modular deconstruction and dynamic reorganization, quantitative mapping rules for operational standardization based on regulatory indicators, and a multi-dimensional evaluation index system with formative feedback, it achieves the adjustability and traceability of drill teaching. This research provides a systematic theoretical framework and technical path for emergency drill teaching under the safety supervision requirements for cruises in Hainan Free Trade Port.*

Keywords: *Cruise emergency drill, Virtual simulation, Teaching model construction, Hainan Free Trade Port, Safety supervision constraints, Multi-dimensional evaluation*

Introduction

The emergency response capability of cruises is directly related to the safety of life at sea and the continuity of ship operations, and the effectiveness of its teaching and training holds an irreplaceable position in the shipping industry. With the development trends of larger cruise ships and more complex routes, the cognitive tasks involved in emergency drill teaching, such as information perception, state diagnosis, action decision-making, and execution verification, exhibit nonlinear coupling characteristics, which impose higher demands on trainees' basic operational skills and advanced coordination skills. The unique characteristics of Hainan Free Trade Port, including multi-port hopping, seasonal meteorological changes, and the precision constraints of the port entry and exit window periods, further compress the time baseline for emergency response. The traditional drill mode combining scripted scenarios and fixed-point practical operations finds it difficult to generate scenario variants with sufficient probability branches and also lacks the diagnostic capability for real-time behavior correction and individualized feedback. Therefore, it is clearly necessary to introduce virtual simulation technology to reconstruct the teaching model of emergency drills. On the one hand, hierarchical modeling and distributed virtual environments can reproduce the spatial topological structure of cruise cabins and the evolution process of disaster physical fields; on the other hand, parametric event chain design and modular process reorganization can adjust the difficulty gradient and training focus according to trainees' capability profiles. This study conducts teaching model construction and evaluation system design around the above issues, aiming to provide an operable technical solution for cruise emergency drill teaching under the constraints of special shipping environments.

1. Theoretical Foundations and Practical Challenges of Cruise Emergency Drill Teaching

1.1 Cognitive Task and Skill Decomposition of the Cruise Emergency Response Process

The cruise emergency response process exhibits notable characteristics such as multi-system coordination, compressed time windows, and dense personnel distribution. From the perspective of cognitive task analysis, the emergency response process can be divided into four recursive stages: information perception, state diagnosis, action decision-making, and execution verification. Each stage corresponds to a specific type of cognitive load. For example, the information perception stage relies primarily on spatial orientation recognition and abnormal signal screening, while the action decision-making stage involves resource scheduling logic and risk priority ranking. The decomposition of the above tasks needs to be combined with the unique cabin layout and passenger flow patterns of cruises, so as to form a quantifiable set of subtask nodes[1].

Based on the results of cognitive task decomposition, the corresponding skill system can be divided into two levels: basic operational skills and advanced coordination skills. Basic operational skills cover directly observable behavioral modules such as emergency equipment activation, cabin isolation operations, and public address command issuance. Advanced coordination skills, on the other hand, are directed toward the information sharing mechanism of the emergency command team, inter-role communication protocols, and reasoning and judgment capabilities under conditions of partial situational information deficiency. A nonlinear coupling relationship exists between the two levels of skills, meaning that the proficiency level of basic skills directly affects the response latency and error recovery efficiency in advanced coordination. Further analysis indicates that the higher the consistency of operation sequences in basic skills, the lower the demand for communication bandwidth in advanced coordination, which implies that basic skills training should be placed in the preceding stage during the teaching process.

1.2 Characteristics of Safety Supervision Constraints under the Special Shipping Environment of Hainan Free Trade Port

Cruise operation routes in Hainan Free Trade Port generally involve multi-port hopping and seasonal meteorological variation zones, forming a dynamic operational profile different from conventional coastal navigation. The safety supervision constraints in this environment are embodied as navigational area accessibility restrictions, precision requirements for the port entry and exit window periods, and the need for rapid verification of the qualifications of foreign shipboard personnel. The mapping of these constraints in emergency drill teaching manifests as follows: drill cases need to incorporate specific port geometric parameters and tidal variation curves, so that trainees face operational boundaries consistent with real navigation in virtual scenarios.

