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The key to intelligent FLNG offloading lies not in perception but in coordination: A systems engineering perspective

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The floating liquefied natural gas (FLNG) unit—a high-end offshore engineering facility integrating offshore natural gas pretreatment, liquefaction, storage, and offloading—is emerging as a critical carrier for the efficient exploitation of deep-sea gas resources.[1] With its inherent mobility, modularity, and high efficiency, the FLNG system enables the economical development of remote and marginal gas fields, effectively reducing dependence on onshore facilities and environmental impact, in line with the global trend of offshore energy development toward deeper waters, farther offshore, and greener solutions.

Among these, the offloading transfer system, as the key link connecting the FLNG unit with LNG carriers and receiving terminals, is critical to the stability and economics of the entire system.[2] However, current FLNG offloading operations face high-dimensional uncertainties arising from complex sea states, multi-body dynamic interference, cryogenic media risks, and human errors. Existing offloading control relies largely on operators' manual experience to judge vessel motion trends and connection timing, lacking real-time perception of dynamic risks and the capability for intelligent decision-making and autonomous execution.

This commentary identifies the integrated implementation of intelligent perception, autonomous decision-making, and coordinated control as the key pathway to achieving intrinsic safety and ultimate efficiency in offloading operations.

OFFLOADING PROCESS MECHANICS

The working environment of an FLNG rigid offloading system differs fundamentally from that of an onshore LNG receiving terminal, and this distinctiveness dictates far more demanding control requirements than those for conventional shore-based facilities. In terms of spatial motion, during side-by-side operations the FLNG unit and the LNG carrier are moored in parallel, and each vessel undergoes six-degree-of-freedom motions under wave excitation.[3] The relative motion between the two vessels is more complex and is further affected by hydrodynamic interference, with the operational wave height generally limited to within 3 meters. The offloading arm, through multiple swivel joints and a floating compensation mechanism, must flexibly accommodate the relative displacement and attitude changes between the vessels while delivering LNG. Once the relative motion exceeds the design envelope, the emergency release system (ERS) is activated, interrupting the operation. The cryogenic LNG medium is transferred through the offloading arm in a liquid state at -162 °C and a pressure of 1.82 MPa. The extremely low-temperature environment imposes stringent requirements on the sealing performance of swivel joints and the low-temperature toughness of piping materials; any minute seal failure may lead to leakage or even cold brittle fracture. The control system must therefore continuously monitor and comprehensively analyze temperature gradients, pressure fluctuations, and seal integrity. The continuity of offshore offloading is strictly constrained by weather windows; once initiated, tens of hours of continuous transfer must be completed within a limited time window. Unplanned shutdowns lead to berthing wait times and cause significant economic and time losses.

These three constraints—dynamic coupling, cryogenic media, and window-limited operations—imply that control technologies for FLNG offloading cannot simply be transplanted from onshore LNG receiving terminals; a dedicated intelligent control technology system must be developed.

DIGITAL TWIN AND VISUALIZATION TECHNOLOGY

Digital twin technology is a core enabling technology for the intelligent upgrading of industrial equipment. By constructing a dynamic model in virtual space that is highly consistent with the physical entity, it realizes closed-loop control characterized by virtual-physical mirroring and virtual-guided control. In the FLNG domain, the application potential of digital twin technology is particularly prominent. Digital twin technology can map the real-time operating state of the offloading system into three-dimensional virtual space, enabling visual monitoring and dynamic simulation of equipment states.[4] By constructing a high-fidelity multi-physics coupled model—integrating structural dynamics, fluid mechanics, and control theory—it can simulate complex physical phenomena such as boom vibration, fluid flow, and mooring tension during offloading, thereby achieving dynamic inference of system behavior. On this basis, digital twins can further provide "simulation rehearsal" capability, simulating system responses under different sea states and operational strategies in virtual space to provide a quantitative basis for operational decision-making.

KNOWLEDGE ONTOLOGY AND INTELLIGENT DECISION-MAKING

A knowledge ontology is a formal specification of a domain conceptualization that, by constructing a unified and unambiguous reference vocabulary, provides the foundation for semantic integration and automated reasoning over heterogeneous data. In an FLNG offloading system, physical entities such as offloading arms, swivel joints, mooring lines, offloading pumps, valves, and pipelines, together with their monitored properties (temperature, pressure, and flow rate), can be explicitly modeled by means of a domain ontology, thereby bridging the semantic gaps among heterogeneous data sources including distributed control systems, sensors, equipment ledgers, and operating procedures. Existing studies have constructed ontologies for offshore petroleum production facilities; such an ontology adopts a basic formal ontology (BFO) as the top-level ontology and the Industrial Ontology Foundry (IOF) core ontology as the middle level, elicits requirements from domain experts through competency questions, defines entity categories and relations in the genus-differentia form, and is ultimately implemented in the OWL 2 language to support description logic queries and automated reasoning.[5] Transitive relations such as composition (component_of) and connection (connected_to) can also be defined, allowing a reasoner to automatically infer the propagation paths of fluids between equipment. This mechanism can be directly transferred to the FLNG offloading scenario to characterize the complete process chain of "storage tank—offloading pump—offloading arm—swivel joint—carrier tank" and the propagation of anomalies such as leakage and pressure fluctuations along the topological structure. Figure 1 illustrates the domain knowledge for intelligent FLNG offloading.

