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Design and implementation of a triple-redundant dynamic positioning control system for deepwater drilling rigs

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ABSTRACT

Triple-redundant control architecture of the main control station is proposed for dynamic positioning (DP) system from a practical point of view according to the International Maritime Organization's (IMO) DP Class 3 notation. To improve the single fault tolerance, both operator station systems and real-time control computer systems are designed with triple modular redundancy. Hierarchical software layers of the triple-redundant control architecture are implemented based on the different real-time response requirements of the layers. Input and output voting are incorporated to the positioning task to detect and isolate faults in the sensors and in the control system. Hard-in-the-loop (HIL) testing system together with model-scale tests are conducted to verify the proposed triple-redundant control architecture. The feasibility and fault-tolerant capability of the triple-redundant hardware and software architecture both in HIL and model tests are demonstrated.

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1. Introduction

Jack-up barge and anchoring have been used by offshore drilling units as a passive mooring solution, which allow a Jack-up or a Spar to position itself on the sea floor above the operation location. However, drilling in deep waters makes the anchoring unfeasible and less economical due to the limited length of mooring lines, besides the problems of cable-lines, pipelines and templates on the sea bottom. The high and continuous energy demand in the global oil and gas markets has motivated the increased use of dynamic positioning (DP) system for marine vessels, especially for deepwater drilling operations. As a positive positioning solution, DP systems enable the vessel to maintain its position and heading exclusively by means of thrusters in the presence of wind, current and wave disturbances [1], allowing many of offshore operations possible that were not feasible by using single-point or multi-point mooring before.

In DP studies, the focus has customarily been on the filtering and controller design since the DP system is commercially available. Advanced controller together with observer design at the plant control level [2,3] has been intensively studied, e.g. nonlinear output feedback controller [4,5], nonlinear passive weather optimal controller [6], fault-tolerance controller [7], backstepping and robust controller [8,9], adaptive fuzzing controller [10]. Guidance systems together with DP operator's manual inputs is usually used to generate a reference trajectory or set-points for the vessel to track as various DP applications required, and advanced guidance system involves optimal path planning, weather routing and way-point tracking. The reference models [1,11] are addressed for the smooth transitions in chasing of the desired way-points. Pipe dynamics and riser end angles response [12,13] can be considered in the DP guidance system for optimal position set-point chasing.

For the low level control, propulsion controller in extreme conditions has been addressed [14,15], where methods for robust thruster controller design accounting for severe thrust losses due to ventilation and in-and-out-of-water effects are developed. A new method based on moment and power control of the propellers and thrusters is proposed by Sørensen et al. [16], where the relationships of force to moment and force to power are used instead of calculating the speed and pitch set-point based on force to speed/pitch relationship. For the energy control of DP system, the power/energy management systems (PMS/EMS) are studied to ensure the sufficient available power for the actual DP operation [17].

For the consideration of high propulsion efficiency, more rotated thrusters and propellers are used in dynamically positioned ships and semi-submersible platforms or rigs nowadays, such as azimuth thrusters and podded propeller, which results in an over-actuated constrained control/thrust allocation problem. The over-actuated control allocation problem generally can be formulated as an

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optimization problem subject to actuator mechanical constraints, power constraints as well as other operational constraints [18–22], where the optimal objective typically is to minimize the use of control effort (or power). Thrust allocation methods for ships and underwater vehicles can be categorize as linear unconstrained model [23], linear quadratic constrained model [24,25] and non-linear constrained model [26]. It should be noted that the on-line iterative solution of linear quadratic constrained model and nonlinear constrained model will be time-consuming at each sample [27], which may affect their usage on the real-time control applications.

In other fields of DP research topics, Metrikin et al. [28] presented the numerical simulation of DP applications in ice, some challenges associated with numerical ice modeling were reviewed and approaches for modeling the ice loads were classified into three groups: empirical and statistical models, experimental data series methods, and physically based modeling. Extensive DP simulators are applied to test and verify the software-based control system, power managements systems, and thruster control systems [24,25,29,30]. Software programming methods for DP capability analysis have been discussed by Mahfouz and Hussein [31], and Mahfouz [32].