Further analysis shows that the above constraint characteristics produce a systematic compression effect on the time baseline of emergency response. For example, in some waters under the jurisdiction of Hainan Free Trade Port, the arrival time window for search and rescue forces is lower than the standard value recommended by the International Maritime Organization, requiring the onboard emergency organization to complete the entire chain of response from detection to action within a shorter time. When this compression effect is converted into teaching requirements, it is necessary to strengthen trainees' adaptability to time pressure and their decision-making speed under limited information conditions. The virtual simulation platform can parametrically reproduce the above constraint characteristics by adjusting the scenario clock multiplier and information update frequency. At the same time, the system can record the distribution of trainees' decision delays during the highly compressed window period, so as to quantify the impact curve of time pressure on operational accuracy.

1.3 Adaptability Limitations of Traditional Drill Teaching Modes in Dynamic Scenario Simulation

Traditional cruise emergency drills mostly adopt an organizational approach that combines scripted reasoning with fixed-point practical operations, and their scenario generation logic is based on preset event sequences and fixed personnel trigger nodes. When facing nonlinear emergency evolution processes, such as concurrent multiple failures or personnel behaviors deviating from expected paths, this approach exhibits problems of insufficient scenario coverage and missing branch responses. The core of dynamic scenarios lies in the probabilistic branching characteristics of causal transmission relationships between events, whereas the scripted mode finds it difficult to generate a sufficient number of branch logic variants without increasing labor costs[2].

From the perspective of feedback generation efficiency, the motion capture and evaluation in the traditional mode rely on observers' manual recording and post-hoc summarization, which results in trainees' inability to obtain real-time behavioral correction signals during the drill process. Especially in complex emergency tasks involving team coordination, delayed feedback makes it difficult for trainees to establish accurate associations between specific communication behaviors and subsequent event outcomes. Virtual simulation technology can compress feedback latency to the millisecond level through embedded behavioral recording and assessment modules, whereas traditional drill methods lack such real-time diagnostic capabilities at the technical architecture level, which constitutes their fundamental adaptability limitation when oriented toward teaching in highly dynamic emergency scenarios. The traditional mode also finds it difficult to generate differentiated feedback reports for individual trainees, as all participants receive similar evaluation information and are unable to identify their specific weak links in cognitive task decomposition.

2. Construction of a Teaching Model for Emergency Drills Based on Virtual Simulation

2.1 Hierarchical Modeling and Interaction Mechanisms for Immersive Emergency Scenarios

The hierarchical modeling of immersive emergency scenarios adopts a construction path that superimposes behavioral rules onto scenario primitives. The bottom layer is the static environment layer, which contains the spatial topological structure of cruise cabins, equipment distribution locations, and emergency signage systems, all of which are geometric and semantic information that does not change over time. The middle layer is the dynamic event layer, which hosts physical process models with spatiotemporal evolution patterns, such as fire spread, water ingress rates, and smoke diffusion. The top layer is the interaction response layer, which records trainees' operational inputs and their modification operations on scenario state variables. The three layers are coupled through event trigger functions; for example, a change in the opening status of a cabin door can alter the boundary conditions for smoke diffusion in the middle layer.

The design of interaction mechanisms needs to satisfy two constraints simultaneously: teaching repeatability and situational authenticity. To achieve the former, the system adopts a discrete event-driven architecture and encodes each trainee operation as a state-change command with a timestamp. To achieve the latter, the interaction responses must follow the physical delays and feedback patterns in actual cruise emergency operations, such as the nonlinear rising curve of water pressure establishment after a fire hose is opened. The virtual environment introduces haptic proxies and spatial audio cues to enhance trainees' perceptual consistency regarding cabin orientation and relative equipment distances, thereby reducing the probability of spatial disorientation in the immersive environment. The interaction interface also supports multimodal input fusion, allowing trainees to use controller operations, voice commands, and head movement tracking simultaneously, so as to simulate the multi-channel information processing demands in real emergency scenarios.

2.2 Teaching-Oriented Parametric Design Method for Emergency Event Chain Logic

The parametric design of emergency event chain logic takes the skill-level decomposition of teaching objectives as input conditions. Each event chain consists of an initial triggering event, intermediate evolution nodes, and terminal evaluation states, in which the branch probabilities and time intervals of the intermediate nodes serve as adjustable parameters. The parametric expression adopts a rule-based logic generator and performs a Cartesian product combination of accident types, such as engine room fires, passenger overboard, and public health events, with the current navigation phases of the cruise, such as berthing, departure, and sea navigation, so as to form the initial condition matrix of the event chain. The parameter value ranges are calibrated according to the statistical data on event evolution times provided in relevant training manuals of the International Maritime Organization. The parametric method also allows for the introduction of external environmental variables, such as wind speed, visibility, and sea state levels, so that the evolution paths of the event chain more closely approximate actual maritime conditions[3].