Serving as the semantic backbone of the digital twin, the knowledge ontology endows condition-monitoring data with explicit semantics, integrating scattered time-series data, equipment information, and process knowledge into a reasoning-capable knowledge graph. This in turn supports semantic querying, correlation analysis, and intelligent decision-making, compensating for the limited interpretability of purely data-driven methods in scenarios with scarce samples and unclear mechanisms.

INTELLIGENT COORDINATION AND CONTROL MECHANISM

The key to intelligent FLNG offloading lies not in "seeing clearly" the system

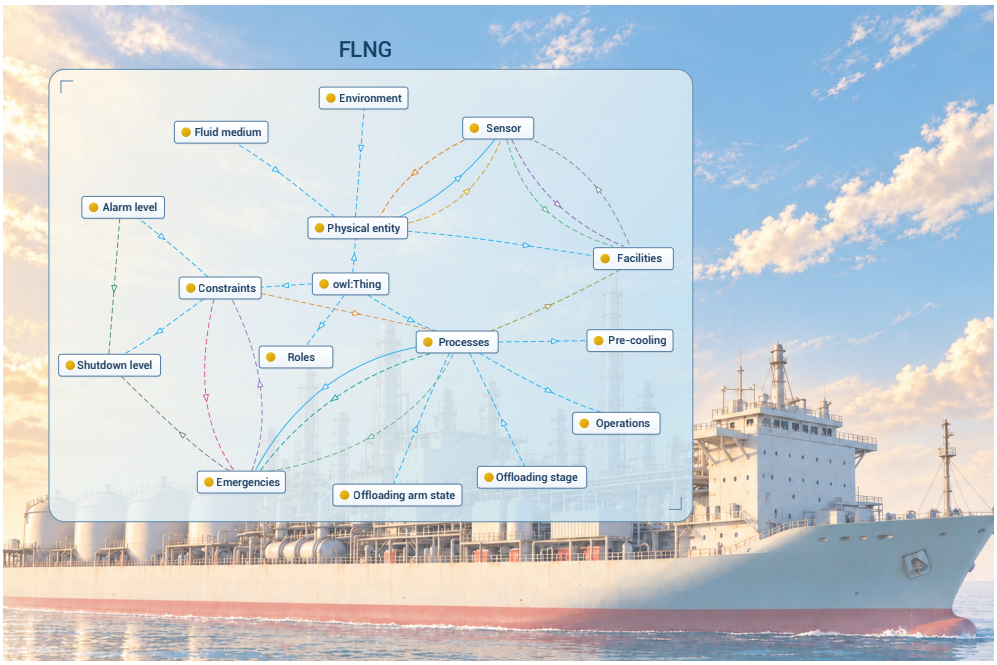


Figure 1. Conceptual Framework of Domain Knowledge for Intelligent FLNG Offloading.

state but in "coordinating" the coupled responses of multiple subsystems under varying sea conditions. Digital twins address the problem of "seeing clearly," and knowledge ontologies address the problem of "understanding correctly," but the intrinsic safety and ultimate efficiency of offloading operations ultimately depend on whether multiple actuators—pumps, valves, offloading arms, mooring, and ballast systems—can be scheduled in a coordinated manner across multiple time scales ranging from milliseconds to hours, so that "perception–decision–execution" forms an unbroken closed loop. The core of coordination is to dynamically solve a multi-objective optimization problem under safety constraints: maintaining the relative motion within the design envelope and ensuring cryogenic seal integrity, while shortening the offloading window and controlling losses and demurrage costs—essentially an online trade-off between safety and efficiency.

To this end, a three-layer "planning–decision–execution" coordination architecture can be established. The planning layer determines the offloading task window and the overall rate profile on an hourly scale based on sea-state forecasts and carrier arrival schedules; the decision layer solves for the optimal offloading parameters under safety constraints on a minute-level cycle, including offloading pump speed, valve opening, ballast compensation, and compliant control commands for the offloading arm; and the execution layer drives the actuators to respond in a coordinated manner on a millisecond-level cycle, ensuring that the system always operates within the design envelope. Coordination is thus not an additional stage after perception but the organizing logic that runs through the entire perception–decision–execution process—the key to advancing FLNG offloading from "seeing clearly" to "controlling reliably."

CONCLUSION

Based on the above analysis, this study recommends that future development of intelligent control technologies for FLNG rigid offloading systems focus on the following directions. At the system architecture level, a layered and decoupled design philosophy should be adopted to build a standardized control framework encompassing data acquisition, data processing, application services, and user interaction, ensuring system scalability and reliability in complex marine environments. At the digital twin level, multi-physics coupled modeling should be integrated with real-time data-driven techniques to progressively advance from static three-dimensional visualization to dynamic simulation-based inference, fully exploiting the core value of digital twins in condition monitoring and operation optimization. At the intelligent early-warning level, "mechanism–data" hybrid ontology-based modeling methods should be developed to overcome the technical difficulties posed by scarce fault samples and non-stationary operating conditions in FLNG scenarios, thereby improving model generalization and interpretability.

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DECLARATION OF INTERESTS

The authors declare no competing interests.