It is important to improve the operational availability and positioning accuracy for DP operated vessels making it possible to conduct all kinds of missions in harsh sea states by employing advanced safety-related design and technologies. Although the International Maritime Organization (IMO) and the different Classification Societies (CS) have different class notations for DP systems [33,34], they all put the same emphasis on the safety of deep-water operations. The research concerned redundant DP control systems, in particular, the actual implementation and realization of Class 2, Class 3 systems are still open. The advanced IT technologies, i.e. N-Modular Redundancy (NMR) with specific voting techniques [35–37] incorporated into safety-critical computer control systems (e.g. fight control system, nuclear power plant control) suggests that it is possible to design sophisticated and much more reliable DP control system to compliant to the higher class notations. Besides, the development of hydroacoustic position (HPR) reference system and the commercialization of global navigation satellite system (GNSS) [38], together with advances in computer science, have made accurate and reliable DP systems possible.

This paper makes an effort to design and implement the triple-redundant main control system of DP Class 3. The control configuration solution of Class 3 notation is discussed in Section 2, the PC-104 bus based hardware architecture of DP processing unit is also presented. In Section 3, the hierarchical software architecture of the main DP control station is implemented with three layers based on its different real-time response requirements, some fault-tolerant capability of the triple-redundant control system is detailed. The hardware-in-the-loop (HIL) testing is conducted to verify the software function and redundancy handling. Finally, model-scaled tests are carried out to verify the proposed control scheme.

2. Development of triple-redundant hardware architecture

2.1. Control solution discussion of DP Class 3 notion

Due to the safety reasons and operational requirements, DP systems are subjected to the IMO's regulations and the different CS' rules, such as DNV GL, ABS, LRS and CCS, etc. According to the IMO's guidelines, dynamically positioned vessels are classified as Equipment Class 1, Class 2 and Class 3 addressing the reliability based on the redundancy and fault tolerance control. Most classification societies have their own notations, for example, the class notations

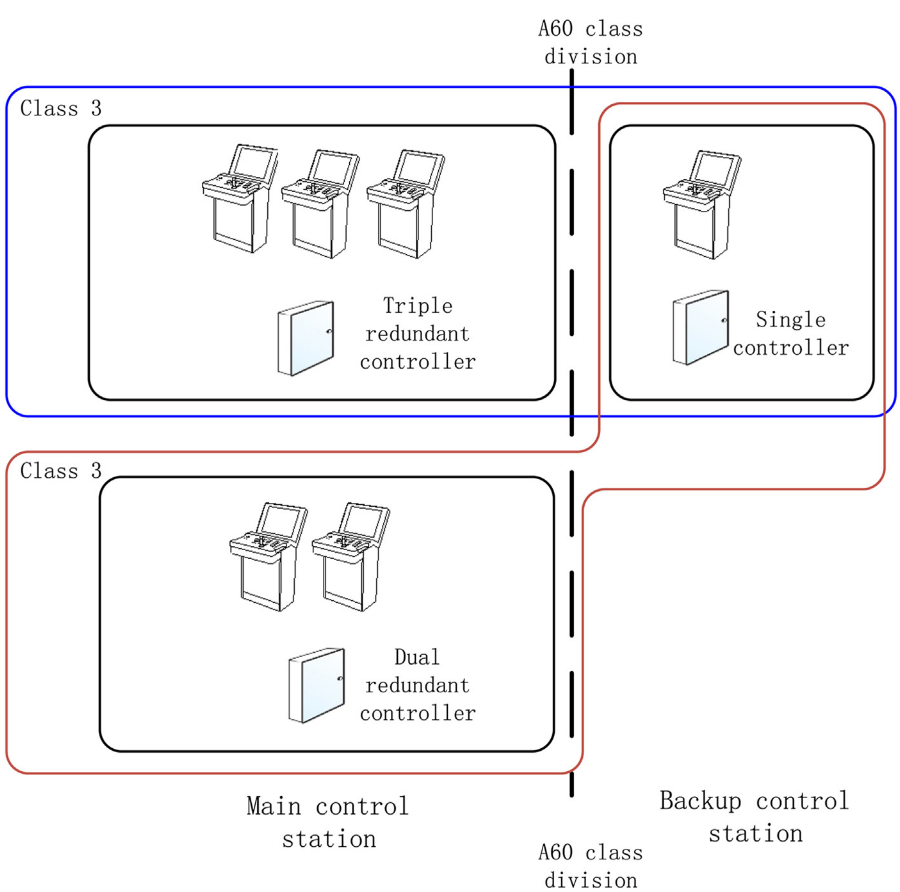

Fig. 1. The control configuration of DP Class 3.

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