The teaching orientation in this design method is embodied as the adjustability of the difficulty gradient. By adjusting the parameters in three dimensions, namely the information presentation delay in the event chain, the insertion frequency of interfering events, and the length of the critical decision window, the system can generate scenario variants that adapt to the capability levels of different trainees. Parametric design also supports intensive training on specific teaching weak links. For example, when the basic skill decomposition shows that trainees have a relatively high error rate in the "information perception" stage, the system can reduce the branch complexity of the intermediate nodes while compressing the information refresh interval, so as to focus training on the cognitive processing efficiency of that stage. All parameter configurations can be stored as preset templates for teaching organizers to call and modify. The parameter configuration library supports version management and can automatically optimize parameter intervals based on accumulated feedback from teaching data, thereby reducing the subjective bias of manual parameter tuning.

2.3 Distributed Virtual Environment Architecture for Multi-Role Collaborative Drills

The distributed virtual environment architecture adopts a client-server model based on permission grading. The server side maintains a unified drill scenario state database, including ship motion attitudes, disaster physical field evolution, and operation histories of each role. The client side loads corresponding interaction interfaces and information display ranges according to the logged-in role type. For example, the commander's view obtains a global overview of cabin states and resource distribution maps, while the view of on-site response personnel displays only local information and communication channels of the deck area where they are located. The network communication protocol adopts a reliable transmission scheme with state synchronization mechanisms to ensure that all clients receive consistent virtual timestamps, thereby avoiding action sequence disorders caused by latency differences. The server side also embeds a timeline management module that supports global pause, step-by-step progression, and playback functions, facilitating the replay and analysis of critical nodes during the teaching process[4].

The logical support for multi-role collaboration is embodied in the formal definition of interdependencies among roles. The system predefines authorization chains and reporting paths between roles. For example, only the commander role has the permission to activate the ship-wide public address system, while other roles can only send information requests to specific superior roles. During the drill, the system automatically records the message transmission frequency and response latency between roles, serving as objective indicators for evaluating team coordination efficiency. To resolve resource conflicts under multi-user concurrent operations, the environmental architecture incorporates a priority-based operation lock mechanism. When two trainees issue mutually exclusive commands to the same virtual device, the system arbitrates the effective operation according to the order of post authorities stipulated in the accident handling procedures. The architecture also supports access from heterogeneous terminals, allowing some trainees to participate in the same drill using virtual reality headsets while others use desktop terminals, thereby lowering the threshold for hardware deployment.

3. Reconstruction of the Teaching Process and Evaluation System Oriented to Regulatory Requirements

3.1 Modular Deconstruction and Dynamic Reorganization of the Virtual Drill Teaching Process

The modular deconstruction of the virtual drill teaching process cuts the complete emergency drill procedure into independently editable teaching units. Each unit corresponds to a subtask with clear start and end boundaries, such as fire detection confirmation, initial alarm triggering, passenger muster station guidance, or fire team deployment. The deconstruction is based on two dimensions, namely the time sequence of emergency response operations and the responsible posts, ensuring that different units not only have logical predecessor-successor relationships but also allow independent operation when detached from the original sequence. Each teaching unit encapsulates the required virtual scenario slices, role permission configurations, and evaluation indicator sets, thus forming self-consistent teaching objects.

The dynamic reorganization mechanism allows teaching organizers to adjust unit combinations according to trainees' capability profiles. The reorganization rules are based on the decision tree structure of cruise emergency response and designate some non-critical path units as skippable or adjustable in sequence. For example, when trainees have already mastered the units related to communication protocols, the system can replace that unit with a time-compressed version, retaining only its logical interfaces with other units. Specific constraints in the navigation environment of Hainan Free Trade Port, such as the shortened window for personnel evacuation in narrow waterways, can be reflected by inserting additional judgmental units that require trainees to rank two evacuation strategies within a limited time. The reorganized teaching process automatically generates new evaluation weight distributions, so as to avoid assessment blind spots caused by unit skipping[5].

3.2 Quantitative Mapping Rules for Operational Standardization Based on Regulatory Indicators

Regulatory indicators originate from the verifiable requirements of navigation water safety management authorities regarding cruise emergency capabilities. These indicators exist in the form of qualitative or semi-quantitative normative texts, such as emergency communication response time limits, passenger muster station headcount accuracy rates, or the completion sequence of fire-fighting equipment operations. The quantitative mapping rules first convert the above normative texts into operational elements with clear observable variables. Each operational element corresponds to a behavioral event that can be captured by the virtual simulation system, such as pressing an alarm button, sending a command on a specific channel, or completing a sequence of protective equipment donning actions. The granularity setting of operational elements matches the sensor triggering frequency in the virtual system, so as to avoid unobservable ambiguous indicators.

The core of the mapping rules lies in converting the allowable deviation ranges in the regulations into boundary conditions for the scoring function. Taking emergency communication as an example, the regulations require that the time interval from detection to alarm should not exceed a certain threshold. The mapping rules set this threshold as the starting point of a linear penalty function, and after the threshold is exceeded, the penalty rate is set in segments according to the overtime multiplier. For regulations involving operational sequences, such as the requirement that ventilation must be isolated before releasing extinguishing agents, the mapping rules adopt a sequence constraint matrix to describe permitted and prohibited sequence combinations. The relationship between each pair of operational elements in the matrix is encoded as binary judgment values, either permitted or prohibited. During the drill, the system scans the trainees' operational sequences in real time and compares them against the matrix. Once a prohibited sequence is violated, an immediate marker is triggered. The above mapping rules are stored as editable configuration files, so as to enable rapid synchronization when regulatory indicators are updated.

3.3 Multi-Dimensional Evaluation Index System for Formative Feedback in Drill Teaching

The evaluation index system required for formative feedback differs from summative evaluation, and its design goal is to provide a basis for behavioral adjustment during the drill process rather than after its completion. The index system includes three dimensions: the temporal dimension records the deviation values between the timestamps of trainees' completion of each subtask and the standard time window; the sequential dimension records the edit distance between the operational path and the reference path; and the state dimension records the differences between the instantaneous values of key variables in the virtual scenario, such as the fire spread area and the cumulative number of evacuated passengers, and the target control ranges. The indicators of the three dimensions are sampled synchronously on the time axis, and the sampling frequency is dynamically adjusted according to the time sensitivity of each subtask, with higher sampling rates adopted in highly sensitive phases, such as before and after decision points.

The comprehensive output form of the multi-dimensional indicators consists of two complementary views: a real-time visualization dashboard and a post-hoc heatmap. The real-time dashboard displays the degree of deviation of each trainee in the current dimension, and uses non-verbal symbols, such as color gradient changes or graphic contour shifts, to indicate the direction of attention, so as to avoid disrupting immersion. The post-hoc heatmap superimposes the indicators of the three dimensions onto the spatial layout of the virtual scenario. For example, when three markers, namely high temporal deviation, high sequential deviation, and state variable exceedance, appear simultaneously near a certain cabin, it indicates that there are systematic problems in the teaching module corresponding to that area. The index system also supports correlation analysis among indicators, detecting whether the sustained deviation of one dimension predicts the deterioration of another dimension. For example, when the accumulation of sequential operation deviations reaches a certain level, the temporal deviation begins to increase significantly, which provides an early-warning basis for teaching intervention.

Conclusion

Starting from cognitive task decomposition, this study systematically analyzes the hierarchical skill structure in the cruise emergency response process and the impact of safety supervision constraints in Hainan Free Trade Port on drill teaching, and identifies the adaptability limitations of existing traditional modes in dynamic scenario simulation. On this basis, this study constructs a teaching model for emergency drills based on virtual simulation, covering hierarchical modeling of immersive scenarios, parametric design of event chain logic, and a multi-role distributed collaborative architecture. It also proposes methods for modular deconstruction and dynamic reorganization of the teaching process, quantitative mapping rules for operational standardization based on regulatory indicators, and a multi-dimensional evaluation index system for formative feedback. The above achievements provide a theoretical basis and design paradigm for the application of virtual simulation technology in the field of cruise emergency teaching. Future research can be deepened along the following directions: first, to explore adaptive parameter optimization algorithms based on trainees' behavioral data, so that the branch probabilities and difficulty gradients of event chains can dynamically match changes in individual cognitive load; second, to incorporate eye-tracking and physiological signal indicators into the evaluation system, so as to more finely characterize the cognitive processing efficiency in the information perception and state diagnosis stages; and third, to expand the large-scale concurrency capability of the distributed virtual environment, so as to support the construction of joint drill scenarios involving multi-ship coordination or ship-shore linkage.

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